COLLEGE OF
SCIENCE AND
ENGINEERING

Robotic Explorer for Psyche's Hypothesized Surfaces

Project Report

Team 22.5
MEGR 4890

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5/27/2022

Disclaimer

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Executive Summary

16 Psyche is a metal-rich asteroid situated in the main asteroid belt. An ASU-led NASA mission to explore the asteroid from orbit will launch later this year and reach Psyche around 2026. The goal of our project is to design a robotic explorer that could be used to explore Psyche's surfaces for future missions. Psyche has challenging conditions that need to be considered such as its low gravity (1.5% of Earth's), lack of atmosphere, temperature range (-200 to –25 °C). We defined additional requirements that the rover should be able to meet such as the ability to traverse after flipping on its back and the ability to right itself if stuck on its side. Additionally, the rover must be able to roll over 20 cm rocks. Finally, the instruments must be secure and able to always operate. The team was concerned with the feasibility of a wheeled rover and explored that design as well as different solutions to move the rover across Psyche's terrain. We used MSC Adams and MATLAB simulations to assess how these solutions would perform under Psyche's conditions. After this analysis, we determined that the traditional wheeled rover would work on Psyche, with some modifications. Our rover uses large wheels to generate the required clearance as well as giving the rover the ability to drive on both its top and bottom sides. The instruments sit on a rotating plate to allow continuous operation when the rover is driven on either side. Finally, we designed a mechanism that will allow the rover to correct itself after being stuck on its side.

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1 Introduction

In August of 2022, NASA is launching a satellite to investigate the asteroid Psyche which is hypothesized to be the remnant of a planet's core. Psyche is one of the largest asteroids in the main asteroid belt, which is located between Mars and Jupiter. It has an average diameter of 140 miles (about the distance between Seattle and Portland). It is thought to be composed of a mixture of metal, rock, and porous space. Our project is based on a hypothetical second mission to explore Psyche's surface, given a successful initial mission. Our goal is to design a prototype robotic explorer capable of efficiently traversing Psyche's hypothesized surfaces and, ideally, able to adapt to each mid-traverse. The goal of this robotic explorer would be to traverse one of Psyche's two main craters, which is approximately 4 miles deep and 33 miles wide.

1.1 Specifications

To start, we developed objectives and constraints related to the project to guide the design. The objectives for the rover are primarily what the rover needs to be able to do to complete its mission. The constraints relate to specific metrics and requirements that need to be considered in order to complete these objectives successfully. Our constraints are broken up into two categories, one is the conditions of Psyche, and the other are constraints for the rover's design.

1.1.1 Objectives for the rover

1. Navigate Psyche's main crater.

Navigating the main crater was specified by the team in order to narrow down what our rover's goal would be during its mission. The main crater was chosen for exploration because of its relatively flat surface. Exploring this main crater could also allow the rover to gain data related to impacts into the crater and asteroid.

2. Traverse over large rocks.

We believe that Psyche has many rocks and other structures that would need to be traversed. Later in this section, we define a specific height of rock which the rover needs to go over, but as a baseline the rover will need to be able to traverse different obstacles that would appear in the terrain such as rocks and small cavities.

3. The rover must carry the equipment safely.

For the rover to function and perform its mission correctly, all the equipment must be safely carried on the rover. It must be protected from any strikes with terrain, the equipment must be kept at an appropriate orientation for the instruments to function and the temperature of the equipment must be kept within the functional range. If an unexpected situation occurs, the rover will have recovery systems designed to rotate the rover and equipment cluster back to the correct orientation.

1.1.2 Constraints

Table 1 shows the constraints listed 1-6.

1. Psyche's gravity is a very small fraction of Earth's. When starting the brainstorming process, we had to consider whether a traditional wheeled rover would be able to move anywhere across Psyche's surface. This small gravity required us to explore alternate methods of locomotion and compare them.
2. Without an atmosphere, conventional design choices that would be made to achieve a certain goal on Earth are not feasible on Psyche. Choices on items like sensors would need to be double checked to confirm their ability to be used without an atmosphere.
3. The instruments need to be kept within a functional temperature range (-40 to 40°C) to operate. Due to the cold temperatures of Psyche, many of the sensors and instruments would not work without some type of heating element to keep them warm. Additionally, materials would need to be chosen with this in mind.
4. Sunlight is only available on Psyche for half an orbit. Psyche completes its orbit around the Sun in around 5 Earth years. Thus, the rover will have continuous sunlight for 2.5 years which constrains some of the options for power in our design.
5. Being able to traverse over rocks 20 cm in height was a pseudo-arbitrary number selected by the team based on visualizing the size of the rocks. The number does not represent a requirement from outside, but a number in order to give our design a quantifiable goal.
6. To keep the motion from going unstable, we need to keep the wheels in contact with the ground while driving. One or two wheels would be fine to lose contact and we expect this to happen as it traverses over smaller rocks.

Table 1: Rover and Environment Constraints

	Type of Constraint	Constraint Variable
1	Psyche's Conditions	Gravity 1.5% of earth (.144 m/s^2)
2		No atmosphere (vacuum)
3		Temperature (-200 to -25 °C)
4		Available sunlight
5	Rover Constraints	Traverse rocks of 20 cm in height
6		(Wheeled Rover) Minimum velocity for at least 2 wheels to remain in constant surface contact

1.2 Process Background

To gain understanding of vehicle design in space, we looked at what existing solutions had already been done. As mentioned, Psyche's gravity is 1.5% of the Earth's gravity. With that gravity, there are two types of designs that could be used.

The first are traditional wheeled rovers, like the Lunar rover or Mars rovers. We focused on the Perseverance and Curiosity rover on Mars due to Mars having a lower gravity than Earth, which is 3.721 m/s^2 (or 38% of Earth's). Additionally, these rovers are recent missions, having launched within the last 12 years so the features on those rovers are up to date and could be translated to use on Psyche. However, a gravity of 3.721 m/s^2 is high enough to create the frictional force required to create motion. The frictional force is proportional to gravity. Since Psyche's gravity is a smaller percentage, we cannot rely on the robotic explorer to be same way as the Perseverance rover.

The second group of design we looked at were micro-gravity solutions and other forms of alternative locomotion. Microgravity environments, which are environments which have very small gravity, approximately 10^{-6} m/s^2 or less. These gravity environments mean traditional wheel rovers are not able to traverse as contact force is minimal. The method of traversing for such low gravity environments is done by bouncing, tumbling motions which are created by accelerating, then braking a flywheel. NASA's Hedgehog, shown in Figure 1, utilizes this method of locomotion.

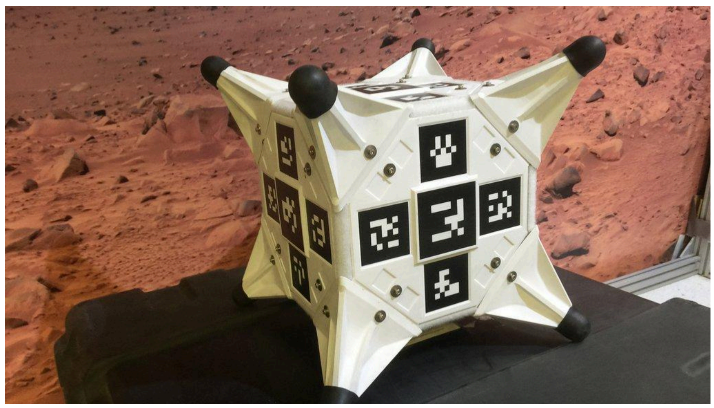

Figure 1: NASA Hedgehog Rover [1]

To understand these different forms of locomotion and predict their feasibility in Psyche's gravity, we used a multi-body dynamics simulation called MSC Adams. For the wheeled rover method, we simulated a wheel hitting a step at different speeds. The set-up for this simulation is shown in Figure 2. For this and all other images of the software, a graduation cap watermark will be present due to the educational license being used.

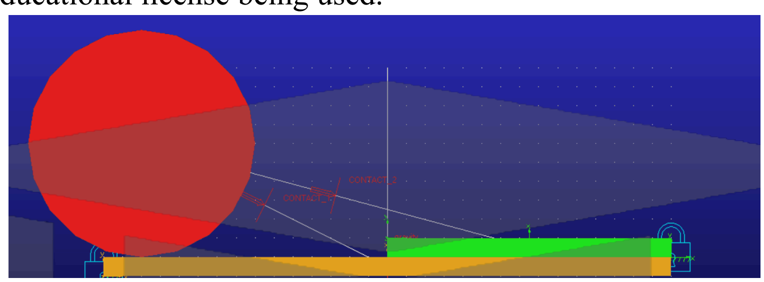

Figure 2: MSC Adams Set up for Simulation of Dynamic Wheel Moving in Psyche's Gravity

In this simulation, we set the wheel's radius to be 0.3 m with the weight of 100 kg. Due to not knowing Psyche's surface contact conditions, we used Mar's surface conditions to approximate it instead [2]. With that mass, the fastest that the rover could go and have stable motion after the step would be 0.15 m/s. This proves that wheeled rovers are possible in Psyche's environment.

Continuing to use MSC Adams, we simulated the micro-gravity design based on NASA's Hedgehog using a simple cube shape with all the parameters to get a similar profile. To simulate the flywheel, we applied a torque to the cube. A torque of 0.2 N-m was used to generate the tumble motion across the surface and a torque of 8 N-m created the larger hopping motion.

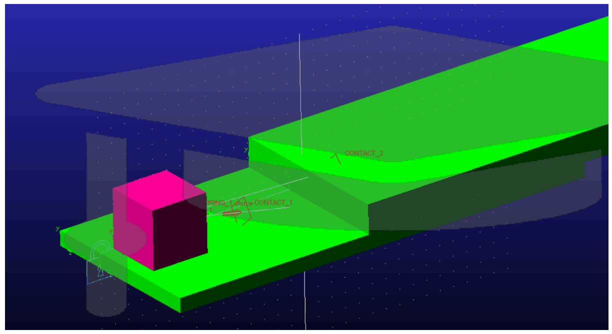

Figure 3: MSC Adams Simulation Set Up of Hedgehog Rover under Psyche's Gravity

1.2.1 Motion Analysis

While working on these simulations, we also created a program using Python, a programming software, to utilize dynamic motion equations to determine feasible speeds for a wheeled rover to not lose contact with the ground while going over a step of a specified height. For simplicity, we approximated the rover as just one wheel.

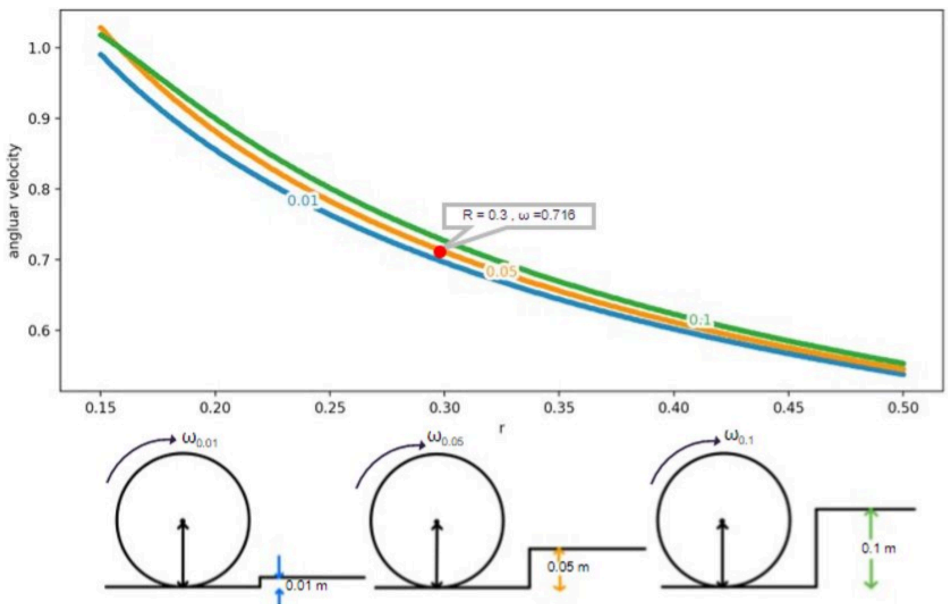

Figure 4: Max Velocities for No Contact Loss given a Wheel Radius and Step Height, Plotted

Figure 4 shows the critical angular velocity at which the wheel will start to lose contact with the surface for different step sizes. The x-axis on the graph are the different radii of wheels in meters. On the y-axis, the angular velocities are shown in radians per second. Each different colored line in the group presents a specific step height and the step height is visualized relative to a 0.2 m wheel under the graph. From this graph, we can check a specific radius and determine what an acceptable angular velocity would be. To demonstrate, the figure shows a wheel radius of 0.3 m and a step height of 0.05 m which corresponds to a maximum velocity of 0.716 rad/s

1.3 Final Solution Overview

Given the objectives and constraints, we created initial concepts and evaluated them. The concepts and iterations are shown in Appendices A and B, respectively. After all the analysis we conducted and designs considered, the final design decision for the robotic explorer is a mid-sized four wheeled rover. The rover is approximately the size of a golf cart. Without a specific idea of what equipment would be included, we based the rover's equipment on what was used for the Mars Perseverance rover. Figure 5 shows an overall image of our final model, which was made in SolidWorks, a computer aided design software.

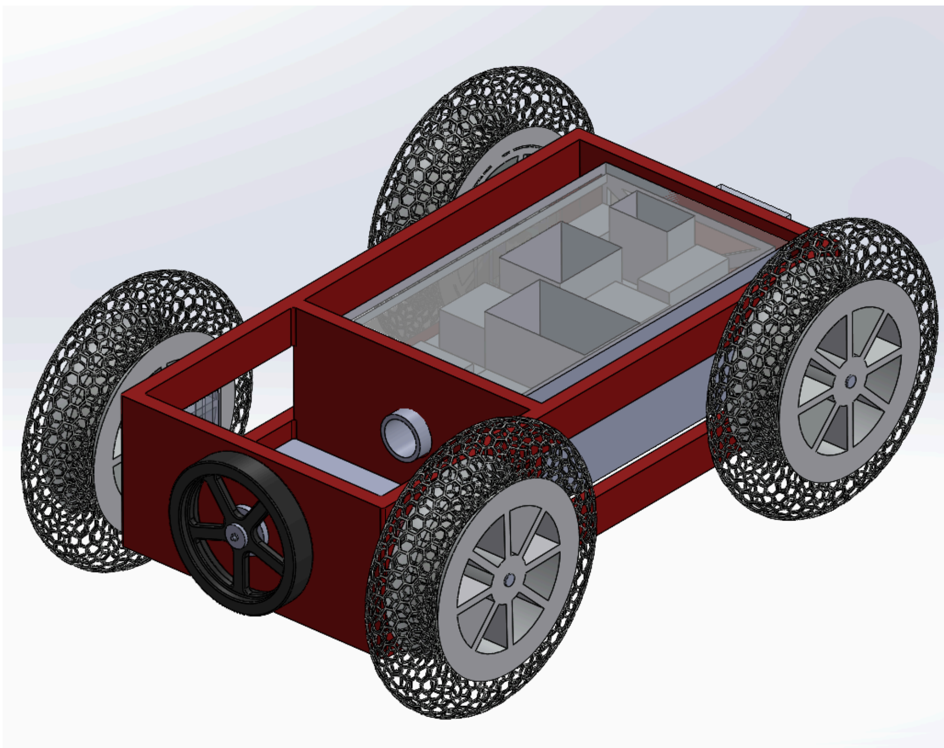

Figure 5: CAD model of the developed Robotic Explorer

1.3.1 Rover properties

From our constraints, we decided the rover must be able to traverse over rocks that are smaller than 20cm. For a wheel to be able to roll over a step, the step cannot be larger than the radius of the wheel. Thus, the minimum diameter that the wheel can be to go over a 20cm step is 40cm. In our final design, the wheels were designed so that both top and bottom had 25 cm of clearance. Based on this, the final wheel diameter is 90 cm. The maximum speed the rover can travel and remain on the ground was determined analytically using the python program mentioned in Section 1.2.1 and confirmed using an Adams dynamics simulation.

1.3.2 Recovery system

Due to low gravity and unknown terrain, we have designed recovery systems to prepare for unexpected situations. The final design allows for the rover to be able to traverse on either its bottom or top sides. To accommodate this, the equipment on the rover can rotate 180^{o} to allow for correct orientation of equipment that is required to face a certain direction.

If the rover is at any point stuck on its side unable to traverse, we have included a system to help the rover return to either its bottom or top sides. Pictured at the front of the rover in Figure 5, a flywheel's rotation is used for this system. The details of this system will be explained in section 2.6.

2 Detailed Design

The previous section outlined a few of the guidelines for our rover's design as well as a short overview of the various systems included in our design. This section will expand on the specific components that are present in the rover's design and information on how they will work and why they were chosen.

2.1 Body

The body geometry is a simple rectangular prism that is 1m x 2m x 0.5m (LxWxH). It is divided into two main sections. One being where the power source will go and the other being where the instrument cluster is located as shown in Figure 6. There will be a small cutout in the center of the wall dividing both sections for wires and heat to pass through. The instrument cluster can rotate 180 degrees, so the scientific payload is always correctly oriented. The other compartment will store the power and other electronics to make the rover functional.

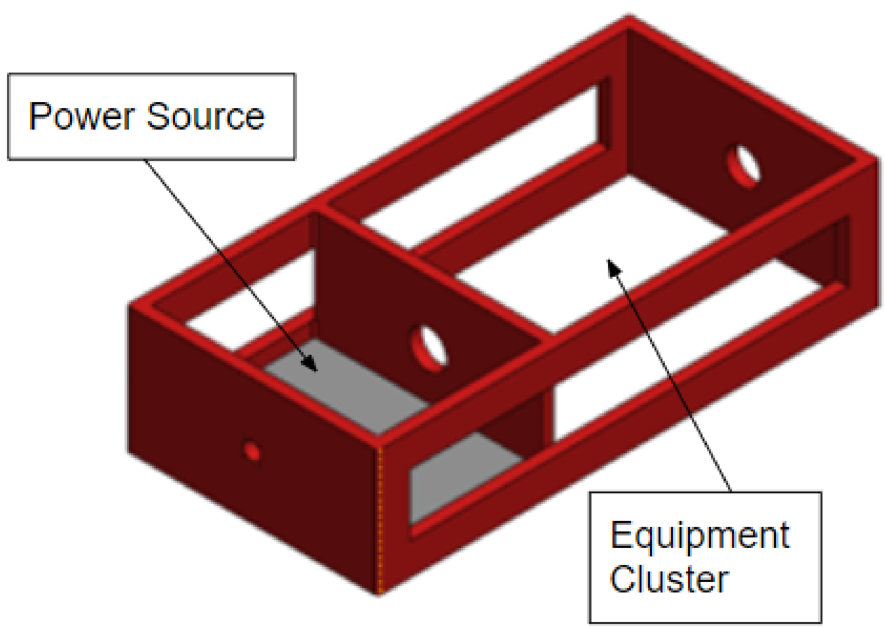

Figure 6: Rover body

2.2 Wheels

Our wheels are designed to be able to traverse over Psyche's hypothesized terrain. The main inspiration for this design is from the Lunar Rover Vehicle launched by NASA during the Apollo missions [3].

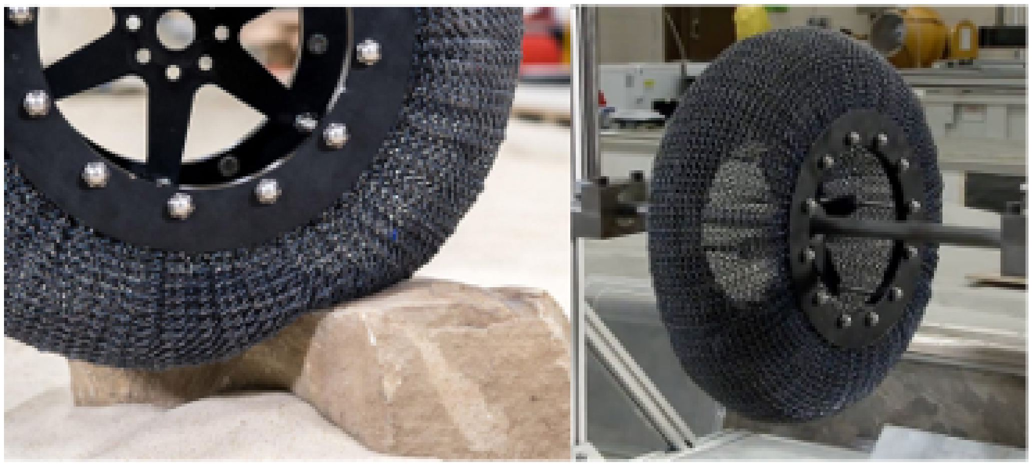

Figure 7: Mesh Wheel Inspiration from the Lunar Rover [2]

The wheels are made of a solid core with spokes like an automotive wheel to give it the necessary strength and the outer ring is a metal wire mesh that gives the wheels the ability to deform slightly under load. These wheels work well in Psyche's environment for a few reasons. First, they do not need any air or rubber to create traction. These would not be feasible on Psyche due to the lack of an atmosphere. The mesh outer portion was able to traverse the Moon's loose sediment well and this design should perform well on Psyche given that the surface of Psyche has a similar type of sediment. Until data is received back from the orbiter in the future, little is known specifically about that sediment. So, this design moves forward with the assumption that these wheels would work on Psyche.

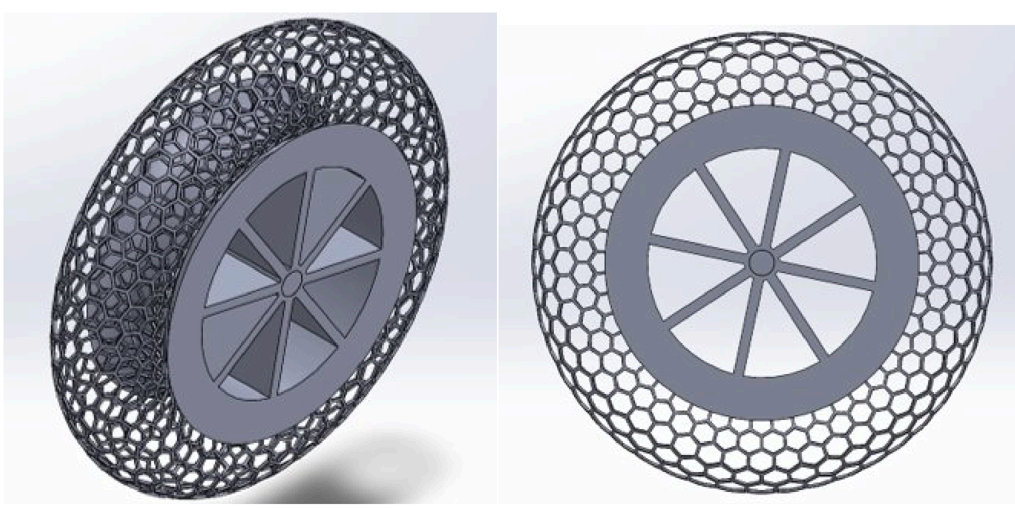

Figure 8: Solid works image of Rover Mesh Wheel

Note: CAD model has a lesser degree of detail due to computing limitations. The wheel mesh would be more fine rather than coarse.

2.3 Driving

This section will describe the design specifications of the rover's ability to traverse and reactions to the environment.

2.3.1 Motors

To drive the rover, each wheel will have its own motor connected to it. This keeps our design simple due to lack of wiring that needs to run between the wheels and allows us to use differential skid steering, which will be explained in the next section. The motor we chose to implement on our rover is the Maxon EC-32 [7]. Used on NASA's Perseverance rover, its space applications and power delivered fit the profile that is needed for this rover.

2.3.2 Steering

The steering mechanism that the rover will use is differential skid steering. Differential skid steering works by steering through an uneven speed between sides of the rover. Shown in Figure 9, the left side of the wheel drives at a higher speed than the right side, which results in the rover steering towards the right. The sharpness of the turn can be adjusted by changing the ratio between the speeds at which each motor is driven.

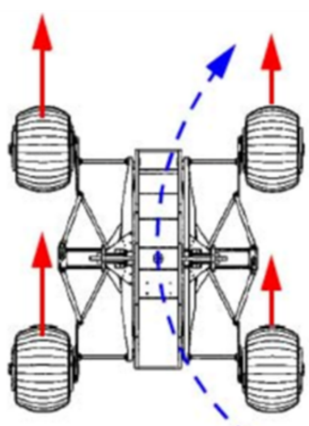

Figure 9: Differential Skid Steering Visual

2.3.3 Validation

To verify these design choices, we once again used MSC Adams. We used the same conditions for the simulation as previous ones using Psyche's gravity combined with Mars surface contact conditions [3]. The inputs are shown in Table 2. Using SolidWorks, we found the moments of inertia for the rover model. While the MSC Adams model is simpler than the CAD model, inputting the moments of inertia will give us accurate results.

Table 2: Surface Contact Parameters from ref [3]

Friction Parameters	Value
Stiffness (N/m)	7.5310^7
Force Exponent	2
Damping (kg/s)	8140
Penetration Depth (m)	0.002
Static Coefficient	0.757
Dynamic Coefficient	0.597
Stiction Transition Velocity (m/s)	0.03
Friction Transition Velocity (m/s)	0.05

Through our analytical results found in section 1.2.1, we found that a good speed for our rover is 0.23 m/s. This produces a stable enough motion such that when the wheels hit the 0.2 m rocks, the rover will not spin uncontrollability and lose surface contact on too many wheels.

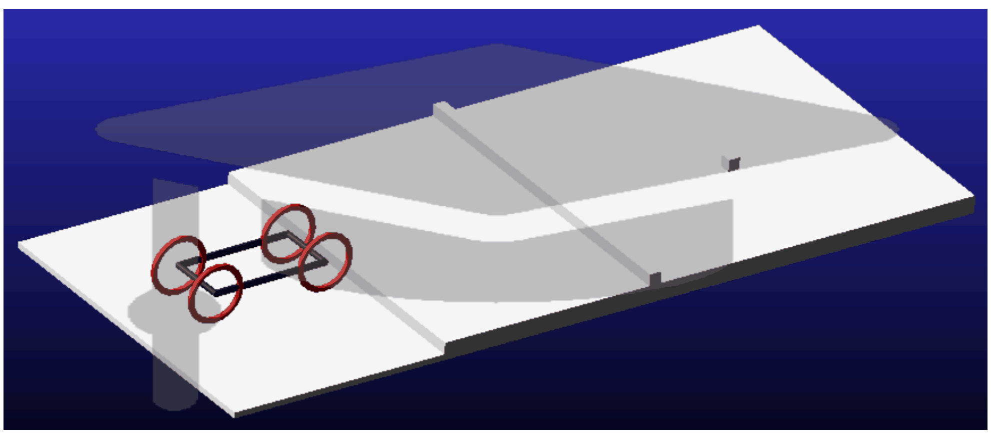

Figure 10: MSC Adams Set Up of Vehicle Driving Simulation Set-up

To verify if the motion is correct, the change of angular momentum as seen in equation 1 is analyzed.

$$\Delta L = T\Delta t \tag{1}$$

The equation above is the equation for angular momentum where T is torque and Δt is the duration of torque applied and ΔL is the change in angular momentum.

Figure 13, the y-axis represents the angular impulse (change of angular momentum about the center of mass of the rover) and the x-axis represents time. When the front wheels hit the rock, there is a low angular impulse of approximately 4.9 N-m-s. When the back wheels hit the rock, there is a high angular impulse of approximately 9 N-m-s. This phenomenon happens because the center of mass of the rover is more toward the back, since that is where all the equipment will be located.

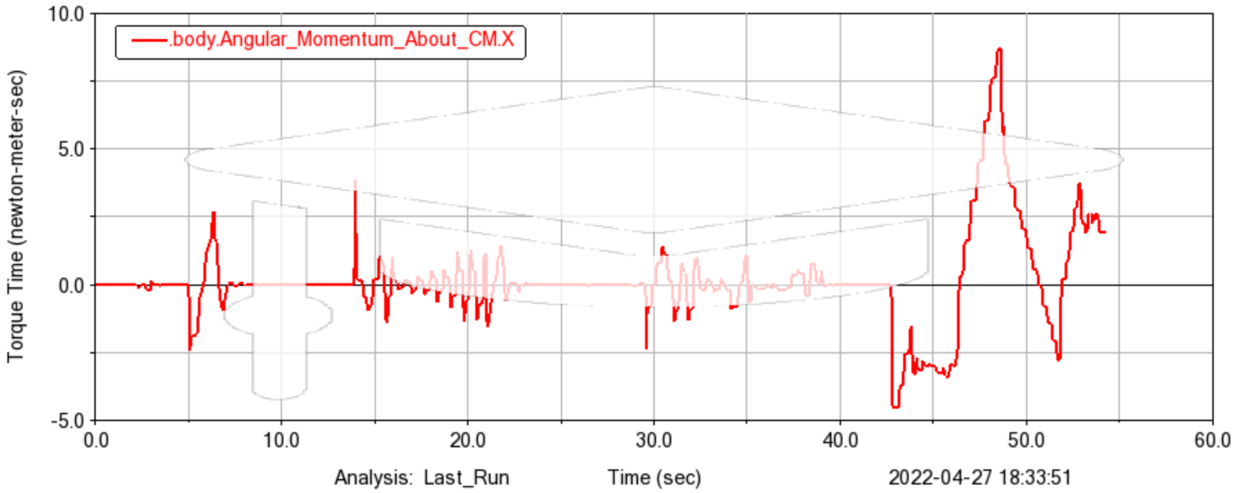

Figure 11: Angular Impulse Graph (Peak 1 = Front Wheels, Peak 2 = Back Wheels)

2.4 Power

Our rover will be powered by the multi-mission radioisotope thermoelectric generator (MMRTG) [4]. This power source was featured on the Perseverance rover as well and operates by converting the heat produced by decaying radioactive isotopes into electricity. The MMRTG on the Perseverance rover produces 110 Watts of power over a lifetime of 14 years [6]. The current MMRTG is 64 cm in diameter (measured from fin tip) and a length of 66 cm [6]. This MMRTG is slightly larger than ideal for our rover so should this rover become a real mission in 10+ years then a more efficient and better sized MMRTG should be made specifically for this rover.


Figure 12: MMRTG power source

2.5 Equipment

Our rover will use various pieces of equipment to perform its mission. It will take data, pictures and possibly samples to return to Earth. For simplicity during our project, we decided to outfit our rover with equipment from the NASA Perseverance rover. If an actual rover was made, not all the equipment could be chosen. Equipment may also be downsized or changed in order to better fit the rover. The table below shows the different pieces of equipment and their functions as well as total mass and power draw.

Table 3: List of Scientific Payload on the Rover

Equipment	Job	Total mass (kg)	Power (W)
ROPEC drill	Sample drill	4	100
Mastercam-Z	Take high-definition video, panoramic color, and 3D images	4	17.4
MEDA	Mars Environmental Dynamics Analyzer measures weather and the amount and size of dust particles in the atmosphere	5.5	17
PIXL	To measure the chemical makeup of rocks at a very fine scale	6.92	25
RIMFAX	To see geologic features under the surface with ground-penetrating radar	3	5-10
SHERLOC	Fine-scale detection of minerals, organic molecules and potential biosignatures	4.72	48.8
SuperCam	To identify the chemical composition of rocks and soils, including their atomic and molecular makeup	10.6	17.9
Power Source	MMRTG Provide power to the rover. Includes 2 lithium batteries	45	-110
Engineering Cams	Hazard avoidance and navigation cameras	6 - (0.25 kg each)	2.2
Communication	Antennas	0.5	10.7

For our CAD model, we took the dimensions of each piece of equipment from the NASA website [7][8] and used simple boxes with those dimensions to represent the location of the equipment on the instrument cluster.

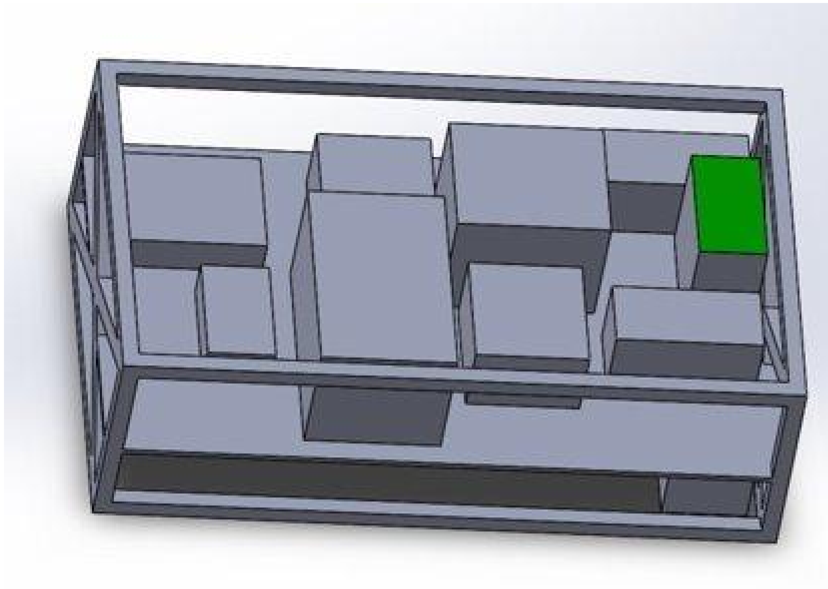

Figure 13: Rotating Equipment Cluster

Mentioned briefly in section on power, the equipment cluster will be heated by the excess heat coming from the MMRTG. Around this equipment will be insulation that will keep that heat from escaping in the vacuum. Openings will be created for any equipment that needs one like a drill or other collection mechanism.

One of the two mentioned recovery systems is the ability for the equipment cluster to rotate in response to the rover’s orientation. This means that no matter what side the rover is on that the equipment will be in the correct orientation to continue performing its mission tasks. If rover flips over 180 degrees, the equipment cluster will rotate after it is determined safe to do so. The system will determine if it is safe by checking for the necessary clearance under the rover’s body since the cluster extends past the vertical profile of the body. The system will determine this using the diffuse sensor mounted on top and bottom of the cluster. If the rover doesn’t have the clearance to make the rotation, it will drive forward until the sensor confirms that the clearance is available to make a safe rotation.

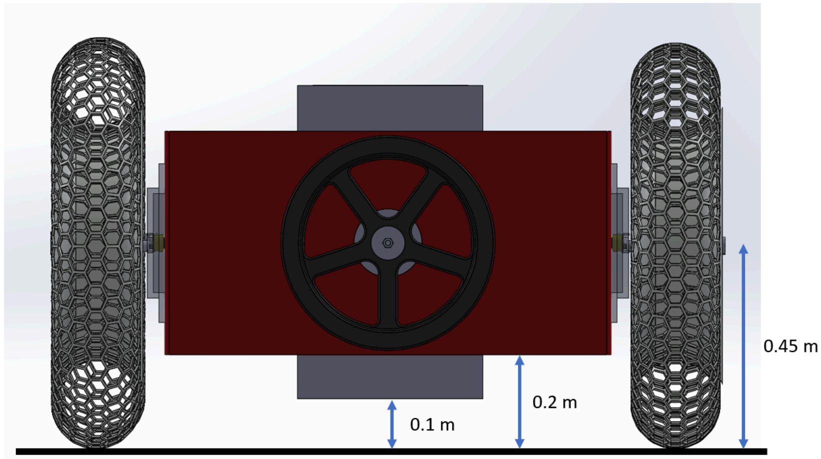

Figure 14: Equipment cluster rotation demonstration

2.6 Flywheel

The second recovery system will be a flywheel that is attached on the front of the rover as seen in figure 17, near the power source. The flywheel uses the same principle of the Hedgehog rover. The flywheel will rotate at a certain speed, then applies the band brake, to generate angular momentum to flip the rover back on its wheels. Due to the low gravity, the flywheel will be able to produce enough torque to flip the rover.

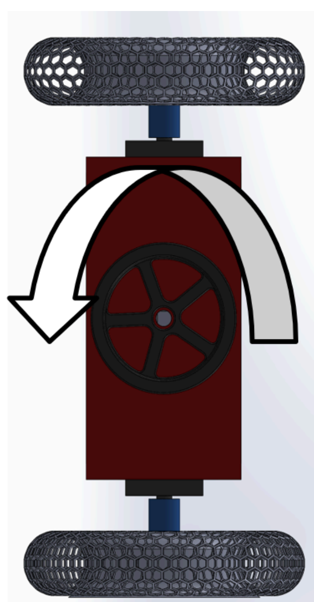
Figure 15: Flywheel on the end of CLANK

Table 4 outlines the size, mass, and speeds of the flywheel for the flywheel to flip CLANK upright.

Table 4: Properties of the Flywheel

Properties	Values
Diameter	0.48 m
Mass	10 kg
Minimum, $\omega_{f.min}$	86.7 rad/s 828 rpm
Maximum, $\omega_{f,max}$	93.8 rad/s 896 rpm

Equations 2 and 3 are derived from the research conducted by Stanford and NASA's Jet Propulsion Laboratory in exploring small solar system bodies [9]. The equation considers the mass of the rover m_p, Psyche's gravity g, the length from the center to the axis of rotation l, the tipping angle of the rover α, the angle of the surface β, inertia of the flywheel I_f, and the ratio of the inertia of the flywheel to the inertia of the rover about its corner η. This calculation is shown in greater detail in Appendix F.

$$\omega_{f,min} = \sqrt{\frac{2m_p gl(1-coscos\,(\alpha+\beta)\,)}{\eta I_f}} \quad (2)$$

$$\omega_{f,max} = \sqrt{\frac{gcos(\beta)}{\eta^2 lcos(\alpha)}} \quad (3)$$

The minimum angular velocity describes the minimum speed the flywheel must be rotating when the brake is applied in order to generate enough torque to right the rover. The maximum angular velocity describes the maximum speed the flywheel can rotate and still maintain contact with the ground when the brake is applied. Speeds faster than this will send the rover into the air, making it more difficult to control and is thus undesirable.

The next simulation done was to verify if the recovery flywheel system can flip the rover back on its wheels. After the flywheel spins to its optimal speed, it will generate an instantaneous torque that will generate momentum to flip the rover.

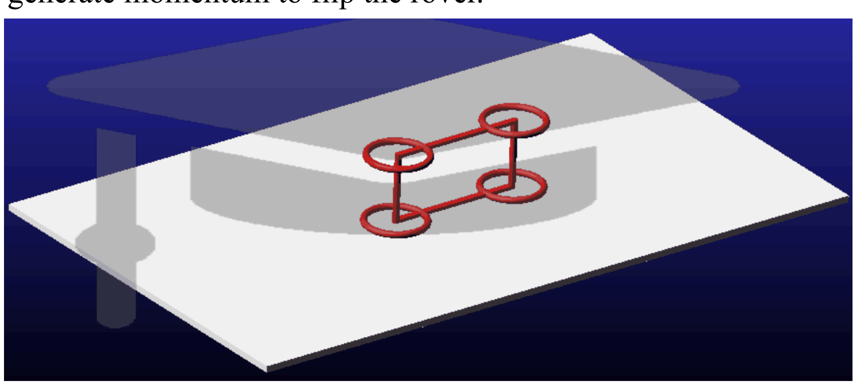

Figure 16: Adams Simulation Set-up of Flywheel righting the Rover on Psyche

The momentum generated is found using equation 4, where it is the integral of the torque over time. The momentum that needs to be generated is 45 kg-m/s as seen in figure 17. This is reasonably based on the NASA hedgehog equations 4.

$$\Delta L = \int \tau dt \tag{4}$$

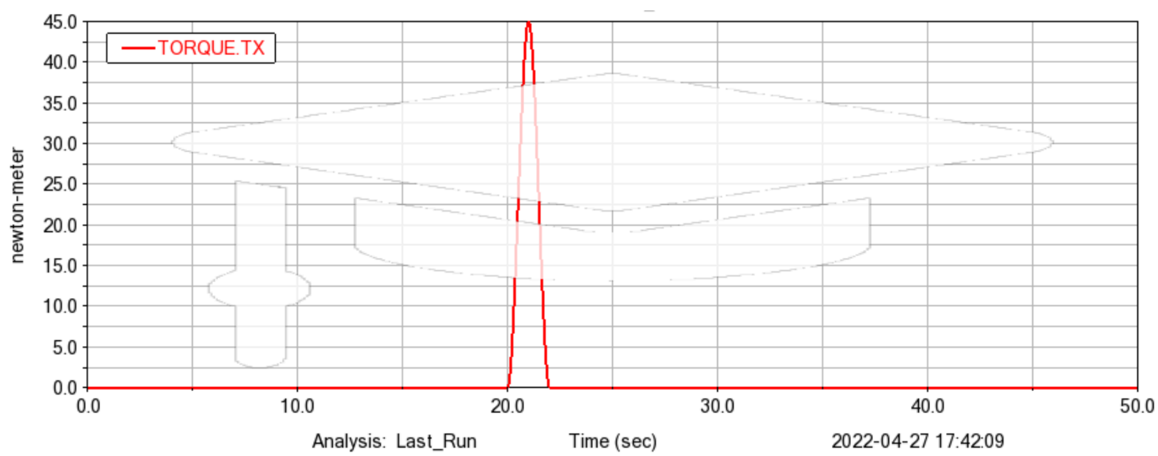

Figure 17: Angular Momentum Generated by Adams

3 Physical Prototypes

After developing our rover, we created two different physical prototypes to test the implementation of those designs in the real world. Due to the difference in conditions, these prototypes do not match performance on Psyche but give insight into the feasibility.

3.1 Rover Prototype

In order to demonstrate the function of the rotating equipment cluster and how this would function as a recovery system, we created a small functional model shown in Figure 18. While not dimensionally accurate, the model is close enough given the limitations of our materials. The parts we used are included in Appendix C. We chose to model this feature because it is an important part of the rover, being one of the recovery systems. Additionally, this system operates independent of gravity so the feature would function the same on Earth and on Psyche.

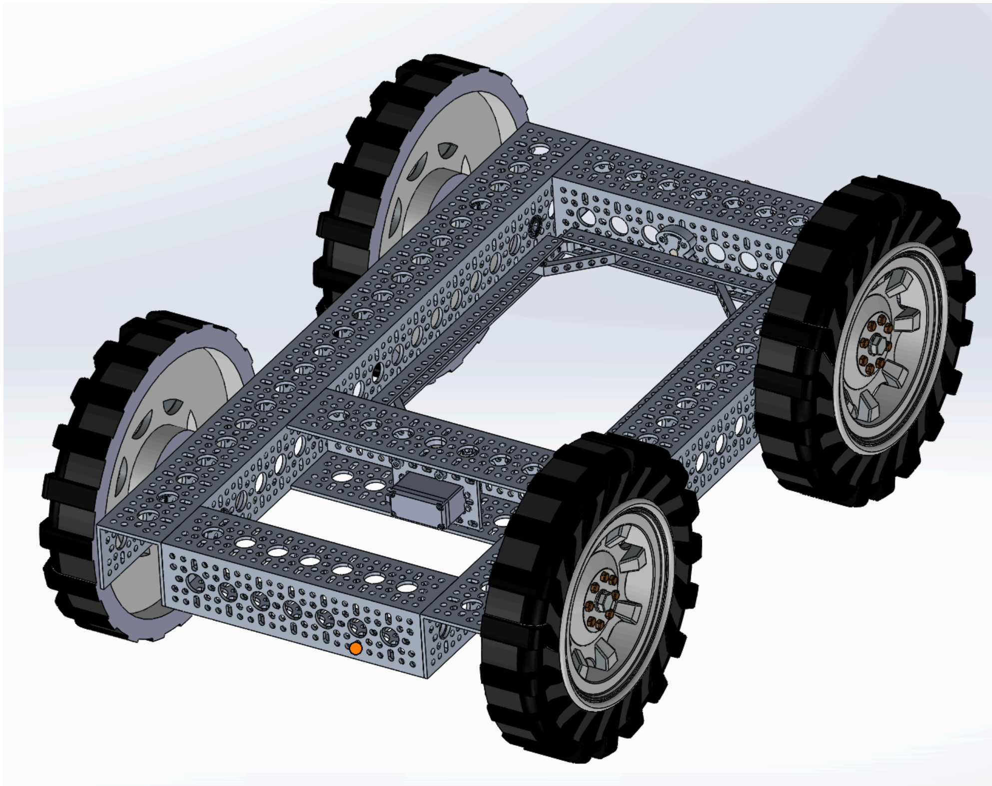

Figure 18: CAD model of Prototype (20”x10”) to show Equipment Cluster Rotation

In figure 19, our physical rotating equipment cluster model is seen starting in the upside-down position and then shown in its progression of flipping itself back upright. This feature is controlled by an Arduino microcontroller and triggered by an ultrasonic sensor reading. When needed, a servo motor will be activated that rotates the cluster 180 degrees. The code for the Arduino is provided in Appendix E.

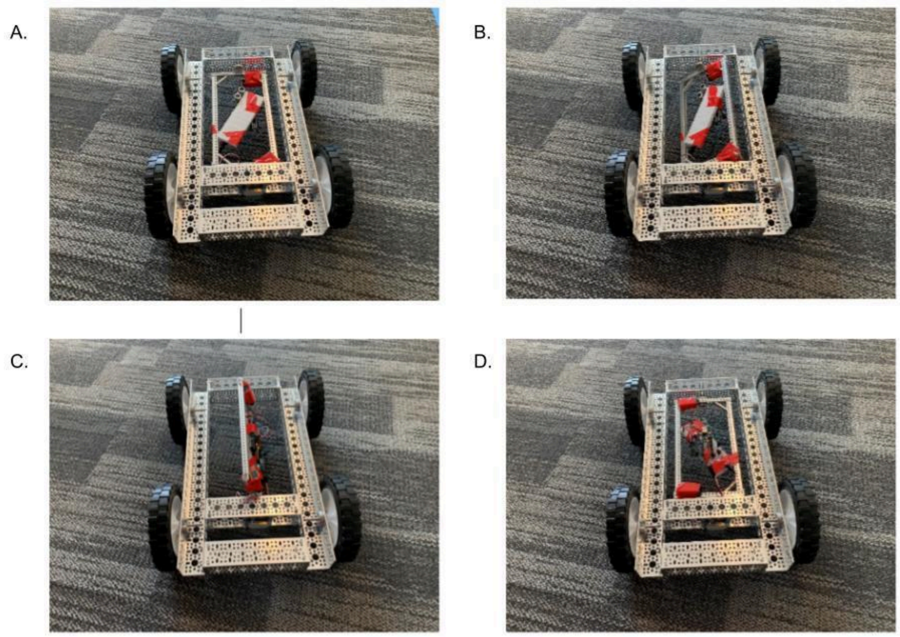

Figure 19: Progression of rotating equipment cluster model

For our prototype, we used an ultrasonic sensor. However, this feature would be controlled by a diffuse photoelectric sensor on the Psyche rover due to the lack of atmosphere on Psyche.

3.2 Flywheel Testbed

The goal for building the flywheel testbed is to prove the ability to rotate a given body from one orientation to another via the acceleration and stopping of a motor. Ideally, this physical model of the flywheel would be attached to the main prototype but was not feasible due to the high speed required by the motor to rotate it successfully in Earth's gravity. Instead, we created a smaller body that requires a lower speed to achieve the desired motion, which is going from upright (pictured in figure 20) to on one of its sides.

Figure 20: Test Bed with Flywheel Attached by a Motor

For prototyping purposes, a Micro Geared Motor is used to spin the prototype flywheel above as seen in figure 21. View Appendix E for the code to control the motor by Arduino Uno.

Figure 21: Micro Geared Motor with Encoder [10]

4 Ethical Considerations

4.1 Environmental

A rocket launch has negative effects on the environment from the release of fuel into the atmosphere. Historically, rockets were built to be only single use which had adverse effects on the environment. Today and in the future, rockets are becoming multi-use and more sustainable, working to lessen the environmental impact that a launch would have.

4.2 Health and Welfare

In the event of a failed launch, safety precautions must be taken to prevent debris from ending up in public areas. Likely, if this mission were to take place, the launch would occur at a NASA site already set up which already follows these considerations. Another special consideration related to this launch would be protecting the power source in the event of a failed launch.

4.3 Economic/Social Factors

The development of a robotic explorer that can traverse asteroids can improve the breadth of human knowledge. It can lead to more inspiration and interest in the field of space robotics, leading to more funding for space companies by the government or investors. By sending a rover to 16 Psyche, the metal asteroid can help us learn more about the formation of Earth's core, since it is believed the asteroid is a remnant of a planet's core. This is the closest we will be able to get to visiting Earth's core so the data we receive is of high importance.

5 Final Recommendations

We have final recommendations based on our work completed that serve both as a reflection on what could be changed in our design or process as well as further design iteration for future teams.

5.1 Improvements to Traversing Capabilities

The wheels for the Rover assume that the surface of Psyche is like the moon's surface. If the Orbiter mission to Psyche proves this to be true, the wheels may only need titanium threads to improve traction across the surface. If further exploration shows a different surface condition on Psyche, new wheels will need to be designed and tested to function well on the surface.

Additionally, developing and fine tuning an autonomous navigation system for the rover that will be able to successfully navigate around obstacles. There is already extensive research on this topic, and we would recommend building off these ideas to fine tune our applications.

The steering for the rover could also be improved. Differential skid steering is not an efficient method of steering because of unpredictable power losses. Due to the unpredictable power losses, conducting a power analysis, which is an important aspect of space exploration, is difficult. As a future recommendation, we suggest using an explicit turning mechanism where the wheels turn in the direction of motion.

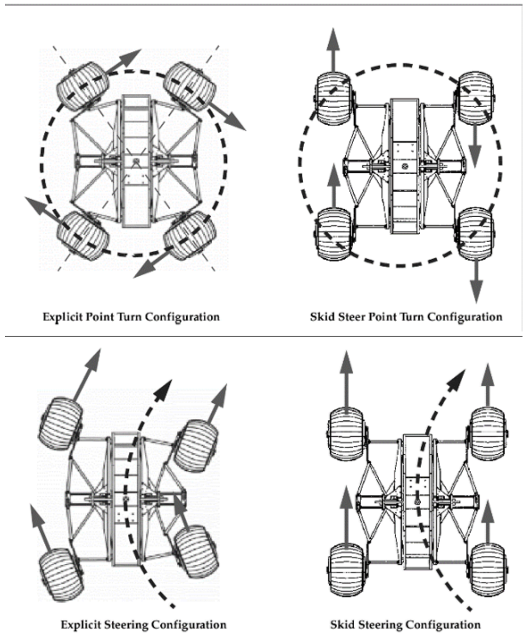

Figure 22: Explicit and Skid Steering comparison

5.2 Recovery System

Further iteration can be done on the recovery system to further develop its ability to deal with complex situations. With more time, the full model could be imported into MSC Adams, and we could make a test track for the rover. In the future, the data received from the orbiter will add more certainty to the design and further develop constraints and conditions.

References

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[2] Zhou, Feng, and et. al. “Simulations of Mars Rover Traverses - Keck Institute for Space Studies,” August 21, 23AD. https://www.kiss.caltech.edu/papers/xterramechanics/papers/simulations.pdf.

[3] Photograph. November 24, 2017. *The Next Mars Rover’s Wheels Won’t Get Torn Apart by the Red Planet*. https://www.universetoday.com/137962/next-mars-rovers-wheels-wont-get-torn-apart-red-planet-1/.

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Appendix A: Initial Concepts

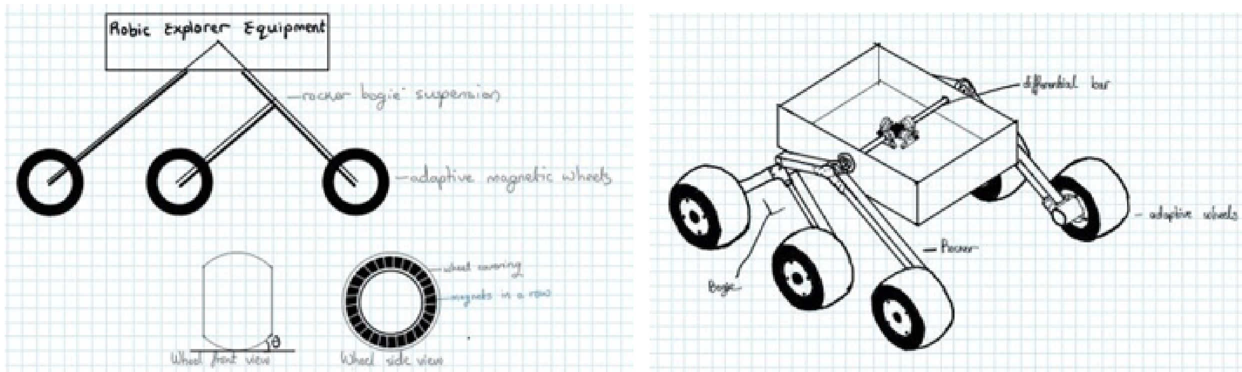

Figure 27: Rocker Boogie Suspension Design

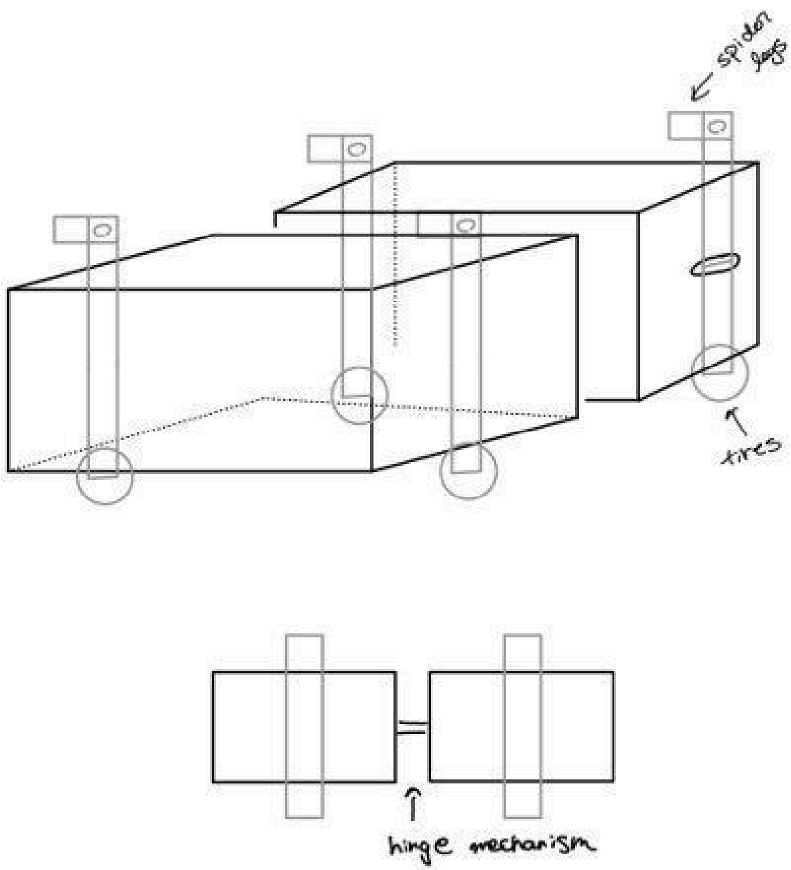

Figure 28: Arm Design

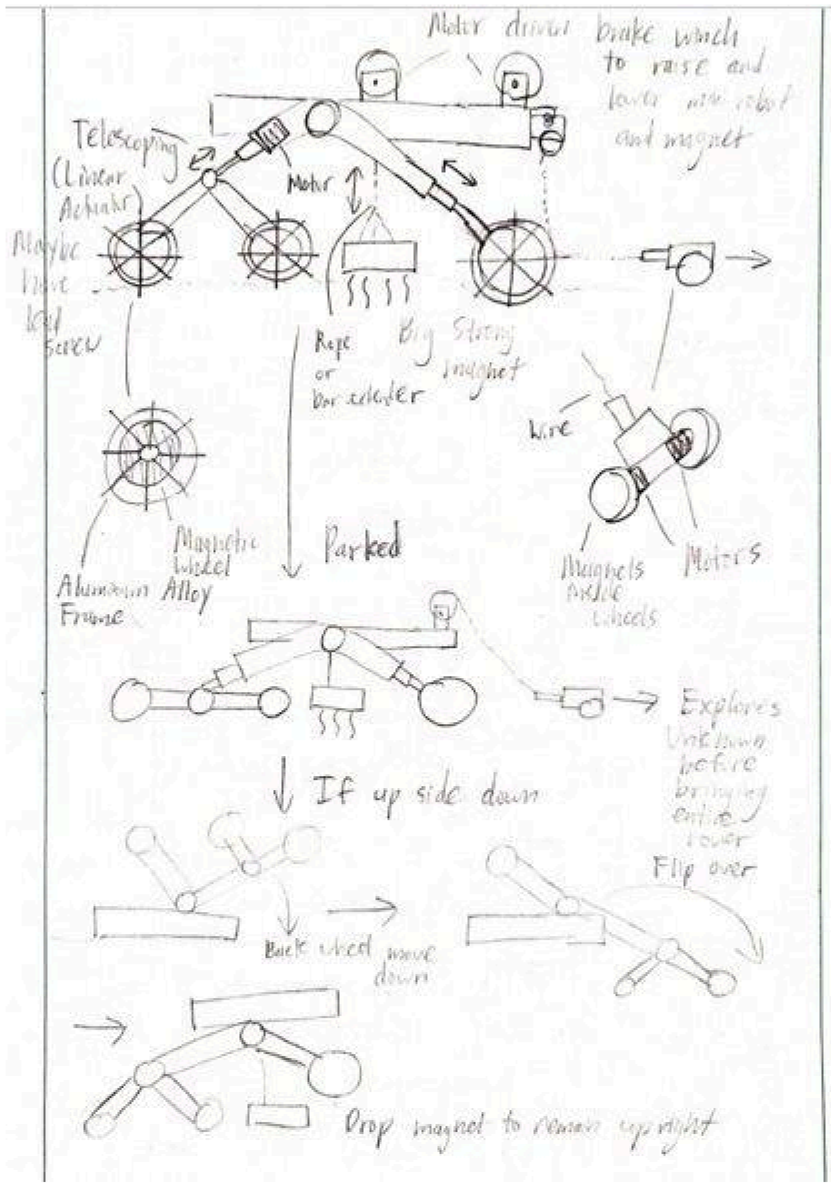

Figure 29: Magnetic Rover

Appendix B: Rover Specifications and Drawings

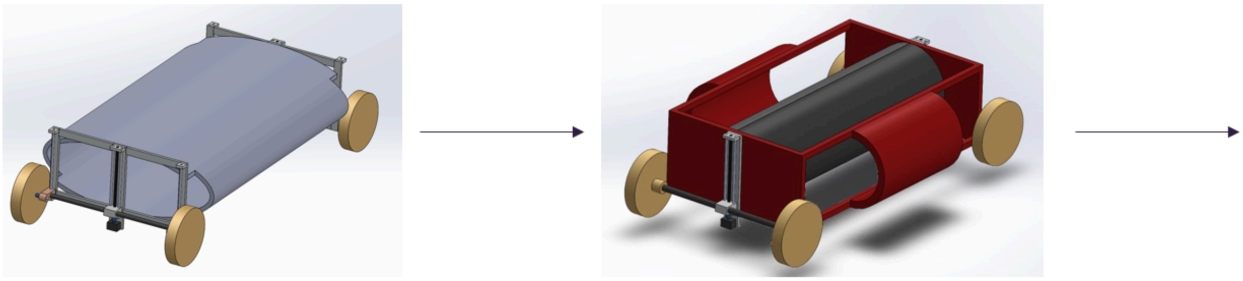

Figure 23: Iterations of the Rover to Figure 5

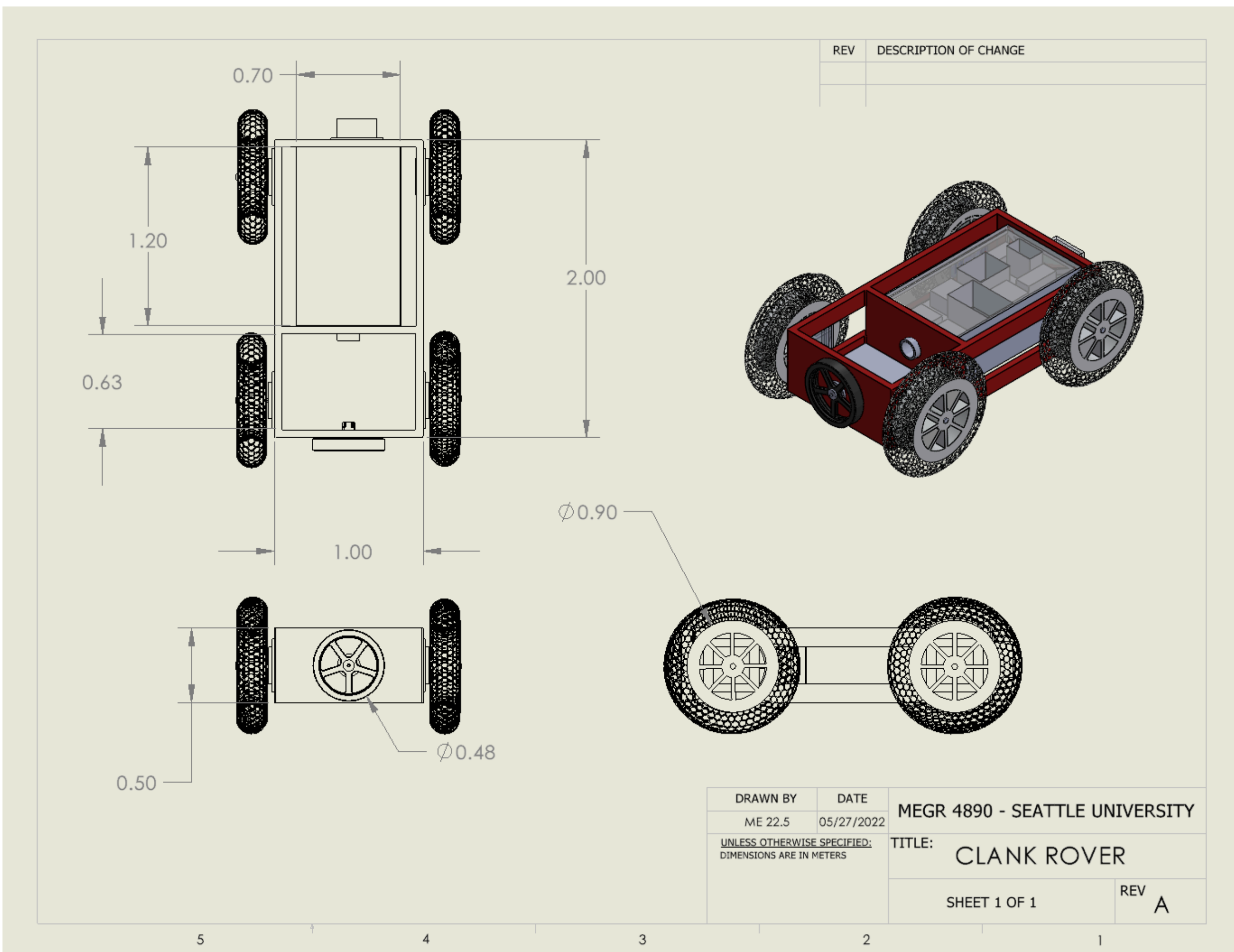

Figure 24: Dimensions of Full-Scale Rover

Table 5: Moments of Inertia approximated from SolidWorks that are used in MSC Adams

Moment of Inertias ($kg - m^2$) taken at the center of mass		
$I_{xx} = 32.64$	$I_{xy} = -1.83$	$I_{xz} = -0.46$
$I_{yx} = -1.83$	$I_{yy} = 107.7$	$I_{yz} = -0.01$
$I_{zx} = -0.46$	$I_{zy} = -0.01$	$I_{zz} = 81.80$

Appendix C: Component Specification

This appendix contains a list of the parts used in the prototype device.

Item	Quantity	Link
2000 Series Dual Mode Servo (25-2, Torque)	2	2000 Series Dual Mode Servo (25-2, Torque) - goBILDA
1204 Series Gusseted Angle Mount (2-1)	5	https://www.gobilda.com/1204-series-gusseted-angle-mount-2-1/
1101 Series U-Beam (19 Hole, 152mm Length)	4	https://www.gobilda.com/1101-series-u-beam-19-hole-152mm-length/
1101 Series U-Beam (35 Hole, 280mm Length) Note: Cut to 232 mm	4	https://www.gobilda.com/1101-series-u-beam-35-hole-280mm-length/
1611 Series Flanged Ball Bearing (6mm ID x 14mm OD, 5mm Thickness) - 2 Pack	12	https://www.gobilda.com/1611-series-flanged-ball-bearing-6mm-id-x-14mm-od-5mm-thickness-2-pack/
1309 Series Sonic Hub (6mm D-Bore)	3	https://www.gobilda.com/1309-series-sonic-hub-6mm-d-bore/
2910 Series Aluminum Clamping Collar (6mm ID x 19mm OD, 9mm Length)	10	https://www.gobilda.com/2910-series-aluminum-clamping-collar-6mm-id-x-19mm-od-9mm-length/
2807 Series Stainless Steel Shim (6mm ID x 9mm OD, 0.50mm Thickness) - 12 Pack	1	https://www.gobilda.com/2807-series-stainless-steel-shim-6mm-id-x-9mm-od-0-50mm-thickness-12-pack/
2101 Series Stainless Steel D-Shaft (6mm Diameter, 90mm Length)	6	https://www.gobilda.com/2101-series-stainless-steel-d-shaft-6mm-diameter-90mm-length/
ServoBlock™ (Standard Size, 25 Tooth Spline, Hub Shaft)	2	https://www.gobilda.com/servoblock-standard-size-25-tooth-spline-hub-shaft/
1120 Series U-Channel (21 Hole, 528mm Length)	2	https://www.gobilda.com/1120-series-u-channel-21-hole-528mm-length/
1120 Series U-Channel (7 Hole, 192mm Length)	3	1120 Series U-Channel (7 Hole, 192mm Length) - goBILDA

1201 Series Quad Block Pattern Mount (43-2)	6	https://www.gobilda.com/1201-series-quad-block-pattern-mount-43-2/
2804 Series Zinc-Plated Steel Low Profile Socket Head Screw (M4 x 0.7mm, 8mm Length) - 25 Pack	1	https://www.gobilda.com/2804-series-zinc-plated-steel-low-profile-socket-head-screw-m4-x-0-7mm-8mm-length-25-pack/
2800 Series Zinc-Plated Steel Socket Head Screw (M4 x 0.7mm, 8mm Length) - 25 Pack	2	https://www.gobilda.com/2800-series-zinc-plated-steel-socket-head-screw-m4-x-0-7mm-8mm-length-25-pack/
Servo Programmer for 2000 Series Mode Servo	1	https://www.gobilda.com/servo-programmer-for-2000-series-dual-mode-servo/
8 In. Solid Rubber Tire With PVC Hub	4	https://www.harborfreight.com/8-in-solid-rubber-tire-with-pvc-hub-63014.html
5pack 9v Battery Clip with 2.1mm X 5.5mm Male DC Plug for Arduino by Corpco	1	https://www.amazon.com/5pack-Battery-2-1mm-Arduino-Corpco/dp/B01AXIEDX8/ref=sr_1_3?keywords=arduino+battery&qid=1646690303&sr=8-3
Amazon Basics 8 Pack 9 Volt Performance All-Purpose Alkaline Batteries, 5-Year Shelf Life, Easy to Open Value Pack	1	https://www.amazon.com/Amazon-Basics-Performance-All-Purpose-Batteries/dp/B00MH4QM1S/ref=sr_1_5?crid=61F2P22PBIDQ&keywords=9+volt+battery&qid=1646691047&sprefix=9+volt+battery%2Caps%2C123&sr=8-5

Appendix D: Prototype Components for Demonstrating Flywheel Rotation

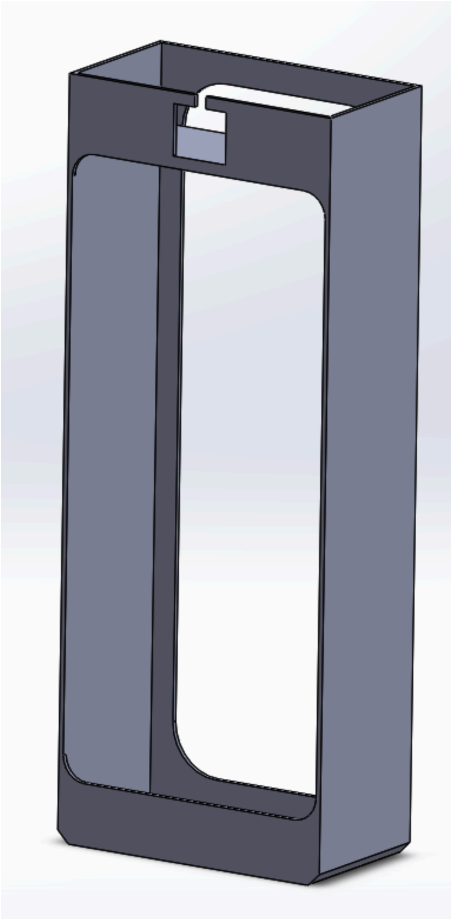

Figure 25: CAD Model of Flywheel Testbed

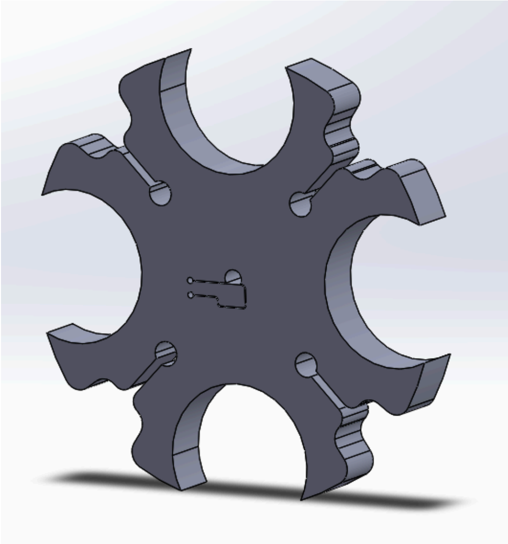

Figure 26: CAD Model of the Prototype Flywheel

Appendix E: Code

This is the Arduino code used to control the rotating equipment cluster model. When the ultrasonic sensor reads a distance greater than 15 cm, it will trigger a 180-degree rotation from the servo motor. The ultrasonic sensor will continue to take readings until it again reads a distance greater than 15 cm, then it will rotate 180 degrees in the opposite direction to return to its initial position.

```
#include <Servo.h>

Servo myservo;  // create servo object to control a servo
// twelve servo objects can be created on most boards

#define echoPin1 2 // attach pin D2 Arduino to pin Echo of HC-SR04
#define trigPin1 3 //attach pin D3 Arduino to pin Trig of HC-SR04

int pos=0;  // variable to store the servo position
long duration1;
int distance1;

void setup() {
  myservo.attach(9);  // attaches the servo on pin 9 to the servo object
  pinMode(trigPin1, OUTPUT); // Sets the trigPin as an OUTPUT
  pinMode(echoPin1, INPUT); // Sets the echoPin as an INPUT
  Serial.begin(9600); // // Serial Communication is starting with 9600 of
baudrate speed
  myservo.write(pos);
}

void loop() {
  // Clears the trigPin condition
  digitalWrite(trigPin1, LOW);
  delayMicroseconds(2);
  // Sets the trigPin HIGH (ACTIVE) for 10 microseconds
  digitalWrite(trigPin1, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin1, LOW);
  // Reads the echoPin, returns the sound wave travel time in microseconds
  duration1 = pulseIn(echoPin1, HIGH);
  // Calculating the distance
  distance1 = duration1 * 0.034 / 2; // Speed of sound wave divided by 2 (go
and back)

  if(myservo.read()<5){
    if (distance1 > 15) {
```

```
      delay(3000);
      for (pos = 0; pos <= 118; pos += 1) { // goes from 0 to 180 degrees
                                        // in steps of 1 degree
      myservo.write(pos);   // tell servo to go to position in variable 'pos'
      delay(15);
      }
      delay(3000);
    }
  }

  Serial.print("Distance= ");
  Serial.println(distance1);

  // Clears the trigPin condition
  digitalWrite(trigPin1, LOW);
  delayMicroseconds(2);
  // Sets the trigPin HIGH (ACTIVE) for 10 microseconds
  digitalWrite(trigPin1, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin1, LOW);
  // Reads the echoPin, returns the sound wave travel time in microseconds
  duration1 = pulseIn(echoPin1, HIGH);
  // Calculating the distance
  distance1 = duration1 * 0.034 / 2; // Speed of sound wave divided by 2 (go
and back)

  if(myservo.read()>100){
    if (distance1 > 15) {
      delay(3000);
      for (pos = 118; pos >= 0; pos -= 1) { // goes from 0 degrees to 180
degrees
      // in steps of 1 degree
      myservo.write(pos);              // tell servo to go to position in
variable 'pos'
      delay(15);
      }
      delay(3000);
    }
  }
}
```

Below is the Arduino Code written in C++ again to control a Micro Metal Geared motor w/Encoder. Every few seconds, the motor spins until it reaches its maximum speed of 15000 RPM, then stops, to create an instant torque of 0.8 kg-cm [10] to knock over the testbed.

```
int motorPin1=9;
int motorPin2=6;
```

```
void setup() {
  // put your setup code here, to run once:
  pinMode(motorPin1, OUTPUT);
  pinMode(motorPin2, OUTPUT);
}

void loop() {
  // put your main code here, to run repeatedly:
  //for(int i=100; i<255; i++){
  //  analogWrite(motorPin, i);
  //  delay(15);
  //}
  //delay(1000);
  //digitalWrite(motorPin, LOW);
  //delay(3000);
  digitalWrite(motorPin1, LOW);
  for(int i=50; i<255; i++){
    analogWrite(motorPin2, i);
    delay(20);
  }
  delay (2000);
  digitalWrite(motorPin1, HIGH);
  digitalWrite(motorPin2, LOW);
  delay(50);
  digitalWrite(motorPin1, LOW);
  digitalWrite(motorPin2, LOW);
  delay(2000);

}
```

Appendix F: Derivation

The values used in Equation 2 and Equation 3 to find the desired range of speeds for the flywheel are shown below.

m_p	$150\ kg$
g	$.144 \frac{m}{s^2}$
l	$1.12\ m$
α	$22.7\ deg$
β	$0\ deg$
I_f	$\frac{1}{2}m\left(r_i^2 + r_o^2\right) = 1.95\ kg - m^2$
I_p	$I_p = I_{cm} + m_p l^2 = 270\ kg - m^2$
η	$= I_f/I_p$

Note that for the calculation of β, we assumed a value of zero because this is the scenario in which the flywheel would have the highest minimum speed. If the rover was situated on a slope, the flywheel would need to produce less torque to flip the rover with the downhill side of the slope.

Additionally, moment of inertia values of the rover, I_p, were taken from the Solidworks and MSC Adams calculated values.