Soil Interaction and Motion Planning for the Axel Rover

Senior Thesis

California Institute of Technology

Mechanical Engineering

Ruslan Kurdyumov

Mentor: Prof. Joel Burdick

Abstract

Soil interaction experiments were conducted on the Axel rover at JPL. Axel is a symmetric, two-wheeled, tethered rover designed for accessing extreme planetary terrain. The tests were conducted to develop motion planning algorithms that would enable Axel to successfully navigate through different soil types and slope angles without getting stuck, while optimizing power usage. Slip ratio increased roughly linearly with increasing wheel speed and increased drastically with increased slope angle. Slip ratio was about 2 times higher for loose sand than for compact sand. Power usage increased linearly with slope angle, and was over 1.5 times higher in loose sand than in compact sand. Further work involves testing at higher slope angles and developing reliable sinkage test beds.

Table of Contents

Introduction

Motivation

In light of the discovery of bright deposits on Martian crater walls, there is increasing interest within NASA to develop new technology to access extreme planetary terrains. Current rover technology is incapable of accessing these scientifically interesting areas. Axel is a minimalist tethered rover designed for sampling extreme planetary terrains, such as crater walls. Axel consists of two wheels connected by a cylindrical body, caster arm, and actively controlled tether. Motion is achieved through only three actuators: one for each wheel, and one for the caster arm and tether. The current version of Axel is human-controlled and has primitive motion planning. Axel is able to navigate through rough terrain by using its paddlewheels, tether, and the reaction from the caster arm (see Figure 1). We seek to develop motion planning algorithms for Axel that would allow the rover to successfully navigate to a target on different slopes and soil compositions while optimizing power usage and avoiding getting stuck.

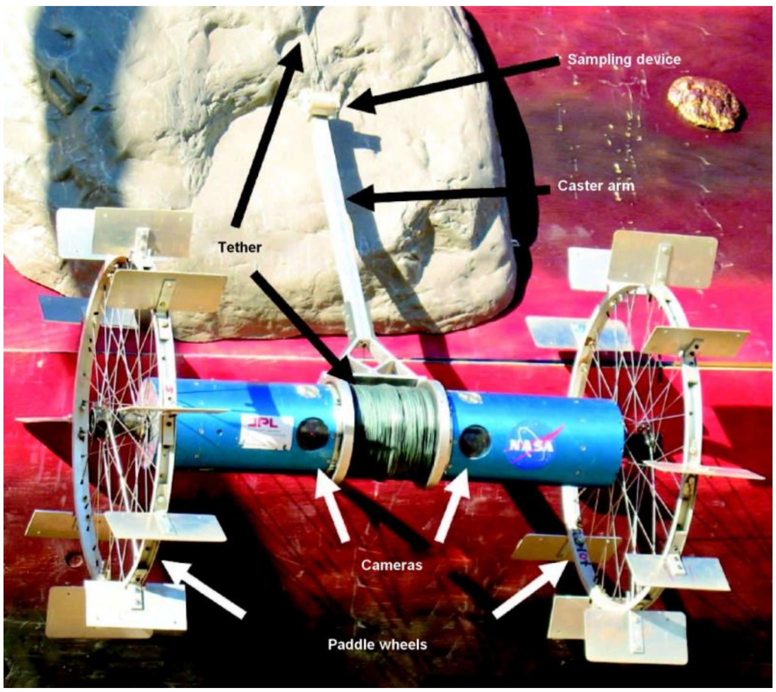

Figure 1: Labeled Axel rover [1]

Previous work

Previous terramechanics work on Axel has revealed some valuable insights. Models of the paddlewheels reveal superior performance than traditional wheels at higher contact point angles[2]. Moreover, the sinkage of the paddlewheels in soft soils is not significant enough to impair their performance. Finally, the efficiency of the paddlewheel design is about half the efficiency of a traditional wheel design for speeds of 0.1 to 0.4 m/s.

Some experimental work has been done on energy use by Axel. Table 1 lists standardized energy costs related to operating Axel using different driving modes on different ground types. Rolling mode involves driving by rotating the wheels, tumbling mode involves driving by using the caster arm, and driving mode is a combination of the two used on slopes. The tests were done on an old version of Axel without paddle wheels, so results are not directly comparable. However, we will still examine how well the values compare (for consistency) in the 'Comparison to previous work' section.

Table 1: Comparing Energy Costs [3]

Drive Mode	**Ground Type**	**Ground Inclination**	**Avg. Max Energy Cost ± Standard Error (J/kg*m)**
Rolling	Loose sand	0°	35.55 ± 1.05
Tumbling	Loose sand	0°	19.71 ± 0.46
Driving	Packed dirt	13°	35.84 ± 0.50
Rolling	Packed dirt	13°	28.42 ± 2.03

Methods

Slip testing methods

In order to experimentally test slip and sinkage of Axel, tests were performed at the Mini Mars Yard and the Mars Yard at JPL. In the Mini Mars Yard, two flat, 15-foot long tracks were prepared – a compact sand track and a loose sand track (Figure 2). In the Mars Yard, four sloped tracks were constructed: Track 1 with an average slope of 6.6°, Track 2 with an average slope of 4.4°, Track 3 with an average slope of 7.0°, and Track 4 with an average slope of -4.3° (Axel was driven downhill). The tracks are summarized in Table 2. Slope angles were derived by using a digital angle meter to measure the slope angle along the length of the track. The results are presented in the Appendix. The tracks consisted of somewhat compact soil, composed of rocky clay with small pebbles (Figure 3).

Figure 2: Compact sand track (left) and loose sand track (right)

Figure 3: Track 2 (left) and Track 3 (right). Note that Tracks 1, 2 and 4 were constructed in the same general vicinity so their soil properties were similar.

Table 2: Track Summaries

Track name	Length (ft)	Slope angle (deg)	Location	Soil type
Compact	15	0	Mini Mars Yard	Sandy, compact
Loose	15	0	Mini Mars Yard	Sandy, loose
1	10	6.6	Mars Yard	Clayey with small pebbles
2	13 ft, 1 in.	4.4	Mars Yard	Clayey with small pebbles, end of track somewhat loose and sandy
3	12	7.0	Mars Yard	Clayey with small pebbles
4	10	-4.3	Mars Yard	Clayey with small pebbles

Since Axel does not currently have accurate on-board sensors to measure wheel rotation, the caster arm was used to drive Axel. Once the head of the arm rotated into the ground, the caster arm rotation converted to wheel rotation. Previous calibration measurements provided angular speeds for the caster arm based on observed ‘caster speeds’ (pre-programmed speeds displayed while operating the caster arm). The calibration measurements were obtained by timing one rotation of the caster arm for three different caster speeds. A theoretical body speed could be derived by assuming that the caster rotation was fully transformed into wheel rotation once the caster arm hits the ground.

Since the on-board accelerometer did not provide reliable data, Axel’s body speed was measured by timing how long it took the rover to navigate the tracks.

Sinkage testing methods

Sinkage data was acquired by attaching adhesive tape to a paddle on Axel’s left and right wheel. The sinkage for each wheel was determined by the depth of the sand residue left on each paddle.

Power testing methods

Power usage data was acquired from Elmo controller voltage and current measurements on the caster arm as each trial was conducted.

Results

Calibration of caster speed

Previous calibration measurements of the Axel caster arm angular speed have been done (Figure 4). The linear fit is accurate with $R^2 \approx 1$. Assuming perfect conversion of caster arm rotation to wheel rotation, the angular speeds correspond to 0.05, 0.10, and 0.15 m/s, respectively. The linear fit was also assumed to apply to the full range of Axel caster speeds (1 to 14), although caster speeds higher than 13 (0.33 m/s) were not used during experimentation since the caster motor is saturated at speed 14.

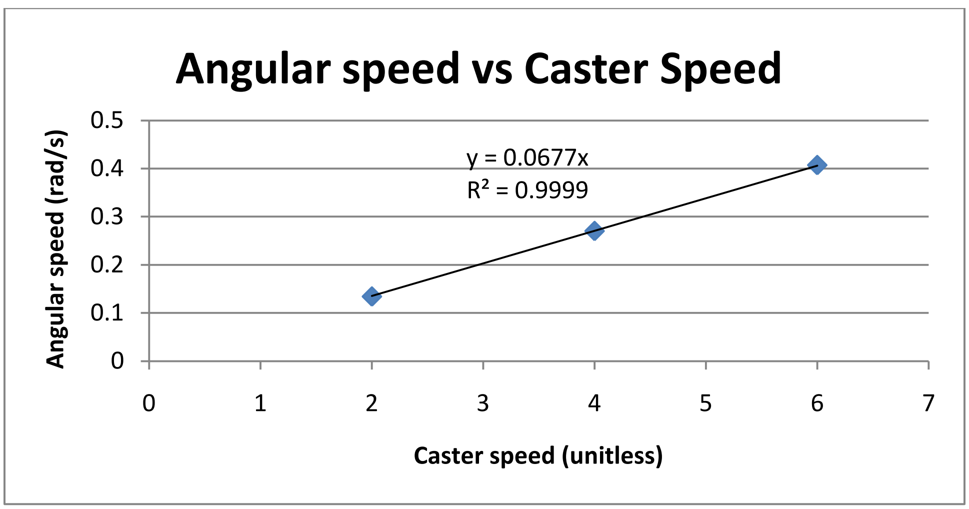

Figure 4: Calibration curve for caster arm speed

Flat track slip

The results of testing on flat ground are summarized in Figure 5.

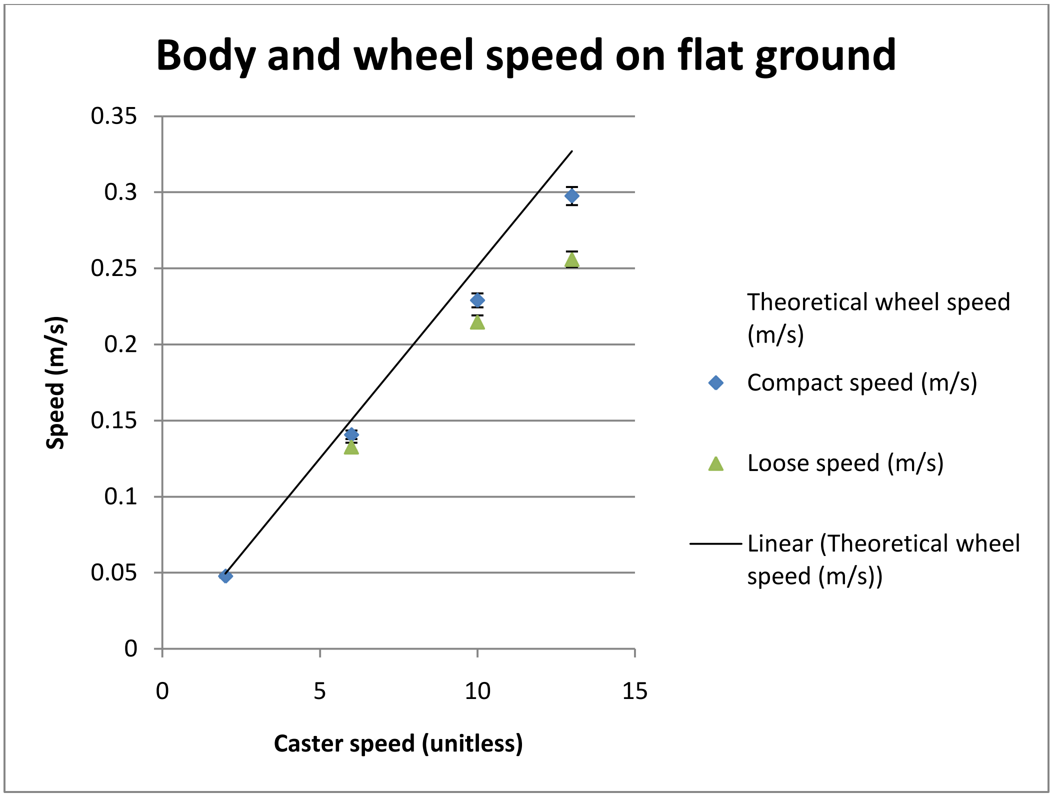

Figure 5: Comparison of body vs. wheel speeds for a range of caster speeds and two soil types on flat ground

The body speeds in compact and loose sand are slightly lower than the corresponding wheel speeds. Although this result may seem surprising at first, it must be noted that Axel adjusts the input torque to the caster motor to maintain a constant caster arm angular velocity. Therefore, the energy costs in compact vs. loose sand will vary (see Power Usage section). As an example, occasionally, on the loose sand track, the input link would jam into an accumulated pile of sand, causing the caster arm motor to stall. The motor would shut off, so data could only be taken on the length of the track that was completed.

The results indicate that body speeds are lower than theoretical wheel speeds for the full range of caster speeds, indicating slip is occurring. This discrepancy can be summarized by a slip ratio, defined in the terramechanics literature [4] as:

$$s = \frac{r * w - v}{r * w}$$

The slip ratio depends on r, the wheel radius, w, the wheel angular velocity, and v, the linear speed of the rover. For reference, the slip ratio of a rover should be below 0.4 to avoid serious slip-sinkage [5]. See Figure 6 for a summary of slip ratios at the full range of wheel speeds.

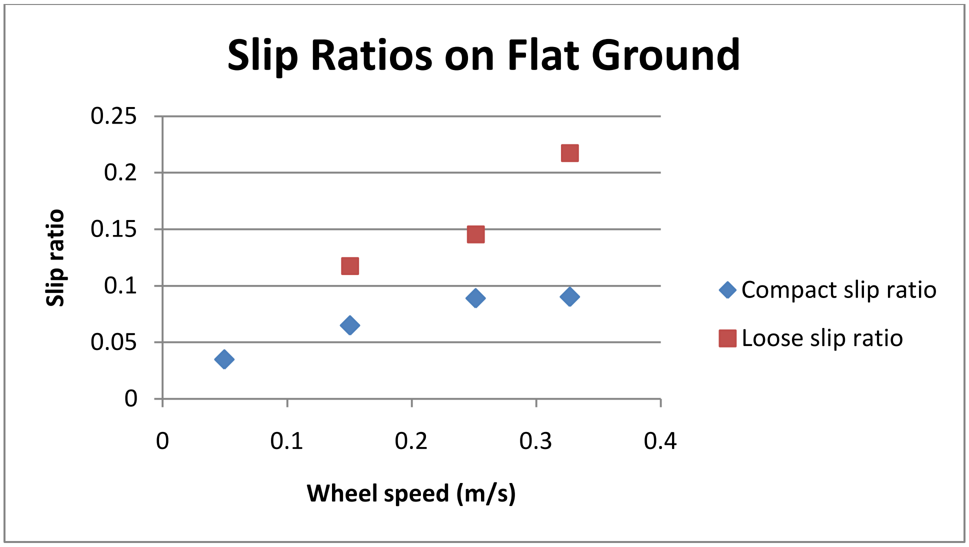

Figure 6: Comparison of slip ratios for compact vs. loose sand on flat ground

There are several notable results. Slip increases (in a roughly linear way) as wheel speed increases, as expected, since the paddle wheel edges have less time to grip the contact surface. The loose slip ratios appear to increase in a concave up manner, while the compact slip ratios appear concave down. Also, slip is about twice as high for the loose sand track because the loose soil is more likely to be displaced by the paddle wheels as they rotate Axel forward.

Overall, there was a noticeable slip ratio for the compact sand track and a significant slip ratio for the loose sand track. The slip ratio could be due to several factors, which can be grouped into two primary causes: losses in conversion of caster rotation to wheel rotation, and losses during wheel rotation.

Losses in conversion of caster rotation to wheel rotation

1. Friction in the caster-body interface

Once the caster arm was in contact with the ground, before wheel rotation could begin, the friction between the caster assembly and the cylindrical body had to be overcome. Also, friction between the two interfaces would reduce the conversion of caster rotation to wheel rotation. This effect is negligible, however, since Axel would compensate for it by increasing the power to the caster arm to maintain a constant angular velocity. In fact, all losses in conversion of caster rotation to wheel rotation would affect power usage much more than they would affect slip.

Losses during wheel rotation

2. Friction losses from the trailing caster arm

Friction losses from the trailing caster arm resulted when the end of the link was in contact with the ground. These losses were probably minor since the normal force at the end of the caster arm in contact with the ground is minimal, due to the long length of the arm.

3. Paddlewheel contact angle

Forward motion of Axel tends to follow several steps, which were readily observable at lower speeds. Rotation would begin with the wheel resting on two paddles and with the caster arm contacting the ground. Once sufficient torque was applied, Axel would roll over the front paddle until it was vertically aligned. Axel would then tumble until a new front paddle gripped the ground. At this point the caster arm would lose contact with the ground. Once it rotated and hit the ground again, the process would repeat. Because of this process, the inclination angle of the forward paddle varied between 0 and 18 degrees when torque was applied (Axel has 10 paddles, so the spacing between each paddle is 36 degrees). However, even at 18 degree inclination, 95% (cos18°) of the angular speed would be converted into forward speed, so this effect could not be the primary cause of the discrepancy (Figure 7).

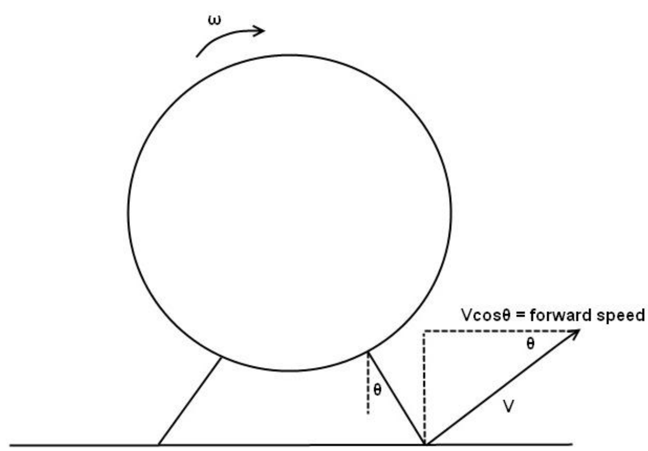

Figure 7: Conversion of angular speed to forward speed as Axel contacts the ground

4. Paddle slip

The most obvious source of slip was the actual slippage of the paddle along the contact surface. This effect was observable under most of the operating conditions, but it was difficult to quantify since it occurred so quickly.

Flat track sinkage

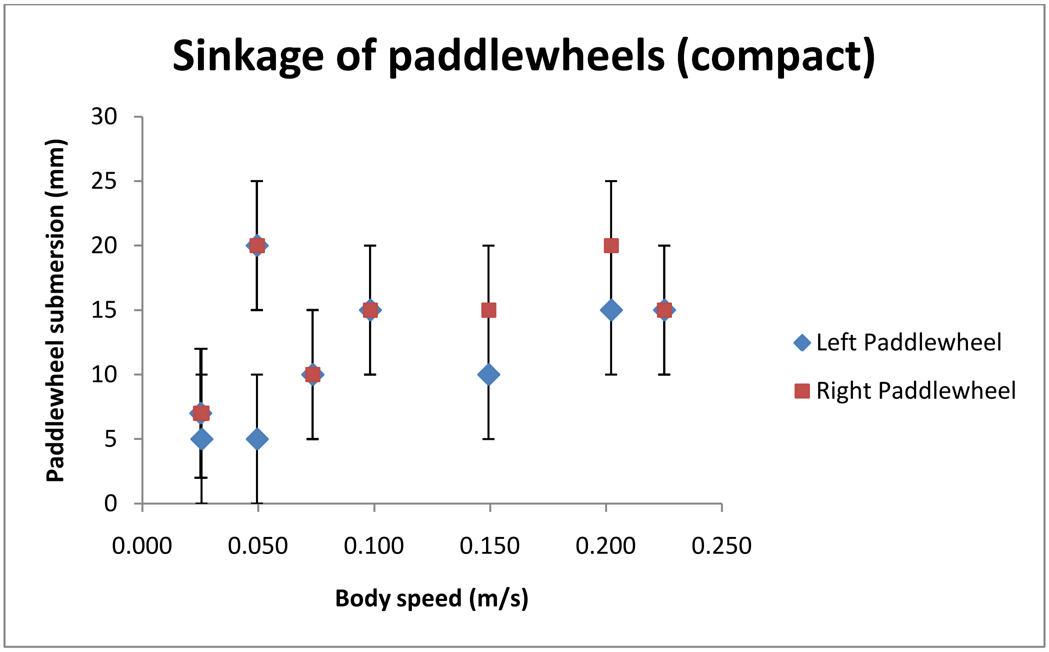

Figure 8: Submersion of left and right paddlewheels in compact sand

Data on paddlewheel submersion in compact sand are in Figure 8. The paddlewheels were almost entirely submerged in loose sand (depth of 8-9cm) at all speeds, so data on submersion was not taken on all loose sand trials. There appears to be a slight positive correlation between body speed and submersion of paddlewheels, but it is inconclusive. Submersion of the wheels was difficult to determine from the adhesive tape since the front and rear of the paddles tended to have differing values. In general, the back of the paddles had more sand stuck to the adhesive since sand was pushed onto the paddle as it rotated out of the track. Therefore, the front of the paddles was used as a more reliable indicator of paddle submersion. Overall, the quality of submersion data needs to be improved, since the results tended to vary even between the right and left paddlewheel for a given body speed.

Sloped track slip

The results of testing on slopes at the Mars Yard are summarized in Figure 9. Results from Track 3 (7.0°) were not included because the caster motor stalled on each trial, so Axel was not able to complete the course. Moreover, attempts to drive Axel downhill through the track led to rolling at the lowest caster speeds, so downhill data could not be obtained either. Tracks 1, 2 and 4 had similar soil properties, so the primary parameter determining slip was the slope of each track.

Track 1 was the steepest track that Axel successfully completed, at an average inclination of 6.6°. However, Axel only completed the full track at the highest caster speed. Axel completed less than half the track at caster speed 10 (0.25 m/s), and no data could be gathered at lower speeds since Axel could not ascend the slope at all. Axel's body speed was significantly lower than the wheel speed, suggesting that slip was a major factor.

Axel was more successful in ascending Track 2, at an average inclination of 4.4°. Axel could navigate up the slope at speeds as low as 0.15 m/s. Axel's body speed was again lower than the wheel speed, but the discrepancy was smaller than the one at 6.6°.

Axel descended down Track 4, so the body speed should be above the wheel speed given that occasional rolling took place. However, some slip effects were still taking place since the discrepancy between wheel speed and body speed was negligible. An unexpected result was that rolling was not significantly increased by increasing the caster speed. Given that continuous rolling occurred at a downhill slope of 7.0°, we can safely predict that an untethered Axel will begin continuous rolling at a downhill slope between 4.3° and 7.0°.

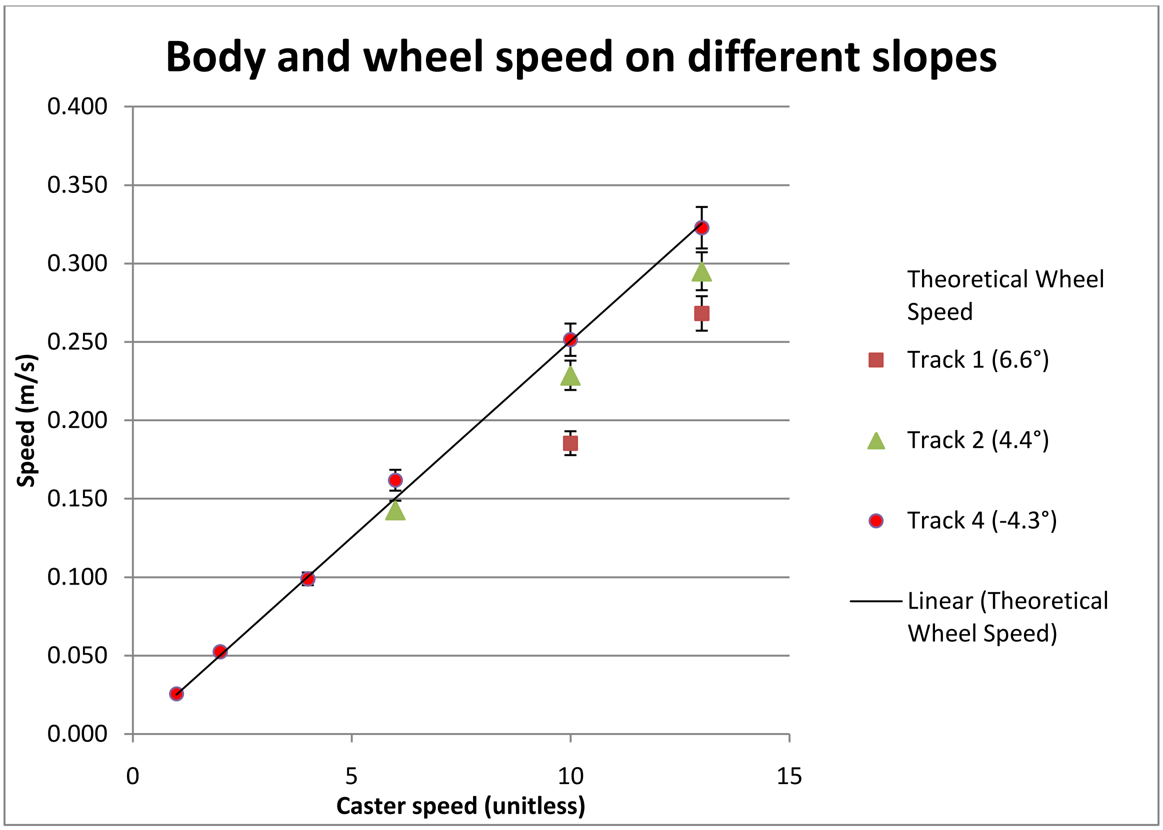

Figure 9: Comparison of body vs. wheel speed for a range of caster speeds on different slopes

Overall, slip tended to increase with increased slope angle. Table 3 summarizes the slip results for the different slopes. Results from the flat ground trials are also included for comparison.

Table 3: Comparison of slip ratios for different soil types and slope angles

Theoretical Wheel Speed (m/s)	Slip ratio (6.6°, compact)	Slip ratio (4.4°, compact)	Slip ratio (-4.3°, compact)	Slip ratio (0°, compact)	Slip ratio (0°, loose)
0.025			-0.053		
0.050			-0.059	0.035	
0.100			0.011		0.078
0.150			-0.075	0.065	0.118
0.250	0.262	0.090	0.000	0.089	0.145
0.326	0.180	0.098	0.013	0.090	0.217

From Table 3, we can conclude that sinkage has a significant effect on slip of Axel. Complete sinkage of the paddles in the loose sand trials resulted in a slip ratio of around 0.22 at a speed of 0.33 m/s, which is comparable to the slip ratios of Axel on a 6.6° compact sand slope.

Slope angle also had a considerable effect on Axel slip. The steepest slope that Axel successfully ascended (6.6°) had slip ratios as high as 0.26, almost three times higher than the slip on compact, flat ground. We expect even higher slip ratios at the slope angles that Axel is expected to ascend (above 20°).

Sloped track sinkage

Just as in the flat tracks, sinkage data was hard to reliably acquire. Rough sinkage values for tracks 1, 2, and 4 were 10, 10-15, and 20mm. However, it is difficult to estimate the error of these values, so correlations between slip and sinkage cannot be dependably drawn.

Power Usage

To supplement the slip data, data on power usage was gathered while running Axel through all the tracks in the Mars Yard and Mini Mars. For motion planning purposes, looking exclusively at slip is misleading since Axel variably adjusts the input power to the caster arm to keep a constant angular velocity. Space applications place a high cost on power requirements, so optimizing power usage is as important as reducing slip.

Power usage was derived from the voltage and current readings on the caster arm Elmo controller. The data is oscillatory since the motion of Axel driven by the caster arm follows an oscillatory pattern (Figure 10). Power usage while the caster arm is rotating is at a minimal base level. Once the caster arm hits the ground and provides a reaction force, the power usage spikes to allow Axel to roll over a paddle. Once Axel has rolled over the paddle, the caster arm loses contact with the ground and begins rotating again. Since Axel currently has 5 large and 5 small paddles, the power usage for the large paddle is larger than for the small paddle. The primary reason is that Axel can more easily roll over the small paddles since each small paddle is supported by two larger paddles.

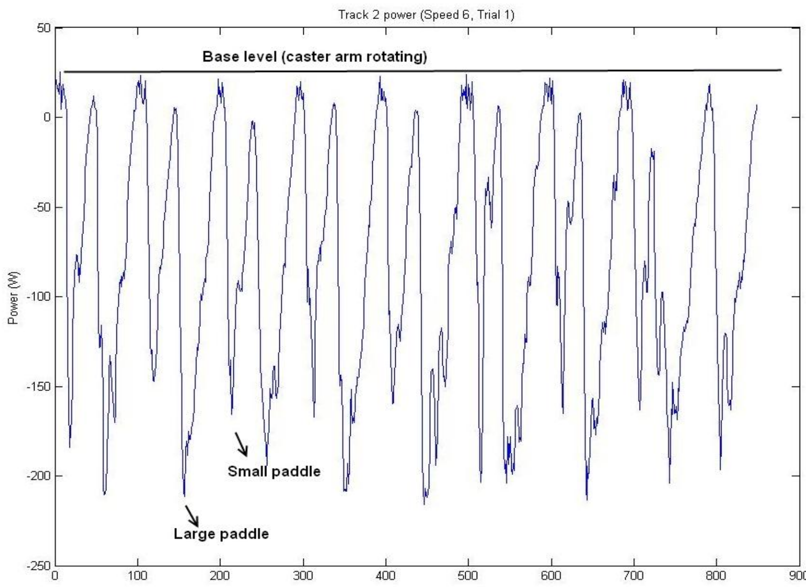

Figure 10: Power usage data (time vs.power) with spikes each time Axel rolls over a paddle

The average power usage data was found for each trial by averaging the power values across the maximum integral number of revolutions.

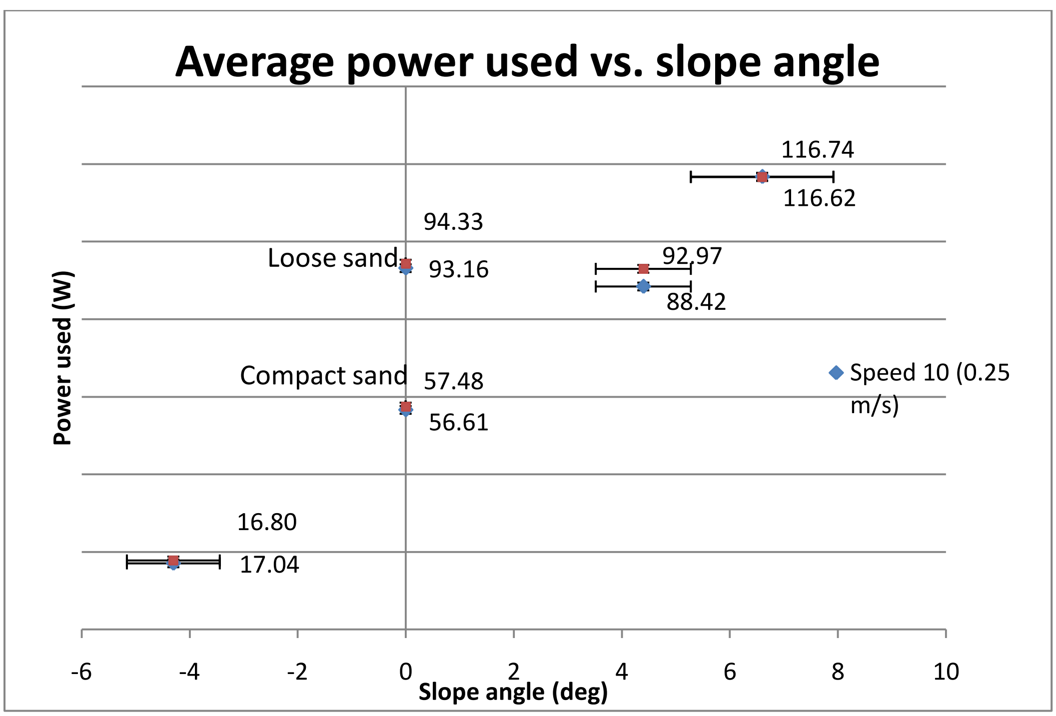

Figure 11: Average power used at different slope angles, soil types, and caster speeds

Several important results can be derived from the average power used (Figure 11). The compact soil results followed a highly linear trend (the R^2 values for speeds 10 and 13 are over 0.99). Although further testing must be done at higher slope angles, we can reliably predict power usage at typical operating speeds for small slope angles.

Another important result is that power usage is over 1.5 times higher in loose sand than in compact sand. This is the extreme case result, since the loose sand track resulted in complete sinkage of Axel's paddles. Further testing of Axel on loose sand slopes can offer predictive power for the full range of sloped conditions.

Using these two results, motion planning algorithms can be constructed to minimize power usage. There is a significant power cost associated with crossing over loose soil, but this cost is overtaken by the power cost of ascending a steep slope (above 5°, see Figure 11). Moreover, as illustrated by Table 3, the danger of high slip on sloped ground is just as severe as high slip on loose soil. Therefore, we can anticipate that avoiding the highly sloped, loose soil areas in a given terrain map would be a crucial part of any motion planning algorithm.

Comparison to previous work

Once we have obtained power data, we can calculate energy costs and compare them with the values found in the previous work section. The most comparable value (using the tumbling mode) is reproduced below[3]:

Table 4: Avg. max energy cost for non-paddlewheel version of Axel

Drive Mode	Ground Type	Ground Inclination	Avg. Max Energy Cost ± Standard Error (J/kg*m)
Tumbling	Loose sand	0°	19.71 ± 0.46

We can compare this value to the values derived from the power usage data on loose and compact sand at several caster speeds (corresponding to 0.15, 0.25, and 0.33 m/s respectively). All the values are for flat ground.

Table 5: Average energy cost values for Axel on flat ground

Ground type	Caster speed	Avg. Energy Cost (J/kg*m)	Standard error (J/kg*m)
Loose sand	6	32.76	2.56
Loose sand	10	21.67	1.75
Loose sand	13	18.47	1.32
Compact sand	6	20.34	0.20
Compact sand	10	12.36	0.37
Compact sand	13	9.66	0.40

Although the previous version of Axel used regular wheels instead of paddle wheels, the energy cost values for loose sand are comparable, particularly at the higher drive speeds. Another important result is that average energy costs tend to decrease as Axel moves more quickly. The primary reason for this result is that average power used does not increase with caster speed. Most of the power usage occurs when Axel is rolling over a paddle. Since the relative time spent rolling over a paddle compared to not rolling is the same for all caster speeds, and the power usage while rolling is the same, the power usage is unchanged for higher caster speeds. Therefore, the primary scaling factor in the average energy cost values is the speed of Axel, which is evident in Table 4.

Motion Planning

Motion planning strategy

A general motion planning strategy for Axel based on refinement is summarized in Figure 12. The strategy assumes that a model of Axel's environment is available or that Axel is able to map its environment. Axel must also be able to localize itself within the environment. The model of the environment must include data on elevation, soil types, and obstacles.

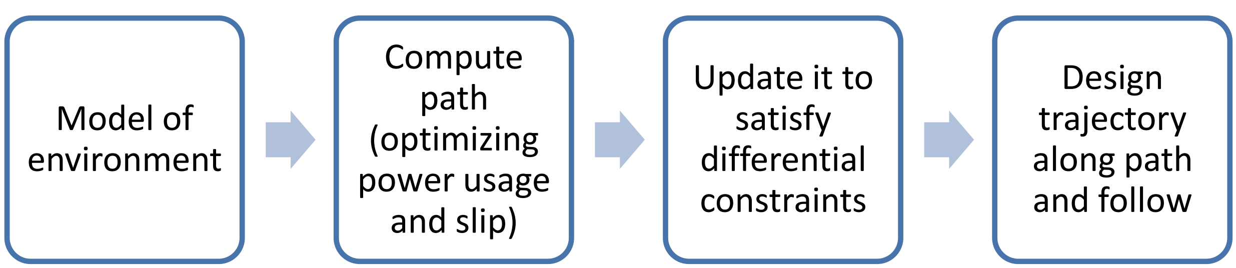

Figure 12: A general motion planning strategy for Axel

Given an environmental model, an algorithm must be chosen to create a path through the environment to a specified goal. A possible algorithm is one utilizing gradient descent. A cost function could be created for the environment that quantifies costs related to power usage, slip, and obstacles. Experimental results will help inform the relative values of these costs. For example, power usage would linearly increase with slope angle, as found in the Results section. To find the minimum of the cost function and create a path, we utilize the gradient descent algorithm. We then follow the inverse of the gradient until arriving at the obstacle.

Once the path is computed, we must update it to satisfy differential constraints, such as the velocity of Axel.

Finally, to follow the path, a trajectory must be created for Axel, with a feedback control law designed to follow the trajectory.

Note that if Axel is mapping the environment in real time, the environmental model will change, so the optimal path will be updated in real time as well.

Conclusions

Key insights

Experimental work on Axel has revealed several important insights:

- Slip ratio increases with increased wheel speed, roughly linearly, in loose and compact sand

The slip ratio increases to around 0.1 for compact sand and over 0.2 for loose sand under typical caster arm speeds. This is below the critical 0.4 slip ratio value, but still a significant amount of slip.

- Slight correlation between body speed and sinkage of paddle wheels, but it is inconclusive

The sinkage data was unreliable, although it appeared to indicate a slight positive correlation between body speed and wheel sinkage. This fact, coupled with the lack of theory for paddle wheel soil mechanics, means that a novel soil interaction model predicting sinkage is beyond the scope of this paper.

- An untethered Axel will begin continuous rolling at a downhill slope between 4.3° and 7.0°

This prediction is based on two experimental results. Axel did not continuously roll down Track 4 at any of the caster speeds, and it continuously rolled down Track 3 at the lowest caster speed setting.

- Slip ratios increase significantly as slope angle increases

The steepest slope that Axel successfully ascended using caster arm driving was 6.6°. Axel had slip ratios as high as 0.26 while ascending the slope. Since slip ratios tended to drastically increase with slope angle, we expect that higher slope angles will result in severe slip of Axel.

- Power usage linearly increases with slope for compact sand

Sloped tests revealed that a strong linear relationship exists between power usage and slope angle for compact sand, at least for slope angles up to 6.6°. This result is useful for motion planning purposes since it can be used to predict Axel power usage if the soil type is known.

- Power usage is over 1.5 times higher for loose sand vs. compact sand on flat ground

Flat ground testing revealed that the power used on the loose sand track was over 1.5 times the power used on the compact sand track. This result is somewhat limiting since it only applies to flat ground, but it provides a baseline figure for motion planning purposes.

Limitations

Several of the key limitations of this study are:

- Due to sensing constraints, only the caster arm was used for driving Axel. Because of this constraint, Axel had difficulty in traversing over loose sand at low speeds, and could not climb slopes over 7°. If accurate sensors could be installed on the wheels, then driving by using the wheels would allow results to be significantly extended.

- To focus on soil interaction, Axel was driven without using the tether. Although this proved helpful in isolating wheel-soil effects, Axel will inevitably use its tether, so the results are fundamentally limited to a non-tethered version of Axel. However, since the tether is designed to assist Axel in situations where the rover would generally become stuck, we can classify the results as a worst-case scenario which may be remedied by the tether.

Further work

There are a few extensions of this work that could naturally follow. First, slip ratios need to be tested at the full range of Axel operating speeds. As mentioned above, since driving Axel was limited to caster arm actuation, Axel's speed could not exceed 0.33 m/s. Tests above this speed need to be conducted by driving the wheels. Moreover, driving the wheels will allow tests to be conducted at slope angles above 7°.

A reliable method to measure sinkage will result in more useful data. If reliable sinkage data can be obtained, then work on a novel soil interaction model involving paddle wheels will be more effective.

We found increases in slip ratio and power usage on sloped tracks and loose sand tracks. If sloped, loose sand tracks can be prepared, then the combined effect of these parameters can be quantified.

Acknowledgements

I would like to thank Prof. Joel Burdick for his role as my mentor. He has provided guidance throughout my senior thesis. I am also thankful to Prof. Nadia Lapusta, the Undergraduate Thesis Committee Chair, for offering feedback and asking questions as my work progressed. Finally, I would like to thank Pablo Abad-Manterola for helping me with data collection and offering his advice.

References

1. Abad-Manterola, P., et al., *Axel A Minimalist Tethered Rover for Exploration of Extreme Planetary Terrains.* Ieee Robotics & Automation Magazine, 2009. **16**(4): p. 44-52.
2. Abad-Manterola, P., et al., *Wheel Design and Tension Analysis for the Tethered Axel Rover on Extreme Terrain.* 2009 Ieee Aerospace Conference, Vols 1-7, 2009: p. 64-71.
3. Nesnas, I.A.D., et al., *Axel mobility platform for steep terrain excursions and sampling on planetary surfaces.* 2008 Ieee Aerospace Conference, Vols 1-9, 2008: p. 15-25.
4. Wong, J., *Theory of ground vehicles*. 2001: Wiley-Interscience.
5. Ding, L., et al., *Wheel slip-sinkage and its prediction model of lunar rover.* Journal of Central South University of Technology, 2010. **17**(1): p. 129-135.

Appendix

Slope angle measurements

	Track 1	Track 2	Track 3	Track 4
Angles (deg)	6.2	5.0	8.3	5.2
	6.6	3.0	8.4	4.2
	7.1	4.4	7.6	4.9
	7.9	5.5	6.6	4.2
	5.1	4.6	5.6	3.0
		3.6	5.3	
Average	6.6	4.4	7.0	4.3
Std. Dev.	1.0	0.9	1.3	0.8

Raw Data

Mini Mars Yard First Run

Trial	Caster speed	Wheel speed (m/s)	Distance (ft)	Time (s)	Body speed (m/s)	Soil	Left Submersion (mm)	Right Submersion (mm)
1	3	0.150553	15	60.6	0.075	Compact sand		
2	1	0.049543	15	181.9	0.025	Compact sand	7	7
3	1	0.049543	15	178.5	0.026	Compact sand	5	7
4	2	0.100048	15	92.4	0.049	Compact sand	20	20
5	2	0.100048	15	92.3	0.050	Compact sand	5	20
6	3	0.150553	15	62.2	0.074	Compact sand	10	10
7	3	0.150553	15	62.2	0.074	Compact sand	10	10
8	1	0.049543	15	333.4	0.014	Loose sand	80	30
9	1	0.049543	STOPPED MOVING			Loose sand		
10	1	0.049543	STOPPED MOVING			Loose sand		
11	3	0.150553	STOPPED MOVING			Loose sand		
12	6	0.302068	STOPPED MOVING			Loose sand		
13	4	0.201058	8.86	29.3	0.092	Loose sand	90	90
14	6	0.302068	15	32.1	0.142	Loose sand	90	90
15	8	0.403078	8.86	14.7	0.184	Loose sand	90	90
16	10	0.504088	15	20.1	0.227	Loose sand	90	90

17	4	0.201058	15	46.5	0.098	Compact sand	15	15
18	6	0.302068	15	30.6	0.149	Compact sand	10	15
19	8	0.403078	15	22.6	0.202	Compact sand	15	20
20	10	0.504088	15	20.3	0.225	Compact sand	15	15
21	3	0.150553	13.75	63.4	0.066	Loose sand	90	90
22	5	0.251563	15	41.2	0.111	Loose sand	90	90
23	7	0.352573	15	27.1	0.169	Loose sand	90	90
24	9	0.453583	15	21	0.218	Loose sand	90	90

Mini Mars Yard Second Run

Soil	**Caster speed**	**Trial**	**Wheel speed (m/s)**	**Distance (ft)**	**Time (s)**	**Body speed (m/s)**
Compact	2	1	0.050098	15	94.99	0.048131382
Compact	2	2	0.050098	15	95.27	0.047989923
Compact	2	3	0.050098	15	96.85	0.047207021
Compact	6	1	0.150294	15	32.23	0.141855414
Compact	6	2	0.150294	15	32.52	0.140590406
Compact	6	3	0.150294	15	32.77	0.139517852
Compact	10	1	0.25049	15	19.93	0.22940291
Compact	10	2	0.25049	15	19.89	0.229864253
Compact	10	3	0.25049	15	20.08	0.227689243
Compact	13	1	0.325637	15	15.37	0.297462589
Compact	13	2	0.325637	15	15.42	0.296498054
Compact	13	3	0.325637	15	15.31	0.298628347
Compact	14	caster speed saturated				
Loose	6	1	0.150294	15	34.94	0.130852891
Loose	6	2	0.150294	9.916666667	22.37	0.135118462
Loose	6	3	0.150294	7.666666667	17.66	0.132321631
Loose	10	1	0.25049	15	20.88	0.218965517
Loose	10	2	0.25049	15	21.59	0.211764706
Loose	10	3	0.25049	15	21.39	0.213744741
Loose	13	1	0.325637	5.375	6.83	0.239868228
Loose	13	2	0.325637	15	18	0.254
Loose	13	3	0.325637	15	16.68	0.274100719

Mars Yard Data

Track	Angle (deg)	Caster speed	Trial	Wheel speed (m/s)	Distance (ft)	Time (s)	Body speed (m/s)
1	6.6	13	1	0.327	10.00	10.22	0.298
1	6.6	13	2	0.327	4.50	6.29	0.218
1	6.6	13	3	0.327	10.00	10.58	0.288
1	6.6	10	1	0.251	4.58	7.27	0.192
1	6.6	10	2	0.251	3.04	5.19	0.179
2	4.4	6	1	0.150	13.08	27.52	0.145
2	4.4	6	2	0.150	12.42	27.45	0.138
2	4.4	6	3	0.150	13.08	27.35	0.146
2	4.4	10	1	0.251	13.08	17.35	0.230
2	4.4	10	2	0.251	13.08	17.24	0.231
2	4.4	10	3	0.251	13.08	17.73	0.225
2	4.4	13	1	0.327	13.08	13.13	0.304
2	4.4	13	2	0.327	13.08	13.55	0.294
2	4.4	13	3	0.327	13.08	13.89	0.287
3	7	13	1		Did not move, rolled downhill at speed 2		
4	4.3	1	1	0.024	10.00	116.03	0.026
4	4.3	1	2	0.024	10.00	122.32	0.025
4	4.3	1	3	0.024	10.00	119.63	0.025
4	4.3	2	1	0.050	10.00	58.16	0.052
4	4.3	2	2	0.050	10.00	56.63	0.054
4	4.3	2	3	0.050	10.00	59.68	0.051
4	4.3	4	1	0.100	10.00	31.48	0.097
4	4.3	4	2	0.100	10.00	30.27	0.101
4	4.3	4	3	0.100	10.00	30.74	0.099
4	4.3	6	1	0.150	10.00	18.18	0.168
4	4.3	6	2	0.150	10.00	19.49	0.156
4	4.3	6	3	0.150	10.00	18.9	0.161
4	4.3	10	1	0.251	10.00	12.24	0.249
4	4.3	10	2	0.251	10.00	12.33	0.247
4	4.3	10	3	0.251	10.00	11.82	0.258
4	4.3	13	1	0.327	10.00	9.43	0.323
4	4.3	13	2	0.327	10.00	9.36	0.326
4	4.3	13	3	0.327	10.00	9.54	0.319