NAU Psyche Rover

Final Proposal

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PSYCHE STUDENT COLLABORATION DISCLAIMER

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EXECUTIVE SUMMARY

The purpose of the Psyche mission is to explore a large M-type asteroid, known as (16) Psyche located about three times further from the sun than the Earth [2]. The Psyche asteroid is believed to be comprised largely of metallic iron and nickel, similar to the composition of the Earth's core. Scientists are attempting to gain more information about the asteroid. With the newfound information, they might hopefully be able to determine whether Psyche is the remains of what was, at one point, a planet whose rocky outer layers were stripped away as the result of many violent collisions billions of years ago. The use of an orbiter will likely aid in the process of determining the origins of the Psyche asteroid. With the information retrieved through an orbiter, future missions may be motivated to explore the surface of the asteroid. This is where our group comes in, commencing the next stage for (16) Psyche's exploration.

Our team consists of six mechanical engineering undergraduates. Our task is to design, test, and manufacture a rover capable of traversing the hypothesized surfaces of the Psyche asteroid. The prototype developed by our team must have the ability to traverse surfaces like those hypothesized to be found on Psyche. The sponsor for this project has provided our group with set conditions and requirements as well as a budget to be used for expenses during the manufacturing stage.

The rover design highlighted within this proposal incorporates the use of redundant movement systems that aid in its ability to traverse harsh surfaces. Multiple concept variants were first generated, but most were ruled out based on their inability to meet the engineering requirements of this project. Among these variants, three were chosen and compared against each other. One of the three, chosen concept variants incorporated the rocker-bogie suspension system. This suspension system utilizes two separate arms connected at one point; this allows the rover to remain level as it rolls over obstacles. The second concept variant utilized tank tracks for traction. Both concepts lacked the fundamental ability to climb high relief surfaces. For this reason, the group decided upon the third concept variant, which incorporated legs. The legged design would theoretically allow the rover to traverse nearly any surface conditions. The third concept variant also incorporated "gecko foot" gripping material, which would theoretically grant it the ability to cling to the surface of the asteroid.

After researching the subsystems of concept variant three, and the effects of gecko grip material on surfaces like those expected on Psyche, the group finalized the design. Calculations were performed to determine the approximate mission life, provided traction for the rover, and power system life. The results of these calculations satisfied the engineering requirements for this design. The next step was developing the CAD model of the Gecko rover, which consisted of three main subsystems, the rover body, legs, and feet. Each leg and foot assembly operates independently from each other, and the rover body can extend and contract via a scissor-lift type section. These forms of movement incorporated the redundancy that the group was aiming for. Once the CAD model was completed, the group tested separate portions of the assembly within SolidWorks. A stress and strain analysis were performed on sections of the rover feet as well as the rover body. Similar effects to those expected on Psyche were incorporated into these tests, this ensured that the rover would perform as expected on Psyche's surface.

The group generated a bill of materials for both a full-scale model of the Gecko rover, and a small-scale prototype which the group will build in the Spring 2021 semester. The next steps for this project include ordering the components for the small-scale prototype, assembling, and testing the prototype, gaining client approval, and developing a presentation for UGRAD. During the winter 2020 break, group members will continue meeting, developing, and eliminating sources of potential failure from the rover design. The goal of our team is to begin building the small-scale rover when the Spring 2021 semester begins.

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1 BACKGROUND

1.1 Introduction

(16) Psyche is a metallic type asteroid in the asteroid belt. The Psyche asteroid has a diameter of approximately 140 miles and is unlike most asteroids ever studied or visited by spacecraft [2]. What makes Psyche so different is that scientists believe it may be comprised mostly of iron and nickel, which are similar elements to that of the Earth's core. Scientist have hypothesized that the Psyche asteroid was once a planet that lost its rocky outer layers because of a violent impact billions of years ago. NASA has planned a mission to launch to Psyche in August of 2022 which will arrive at Psyche in early 2026 [3]. This mission is to map and observe Psyche from an orbiting satellite, determine its magnetic field properties, and discover whether the asteroid could indeed be a remnant planetary core. Our project is a hypothetical future mission to Psyche, which would entail landing a rover on the asteroid to observe it at ground level. This hypothetical rover will take many years to design and test. In this project different systems and subsystems of the rover are analyzed to create the most optimal rover for this hypothetical mission. The Psyche Rover must be able to traverse the five hypothesized surfaces as well as collect data and sample specimens, all while operating remotely. This rover will be crucial for scientists to better understand just what Psyche is, and possibly help us understand how planets form. There is only so much one can observer from orbit, and to truly understand what Psyche is, scientists may wish to get to the surface of the asteroid. This rover would be the first rover made on Earth to investigate a metallic type asteroid rather than a rocky or icy body. Upon completion of such a mission scientists would be able to compare the results with their expectations and determine whether the asteroid could indeed be a remnant planetary core.

1.2 Project Description

Following is the original project description provided by the sponsor:

NASA Psyche Mission is set to launch in 2022 and arrive at the asteroid in 2026. It is an orbiter mission and will not land on the surface. It is possible to imagine, however, that after learning about Psyche from orbit, there may be scientists and engineers interested in proposing a subsequent mission to actually land on the asteroid to explore its surface. In this capstone project, you are that team! Designing to the range of hypothesized surfaces that might be found at Psyche (and keeping in mind other constraints such as its gravity), you will design (and, if your capstone supports/allows, create a prototype of) a robotic explorer capable of efficiently traversing each of the hypothesized surfaces and, ideally, able to adapt to each of them mid-traverse. Hypothesized surfaces may include mostly flat metallic surface, flat metallic with metal and/or rocky debris, rough/high-relief metallic and/or rocky terrain, high-relief metallic crater walls. Specifications will be provided for the team to inform the design. ABOUT PSYCHE CAPSTONE: This is an exciting opportunity to test your design skills, problem solving, and creativity! You will become part of a larger community of students working on a range of projects with Psyche and have the opportunity to meet members of the Psyche mission team.

2 REQUIREMENTS

The first step in the design process for this project was to collect data on the rover requirements based on the customer requirements defined by the sponsor. With these customer needs, engineering requirements were generated to provide specific design requirements. The next step was to generate a House of Quality to rank the customer needs against the engineering requirements as well as other rovers currently in use. The subsequent steps involved developing a black box model and a functional model which describe the functions of the rover. Understanding these sections of the project are necessary to move on to the design of the rover.

2.1 Customer Requirements (CRs)

In this section, the customer requirements defined by the sponsor are stated and explained. These requirements are to be followed while designing the rover to achieve an optimal design that meets all the criteria provided. Each of these requirements can be seen in Table I where they are weighted in accordance with their importance to the project.

TABLE I

RANKING OF CUSTOMER REQUIREMENTS

Customer Requirement	Rank (#)
Rover Adaptability	1
Size	1
Power Supply	1
Weight	2
Durability	1
Longevity	2
Redundancy	2
Speed	3

The customer requirements displayed above have been ranked based on their impact on the design of the rover. The customer requirements that ranked the highest are the rover adaptability, power supply, size, and the durability. The adaptability requirement is a top priority because the rover must have the ability to traverse the five different hypothesized surfaces of the Psyche asteroid. The power supply is also weighted equally to the adaptability because the rover has a high demand of torque to move across the surface which requires more power. The size of the rover is also one of the top-ranking requirements. The size of the rover (either large or small) will aid in its exploration of high relief areas and/or craters. The durability of the rover is a high priority because the rover needs to stay intact throughout the Mission Life. The next highest-ranking requirements are the weight, longevity, and redundancy. The weight is important because transporting a heavy rover compared to a lighter one will require a bigger rocket, more fuel, and more time to get to the asteroid, all of which would drive up cost. In addition, the weight of the rover will change with respect to the scale that the rover is built to. Longevity of the rover is also important and is directly correlated to the durability of the rover. This is because if the rover becomes damaged, the longevity of the mission will decrease as a result. Having redundancy in the design of the rover is a very important requirement. Redundancy is needed to provide instantaneous troubleshooting when certain systems on the rover fail. It is also important to design redundant systems of movement to prepare for all possible obstacles. Lastly the customer requirement that was ranked lowest was the speed of the rover. This is ranked as least important because it will be difficult and impractical to traverse the hypothesized surfaces at a fast speed, although it is important that the rover doesn't travel too slow because that could affect the amount of the surface that is explored.

2.2 Engineering Requirements (ERs)

The engineering requirements displayed in Table II were generated based on the customer requirements listed in the previous section. These variables are all requirements that the team needs to meet while designing the rover. In addition, each of the engineering requirements has a target value to be met.

TABLE II

ENGINEERING REQUIREMENTS WITH TARGET VALUES

Engineering Requirement	Target Value
Material Strength	276 MPa
Mission Life	3 Months
Mass	120 kg
Volume	8 m^3
Torque	475 N*m
Ground Clearance	1 m
Power	0.1475 hp

These engineering requirements displayed above all correlate to the design of the rover with respect to the customer requirements previously defined. The Material Strength has a target value of approximately 276 MPa. This was based on the frame materials effect on the weight of the rover as well as the strength of the structure. The targeted mission life of this rover was based on the typical three-month life of most current rover mission lives (i.e. Spirit Mars Rover). The mass and volume of the proposed rover was determined from a fraction of the Curiosity Rover's mass and volume. It is only a fraction of the size because the team decided to go with a smaller rover then the Curiosity (which is over nine feet wide and seven feet tall). The mass target value also will aid in the determination of the power systems used as well as any other devices or subassemblies that are on the rover. If the motor's torque is too high, the rover could potentially leave the surface of the asteroid due to the low gravity conditions. The torque target value is a conjecture which will later be modified upon further torque analysis into the selected design. The ground clearance of the rover was selected to be one meter. This was based off the overall height of the rover. The rover needs to have a high ground clearance to successfully traverse the many hypothesized surfaces. Lastly, the targeted power of 0.1475 hp was based on the torque requirement. The motors on the rover need to output this amount of horsepower to produce the required amount of torque to move the rover.

2.3 Functional Decomposition

The main functions of the Psyche Rover are shown below in Figure I. The major change the team decided on was to just have one power source. The team decided upon only using nuclear power. The team concluded that using solar as and energy source could prove problematic. The panels are not durable and could break or be chipped during operation. Nuclear offers more power for a longer period. Navigation is also an important subsystem for the Psyche Rover. Without navigation the rover will not be able to know where it is going and where it has already been. The major navigation systems reviewed in this project are GPS, solar tracking, Lidar, and GESTALT. The navigation that was decided on for this rover is lidar and cameras. After navigation systems the next subsystem is how the rover moves. The drive systems explored in this project are Rocker-Bogie, tracks, magnetic tracks, screw drive, bio-inspired legs, and the rolling "Spherical Gyrover". All these systems have their advantages and disadvantage, but the system chosen for this rover is the bio-inspired legs. This was chosen because of the amount of degrees of freedom that can be achieved with legs as opposed to all the other options. The final subsystem of the Psyche Rover is attachment to the surface of the asteroid. Suction cups, claws, anchors, and thrusters are possibilities we discuss in this project. With the correct combination of subsystems, the Psyche Rover will be extremely versatile as well as reliable.

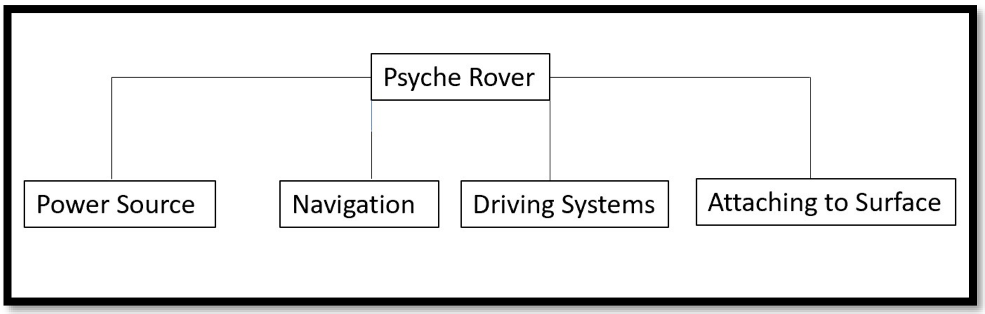

FIGURE I

PSYCHE ROVER FUNCTIONAL DECOMPOSITION

2.3.1 Black Box Model

Figure II below shows the black box model for the Psyche Rover. This black box model consists of materials (solid arrow), energies (hollow arrow), and signals (dashed arrow). The material used for this rover is the hand which equates to driving the rover manually using remote communication. The power used for the rover is nuclear which will allow the rover to move in a translational motion. The signals will be data and Artificial Intelligence (AI). The data will allow the rover to operate when direct contact is not possible. The AI will allow the rover move and collect data without direct human interference. This model was critical to help the Psyche Team visualize the necessary systems for the rover. It allowed the team to recognize the two types of signals for optimal navigation and movement. It also showed the team how critical it will be to have two power source in case one fails.

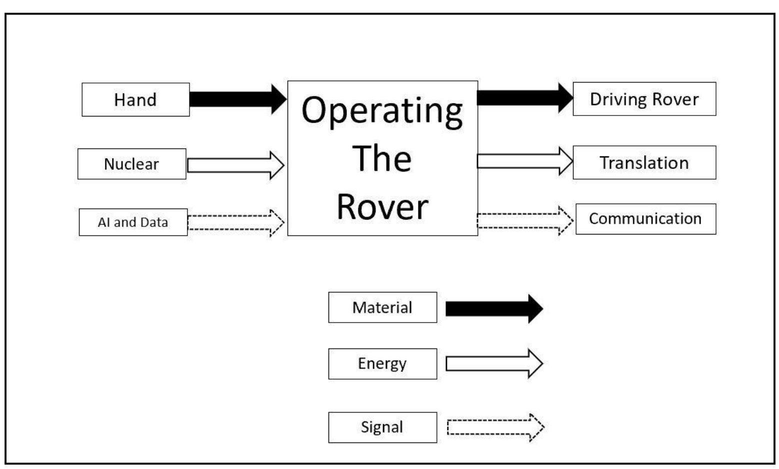

FIGURE II

PSYCHE ROVER BLACK BOX MODEL

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The functional decomposition for the Psyche Rover is shown below in Figure III. This model was important for visualizing the necessary subsystems needed for the Psyche Rover. The model shows a human hand as a material. This helped the team realized we need to be able to operate the rover when we were able to have direct contact. The Psyche Team also needs to be able to operate the rover while direct contact with the rover was not possible. This is where the data and Artificial intelligence (AI) signals come into play. The data will be saved and imported into the rover so it can still operate without human direction. The AI will allow the data to grow even when not been driven by a person. This functional model made the Psyche Team agree that the best power system would be nuclear. Nuclear power was chosen because of its ability to produce a lot of power for a long period of time. This power system will allow the rover to move translation around the asteroid.

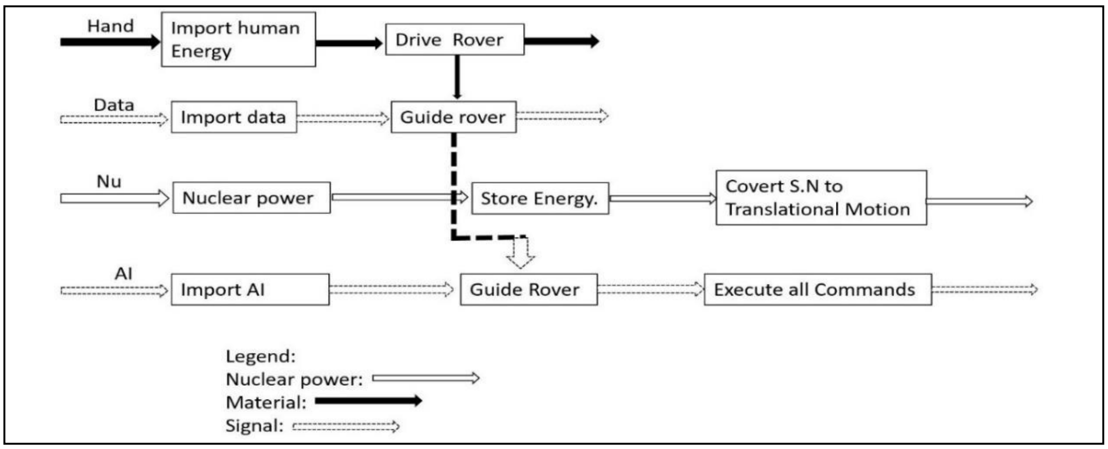

FIGURE III

PSYCHE ROVER FUNCTIONAL MODEL

2.4 House of Quality (HoQ)

The House of Quality is an important step in the engineering design process, it determines the engineering requirements for a project. The translation between customer needs and engineering requirements allows for target values to be met, providing an adequate device to the customer. NAU Psyche generated a house of quality with the customer requirements listed in the project statement, (Appendix A, Table VI) . The group added other customer requirements, to provide metrics in further engineering requirements. The customer requirements stated explicitly in the project description included the ability of the rover to traverse the five hypothesized surfaces of the Psyche asteroid. Built into this requirement, lies multiple others, such as weight of the rover, durability, redundancy, speed. All these requirements ultimately affect the rover's ability to complete its primary goal. For this reason, NAU Psyche decided to include them in the house of quality. Other important customer requirements for this project include the size of the rover, power system for the rover, longevity, and speed.

The customer requirements were then translated into engineering requirements by NAU Psyche. The engineering requirements for the NAU Psyche Rover include material strength, mission time, mass of the rover, volume of the rover, torque supplied to the rover's drive system, ground clearance and travel of the rover, and power for the rover. Of the generated engineering requirements, NAU Psyche determined that power, mass, torque, and material strength were the most critical toward mission success. The power system was determined to be the most critical engineering requirement, as it affects the torque of the rover, the mission life, durability, reliability, and redundancy components of the rover. Without an adequate power supply, these aspects of the rover would be lacking, which could lead to mission failure. NAU Psyche determined that the rover would need a power supply capable of producing and storing at least 110 Watts. The strength of the rover's materials would also need to be at least 276 Megapascals, this was determined based on the material strength of space-grade aluminum [4]. The team also noted that a reasonable mass for the rover would be around 120 kg, this was determined based on the mass of previous planetary rovers [5].

The house of quality was also used to perform a benchmark analysis against previous NASA Mars rovers, Curiosity, and the Mars Opportunity rover (Appendix A, Table VII). The benchmarking analysis ranked the two competitors against each other, with the criteria being the engineering requirements for this project. Research was conducted for each rover, to ensure accurate benchmarking. The Mars Curiosity rover ranked higher than the Opportunity rover in most of the engineering requirements. This provided a sort of datum point for the NAU Psyche team to gauge and base their design. Elements such as mass and speed of the rover were obtained from the analytics of the Mars Curiosity rover. The house of quality also aided in concept generation and selection. A Pugh chart was generated, accounting for every customer requirement. Ten concept variants were created and ranked qualitatively on how well they would meet the customer requirements from the house of quality. The top three ranked concept variants from the Pugh chart were then ranked using a decision matrix. The decision matrix contained the most critical engineering requirements generated from the house of quality. Each of the top three concept variants were ranked quantitatively on how well they would be expected to meet the engineering requirements. Assumptions were made for the concept variants, each concept would have approximately the same mass, and be the same size.

2.5 Standards, Codes, and Regulations

The standards, codes, and regulations we will be using for our project are acquired from NASA. Each NASA standard follows a subset of standards from organizations including but not limited to the Department of Defense, ASTM International, Government Electronics and Information Technology Association (GEIA), and SAE International. Each handbook or standard listed in the table below is comprised of multiple sub-standards which are beyond the scope of this report. This list forms an acceptable corpus of information which will guide the team moving forward. It contains standards of practice for software systems, structural design, fracture control, factors of safety, welding, threaded fastening systems, safety, corrosion protection, avoiding electrostatic discharge, and EEE parts standards. It also details best practice for measuring and testing equipment, modeling, uncertainty analysis, and measurement accuracy. Lastly, the team will be following the ASME standards for dimensioning and tolerancing our drawing.

TABLE III

STANDARDS OF PRACTICE AS APPLIED TO THIS PROJECT

Standard Number or Code	Title of Standard	How it applies to Project
NASA-HDBK-2203	NASA Software Engineering Handbook	NASA guidelines for safe and reliable software [6].
NASA-HDBK-4002	Mitigating In-Space Charging Effects – A Guideline	NASA guidelines for avoiding charge build up on spacecraft [6].
NASA-HDBK-4007	Spacecraft High-Voltage Paschen and Corona Design Handbook	Electrical design techniques that can mitigate deleterious effects from operating high-voltage systems in space [6].
NASA-STD-4003	Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment	Electrical bonding requirements for space vehicles [6].
NASA-HDBK-5010	Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware	Fracture control implementation guidance for hardware [6].
NASA-STD-5001	Structural Design and Test Factors of Safety for Space Flight Hardware	NASA structural design and test factors to ensure safe and reliable structural designs [6].
NASA-STD- 5006	General Welding Requirements for Aerospace Materials	Establishes the processing and quality assurance requirements for manual, automatic, machine, and semiautomatic welding for Space Flight applications [6].
NASA-STD-5009	Nondestructive Evaluation Requirements for Fracture Critical Metallic Components	Establishes nondestructive methods for evaluating fracture in metallic components [6].
NASA-STD-5017	Design and Development Requirements for Mechanisms	Design, development, and test requirements for mechanism whose operation is required for safety or mission success [6].
NASA-STD-5019	Fracture Control Requirements for Space Flight Hardware	Methodology to address the consequences of naturally occurring and service-induced flaws, damage, or cracks in a part or structure [6].
NASA-STD-5020	Requirements for Threaded Fastening Systems in Space Flight Hardware	Requirements for design and analysis of threaded fastening systems in Space Flight hardware [6].
NASA-STD-6001	Flammability, Offgassing, and Compatibility Requirements and Test Procedures	Evaluating flammability and compatibility of materials [6].
NASA-STD-6012	Corrosion Protection for Space Flight Hardware	Corrosion protection requirements applicable to the surface treatment and finishing of space flight hardware [6].
NASA-STD-6016	Standard Materials and Processes	Materials and Processes standards for off-the-shelf items [6].

	Requirements for Spacecraft	
NASA-HDBK-7009	Nasa Handbook for Models and Simulations: An Implementation Guide for NASA-STD-7009	Provides technical information, clarification, examples, process, and techniques to help institute good modeling and simulation practices [6].
NASA-STD-7009	Standard for Models and Simulations	Standards for models and simulations [6].
NASA-STD-7012	Leak Test Requirements	Test requirements for pressurized or sealed liquids to prevent leaks [6].
NASA-GB-8719.13	NASA Software Safety Guidebook	How to address creation and assurance of safety-critical software [6].
NASA-HDBK-8739.19-2	Measuring and Test Equipment Specifications, NASA Measurement Quality Assurance Handbook - ANNEX 2	Measuring and Test Equipment Specifications, including instruments, sensors, transducers, DAQ systems, etc [6].
NASA-HDBK-8739.19-3	Measurement Uncertainty Analysis Principles and Methods, NASA Measurement Quality Assurance Handbook - ANNEX 3	Uncertainty analysis principles and methods [6].
NASA-HDBK-8739.19-4	Estimation and Evaluation of Measurement Decision Risk, NASA Measurement Quality Assurance Handbook - ANNEX 4	Assuring measurement accuracy [6].
NASA-HDBK-8739.21	Workmanship Manual for Electrostatic Discharge Control (Excluding Electrically Initiated Explosive Devices)	Guidance on limiting electrostatic discharge which may injure personnel or damage/destroy electronics [6].
NASA-STD-8739.10	Electrical, Electronic, and Electromechanical (EEE) Parts Assurance Standard	Managing the selection of EEE parts to control risk and enhance reliability [6].
NASA-STD-8739.4	Workmanship Standard for Crimping, Interconnecting Cables, Harnesses, and Wiring (Revision A 2016-06-30)	Requirements for interconnecting cable and harness assemblies that connect EEE components [6].
ASME Y14.5-2018	Dimensioning and Tolerancing	Standards for dimensioning and tolerancing CAD drawings [7].

3 Testing Procedures (TPs)

To ensure smooth operation with the proposed rover each of the subsystems within the rover will be tested against how they satisfy and fulfil each engineering requirement. The engineering requirements that these procedures aim to satisfy are displayed in Appendix A. Each of these requirements will be tested in different ways to determine what each of the parts requires to run smoothly. These tests are discussed below in the following subsections.

3.1 Testing Procedure 1: Material Strength

Material strength is an important engineering requirement for this project. The chosen materials must be strong enough to withstand the weight of the rover on the asteroid. If the material is too weak, the material can fail earlier than expected resulting in a shorter mission life. The engineering requirements for volume and mass directly correlate to this section therefore will be represented here. If the volume dimensions are too small, the material is likely to fail. The mass of the material causes the overall weight that causes stress on the overall system. A lightweight material must be used for the frame and legs that will be strong enough to last the full mission life. Weight for this rover is not a significant issue since the asteroid has a very small gravitational force. The issue about weight for this mission depends on the rocket that will be sending this rover to the asteroid. The rover cannot weigh an immense amount to allow the rocket to be able to leave Earth's atmosphere without losing a significant amount of fuel. For material strength, two different tests are being considered.

3.1.1 Testing Procedure 1: Objective

To test the material strength for the rover, two different tests can be conducted. The first test is a three-point bending test. The team has conducted this test in a material science lab before therefore we are familiar with the process. This test can be conducted using multiple different attachments. For this test, the material will be fixed to each end to simulate the weld of the frame. This test can only be conducted if the team is allowed access to the lab with the equipment. The test can be done at different weights to find the pint where the material begins to bend. The other test that can be done is a compressive test. This test can be done using the SOLIDWORKS program. This will allow the team to perform the test without needing excess equipment. This test will simulate the deformation in the frame to visualize how the material will perform. This test is not very accurate since the metal frame will plastically deform before it fractures. This test will allow enough information to get an understanding of how the material and frame will perform without needing equipment to conduct the test.

3.1.2 Testing Procedure 1: Resources Required

For the first test that was explained in the section before, the team would need access to the materials science lab in the engineering building. The full team would be present to help and visualize the effects of the material through this test. A decision can then be made if the material needs to be upgraded to another stronger material. If the full team cannot be present, only two to three team members will be needed to conduct this experiment. The equipment needed for this test is a set of weights that can be added one by one to find the point of failure in the material. A system that can clip the beam at the ends to simulate the welding will also be needed. After the test, a series of calculations can be performed to find the amount of force that was applied to the beam when it failed. The second test can be performed using SOLIDWORKS, therefore will not require any equipment. Only one team member will be needed to conduct this experiment.

3.1.3 Testing Procedure 1: Schedule

Before the three-point bending test can be conducted, the material to be tested must be purchased. This forces the team to predict the necessary dimensions that will be needed. This experiment should only take about an hour to perform. This test will be completed any time after the material is collected but before the frame of the rover is constructed. The second test allows the team to cycle through different dimensions and materials in SOLIDWORKS. This will bypass the need to purchase material beforehand and allows the teams to not use the budget for experimentation. This experiment can be done anytime next semester. The only requirement is a complete 3-D design that will be completed by the end of the fall semester. The test will take a minimum of around 30 minutes if the first series of tests prove the initial conditions are acceptable.

3.2 Testing Procedure 2: Ground Clearance/Travel

Ground clearance is a necessary engineering requirement since the rover must be able to climb over obstacles without damaging the bottom. The legs must be able to raise the rover over the rocks and debris and still be able to walk. If the rover weighs too much, the rover will have a small ground clearance that can cause structural damage of the material below. This can cause critical failure to the rover if the wiring or other important components are damaged. How far the rover can travel is another important engineering requirement. The rover will be expected to fulfil its mission and navigate over a certain portion of the asteroid to obtain the data needed. This can be tested by comparing the smaller prototype that will be created to a hypothetical larger rover.

3.2.1 Testing Procedure 2: Objective

Each engineering requirement mentioned in the section above will be tested with a comparison to the prototype. The team plans to create the smaller scale prototype as soon as possible in the spring semester to allow for testing. Depending on the positioning of the rover's legs, the ground clearance can be estimated. This will indicate whether if the legs need to be repositioned for the final design. The travel engineering requirement can be calculated by scaling the size from the prototype being created next semester. The minimum operational height can be subtracted from the max height of the rover from the ground. This test may be conducted in SOLIDWORKS as well since the rover will rotate at the hinge located in the middle. A series of calculations can be made for the power source life and over time fatigue of the components to find the expected mission life. This will allow a prediction of how far the rover can travel.

3.2.2 Testing Procedure 2: Resources Required

If the 3-D SOLIDWORKS model is not used to conduct these tests, the completed prototype will be needed to conduct the testing. Since the travel engineering requirement is tested using a series of calculations, no other equipment will be needed. It is planned that the entire project team will perform the tests together so that everyone will have the opportunity to get experience as well as visualize the process. If there are team members that cannot be present for the test, only one or two people will be needed to conduct the tests.

3.2.3 Testing Procedure 2: Schedule

These tests require the completed 3-D SOLIDWORKS model or the completed prototype. Therefore, the tests can be conducted either right away next semester or after the prototype is complete. The tests would provide the best results from the prototype, but if the construction takes longer than expected the 3-d model will be used. Each test should only take about an hour or two to perform. More time will be dedicated to the tests if the results are unsatisfactory.

3.3 Testing Procedure 3: Torque

The torque will need to be tested to determine if the legs will move properly. If an insufficient amount of torque is introduced, the legs will not be able to move to their full extent. This will cause issues with the rover's maneuverability and its ability to climb. Since the gravitational pull is much lower than on Earth, the legs will not weigh as much. This allows the rover to operate with less torque and power per operation. The torque can be tested two different ways.

3.3.1 Testing Procedure 3: Objective

One way is to use a dynamometer that can be sued to measure the torque. The other test is performed by attaching a string to a weight that is connected to a lever. This will allow for the force applied to be calculated. The dynamometer approach will require the team to have access to the device. The equipment is too expensive to be purchased using the project budget. If the team cannot find access to the device, the other test will be used.

3.3.2 Testing Procedure 3: Resources Required

If the first test is chosen, the team will need to obtain a dynamometer. This device will be borrowed from the university if they will allow it. The device will not be purchased due to the price. If the tea mis not permitted access to the device, the other test will be used. For the second test, a string ill need to be purchased that will be able to withhold the weight. Fishing line is being considered to be used in this experiment. The components that need to be tested for torque will also need to be purchased. Only one of these parts will be needed for each type to perform the test. All team members will participate in this test but if they are not available, only two or three people will be necessary.

3.3.3 Testing Procedure 3: Schedule

With the dynamometer, the test will only take about 30 minutes to complete. The rover parts will need to be obtained before the test can be done. The team plans to obtain most of the required parts before the spring semester. If the motors are purchased by then, the tests can be done in the early semester. If not, the experiment will be performed when the needed parts are acquired.

3.4 Testing Procedure 4: Power

The final important engineering requirement for this project is power. The rover will require sufficient power for all motors to run. There will need to be enough power to power all six legs with excess to power the other electrical components. With insufficient power, the rover would fail immediately. Therefore, this engineering requirement is important. Two different tests can be done for the power of the system. One is by using a dynamometer, the other is by creating a energy consumption model.

3.4.1 Testing Procedure 4: Objective

As mentioned before, the dynamometer can measure torque and rotational speed of a motor or engine. These measurements can be used to calculate the instantaneous power. This value can be multiplied by how many of the same part are being used in the system. With this, the power required by the rover will be known. If the team cannot get access to a dynamometer through the university, an energy consumption model will be created. This model uses calculations for speed, drag forces, inertia forces, and more to be summed together. This sum can be used to compute the energy consumption.

3.4.2 Testing Procedure 4: Resources Required

The team will need a dynamometer to conduct this test. This will need to be borrowed from the university due to the price. If this equipment cannot be obtained, the model will be used. The energy consumption model does not require any extra equipment but does require time. It may take some time to compute each of the variables to find the result. With a dynamometer, the team can carry out with the experiment with only two members. The model would require the full team to work on the calculations since this process would be demanding.

3.4.3 Testing Procedure 4: Schedule

The test can be accomplished once the team gets access to the dynamometer. Otherwise, the team would need to follow through with the energy consumption model. The model calculations can be completed once the motors that are being used is known. As mentioned before, many parts will be purchased before the spring semester. If the motors are purchased, the model can be generated right away. With the dynamometer, the test will take about 30 minutes. Without the device, the model calculations will take about 3-5 hours depending on how precise the team wants the results to be.

4 Risk Analysis and FMEA

The FMEA analyzes the three main subsystems of the rover; the body frame, the legs, and the feet (See Appendix B). For each subsystem, all expected potential failures were categorized and assessed for severity, occurrence, and detection. Each category is rated on a scale from 1-10, with 1 being the least and 10 the most. For severity, the score correlates to how serious the potential failure would be for the mission if it occurred with 1 indicating 'not severe' and 10 indicating 'critical systems failure'. Occurrence rates how often this hypothetical failure would occur with 1 indicating 'not often' and 10 indicating 'frequently'. Finally, detection rates how easily the potential failure could be discovered, with 1 indicating 'very easy to discover' and 10 indicating 'very difficult to discover'. Risk priority numbers (RPN) were calculated using the product of the three scores. The RPN rating ranges from 1-1000; the higher the rating, the worse the failure. From the RPN scores, ten critical failures were determined which are explored in depth in section 4.1.

4.1 Critical Failures

The top ten failures detected from our FMEA are as follows:

1. Solar radiation damage in electronics (RPN = 315)
2. Thermal shock in electronics (RPN = 315)
3. Static discharge in electronics (RPN = 315)
4. High cycle fatigue in motor (RPN = 224)
5. Solar radiation damage in motor (RPN = 224)
6. Adhesive wear in Gecko Grip (RPN = 180)
7. Impact wear in Gecko Grip (RPN = 180)
8. Impact wear in Micro-spine gripper (RPN = 125)
9. Yielding in PLA components (RPN = 90)
10. Shearing in fasteners (RPN = 40)

Solar radiation damage in the electronics could occur if they are exposed to the sun for long periods of time. To mitigate this risk, shielding material such as aluminum can be used to protect electrical components from damage. This material would need to encase the entire body of the rover to prevent radiation effects. Similarly, thermal shock can be prevented using shielding material, which can insulate electronics which are sensitive to thermal extremes. Static discharge occurs when charge builds up on one surface of the rover from solar radiation and discharges rapidly to a parallel surface. This can be prevented using grounds and by paying careful attention to the geometry of the final design, including limiting parallel surfaces with free space in between. High cycle fatigue in the motor will likely occur if the rover outlasts its original mission life and remains functioning for many years. This is impractical to design against since it would require oversizing the motor and is unnecessary because this design will be concerned with failures during the rover's mission life. Solar radiation damage in the motor is also of top concern, and will be mitigated using shielding material, like the electronics. Adhesive wear and impact wear in the Gecko Grip are possibly the most critical for our design process since they are extremely likely to occur during the life of the rover. To mitigate this risk, the team has considered several options including cleaning solvents like acetone or rubbing alcohol, mechanical cleaning, and covering or removing the grips while not in use. Each method has various drawbacks. Cleaning solvents may contribute to wear on the rover's feet, mechanical cleaning may not be effective enough, and covering or removing the grips will likely add complicated structures which will also have the capacity for failure. Impact wear in the Micro-spine grippers could lead to individual spines falling out, which reduces the overall effectiveness of the grip. This can be mitigated through proper selection of material for the spines, which would have adequate strength and flexibility to prevent yielding. Furthermore, the method of attachment between the individual springs in the spine assembly and the base of each pad must be strong enough to prevent failure. Possible methods of attachment include glue, mechanical attachment, and welding. Glue is the easiest method, but it also has the most potential for failure in the Psyche environment. Mechanical attachment would require very tiny and precise mechanisms, which could drive up cost exorbitantly. Finally, welding would require very precise and time-consuming application, since each pad has 35 spines, each claw has 7 pads, each foot has 5 claws, for a total of 1225 spines per foot (7350 spines total). Yielding in PLA components could occur due to the conditions on Psyche, including radiation damage, thermal cycling damage, and general wear and tear. However, this is a material we have only considered using for prototyping applications; therefore, it is something we could address in a hypothetical final design. Finally, shearing in the fasteners could compromise the functionality of our rover. To prevent this, detailed stress analyses will be performed to determine any weakness in our assembly which we can then modify to reduce the risk of failure.

4.2 Risks and Trade-offs Analysis

For each failure mode, potential solutions were determined which could prevent the failure from occurring. These potential solutions are indicated in TABLE XI in Appendix B. In general, attempting to address potential failures would increase the cost and/or weight of the rover. Many of the solutions to these failures are things that should be addressed on paper, but not necessarily applied in prototyping due to their effects on the cost of the design. For instance, adding shielding material like aluminum to the rover's frame will address many of the potential failures including solar radiation damage and thermal shock, but would be difficult to accomplish within the scope of this project. Furthermore, it will not affect the testing of our prototype if the rover's frame is bare. Therefore, for many of the potential failures moving forward they will be addressed on paper but may not be added to the prototype for reasons of budget and time constraints.

In general, the potential failures the team will focus on moving forward are those involved with our main goal, traversing the hypothesized surface of the asteroid. The rover must be able to traverse any expected obstacle without failure, therefore our attention will go towards testing the rover and finding bugs in its programming which may prevent it from overcoming obstacles. Furthermore, we will seek to address issues with the rover's two methods of attachment, the Gecko Grippers and Microspine Grippers. If either of these systems fail, it could compromise the ability of the rover to climb, which is one of the key requirements for this project. Regarding wear on the pads, the proposed solutions are withdrawing the pads, covering the pads, and cleaning the pads with some type of solvent. Each method has its own drawbacks. Both withdrawing the pads and covering the pads will require adding moving parts to our assembly which will increase the overall complexity and cost of the design, and lead to more potential avenues of failure. Using a solvent to clean the pads may compromise the integrity of other parts on the rover and would require a container which can store and dispense the liquid, also adding to our cost, weight, and overall complexity. The best way to determine how we can clean and maintain the pads will be through testing different methods to see what works best.

5 DESIGN SELECTED – First Semester

This section details the process of selecting the rover design. This section contains the design chosen by NAU Psyche, as well as the rationale for choosing this design. The subsystems of the chosen design are also highlighted within this section, with brief descriptions. Design selection is critical for the engineering process; therefore, this section highlights NAU Psyche's implementation plan for second semester capstone. The chosen design will be manufactured during second semester capstone. NAU Psyche believes the chosen design will have the capability of traversing the various surfaces of the Psyche asteroid.

5.1 Design Description

For our mission we are creating a rover that can traverse the hypothesized surfaces of 16 Psyche. The rover must have the ability to travel over flat surfaces, rocky surfaces, rubble strewn paths and even cliff faces made of metal. Many past rovers have had issues with their wheeled systems. NASA's Spirit rover had a front wheel lock up shortly after landing. This could have ended the mission if NASA had not realized the rover could still drive in reverse and drag the leg. Curiosity had issues with damage to the wheels, once again this could have ended the mission or at least made it so the area the rover could explore would be where it could reach with its arm. With this knowledge of past wheeled rovers that incorporated one method of movement the initial idea for the team's project was to incorporate redundancy in the movement system. Our rover needed to be able to roll, walk, inchworm and climb. The unpowered position of the rover limbs would be tight against the body so in case of failure the limb could retract and be free of the functional limbs. If a wheel failed, then the rover could walk on limbs and feet, if that failed the whole-body segments could extend and contract to inchworm forward. The ability to inchworm is also helpful in climbing. The rover can stretch up a wall and anchor the front half, then lift its back and middle segments up and anchor those, then repeat.

The initial concept for this rover was an eight-legged rover. Each leg would have multiple degrees of movement. This rover was designed with redundancy of "methods of movement". We had a standard wheeled method of movement to traverse flat and slightly rubble strewn paths. To deal with larger obstacles or low relief features there is a walking mode. This mode, for example, can pick its way up or down a shallow hill. The most unique "method of movement" is the "inchworm". This feature would make use of the rovers segmented body and extend the front half forwards and plant the front legs. Next, it lifts its middle body and moves that forward. Finally, it will bring the rear up. This method of movement is slow and would not be ideal for moving distances but would be helpful in traversing the low relief and climbing high relief cliff faces. With drill and anchoring systems added to the feet of the rover, this "method of movement" could climb sheer cliff faces and even invert if the need arose. Upon initial brainstorming the team decided to reduce the number of legs to 6. This would still allow all methods of movement and reduce the weight, cost and complexity of the rover. It also avoids overcrowding of components and leaves more room for science packages that would be attached to the rover.

Sub-Systems

Frame

The frame started out as a rectangular box with shoulder assembly boxes on all four corners and the middle. This was a static frame with legs. This would allow walking and rolling to occur but not the inchworm method of movement. From this the frame was segmented into three and a leadscrew system was introduced to extend the segments in and out. However, we needed to be able to articulate the body so it could bend at the middle segment. To allow for this articulation we changed the middle body segment into a double box with a hinge in the top. A curved rack and pinion system will be added to power this system. We changed out the leadscrew for a scissor lift design. We felt this gave the body segments more resistance to issues cause by rotation of the body segments.

Shoulder joint

The shoulder joint is a metal cage built into the frame of the robot and a block joint designed to rotate in the cage. This will be connected at the top and bottom of the cage and set into bearings. These shoulder joints will be powered by a worm and gear to allow the motor to not stick up out of the rover or to take up too much real estate inside the rover. The worm gear system should also provide plenty of torque to assist in climbing and walking.

Leg

The leg assembly consists of an upper and lower segment that connect the shoulder to the foot of the rover. Again, the group plans on implementing a worm gear system to give power to the leg.

Foot

As currently designed the claw assembly is just an articulating claw designed to have gecko grip material or micro-spine grippers attached to it, it still will need to be paired up with a wheel assembly. The claw uses a screw to open and close

TABLE IV

Calculations on speeds of different methods of movement

Driving Mode			
Metric	symbol	measurement	unit
Diameter of wheel	d	0.41	m
Speed of driving motor	n	2044	rpm
Circumference of wheel	Cir	1.288052988	m
Speed of driving wheels	v	43.87967179	m/s

Walking Mode			
Metric	symbol	measurement	unit
Speed of should motor	n	100	rpm
Length of leg	r	0.76	m
Linear velocity of foot	Vfoot	7.95870138	m/s

Inchworm Mode			
Metric	symbol	measurement	unit
Speed of body motor	n	115	rpm
radius of pinion Pd	r	5.296	mm
linear velocity of body segment	Vbody	63.77851959	mm/s
Number of body segment moves per cycle	moves	3	
distance of move		0.31	m
time per move		4.860570644	s
Time per cycle to move 0.31m		14.58171193	s

5.2 Implementation Plan

The team will work over holiday break as previously agreed upon. We will be following the scheduled laid out below to ensure the rover meets client requirements.

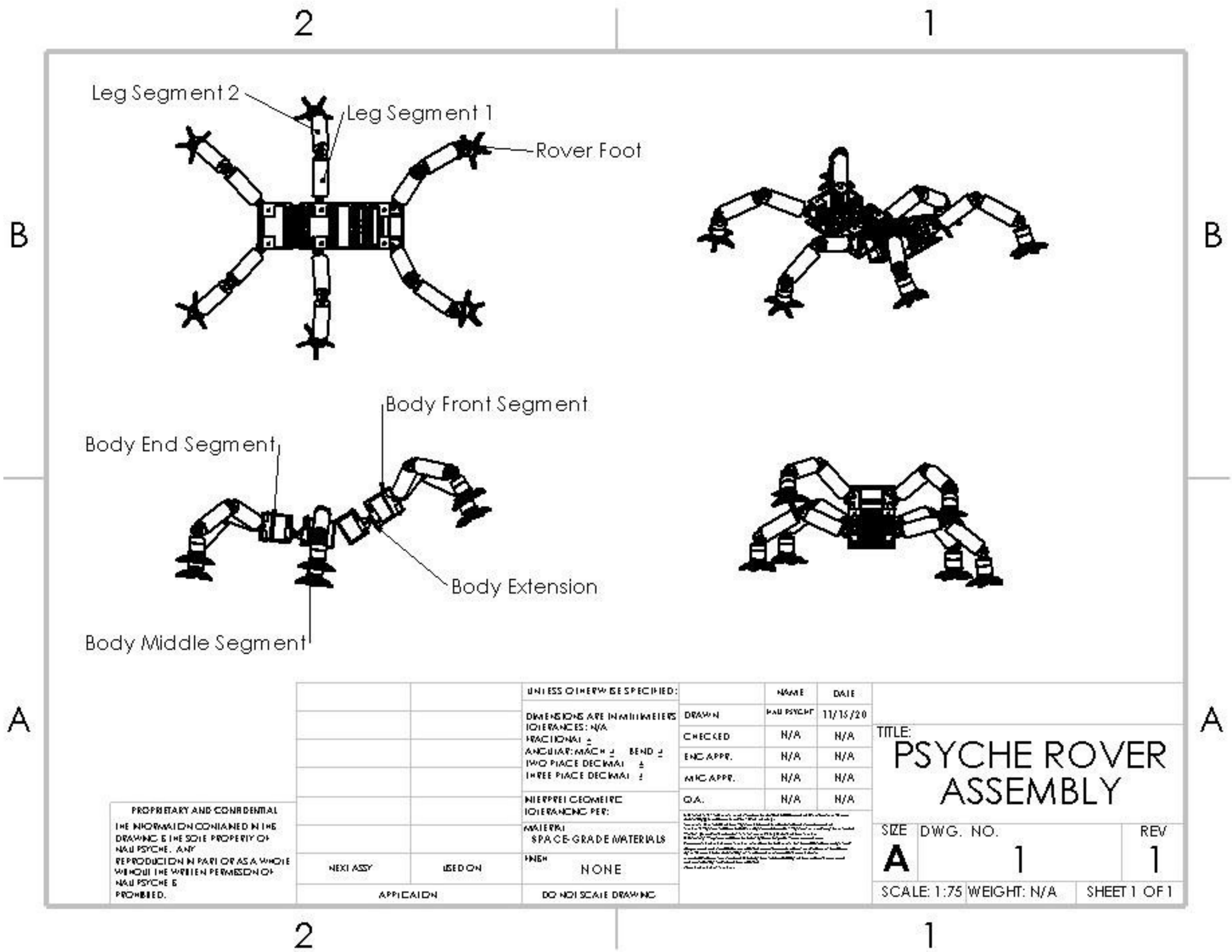

FIGURE IV

PSYCHE ROVER ENGINEERING DRAWING

FIGURE V

EXPLODED VIEW OF GECKO ROVER CAD MODEL

Schedule for post ME-476C

Week -4

Meeting Monday Dec 7th – All members

Topics:

Assign sub-teams, suggestions below, any member can assist even if not on sub-team

Programming – Jacob & Sean

CAD – Isaac & John

Assembly – Chad, Kate & Sean

Wiring - Kate & Jacob

Have teams contact experts in the field for assistance and mentorship

Set final scale of model

Redesign leg to include a wheel system, end of upper arm possible

Examine each part of rover.

Decide material for model

Order COTS parts

Discuss rebuild of CAD model

- Discuss 3D printed parts
  - Plan ordering of 3D printed parts
- Discuss Custom parts
  - Assign who will make parts
  - Set due dates for parts
- Discuss suppliers for parts
  - Order parts
- Get report from programmers
  - What do you need to program?
  - Can we run X number of motors with Arduino? Check with sparkfun forums
  - If not, can we build a static or less dynamic model and a full functioning leg decide path.
- Get report from motor team
  - Examples of motors
    - See about ordering, private buy
  - Examples of gearboxes
    - See about ordering, private buy
- Decide on primary and secondary build spaces
- Choose parts storage place
- Choose person responsible for inventory of parts

<u>Week -3</u>

Meeting Monday Dec 14 – All Members

Topics:

- Report from CAD team
- Have 3D printed parts been ordered?
- Have parts come in
- Have motors come in
- Set date for assembly team to meet

<u>Week -2</u>

Meeting Monday Dec 21 – All Members

Topics:

- Short week
- Report from assembly team
  - Plan for proceeding
- Report from CAD

Plan for proceeding

Report from programming

Plan for proceeding

Report from wiring

Plan for proceeding

Talk about flow charts for moving parts

Nasa style block diagram

Week -1

Meeting Monday Dec 28 – All Members

Topics:

No Meeting, Holiday Break

Week 0

Meeting Monday Jan 4 – All Members

Topics:

Discuss postmortem paper due week 1

Week 1

Meeting Monday Jan 11 – All Members

Topics:

Postmortem Due

Week 2

Meeting Monday Jan18 – All Members

Topics:

Major assembly should be completed

Revisions and rebuild of parts

Self-learning Due

Week 3

Meeting Monday Jan 25 – All Members

Topics:

Week 4

Meeting Monday Feb 1 – All Members

Topics:

Start operations manual

Week 5

Meeting Monday Feb 8 – All Members

Topics:

Hardware Review Due

HR summary Due

Peer Eval 1 Due

Week 6

Meeting Monday Feb 15 – All Members

Topics:

Website Check

Week 7

Meeting Monday Feb 22 – All Members

Topics:

Week 8

Meeting Monday Mar 1 – All Members

Topics:

Midpoint Presentation

Midpoint Report

Week 9

Meeting Monday Mar 8 – All Members

Topics:

Individual Analysis II

Week 10

Meeting Monday Mar 15 – All Members

Topics:

Rover needs to be completed

Device summary

Peer Eval 2

Week 11

Meeting Monday Mar 22 – All Members

Topics:

Drafts of poster

Week 12

Meeting Monday Mar 29 – All Members

Topics:

Testing Proof

Week 13

Meeting Monday April 5 – All Members

Topics:

UGRADS practice

Final Poster

Operations Manual

Week 14

Meeting Monday April 12 – All Members

Topics:

UGRADS

Week 15

Meeting Monday April 19 – All Members

Topics:

Final report

Final CAD package

Week 16

Meeting Monday April 26 – All Members

Topics:

Finals week

Website check

Peer Eval 3

TABLE V

TENTATIVE BILL OF MATERIALS FOR SMALL SCALE ROVER PROTOTYPE

Tentative Bill of Materials for Small Scale Prototype								
Manufacturer	Part No.	Description	Quantity	Source	Unit Price ($)	Comment	Total Price ($	
Rev Robotics	1	1" Aluminum Extrusion (4 feet)	12	Rev Robotics	16.5	Used for frame and legs	198	
Rev Robotics	2	HD Hex Motor	33	Rev Robotics	28	Motors for legs, feet, and body extensior	924	
Elegoo	3	Arduino Mega	2	Amazon	15.99	For electronics (motors, servos, etc.)	31.98	
Elegoo	4	Arduino Jumper Wires (Owned	1	Amazon	6.98	Connect motors and servos to Arduino	0	
Elegoo	5	Circuit Bread Boards	2	Amazon	8.99	Used for circuit connections	0	
Makerbot	6	PLA Filament (Owned)	3	Amazon	59	3D Print parts for components	0	
Bolt Depot	7	12mm Hex Bolts	100	Bolt Depot	94.12	Fasten components together	94.12	
Grainger	8	12V Battery (Owned)	1	Batteries +	12.44	Power electrical components	0	
Setex	9	Nano Grip Tape	1	Setex	57.49	Grip Tape for rover feet	57.49	
JJ Needles	10	Micro-Spine Gripper	1	JJ Needles	36.54	Used for grip on rover feet	36.54	
							1305.59	Running Total

6 CONCLUSIONS

The problem presented to the NAU psyche team was to design a hypothetical rover that can traverse multiple hypothesized surfaces. The surfaces that the rover must traverse are flat surfaces, rocky surfaces, rubble strewn paths and cliff faces made of metal. The Psyche rover must be able to operate for 3 months. The rover must be able to withstand the environment of the Psyche asteroid. The rover must have enough clearance to avoid hitting rocks/metallic objects. The rover must have enough power to operate all motors, as well as have the power to climb steep or sandy surfaces.

The NAU Psyche team made the frame by designing three rectangular boxes. The team connected these boxes via a scissor lift design that will be moved by a curved rack and pinon system. The shoulder joints that connects to the frame to the legs is made up of a block joint which will rotate in the frame. This will allow for more degrees of freedom. These joints will be powered by worm gears. The team decided on using six legs to move the rover. The legs are made up of two segments, an upper segment and a lower segment. This was chosen to give the rover more maneuverability because a solid leg has less degrees of freedom. The foot of the legs is made up of an articulating claw designed that will have gecko grip material. This material will allow the rover to climb and traverse surfaces. In addition to the gecko grip material the rover will have micro-spine grippers. This was added to pick up the role that the gecko grip material cannot do. This rover will be powered with nuclear power. The navigation picked for this rover is lidar and cameras positioned around the rover.

7 References

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8 APPENDICES

8.1 Appendix A: House of Quality and Quality Function Deployment

TABLE VI

NAU PSYCHE ROVER HOUSE OF QUALITY

House of Quality (HoQ)										
Customer Requirement	**Weight**	**Engineering Requirement**	Material Strength	Mission Time	Mass	Volume	Torque	Ground Clearance	Travel	Power
1. Traverse the 5 Hypothesized Surfaces	9		3	1	3	1	9	9	9	9
2. Size	3		1	1	9	9	3	3	3	9
3. Power System (Solar, Nuclear)	9		1	3	9	3	9	1	1	9
4. Weight	9		9	1	9	3	3	1	3	9
5. Longevity (Mission Life)	3		3	9	1	1	1	1	1	3
6. Durability	9		9	9	3	1	3	3	1	3
7. Redundancy	3		1	9	3	3	1	3	3	9
8. Speed	1		3	1	3	1	3	9	9	9
Absolute Technical Importance (ATI)			216	184	258	112	234	156	156	342
Relative Technical Importance (RTI)			13%	11%	16%	7%	14%	9%	9%	21%
Target ER values			276	3	120	8	475	1	0.6	110
Tolerances of Ers			5	0.25	5	0.25	5	0.25	0.25	0.125
Units			Mpa	Months	kg	m^3	Nm	m	m	Watts
Testing Procedure (TP#)			1	1,4	4	4	3	2	2	4
Approval (print name, sign, and date):										
Team member 1: __Isaac Anderson__	9/18/2020									
Team member 2: __Kate Collette__	9/18/2020									
Team member 3: __John Dynda__	9/18/2020									
Team member 4: __Jacob Sasse__	9/18/2020									
Team member 5: __Chad Schafer__	9/18/2020									
Team member 6: __Sean Sullivan__	9/18/2020									
Client Approval: Cassie Bowman										

TABLE VII

QUALITY FUNCTION DEPLOYMENT WITH BENCHMARKING ANALYSIS

Benchmarking Analysis
▫ Opportunity Mars Rover
Δ Curiosity Rover

Customer Needs \ Engineering Requirements	Importance	Material Strength	Mission Time	Mass	Volume	Torque	Ground Clearance	Travel	Power	Customer Competitive Assessment (Benchmarks): 1 Worst	2	3	4	5 Best
Traverse the 5 hypothesized Surfaces w/ low gravity	9	3	1	3	1	9	9	9	9		▫		Δ	
Size	3	1	1	9	9	3	3	3	9	Δ		▫		
Power system (Solar, Nuke)	9	1	3	9	3	9	1	1	9			▫		Δ
Weight	9	9	1	9	3	3	1	3	9		Δ		▫	
Longevity (mission life)	3	3	9	1	1	1	1	1	3		Δ			▫
Durability?	9	9	9	3	1	3	3	1	3			▫	Δ	
Redundancy	3	1	9	3	3	1	3	3	9			▫	Δ	
Speed	1	3	1	3	1	3	9	9	9		Δ		▫	
Technical Importance: Absolute		216	184	258	112	234	156	156	342					
Technical Importance: Relative		13%	11%	16%	7%	14%	9%	9%	21%					
Target Value		276	3	120	8	475	1	0.6	0.1475					
USL		350	12	160	15	510	1.3	0.75	0.16					
LSL		16	2	80	1	375	0.8	0.4	0.13					
Units		Mpa	Months	kg	m^3	Nm	m	m	hp					
Design Competitive Assessment	Worst: 1													
	2			Δ	Δ			▫	▫					
	3	▫	Δ			▫	▫							
	4	Δ		▫	▫	Δ			Δ					
	Best: 5		▫				Δ	Δ						

8.2 Appendix B: FMEA Analysis

TABLE VIII

FMEA FOR ROVER FRAME

Product Name: Gecko Rover Subsystem Name: Rover Frame	Development Team: NAU Psyche Page No. 1 of 3 FMEA Number 1 Date: 11/13/20							
Part Number and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Detection (D)	Recommended Action	RPN
1 (Main Component of Rover Frame)	Yielding, Force and/or Temperature Induced Deformation	System Failure	6	Overstressing	2	2	Select Materials with High Material Strength	24
2 (Actuates Frame Extension)	High-Cycle Fatigue, Solar Radiation Damage	Noise, Poor Performance	8	Over Voltage/Current, Impact Loading	4	7	Select Adequate Motors	224
3 (Sends Signal to Electronics)	Solar Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315
4 (Connects Electronics to Arduino)	Solar Radiation Damage, Thermal Shock. Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315
5 (Creates Circuit Connections)	Solar Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315
7 (Fastens Components)	Yielding, Impact Fatigue, Impact Deformation, Deformation Wear	Erratic Operation	5	Overstressing, Impact Loading, Assembly Errors, Tolerance Stackup	4	2	Tighten bolts to specifications, use proper fasteners	40
8 (Powers Electrical Components)	Solar Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315

TABLE IX

FMEA FOR ROVER LEGS

Product Name: Gecko Rover	Development Team: NAU Psyche Page No. 2 of 3 FMEA Number 2 Date: 11/13/20							
Subsystem Name: Rover Legs								
Part Number and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Detection (D)	Recommended Action	RPN
1 (Main Component of Rover Frame)	Yielding, Force and/or Temperature Induced Deformation	System Failure	6	Overstressing	2	2	Select Materials with High Material Strength	24
2 (Actuates Leg Segments)	High-Cycle Fatigue, Radiation Damage	Noise, Poor Performance	8	Over Voltage/Current, Impact Loading	4	7	Select Adequate Motors	224
3 (Send Signals to Electronics)	Solar Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315
4 (Connect Electronics to Arduino)	Solar Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315
5 (Creates Circuit Connections)	Solar Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315
7 (Fastens Components)	Yielding, Impact Fatigue, Impact Deformation, Deformation Wear	Erratic Operation	5	Overstressing, Impact Loading, Assembly Errors, Tolerance Stackup	4	2	Tighten bolts to specifications, use proper fasteners	40
8 (Powers Electrical Components)	Solar Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315

TABLE X

FMEA FOR ROVER FOOT

Product Name: Gecko Rover	Development Team: NAU Psyche Page No. 3 of 3 FMEA Number 3 Date: 11/13/20							
Subsystem Name: Rover Foot								
Part Number and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Detection (D)	Recommended Action	RPN
2 (Actuates Worm Gear)	High-Cycle Fatigue, Radiation Damage	Noise, Poor Performance	8	Over Voltage/Current, Impact Loading	4	7	Select Adequate Motors	224
3 (Send Signals to Electronics)	Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315
4 (Connect Electronics to Arduino)	Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315
5 (Creates Circuit Connections)	Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315
6 (Main Material for Foot Components)	Yielding, Force and/or Temperature Induced Deformation	System Failure	9	Overstressing, Impact Loading, Assembly Errors, Tolerance Stackup	5	2	Redesign CAD Model	90
7 (Fastens Components)	Yielding, Impact Fatigue, Impact Deformation, Deformation Wear	Erratic Operation	5	Overstressing, Impact Loading, Assembly Errors, Tolerance Stackup	4	2	Tighten bolts to specifications, use proper fasteners	40
8 (Powers Electrical Components)	Radiation Damage, Thermal Shock, Static Discharge	Poor Performance, System Failure	9	Over Voltage/Current	5	7	Shield Electronics from Solar Radiation	315

TABLE XI

TRADE-OFFS ANALYSIS FOR POTENTIAL FAILURES

Potential Failure Mode	**Possible Solution**	**Trade-Offs**	**RPN**
Solar radiation damage in electronics	Shielding material	Increases weight, cost	315
Thermal shock in electronics	Insulation	Increases weight, cost	315
Static discharge in electronics	Shielding material, limiting parallel surfaces	Increases weight, cost	315
High cycle fatigue in motor	Oversize motor	Increases weight, cost, energy consumption	224
Solar radiation damage in motor	Shielding material	Increases weight, cost	224
Adhesive wear	Covering Gecko Gripper pads	Adds moving part, adds complexity	180
Adhesive wear	Withdrawing Gecko Gripper pads	Adds moving part, adds complexity	
Adhesive wear	Cleaning solvent	Requires container for liquid, limited supply, could compromise polymer components and/or electrical components	180
Impact wear in Gecko Gripper	Covering Gecko Gripper pads	Adds moving part, adds complexity	180
Impact wear in Gecko Gripper	Withdrawing Gecko Gripper pads	Adds moving part, adds complexity	180
Impact wear in Microspine Gripper	Choosing spine material with high ductility and material strength	Increases cost, may be difficult to acquire or expensive to commission	125
Yieding in PLA components	Do not use PLA components	Increase cost significantly	90
Shearing in fasteners	Oversize fasteners	Increases weight, cost	40

8.3 Appendix C: ME 486C Spring 2021 Schedule

TABLE XII

PROPOSED SCHEDULE FOR NEXT SEMESTER

SUBJECT TO CHANGE – CHECK COURSE WEBSITE OFTEN

Week	Mon	Tues	Wed	Agenda Item	Assignment Due**
1	1/13	1/14	1/15	Team/Staff Meetings	**Post Mortem Due**
2	1/20	1/21	1/22	Team/Staff Meetings	*Jan 20 - MLK Jr Day* **Self Learning Due**
3	1/27	1/28	1/29	Team/Staff Meetings	
4	2/3	2/4	2/5	Team/Staff Meetings	
5	2/10	2/11	2/12	**Hardware Review**	**HR summary and Peer Eval 1**
6	2/17	2/18	2/19	Team/Staff Meetings	**Website Check**
7	2/24	2/25	2/26	Team/Staff Meetings	
8	3/2	3/3	3/4	**Midpoint Presentation**	**Midpoint Report**
9	3/9	3/10	3/11	Team/Staff Meetings	**Individual Analysis II**
Spring Break					
10	3/23	3/24	3/25	**Final Product Completed**	**Device summary and Peer Eval 2**
11	3/30	3/31	4/1	Team/Staff Meetings	**Drafts of poster**
12	4/6	4/7	4/8	**Testing Proof Completed**	**Testing Proof**
13	4/13	4/14	4/15	UGRADS practice	**Final Poster and Operation Manual**
14	4/20	4/21	4/22	**UGRADS (Friday)**	**Final Presentation**
15	4/27	4/28	4/29	Team/Staff Meetings	**Final Report and CAD package**
Finals Week					**Website and Peer Eval 3**

TABLE XIII

CURRENT CALENDAR LAYOUT FOR POST ME-476C

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday		
Taking week off 29	Taking week off 30	Taking week off 1	Taking week off 2	Taking week off 3	Taking week off 4	Taking week off 5	Dec 2020	Week -5
6	7	8	9	10	11	12		Week -4
13	14	15	16	17	18	19		Week -3
20	21	22	23	24	25	26		Week -2
27	28	29	30	31	1	2	Jan 2021	Week -1
3	4	5	6	7	8	9		Week 0
10	First Day Spring 2021 11	12	13	14	15	16		Week 1
17	Martin Luther King Day 18	19	20	21	22	23		Week 2
24	25	26	27	28	29	30		Week 3
31	1	2	3	4	5	6	Feb 2021	Week 4
7	8	9	10	11	12	13		Week 5
14	15	16	17	18	19	20		Week 6
21	22	23	24	25	26	27		Week 7

28	1	2	3	4	5	6	Mar 2021	Week 8
7	8	9	10	11	12	13		Week 9
14	15	16	17	18	19	20		Week 10
21	22	23	24	25	26	27		Week 11
28	29	30	31	1	2	3	Apr 2021	Week 12
4	5	6	7	8	9	10		Week 13
11	12	13	14	15	16	17		Week 14
18	19	20	21	22	23	24		Week 15
25	26	27	28	29	Last Day Spring 2021			Week 16