Terramechanics: Testing Wheel Designs for Planetary Surfaces

Kailyn Cage
Mentor: Dr. Mary L. Bowden, Professor of Aerospace Engineering
University of Maryland, College Park

Abstract

Planetary Exploration Missions have been an ongoing aspect of the NASA tradition since 1957. In an effort to better understand the surfaces, atmospheres, and geographic properties of planets in the solar system, the planetary rover was invented. In 1997, the Pathfinder landed on Martian terrain. The Pathfinder contained an important robotic vehicle, the planetary rover Sojourner. Sojourner, developed by United States scientists and engineers, was the first rover to land on the surface of Mars. On soft, usually sandy, rocky surfaces the planetary rover has engaged in loss of traction and wheel slippage. In order to investigate wheel-surface interaction, an automated test simulation system was designed and built in the Space Systems Laboratory and the Manufacturing building at the University of Maryland. Experiments that tested the draw-bar pull produced at varying weights with multiple wheel designs in a manual test simulation system state were conducted in an effort to confirm previous assumptions. In an effort to measure the force required to pull a weighted cart through the sandy surface, a series of tests were conducted in which the force was measured over a short period of time using the test simulation system. Wheel-slippage occurred in several cases as the weight increased on the more narrow wheels. After the force was measured and recorded with the force gauge and the Logger Pro III software, the depth of the tread was measured. This process of collecting data was repeated for three different wheels and each wheel was tested under four and then six different weight conditions. In a continuation of the current experiment, a second experiment will be conducted in the near future to determine the draw-bar pull produced from varying wheel designs in an automated test simulation system with varying weights. Also, future experiments will test the torque produced from the wheel-surface interaction.

Introduction

> *"Ten months ago, as Spirit was driving south beside the western edge of a low plateau called Home Plate, its wheels broke through a crusty surface and churned into soft sand hidden underneath." (Brown & Webster, 2010)*

One of the major issues surrounding wheel-surface interaction is the wheel-slippage issue. Presently, there does not exist any valid explanations as to why rovers are unable to avoid wheel-slippage on planetary surfaces, specifically on Mars. The primary goals for a planetary rover are the capacity to navigate in an unknown, hostile terrain, recognize and negotiate obstacles, deploy scientific instruments, and acquire samples from scientific targets (A. Ellery, 2005). Although the Sojourner made astounding landmarks as the first rover to successfully land and explore the Martian surface, it also experienced several problems related to navigating through the rocky, clay-like, sandy surface. In spite of all the issues that Sojourner faced while attempting to navigate through the intransigent Martian surface, the one that created the most frustration among the NASA Jet Propulsion Laboratory scientists and engineers was the issue surrounding wheel-slippage ("MARS PATHFINDER," 1997). Because of wheel-slippage, the scientists and engineers thought very critically about every move the Sojourner made. Due to several factors involved in space exploration, the wheel-surface interaction and concerns surrounding wheel-slippage represent the need for improvements in planetary rover wheel designs for future space missions.

Purpose of Study and Research Questions

Influencing better wheel designs for future planetary rovers requires conducting a series of three or four experiments in an attempt to reconcile several contributing agents associated with wheel-slippage. These agents consist of wheel design, wheel load, surface conditions, and design limitations. Currently, the focus is on the draw-bar pull produced from three different wheel designs tested on a simulated martian-like surface. In an effort to build a working test simulation system and collect meaningful data in reference to the tested wheel designs. Two sets of questions were derived and separated into categories of Current and Future research questions.

Current Research Questions:

1. Can a test simulation system be designed that reliably allows evaluation of multiple wheel designs?
2. What procedures must be followed to obtain repeatable data?
3. How can the sensors and test setup be calibrated?
4. Does weight affect the pull force necessary to make a wheel roll across a surface?

Future Research Questions:

1. How do surface characteristics affect the necessary pull force?
2. In what configuration does the wheel start to slip?
3. How can a wheel be designed to operate more effectively without slipping on a given surface?

Significance of Research

In order to affect the future wheel design of planetary rovers, it is essential to propose solutions that produce applicable findings. These findings ensure that further research will be conducted by proposing an applicable solution that will impact future designs of planetary rover wheels. Additionally, this data can also be applied to earth-based wheel operated designs. As a result, designs such as wheel chairs, scooters, and cars can benefit from a design-based feature that allows for functionality on soft surfaces, such as sand. Furthermore, for the past 27 years, planetary rovers have experienced wheel slippage issues on planetary surfaces. If a solution could be proposed to limit the issues surrounding wheel-slippage, the rovers would have a less challenging time navigating throughout planetary surfaces. Not only would a valid solution ease navigational surface problems, but also it would permit the planetary rover the manuevrabiltity, on these intrasigent surfaces, needed to carry out the mission. The solution would serve to limit the setbacks NASA missions face based on planetary surface interference. Thus, the experimental goal would be to make advancements toward a solution beneficial in limiting current set backs.

The experiment was broken down into three phases and had an essential relationship with each componential phase. The design of the test simulation system was needed to complement the design of the wheel assembly cart which, in turn, needed to be correctly calibrated in order to collect accurate draw bar pull measurements. In the first phase of this project the test simulation system was built. It was later calibrated which in turn allowed accurate measurements of the force required to roll a wheel along a sandy surface (draw bar pull). This system was initially designed to be assembled around the existing sand-box test facility. However, after deliberating and testing different designs in real-time, the design was modified, and the test system was configured to attach to the existing sand-box test facility. The design also entailed some adjustment capabilities so that dimensional modifications could be made; if necessary, for future testing. Additionally, after the test simulation system was designed and assembled, it needed to be calibrated in order to accurately obtain force measurements during the testing. The next phase of the project was to design and build a wheel assembly cart. The wheel assembly cart was a two-wheeled cart designed with an axle that runs underneath the cart for an even weight distribution. The cart was designed so that it could be easily attached and removed from the test simulation system. This design provided the modifiable nature which was useful so that different wheel configurations could be mounted and tested. It also provided space so that different weights could be added to load up the wheels as they were being tested. Data were collected during the final phase of the preliminary project to search for interesting trends. This was completed by measuring the results of different wheel designs, loaded with different weights, and being rolled along known sandy surfaces. Data were collected and recorded for each configuration. As a result of the data suggesting interesting trends, new configurations will be tested in the future.

Delimitations of Research

During the designing, analyzing, and building phases of the experiment, several limitations presented themselves in the form of budget restrictions, limited laboratory materials, and complications with the design structure, in addition to issues surrounding the laboratory's milling machinery. As these limitations presented themselves as inhibitors of research progress, they were handled in a manner that would not cause major setbacks in the completion process. Alternative laboratories, such as the wind tunnel, were used to mill the fixture that attached to the cart. The design of the structure was also altered in order to adjust for the inefficiencies based on the unavailability of the milling machinery. Instead of milling the legs of the aluminum structure, holes were created below the surface of the test sand box. This allowed for the building of a test simulation system that was directly attached to the sand box instead of around the testing facility.

Definitions

The index terms that will be used throughout this entire paper can be described by the following definitions. Some terms are defined for this particular experiment, so they can not be referenced for any future studies.

Wheel-surface Interaction. The physical energy transfer in the interaction between the robots mobility system e.g. automobile locomotion (wheels) and the planetary terrain (A. Ellery, 2005).

Planetary Rovers. Two words are combined to complete this definition, planet and rover. Planet is a large non-luminous ball of rock or gas their orbits a star (Planet, 2004). Rover is a vehicle for exploring the surface of an extraterrestrial body (as the moon or Mars) (Rover, 2010).

Wheel-slippage. The act of the wheel interacting with the surface, in turn causing wheel to slip on the surface based on the geographical properties of the surface.

Martian Surface. This term is composed of two words, Mars and surface. Mars is the fourth planet in order from the sun and conspicuous for its red color (Mars, 2010). Surface is the exterior or upper boundary of an object or body; and external part or layer to all outward appearances (Surface, 2010).

Space Exploration. The investigation of the universe beyond Earth's atmosphere by means of manned and unmanned spacecraft (Space Exploration, 2010).

Terramechanics. The interaction of a wheeled instrument and a surface, also referring to the analysis of surface properties for multiple terrain types (Kushwaha, 2010).

Torque. A force that produces or tends to produce rotation or torsion; a measure of the effectiveness of such a force that consists of the product of the force and the perpendicular distance from the line of action of the force to the axis of rotation (Torque, 2010).

Planetary Surface. The two words that complete this definition are planet and surface. Planet is a large non-luminous ball of rock or gas their orbits a star (Planet, 2004). Surface is the exterior or upper boundary of an object or body; and external part or layer to all outward appearances (Surface, 2010).

Draw-bar Pull. The difference between soils thrust and motion resistance (A. Ellery, 2005).

Test Simulation System. The aligned track fixture used to pull multiple wheeled carts along the simulated sandy Martian surface.

Analysis and Discussion of the Literature

Background information regarding planetary rovers, planetary surfaces, Terramechanics, and complications with wheel slippage will be discussed in this chapter. This information provides context for the experimental design. The review of literature supports the need for this experiment in an effort to eventually design a better planetary rover wheel.

Planetary Rovers

The Viking to Mars Project of 1975 made history as "the first mission to land on another planet and return with both imaging and non imaging data over an extended period of time" ("Viking to Mars" , 2010).Since that time planetary rovers have been sent on missions to discover and investigate properties of planets in the solar system. On July 4, 1997 the Pathfinder, an interplanetary space craft, successfully landed in on Martian soil containing the pyramid shaped "Mars station complete with camera, weather tower and instrument-laden rover named Sojourner, in an historic safe landing on the Martian surface at 1707" (Curtis, 2005). Sojourner, the first successful rover to land on the surface of Martian soil, lasted 12 times its design lifetime of 7 days. After the success of Sojourner, rovers Spirit and Opportunity were sent to explore Mars in 2004. Spirit and Opportunity had a mission that consisted of obtaining geographical information on the surface of Mars. While these current rovers had an improved design lifetime of 6 months they each have far surpassed their design lifetime as they are still on Martian soil 6 years later.

Planetary Surfaces

While Spirit and Opportunity have achieved great success they have also experiences several issues on Mars surfaces. Mars has a sandy almost clay stricken and rocky surface and the rovers tend to have difficulty navigating through this terrain. As well, other planetary surfaces such as the lunar surface has a sandy loose disheveled appearance comprised of dust and rock clast (Liang, Hai-bo, Zong-quan & Jian-guo, 2010). These surfaces are also referred to as regolith (Ishigmi, Miwa, Nagatani, & Yoshida, 2007). Surfaces such as the Lunar and Martian soil, contribute to the challenging issues faced by the rovers on planets in the solar system. Not to mention the weather patterns on the lunar and Martian surfaces are unpredictable which also contribute to the difficulty faced by rovers in reference to their navigation through this difficult terrain after storms.

While traveling through Martian terrain, Spirit entered a low plateau area entitled "Home Plate" and broke though a hard surface into a soft sandy terrain underneath. Needless to say, Spirit became entrapped in the terrain of the Martian Surface. On January 26, 2010, after 10 perpetuate months of making attempts to release Spirit from the draconian Martian surface, NASA headquarters announced that Spirit would now act as a stationary observer (Brown & Webster, 2010). Although there are many benefits of the Spirit acting as a stationary observer it is inauspicious that the full mission of Spirit can not be completed. The mission included observation of the complete left side of the planet Mars.

Terramechanics

Terramechanics play a major role in the process of analyzing the issues that may present themselves as rover wheels and planetary surfaces interact. Terramechanics is often described as the interaction of a wheeled instrument and a surface, usually referring to different surfaces and the analysis of the surface properties (Kushwaha, 2010). An experiment conducted at the Harbin Institute of Technology located in China, describes terramechanics as encompassing several measurable properties of the rover, elements of planetary surfaces and their interactions. Furthermore, it associates terramechanics theory with mechanical design, performance evaluation, simulation, soil parameter identification, mobility control, and path planning (Liang et al., 2010). In this experiment the focus lies in the interaction between the wheel and the surface of the planet which in most cases if not all lead to the issues associated with wheel- slippage.

Future planetary exploration missions will require rovers to perform challenging mobility tasks in tough terrain (Volpe, 2003). Wheel terrain interaction plays a critical role in the rough terrain mobility (Bekker, 1956, 1969; Wong, 1976). A robot traveling through loose sand has very different mobility characteristics than one moving across firm clay, for example (Iagnemma, Kang, Shibly, & Dubowsky, 2004). "It is important to estimate terrain physical parameters online, because this would allow a robot to predict its ability to safely traverse terrain (Iganemma, Shibly, & Dubowsky, 2002). Due to the fact that different surfaces can have several dangerous characteristics for rovers, it is essential to understand the relationship of the rover wheel with every plausible surface.

Complications Regarding Wheel Slippage

Spirit and Opportunity were originally sent to Mars to explore the geographical properties of the planet. These twin robots were developed to be geologists, and their task was to find answers regarding the history of water on Mars ("Mars Exploration," 2010). In order to accomplish this goal several factors had to be taken into consideration. One important factor is the wheel slippage or wheel slip-sinkage complication. The surface of Mars is very similar to the Moon as mentioned previously; these surfaces are covered in regolith. For the planetary rover, these surfaces are considered challenging terrain. "While moving on such a challenging terrain, severe slip-sinkage will occur for rover's wheels, making the vehicle decrease tractive performance, deviate from scheduled path, and even get stuck in the soil. Slip-sinkage is an important failure for the planetary rover's moving on deformable terrain" (Liang et al., 2010). "In 2005, it took five weeks for the "Opportunity" Mars Rover to escape from the Purgatory Dune after getting stuck" (Liang et al., 2010). Although the planetary rover can not combat every obstacle it faces on a planetary surface, it can be better equipped to successively traverse the terrain. This includes the capability of minimizing the time it takes the rover to release it's self when it becomes entrapped in the surface.

Summary and Implications of the Literature

The information mentioned in the sections planetary rovers, planetary surfaces, Terramechanics, and complications with wheel design confirm the issues faced by planetary rovers at this time. The articles mentioned in these sections suggest that there is indeed a need for a solution to the wheel slippage issue. Several of the mentioned articles, analyze the relationship between surfaces and rover wheels. Although in all of the mentioned articles, there has not yet been an attempt to design a wheel that interacts successfully with multiple terrains, with no human interference. Research suggests that there is a need for a better wheel design; therefore the findings of this experiment will complement current research in the field of planetary rovers. As the relationship between the draw-bar pull force and the depth of the tread is further explored, the goal of developing a better wheel design for the planetary rover is within reach.

Research Design and Methodology

Purpose of Study and Research Questions

As mentioned in chapter one, it is imperative to recognize the issues that the planetary rover faces when traversing planetary terrain under multiple weather conditions. Due to several factors involved in space exploration, the wheel-surface interaction and concerns surrounding wheel-slippage, there is a need for improvements in planetary rover wheel designs for future space missions.

Influencing better wheel designs for future planetary rovers requires conducting a series of three or four experiments in an attempt to reconcile several contributing agents associated with wheel-slippage. These agents consist of wheel design, wheel load, surface conditions, and design limitations. Currently, the focus is on the draw-bar pull produced from three different wheel designs tested on a simulated martian-like surface. In an effort to build a working test simulation system and collect meaningful data in reference to the tested wheel designs. Two sets of questions were derived and separated into categories of Current and Future research questions.

Current Research Questions:

1. Can a test simulation system be designed that reliably allows evaluation of multiple wheel designs?
2. What procedures must be followed to obtain repeatable data?
3. How can the sensors and test setup be calibrated?
4. Does weight affect the pull force necessary to make a wheel roll across a surface?

Future Research Questions:

1. How do surface characteristics affect the necessary pull force?
2. In what configuration does the wheel start to slip?
3. How can a wheel be designed to operate more effectively without slipping on a given surface?

Data Collection and Data Sources

Data was collected using a force gauge and Logger Pro III software.The data was then read into an Excel spreadsheet document for further analysis. The draw-bar force measurement was collected from each of wheel, under each weight condition for the duration of the testing. A single trial consisted of the following:

- Smooth the sand within the test simulation system.
- Set the cart on the pristine track.
- Add weight to the cart.
- Check the balance of the cart, and the alignment of the wheels.
- Roll the cart along, over a certain distance.
- Read and record the pull force necessary to make the wheels roll.
- Measure the depth of the tire treads within the sand.
- Identify situations where wheel slippage occurs.

The draw-bar pull force measurement was recorded in our system during each trial as each set of wheels road across the surface of the sand for a period of five seconds. In the span of five seconds, 251 variations of the drawbar pull force measurements were recorded in the Logger Pro III software. In order to gain an accurate draw-bar pull force measurement, the average drawbar pull force was recorded. Once the average drawbar pull force was recorded, the depth of the wheel tread was measured. The tread was measured accurately through the use of the sand smoother mechanism and a tape measure. This depth measurement was the recorded in our spreadsheet and used for comparison of the other two wheels, under the same weight condition.

Data Analysis Strategies

Based on the data collected, the research questions posed in the initial study can be answered. After several improvements and alterations a reliable test simulation system was developed in the Space System Laboratory and stationed in the Manufacturing Building, both located at the University of Maryland, College Park. This system allowed for multiple wheel designs to be tested reliably. The data represented in Table IV represents the relationship between the draw-bar pull force and the wheel. It is evident that as the weight increases for each type of wheel, a greater draw-bar pull force is required to pull the wheel though the sand. Furthermore, our data set was rich enough to answer some of the future research questions as well. The wheel configuration starts to slip when weight is added to the one inch wheel, the two inch wheel configuration also slips during and after the forth weight condition (Table VI). There are two main conclusion that can be made is regard to the overall analysis of the collected data. First the more weight is added to the wheel, the more the sand will compact, and thus a greater draw bar pull force is required to move the system and slippage may occur. In our cases for the narrower wheel type's slippage did occur as the wheels had to bare more weight.

Strategies for Minimizing Bias and Error

Two sets of experimental procedures were conducted in an effort to obtain meaningful data. In the first set of experimental procedures the draw-bar pull force and the depth measurement were recorded under weight conditions of 2 pounds, 5 pounds, 10 pounds, and 20 pounds. Under these conditions, the weight was too heavy to record a meaningful data. In the last two conditions the weight was too heavy for the wheels. The axle of the 2 inch wheel was bent under the same conditions; furthermore slippage occurred in every trial for the last two weight conditions. Due to the fact that wheel slippage occurred under every weight condition for the last two test wheels, it was necessary for us to repeat the experiment under new weight condition. Repeating this experiment would provide an opportunity to collect the data necessary to draw purposeful conclusions.

In the second set of experimental procedures the drawbar pull force and the depth measurement were still observed and recorded. Although in this second set of experimental procedures the weight conditions were altered to six different weights including 0 pounds, 1 pound, 2 pounds, 3 pounds, 4 pounds and 5 pounds. I did these little weight conditions, very attractive results were derived. Furthermore wheel slippage occurred as expected and the one-inch wheel under every weight condition. Although slippage occurred in the second set of experimental conditions, the results were experimentally validated because they didn't occur as a result of a malfunctioning test system or inconsistencies within the wheel assembly cart fixture.

By conducting the experimental procedures under two sets of weight conditions, the data collected was quickly analyzed and errors in the experimental procedures were uncovered. This allowed for the identification of the experiment to bias and error in our test apparatus and data collection tools. After conducting the second set of experimental procedures it was determined that the first set of experimental procedures contained bias in the test apparatus and errors within the interaction of the force gauge and the wheel assembly cart.

Limitations of the Study

Several limitations occurred in the process of conducting experiments who procedures. These limitations occurred in the form of a dragging crossbar, forced a wheeled treads, altered wheel assembly cart fixture and friction between the track and the crossbar. These presented issues limited the completion of the experiment in an expedited manner. Not only did these issues inhibit the completion of our experiment but they also required the experiment to be repeated. Through repeating this experiment several of the limitations disappeared under the lower weight requirements, thus allowing for meaningful data to be collected and the limitations of the experiment to be resolved.

Findings, Conclusions and Recommendations for Future Research

Findings

A series of six weight conditions were comprised (Table II) in order to obtain meaningful data. The weights tested played essential role on the accuracy and precision of the data collection process. Three different wheels were tested, each having different treads and wheel widths (Table III). The differences in wheel widths allowed for data analysis in comparing the wheels and the depth of the wheels treads.

Table II

Condition	Weight (lbs)
1	0
2	1
3	2
4	3
5	4
6	5

Table III

Wheel	Width (in)
1	4
2	1
3	2

The draw bar pull force was collected for each wheel under the six weight conditions (Table IV). The draw-bar pull force was measured in Newton's (N).

Table IV. The force under each tested condition for the three wheel types.

	1 (N)	2 (N)	3 (N)	4 (N)	5 (N)	6 (N)
1	2.27	3.10	3.67	4.82	5.58	8.20
2	2.15	3.53	5.52	6.52	8.89	11.05
3	2.87	3.36	5.16	7.10	9.10	12.03

The depth of the tread, for each tested wheel under the six weight conditions was measured (Table V). The depth was measured from the bottom of our test system to the bottom of the tread in the sand, and this measurement was recorded in inches.

Table V. The depth of the tread for each tested condition for the three wheel types.

	1 (in)	2 (in)	3 (in)	4 (in)	5 (in)	6 (in)
1	0.063	0.075	0.084	0.125	0.125	0.131
2	0.234	0.281	0.375	0.406	0.469	0.500
3	0.125	0.156	0.200	0.250	0.319	0.438

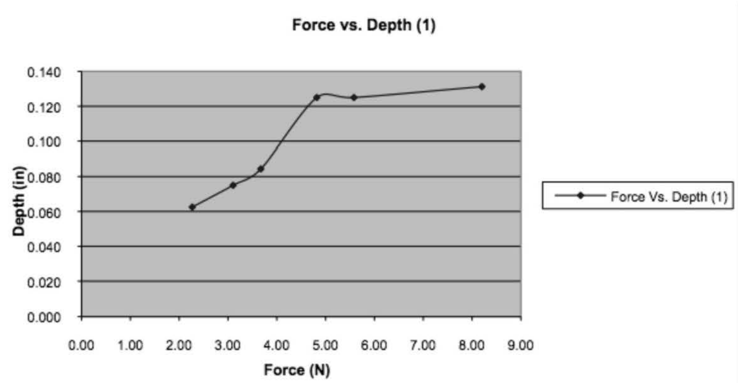
Wheel-slippage occurs with four wheels two (1 in) and three (2 in). Slippage occurs in every trial for wheel two, although it does not occur throughout under the first weight condition (Table VI). In the case of the third wheel slippage is not seen until the fourth weight condition (Table VI). In the fourth weight condition slippage does not occur throughout the entire trial which is denoted by s/, but in the preceding weight conditions slippage is relevant throughout the entire trial. Slippage does not occur in any of the tested weight conditions for the first wheel (4 in) (Table VI).

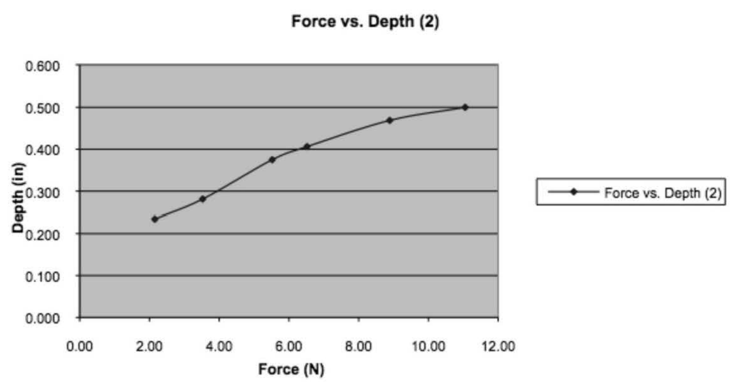
Table VI. The s denotes slippage and the n denotes no slippage. The s/ means Wheel-slippage does not occur throughout the entire trial.

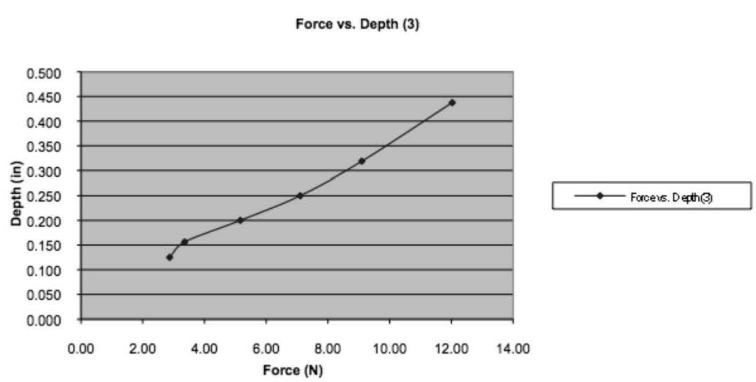
	1 (lb)	2 (lb)	3 (lb)	4 (lb)	5 (lb)	6 (lb)
1	n	n	n	n	n	n
2	s/	s	s	s	s	s
3	n	n	n	s/	s	s

There is an increasing relationship between the depth and the draw-bar pull force (Fig. 1) for the first wheel. Under heavier conditions the depth of the wheel in the sand increases in smaller increments. While the depth of the second wheel increases in a constant manner in large increments when compared to the first wheel (Fig. 1). The third wheel experiences a drastic jump in the depth measurement under the 5 pound weight condition (Fig. 1).

Figure I. Result of the force and depth data sets for the three tested wheels.





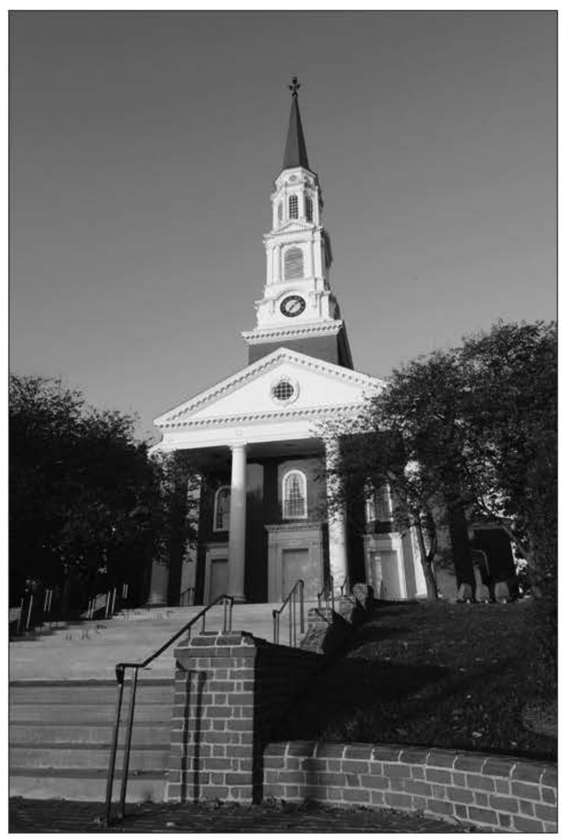


Conclusions

Several steps were taken toward the overall goal of this research which is to suggest a better planetary rover wheel design for future planetary rovers. The test system did not function properly with extremely heavy weights so a new test trial was conducted in an attempt to obtain meaningful and repeatable data. The limitations of the study appeared in the form a limited budget, non functioning materials, and the malfunctioning milling equipment in the Space Systems laboratory. After redesigning the structure of the test simulation system, the milling equipment was no longer required. After subjugating several obstacles that presented themselves and hinders to the research process, a functional test simulation system was built. With this functioning test system repeatable data was collected, analyzed and interpreted. By understanding the relationship between the draw-bar pull force and the weight applied to the wheels, our research concluded that the more the weight added to the wheel the more the sand will compact which in turn requires a greater draw-bar pull force.

Recommendations for Future Research

Because interesting trends were also unveiled between the depth of the wheel tread and draw-bar pull force, future research is necessary to determine explanations of these trends. In the near future, tests that explain the relationship of wheels with multiple surfaces will be conducted. In addition, research that involves testing different wheel types as well obtaining the torque calculation will also be conducted. The information from these future experiments will provide much needed insight as to which wheels are most efficient for planetary surfaces. More importantly, these experiments will lend insight to the direction of our research. By conceptualizing this direction, the focus will be narrowed which will allow for a great leap towards the overall goal of developing a multi- surface transversal rover wheel.



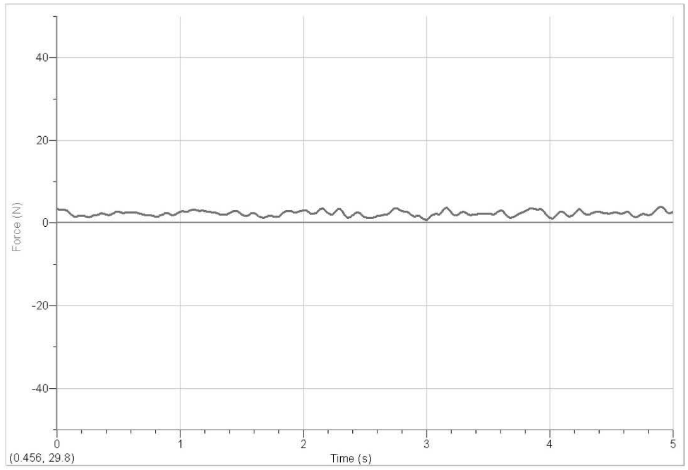
Appendicies

Appendix A: Raw Data

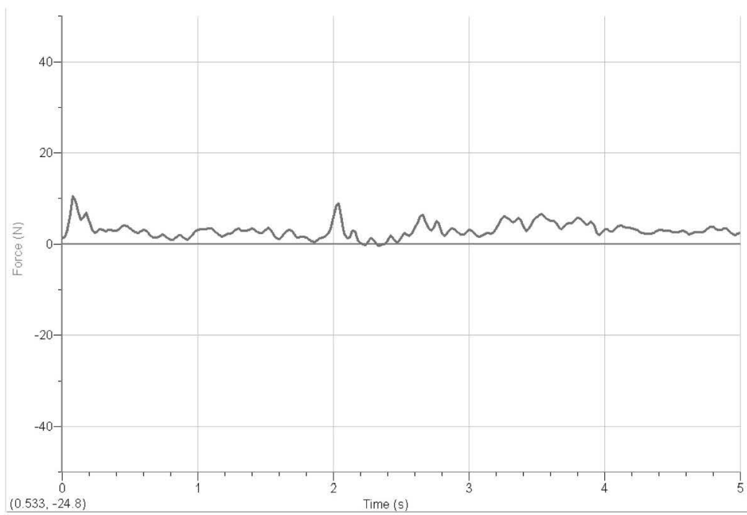
Data for the first wheel (4in) with no weight
Trial 1 Data: Weight 1

Time (s)	Force (N)	Avg Force	Depth
0	3.305556	2.2684391	0.0625
0.02	3.185897		
0.04	3.185897		
0.06	3.096154		
0.08	3.036325		
0.1	2.497863		
0.12	1.899573		
0.14	1.510684		
0.16	1.42094		
0.18	1.600427		
0.2	1.75		
0.22	1.75		
0.24	1.480769		
0.26	1.391026		
0.28	1.540598		
0.3	1.779915		
0.32	1.899573		
0.34	2.07906		
0.36	2.318376		
0.38	2.138889		
0.4	1.959402		
0.42	1.809829		
0.44	1.929487		
0.46	2.258547		
0.48	2.587607		
0.5	2.647436		
0.52	2.497863		
0.54	2.40812		
0.56	2.467949		
0.58	2.557692		
0.6	2.497863		
0.62	2.497863		
0.64	2.438034		
0.66	2.318376		
0.68	2.138889		
0.7	2.019231		
0.72	1.839744		
0.74	1.809829		
0.76	1.779915		
0.78	1.600427		

Appendix B: Graphs of Raw Data

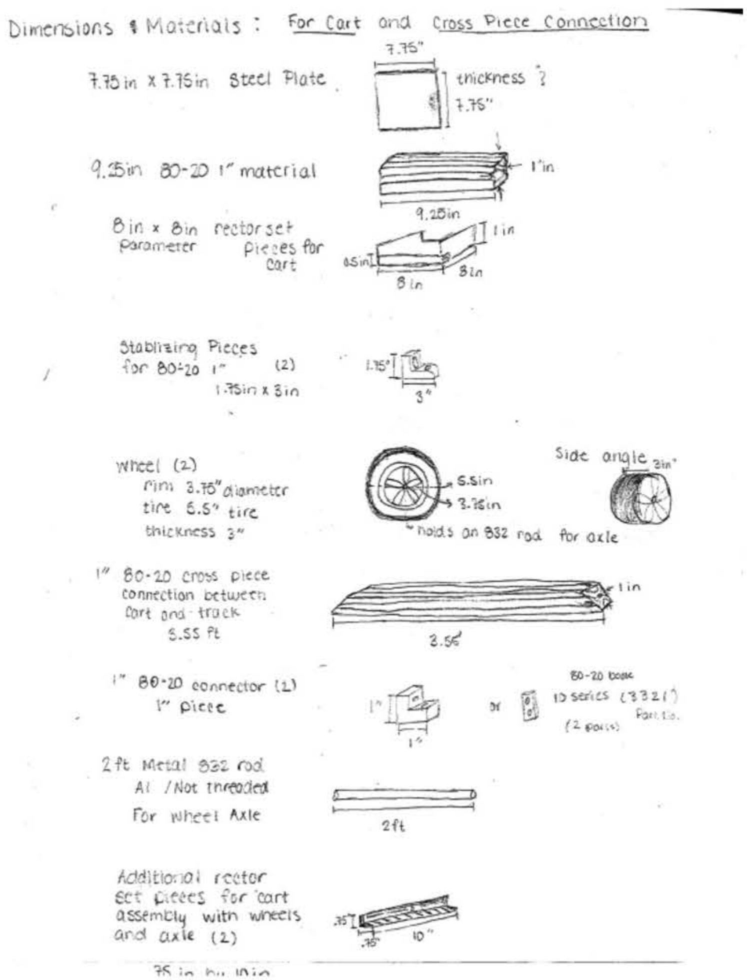


Wheel 1 with no weight

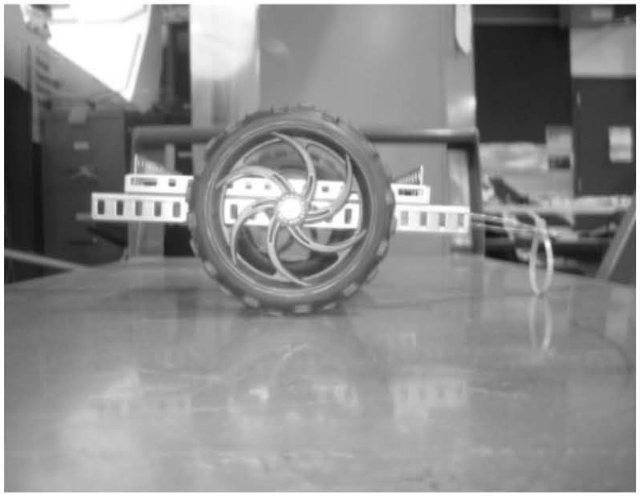


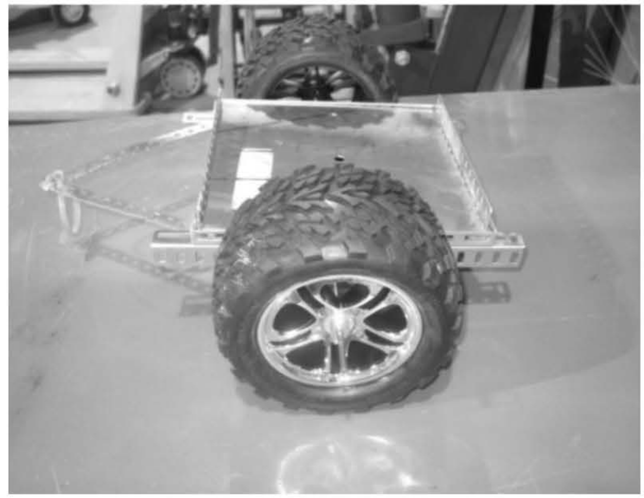
Wheel 1 with I lb

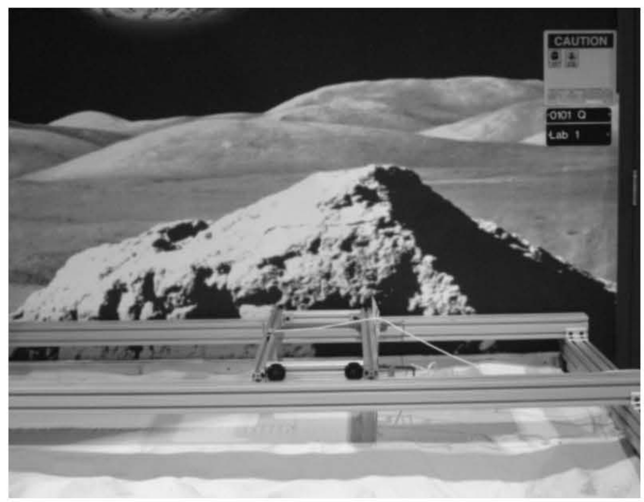
Appendix C: Initial Sketches of Apparatus

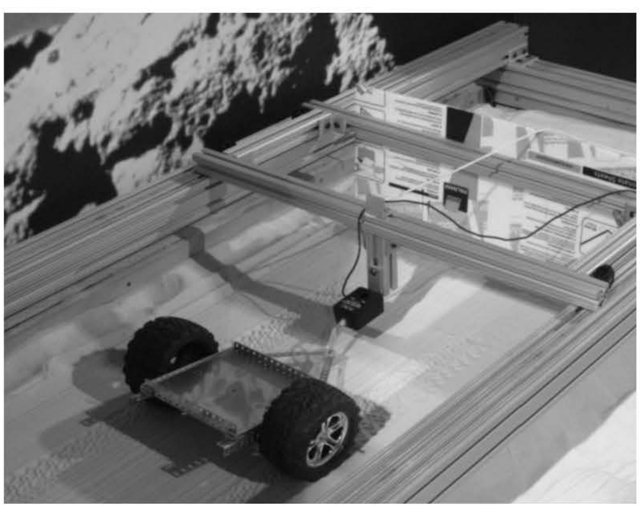


Appendix D: Images of the Apparatus









References

Bekker, G. (1956). *Theory of Land Locomotion*. Ann Arbor, MI: University of Michigan Press

Bekker, G. (1969). *Introduction to Terrain-Vehicle Systems*. Ann Arbor, MI: University of Michigan Press

Brown, D., & Webster, G. (2010). *Now a Stationary Research Platform, NASA's Mars Rover Spirit Starts a New Chapter in Red Plan*et Scientific Studies. Retrieved June 16, 2010 from http://marsrover.nasa.gov/newsroom/pressreleases/20100126a.html

Curtis, A.R. (2005). Rolling Across the Red Planet: Pathfinder and Sojourner Explore Mars. Retrieved June 16, 2010 from http://www.spacetoday.org/SolSys/Mars/MarsExploration/MarsPathfinder.html

Dooling, D. Planetary Rovers Might Roam Better with an Elastic Loop Mobility System. (2010). Retrieved June 16, 2010 from http://science.nasa.gov/science-news/science-at-nasa/msad28apr98_1b/

Ellery, A. (2005). Enviornment – robot interaction – the basis for mobility in planetary micro-rovers. Robotics and Autonomous Systems, 29-39. doi:10.1016/j.robot.2004.08.007

Iagnemma K., Kang S., Shibly H., & Dubowsky S. (2004). Online Terrain Parameter Estimation for Wheeled Mobile Robots With Application to Planetary Rovers. *IEEE Transactions on Robotics, Vol.20, NO.5*. doi:10.1109/TRO.2004.829462

Iagnemma K., Shibly H., & Dubowsky S. (2004). On-line Terrain Parameter Estimation for Planetary Rovers. *IEEE International Conference Robotics and Automation,* 3142-3147. doi:10.1109/ROBOT.2002.1013710

Ishigmi G., Miwa A., Nagatani K., & Yoshida K. (2007). Terramechanics-Based Model for Steering Maneuver of Planetary Exploration Rovers on Loose Soil. *Journal of Field Robotics 24(3),* 233-250. doi:10.1002/rob.20187

Kushwaha, R. (2010). International Society for Terrain – Vehicle Systems. *Journal of Terramechanics: Application to Terrain – Vehicle Systems*. Retrieved June 16, 2010 from http://www.elsevier.com/wps/find/journaldescription.cws_home/302/description#description

Liang, D., Hai-bo, G., Zong-quan, D., & Jian-guo T. (2010). Wheel slip-sinkage and its prediction model of lunar rover. *Central South University Press and Springer-Verlag Berlin Heidelberg.*doi:10.1007/s11771-010-0021-7

Mars. (2010). In *Merriam-Webster Online Dictionary*. Retrieved August 11, 2010, from http://www.merriam-webster.com/dictionary/mars

NASA Headquarters, Jet Propulsion Laboratory. *MARS PATHFINDER WINDS DOWN AFTER PENOMINAL MISSION.* (1997). Retrieved June 16, 2010 from http://www.xs4all.nl/~carlkop/pathfi.html

NASA Jet Propulsion Laboratory, California Institute of Technology. (2010). *Mars Exploration Rover Mission: Overview*. Retrieved August 1, 2010 from http://marsrover.nasa.gov/overview/

NASA Jet Propulsion Laboratory, California Institute of Technology. (2010). *Viking to Mars*. Retrieved June 16, 2010 from http://www.jpl.nasa.gov/missions/missiondetails.cfm?mission=Viking

Planet. (2004). *In Columbia Electronic Encyclopedia*. Retrieved August 11, 2010, from http://www.reference.com/browse/planet

Rover. (2010). In *Merriam-Webster Online Dictionary*. Retrieved August 11, 2010, from http://www.merriam-webster.com/dictionary/rover

Space Exploration. (2010). In Encyclopedia Britannica. Retrieved August 11, 2010, from Encyclopedia Britannica Online: http://www.britannica.com/EBchecked/topic/557348/space-exploration

Surface. (2010). In *Merriam-Webster Online Dictionary*. Retrieved August 11, 2010, from http://www.merriam-webster.com/dictionary/surface

Torque. (2010). In *Merriam-Webster Online Dictionary*. Retrieved August 11, 2010, from http://www.merriam-webster.com/dictionary/torque

Volpe, R. (2003). Rover functional autonomy for the Mars mobile science laboratory. *IEEE Aerospace Conference,* 643-652. doi: 10.1109/AERO.2003.1235474

Wong, J. (1976). *Theory of Ground Vehicles*. New York: Wiley