NORTHERN ARIZONA UNIVERSITY

NAU Psyche Exploration Robot

Final Report

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EXECUTIVE SUMMARY

The purpose of the Psyche mission is to explore a giant metal asteroid, known as Psyche 16 located about three times further from the sun than the Earth. The Psyche asteroid is believed to be comprised mainly of metallic iron and nickel, like the composition of the Earth's core. This asteroid poses an interesting question, "could Psyche be the core of an early planet, that could have been as large as Mars?" Scientists at NASA are attempting to gain more information on the asteroid. With the newfound information, they might hopefully be able to determine whether Psyche 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 would likely aid in the process of determining the origins of the Psyche 16 asteroid. With the information retrieved through an orbiter, future missions may involve exploring the surface of the asteroid. This is where our group comes in, commencing the next stage for Psyche 16'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 16 asteroid. The prototype developed by our team must have the ability to traverse surfaces like those expected 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 operate 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 leg model of the Gecko rover, and a small-scale prototype. The team proceeded to build and test both the full scale-leg model and the small-scale rover. The procedures and steps taken to complete this project are outlined below in this document.

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Dr. Sarah Oman: Second semester instructor.

TABLE OF CONTENTS

Contents

Table of Tables

Table of Figures

1 BACKGROUND

1.1 Introduction

16 Psyche is a metallic-type asteroid which orbits within the asteroid belt. The Psyche asteroid has a diameter of approximately 140 miles and is unlike most asteroids ever studied or visited by human spacecraft. What makes Psyche so different is that it appears to not have rocky or icy bodies. Scientists believe that Psyche is 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. 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 scientist 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 must 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 this mission scientists will 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 had to be followed while designing the rover to achieve an optimal design that met all the criteria provided. Each of these requirements can be seen in **Error! Reference source not found.** where they are weighted in accordance with their importance to the project.

Table 1. NAU Psyche Robotic Explorer Customer Requirements

Customer Requirements		**Priority**
Rover Adaptability	The rover must be able to adapt and overcome potential challenges it may face when exploring the asteroid.	High
Size and Weight	The final product must be a reasonable size and weight.	Low
Power Supply	The product should have a viable power source capable of powering all system operations.	Optional
Longevity	The rover should be operational for the expected duration of the mission.	High
Durability	The rover should be durable enough to potentially maintain operation beyond the mission life.	High
Redundancy	The rover should have some redundant movement systems in place to enhance its traversability.	Optional
Traversability	The rover should have the ability to traverse the various hypothesized surfaces of the 16 Psyche asteroid.	Highest

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, longevity, durability, and traversability. The traversability requirement is a top priority because the rover must be able to traverse the five different hypothesized surfaces of the Psyche asteroid. That is the primary goal of this project, therefore it ranks as the top requirement from the customer. The rover adaptability is also ranked high because the rover must be durable enough to traverse the potentially rough terrains of the 16 Psyche asteroid. The longevity is another customer requirement with high priority, the rover must remain operation for the full duration of the mission. The next highest-ranking requirements are the size and weight, power supply, and redundancy. The weight has a lower priority due to the hypothesized gravity of the asteroid, which is 0.144 $\frac{m}{s^2}$. Hypothetically, if the mission were to take place in the future, launch conditions could be affected by the weight of the rover. NASA has launched many exploration robots with relatively large weights with little to no difficulties. Having redundancy in the design of the rover is an important requirement. Redundancy provides instantaneous troubleshooting when certain systems on the rover fail. It is also important to design redundant systems of movement in order to prepare for all possible obstacles that could be present on the asteroid.

2.2 Engineering Requirements (ERs)

The engineering requirements displayed in **Error! Reference source not found.** were generated based on the customer requirements listed in the previous section. These variables are all requirements that the team needed to meet while designing the rover. In addition, each of the engineering requirements has a target value to be met.

Table 2. NAU Psyche Robotic Explorer Engineering Requirements

Engineering Requirements		**Units**	**Target Value Small-Scale**	**Target Value Leg Model**	**Priority**	**Analysis**
Model Mass	The models should be of reasonable mass to be operational with the given actuators (servos/motors).	kg	3.86	3.5	3	Determined based on CAD model, material properties (density) included in the model to find model's total mass.
Model Volume	This ER is tied to the overall size and mass of the models, account for servo and motor torques.	m^3	0.25	0.1	5	Determined based on CAD model, mass properties within SolidWorks.
Torque	This ER revolves around torque requirements for both servos and motors for the small-scale and full-scale leg models.	Nm	1.98	20.3	1	Torque analysis conducted for both models to determine necessary torque output for operation.
Ground Clearance	This ER is more important for the small-scale model, as it should have the ability to clear obstacles in its path.	cm	17.78	92	4	Determined for small-scale model based on CAD model arm lengths and angles during movement. Determined for full-scale leg model based on hypothetical rover height.
Power	This ER revolves around the power source for both models, should be optimal for the requirements of the servos and	W	30.59	54.4	2	Calculated from vendor specifications on the servos and motors for the small-scale and full-scale leg model.

	motors.					

The above engineering requirements were created using a quality functional deployment approach. A QFD provided the team with a guide on where to direct resources while meeting the customer requirements.

2.3 *Functional Decomposition*

The main functions of the Psyche Rover are shown below in Figure 1. The major change the team decided on was to change the power source to DC instead of nuclear. 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. Navigation is another aspect changed by the team. The team decided not to put a navigation system in due to time and budget constraints. 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.

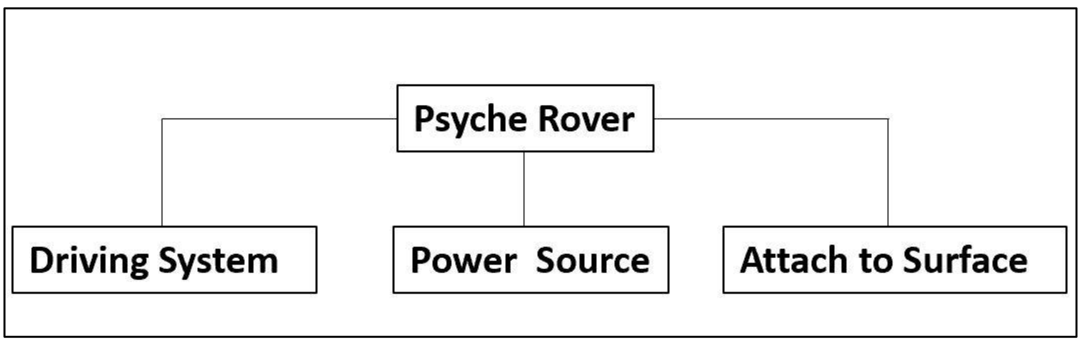

Figure 1. Functional Decomposition of the Psyche Rover

2.3.1 Black Box Model for Small-Scale Robotic Explorer

Figure 2 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 DC which will allow the rover to move in a translational motion. The signals will be data which includes the actual programming of the rover. The data will allow the rover to operate when direct contact is not possible. This model was critical to help the Psyche Team visualize the necessary systems for the rover. It also showed the team how critical it will be to have two typs of movement in case one fails.

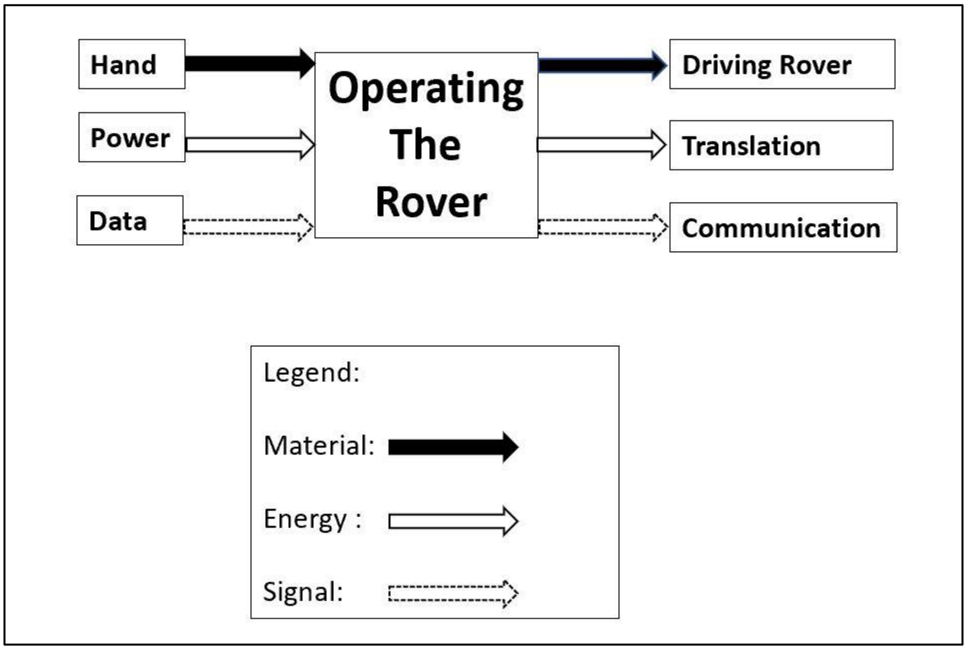

Figure 2. Black Box Model of the Small-scale Rover

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

The functional decomposition for the Psyche Rover is shown below in Figure 3. This model was important for visualizing the necessary subsystems needed for the Psyche Rover. The model shows a human hand as a material. 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. The data will be saved and imported into the rover so it can still operate without direct human contact. This functional model made the Psyche Team agree that the best power system would be DC. DC 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.

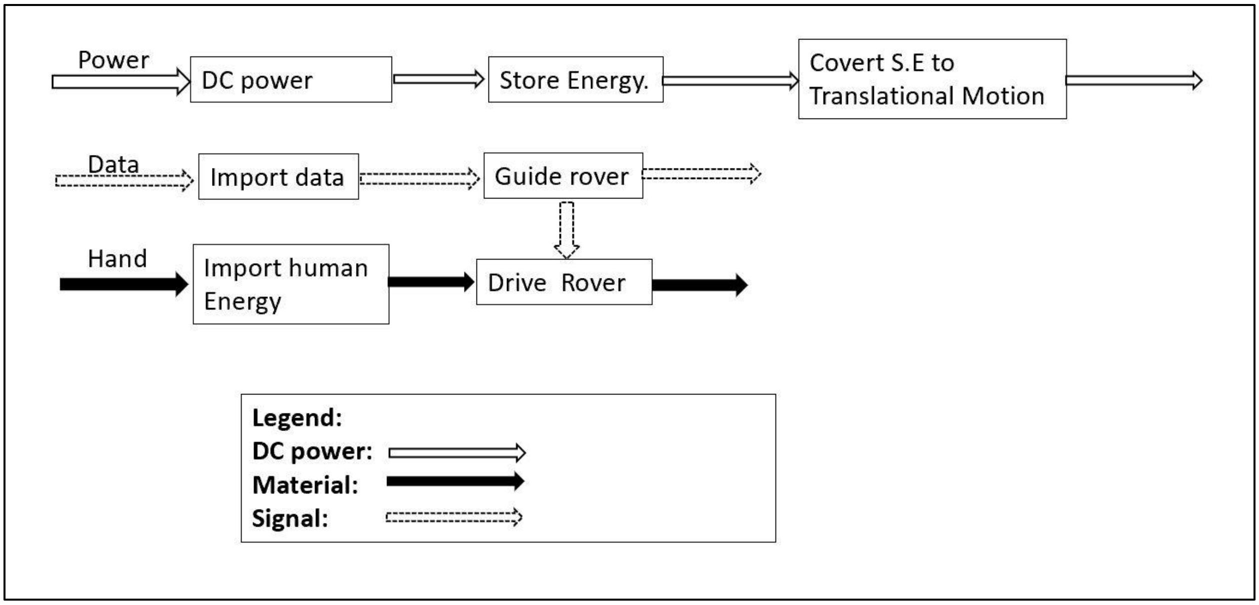

Figure 3. Functional Model of the Small-scale Rover

2.3.2 Black Box Model for Full-Scale Leg

Figure 4 below shows the black box model for the full-scale leg model. This black box model consists of materials (solid arrow), energies (hollow arrow), and signals (dashed arrow). The material used for this full-scale leg model is the hand which equates to operating the leg manually using remote communication. The power used for the rover is DC which will allow the leg to move in a translational motion. The signals will be data which includes the actual programming of the leg. The data will allow the leg to operate when direct contact is not possible. This model was critical to help the Psyche Team visualize the necessary systems for the full-scale leg model.

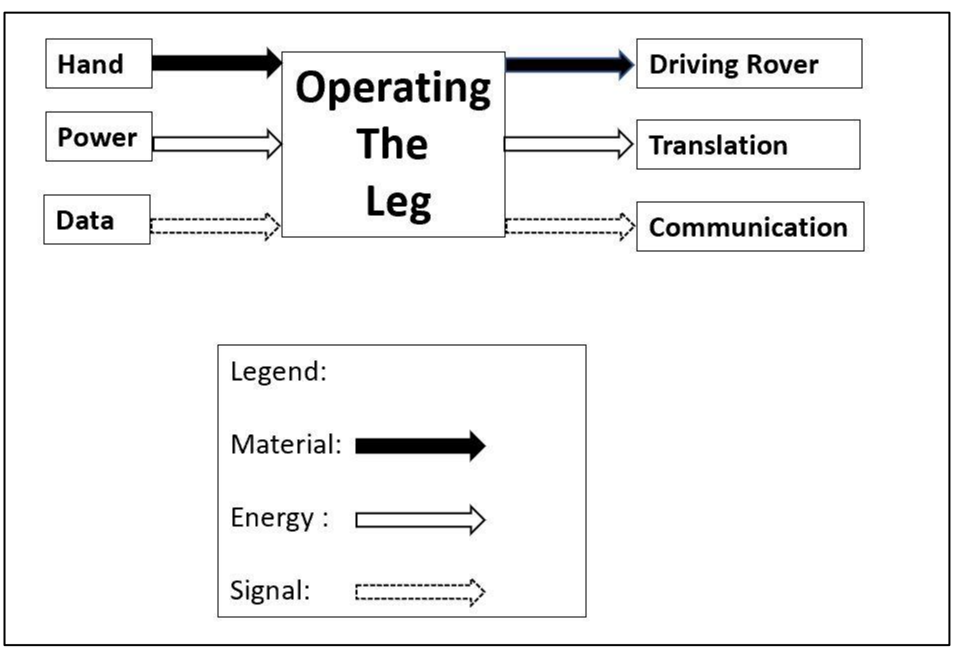

Figure 4. Black Box Model of Full-scale Leg Model

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

The functional decomposition for the full-scale leg model is shown below in Figure 5. This model was important for visualizing the necessary subsystems needed for the full-scale leg model. The model shows a human hand as a material. The Psyche Team also needs to be able to operate the leg while direct contact was not possible. This is where the data came into play. The data will be saved and imported into the rover so it can still operate without direct human contact. This functional model made the Psyche Team agree that the best power system would be DC. DC was chosen because of its ability to produce a lot of power for a long period of time. This power system will allow the leg to move translation around the asteroid.

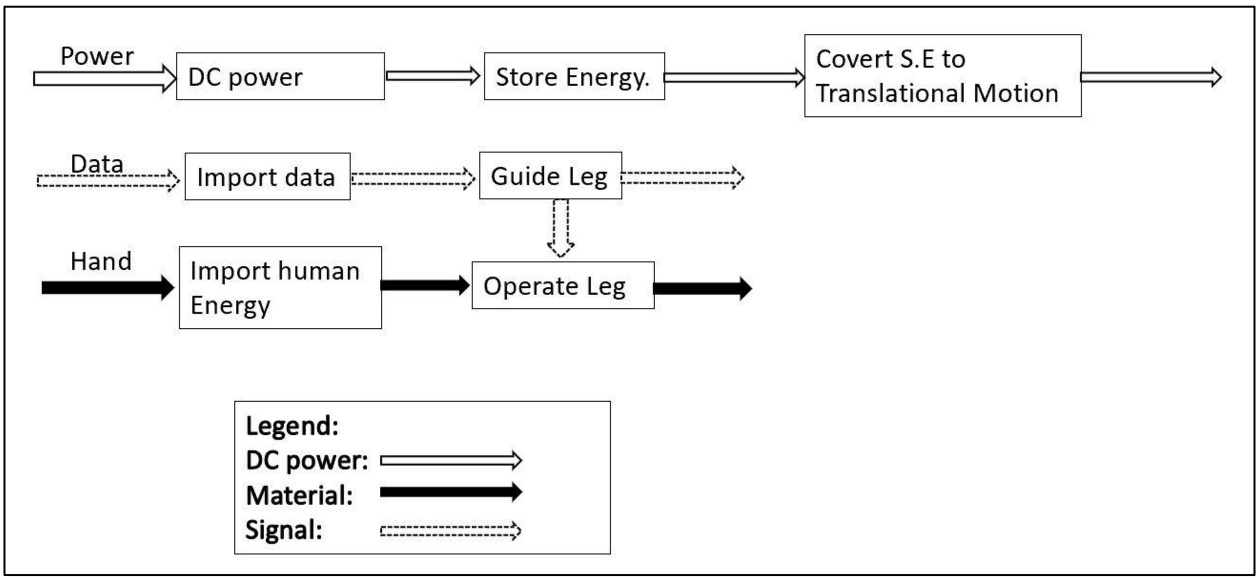

Figure 5. Functional Model of Full-scale leg Model

2.4 House of Quality (HoQ) – Small-Scale Robotic Explorer

The House of Quality (HoQ) for the small-scale model was utilized to compose critical design decisions, Table III. The most critical engineering requirement determined by the HoQ for the small-scale model was the power output. This engineering requirement (ER) was developed to account for the power supplied to the electronical components of the model. The power output required was determined through ER testing procedure 5. The team analyzed each electrical component present on the model, the power requirements of each component were gathered directly from the vendors. Through the analysis, the team determined that a power supply capable of outputting 30.59 Watts was necessary for the model to operate properly. A 7.2 Volt, 3600 mAh battery was selected for use. Further analysis was conducted to determine the amount of operation time for the model. On a full charge, the model would have the ability to operate at full capacity for 0.847 hours. Based on the HoQ for the small-scale model, the team determined that the second most critical engineering requirements (ER) were the power and torque requirements. The target value for the torque output of the servos on the small-scale model was an important element to consider because it directly affected the rover's performance. The team had to select servos capable of outputting 1.98 Nm of torque, this value was determined based on ER proof 1. This torque output was necessary for the small-scale model to lift its body from the ground and retain its position. This HoQ allowed the team to determine the engineering requirements for the small-scale model based on the requirements specified by the client.

Table 3. Small-Scale Psyche Robotic Explorer House of Quality

Small-Scale Psyche Robotic Explorer House of Quality									KEY
Customer Requirements	Importance	Engineering Requirements							
		Model Mass	Model Volume	Torque	Ground Clearance	Power	Material Strength	Percent Infill	
Rover Adaptability	9	3	3	9	9	3	3	1	9 = Highest
Size and Weight	3	9	9	9	9	9	3	9	3 = High
Power Supply	3	9	3	9	1	9	1	1	1 = Low
Longevity	9	3	3	3	3	9	9	3	
Durability	9	3	3	3	3	3	9	3	
Redundancy	3	1	1	1	1	3	1	1	
Traversability	9	3	3	9	9	9	3	3	
Technical Importance: Absolute		165	147	273	249	279	231	123	
Technical Importance: Relative		11%	10%	19%	17%	19%	16%	8%	
Target Value		3.86	0.25	1.98	17.78	30.59	65	15	
USL		4	0.5	2	18	45	72	20	
LSL		3.5	0.2	1.98	17	40	40	10	
Units		kg	m3	Nm	cm	W	MPa	Percentage	
Testing Procedure		2	3	1	4	5	N/A	N/A	

2.5 *House of Quality (HoQ) – Full-Scale Leg Model*

The House of Quality (HoQ) for the Full-Scale Leg Model was used to inform critical design decisions (see Table 4). From our HoQ analysis we determined that the mass and ground clearance scored as most critical to the design, however torque and power were both close seconds. Least important to the design was model volume. Mass is critical because any increase in the rover's weight means a higher payload for the delivery rocket which would greatly increase the overall cost and reduce the feasibility of the mission. Ground clearance scored high because it is strongly correlated to adaptability, weight, and traversability. If the rover legs are too small, the rover will sit close to the ground and will have trouble maneuvering around obstacles. The information gained from our HoQ allowed us to prioritize critical design features, like clearance, without having to worry much about other features like model volume.

Table 4. Full Scale Leg Model House of Quality.

Full-Scale Leg Model Psyche Robotic Explorer House of Quality							KEY
Customer Requirement	Importance	Engineering Requirements					9 = Highest
		Model Mass	Model Volume	Torque	Ground Clearance	Power	3 = High
Rover Adaptability	9	9	3	3	9	1	1 = Low
Size and Weight	3	9	9	3	9	3	
Power Supply	3	3	3	9	1	9	
Longevity	9	1	1	3	1	3	
Durability	9	3	1	1	1	1	
Redundancy	3	9	3	3	3	3	
Traversability	9	3	1	9	9	9	
Technical Importance: Absolute		207	99	189	219	171	
Technical Importance: Relative		23.39%	11.19%	21.36%	24.75%	19.32%	
Target Value		3.5	0.1	20.3	92	54.4	
USL		5	0.2	30	1.2	60	
LSL		1	0.05	20	0.8	50	
Units		kg	m3	Nm	cm	W	
ER Proof #		1	2	3	4	5	

2.6 Standards, Codes, and Regulations

Table 5. 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 [1].
NASA-HDBK-4002	Mitigating In-Space Charging Effects – A Guideline	NASA guidelines for avoiding charge build up on spacecraft [1].
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 [1].
NASA-STD-4003	Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment	Electrical bonding requirements for space vehicles [1].
NASA-HDBK-5010	Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware	Fracture control implementation guidance for hardware [1].
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 [1].
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 [1].
NASA-STD-5009	Nondestructive Evaluation Requirements for Fracture Critical Metallic Components	Establishes nondestructive methods for evaluating fracture in metallic components [1].
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 [1].
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 [1].
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 [1].
NASA-STD-6001	Flammability, Off gassing, and Compatibility Requirements and Test Procedures	Evaluating flammability and compatibility of materials [1].
NASA-STD-6012	Corrosion Protection for Space Flight Hardware	Corrosion protection requirements applicable to the surface treatment and finishing of space flight hardware [1].
NASA-STD-6016	Standard Materials and Processes Requirements for Spacecraft	Materials and Processes standards for off-the-shelf items [1].

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 [1].
NASA-STD-7009	Standard for Models and Simulations	Standards for models and simulations [1].
NASA-STD-7012	Leak Test Requirements	Test requirements for pressurized or sealed liquids to prevent leaks [1].
NASA-GB-8719.13	NASA Software Safety Guidebook	How to address creation and assurance of safety-critical software [1].
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 [1].
NASA-HDBK-8739.19-3	Measurement Uncertainty Analysis Principles and Methods, NASA Measurement Quality Assurance Handbook - ANNEX 3	Uncertainty analysis principles and methods [1].
NASA-HDBK-8739.19-4	Estimation and Evaluation of Measurement Decision Risk, NASA Measurement Quality Assurance Handbook - ANNEX 4	Assuring measurement accuracy [1].
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 [1].
NASA-STD-8739.10	Electrical, Electronic, and Electromechanical (EEE) Parts Assurance Standard	Managing the selection of EEE parts to control risk and enhance reliability [1].
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 [1].
ASME Y14.5-2018	Dimensioning and Tolerancing	Standards for dimensioning and tolerancing CAD drawings [2].

3 DESIGN SPACE RESEARCH

3.1 Literature Review

In designing our robotic explorer, research was pulled from a wide variety of sources ranging from journal articles to NASA's JPL. The team went over topics including navigation, surface conditions, existing rovers, power systems, drive systems, and suspension. The results of the research informed us when it came to design generation and narrowed down the scope of our project. For instance, from the research we were able to determine that a solar powered system alone may not be sufficient to power the robotic explorer, since Psyche's rotation is perpendicular to its orbit and thus one side of the asteroid will be in the dark for months at a time. Another result of this research was the idea of redundancy of motion, since there are so many unknowns when it comes to the surface conditions on the asteroid. This was something that our client emphasized heavily, and thus was a major factor in designing our robotic explorer. The research also inspired some of our final design decisions, such as Micro spine grippers and gecko adhesives on the toes, as well as the claw and climbing abilities of the final design.

3.2 Benchmarking

An essential part of the design process involves benchmarking a design against others of the same category. The practice of benchmarking allows engineers to develop a datum point for the engineering requirements generated for their design. Often, benchmarking analysis is conducted with vendor specific information on products. Other times, benchmarking is conducted through reviews of a product. Benchmarking can also be conducted through meetings or interviews with employees to see how the design problem has been approached before. Research on various products is typically conducted during the benchmarking process, to gather as much information and develop a datum point for solving a design problem. In this section, the NAU NASA Psyche Robotic Explorer team highlights the benchmarking process for their design problem.

3.2.1 System Level Benchmarking

The description and purpose of this mission is similar in nature to NASA's previous exploration missions. Information was gathered on these previous exploration robot missions, approaches toward solving a design problem. The design problem in question is like the design problem for this project, in which NASA was tasked with designing an exploration robot capable of traversing the hypothesized surface of its destination. Inspiration was taken from NASA's many Mars exploration missions, designs utilized by NASA on these missions were studied for this benchmark analysis.

3.2.2 Existing Design #1: Drive Systems

Articulated robots are a special class of robots identified for their ability to operate with a wide range of motions. These articulated robots have highly sophisticated mobility systems, placing them in this class and allowing them to easily maneuver a wide range of motions. Some of the most recent applications for these types of robots are planetary explorations, rescue operations, mine detection, agriculture, military missions, inspection and cleanup operations of hazardous waste storage sites, remote ordinance neutralization, search and recovery, security, and firefighting to name a few [1].

The specific application of articulated suspension systems for rovers has pushed space exploration forward in the past 20 years. Since 2004 with the landing of the Spirit Rover on Mars, NASA has used rovers with articulated suspension systems to conduct planetary exploration [2]. To this day, rovers with articulated suspension systems remain one of the best methods for planetary exploration as they allow scientists to observe the direct surface of planets and other space formations.

3.2.2.1 Existing Design #1: Rocker Bogie Suspension System

Over the years, NASA has designed and launched many planetary rovers. Notable mentions include the Mars Curiosity rover, as well as the Pathfinder rovers. One common element of these rovers is the rocker-bogie suspension system. NASA decided to implement the rocker-bogie suspension system when the Mars Exploration Program was first created. This decision was due to the lineage and trusted results from the suspension system.

The rocker-bogie suspension system consists of two variable arms located on the side of the rover's main body. The larger, main arm is attached at the rover's center of mass and is connected via a pin. The smaller arm is connected via a pin to the larger arm. Each system of arms has three wheels, totaling six wheels for the whole rover. The pin system allows the arms to rock and pivot based on uneven terrain, Figure 6Error! Reference source not found.**.** The ability for the arms to rock and pivot prevents the entire body of the rover from angling when traversing elevated terrain.

Figure 6. Rocker Bogie Suspension System

3.2.2.1.1 Swing Arms

The arms implemented in the rocker bogie suspension are strategically placed along the rover. The main pivot point is generally located at the center of mass of the rover, to prevent any tipping. The material of the arms is also important to consider for the design. In the case of the Psyche rover, the arms would likely be comprised of a low strength, lightweight metal such as aluminum. The acceleration due to gravity on the Psyche asteroid is much lower than the gravity on Earth, therefore the arms likely would not be placed under severe loading. The double arm system allows the front wheel to roll over objects before the middle wheel, all while keeping the body of the rover parallel to the ground. The middle wheel then rolls over the object independent upon the back wheel. The back wheel then rolls over the object without lifting the back end of the rover. The body of the rover remains parallel to the ground at all points of travel over the object.

3.2.2.2 Existing Design #2: Gecko Foot Travel System

Currently, NASA is researching Gecko gripper technology for robots designed to clean the outside of spacecraft. The technology works via millions of tiny hair-like appendages that protrude from the surface of the gripper. The hairs are near microscopic and stand straight up, however, they fold down when a shear force is applied to them. When folded down, Van der Waals forces allow them to stick to the surface of nearly any material. The implementation of Gecko grippers could allow the Psyche rover to grip potentially slick, slippery surfaces with ease. For this reason, implementing the Gecko gripper would enhance the rover's traversing capabilities.

3.2.2.2.1 Van der Waals Forces

The Gecko gripper relies on Van der Waals forces to stick to objects. Van der Waals forces are created when intermolecular forces are generated between particles. In the case of the Gecko gripper, the forces that are generated stem from fluctuations in charge distributions between neighboring molecules [3]. The charge fluctuations naturally fall into synch, creating an attractive force between the surface molecules and the hair molecules of the Gecko gripper.

Experiments were conducted to determine what causes the attractive force between a gecko's foot and surfaces. In the experiment, geckos were placed on a surface made of silicon dioxide, which is polar. Geckos were also placed on a surface made of gallium arsenide, which is not polar. The geckos were able to stick to both surfaces, proving that Van der Waals forces were the cause of attraction [3].

3.2.2.2.2 Tiny Hairs

The gecko foot operates via millions of microscopic hairs. Typically, these hairs stand straight up, however, as the gecko begins climbing a surface, a shear force is applied. Once applied, this shear force causes the hairs to fold down. At this point, the Van der Waals forces between the hair molecules and surface molecules take effect. The hairs are so small that when standing, the Van der Waals forces are tiny. When folded down, however, these forces become exponentially larger.

The number of hairs on a gecko foot is important for sticking to slippery surfaces. The sheer number of hairs on the gecko foot allows for large Van der Waals forces to occur, allowing them to climb nearly any surface. In the case of this project, the hairs would be synthetically manufactured with the gripper. The manufactured hairs would function similarly to the real, microscopic hairs on a gecko's foot.

3.2.2.3 Existing Design #3: Tracks

Tracks have been used for many years to help vehicles perform over rough terrain. The treads used for tanks or other rough terrain vehicles are designed to conform to the surface being driven on. An elastic material is used for the treads to allow the tracks to deform to the shape of the surface. Other treads use links of metal to allow slip between one another. The tracks work like a conveyor belt. The engine rotates the steel sprockets which move the track. The wheels between the treads rotate with the moving track. The tracks have better traction than wheels due to the larger amount of surface area interacting with the ground. Due to the large surface area contact, the weight of the vehicle is distributed more than tires. Using tracks still allows the vehicle or rover to travel at descent speeds. Rovers usually operate at slow speeds so tracks are still viable. Downsides of tracks include the power needed and the issue with soft surfaces. For tracks to work, a large engine is needed which may be an issue with the weight and size of the rover. Engines can be very heavy which can make launching the rover into space an issue. The tracks are known to get stuck in soft materials such as sand or gravel. This can be problematic since there would be no way of getting the rover unstuck.

3.2.3 Navigation Systems – Benchmarking

Navigation systems for space rovers have developed tremendously in the last 16 years after the landing of the Spirit Rover on Mars [2]. Navigation systems play a critical role in determining the effectiveness of a rover's ability to traverse a surface of the space body in question. The incorporation of an automated navigation system allows the rover to capture and analyze its environment without human interaction. This phenomenon is critical to the success of this specific mission due to the sheer distance between Psyche 16 and Earth. The navigation system on-board the NAU Psyche Rover will likely be automated for this reason.

NASA has implemented various navigation systems into their planetary rovers over the past 20 plus years. The effectiveness of specific navigation systems depends on the environment with which the rover will interact. In the case of Psyche 16, the hypothesized surfaces include flat metallic surfaces with metal and/or rocky debris. Determining the optimal navigation system based on the environment of the asteroid is likely to influence the success of the mission.

3.2.3.1 Subsystem #1: GESTALT

Mars rovers such as the Spirit, Curiosity, and Opportunity rovers have relied on an onboard path planner known as GESTALT [4]. This onboard path planner is considered conservative when it comes to rough, debris ridden terrain. GESTALT falls short in its ability to determine a suitable path through a terrain that has 10% cumulative fraction of area covered with rocks. In the case of the Psyche asteroid, it is unlikely that there will be rocky debris in the path of the rover. It is likely, however, that there will be plenty of metallic debris in the rover's path. For this reason, the State-of-the-art (SOTA) GESTALT path planner will likely not be a viable option for the design of NAU Psyche Team's rover. A potential solution for this likely phenomenon is to provide an alternative onboard path planner that is slightly less conservative than GESTALT.

3.2.3.1.1 Existing Design #1: Conservatism (Risk Assessment)

In the case of rovers, it is imperative to provide a level of conservatism toward on-board algorithms. This conservatism is likely to be a factor that will allow the rover to determine whether certain paths are safe to traverse. A golden rule of thumb for planetary rovers, is to provide enough conservatism producing false positives (a safe path is incorrectly determined to be an unsafe path). The goal is to eliminate false negatives (an unsafe path is incorrectly determined to be a safe path) [4]. False negatives can be the reason that rover missions are unsuccessful. It is essential to program onboard path planners with a certain level of conservatism because no individual can travel the vast distances to repair these rovers.

The incorporation of conservatism into the onboard path planner of the Psyche Rover is likely to improve its traversing capabilities. The rover will tend to avoid paths deemed unsafe and only travel along those that will not result in a potential catastrophe. The inclusion of a risk assessment into the onboard navigation system will ensure that the requirement "rover adaptability" is met. The risk assessment will allow the rover to adapt to its environment and determine the path most safe to traverse.

3.2.3.1.2 Existing Design #2: Raw Image Generator

The raw image generator captures a still photo of the rover's environment. This initial photo allows the rover to further analyze its surroundings. The captured photo applies Stereo Vision Software to capture nuances in the surrounding environment [5]. This photo is the first in a series that is analyzed to generate a highly detailed, accurate digital environment. This photo is a flat photo that generates the front, 2D view of the rover, Figure 7. The raw image generator provides a base for the rover's ability to adapt to its surroundings.

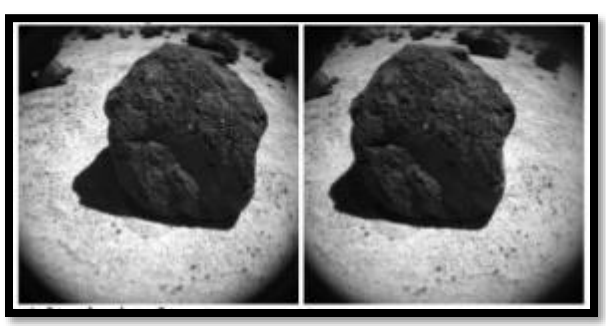

Figure 7. Raw Image Generation of rover's surroundings [5]

3.2.3.1.3 Existing Design #3: Rectified Image Generator

After a raw image of the rover's surroundings is captured, the GESTALT system generates a rectified image.

This rectified image is generated by determining the depth of each pixel of the raw image relative to the rover's position [5]. This process is completed via triangulation, determining a point in 3D space given its projections onto at least two images. In simple terms, the image is shifted and placed above the original image, producing epi-polar lines between the two images, these lines are analyzed to determine the depth of various objects within the images.

The result of the rectified image generator is a 3D view of the rover's surroundings, Figure 8. The field of vision is subject to change depending on the camera implemented within the GESTALT system. In the case of the NAU Psyche Rover, the GESTALT system would likely require an image capturing device (camera) with a wide field of vision. This wide field of vision would allow the rover to capture images of large metallic formations along the surface of the asteroid. A camera with a wide field of vision would also likely prevent the rover from potentially falling into small craters along the surface of the asteroid that would otherwise be impossible to "see".

Figure 8. Rectified Image Generation of rover's surroundings [5].

3.2.3.1.4 Existing Design #4: Laplacian Image Generator

The next step in image processing for the GESTALT system involves Laplacian Image Generation. In short, Laplacian Image Generation occurs when multiple instances of a photo are captured. In the case of the GESTALT system, these instances are rapidly being captured and rectified images are being generated. Favorable aspects from these rectified images are being implemented into a "final" image that highlights the fine details of the rover's surroundings. This step can almost be thought of as photo "sharpening" in which multiple instances of an image are being captured and analyzed to determine favorable aspects from each individual instance [6].

The result of the generated Laplacian Image is a more refined 3D interpretation of the rover's surroundings Figure 9. This step is crucial in determining the conditions of the rover's surroundings. Details such as "cracks on the ground" or relief steps along the rover's path are determined in this step of image processing. The Laplacian Image Generator provides a detailed, near-final representation of the rover's surroundings, potentially allowing the rover to adapt to surface conditions along its path of travel.

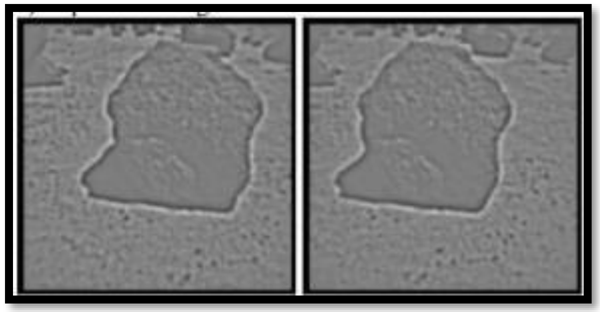

Figure 9. Laplacian Image Generation of rover's surroundings [5].

3.2.3.1.5 Existing Design #5: Elevation Map Generator

The final step in image processing for the GESTALT onboard navigation system involves generating an elevation map of the rover's surroundings. This process includes an elevation map assigned various colors depending on the elevation or "height" of a particular aspect within the image, Figure 10**.** This process determines the height of objects around the rover, allowing for the risk assessment to determine if an obstacle is too tall to traverse. Likewise, obstacles determined small enough to traverse are captured in this stage of image generation on the GESTALT system.

The result of the Elevation Map is a still of the 3D image represented by colors of the rainbow, ranging from red to violet. Spaces marked red within the image are represented to have a low elevation or "height" while spaces marked with violet are determined to have a high elevation. The colors between red and violet are based on a scale relative to the scale of the photo captured by the GESTALT system. This function allows the GESTALT system to analyze various fields of vision depending on the path to be traveled. This step of image generation provides a basis for the elevation of elements surrounding the rover, again improving its ability to adapt to the path of travel.

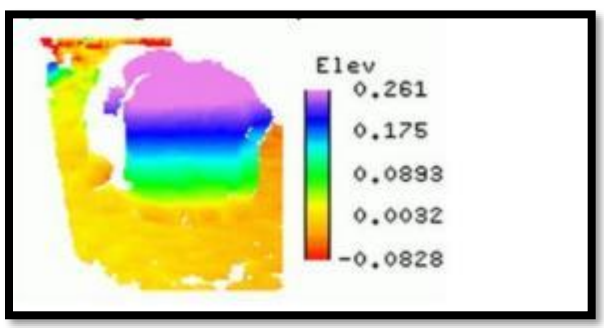

Figure 10. Elevation Map Generation of rover's surroundings [5].

3.2.3.2 Subsystem #2: Lidar

Lidar serves to aid in the rover's navigation of the asteroid. An input signal is sent to the mechanism, providing a detailed map of the rover's surroundings. The Lidar system receives a data signal and outputs data that is an input for the translational movement of the rover. This subsystem is a critical element to ensure the rover's traversing capabilities. Like the GESTALT system, Lidar can provide detailed information about the position of the rover, as well as its surroundings. In short, Lidar uses a laser sensor that is fired rapidly, returning data of surrounding objects. An inertial measurement unit is then used to map the surrounding area, Figure 11. One of the advantages to using Lidar over many other navigation subsystems is that Lidar is operational even while the rover is in motion.

The ability to map an area while in motion could prove to be beneficial for this project. Although the rover is not expected to exceed speeds of more than 0.25 miles per hour, having the ability to navigate and move simultaneously could improve the performance of the rover. Essentially, Lidar will allow the rover to travel a navigate a region faster than the GESTALT system since the rover can move while navigating. There is potentially one disadvantage of Lidar versus the GESTALT system, however. The GESTALT system provides a more detailed mapping of the rover's surroundings. For this reason, the team has chosen to implement both the Lidar and GESTALT systems of navigation into the design of the rover.

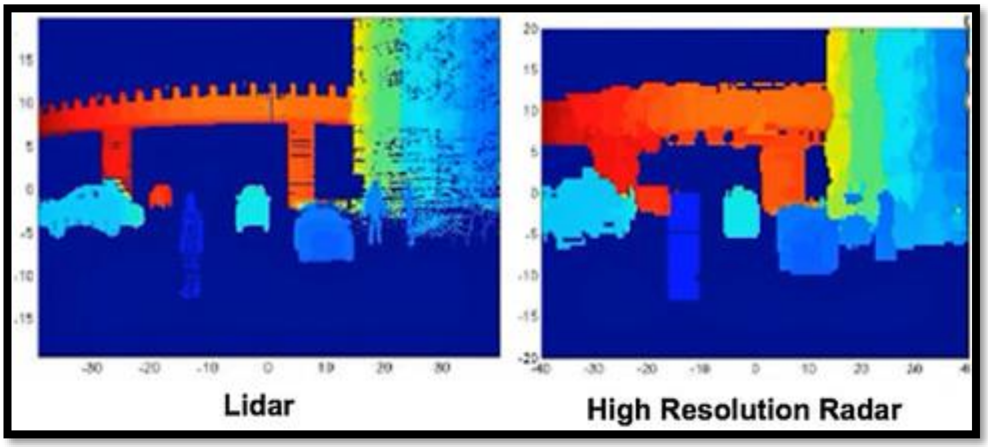

Figure 11. Comparison of High-Resolution Radar vs. Lidar Navigation [7].

3.2.3.2.1 Existing Design #1: Mobile Lidar

This specific type of Lidar utilizes a collection of Lidar points from a moving platform. This is the type of Lidar that was explained in the description of the system. Mobile Lidar could potentially allow the rover to navigate a large area in a shorter amount of time than nearly any other form of navigation. Most mobile Lidar systems incorporate several Lidar sensors placed on the vehicle in question [8]. Mobile Lidar systems typically consist of a Lidar sensor, cameras, GPS, and an internal navigation system.

The sheer number of components within the Lidar system is a definite concern of the team. To reduce the overall mass of the rover, the components must be sourced and only the ones with the smallest mass should be implemented into the rover. The Lidar system will likely be a backup source of navigation for the Psyche Rover, providing navigation in scenarios where time is of the essence.

3.2.3.2.2 Existing Design #2: Static Lidar

This form of Lidar is the same laser-based system, mounted on a tripod. Typical applications for static Lidar include surveying, mining, archaeology, etc. [8]. This system operates in a similar fashion as the mobile Lidar; however, it is more difficult to move around. In the case of this experiment, static Lidar is not a likely candidate for navigating the rover.

The incorporation of static Lidar would likely hinder the rover's ability to quickly adapt to its environment. This short coming could potentially pose a severe complication in which the rover is not able to complete the mission in the expected mission life.

3.2.3.3 Subsystem #3: GPS

GPS is a system of navigation that is typically implemented on Earth. There are, however, some limitations to GPS over the other forms of navigation mentioned above. The use of GPS requires an advanced satellite infrastructure [9]. For this reason, GPS is often not used for space exploration. Satellite infrastructure is not well developed in space as of 2020. For this project however, it is possible that the satellite infrastructure in space could be improved before the rover lands on the surface of the asteroid. The orbiter mission is not expected to arrive at the asteroid until 2026 and tests must be conducted before a potential rover is sent to explore the surface of the asteroid.

However hopeful, this time frame does not fit the likely window to improve satellite infrastructure in space. The amount of time necessary to launch satellites into deep orbits is sure to exceed the expected window of time before the potential rover mission. Despite this statistic, GPS was still considered for this project due to its variable capabilities on Earth. GPS may not inherently be implemented into the design of the rover; however, it is possible that some elements of GPS will be.

3.2.3.3.1 Existing Design #1: Satellite Infrastructure

Satellites orbit and capture images of Earth's features every day. These images can be used to identify key features on the Earth's surface. In 2018, NASA captured extraordinary images from the Earth's surface. The key images mentioned in [10] were Hurricane Florence, Australia's Lake Eyre Basin, Alaska's Chukchi Sea, Hawaii's Kilauea, and many more. These images would not have been possible without the advanced satellite infrastructure around Earth.

GPS relies on a system of 30 plus satellites that orbit the Earth. These satellites are constantly sending out signals. Devices that rely on GPS for navigation can receive these signals. Once four or more satellite signals are received by a device, it calculates the approximate location of said device [11]. This requires satellites that orbit a space body, constantly sending pinging signals.

Figure 12. NASA Satellites orbiting the Earth [11].

One potential solution for the lack of satellite infrastructure near the Psyche asteroid could be to use the orbiter as a sort of satellite. This option poses its own unique difficulties however, developing a means of advanced communication between the orbiter and satellites orbiting Earth could prove to be a difficult task. The surface conditions of the asteroid are still hypothesized so the implementation of satellite images will allow scientists to further understand the asteroid, how it was formed, etc. This is the essence of the NASA Psyche Orbiter mission.

3.2.3.4 Project Scope vs. Navigation Systems

For the scope of this project, it is highly unlikely that the team will fully design an onboard path planner with all the safeguards necessary to traverse the various terrains of the Psyche asteroid. There are, however, alternatives to ensure that the rover will be successful in its mission. Some alternatives for complex onboard navigation systems include but are not limited to sun tracking, GPS, etc.

3.2.4 Orbit and Surface Conditions

With the use of several ground-based observations, the Psyche asteroid has been classified as an M-Type asteroid. M-Type asteroids have partially known compositions that are typically made of nickel-iron metallic cores. The size of the Psyche asteroid is approximately 200 km across which defines it as one of the largest metal-rich asteroids in the main asteroid belt [12]. With research, the orbital parameters of the Psyche asteroid have been found with high accuracy along with the orbit period of Psyche around the sun. Based on this research it has been concluded that Psyche rotates uniformly around its principal moment of inertia axis [13]. The craters on Psyche's surface are still a mystery, but some computer simulations have been conducted to investigate what the craters on the surface might look like.

3.2.4.1 Orbit

With several adaptive optics (AO) images taken at the W.M. Keck and Gemini telescopes, derivations of the rotational pole of the asteroid were able to be made. These telescopes have been collecting data on the asteroid for a span of 14 years providing a range of viewing geometries. With these geometries a model that yields very small uncertainties in the triaxial ellipsoid dimensions as well as the rotational pole was generated [14]. With the rotational pole information found, it was concluded that the data was consistent with other measurements but with a smaller uncertainty.

With this research as well as research conducted with radar, it was found that Psyche orbits the sun between Mars and Jupiter at 235 to 309 million miles. Based on this, the psyche asteroid takes about five earth years to orbit the sun, but just a little bit over four hours to rotate once on its own axis [13].

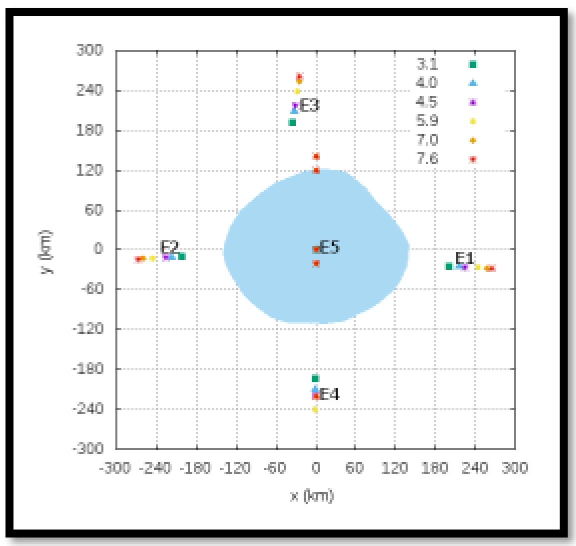

Figure 13. Location of asteroid equilibrium points [15].

The location of Psyche's equilibrium points has been found based on densities from 3.1 to 7.6 g/cm3. The locations of these equilibrium points can be seen in Figure 13 where each point is labeled based on the density it was found at. It was found that the points E1 and E2 are unstable, and that points E3, E4, and E5 remained stable while rotating [15].

Furthermore, based on the use of radar observations and light curve inversions, a shape model with the axis of rotation has been generated [16]. This can be seen in Figure 14 below.

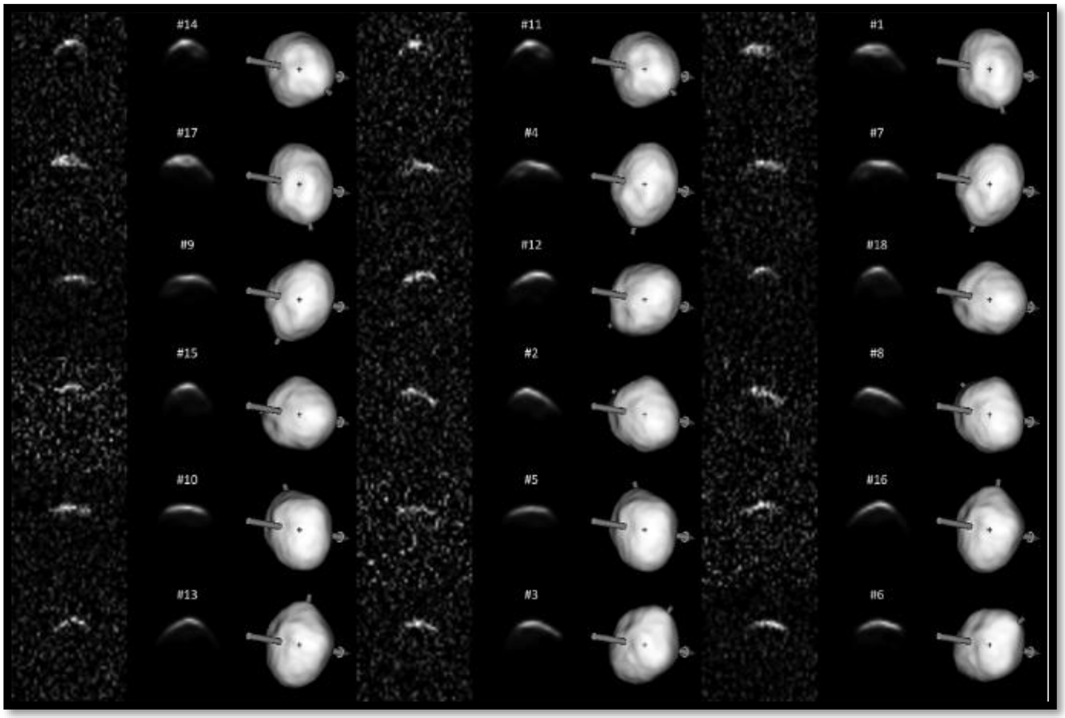

Figure 14. Shape Model of the Psyche Asteroid [16].

Within the figure above, the left images are of radar images of Psyche, the middle one is the simulated radar image using the shape model of Psyche, and the right one is the shape model with the inclusion of the rotational axis [16].

With more detailed data provided after the Psyche orbiter mission concludes, better information on how Psyche orbits and rotates will aid in the design and landing of the rover. This can help because with data on how the asteroid orbits, a plan of landing location and speed can be calculated to complete a safe landing.

3.2.4.2 Surface conditions

The Psyche asteroid is by far one of the most intriguing main-belt asteroids. To confirm that Psyche is an M-type asteroid several studies and measurements have been taken. First, several spectroscopic measurements have showed consistency with iron-nickel meteorites that have been observed [17]. However, these same measurements have discovered that there is a fine-grained silicate regolith that overlays the hypothesized metallic bedrock of the asteroid. Another study that can support the M-type asteroid statement is the radar observations of the asteroid. From these radar observations, the high mean bulk density of the asteroid was found to be between 3.8 and 4.6g/cm3 [14]. This density of the asteroid is larger than the densities of Siliceous (S) or Chondritic (C) type asteroids which proves that it is an M-type, but the it is also smaller than the density of iron meteorites which proves that it is not 100% iron meteorite. In addition, the radar albedos are three times larger than the S and C type asteroids which classifies it as an M-type. These studies have also shown that silicates and hydrated silicates are present on the surface of the asteroid.

With the presence of silicates on the asteroid several hypotheses have been made as to how they got their as well as how the asteroid formed. One hypothesis is that Psyche is the result of several series of collisions which stripped away the silicate mantle, whilst leaving a little bit of the silicates still on the surface [18]. Another hypothesis is that the asteroid could have been shattered by impacts leaving behind rubble piles of mantle and core material [19]. However, with this hypothesis there are no asteroid families associated with the missing mantle of the asteroid, so this hypothesis is not completely accurate. The asteroid also could have formed near the sun [20]. With this hypothesis, the surface of the asteroid could be composed of a highly reduced material that did not melt. The last hypothesis is that the asteroid formed as a result of Ferro volcanism which is the process of exhumed metal rich material coming up to the surface [21]. Each of these hypothesis as to how silicates ended up on the surface as well as to how the asteroid was formed are the basis of the research onto the surface conditions of the asteroid.

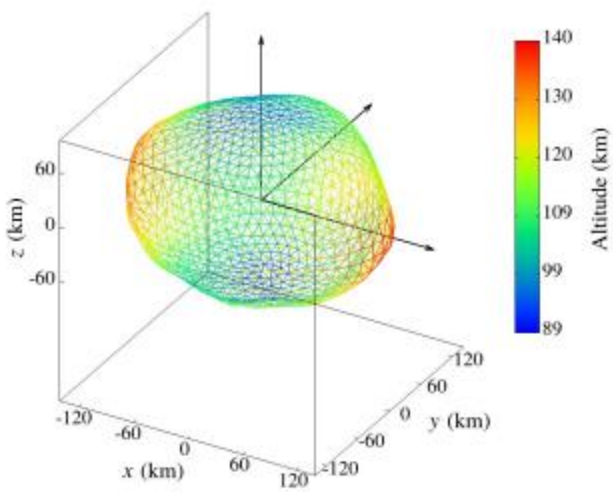

Figure 15. Three-dimensional view of the polyhedron shape model of 16 Psyche [15].

Further research into the surface of the Psyche asteroid has produced a few different shape models which have revealed a few quasi-circular depressions on both the southern and northern hemispheres. On the southern hemisphere of the asteroid two craters were discovered. One being wide and shallow and the other being deep and narrow [18].

Based on the shape models of Psyche, iSALE simulations were conducted to try and simulate how the craters on the surface of the asteroid were made. These simulations were of vertical impacts of 10 to 100 m

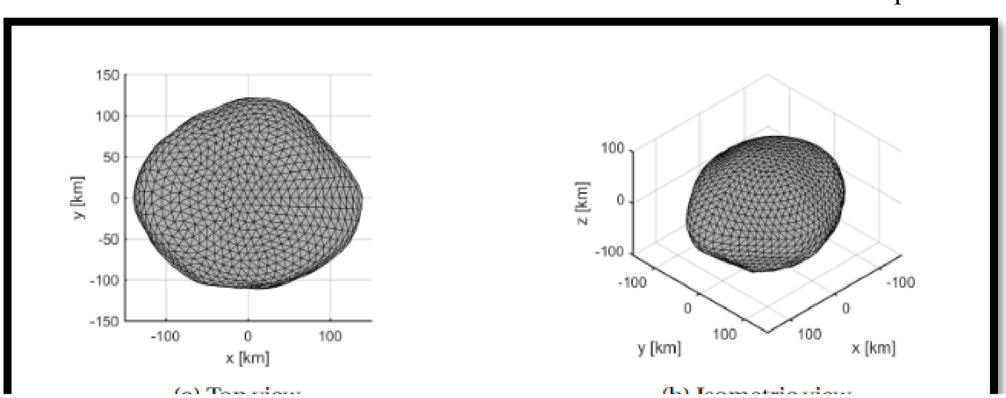

Figure 16. Shape Model of the 16 Psyche Asteroid [16].

radius dunite spheres impacting the surface at about 5 km/hr. into an iron and rocky layer of various depths [22]. The crater density profiles from these simulations can be seen in Figure 17. The crater density profiles for impacts into a various depth iron layer covering a dunite mantle can be seen in the left of Figure 17. The crater density profiles for the impacts into various ranges of dunite layer over an iron layer with a dunite mantle can be seen in the right of Figure 17.

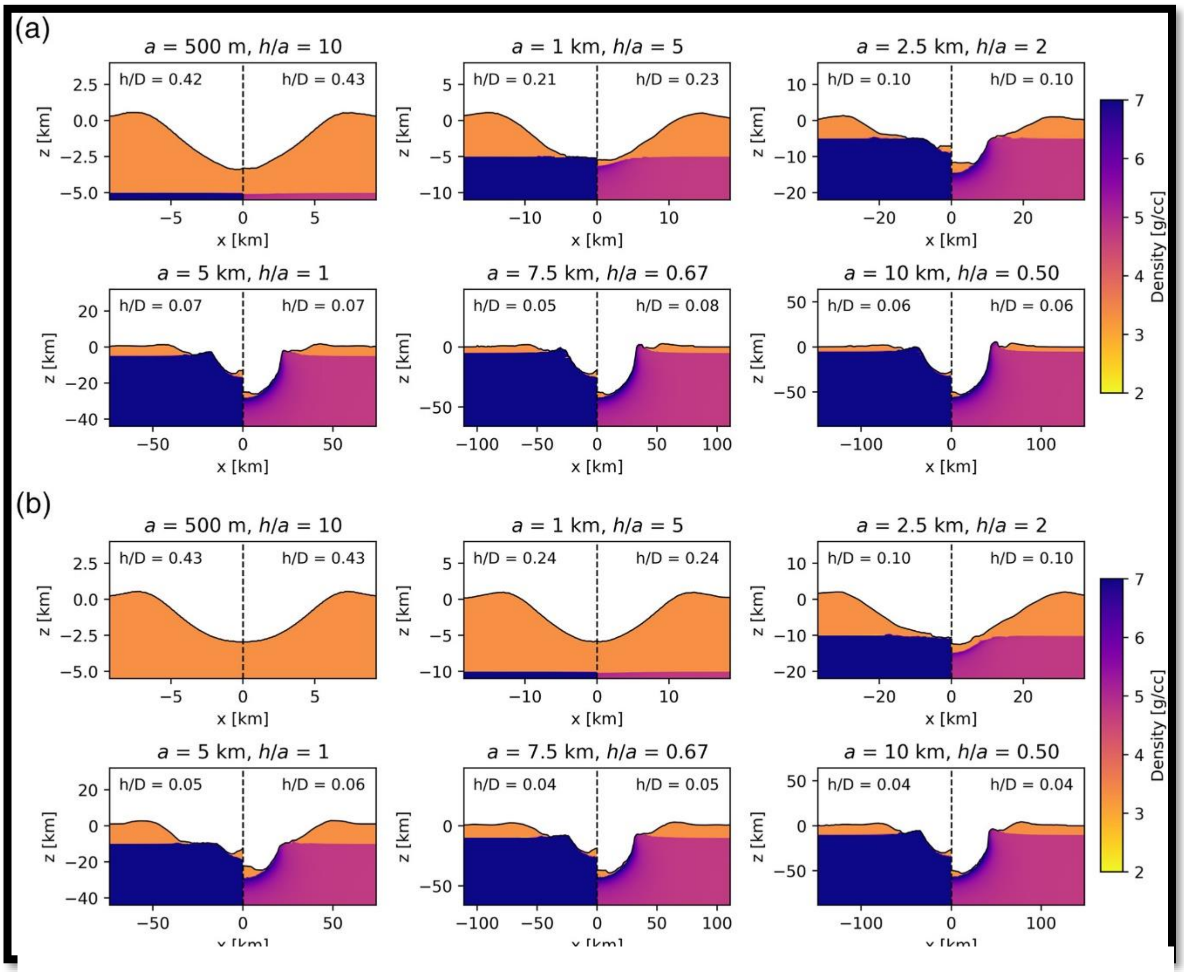

Figure 17. Crater profiles on the surface of Psyche [22].

The figure above shows the crater profiles for various impacts of projectile radii of 0.5 to 10 km into a dunite mantle either covering a solid or porous iron substrate. For each of the testing scenarios displayed, the ratio of upper layer thickness to crater diameter (h/d) aids in determining which specific sized craters align with a material morphology. For example, if the ratio of upper layer thickness to crater diameter is less than 0.2, then a wide crater in the dunite mantle with a small shallow crater in the core will be formed as a result of the dissipation of kinetic energy in the dunite mantle [22]. One major thing to note is that these experimental simulations were conducted with an impact straight on to the surface of the asteroid where actual impacts would likely occur around a 45-degree impact angle [23]. With this change in impact angle the craters geometry would likely change from circular to ellipsoidal.

With further studies of the surface conditions of the Psyche asteroid, better data will be available on the differing surfaces and craters. This data will be available after the Psyche orbiter mission occurs in 2026. This orbiter mission will provide estimates of the age of the surface of the asteroid as well as structural and compositional properties that will aid in the design of a future rover.

3.2.5 Redundancy of Movement

Past wheeled rovers have had issues with damage to legs or wheels on stone and regolith planets such as Mars. For example, the Spirit Rover landed with six wheels and soon lost movement in its right front wheel causing the rover to have to drive in reverse. The Psyche Rover is being designed with redundancy of movement systems in mind as it will be used on a metal asteroid. If a damaged limb can be positioned out of the way by returning to its default position against the body by a mechanical system, then the other movement systems could be used to proceed. The types of movement systems discussed were rolling on wheels, walking on wheels or the sides of wheels, and a body that was able to inchworm as well as climb.

Most of the systems of movement would come from the design of the limbs. Designing the closest joint to the wheel axle to be able to turn the wheel 90°, the wheel then becomes a foot. Incorporating either NASA's micro spine or gecko gripper system in that foot would allow for climbing. With use of a hip joint attaching the leg to the body will allow for walking of that leg which would allow to climb in large debris or boulders.

Having the front half of the body able to extend forward from the mid-section joint as well as the back half of the body being able to do the same will allow for the whole rover to inchworm forward. This will also assist in climbing. Having the body segments able to bend at least 75° from the horizontal axis would allow the front half of the rover to walk/climb a vertical cliff face. Once angled it would extend the front body up the wall. It would then anchor to the wall, using either the gecko foot, micro spine gripper system or reusable concrete anchors and retract the mid and back segments up. The lower segments could then secure allowing the front to proceed up the wall.

Other issues with past rovers include communication issues. Pathfinder's Sojourner Rover communicated with Earth via its lander. When the lander stopped communicating after a few months on Mars we could no longer communicate with the rover. In the case of Spirit after getting stuck in soft sand it continued to work until communications stopped. Aside from redundant movement systems we could consider redundant communications systems with both the rover and the lander having a communications system designed to communicate with the vehicle that delivers the rover to the planet. That way the system can always communicate back to earth. The rover itself could have software designed to map out the path and return the rover to its lander in case of communication blackout. Separate communications system between lander and rover might allow NASA to regain communication.

3.2.6 Total Available Solar Power

Although we have not yet determined our rover's power source, solar arrays could be a critical aspect of our design, even if they are only used in a supplemental fashion. One of the most important calculations when designing arrays is determining their energy output. This individual analysis will calculate the total amount of energy that Psyche receives from the sun. Psyche is on average 3 AU from the sun [24]. An AU, which stands for astronomical unit, is approximately 1.49E8 km [24]. The total amount of energy from the sun to earth was calculated by NASA using the inverse square law, which is 1/d^2, with d standing for the distance away from the sun. Using the distance 3 AU and the inverse square law Psyche will receive about 11.1% of the solar energy that the earth receives from the sun. NASA calculated that the earth receives 13608.8 w/m^2 of solar energy, which means that Psyche will receive approximately 151.2 w/m^2 [42]. In other words, 151.2 w/m^2 is the total amount of energy that can be harnessed from the sun on psyche. This individual analysis will determine how much of this energy could be harnessed by the rover, which will depend on several factors including the array's efficiency.

4 CONCEPT GENERATION

4.1 *Full System Concepts*

This section will be going over the three concepts that received the highest rating. Some specifics will be discussed in detail. The important pros and cons of the rover will also be listed to give an idea of their effectiveness and drawbacks. The top three full system designs discussed within this section were ranked against each other through a decision matrix. The decision matrix used by the NAU Psyche Robotic Explorer Team can be seen in Appendix A. It is important to note that concept variants were generated based on the subsystem concepts mentioned in this section. These concept variants can be seen in Appendix B. The concept variants generated by the team were ranked against each other through a Pugh Matrix, Appendix C, the top three ranked variants are highlighted in the sections below.

4.1.1 Full System Design #1: Frog Baby Rover

The Frog Baby rover is an interesting and compact concept, Figure 18. The rover is provided with six legs with three on each side. The feet of the rover will incorporate the claw system to attach to the surface. The claws will be able to grip and dig into the surface material. The legs will be able to roll into the body to allow the rover to roll around the surface of the asteroid. The Frog Baby will be equipped with cameras on the front and back of the rover body. This could allow for the rover to travel in either direction. The pros of this rover include great maneuverability over the required surfaces and the ability to flip itself over easily. The cons of the rover include the complexity of the leg movement and how they would be controlled by person or artificial intelligence. The rolling mechanic may also cause damage to the rover and create difficulty for the attachment to the surfaces.

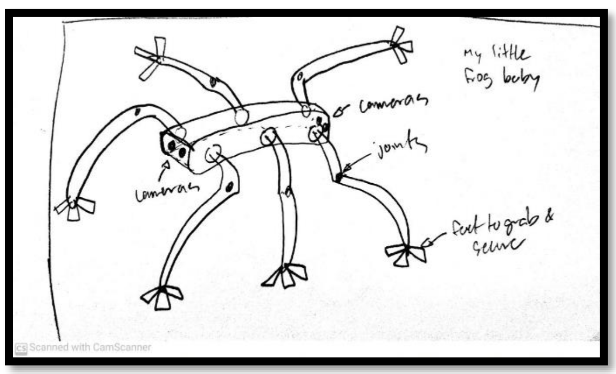

Figure 18. Frog Baby concept design, John Dynda.

4.1.2 Full System Design #2: Spider Gecko Rover

The Spider Gecko rover is unique design that uses a legged system to get around, Figure 19. There will be eight legs, each equipped with a gecko foot. The gecko foot allows for the attachment to the surface of the asteroid. This will allow the rover to climb in the low gravity conditions. The rover will also be equipped with both solar and MMRTG power sources. The sketch below shows a rough idea of what the rover could look like. The pros of this rover include the ability to adapt to each hypothesized surface with the leg and feet system. The rover will also have exceptional power generation. There are also some cons to this rover. The solar panel placement would make it difficult for direct sunlight to hit the rover. The legs also make the rover maneuverability much more complex than a simple wheeled system.

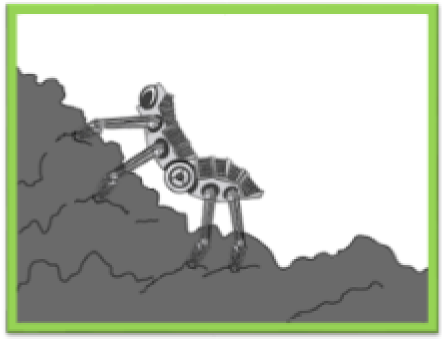

Figure 19. Spider-Gecko concept design, Kate Collette.

4.1.3 Full System Design #3: Tracked Rover

The Tracked Rover uses tracks like a tank to move around the asteroid, Figure 20. The tracks will have hooked treads to be able to dig into the surface to allow the rover to attach to the surface. The rover will incorporate a combination of both solar and nuclear power. The shape of the rover allows for optimal solar power generation and has enough space for the required equipment. The tracks allow the rover to traverse almost any surface. The rover has issues with climbing since it does not attach to the surface efficiently. The track system also would require a large amount of power.

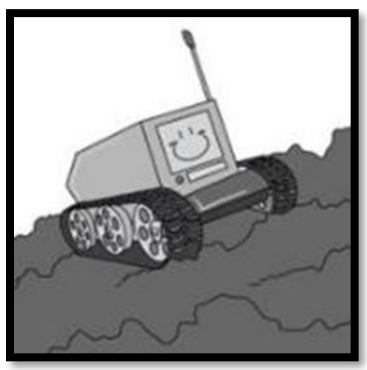

Figure 20. Track rover concept design, Kate Collette.

4.2 Subsystem Concepts

This section will be discussing the different concepts that were thought out and created for three critical subsystems required for the rover. These three subsystems include the power source, navigation, and attachment to the asteroids surface. Each concept will be discussed in detail and will have figures to help visualize the design.

4.2.1 Subsystem #1: Power Source

4.2.1.1 Design #1: Solar Power Source

Many rovers in past missions have used solar panels to power the rovers. Solar power is a useful and semi-consistent power source. Installing solar panels on the top of the rover will allow the batteries to be charged over time. Solar is much cheaper than other alternatives such as nuclear power. A problem with solar panels for this rover is the distance from the Sun. The asteroid is in the asteroid belt which is further than any other rover mission. Solar power may not be as effective at such a distance. Solar panels can also be covered by dust and debris to lessen the output power. When the rover is on the dark side of the asteroid, no power will be generated.

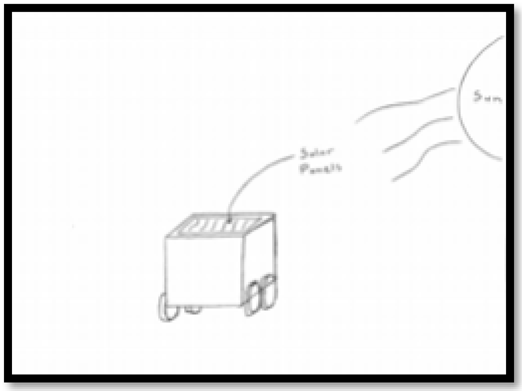

Figure 21. Solar power source, Isaac Anderson.

4.2.1.2 Design #2: Nuclear Power Source

Nuclear power is an excellent and very effective solution. The nuclear battery can output a large amount of power at any time, even when the rover is not facing the Sun. The nuclear battery that would be used is the MMRTG or the multi-mission radioisotope thermoelectric generator. This power source is consistent source of power. The issues with this method are the size and price. The generator is quite large and would require a great amount of space in the rover. The price is also an issue since the nuclear battery is over 100 million.

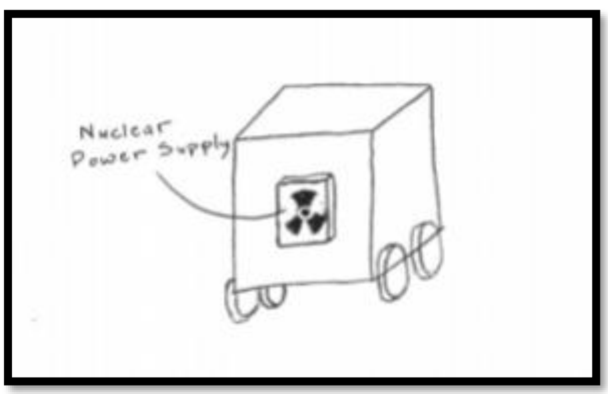

Figure 22. Nuclear power source, Isaac Anderson.

4.2.1.3 Design #3: Nuclear and Solar Power Source

Another power generation solution that was discussed was to combine both solar and nuclear. This would guarantee that the rover has sufficient power to operate as often as possible. This could allow for the mission life to be greatly extended. If one system fails, the other can take its place and generate all the needed power. The issue with this idea is the price. The MMRTG system and the solar panels will be needed and purchased.

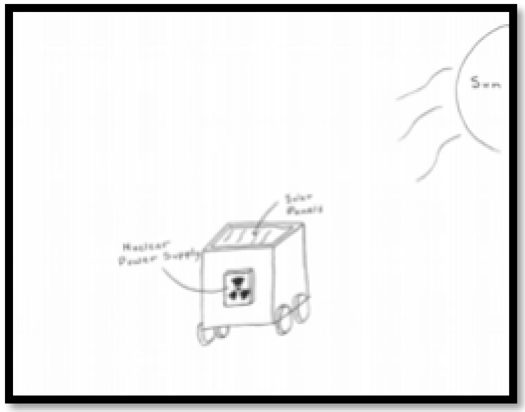

Figure 23. Combination solar and nuclear power source, Isaac Anderson.

4.2.1.4 Design #3: Catapult (Mechanical Energy Generation)

The catapult power method uses kinetic energy to move around the asteroid, Figure 24. The catapult would throw an object in one direction and would roll in the other. This method would likely be the least expensive but would have the most cons. The mechanism would take up most of the rover and would be difficult to control. An outside power source would be needed to set the device. The system is also very unreliable.

Figure 24. Catapult concept design, John Dynda (Dr. Trevas Idea).

4.2.2 Subsystem #2: Navigation

4.2.2.1 Design #1: GPS

A GPS system would help the rover traverse the asteroid using artificial intelligence or help an operator find the best route to take. This would likely be the simplest tool for navigation. The rover could easily be programmed to travel on its own. The issue with this system is that the rover could easily get itself stuck by driving into a crater. This would also require a map of the asteroids surface from a satellite or probe.

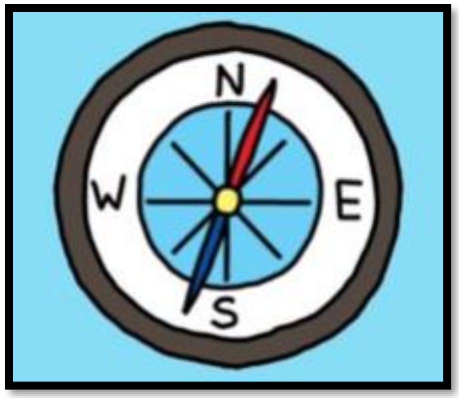

Figure 25. GPS navigation, Jacob Sasse.

4.2.2.2 Design #2: Sun Tracking

Solar tracking would use the position of the sun to determine where the rover is on the asteroid. This system can improve the solar panel power system by allowing the panels to be facing the sun for maximum power generation. This system is unreliable and requires a much greater understanding of the day and month cycle of the asteroid. The rover would not be able to be programmed to travel independently.

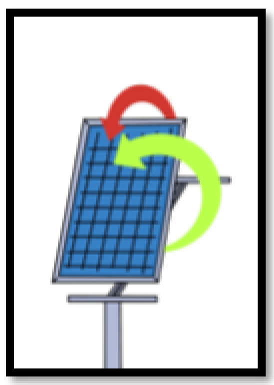

Figure 26. Solar tracking navigation, Kate Collette.

4.2.2.3 Design #3: Lidar

A lidar system works by gathering information about surrounding objects. The system scans the surroundings and generates a simple image of the obstacles. This is done using a pulsed light is collected by a range measurement sensor. This would allow the rover to be programmed to traverse the asteroid independently. This artificial intelligence would be advanced enough to avoid obstacles and stay away from places it can potentially get stuck. The device must be mounted on a spinning platform which would draw power from the rover. The device may be easily broken or disabled due to the spinning platform.

4.2.2.4 Design #4: GESTALT

Gestalt works by cycling through a routine that determines the next best direction to go. The rover is given waypoints to determine where to travel. The rover gathers data based on its surroundings using cameras to find the best route. This software would allow the rover to operate completely independent. This is the most advanced method for the rover to travel alone. The issue with the system is that it has only been used with wheeled rovers. The system may not work as smoothly with a legged rover.

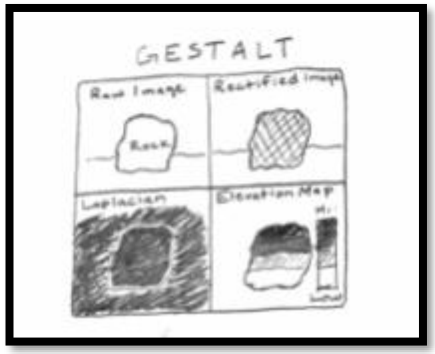

Figure 27. GESTALT navigation, Isaac Anderson.

4.2.3 Subsystem #3: Attachment to Asteroid Surface

4.2.3.1 Design #1: Magnets

Due to the asteroids metallic surface, an idea to use magnets to connect to the surface was created, Figure 28. The magnet would allow the rover to climb and travel very easily. The issue with this concept is that the magnets would need to be turned on and off frequently and use a decent amount of power. The magnets may not work on every surface on the asteroid. If there is a collection of dust or the surface is made of a nonmetallic metal, the foot would not work.

Figure 28. Magnetic attachment, Kate Collette.

4.2.3.2 Design #2: Claws

A claw could be used to either grab the surface or dig into the material to attach to the surface, Figure 29. The claws could allow the rover to climb and possibly gather samples from the asteroid if needed. The claws would require a large amount of power and may not work on specific surfaces. The claws may not be powerful enough to dig into certain metals found on the asteroid.

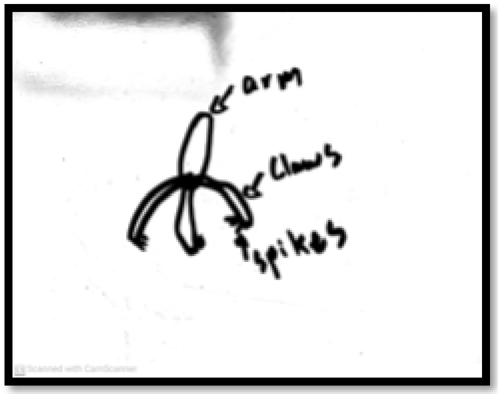

Figure 29. Claw attachment, John Dynda.

4.2.3.3 Design #3: Anchors

Another concept for surface attachment is an anchor, Figure 30. The anchor is shaped like a grapple that can be used to dig or wedge itself to an object. The system could be used to climb but would not be useful in many situations. The anchor would require something to launch the device and bring it back in. This would require a large amount of power. It is also easy for the anchor to be stuck and need to be separated from the rover for it to move.

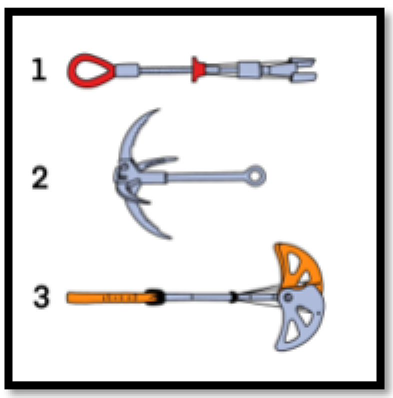

Figure 30. Anchor attachment, Kate Collette.

4.2.3.4 Design #3: Thrusters

Thrusters could be used to attach to the asteroid surface. If the rover were to drift away it could use these thrusters to land safely on the surface. This concept would require a fuel source for the thrusters to work. Since the fuel source is limited, the thrusters would only be used a certain number of times. Each thruster required would also need power and space to be installed on the rover.

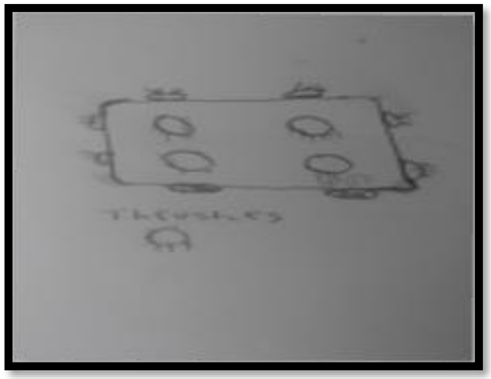

Figure 31. Thruster attachment, Chad Schafer [25].

4.2.4 Subsystem #4: Drive System

4.2.4.1 Design #1: Legged Rover (Gecko Foot)

The gecko foot is a bio-inspired concept that will use the “sticky” toes of a gecko. This device is being researched by NASA to allow for improved spacewalks. By incorporating this device on the legs of the rover, the rover should be able to traverse most if not all hypothesized surfaces of the asteroid. The issue with a leg rover is that they are much more complicated than wheels. Programming how the legs walk on an uneven surface and creating the artificial intelligence for the rover could become very complicated.

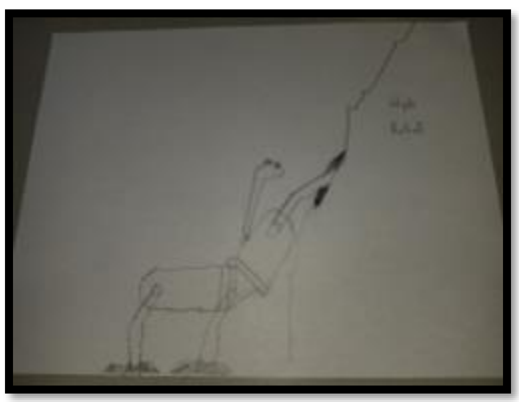

Figure 32. Legged rover, Sean Sullivan.

4.2.4.2 Design #2: Spiky Wheel

Spiked wheels can help grip the surface and reduce possible slipping on the surface, Figure 33. Due to the low gravity of the asteroid, the traction may be an issue. With the spiked wheels, the rover could traverse the slippery metallic surface. The cons for this concept are durability and the spikes getting stuck. The spikes may be wedged into a crevasse that would cause the rover to become immobile. The spikes could be worn down quickly and become irrelevant over time. The spikes may not help the rover's traction over certain surfaces without rocks or debris that help the wheel from slipping.

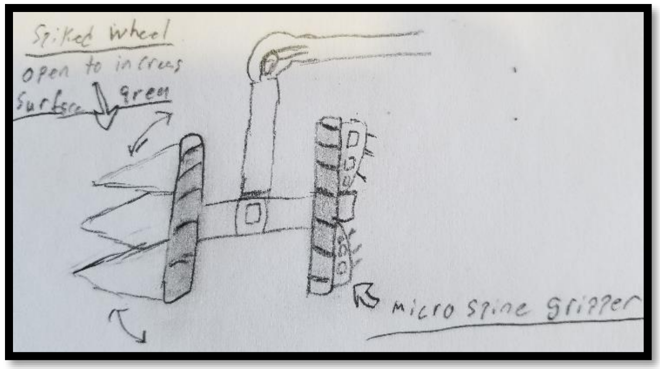

Figure 33. Spiky Wheel, Sean Sullivan.

4.2.4.3 Design #3: Rocker-Bogie Suspension

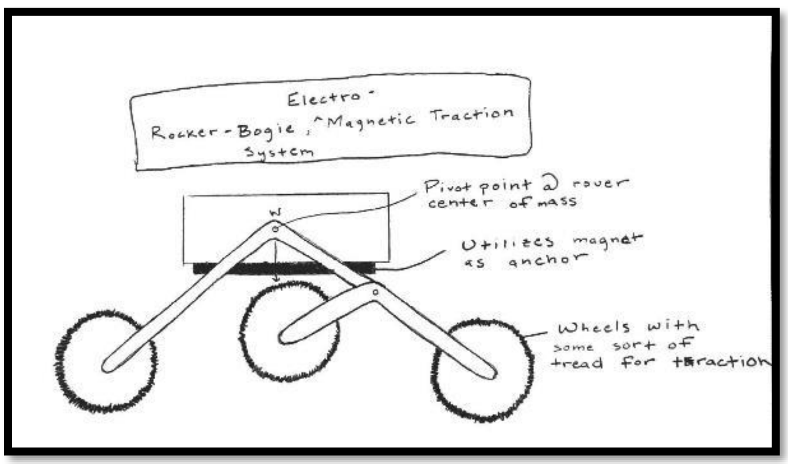

Figure 34. Rocker-Bogie suspension, Isaac Anderson.

This concept variant utilizes the rocker-bogie suspension system, Figure 34. This design is popular among NASA Mars rovers. There may potentially be high relief segments of the Psyche asteroid, placing this concept variant at a disadvantage to potentially flipping over and getting stuck. Despite being an optimal choice for Mars rovers, the difference in surface conditions would likely cause problems for a rover with this form of drive system.

4.2.4.4 Design #4: Tank Tracks

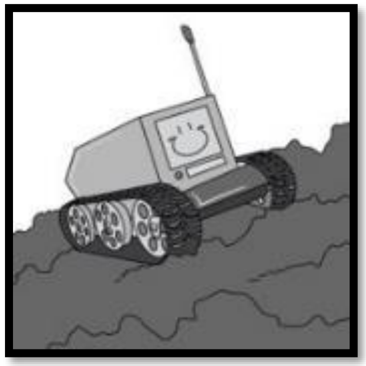

Figure 35. Tank tracks, Kate Collette.

This variant utilizes tank tracks, Figure 35, allowing movement of the rover. This variant is at a disadvantage due to the low traction between the metallic tracks and metallic surface of the Psyche asteroid. For this project, the tank tracks would not produce enough friction with the surface of the asteroid to prevent slipping in high relief areas.

4.2.4.5 Design #5: Screw Drive

This concept variant relies on a style of screw drive, allowing for motion of the rover. The Psyche asteroid is hypothesized to be metallic in nature, putting this concept variant at a disadvantage to other variants of this subsystem. The screw drive would likely work well on sandy or other soft surfaces. The screws would drive under the surface, providing traction for the rover to move without slipping.

4.2.4.6 Design #6: Magnetic Tank Tracks

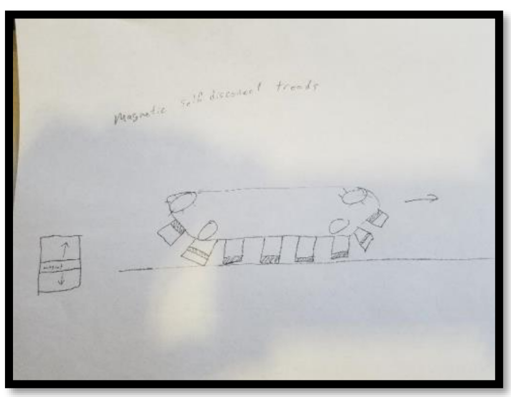

Figure 36. Magnetic tank tracks, Sean Sullivan.

This concept variant is like the other tank tracked variant. This form of drive system relies on the magnetic field of the Psyche asteroid being strong enough to support traversal of the rover, Figure 36. This metric has not been specifically stated; therefore, this design is at a disadvantage to other concept variants in this subsystem. Like the normal tank track concept variant, the required torque for this design is much too small to disperse among the multitude of gears that would operate the tracks.

4.2.4.7 Design #7: Spherical Gyrover

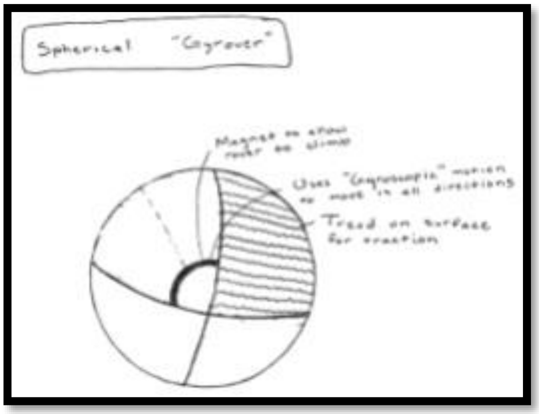

Figure 37. Spherical Gyrover, Isaac Anderson.

This specific design utilizes gyro technology connected to a magnet that can be pointed in any direction, moving the rover, Figure 37. This design relies on the magnetic field of the Psyche asteroid, whose strength has not been specified. For this reason, this concept variant is not a likely candidate for the final design. This form of drive system could prove beneficial in situations where a legged or wheeled rover could potentially flip over. The spherical design of this rover would likely prevent it from flipping over and getting stuck.

4.2.4.8 Design #8: Frog Baby Legs

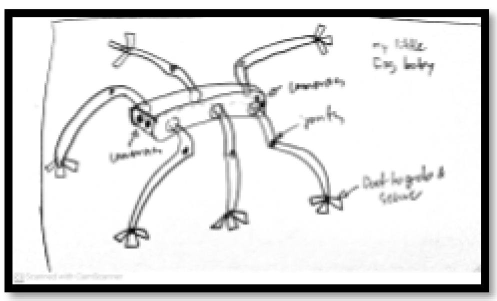

Figure 38. Frog baby legs, John Dynda.

This design utilizes metal legs to move, Figure 38. The feet resemble frog feet and are comprised of metal. This concept variant has an advantage that others do not, the legs can fold up, allowing the rover to roll. This form of traversal would prevent the rover from flipping over and getting stuck. Some potential drawbacks of this concept variant are the rover getting stuck upside down after rolling. The rover could also slip along the surface of the asteroid because of the metal feet.

5 DESIGN SELECTED – First Semester

5.1 Design Description

For this mission the team is 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.

After discussing mobility, the team decided to remove two legs, for a total of six, since it was determined that the robotic explorer would function equally well with six legs, and this would reduce the overall weight, cost, and build time of the design. At the start of spring semester, the team began the prototyping process by modeling a scaled down version of our final design from fall semester, using wood (see Figures 39-41). From this design we learned that a six-legged design was appropriate, and the scissor lifts worked exactly as planned to extend and contract the body segments. This design also allowed us to visualize where the most work would need to be done, for instance in the leg joints and how the legs will attach to the frame.

Figure 39. Wooden prototype climbing mode utilizing midbody hinge.

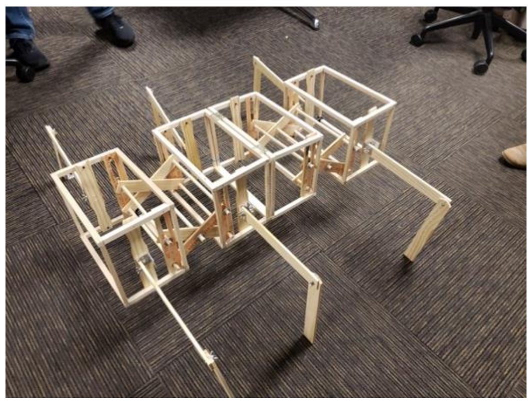

Figure 40. Wooden prototype extended body segment mode.

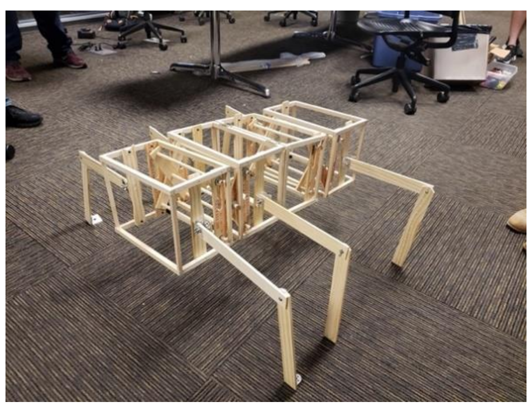

Figure 41. Wooden prototype contracted body segment mode.

The final thing we learned from completing the wooden prototype was that there was no way we were going to physically prototype the entire robotic explorer, given our time and budget constraints. However, this allowed us to narrow down which aspects of the design were the most important to prototype in order to demonstrate the viability of our final design. The conclusion of this analysis was that we would move forward in two teams, one focused on a small-scale robotic explorer, and one focused on a full-scale leg model. The small-scale model would serve to demonstrate the traversability of our rover over a variety of surfaces, which was critical to our client. The full-scale leg would demonstrate leg actuation and mobility for the full-scale design. The team moving forward with the small-scale robotic explorer was John Dynda and Isaac Anderson. The team moving forward with the full-scale leg model was Chad Schafer, Sean Sullivan, Kate Collette, and Jacob Sasse. The proposed design for the small-scale robotic explorer and full-scale leg model are detailed below.

5.1.1 Physical Model: Small-Scale Robotic Explorer Team

Isaac Anderson and John Dynda were tasked with creating a fully mobile small-scale version of our final design. To do this, they simplified the legs from the final CAD model by removing the claw and the wrist joint. Then, they laid out a plan to tackle the small-scale model and came up with an initial CAD model to demonstrate where the design was headed (see Figure 42). This model was designed around 3D printed parts, which was the only method available to the team that met the time and budget constraints.

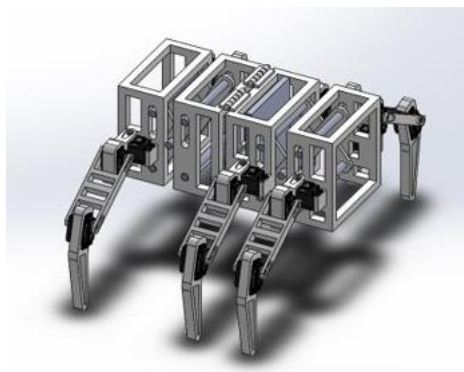

Figure 42. Initial design of small-scale robotic explorer.

5.1.2 Physical Model: Full-Scale Leg Model Team

Chad Schafer, Sean Sullivan, Kate Collette, and Jacob Sasse composed the full-scale leg team. Since much of the work was already completed for the small-scale robotic explorer model, most of the team members continued with the full-scale leg model since almost none of the initial design was completed. Over the first half of spring semester, the leg team designed a CAD model of the leg with each piece that would be needed for the assembly. The result of this full-scale initial mock-up can be seen below.

Figure 43. Initial design of full-scale leg model.

From there, both teams refined their designs through repeated iteration during the prototyping process, which will be detailed in section 6 below.

6 IMPLEMENTATION – Second Semester

The following sections depicts the NAU Psyche Robotic Explorer capstone team's implementation that occurred during the second semester of capstone. The team was tasked with the design and manufacture of a robotic explorer capable of traversing the previously mentioned surfaces expected on the Psyche asteroid. One of the requirements for this project involves building and testing a scaled model of the rover that the team designed during the first semester. The major milestones in the implementation process include design changes, different iterations of the design, as well as an entire separate design of a full-scale leg model. These milestones are discussed in detail in the following sections.

6.1 Design Changes in Second Semester: Small-Scale Robotic Explorer

6.1.1 Design Iteration 1: Change in Scale discussion

Originally, the rover was meant to be large in volume, compared to the physical small-scale model. The original design was created with exploration of the 16 Psyche asteroid in mind. Due to time limitations in the second semester of this project, the team decided to reduce the size of the model. The newly designed small-scale model features all the functions that the original model featured. These functions include but are not limited to the scissor lift portions, as well as the hinged portion of the model. The scissor lift portions are not automated on the small-scale model, however. This is due to the size of the model, as it would be virtually impossible to find a lead screw small enough to drive the scissor lift. Differences between the full-scale model and small-scale models are highlighted in the figures below.

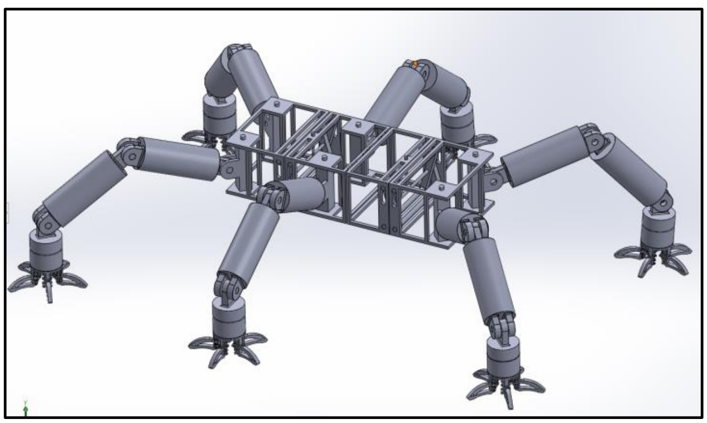

Figure 44. Full-Scale NAU Psyche Gecko Rover

As seen in *Figure 44* above, the full-scale model implemented cylindrical legs. The team developed a new leg design for the small-scale model. The new leg design incorporated segments where servo motors could easily attach. This new design ensured that that legs could be operated via the servo motors. The small-scale CAD model can be seen below, *Figure 45* .

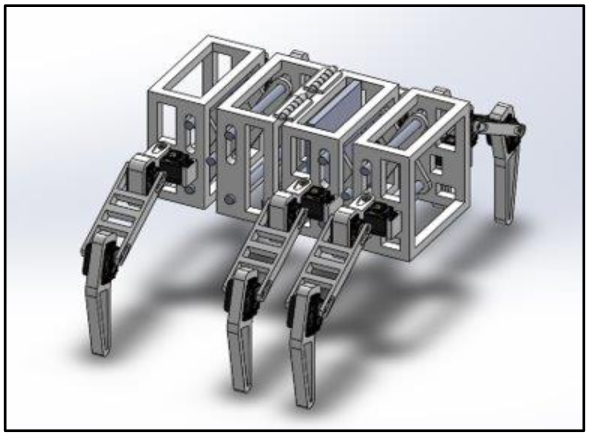

Figure 45. Small-Scale NAU Psyche Rover

6.1.2 Design Iteration 2: Reduced Mobility in Small-Scale Model

The original rover design featured components like a scissor lift portion, which could allow the body segments to extend and contract. The intent of this component was to provide the rover with a form of redundant movement. Ideally, the model would have the ability to "inchworm" its way along a surface if one or more of its legs failed. This component was removed from the final design due to a few restrictions regarding the size of the model, and the time constriction of the project. Initially, these scissor lift portions were to be operated via a lead screw, which would be rotated by a motor. The scissor lift components of the small-scale model were too small to utilize a lead screw. The team also faced the issue of time constrictions. It was not feasible to include this element to the final small-scale model design. It is important to note that the small-scale model contains to the scissor lift portions. The body segments can extend and contract, however they are not automated with a motor. These scissor lift portions can be seen in Figure 45 above, without the incorporation of motors.

Another change in the small-scale model's design includes the elimination of the claw portion. The claw was removed from the small-scale model due to sizing limitations. Most parts of the small-scale model were 3D printed. The team determined that it would be impossible to print the miniature components of the claw. Another reason the claw was removed was due to power sourcing limitations. All electronics of the small-scale model are powered via a 7.2V RC battery. This is one of the largest batteries that is safe to use with Arduino technology. The incorporation of a claw would require the use of two separate motors. These motors would be present on each claw, there would be six (6) claws. The incorporation of 12 motors would require a battery with a higher power output, pushing the safety limits of the Arduino technology. The leg segments of the full-scale and small-scale models are shown below for comparison.

Figure 46. Full-Scale Model Leg

Figure 47. Small-Scale Model Leg

As seen in *Figure 46*, the leg portion contains the claw. In *Figure 47*, the claw is not a part of the leg model.

6.2 *Design Changes in Second Semester: Full-Scale Leg Model*

6.2.1 Design Iteration 1: Shoulder Ring Gear Changes

The first design change came after testing the shoulder swivel of the leg model. As the planetary gear housing rotated, the motor being used for the sun gear was rubbing against the inner side of the housing. This later became an issue which caused the system to fail. The gears became bound and resulted in a fracture on one of the pegs located on the gear carrier plate. This was fixed by redesigning the carrier plate and raising the system. The carrier plate was reprinted at a higher infill and redesigned to have a stronger base at the pegs. This strengthened the piece significantly resulting in better performance. The system was also raised off the table using spacers. This allowed for the motor to avoid contact with the lip that the ring gear rested on. The extra space designated to the inner motor also reduced the possibility of the gears binding and failing. As an extra precaution, the teeth of each gear were shaved down in size to avoid failure due to binding.

6.2.2 Design Iteration 2: Claw Lead Screw to Motor Attachment

Previously, the motor used to open and close the claw was positioned at the top of the wrist segment and used two worm gears to guide the lead screw. This design was changed for simplicity and efficiency. The new design attaches the lead screw directly to the shaft on the motor as seen in Figure 43 below.

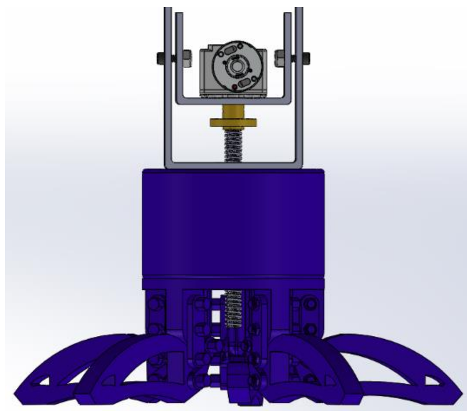

Figure 43. Lead Screw Motor Attachment

The lead screw was attached using a hub and set screw to secure it to the motor shaft. The motor was secured to the wrist segment using a u-bracket. This new design does not require a tight mesh between the two worm gears. The worm gears are more likely to fail over time as they undergo stress and eventually separate. This would require repairs to recreate the tight mesh between the gears. This new design also allows for the claw to apply more pressure to the object it is lifting resulting in more efficiency.

7 RISK ANALYSIS AND MITIGATION

7.1 Potential Failures Identified First Semester

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.

7.2 Potential Failures Identified This Semester

There are a few potential failures for the rover that was identified after creating the small-scale and leg model prototypes. One potential failure can occur at the base joint of the leg attached to the shoulder. If the gear is not made of a strong material, the part could fail. This failure was observed as the leg model was being tested. With all leg segments straight and at a zero-degree angle, the 3D printed gear at 10 percent infill failed resulting in a need for redesign. The gear was 3D printed at 100 percent infill but is still subject to failing in the future. The planetary gear system in the shoulder of the leg can also fail if not properly maintained. If the gears are not positioned correctly and are uneven in a significant way, then the gears can bind resulting in a fracture in the carrier plate. This issue was addressed by increasing the support at the base of the pegs located on the carrier plate. The teeth on the gear were also shaved down in size to allow the gears space in the mesh. The motor being used for the claw is also subject to failure. During testing, the attachment of the lead screw to the motor shaft failed as the claw attempted to grab something with significant pressure. A hub and set screw were used to fix the lead screw which proved to be successful. This separation can occur again if the claw attempts to grab something with immense pressure. The small-scale also revealed possible failures for the overall design. The first failure occurred with the usage of inefficient motors. Small servos were used at first on this model to save money and time. The body of the rover was large and had more weight than the servos could hold. This caused the legs of the rover to be weak and fail to lift the body. By reducing the weight and using appropriate motors for the rover's size, this potential risk can be reduced. Another potential failure found by testing the small-scale rover corresponds with the power source. When a significant power source or a battery that is not properly charged, the rover will not provide the needed power to each of the motors. Some of the motors will receive less power than others causing the rover to tip forward. The rover would be able to lay itself down and stand back up but will likely stumble and fall again. Using a reliable power source can reduce the possibility of this failure.

7.3 Risk Mitigation

Motors

Clean motor by blowing out dirt form windings and wipe commutator and brushes. If brushes are half worn, then replace them to prevent failure.

Planetary Gear System

Visually inspect the gear system for unusually wear and cracks in the gears teeth. If a gear is found to have a large amount of wear or cracked teeth replace that gear immediately. On earth use Vaseline for lubricating planetary gears. If on Psyche the best grease to use would be Castrol Braycote.

Base Mount

If the base is not performing smoothly, lubricate the bearings on the planetary gears and on the turntable. The gears themselves could also be lubricated to ensure smooth operation. Inspect each if the connection points for unusual wear or cracks. A crack can result in a catastrophic failure if not properly inspected. To prevent the gears from binding, ensure that the base is leveled with the board it is attached to.

Joints
First visually inspect the joint for unusual wear, if unusual wear is detected proceed to look for bent pieces and replace if necessary. Next check all fasteners for tightness. If a loose fastener is detected, tighten each loose fastener is a star pattern.

Gears
Visually inspect all teeth on each gear for unusual wear or cracked teeth. If a tooth is missing replace the gear immediately to prevent any further damage. Once each tooth has been inspected begin to lubricate each gear to prevent any further wear.

Claw
Visually inspect the toes for cracks or wear. If damage is found, replace them immediately to avoid failure. Check all fasteners to ensure they are tight and will not fall off. Also make sure they are not over tightened which could cause the toes to be stuck. Inspect the small linkages on each toe for damage. If damage is found, replace the linkage. Ensure that the claw housing cap is secure and level with the wrist plate. If the lead screw is off center, the mechanism can bind and fail.

Lead Screw
Ensure that the lead screw is well lubricated with an oil to avoid binding on the lead screw. Inspect the screw for any abrasions or burrs that could cause the system to bind or run inefficiently. If there is any damage to the screw, replace it immediately before operating the claw mechanism.

Wiring
Visually inspect each wire for abrasions. If an abrasion is found cut the wire and splice each end of the wire. Next place a section of wire heat-shrink tubing on one side of the wire. Ensure that the section of the heat shrink tubing is long enough to cover all exposed portions of the wire. Next wire the two exposed ends of wire together. Next place the hear shrink tubing over all exposed wires. Use a heat gun to heat all portions of the heat shrink tubing until all of it adheres to the wire. Visually inspect all wire connection points to ensure a solid connection.

Batteries
This system runs off a 12 Volt DC 14AH Duracell battery and the PS2 uses two AAA type batteries. The 12V needs recharging and the AAA batteries get replaced as needed.

8 ER Proofs

8.1 ER Proofs for Small-Scale Robotic Explorer

8.1.1 ER Proof #1 – Servo Torque Requirement

This analysis was conducted to ensure that the servos chosen for the small-scale model were sufficient to support and move the model. The variables used in this analysis included the materials used in construction of the small-scale model, the mass of each individual part of the small-scale model [kg], the servo specifications provided by the supplier [kg-cm] [26], earth's gravitational constant [m/s^2], and the lengths of each leg segment [m]. This analysis was performed under conditions present on Earth, rather than the 16 Psyche asteroid. This was done to produce results that could easily be tested once the model was fully assembled. The material and mass of each component of the small-scale model was determined using Solid works. This ensured accuracy since every component of the rover was 3D printed based on the CAD models. The variables and assumptions used in this analysis can be seen below in Table 6.

Table 6. Analysis Variables

Variable	Value	Units
Material	PLA	N/A
Total Mass of Small-Scale Model	3.86	kg
Servo Specifications	13	kg-cm
Gravitational Constant	9.81	m/s^2
Leg Segment Lengths	Varied	m

To improve accuracy for the analysis, the mass of each individual part of the small-scale model was used to determine the total mass of the completed rover assembly. The individual parts used in the small-scale model can be seen below in Table 7 with their corresponding instances and masses.

Table 7. Small-Scale Model Parts/ Masses/ Instances

Part	Mass [kg]	Instances
Leg Segment 1	0.04767	6
Leg Segment 2	0.04258	6
Leg Segment 3	0.05549	6
Left End Body Segment	0.39225	1
Middle Left Body Segment	0.35644	1
Middle Right Body Segment	0.39047	1
Right End Body Segment	0.38635	1
Scissor Lift Arms	0.02269	8
Middle Scissor Lift Shaft	0.02262	2
Scissor Lift Shaft	0.02747	8
Hinge Part 1	0.00399	2
Hinge Part 2	0.00348	2
Hinge Pin	0.00235	2
20kg Servos	0.055	18

Each part was modeled within Solid works with the same material properties as PLA, the filament material they were printed from. The density of PLA was obtained from [27], and was used to create a new material in Solid works. Each part of the small-scale model was then assigned this material and its properties. The individual masses of each part were obtained by using the "mass properties" tool within Solid works. These individual masses were multiplied by their number of instances within the small-scale assembly using equation (1).

$$Total\ Part\ Mass = Individual\ Part\ Mass * Instances \quad (1)$$

The purpose of this analysis was to determine the torque requirement of each servo given a specific movement scenario of the small-scale rover model. Moving forward with the analysis, the total mass of the small-scale rover was calculated using equation (2). This combined mass of the small-scale model was then multiplied by Earth's gravitational constant to convert it into a force (weight), equation (3). This force was used to determine the required torque output of each individual servo.

$$Total\ Rover\ Mass = \sum Total\ Part\ Mass \quad (2)$$

$$Total\ Rover\ Weight = Total\ Rover\ Mass * Gravitational\ Constant \quad (3)$$

The total weight of the small-scale model can be seen in Table 8 below.

Table 8. Part and Total Weight of Small-Scale Rover Model

Part	Mass [kg]	Instances	Total Part Mass [kg]	Weight [N]
Leg Segment 1	0.04767	6	0.28602	2.8058562
Leg Segment 2	0.04258	6	0.25548	2.5062588
Leg Segment 3	0.05549	6	0.33294	3.2661414
Left End Body Segment	0.39225	1	0.39225	3.8479725
Middle Left Body Segment	0.35644	1	0.35644	3.4966764
Middle Right Body Segment	0.39047	1	0.39047	3.8305107
Right End Body Segment	0.38635	1	0.38635	3.7900935
Scissor Lift Arms	0.02269	8	0.18152	1.7807112
Middle Scissor Lift Shaft	0.02262	2	0.04524	0.4438044
Scissor Lift Shaft	0.02747	8	0.21976	2.1558456
Hinge Part 1	0.00399	2	0.00798	0.0782838
Hinge Part 2	0.00348	2	0.00696	0.0682776
Hinge Pin	0.00235	2	0.0047	0.046107
20kg Servos	0.055	18	0.99	9.7119
Total	1.81	N/A	3.86	37.83

At this point in the analysis, two movement scenarios were developed where the expected torque output of the servos was maximum. One of the movement scenarios involves the legs to be positioned in a manner that would allow the rover to simply move forward. The leg positions for this movement can be seen in Table 9 below. Each leg segment and corresponding servo for movement scenario 1 can be seen in Appendix A.

Table 9. Leg Segment Positioning for Movement Scenario I

Simple Forward Motion					
Part	**Length (mm)**	**Length (m)**	**Positioning (degrees)**	**Lever Arm Length (mm)**	**Lever Arm Length (m)**
Leg Segment 1	85.00	0.09	0.00	314.30	0.31
Leg Segment 2	140.00	0.14	0.00	229.30	0.23
Leg Segment 3	170.00	0.17	45.00	89.30	0.09

The lengths of each individual leg segment were obtained from the dimensions of the part model within Solid works. These lengths were then used to determine the lever arm length for each servo in the leg assembly, equations (4-6). Leg segment 1 is closest to the body of the model, therefore the servo that rotates leg segment 1 has the longest lever arm. Leg segment 3 is furthest from the body of the rover, therefore the servo that rotates leg segment 3 has the shortest lever arm. The positioning of the legs was decided based on the most optimal stance of the rover to move forward.

$$Lever\ Arm\ Length\ 1 = Length\ 1 + Length\ 2 + (Length\ 3 * SIN(Positioning\ 3)) \quad (4)$$

$$Lever\ Arm\ Length\ 2 = Length\ 2 + (Length\ 3 * SIN(Positioning\ 3)) \quad (5)$$

$$Lever\ Arm\ Length\ 3 = (Length\ 3 * SIN(Positioning\ 3)) \quad (6)$$

Once the lever arm length was determined for each leg segment and their corresponding servo, the required torque output was determined. The required torque output that results in simple forward motion of the rover can be seen in Table 10.

Table 10. Torque Requirements for Simple Forward Motion

Simple Forward Motion				
Part	**Individual Force Loading [N]**	**Individual Lever Arm Length [m]**	**Individual Torque Requirements [N*m]**	**Approximate Individual Torque Requirements [lbf*ft]**
Leg Segment 1	37.83	0.31	1.98	1.46
Leg Segment 2	37.83	0.23	1.45	1.07
Leg Segment 3	37.83	0.09	0.56	0.42

The largest torque requirement comes from servo 1 which is located closest to the body of the rover. Due to its positioning relative to the body of the small-scale model, it has the largest lever arm and therefore largest torque requirement to rotate leg segment 1.

The second movement scenario involves the servos supporting the weight of the small-scale model. In this case, the legs are holding the body of the model up, with constant torque being supplied. The leg positions for this scenario can be seen in Table 11.

Table 11. Leg Segment Positioning for Movement Scenario II

Supporting Body					
Part	**Length (mm)**	**Length (m)**	**Positioning (degrees)**	**Lever Arm Length (mm)**	**Lever Arm Length (m)**
Leg Segment 1	85.00	0.09	0.00	326.45	0.33
Leg Segment 2	140.00	0.14	30.00	241.45	0.24
Leg Segment 3	170.00	0.17	45.00	120.21	0.12

Once the lever arm length for each servo was determined, the required torque output was determined. The required torque output of each servo that results in supporting the rover's weight and remaining still can be seen in Table 12.

Table 12. Torque Requirements for Supporting the Rover's Body

Supporting Body				
Part	**Individual Force Loading [N]**	**Individual Lever Arm Length [m]**	**Individual Torque Requirements [N*m]**	**Approximate Individual Torque Requirements [lbf*ft]**
Leg Segment 1	0.00	0.33	0.00	0.00
Leg Segment 2	37.83	0.24	1.52	1.12
Leg Segment 3	37.83	0.12	0.76	0.56

The largest torque requirement for the movement scenario comes from the servo that moves leg segment 2 instead of the servo that moves leg segment 1. This is because the servo that moves leg segment 1 is only responsible for horizontal movement of the rover. Based on these results, it can be expected that the servos responsible for leg segment 2 will output the most torque during this movement scenario. It is important to note that the individual torque requirement is the requirement for each servo, considering there will be 18 servos in the completed model.

The servo specifications were taken directly from [26]. These specifications were used to determine whether the servos were capable of outputting the required torque. The specifications of the servos can be seen in Table 13.

Table 13. Servo Specifications

Manufacturer	**Part Desc.**	**Expected Operation Voltage (V)**	**Peak Operation Voltage (V)**	**Stall-torque at Peak Operation Voltage (kg-cm)**	**Stall-torque at Expected Operation Voltage (kg-cm)**	**Max Expected Torque Requirement of Servos (N*m)**	**Max Expected Torque Lever Arm of Servos (cm)**	**Total Small-scale Rover Mass (kg)**	**Max Expected Torque Requirement of Servos (kg-cm)**
Seamuing	Micro Servo Motor, MG995 RC Servo, 20kg Metal Gear Servo	5.00	7.20	13.00	10.00	1.98	31.43	3.86	0.12

Further analysis was conducted to determine the stall torque at the voltage the servos would be operating at, equation (7). The results of this analysis can be seen in Table 14Table 14 below.

$$Stall\ Torque = \left(\frac{Stall\ Torque\ at\ Expected\ Operation\ Voltage * Gravitational\ Constant}{100}\right) * Instances \tag{7}$$

Table 14. Stall Torque of Servos at Operation Voltage

Stall-torque at Expected Operation Voltage (N*m)	Max expected torque requirement of servos is less than the expected stall torque of the servos at an operation voltage of 5V. The servos should provide sufficient torque for the rover.
5.89	

In the case of equation (7) the product was divided by 100 because the units of "Stall Torque at Expected Operation Voltage" were [kg-cm]. Based on the result of this analysis, it is reasonable to assume that the servos will have the ability to output more than enough torque to accomplish the two movement scenarios.

8.1.2 ER Proof #2 – [Mass]

The mass of the small-scale model was determined through mass properties of the CAD model within SolidWorks. This proof was a subset of the size of the model, material properties of PLA filament were input into SolidWorks. The density of the material was utilized along with the volume of the model to determine its mass. Design changes were constantly made to the model to determine its optimal mass, a mass where the servos would have the capability of supporting the model. The current sizing of the CAD model was deemed optimal for the servos to function properly and provide viable support to the model. This ER relies on the power output from the power source, without optimal power, the servos would not have the ability to support the full mass of the rover.

8.1.3 ER Proof #3 – [Volume]

The volume of the small-scale model was determined based off the CAD model. Initially, the leg segments of the model were designed. These segments were made a specific size to house the 20kg servos that would power them. The rest of the model was sized around the leg segments, accounting for the total mass of the model. The group ensured to keep the model relatively small so that the servos would be able to support its weight.

8.1.4 ER Proof #4 – [Ground Clearance]

Again, like the other dimensions of the small-scale mode, the ground clearance was determined by the size of the legs. A quick analysis was conducted to determine what the final ground clearance of the small-scale model would be. This analysis follows the dimensions present within the CAD for the small-scale model.

8.1.5 ER Proof #5 – [Power]

This section of analysis utilized a simple calculation. The small-scale team divided the electronics present in the model, determining the power required by each electronic element. The power requirements for each element were collected from information provided by the vendors. The 20kg servos used in the small-scale model were wired in series, therefore the current is split between the twelve servos. To model this, the small-scale team multiplied the current requirement by the number of instances for the 20kg servos in the system by their individual current draw. The total power requirement for the small-scale model was determined to be 30.59 Watts.

Table 15. Small-Scale Psyche Robotic Explorer Power Requirement Analysis

Small-Scale Psyche Robotic Explorer Power Requirement Analysis						
Electronics	**Instances**	**Power Division**	**Voltage Requirement (V)**	**Current Requirement (A)**	**Power Requirement (W)**	**Total Power Requirement (W)**
20kg Servo	12	Series	7.2	4.2	30.24	30.59
Arduino Mega 2560	1	N/A	7	0.05	0.35	

Another analysis was conducted to determine the operation time of the small-scale model on a full charge. The team used a 3600 mAh battery, supplying 7.2V. The analysis for this value can be seen in Table 16.

Table 16. Small-Scale Psyche Robotic Explorer Operation Time Analysis

Amp Requirement (A)	**Power Supply Charge (mAh)**	**Allowable Operation Time on One Charge (hours)**
4.25	3600	0.847

8.2 ER Proofs for Full-Scale Leg Model

8.2.1 ER Proof #1 – [Mass]

The mass of the final leg model weighed in just under four kilos. This is within our upper target limit. This weight was determined using a scale precise to within □1 g. Ideally, a future iteration of the design would have a lower weight. This could be achieved through lighter materials such as titanium and lighter, more efficient motors.

8.2.2 ER Proof #2 – [Volume]

The volume of our final leg model was determined to be around 0.1 m^3. This was an approximation based on the x, y, and z dimensions of the physical model. This is within the target value. The volume was kept down by narrowing the gap between leg segments to just allow for the motors, as well as precisely cutting all frame pieces to the same dimensions as the CAD model. In the end, because the final CAD model was nearly identical to the physical model, we were able to strictly control for volume throughout the design.

8.2.3 ER Proof #3 – [Torque]

The goal of this study is to determine if the motor we selected for the base mount will be able to generate enough torque to rotate the leg. The reason that only this motor torque will be calculated is that the rest of the motors chosen for the full-scale leg model are the same make but will be under less load because they are further from the base and need to actuate less weight. Thus, if the base motor can output enough torque, then the rest of the motors will also be sufficient. The motor torque will be determined using the gear ratio of the planetary gear system which is housed in the base mount of our full-scale rover leg model. This calculation will help us to determine the torque output of the motor with the planetary gear reduction to see if the proposed motor will generate enough torque to rotate the leg segments.

One thing that is critical to note is that the values used in this report correspond to the acceleration of gravity on Earth. On Psyche, the acceleration of gravity is only $0.144 m/s^2$ thus it is quite likely that any motors we choose for testing on Earth will be oversized for the applications on the Psyche asteroid. However, if we size the motors for Psyche's surface gravity conditions, we would not be able to test the actuation of our leg and therefore would not be able to validate our design. As such, this report will move forward using the environmental conditions present on Earth.

Assumptions

Some of the relevant assumptions for this problem are as follows:

- Frictional losses are neglected: assume all the energy generated by the motor is converted to kinetic energy in the form of rotational motion
- Quasi-static: gears are rotating at constant speed
- The teeth of the gears mesh (no jumping)
- Weight of small plastic gears and hardware neglected as they will have minimal effect on the results

Weight of the Rover Leg

To determine the weight of the rover leg, each piece was weighed and then totaled, which came out to approximately 3.91kg. Then the center of mass (COM) was determined with the leg in a fully extended position.

Table 17. Center of mass calculations for full-scale leg model torque analysis.

Part #	Part	Mass (kg)	X Distance (m)	Y Distance (m)			Estimate (do not have exact # yet)
1	Aluminum Leg Segment (Long) A	0.196	0.2286	0			
2	Aluminum Leg Segment (Long) B	0.196	0.2286	0			
3	Aluminum Leg Segment (Long) C	0.196	0.6858	0			
4	Aluminum Leg Segment (Long) D	0.196	0.6858	0			
5	Aluminum Leg Segment (Short) A	0.065	0.9905	0			
6	Aluminum Leg Segment (Short) B	0.065	0.9905	0			
7	Base Mount and Motor	1.119	0	0			
8	Shoulder Joint Motor	0.369	0.03	0			
9	Elbow Joint Motor	0.369	0.4572	0			
10	Wrist Joint Motor	0.369	0.9144	0			
11	Claw Motor	0.369	1.067	0			
12	Claw	0.4	1.1	0			
	Total:	3.909					
			0.0448056	0			
			0.0448056	0			
			0.1344168	0			
			0.1344168	0			
			0.0643825	0			
			0.0643825	0			
			0	0			
			0.01107	0			
			0.1687068	0			
			0.3374136	0			
			0.393723	0			
			0.44	0			
			COM(x)	COM(y)			
			0.470228498	0			

In a fully extended orientation, if the base motor were to try and rotate it would experience the highest moment forces compared to any other leg position. Thus, if the motor can adequately overcome this amount of inertia, it should be able to rotate with the leg in any other orientation. The calculations for the center of mass can be seen in. The calculated value for the COM is 0.47m away from the base gear box. The total weight of the leg is 3.91kg. Thus, the moment force generated by the legs weight is:

$$M = rm * \frac{9.81m}{s^2} = (0.47)(3.91)\left(\frac{9.81m}{s^2}\right) = 18Nm$$

Where:
$r = moment\ arm\ (m)$
And $m = mass\ (kg)$.

Torque Requirements

The selected motor for the base mount has a torque output of 3.8kgf-cm [28]. In SI units that torque output is 0.373Nm. Using the equations for epicyclic gearing the torque after the planetary gear turn-down is:

$$\tau_r = \tau_s \frac{N_r}{N_s} = (0.373)\left(\frac{60}{12}\right) = 1.87Nm$$

[2]

Where:
$\tau_r = torque\ output\ of\ ring\ gear\ (Nm)$
$\tau_s = torque\ output\ of\ sun\ gear\ (motor)\ (Nm)$
$N_r = number\ of\ teeth\ in\ ring\ gear$

And $N_s = number\ of\ teeth\ in\ sun\ gear$.

It is important to note that in our base gear box design, the planetary gears rotate on their axis but do not revolve and the ring gear is what is being driven by the motor. Thus, the carrier is stationary.

The inertia of the leg is calculated as a rod rotating about its end, which is a close enough approximation for the scope of this report:

$$J = \frac{1}{3}m(2 * COM)^2 = \frac{1}{3}(3.91)(2 * 0.47)^2 = 1.15kg * m^2$$

The angular velocity of the ring gear can then be calculated:

$$\omega_r = \frac{N_s + N_r}{N_r}\omega_c - \frac{N_s}{N_r}\omega_s = 0 + \frac{12}{60}(80rpm)\frac{2\pi}{60\ s} = 1.68\ rad/s$$

[29]

The equation for the required torque is:

$$\tau_{rec} = J\alpha + \tau_L$$

[30]

Where:
$\tau_{rec} = required\ torque\ from\ motor$
$\alpha = angular\ acceleration\ \left(\frac{rad}{s^2}\right)$
And $\tau_L = load\ torque$.

Load torque is the sum of mechanical losses to due to friction. Since we are neglecting friction, this value goes to zero. Using time as the dependent variable we can see the optimal torque output of our gear box in Figure 48.

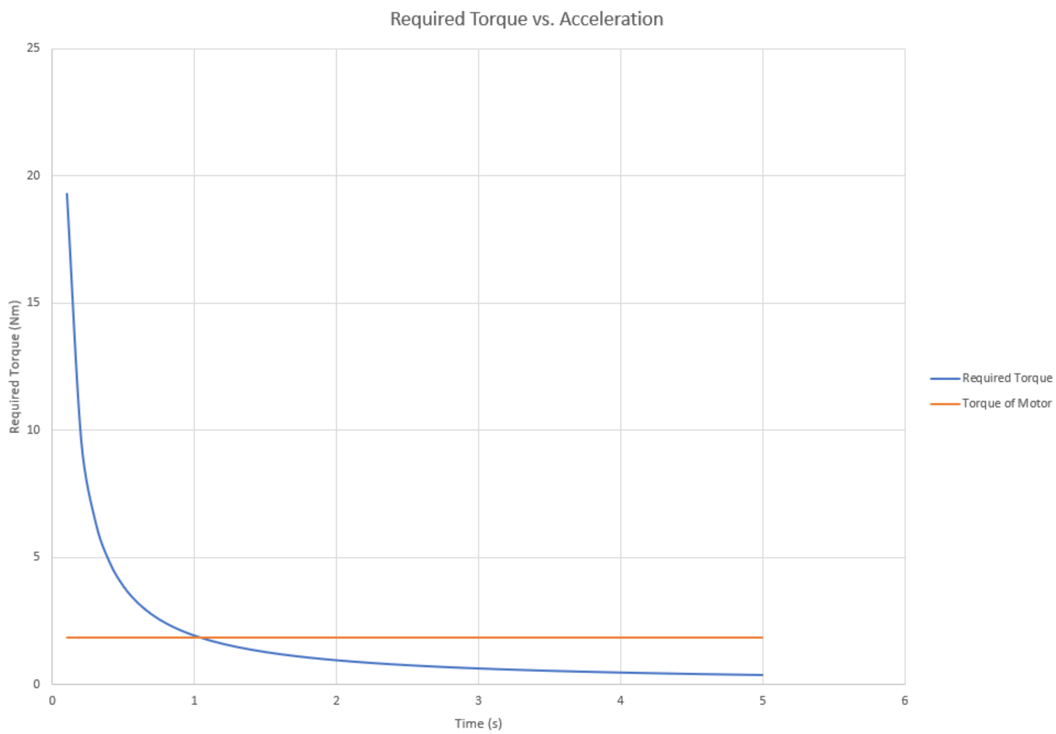

Figure 48. Required motor output torque vs. acceleration.

As can be seen from the above figure, the motor should be appropriately sized so long as the required time to accelerate from 0 to 80rpm is over 1 second. This is more than adequate for our applications and therefore the motor we have chosen for the base gear box should be successful for out applications.

8.2.4 ER Proof #4 – [Ground Clearance]

The ground clearance of our leg is around 90cm, considering that it is mounted on the body no more than 5cm from the base of the rover. The minimum ground clearance we determined was 0.8m, so this value is acceptable. The rover should not stand above 1.2m from the ground, as this could cause stability issues and add unnecessary bulk to the rover.

8.2.5 ER Proof #5 – [Power]

The power output of the leg model's motors is around 50 Watts, based on the manufacturer's specifications [28]. This is the same as our target value, since the target value was determined using the same motors that ended up in the final design.

9 LOOKING FORWARD

Many different adaptations as well as tests and experimenting have been left for the future due to lack of funding as well as time constraints. This future work will consist of a deeper analysis of certain mechanisms in the design as well as possible new proposals to try different things. This section will focus on the possible changes and their solutions as well as how our sponsor can implement the changes to better the project in the future.

9.1 Future Work - Small Scale Robotic Explorer

For the small-scale robotic explorer, the team did not have the chance to acknowledge a few aspects of design that were initially intended for the model. One of the aspects that the team did not have the time to accomplish was the incorporation of a larger battery to power the explorer more efficiently as well as for a longer period of time. Another task that the team did not have the chance to acknowledge was how the servo attachments to the leg segments slip out on occasion due to a large load being applied. This issue would have been resolved by redesigning the joint attachments to include a small holder that held the servo in place on both top and bottom of the motor. The biggest aspect of the design that the team did not have the ability to work on was the hinge portion in the middle of the explorer that allows it to climb higher relief points as well as the scissor lift extenders that allow extension of the body to distribute the rover load across a larger surface area. These aspects of the design have been designed in 3D space, but have not been fully built and tested due to budgeting and timing. Another design change that the team would have liked to do is a redesign of the electrical components mounting station for the explorer. Initially the team desired the rover to be controlled wirelessly via a PS2 Bluetooth controller, but due to connection issues, programming, and the devices capabilities the team decided to pursue AI controlling instead. This design change of the mounting plate is fairly simple and includes removing the Bluetooth module for the PS2 controller and either getting rid of the mounting spot permanently or replacing it with the electronics for the AI. With all of the physical changes to the model that are left in the future work of this project comes one last task of testing the explorer's capabilities on all possible surfaces.

9.2 Future Work – Full Scale Leg Model

Future work for the Full-scale leg model includes refining the code to be able to operate the leg by a PS2 controller. Also, if allotted more time the team would add sensors and switches into the system. Adding these components would make the movements of the leg more precise and fluid.

10 CONCLUSIONS

The team set out in the first semester to design and build a sized scaled rover that could perform well on Psyche. The basic design was created in first semester. During the build in second semester, it was determined that there were too many people trying to work on the small-scale rover project. It had been decided that if there was time at the end of the semester that the team would create a full-scale leg prototype to show full functionality of the rover's leg.

Both goals were accomplished by the end of the semester. The client was satisfied with the two final prototypes and even the wooden proof of concept model.

10.1 Reflection

Since the rover is designed to work on an asteroid typical safety concerns were not applicable. However, since the suggested means of powering the actual rover was a multi mission radio isotope thermoelectric generator (MMRTG), our team went with standard batteries that were safe for use in a school environment.

It was envisioned that in compliance with the Planetary Protection Protocols that NASA follows that the actual rover would be constructed in a clean room.

10.2 Postmortem Analysis of Capstone

Below is a breakdown of the projects second semester. What worked and what could be improved.

10.2.1 Contributors to Project Success

In the beginning of the second semester, it was clear that there were issues with having too many people on the small-scale rover. It was decided that splitting into two work groups was the answer. One group worked on the small-scale rover and the other, starting from scratch, designed and built the full-scale leg model. Despite time limitations and the lack of a spring break where students could work on their project without worry about other classes both sub-groups performed admirably and completed the physical build of the scaled rover and leg model.

Since the team was not looking to build a full rover prototype and just display certain characteristics of the rover full functionality was not needed. What was important was to have the models display the chosen aspects of the rover. This was accomplished.

Due to covid-19 restrictions working at the university was difficult. Instead of trying to schedule a time to work in the NAU Fabrication shop one member opened their garage to the team as a workspace. This was invaluable due to being able to leave the project laid out until the next work sessions. Another student provided most of the tools that the team worked with.

There were lots of lessons learned during the capstone project. Individual analysis lessons involving the project were helpful and allowed students to use knowledge gained from classes in actual application.

10.2.2 Opportunities/areas for improvement

Due to Covid-19 the team had to do most of its meetings in remote. Not being in-person led to a lot of miscommunications. This was a learning experience for the team, but things would have been easier if the school had provided a meeting space for teams to work in with close storage options for project materials.

The school has offered many chances to collaborate with groups during the education for a BS in mechanical engineering. Collaboration strategies are never taught, and teams are never supervised enough for instructors to be able to give guidance when needed.

Professors / advisors only meeting remotely with team made feedback less impactive. Most of the time the team did not know if the professors were satisfied with the work the team was performing.

The NAU Fabrication shop could be improved by having a manager greet the students coming into work. Most of them seem to be disinterested in what is going on with students who come in to work. It is never clear what tools and equipment students are allowed to use. Our team had four members go to the shop and work for two hours and never once get greeted by the staff.

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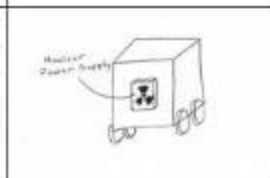
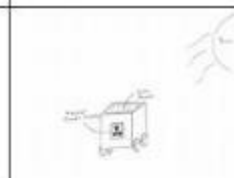
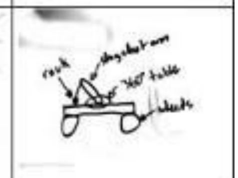
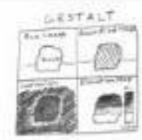
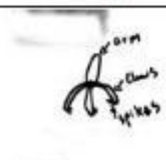
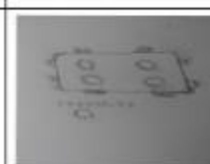
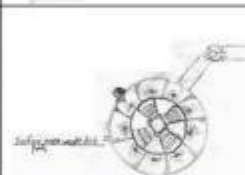
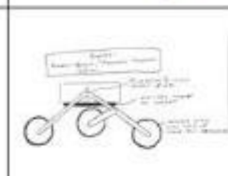
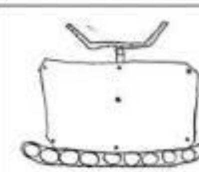
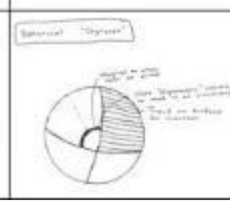
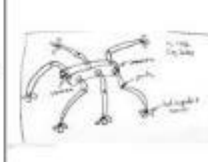
13 APPENDICES

13.1 Appendix A: Decision Matrix

Decision Matrix							
	WEIGHT	Spider Gecko		Tracks		Frog Baby	
Requirements Criteria/Constr.		Rating	Weighted Score	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Power	**0.26**	100	26	100	26	65	16.9
Mass	**0.21**	75	15.75	60	12.6	90	18.9
Torque	**0.19**	90	17.1	60	11.4	75	14.25
Material Strength	**0.18**	90	16.2	95	17.1	70	12.6
Mission Life	**0.16**	80	12.8	70	11.2	60	9.6
TOTAL			87.85		**78.3**		**72.25**
		Highest Weighted Score					

13.2 Appendix B: Concept Variant Morph Matrix

Morph Matrix				
	Concept Variants			
Sub Function	1	2	3	4
Generate Power				
Navigate the Asteroid			Lidar	
Attachment to Surface			1 2 3 	
Traverse Hypothesized Surfaces				
				

13.3 Appendix C: Concept Variant Pugh Matrix

Pugh Matrix

Concept Variants	Baseline	Power	Mass	Torque	Material Strength	Mission Life	Totals	Rank
Concept 1	0	0	0	0	1	-1	0	4
Concept 2	0	1	0	1	0	1	3	1
Concept 3	0	-1	-1	-1	0	0	-3	9
Concept 4	0	0	1	1	0	-1	1	3
Concept 5	0	1	0	0	0	1	2	2
Concept 6	0	-1	0	0	0	0	-1	6
Concept 7	0	0	0	-1	1	-1	-1	6
Concept 8	0	1	-1	-1	0	0	-1	6
Concept 9	0	-1	-1	0	0	-1	-3	9
Concept 10	0	-1	0	1	0	0	0	4