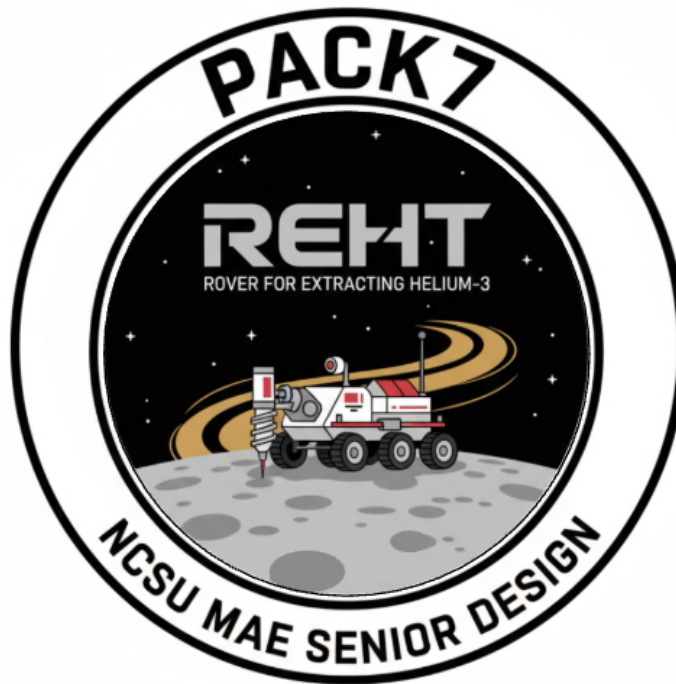


System Readiness Review

PACK7: Rover for Collecting Helium-3

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Nomenclature

APXS	Alpha Particle X-ray Spectrometer
ANSYS	Analysis System
GPU	Graphics Processing Unit
LIBS	Laser Induced Breakdown Spectrometer
MLI	Multi-Layer Insulation
NASA	National Aeronautics and Space Administration
NIR	Near Infrared
PCM	Phase Change Material
REHT	Rover for Extracting Helium-3
RHU	Radioisotope Heater Unit
TEC	Thermo-Electric Cooler
W	Watt

I. Project Purpose

I.1. Personnel

Customers

Table 1: Customer Approval Verification

Name	Affiliation
Dr. Henry Ware	Stackholder
Ali Naderi	Space Section Instructor
Dr. Felix Ewere	Course Instructor

Team Members

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Organizational Structure

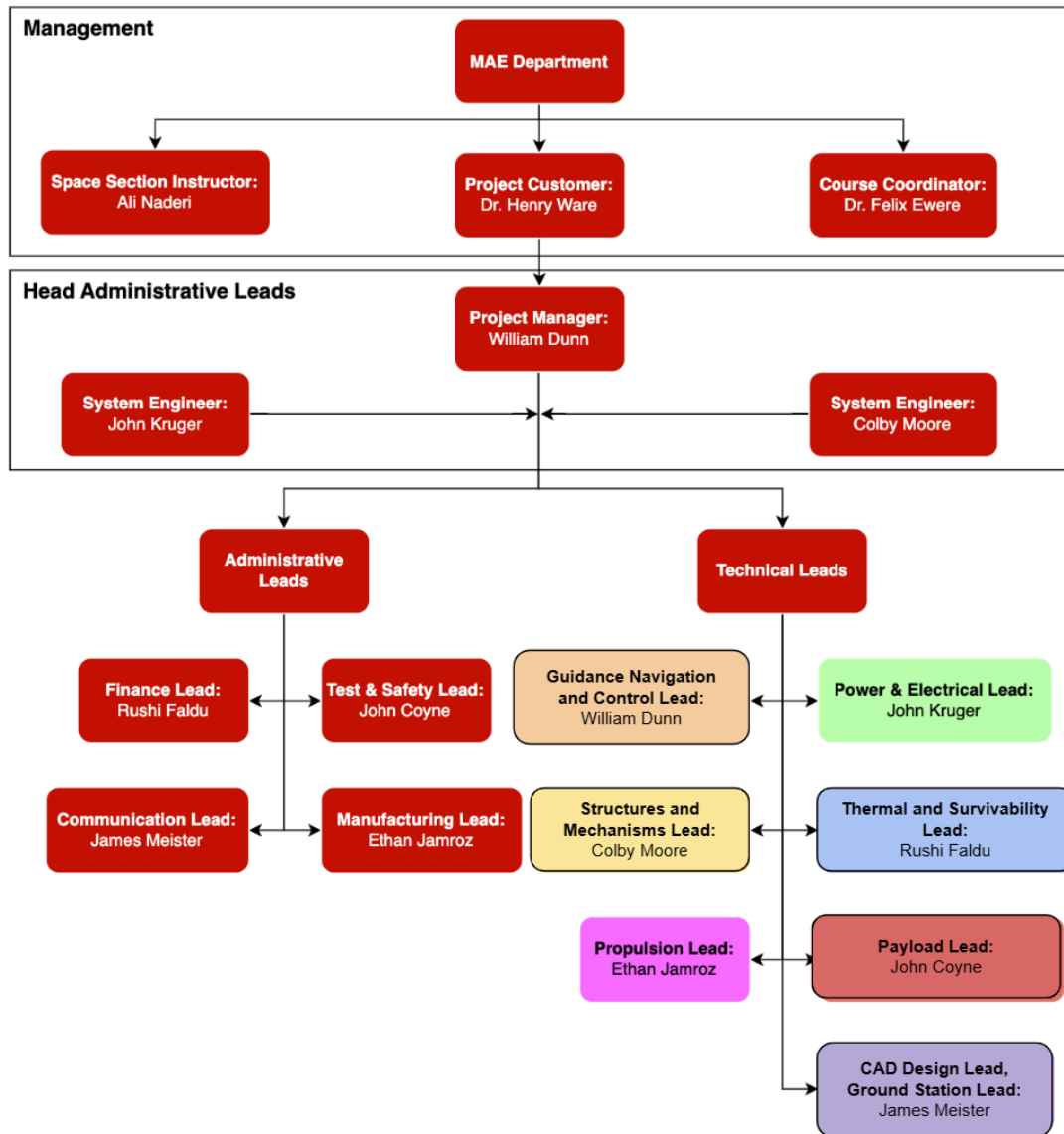


Figure 1: PACK7 Organizational Chart

I.2. Project Overview

In order to effectively plan future large-scale missions, there is a need for hundreds of kilograms of well-preserved, temperature-regulated regolith samples from a variety of locations of interest to be returned to Earth for analysis. Key areas of interest for NASA are likely to include the composition of the regolith, such as the presence of agglutinates and spherules, as well as certain minerals. Another important factor is the grain size of particles present, as well as the quantity of key resources such as H_3 , which can affect mission design. One of the largest impediments to effectively accomplishing this task is in finding a way to effectively maintain the quality of the samples, especially based on the metric of temperature. The temperature of the moon's surface can swing dramatically between $-200^{\circ}F$ and $250^{\circ}F$, which can result in the degradation

of samples, especially when considering the presence of frozen H_2O . To accomplish this, a system is needed that can traverse the lunar surface, collect samples with a focus on the presence of H_3 at depths of up to two meters, and store them at a temperature that maintains the desired properties. In order to meet this need, Pack7 aims to develop REHT capable of traversing the lunar surface, including most mild to moderate craters at extended distances, collecting samples of depths of up to three meters, and storing them in containers held at temperatures classified by NASA as unconditioned and refrigerated. These samples will primarily focus on the presence of Helium-3 and ice. Understanding the composition of the moon's surface is critical to furthering our scientific understanding of this key celestial body, as well as providing a more complete picture for the purpose of establishing a permanent presence there. Failure to understand the regolith in an area of interest can result in missed opportunities as well as damage to equipment due to abrasion from dust.

I.3. Literature Review

I.3.1. Suspension

Apollo Lunar Roving Vehicle (1969): The Apollo rover was the first rover to see use on the moon, the suspension system in use was a double wishbone style using a passive damping system. This system was generally effective for the time, but struggled significantly with the terrain in many locations and required manual piloting to avoid any significant obstacles. Despite this, it offered significantly better speed compared to later systems.

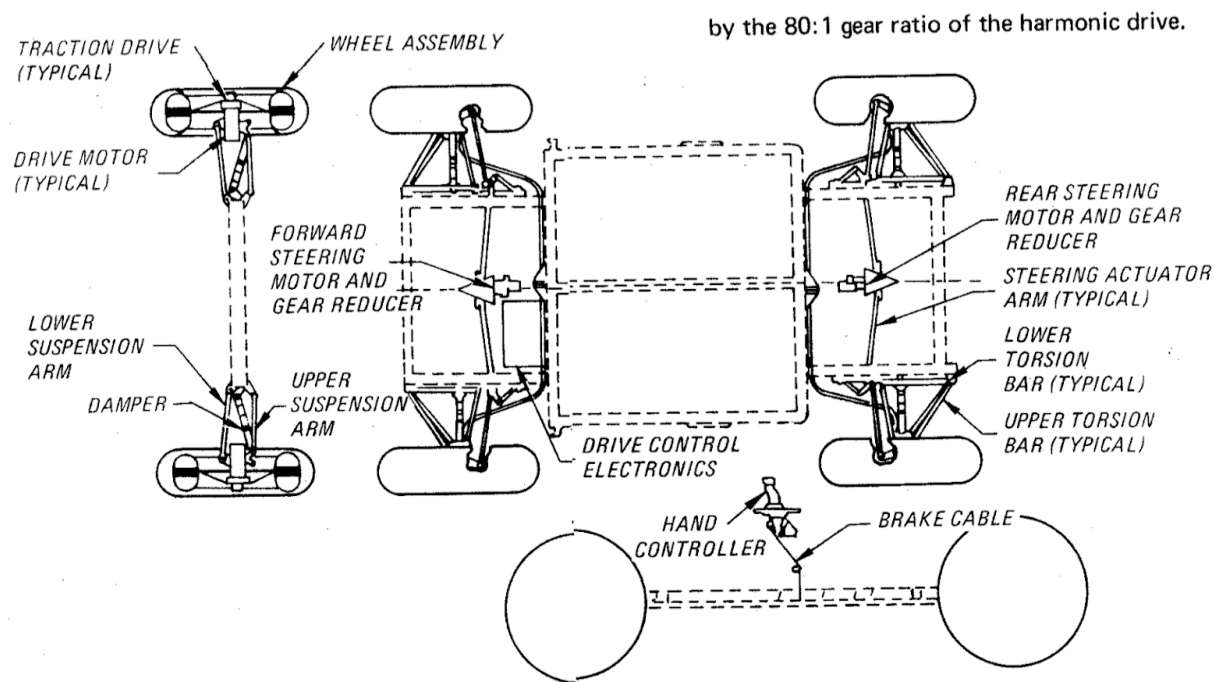


Figure 2: Apollo Suspension System

Rocker Bogie (1988): The Rocker Bogie system was first developed in 1988 by NASA's Jet Propulsion Laboratory. First applied on the mars rover Sojourner, it has been the golden standard for rovers since. It operates through the use of a bogie, which is two arms connected at an angle, connected to and moving relative to a rocker, which is another set of arms connected to the rover and constituting the rear wheels. This enables near constant contact with the ground with all wheels and allows the rover to overcome significant obstacles. This often comes at the expense of speed, requiring significantly slower movement in order to prevent tipping or damage to components.

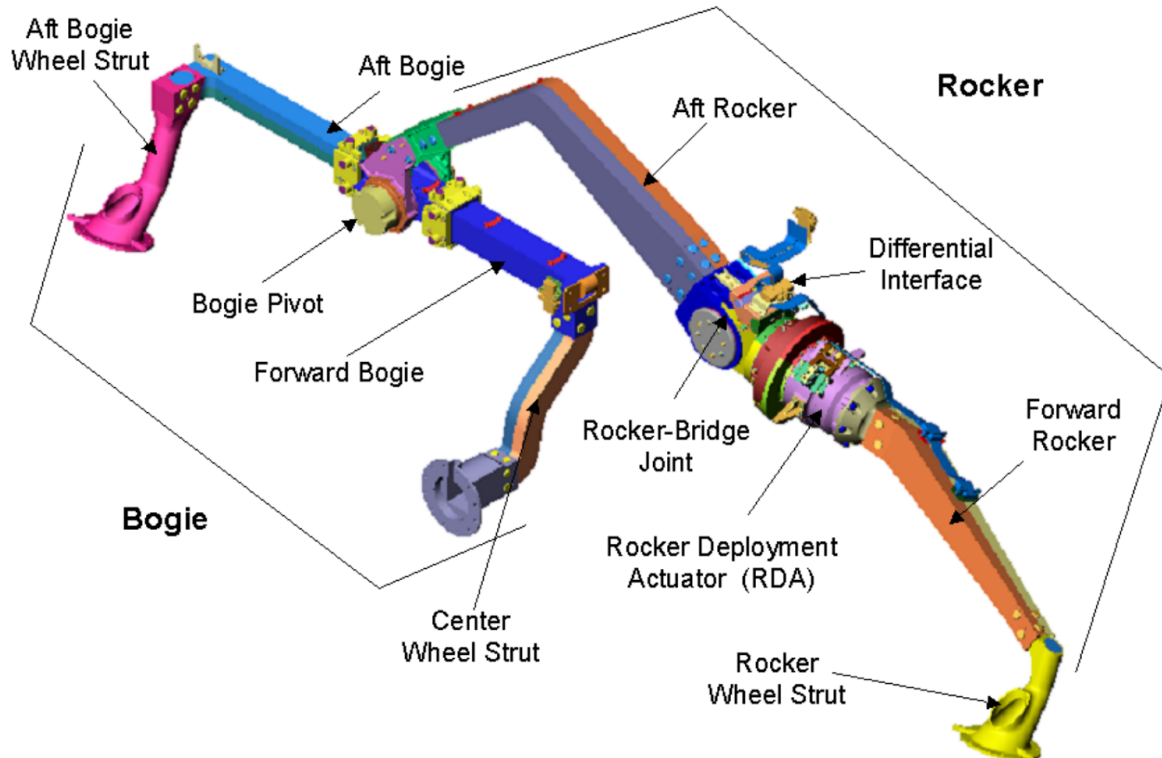


Figure 3: Sojourner Rocker-Bogie

Following its invention, it saw use in the Spirit and Perseverance rovers where it saw further advancements in size and material design. Further optimizations were made over time to its geometry, and the introduction of spring systems to improve its ability to handle higher speeds.

The current state of the art is largely dependent on the objective of the mission and the requirements that this imposes upon the system. The two main systems under consideration are the rocker-bogie, which remains a highly effective, lightweight, and simple system for navigating rough terrain. The second is the obverse-reverse four linkage system, which was first proposed in 2009, and offers some benefit over the rocker bogie in terms of stability and overcoming obstacles at the cost of increased cost and complexity. It operates on similar principles as the rocker bogie, but utilizes additional linkages to further improve flexibility and stability.

I.3.2. Navigation

Apollo Lunar Roving Vehicle (1969): This system utilized dead reckoning systems based on measurements of acceleration and velocity and the time this occurred over. This was then compared to initial positions in order to obtain the current position. The rovers path was predetermined and directly controlled by astronauts or radio signals.

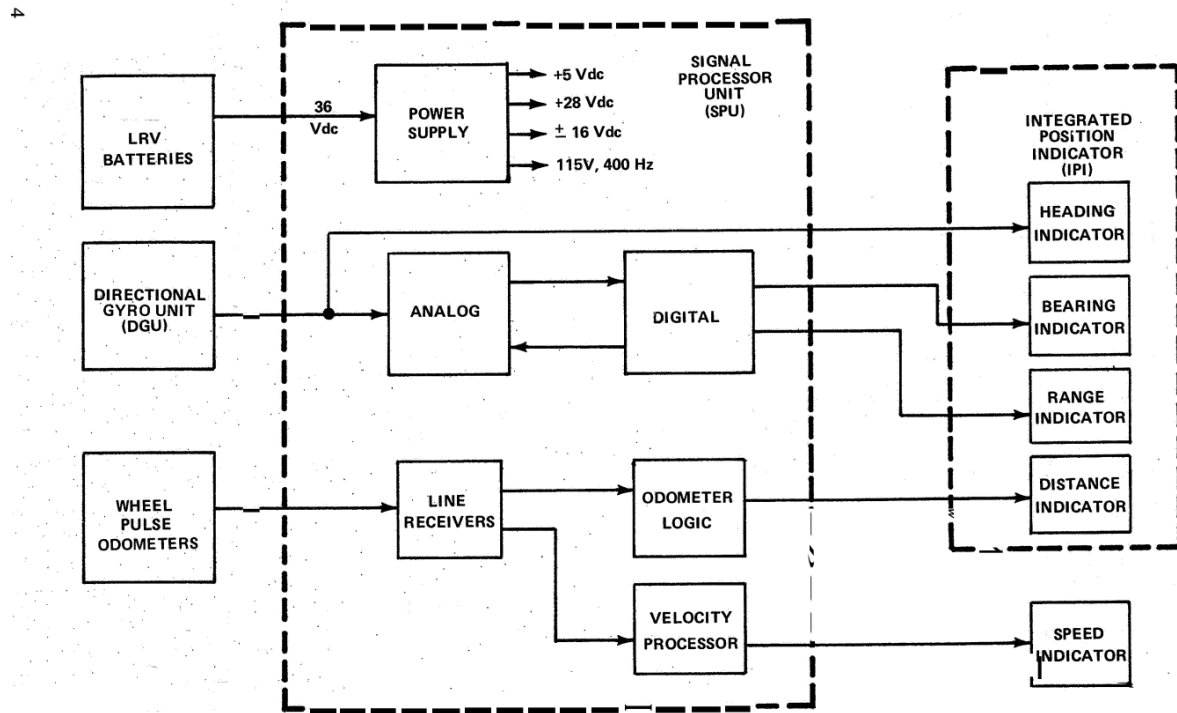


Figure 1. Navigation system block diagram.

Figure 4: Control Diagram for Apollo Roving Vehicle

Lunokhod Rover (1970): Lunokhod 1 was the first remote controlled rover to operate on the moon. It communicated directly with earth via radio signals, sending images of its environment that informed operators responses with controls on what path to follow and at what speed. Due to the distance, there was several seconds between when something occurred on the moon and when instructions could reach the rover making it cumbersome and risky to operate.



Figure 5: Image of Lunokhod 1 rover and navigation systems

Sojourner (1997): This rover, developed by NASA as part of its pathfinder mission, was the first to utilize autonomous systems. It utilized stereo cameras to detect objects in its environment to actively avoid obstructions reducing the need for constant vigilance. It still required user input to target sites of interest however, making it semi-autonomous.



Figure 6: Image of Sojourner and navigation systems

Spirit and Opportunity (2003): These rovers utilized a navigation system known as GESTALT which was able to account for more environmental factors enabling a much greater degree of autonomy than previous systems. However the majority of the navigation design remained consistent with Sojourner.

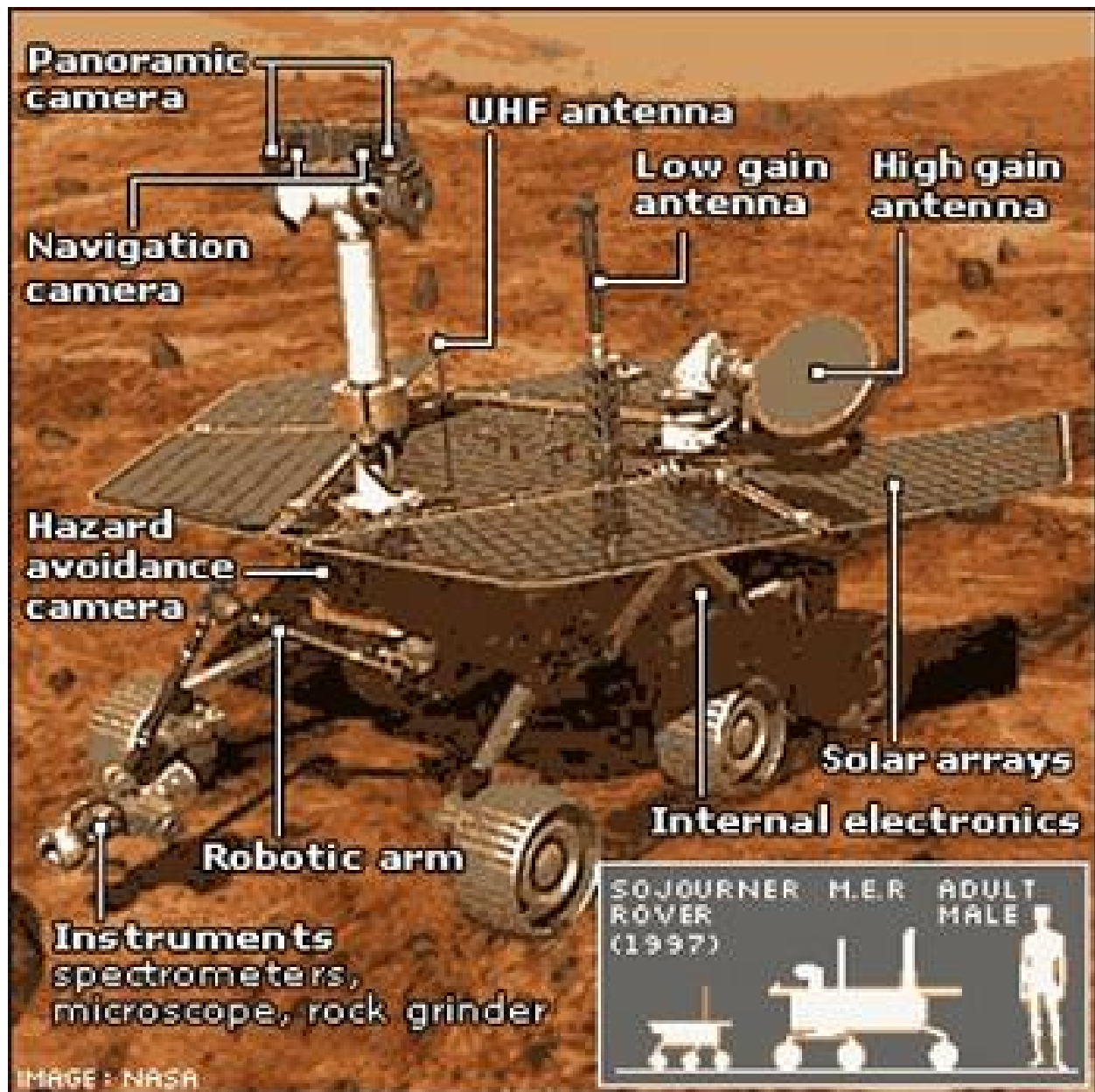


Figure 7: Image of Spirit/Opportunity navigation systems

Perseverance utilized a more complicated autonomous navigation system called AutoNav which operated by creating a 3D map of the surrounding terrain. This was then combined with preexisting data from satellites in order to find the best path around obstacles, ensuring that it could effectively reach its desired location. Additionally, the drone Ingenuity was used to get more detailed information on regions further from Perseverance, further optimizing its route.

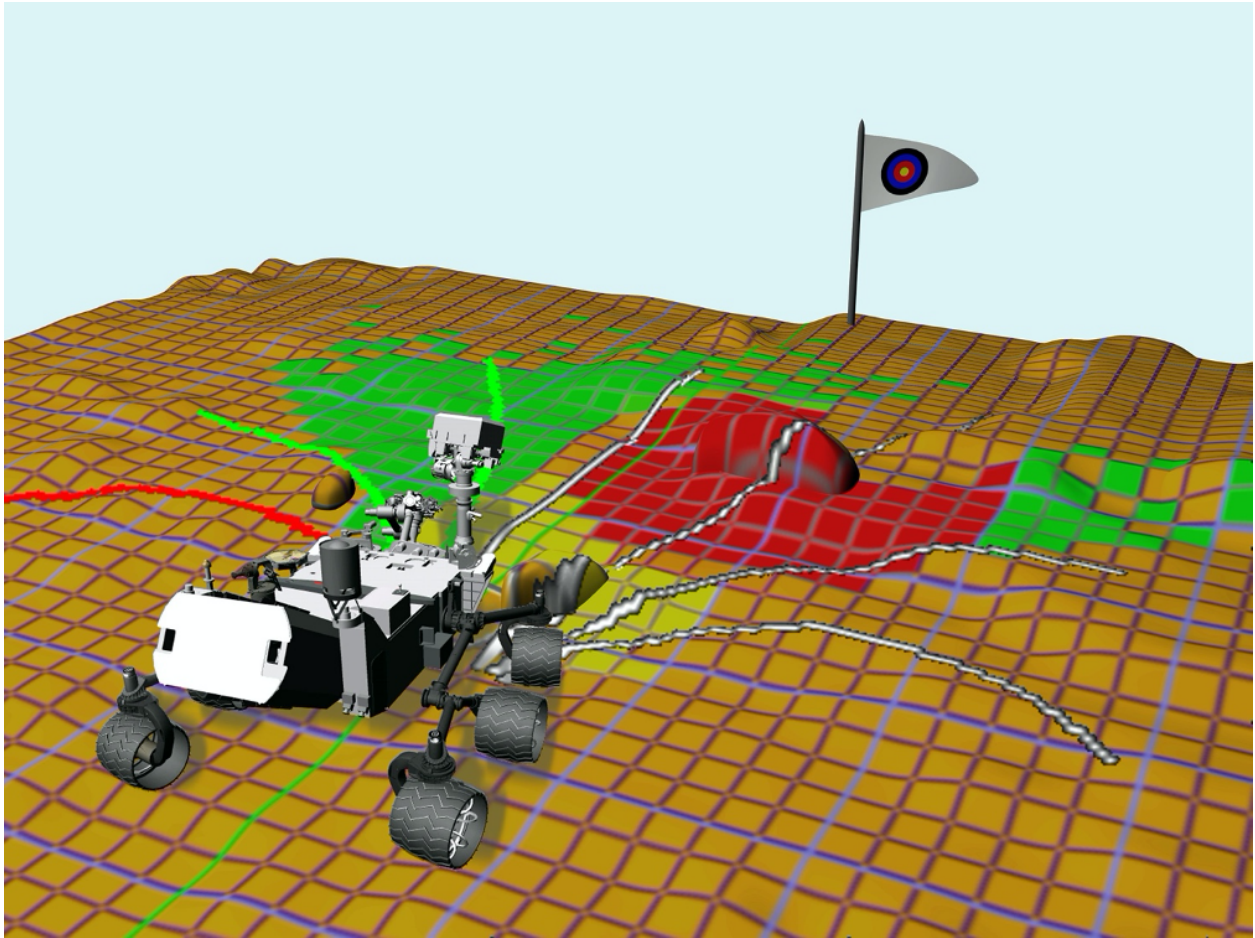


Figure 8: Example of Perseverance's AutoNav system detecting terrain

Overall, the current state of the art for rover navigation technology largely utilizes a combination of onboard sensors to constantly perform low level monitoring of its surroundings through the use of object detection in combination with high level route planning through the use of preexisting data. This generally requires a high level of computing power as well as a stereo camera setup to identify distances.

I.3.3. Structures and Mechanisms

I.3.3.1. Chassis Configuration and Material

Planetary rover chassis designs have a historical tendency to emphasize low mass, high stiffness, thermal stability, and durability through a variety of abrasive environments. NASA rovers are longstanding examples of success in this field, and their designs consistently proving to be effective. NASA's first planetary rover, *Sojourner*, launched in 1996 which utilized a smaller aluminum frame with a box-shaped chassis [8]. Because of mass and power limitations, *Sojourner*'s chassis was minimally instrumented and served the primary purpose of supporting the structure and rigidity of the rover. Some of the main components of this rover are the antenna, solar panel, warm electronics box, cameras/lasers, and alpha proton x-ray spectrometer, shown in Fig 9.

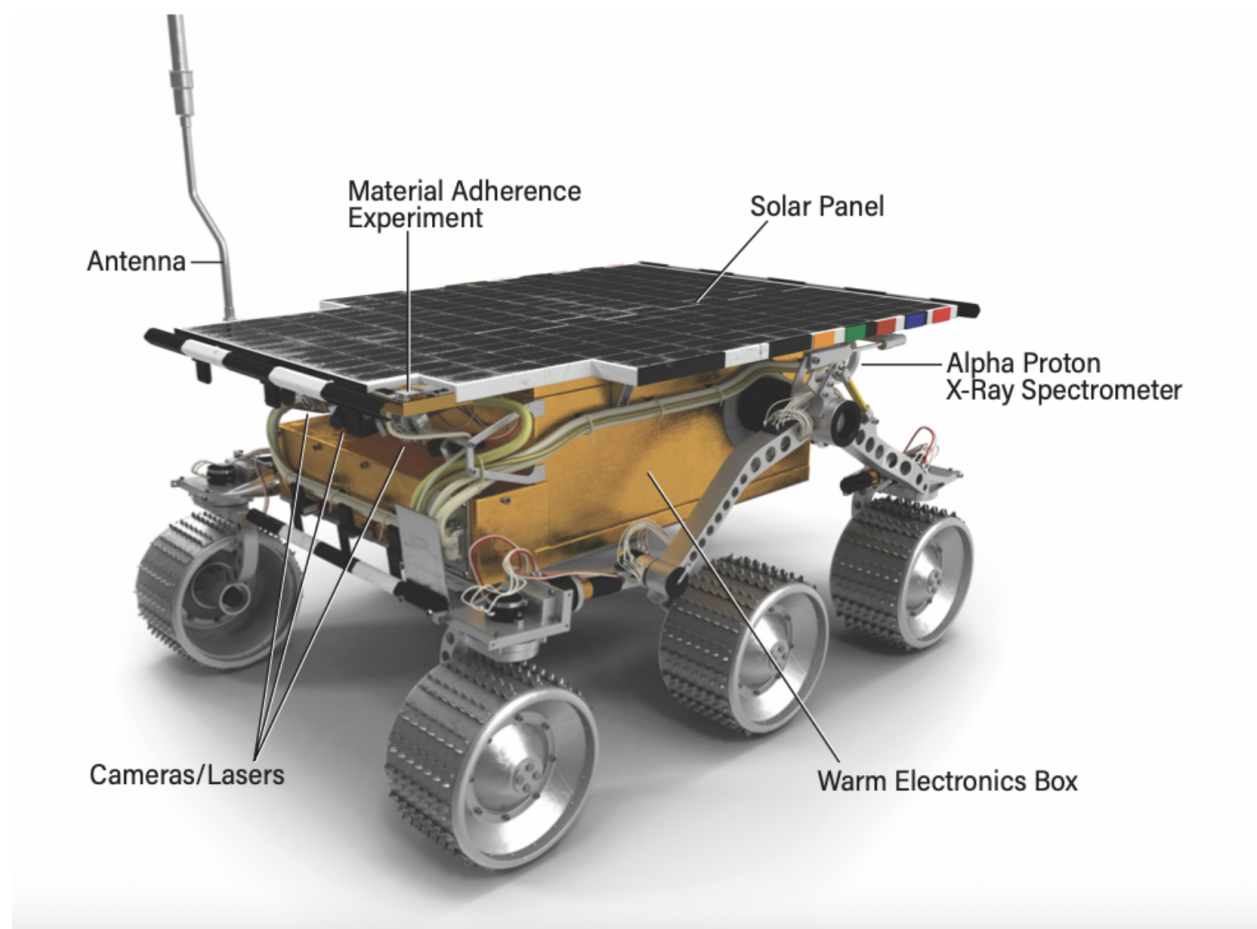


Figure 9: Sojourner Configuration and Components [1].

Building on Sojourner, the Mars Exploration Rovers (MERs), *Spirit* and *Opportunity*, launched in 2003,

and both had a larger, stiffer framework made of aluminum. These chassis were equipped with larger load paths and reinforced decks to support heavier science payloads. Internally, the main body of the MERs consisted of the warm electronics box (WEB), which is a protected, insulated compartment that houses the main electronics of the system. This included all temperature-sensitive electronics such as the computer. This was built from a composite honeycomb material and insulated with aerogel to keep the components functioning in the cold martian environment [2].

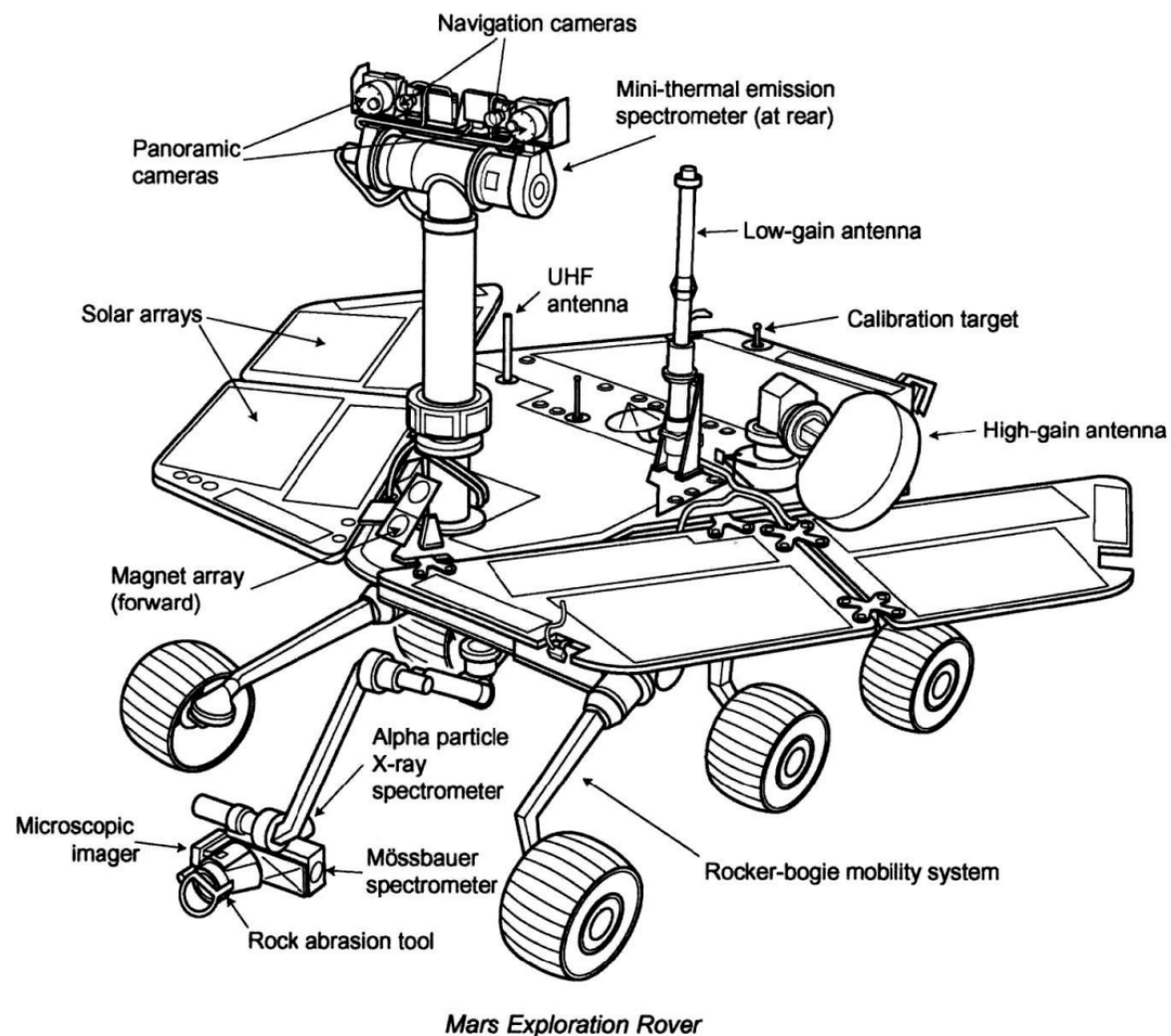


Figure 10: Mars Exploration Rover [2].

The Curiosity rover, launched in 2011, featured a transition in material to higher strength aluminum alloys such as aluminum 7050 and 7075. Titanium was also utilized in high stress areas to ensure rigidity and support mass balance. This alteration was caused by the growing demands of the rover as load mass and rover mass increased. These requirements were tackled through an updated chassis, that was characterized by the formulation of the WEB. The frame incorporated longerons and bulkheads designed to withstand unprecedented mobility loads and the forces from the Sky Crane landing system. The design also provided high torsional rigidity for the many intricate bays, decks, and mounting points [9].

The Perseverance rover, launched in 2021, is NASA's most recent Mars rover mission, which was tasked with searching for signs of ancient microbial life, defining the planet's geology and climate, and collecting samples of Martian rock and soil. In order to accomplish these demanding tasks, NASA built on the Curiosity rover and improved many aspects. Perseverance is the largest rover NASA has sent to Mars, measuring 10 x 9 x 7 feet and weighing 2260 pounds [10]. The chassis houses the rover's computer and electronics within the WEB while also incorporating a rover equipment deck on top for instruments such as cameras and spectrometers. The key materials that Perseverance utilizes are aluminum and stiff titanium for structure and wheels, which are thicker and have different treads than the previous Curiosity rover's wheels.

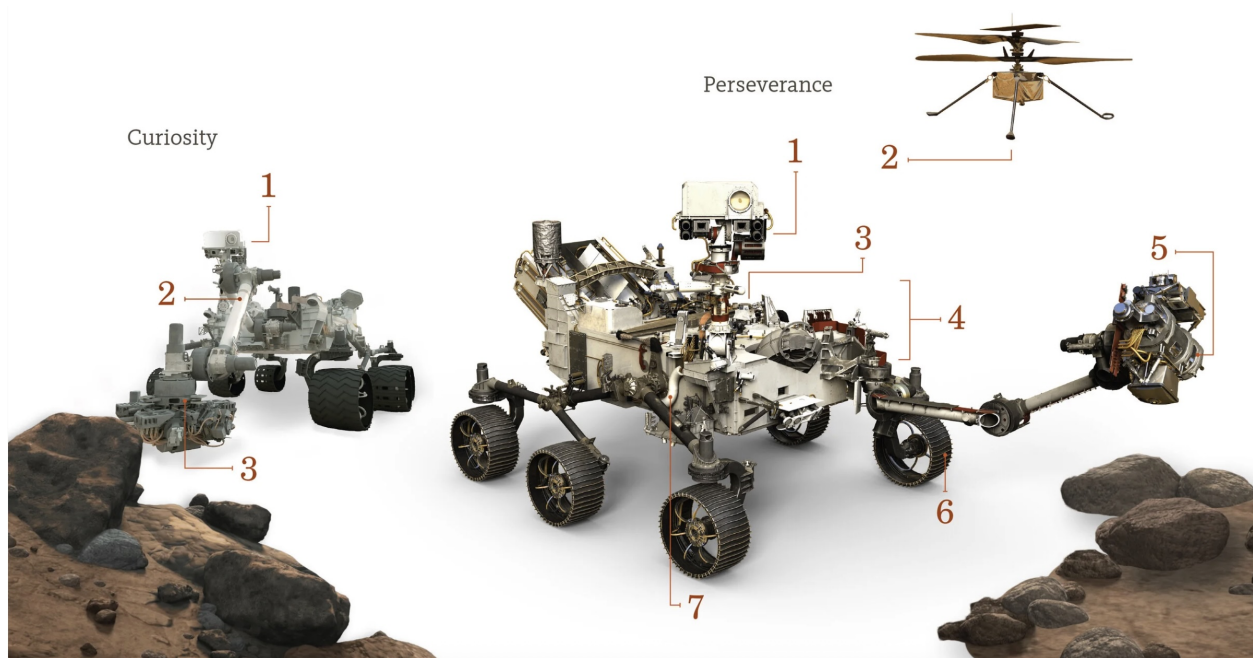


Figure 11: Curiosity and Perseverance Mars Rovers [3].

I.3.4. Drill

The drills on most lunar and martian rovers use a combination of high strength metals to handle the intense loading from the rotary-percussive drill and the rocks it is cutting through. For the actual cutting tips, tungsten carbide bits are used, which can handle the hard surface of the rock. For the rest of the bit it is typical to have heat treated steel or titanium.

I.3.5. Payload

I.3.5.1. Storage

REHT's primary inspiration for storage capabilities similar to that of the Mars Perseverance Rover on its mission back in 2020 to 2021. Not only is this one of the more recent examples of extraterrestrial sample collection to date, the Artemis mission of returning to the moon which the RASC-AL is based off is a direct step for humanity's trip to Mars [6]. Thus is it beneficial to keep some core aspects of their design similar. One such core aspect is the storage capabilities.

The Mars Perseverance Rover uses titanium sample tubes. With a diameter of 23 mm, a length of 142 mm without its 2 mm seal, and a base weight of 57 grams, 43 of these sample tubes were sent up with

the Mars Perseverance Rover for sample extraction and analysis. Each sample tube is slated to collect 15 grams of dust the surface of Mars. The outer portion is made primarily of titanium to ensure the structural integrity of the sample tube. Additionally, it has alumina coating on the outside and titanium nitride coating on the inside to protect samples from potential thermal loading upon the surface of Mars, primarily from that of the sun [6].

The way in which sample collection is done on-board the Mars is through an automated process. First, after a sample is collected through a drill bit, it is hermetically sealed inside a sample tube. The tube is sealed by a small servo motor on-board the rover. Keeping these tubes sealed allows the sample to be preserved until the rover's retrieval in 2031 [11]. Once sealed, the sample is grabbed by a robotic arm and stored on a rack in the "belly" of the rover. Thirty-eight samples are collected in total over the course of the mission, having five witness tubes act as a control sample to see how particles from Earth are affected in Mars' atmosphere [12].

While the Mars Perseverance sample tubes account for some insulation and thermal loading, the scope of REHT's sample conditions go beyond that of the Perseverance rover. This is because the primary sample collected from the lunar surface will be helium-3. One study was conducted by the National Space Science Center in Beijing, China to analyze the thermal release of helium-3 within lunar regolith. After conducting an experiment on ilmenite with a similar chemical makeup to that of the lunar regolith extracted from the Apollo mission back in the 1970's, the researchers were able to find how much each element would release from the ilmenite based on temperature increase. These findings in relation to Helium-3 are listed in the figure below [4].

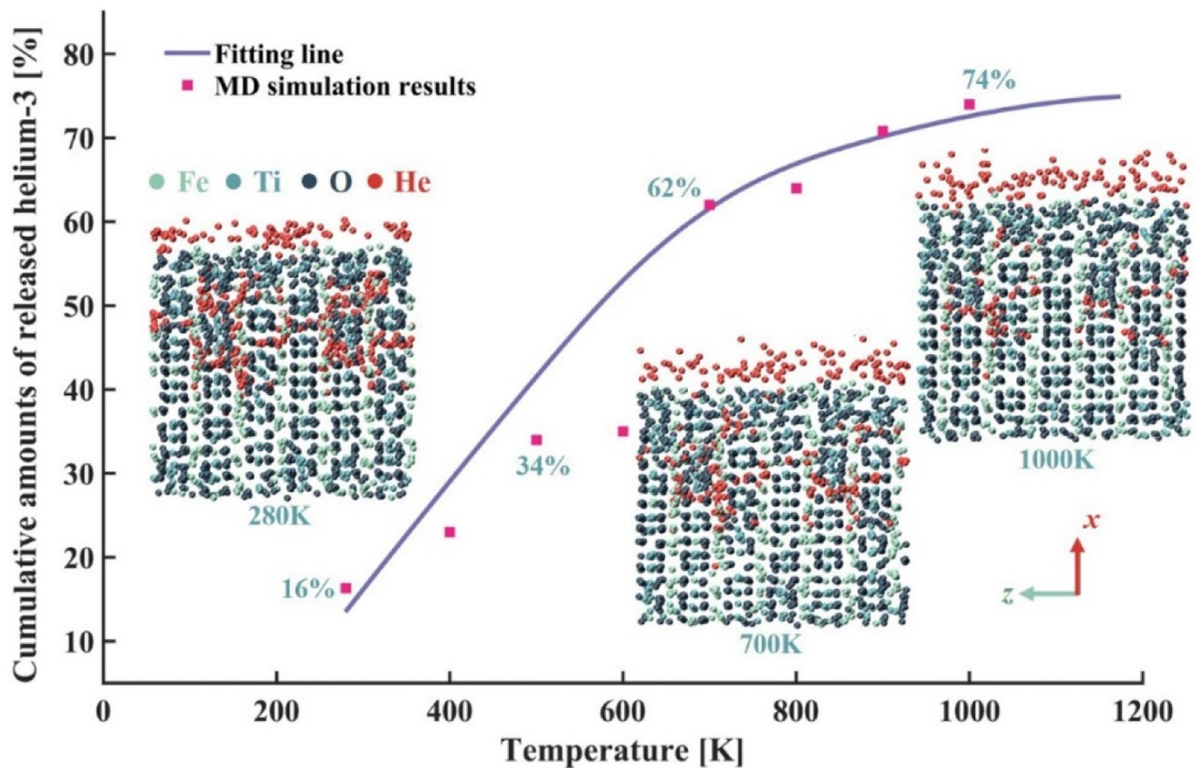


Figure 12: Variations of Helium-3 Released with Temperature [4].

In the figure, it is seen that the higher the temperature raised on the ilmenite, the more Helium-3 is released. It reaches up to a release rate of 74% at over 1000 K. On the other hand, roughly 16% was released at a temperature below 250 K [4]. Considering REHT is meant to preserve the Helium-3 within the samples of lunar regolith, this study illustrates the importance of keeping these samples at a low temperature. Thus, not only should the thermal systems accommodate for keeping the samples at low temperatures, the samples themselves must be able to hold these temperatures.

As such, the model of these sample tubes and how they are stored on-board REHT is heavily based off the Mars Perseverance mission. The titanium sample tubes from that mission provide a good basis for dimensions, collection methods, storage methods, and sealing of samples. The study on helium-3 release with temperature also provides a good basis on how the samples should be stored; allowing some to be stored within a section of storage with limited thermal capabilities as a control sample and others to be stored in a refrigerated storage to better preserve compounds such as helium-3 and ice.

I.3.5.2. Spectrometer

Lunokhod 1, as seen in Figure 7, was the first remotely controlled rover on the lunar surface with a spectrometer. The rover used an APXS, an alpha particle x-ray spectrometer, to perform soil analysis on the lunar surface.[13] This pioneering use of a spectrometer on a rover proved to be a direct predecessor of the now-famous series of Mars rovers in the modern era. Sojourner was the first of the Pathfinder rovers on the Martian surface. It was equipped with a similar APXS and multiple cameras.[14] A spectrometer was a preferred solution to in-situ scanning and analysis of samples, providing preliminary data to scientists on Earth rather than depending upon expensive and complex missions to bring back soil samples to Earth.

The next in line were the two MER robots, Spirit and Opportunity. They were the first rovers to Mössbauer spectrometer on board on Mars. These spectrometers were used to identify iron-bearing minerals on the Martian surface, yielding information about the early Martian environment. Apart from this, the MERS robots also used a Miniature Thermal Emission Spectrometer to identify the mineralogy of rocks on the Martian surface and an APXS to get information about the crustal surface of Mars.[15]

Lastly came the Curiosity and Perseverance rovers on the Martian surface. These rovers were mini laboratories with multiple cameras and spectrometers to collect samples and analyse the Martian surface. But, the most eye-catching technology they used was the ChemCAM (Curiosity rover) and SuperCAM (Perseverance rover) spectrometers. These marked a leap in the capabilities of extra-terrestrial rovers as they marked the first use of Laser Induced Breakdown Spectrometer or LIBS.[16] All of this information is important to identify the use of correct instruments on REHT. Given REHT's mission to identify and collect samples of the lunar regolith containing Helium-3, it is important for REHT to first identify promising samples before collecting them to avoid wasting the precious storage space it has.

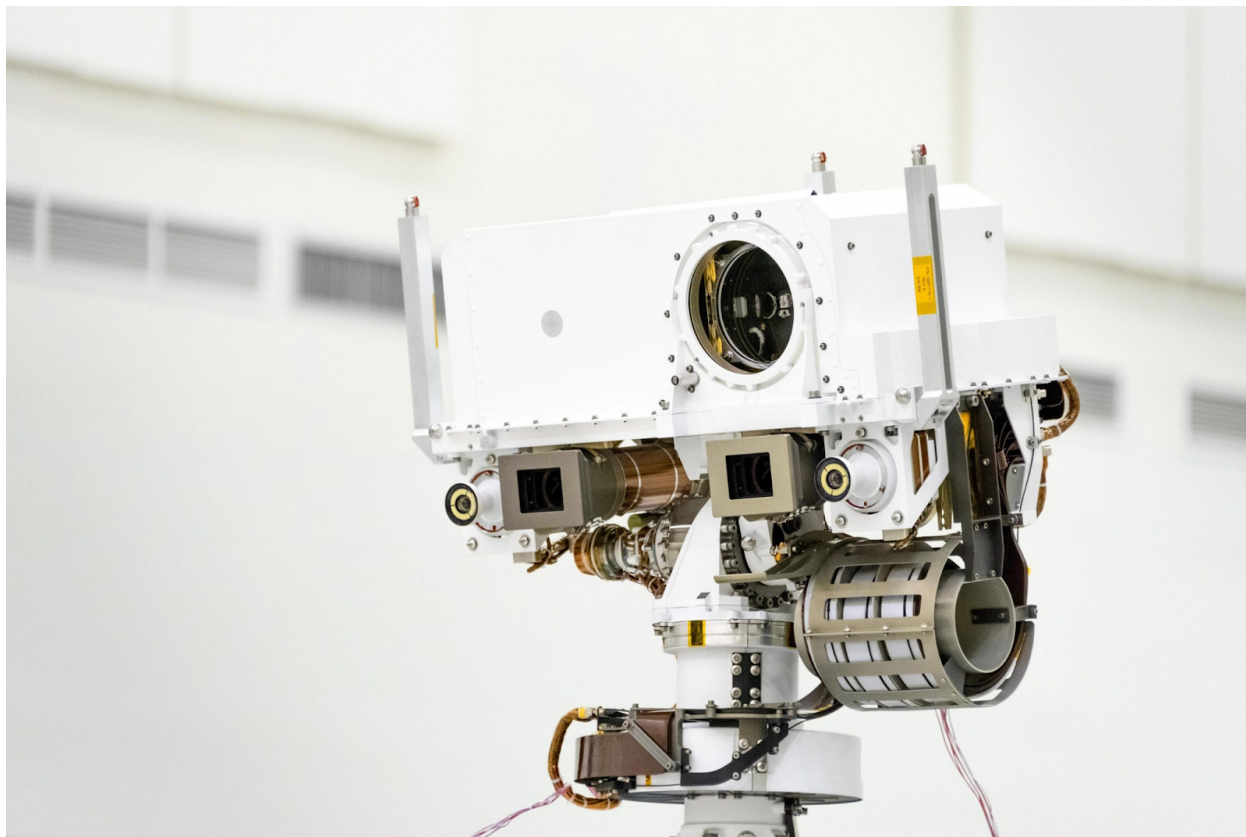


Figure 13: SuperCAM on the Mars Rover Perseverance; LIBS Laser Included

I.3.6. Power and Electrical

Lithium-ion batteries are commonly used on modern rovers. Such was the case for the Mars rovers Spirit and Opportunity, their missions starting in January 2004 and operating to a similar capacity as REHT's mission. The batteries themselves are split up into eight 10 Ah cells with a voltage of 3.6, meaning they hold 288 Wh per battery. Capable of operating between -30 to 40, these batteries were meant to operate under a mission length of 90 sols [7]. Both lasted over 4900 sols, with their mission lengths extended beyond 2011. With a battery mass of 7.15 kg [17], this brings the specific energy to 40 Wh/kg. Given that REHT is designed to operate for about a year in Earth's time, these batteries are more than enough to hold the mission with the use of solar panels.

I.3.7. Thermal Systems

With the extreme environment of space and extraterrestrial planets, thermal systems are an important part of any spacecraft or rover. Historically, these thermal systems have evolved from being simple and passive to complex and active systems that reliably control the temperature of the spacecrafts and rovers. For example, the earliest Lunar and Martian missions relied heavily on radioisotope heating units and other passive heating systems. The Lunokhod lunar rovers used polonium-210 radioisotope heating systems to maintain rover temperature during cold nights on the lunar surface.[13] These were then combined with other forms of passive heating like multi-layer insulation, surface coatings, and even aerogel to keep the heat inside the rovers. The MERS rovers Spirit and Opportunity also used radioisotope heating units with 8 units for each rover.[18]

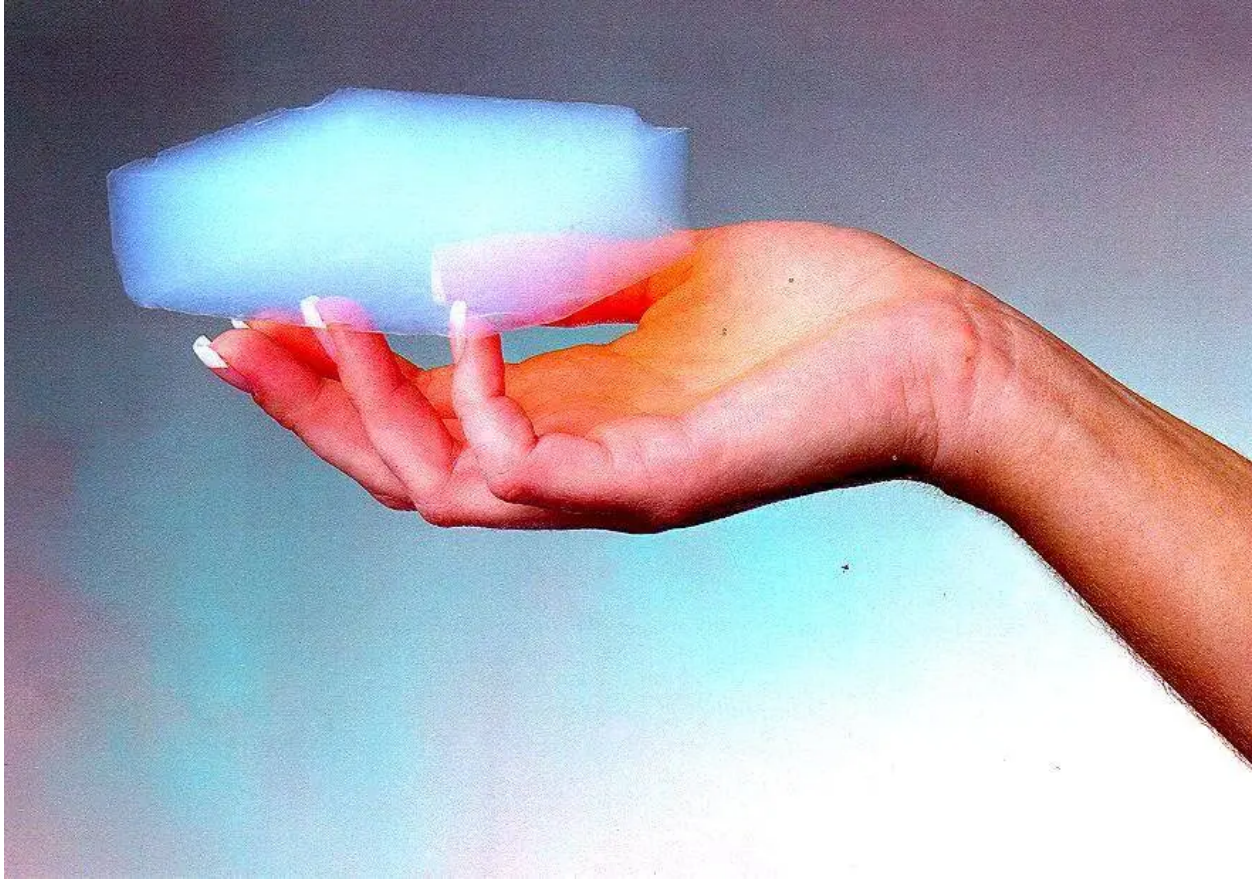


Figure 14: Aerogel used on Stardust Spacecraft 2004

Some of the other passive systems are heat rejection systems like radiators and louvers. These help with heat rejection and keep the rover and its components cool during extremely hot periods on extraterrestrial surfaces.



Figure 15: Rosetta Passive Thermal Louvers, European Space Agency

The latest rovers, Curiosity and Perseverance, used a more advanced and active system known as a mechanically pumped fluid loop system. These rovers pioneered the use of MPFL to actively circulate fluid around the rover, catching all the waste heat and circulating it back to parts of the rover where it is needed.[19] This helped keep the electronics cool and made efficient use of the waste heat. These rovers also use resistance heaters and thermo-electric coolers for specific components like the spectrometer, to regulate the temperatures with more precision.

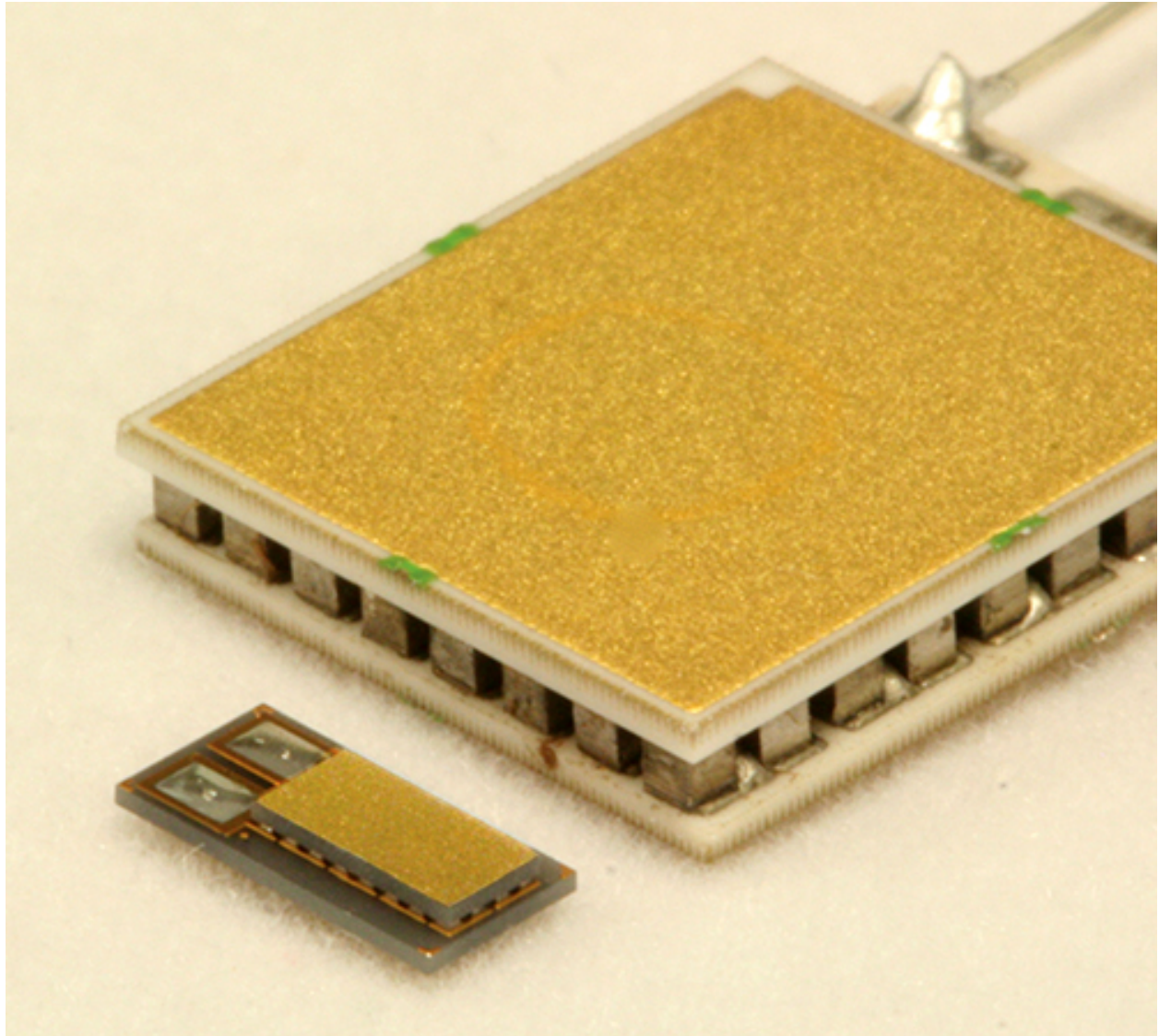


Figure 16: Extremely Small Nextreme Thermoelectric Coolers for Microchip Cooling

I.3.8. Ground System

Ground stations constitute the Earth-based segment of deep-space communication architectures, providing telemetry, tracking, command, and data reception. For lunar missions, such as what what plan for RHET, place strict requirements on ground-station performance due to the large Earth–Moon distance and resulting free-space path loss. Farkasvölgyi et al.[20] note that the lunar link introduces roughly 20,dB more loss than GEO communication, necessitating high-gain antennas, low-noise receivers, and accurate pointing on the ground. Their review also highlights the long operational history of direct Earth–Moon radio links and the parallel development of ground-station capabilities used to support them.

The introduction of lunar communication relays further shaped ground-station roles by shifting some link responsibilities to lunar orbiters while maintaining Earth-based stations as the final node in the communication chain. These relay architectures require coordinated scheduling and consistent compatibility with ground-segment receivers, reinforcing the importance of stable RF systems and reliable link maintenance. Overall, the literature shows that ground stations remain a critical component of lunar communication systems, enabling continuous command capability and the return of scientific and engineering data to Earth.

NASA has built its own space communication networks over time to support missions from low Earth orbit all the way to deep space. The earliest ground stations were created during the Mercury and Gemini programs, when NASA needed a way to stay in contact with spacecraft as Earth rotated. These early stations were spread around the world and gave NASA basic tracking and communication coverage. As missions grew more complex, NASA developed more permanent and capable facilities, leading to the creation of the Deep Space Network (DSN) in the 1960s.

The DSN[21] is made up of three large ground-station complexes located in California, Spain, and Australia. This spacing allows at least one station to “see” a spacecraft at all times. Each site uses large dishes to handle the weak signals coming from deep-space missions like Voyager, Mars landers, and outer-planet probes. The DSN became the backbone for long-distance communication and is still used by nearly every NASA mission operating beyond the Moon.

For missions closer to Earth, NASA created the Near Earth Network (NEN)[22]. Instead of using huge antennas, the NEN uses smaller ground stations around the world to support satellites in low Earth orbit, lunar orbit, and similar distances. These stations handle routine tasks like sending commands, downloading science data, and tracking spacecraft during passes. The NEN works alongside the DSN and gives NASA more flexibility by covering different orbits and mission types. Together, the DSN and NEN form NASA’s main communication infrastructure, allowing the agency to keep in contact with spacecraft across the Solar System.

I.3.9. Communications

Communication devices are the hardware that actually send and receive data between a spacecraft and a ground station. Most systems follow the same basic setup: a radio transceiver, an antenna, and the electronics that manage power, frequency control, and data encoding. According to Wertz Larson (1999) [23], nearly all deep-space and lunar missions rely on stable RF transmitters that can operate for long periods without drifting off frequency. These devices must be lightweight, reliable, and able to survive temperature swings and radiation.

NASA commonly uses S-band, X-band, and sometimes Ka-band radios depending on the mission’s needs. Wertz Larson explain that S-band is good for simple, low-rate links, while X-band and Ka-band allow higher

data rates but need more accurate pointing. Antennas can range from small patch antennas on landers and rovers to larger dish antennas on orbiters. Patch antennas are simple and durable, while dishes provide higher gain when more data needs to be sent.

The way data is packaged is also handled by the communication device. Radio hardware uses modulation, coding, and signal amplification so the ground station can pick out the signal through noise. NASA documentation notes that spacecraft radios usually include a transponder, which both listens for commands and sends telemetry back to Earth.

Overall, the literature shows that communication devices need to balance power, mass, reliability, and data rate. Even though designs vary, most missions still rely on proven RF radios, sturdy antennas, and flight-qualified transponders because they are predictable and well understood.

I.3.9.1. Antenna

Antennas have been central to space communication since the beginning of the space age. Early spacecraft relied on simple monopole and dipole antennas, but deep-space missions quickly required much higher gain. This led NASA to develop large parabolic dish antennas for the Deep Space Network, beginning in the early 1960s. The Goldstone 64-meter dish became one of the first major high-gain antennas designed specifically for interplanetary communication, supporting missions such as Mariner and Apollo [24]. As missions traveled farther from Earth, antenna surface accuracy and pointing precision continued to improve, and NASA adopted new technologies such as beam-waveguide antennas, which guided the radio signal through a series of mirrors to a protected equipment room [25]. These innovations made it possible to receive extremely weak signals from spacecraft millions of kilometers away. Even early communication satellites like Telstar used specialized antenna types, such as helical microwave antennas, to support the first transatlantic television transmissions [26]. Overall, the history of antennas in space communication shows a steady progression toward higher gain, better accuracy, and greater efficiency as mission distances increased.

I.3.9.2. Transceiver

Communication transceivers have also evolved as spacecraft traveled farther from Earth. Early satellites such as Explorer 1 used simple low-power transmitters with very basic modulation [27]. These early systems could only send small amounts of data, often just a few bits per second. As technology improved, spacecraft began using more stable oscillators, better amplifiers, and clearer modulation schemes, which made links more reliable.

By the time NASA started sending probes to the Moon and other planets, missions required two-way communication. This led to the development of full transceivers that could receive commands and send back data using the same radio hardware. Deep-space missions eventually adopted X-band and, later, Ka-band transceivers, which allowed higher data rates and stronger error-correction methods [28]. The Deep Space Network expanded alongside these upgrades, supporting the new frequencies and helping spacecraft maintain a stable link even at extreme distances.

Today's space transceivers use digital modulation, high-efficiency amplifiers, and software-controlled radios, but the core idea remains the same as the earliest missions: provide a stable connection between a spacecraft and Earth so commands and data can move reliably between them.

II. Project Description

II.1. Project Purpose

The Rover for Extraction of Helium Three (REHT) aims to take samples of the lunar regolith in areas where Helium-3 is believed to be present in large quantities in order to ascertain the quantity present and the depth in order to produce a more comprehensive and accurate understanding of its distribution across the moon. It will be taking measurements using a spectrometer, before collecting samples at zero to three meters of depth. From here it will transport these samples to an ascent vehicle to be stored and eventually launched back to earth.

II.2. Mission Statement

REHT shall extract dust containing concentrations of helium-3 and any other extraneous matter (such as ice) over the course of a year in Earth's time. The following subsystems will allow the REHT to complete said objective.

Navigation and Controls: Transfer data between rover and ground station; maneuver around the lunar surface.

Structures and Mechanisms: Survive adverse lunar and thermal conditions; drill beneath surface for sample extraction.

Payload: Store and analyze collected samples.

Power and Electrical: Provide power generation for systems and subsystems.

Thermal Systems: Provide passive and active thermal systems for sustainability of other subsystems.

II.3. Critical Project Elements

Table 3: Technical and Operational Critical Project Elements

Technical		
M.1	Standards	REHT must reach a minimum TRL of 4.
M.2	Power System	Rechargeable solar batteries must supply for all rover systems for duration of mission.
M.3	Communication and Data Handling	REHT must transmit data through satellite uplink back to the customer.
M.4	Structures and Materials	REHT must be lightweight and capable of holding a payload.
M.5	Propulsion	REHT must be capable of traversing lunar landscapes.
M.6	Payload	REHT must recover 150 kilograms of dust containing Helium-3.
M.7	GNC	REHT must travel without requiring customer input.
M.8	Thermal Survivability	REHT must withstand thermal loading of the lunar surface.
M.9	Payload Survivability	100 kg of lunar dust container Helium-3 must remain unconditioned for a return trip to Earth.
M.10	Payload Thermal Survivability	50 kg of lunar dust container Helium-3 must remain refrigerated for a return trip to Earth.
Operational		
O.1	Communication	REHT must relay its location to the customer.
O.2	GNC	REHT must detect and avoid obstructions on the lunar surface.
O.3	Material Survivability	REHT must withstand adverse lunar conditions.
O.4	Sample Retrieval	REHT must drill beneath 2 meters of lunar surface to reach desired sample.

Table 4: Logistical and Financial Critical Project Elements

Logistical		
L.1	Sample Site Selection	REHT must identify ideal locations to drill based on ground-penetrating radar.
L.2	Sample Identification	REHT must identify dust containing Helium-3 through a mass spectrometer.
L.3	Sample Collection	REHT must be capable of collecting Helium-3 underneath the lunar surface.
L.4	Sample Analysis	REHT must analyze collected samples on-board with a spectrometer.
L.5	Thermal Analysis	REHT must identify if the sample is frozen through the on-board temperature probe.
L.6	Thermal Sorting	REHT must sort unconditioned and frozen samples in separate storage compartments.
Financial		
F.1	Sub-Scale Manufacturing	Must assemble sub-scale REHT within budget constraints of 2000 dollars.
F.2	Manufacturing	Must assemble REHT within budget constraints.

The Critical Project Elements (CPEs) of REHT establish the parameters of the mission and the design the rover should have to carry out said mission. These project elements are split into four parts: Technical, Operational, Logistical, and Financial. Technical CPEs introduce the mission objectives and what REHT must do to accomplish said objectives. These give the parameters needed for the rover to survive the lunar environment. Additionally, they give the parameters for payload extraction and subsequent storage. Operational CPEs focus on how REHT shall accomplish its mission objectives listed in the Technical CPEs. The main focus here revolves around maneuverability and the capability to extract samples. Logistical CPEs focus on the analysis conducted during the mission. Much of this analysis is onboard the rover to determine sample concentrations and temperature. Lastly, Financial CPEs highlight the budgetary constraints found in the manufacturing of REHT.

II.4. Concept of Operations

The concept of operations illustrates the mission cycle that REHT will undertake. Once REHT is transported to the Moon through the Artemis program, the rover will scan the lunar surface with the spectrometer to detect any helium-3 concentration in the soil. If present, the onboard drill will excavate two to three meters deep to extract subterranean dust and store it within temperature-controlled units (0 °C for control samples, and below that for refrigerated samples).

The rover will navigate based on the data transfer established between the rover, satellites orbiting the Moon, and a ground station on Earth. From there, REHT will travel from site to site and continue digging until its storage is filled. Once its storage is full, it will travel to a predetermined launch site and replace the filled sample tubes with new ones provided by the launch vehicle. With new sample tubes onboard, REHT can continue collecting lunar dust until its storage is filled again. Thus, it operates in a constant loop of

extracting samples and transferring them to the designated transfer vessel bound for Earth. This loop will continue until REHT collects a total of 150 kg (100 kg controlled and 50 kg refrigerated) of lunar dust.

Once the mission is complete, REHT will travel to the launch site and board the ascent vehicle with its final set of collected samples. The ascent vehicle will then return to Earth with the rover onboard, leading to the rover's recovery and subsequent analysis of the lunar dust.

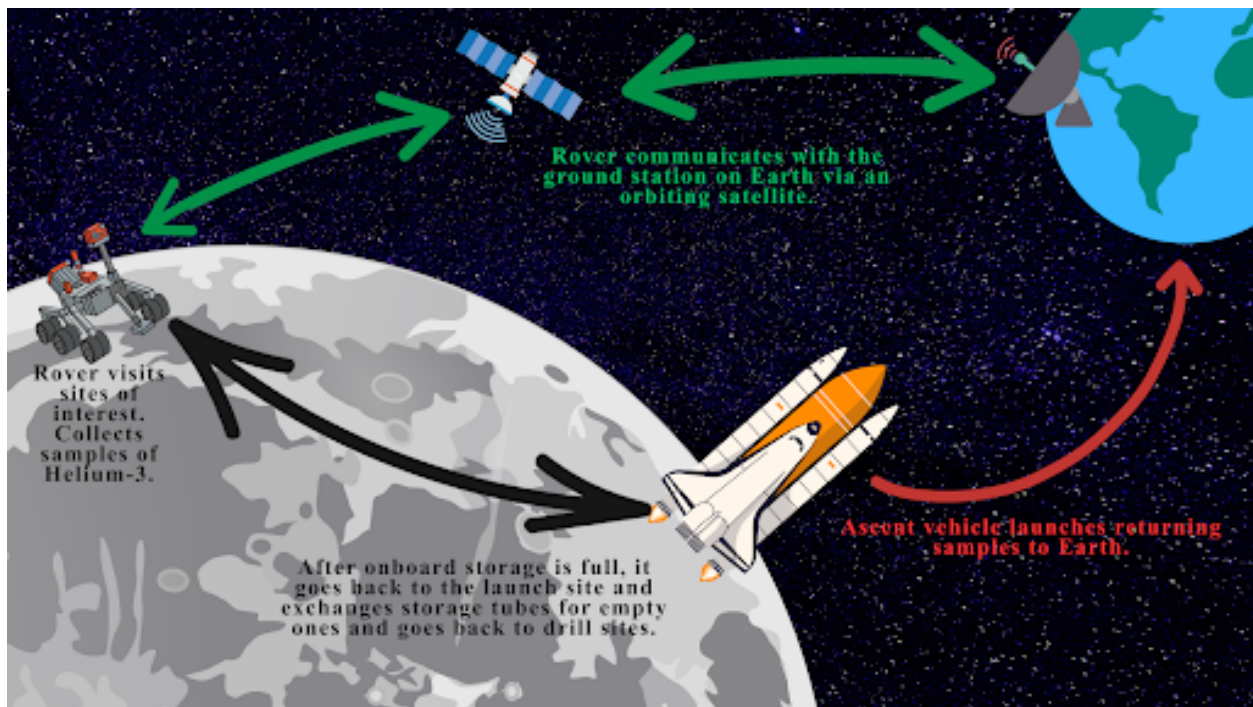


Figure 17: Concept of Operations Diagram

II.5. Functional Block Diagram

The block diagram below highlights various subsystems of REHT and how they interact with each other. It starts from the solar radiation from which the solar panels on REHT harvest energy to recharge the battery. If the battery is completely recharged, the power from the solar panels is redirected to subsystems in need of power. The rover uses an electric power train powered through motors. The power also goes to subsystems like the drilling and storage units, the spectrometer and data processors, batteries and electronics, communications systems, and the passive and active thermal systems. The passive and active thermal systems play an important role by keeping the whole rover and all the subsystems operational through the Moon's harsh temperature range. The passive thermal systems collect heat from heat generating components like batteries, electrical system, and drill and provide it to systems in need of heating during cold temperatures. On the other hand, passive systems also try to prevent rapid temperature fluctuations for different instruments along with keeping them insulated from heat and cold. The active systems help maintain a precise temperature from rover components like the spectrometer, batteries, sample storage system, and the drill to keep the samples and subsystems within desired temperature range for peak performance. Lastly, the communications unit collects data from sample analysis and sends it back to ground stations on Earth via a satellite orbiting the Moon allowing for preliminary analysis of the lunar surface.

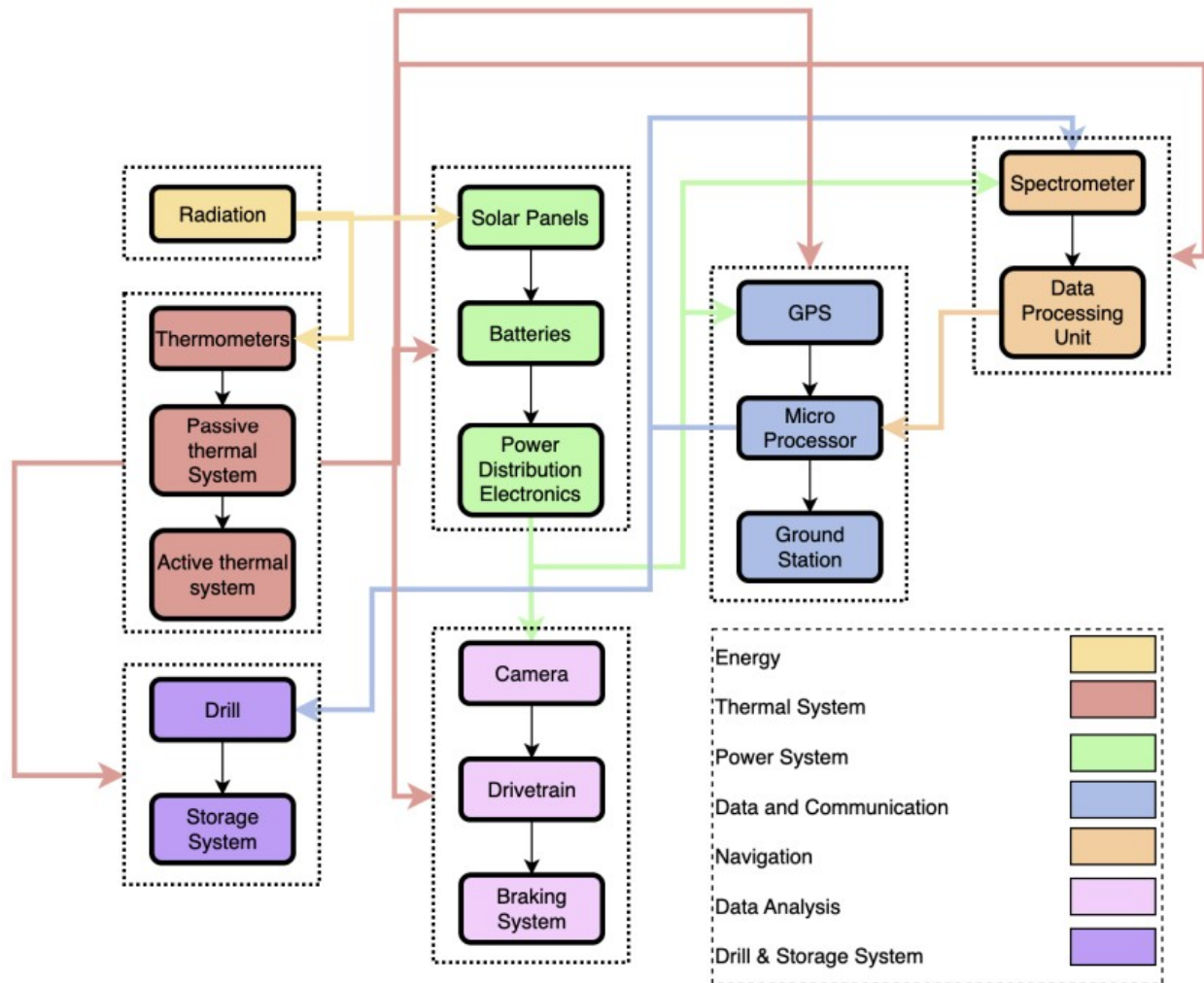


Figure 18: Functional Block Diagram of REHT's Subsystems

Table 5: Technical and Operational Critical Project Elements

Technical		
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II.6. Design Requirements

II.6.1. Navigation and Controls

FR.1: REHT shall be capable of autonomously traversing the distance between sites of interest.

- **DR.1.1:** REHT shall be capable of communicating status and preliminary readings to Earth.
 - **DR.1.1.1:** REHT shall possess a transceiver capable of sending data to lunar satellites at 100 km.
 - **DR.1.1.2:** REHT should possess a transceiver capable of sending data to lunar satellites at 500 km.

-
- * **Motivation:** This is needed to allow scientists and ground stations to know the status of the rover, and to get important updates on whether Helium-3 is present at different locations to better inform future sites of interest, or if special attention should be given to certain areas.
 - * **Verification:** This can be verified based on the range and conditions that the selected transceiver is rated for, and tests can be run by simulating conditions (temperature and radiation present), and then attempting to communicate at range. If, under these conditions, it can communicate at the stated ranges, it will be considered successful.
- **DR.1.2:** REHT shall be capable of receiving data from Earth.
 - **DR.1.2.1:** REHT shall possess a transceiver capable of receiving large data sets from lunar satellites at 100 km.
 - **DR.1.2.2:** REHT should possess a transceiver capable of receiving large data sets from lunar satellites at 500 km.
 - * **Motivation:** REHT aims to be semi-autonomous, requiring inputs of sites of interest from operators on Earth; these will be sent through existing satellite infrastructure and transmitted to the rover. If the receiver is unable to accurately receive this signal, the rover will be forced to operate on preexisting data, which might not align with updated interests based on preliminary results. This would also impact the rover's ability to navigate without knowing its position.
 - * **Verification:** This can be verified based on the range and conditions that the selected transceiver is rated for, and tests can be run by simulating conditions (temperature and radiation present), and then attempting to communicate at range. If, under these conditions, it can receive data at the stated ranges, it will be considered successful.
 - **DR.1.3:** REHT shall be capable of accurately maneuvering on lunar terrain with slopes up to 30°.
 - **DR.1.3.1:** REHT shall possess wheels powered by electric motors with torque sufficient to overcome slopes of 30°
 - **DR.1.3.2:** REHT should possess wheels powered by electric motors with torque sufficient to overcome slopes of 45°
 - **DR.1.3.3:** REHT shall be capable of making turns with less than a 10-foot radius
 - **DR.1.3.4:** REHT should be capable of making turns with less than a 5-foot radius
 - **DR.1.3.5:** REHT shall know its current location relative to the terrain and the site of interest
 - * **DR.1.3.5.1:** REHT shall possess a microcontroller capable of processing data received from satellites and onboard sensors to calculate position.
 - **Motivation:** This mission's success is reliant on being able to take samples at different sites. In order to avoid more costly systems, such as launching directly to each site, the rover needs to be capable of reaching these sites of interest on its own power. This requires the REHT to be capable of traversing the difficult lunar terrain without risking damage and following a suitable path to reach the target destination.
 - **Verification:** Verification will be determined based on whether the rover can traverse the stated inclines on simulated regolith. Whether it can make turns below stated radii on this material, and finally, whether it can identify its location compared to small and large-scale landmarks within 5% of the total distance.

II.6.2. Structures and Mechanisms

FR.2: REHT shall maintain structural integrity during all lunar surface operations.

- **DR.2.1:** REHT's chassis shall support subsystem and payload mass while traversing uneven terrain.
 - **DR.2.1.1:** The structure of REHT shall withstand loads from slopes up to 30° and small surface impacts.
 - * **DR.2.1.1.1:** REHT's frame shall sustain no more than 2% elastic deformation under full operational loading.
 - **Motivation:** Prevents structural failure that could misalign components or disable the rover.
 - **Verification:** Use FEA in SolidWorks or ANSYS under static and dynamic loading conditions.
- **DR.2.2:** The drill assembly shall extract regolith samples to a depth of 2 meters
 - **DR.2.2.1:** The drill structure shall resist torque and vibration during operation
 - * **DR.2.2.1.1:** The drill arm shall operate continuously for at least 2 hours without binding or fatigue.
 - **Motivation:** Ensures reliable Helium-3 sample extraction without mechanical failure.
 - **Verification:** Conduct structural and fatigue analysis under simulated torque and thermal conditions.
- **DR.2.3:** All mechanisms shall remain functional within lunar temperature extremes (-150°C to 150°C).
 - **DR.2.3.1:** Materials shall minimize the thermal expansion mismatch between connected components.
 - * **Motivation:** Prevents seizing or misalignment of moving parts due to thermal cycling.
 - * **Verification:** Perform thermal cycling and material compatibility tests in lunar-simulated conditions.

II.6.3. Payload

FR.3: REHT shall extract samples of subterranean lunar dust containing Helium-3.

- **DR.3.1:** REHT shall extract materials directly from drilling.
 - **DR.3.1.1:** Storage device shall be directly connected to the drill-bit.
 - * **Motivation:** Automation of sample extraction.
 - * **Verification:** Drill into dirt or equivalent material to lunar dust and measure the weight of collected material.
- **DR.3.2:** REHT shall extract a specific weight of samples.
 - **DR.3.2.1:** REHT shall store 100 kg of non-temperature-controlled samples.
 - * **Motivation:** Establish a control sample of natural Helium-3 dust.

-
- * **Verification:** Fill the container with sand or equivalent material to lunar dust and conduct analysis under various thermal loadings. Fill the container with Helium gas and measure leakage from the seal.
 - **DR.3.2.2:** REHT shall store 50 kg of refrigerated samples over course of mission.
 - * **Motivation:** Allows for the collection and safe storage of ice. Also protects the sample from adverse heat effects on the rover.
 - * **Verification:** Fill the container with sand or equivalent material to lunar dust and conduct analysis under various thermal loadings while the container is cooled.
 - **DR.3.3:** REHT shall analyze samples for Helium-3 concentration.

II.6.4. Power and Electrical

FR.4 REHT's shall distribute power to all systems to function during the duration of operation.

- **DR.4.1** REHT shall last one year in Earth's time.
 - **DR.4.1.1** REHT shall be powered by solar batteries.
 - * **Motivation:** Easier, more cost-effective, and safer to test when compared to nuclear power sources.
 - * **Verification:** Power various subsystems separately before connecting them all to the same power source. Measure power output.
 - **DR.4.1.2** REHT shall arrive at the moon with fully charged batteries.
 - * **Motivation:** Best probability of REHT lasting its desired mission time.
 - * **Verification:** Leave the battery connected to the powered-off rover for one to three days.
 - **DR.4.1.3** Batteries shall have a form of recharging/conservation.
 - * **DR.4.1.3.1:** REHT shall be solar-powered.
 - **Motivation:** Increases mission time for the rover by not relying entirely on the charge the rover has once it lands on the moon.
 - **Verification:** Connect the used solar battery to the solar panel to measure its rate of rechargeability.

II.6.5. Thermal Systems

FR.5: REHT shall regulate temperatures across the whole rover during the span of the mission.

- **DR.5.1:** REHT shall maintain the sample storage temperature at 273K.
 - **DR.5.1.1:** REHT should maintain the Helium-3 samples at 215K in ideal conditions.
 - * **Motivation:** Best probability of REHT minimizing the Helium-3 release rate to below 1%.
 - * **Verification:** Measuring the amount of Helium-3 release rate at different temperatures.
- **DR.5.2:** REHT shall maintain temperatures for all the subsystems within the operating range of the subsystems.

-
- **DR.5.2.1:** REHT should be able to keep operating temperatures of subsystems within their operational bounds far from the operational limits.
 - * **Motivation:** Increases the life of all the subsystems and stops their performance from degrading.
 - * **Verification:** Test various thermal systems while operating subsystems at their max heat generation rate.

II.6.6. Ground Station

FR.6: The Ground Station shall enable reliable communication with RHET.

- **DR.6.1:** The Ground Station shall transmit commands to RHET using the designated communication band and protocol.
 - **DR.6.1.1:** The Ground Station should maintain a stable up link signal with sufficient power and modulation quality for RHET to decode commands.
 - * **Motivation:** Ensures RHET receives clear and continuous instructions during operation.
 - * **Verification:** Perform uplink command tests at varying distances and measure command success rate.
- **DR.6.2:** The Ground Station shall receive telemetry and data transmitted by RHET.
 - **DR.6.2.1:** The Ground Station should maintain a high signal-to-noise ratio and sufficient receiver sensitivity to capture low-power rover transmissions.
 - * **Motivation:** Allows operators to accurately monitor RHET's health, position, and science data.
 - * **Verification:** Test down link reception performance using simulated RHET transmissions at adjustable power levels.

II.6.7. Communications

FR.7: The Communications Subsystem shall provide a reliable link between RHET and the Ground Station.

- **DR.7.1:** The Communications Subsystem shall transmit rover telemetry and science data to the Ground Station.
 - **DR.7.1.1:** The subsystem should support a minimum data rate sufficient for health monitoring and image transfer.
 - * **Motivation:** Ensures mission operators receive timely and accurate information about rover status and scientific results.
 - * **Verification:** Measure achievable data rates in testing while transmitting representative telemetry and images.
- **DR.7.2:** The Communications Subsystem shall receive commands sent from the Ground Station.

-
- **DR.7.2.1:** The subsystem should maintain uplink compatibility with the Ground Station’s frequency, modulation, and protocol.
 - * **Motivation:** Guarantees RHET can accept instructions and respond to operator inputs during all mission phases.
 - * **Verification:** Conduct command reception tests at multiple ranges while monitoring command-error rates.
 - **DR.7.3:** The Communications Subsystem shall maintain adequate link quality for two-way communication.
 - **DR.7.3.1:** The subsystem should include error detection and correction to reduce packet loss and improve signal reliability.
 - * **Motivation:** Prevents corrupted data or lost commands from interfering with rover operations.
 - * **Verification:** Evaluate packet error rates using controlled noise environments and simulated link degradation.

III. Design Solution

III.1. Evaluation of Trade Studies

After the CPE’s respective literature review, evidence of feasibility, and trade studies conducted, the baseline design for REHT was chosen. Though these were chosen in part as to how optimal they were in their given subsystem, additional consideration had to be made towards their integration in the rover as a whole and how they may work with the various subsystems.

Table 7: Baseline Design

Critical Project Elements	Components	Selections
Navigation and Controls	• Power Train	• 6 Independent Wheels
Structures and Mechanisms	• Chassis Configuration • Chassis Material • Drill	• Modular Configuration • Aluminum Alloy (7075) • Rotary Percussive Drill
Payloads	• Storage • Spectrometer	• Sample Tube • Laser Induced Breakdown Spectrometer (full scale)
Power and Electrical	• Batteries	• Lithium-Ion
Thermal Systems	• Heating System • Cooling System	• Multi-Layer Insulation (Passive System) • Radiator (Passive System) • Thermo-electric cooler (Active System)

III.2. Navigation and Controls

III.2.1. Design Alternatives

Rocker-bogie system: This system utilizes a set of four arms connected together with a wheel on each that rotates about a pivot, connected to other arms with respective wheels in order to maintain constant contact with the ground and reduce the impact of obstacles on the system.

Obverse and Reverse Four-Linkage: This system operates similar to the Rocker-bogie system which it is derived from, however it offers increased flexibility and dampening capabilities through the use of a more complicated linkage mechanism.

Active Suspension System: Active suspension systems utilize actuators controlled by the microprocessor in order to adjust the length of the arms as the rover moves based on data obtained from various sensors such as cameras and ultrasonic sensors. This enables a much greater degree of control at the cost of weight, and complexity.

Concept	Pros	Cons
Rocker-bogie system	• Simplicity • Reliability • Cost • Stability • Dampening	• Not quite as effective as other options
Obverse and Reverse Four-Linkage	• High flexibility • High stability • Ability to handle complicated terrain • Relatively low cost • Dampening	• Complexity • Difficulty of manufacturing and simulating
Active Suspension System	• Stability • Flexibility • Dampening • Ability to handle complex terrain	• Cost • Complexity • Susceptibility to damage

III.2.2. Trade Studies

V.1.1.2. Suspension Motivation

Our design requires a suspension system in order to reduce vibrations, and prevent the system from experiencing damage due to moving across uneven surfaces. This will also help to further ensure traction on uneven ground ensuring our ability to accurately navigate the lunar surface. This system is necessary to ensure control over the rover as it drives.

V.1.2.2. Suspension Process

After looking at past research and applications, as well as new developments, it was determined that there are three main suspension systems that were worth investigating. These three include an active suspension system, utilizing actuators and active controls in order to adjust the height of the wheels to provide maximum stability, the Rocker-bogie system, which has been historically used by lunar and martian rovers due to its simple and reliable nature, and the Obverse and Reverse Four-Linkage system, which is a recently developed suspension system that serves as an evolution of the Rocker-bogie suspension system.

V.1.3.2. Suspension Criteria

Durability: This is defined as REHT's ability to avoid damage when operating which is key to continued operation. Contributing factors are the complexity and number of parts, which increases the chances of failure, presence of delicate components such as electronics, materials required, etc.

Stability: For REHT, driving stability is the extent to which the rover can avoid tipping as well as its ability to reduce vibrational impacts as it travels. Another important factor is the ability to remain level compared to the surface. Contributing factors include ability to rotate/shift, and dampening traits.

Weight: Weight is the total mass of the suspension system. Factors that contribute to this will include the materials needed, amount of components needed, presence of actuators or other heavy systems, etc.

Manufacturability: This is the ability to actually produce the system and its components. Factors that contribute to this will include the number of components present, their precision, and the difficulty of assembling them.

Complexity: The complexity of the system is defined by the number of moving parts it has, and the number of interactions they have. More complex systems will naturally increase the chances of failure.

Slope: This is defined as REHT's ability to drive up a slope at an incline, with more preference being given for higher potential inclines. The objective of this is to be able to reach slopes of at least 30 degrees. Contributing factors are the extent to which the suspension system can level out the rover, and distribute weight between the wheels appropriately.

Cost: This is the amount of money that will be required to construct the design. Higher component number and precision, as well as presence of more expensive components such as actuators will be a key factor in determining this value.

V.1.4.2. Suspension Methodology on Weights

Durability (17.5%): The criteria is key to ensuring that the suspension system does not sustain serious damage, if it were to become damaged, the rover would be susceptible to serious damage as a result of extreme vibrations and movement over obstacles. This would slow the mission down significantly as

increased focus would be required for navigation to avoid any potential rough terrain, with many locations becoming unavailable. As a result, this was weighted at 15%.

Stability (15%): It is highly important that while driving, the vehicle remains stable to avoid damaging components or tipping. Excessive vibrations are also a substantial threat to the safety of the rover, with them posing significant risks for delicate systems such as the spectrometer. Due to this importance, it was given a weight of 15%.

Weight (15%): Minimizing the weight of this system is highly important to reducing REHT's overall weight. A high weight will increase the structural demand, require more power to move the rover, increase the cost of sending the rover, as well as increase the challenge of navigating rougher terrain and the risk of getting stuck. Due to this importance, it was weighted at 15% of the total weight.

Manufacturability (12.5%): In order for the mission to take place in the first place REHT needs to be assembled. As a result there needs to be a significant amount of focus on the manufacturability of the design. If it is unable to be manufactured properly, or is too difficult, flaws could become present in the components increasing the risk of failure, and changes would likely have to be made to account for this. However, once manufactured appropriately, it no longer has a significant impact on the performance of REHT, as such it was given a rating of 12.5%.

Complexity (12.5%): The complexity of the system has a large impact on the vehicle's performance. While more complicated systems may enhance the performance, they pose a serious risk of failure due to the risk of small parts being damaged, or errors being made in the design. As such, there is a significant benefit to keeping the design simple. Because of this, complexity was rated as 12.5%.

Slope (15%): Because many of the locations that PACK7 is likely to want to reach are in elevated positions or in craters, it is absolutely necessary that we are capable of traversing inclines. If REHT is unable to do so, the scope of the mission will be drastically reduced, and a complete picture of Helium-3 deposits could not be developed. As a result, the weight assigned to this criteria was 15%.

Cost (12.5%): Cost is a key factor to consider due to the importance of acquiring funding for the mission to take place in the first place. If the rover is too expensive to produce, it is unlikely that funds will be available for its development. As such, a high priority needs to be given to minimizing costs where possible. This resulted in a weight of 12.5% being assigned to it.

V.1.5.2. Suspension Concept Scoring

Durability:

Active Suspension (0): Due to the presence of delicate components such as electronics and actuators, in addition to having actively moving parts, there is significant risk of damage if used on the lunar surface.

Obverse and Reverse Four-Linkage (1): Due to the increased number of delicate parts, this design will result in a higher risk of structural damage.

Rocker-bogie (1): This system is likely to be the most durable choice as it generally is simpler with less vulnerability.

Stability:

Active Suspension (1): This type of suspension will have quite high stability as it actively adapts to the terrain as it goes over it resulting in minimal vibrations and chances of tipping.

Obverse and Reverse Four-Linkage (1): As a more advanced version of the rocker-bogie system, it has quite high stability with minimal vibrational presence and a strong ability to traverse the terrain.

Rocker-bogie (0): This system is the least stable of the choices, unable to fully dampen vibrations it may also encounter some challenges with rough terrain.

Weight:

Active Suspension (-1): Due to the addition of actuators, electronics, and other heavy components, this system will weigh significantly more.

Obverse and Reverse Four-Linkage (0): This system contains more components than the rocker-bogie system and as a result will be moderately heavier.

Rocker-bogie (1): Because this system consists of the least components, and is generally simpler it will weigh the least.

Manufacturability:

Active Suspension (-1): Because of the number of moving parts and actuators that would be involved, precise machining would be required to assemble it.

Obverse and Reverse Four-Linkage (0): The obverse and reverse four-linkage system will also require significant amounts of machining, with some components requiring high precision in order to work effectively.

Rocker-bogie (1): This design will require the least moving parts and generally will not need as high a level of precision in manufacturing.

Complexity:

Active Suspension (-1): Due to the need for active control, with many moving and delicate components, the complexity will naturally be much higher than the other designs.

Obverse and Reverse Four-Linkage (0): This system utilizes a relatively complex system in order to maintain stability and dampen vibrations, with a substantial number of moving and delicate parts that interact closely with each other.

Rocker-bogie (1): This system is a simplified version of the obverse and reverse four-linkage, possessing few components and a more simple structure; its complexity is the lowest of the designs.

Slope:

Active Suspension (1): Due to its ability to directly adjust the height of the wheels it is able to accurately control weight distribution making slopes generally easy.

Obverse and Reverse Four-Linkage (1): This system is highly effective at distributing rate and avoiding obstacles making slopes quite easy.

Rocker-bogie (-1): The rocker-bogie system is the weakest design when it comes to slopes, while it is capable of overcoming them, it is likely to struggle as the incline increases.

Cost:

Active Suspension (-1): This system will be the most expensive of the designs due to requirement for additional actuators and electronics, as well as the need for precise components.

Obverse and Reverse Four-Linkage (0): This system will be less expensive than active suspension as

it is purely mechanical, however it requires a higher level of precision in manufacturing and more components overall increasing the price over the rocker-bogie.

Rocker-bogie (1): This design will be the most affordable option to produce, with fewer components and less overall complexity.

Suspension		Active Suspension		Obverse and Reverse Four-Linkage		Rocker Bogie	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Durability	15	-1	-15	0	0	1	15
Stability	15	1	15	1	15	0	0
Weight	15	-1	-15	0	0	1	15
Manufacturability	12.5	-1	-12.5	0	0	1	12.5
Complexity	15	-1	-15	0	0	1	15
Slopes	15	1	15	1	15	-1	-15
Cost	12.5	-1	-12.5	0	0	1	12.5
Total Score		-40.00000		30.00000		55	
Rank		3		2		1	

III.2.2.1. Suspension System

Seen below is a rendering of the rocker-bogie system that our prototype of REHT will utilize for its suspension. This system can be broken into three main components differential, rocker and bogie. The differential is a series of shafts connected by bevel gears that causes the two sides to move in opposite directions, while keeping the body from rotating relative to the suspension system. It uses three shafts, two of which are parallel to each other running from the arms of the rocker-bogie to the center of the chassis's underside where they intersect with a third shaft that runs perpendicular to them. All three of these have bevel gears on them which enable to desired relationship, and are held in place by pillow block bearings which enable easy rotational movement, but no translational. The next aspect of this system is the rocker, this consists of the part of the suspension arms behind the bogie connector and is connected directly to the differential. It is capable of rotating back and forth based on the terrain it is traversing. Next is the bogie, which is characterized by the the 90 degree angle between its two arms. These arms are capable of rotating about the bogie's joint, meaning that it will rotate to keep both sets of wheels in contact with the ground at all times.



Figure 19: CAD Model of Rocker-Bogie Suspension

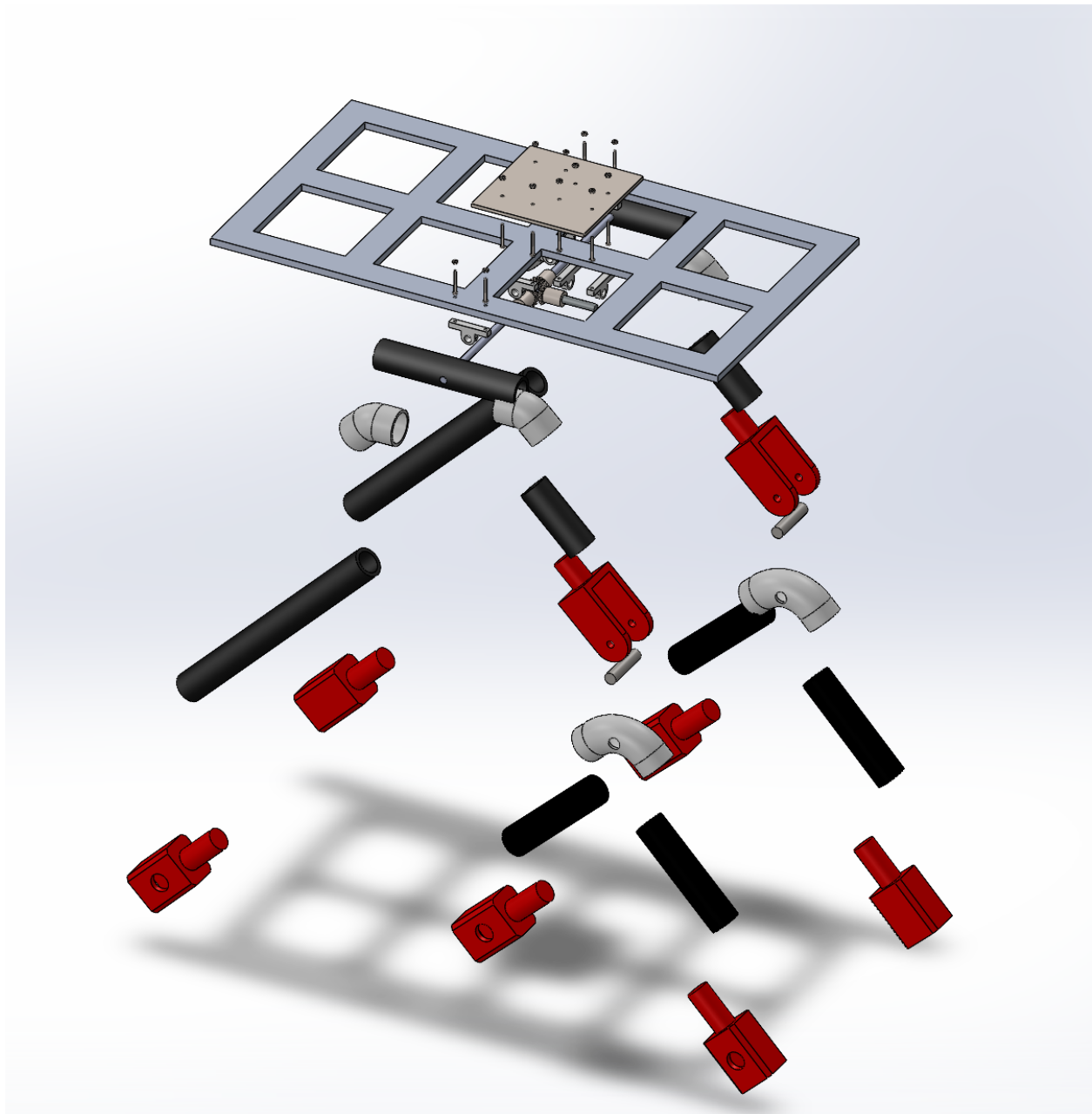


Figure 20: Rocker-Bogie Exploded Design Angle 1

As can be seen in this design, all three shafts are held in place by pillow block bearings connected via screws and nuts directly to the base of the chassis, represented by a sheet of carbon fiber in this model. The bevel gears are capable of locking in place using built in shaft collars to prevent rotation relative to the shafts. Pillow block bearings are made of a zinc alloy that should be more than capable of sustaining the forces present in this design. This system prevents tipping due to the alignment of the bevel gears, if it were to tip in one direction, both horizontal gears would attempt to rotate in the same direction, which the third, perpendicular gear prevents from occurring. Each shaft is made of 6063 aluminum providing sufficient strength while remaining lightweight and machinable. For the full scale, a similar configuration will be utilized, however higher strength materials will be used such as thicker shafts made of materials such

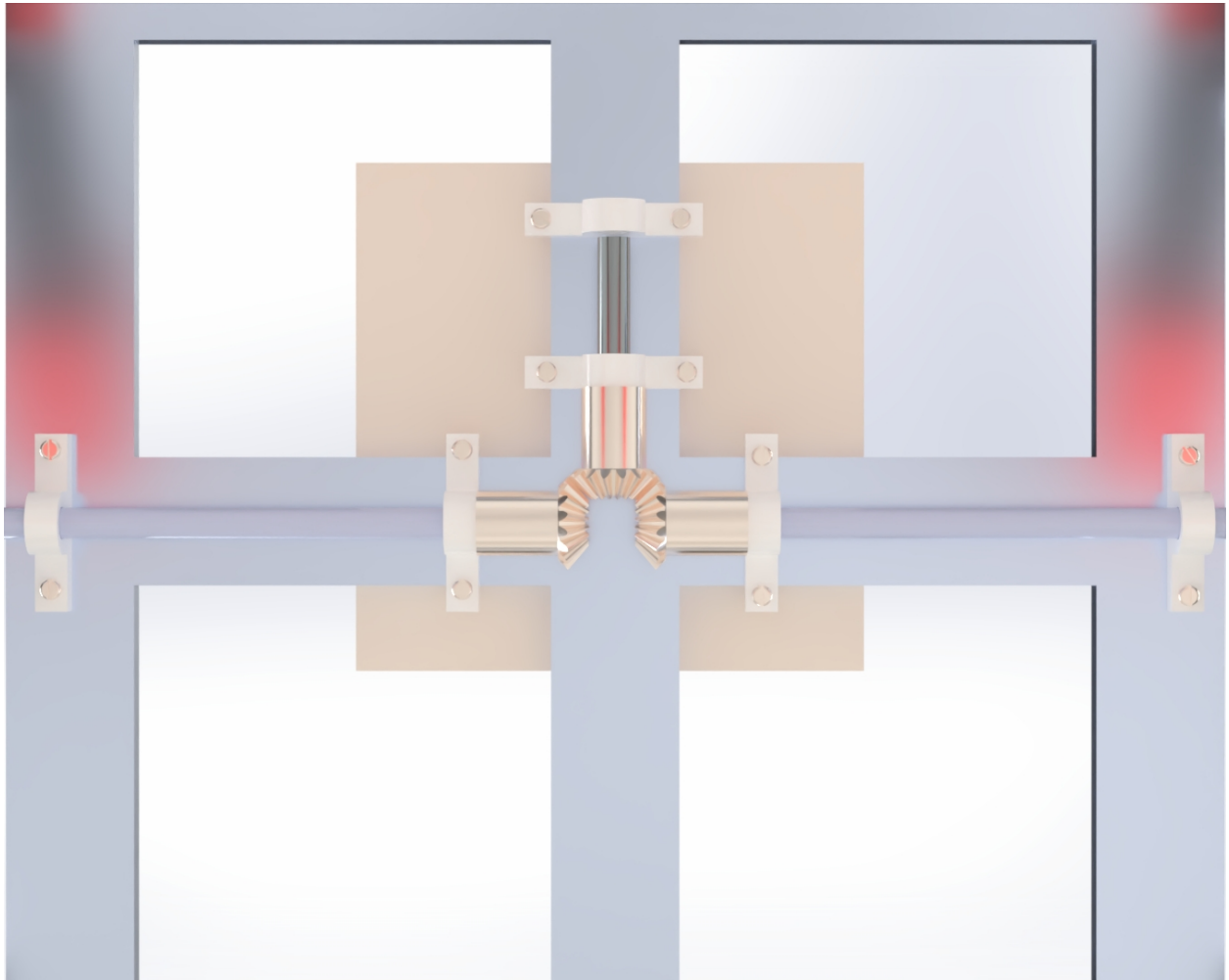


Figure 21: Prototype Differential Bar Design

as aluminum 7075. The shafts would also be custom designed to lock into the rocker arm providing a higher strength connection then required for the prototype. Pillow block bearings would still likely be used, once again with higher grade materials.

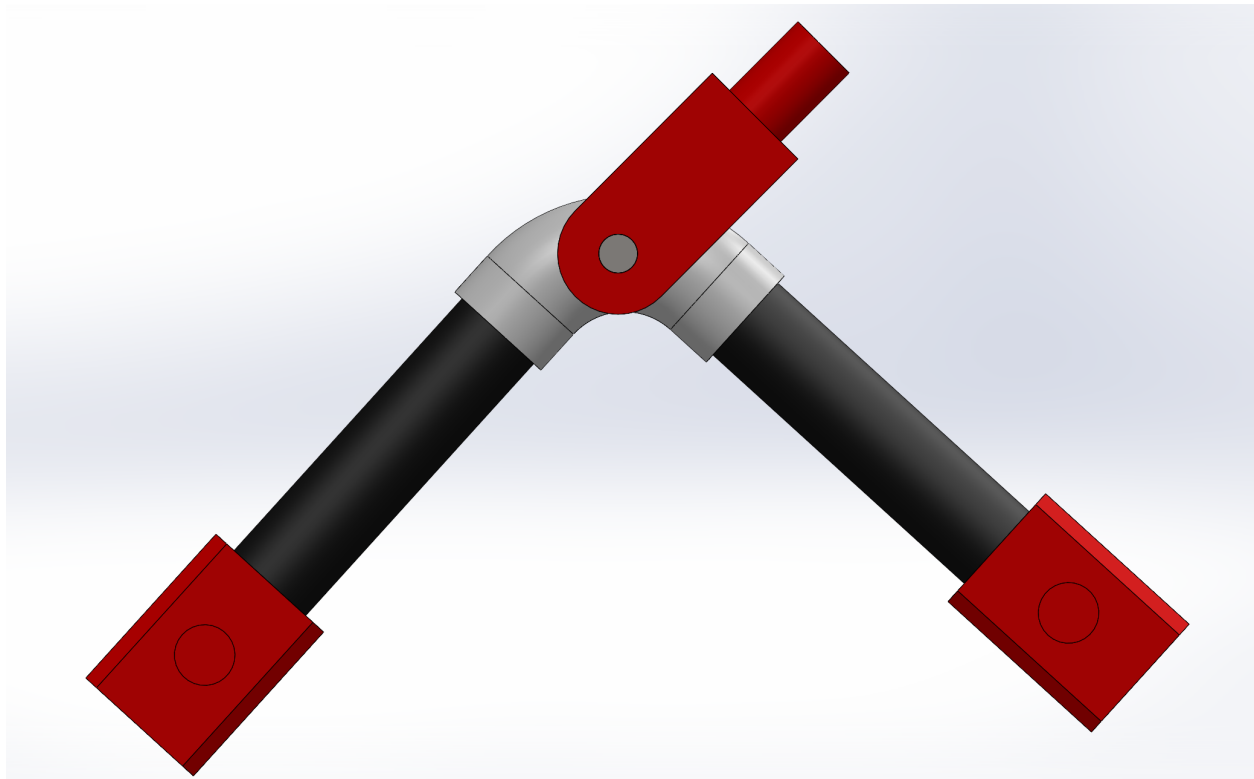


Figure 22: Prototype Bogie Design

The bogie's tubes and connector (black and white components) are made primarily from 2" PVC pipe, the motor housings and the pivot connector, shown in red, are 3D printed using ABS plastic, with a steel shaft serving as the pivot. The tubes will be connected at each end via two component epoxy, which generally has yield strength of well over 50 MPA, far exceeding anything experienced in this design at these locations. PVC was chosen for the prototype due to its high strength, light weight, compatibility, and low cost. It is also hollow which helped reduce weight, and allows wires to be run through it ensuring they are protected. The other components were chosen to be 3D printed due to their unique shapes which would make finding alternatives difficult and expensive. Extensive simulations were run to ensure that all 3D printed components had the required strength to support REHT. On the full scale, the bogie will be constructed from aluminum and titanium alloys such as aluminum 7075, and Ti-6Al-4V in order to support greater weights and endure harsher conditions due to the extreme temperatures and unfiltered UV radiation which would rapidly degrade plastics such as PVC. Mechanical connections would be made through a series of nuts and bolts to ensure much higher levels of performance then required for the prototype. The bottoms of the motor housings would also be sealed in order to prevent dust from entering and damaging components; they were left open for the prototype to enable easy access during construction and testing. The full scale would look more similar to the image below.

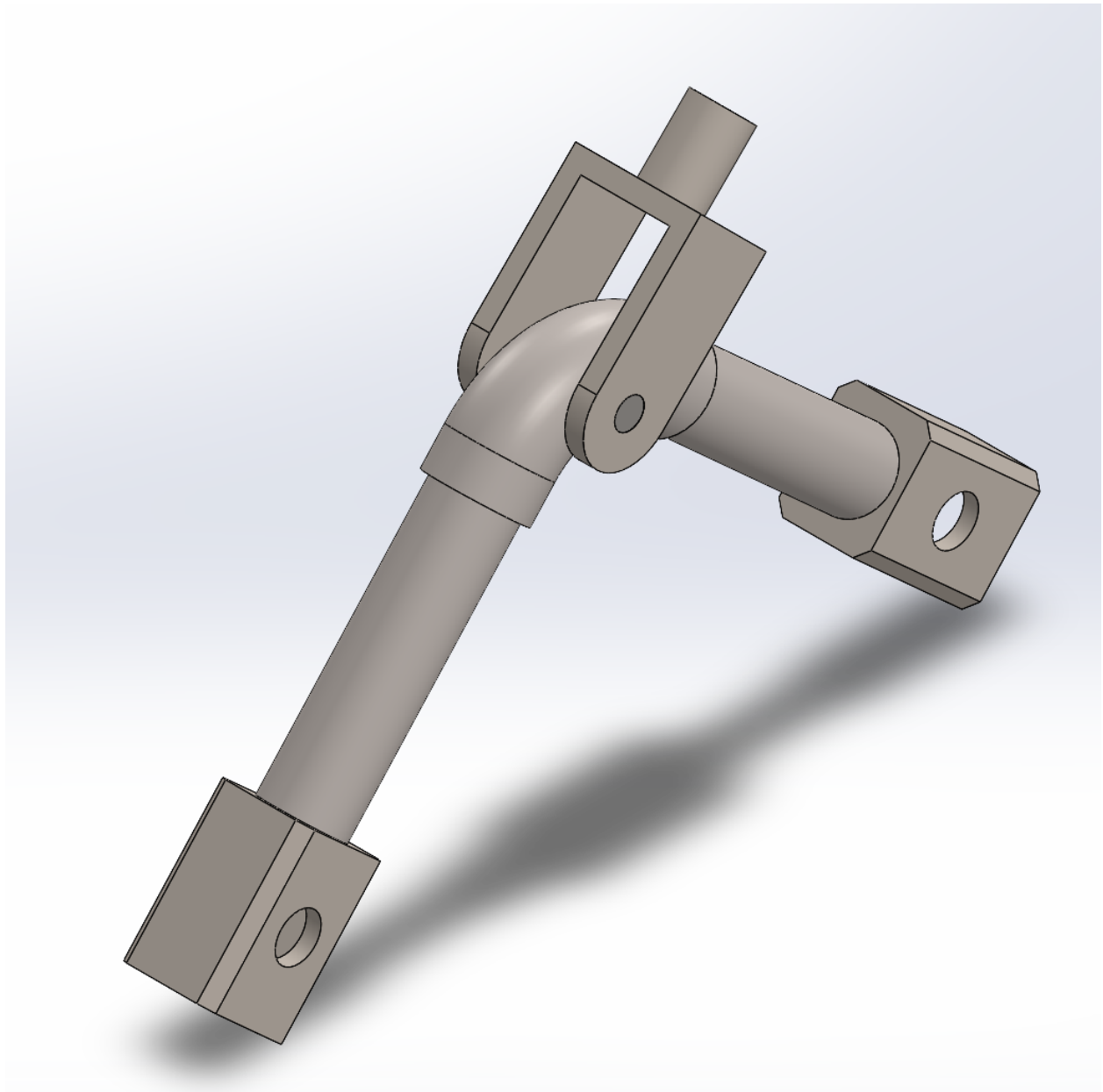


Figure 23: Bogie Design Full Scale

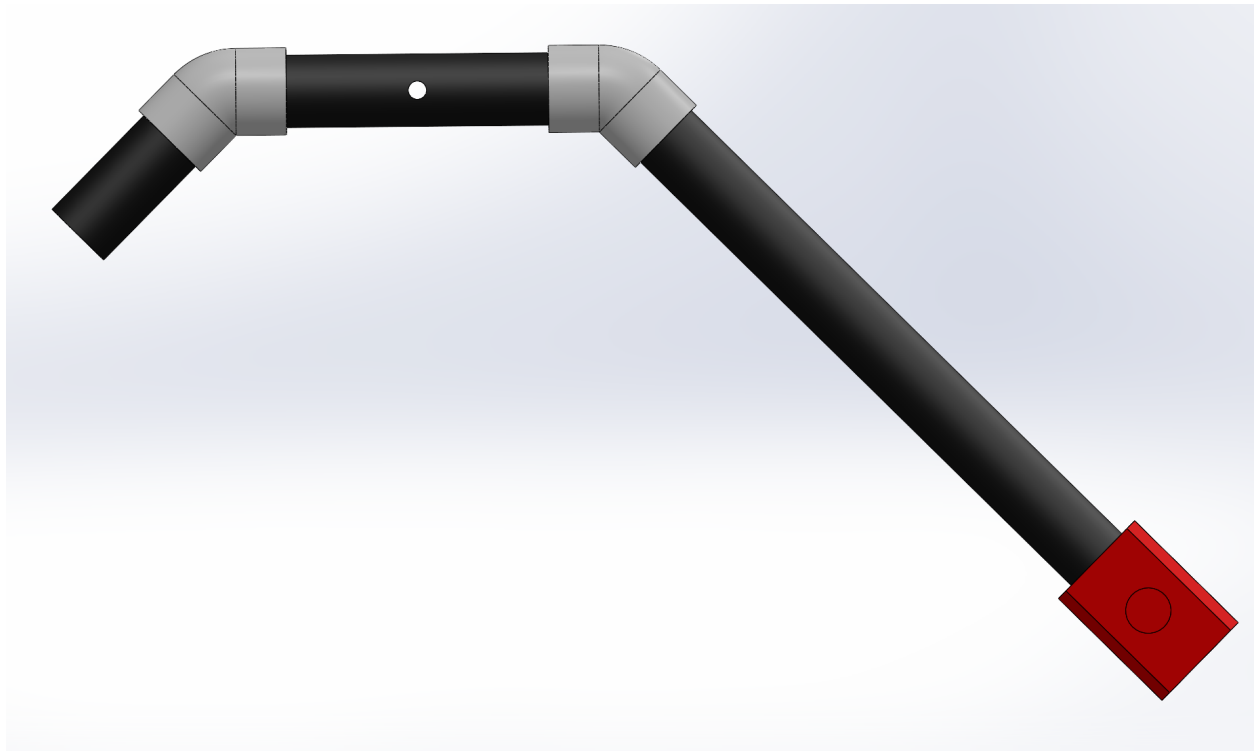


Figure 24: Prototype Rocker Design

The rocker design rotates in coordination with the differential bar to which it is connected via a shaft coupling. This means that the rocker will rise in the front on one side in response to obstacles, while decreasing on the other to compensate. This, in combination with the bogie, enables all wheels to remain in contact with the ground. For our prototype, the rocker is constructed similarly to the bogie, utilizing PVC pipe and preexisting connectors ensuring compatibility when assembling them. The motor housing on the rocker is once again made from 3D printed ABS plastic, and all connections are made with two part epoxy. Once again, similarly to the bogie, these materials will largely be replaced with high grade aluminum and titanium alloys to account for the increased loads and environmental hazards. The designs of some parts will also change to improve efficiency, especially at the interfaces between different components; this will require more advanced machining than is necessary for the prototype.

camera ports. A buck-boost converter was required to step down voltage to a level that the Raspberry pi could handle, while still delivering full power to the motors. Three 24V motor drivers were needed to run our six motors, and a GNSS receiver was selected such that REHT could determine its position for navigation. A LimeSDR Mini was selected as a transceiver to provide quick and reliable communications between REHT and the ground station.

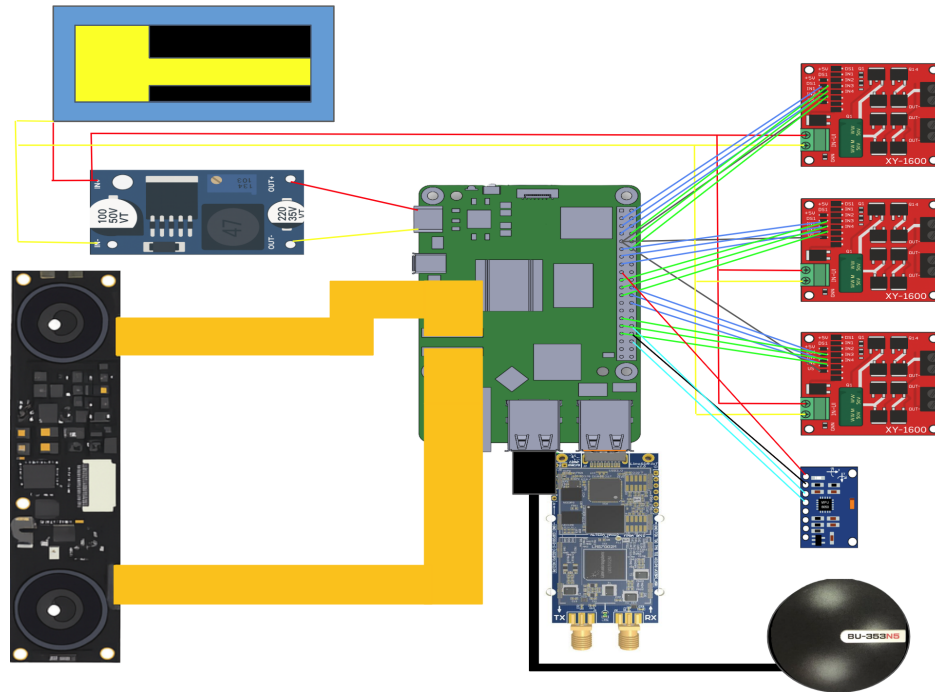


Figure 26: Electronics Wiring for REHT

The image above shows an example of the controls electronics layout of our prototype, including which wires connect to the various pins. A reasonable number of wire splices will be required to transmit 24V to all motor drivers at once, and to the buck-boost converters. The GPS module and transceiver plug in via USB, enabling easy access and minimal setup. The stereo camera requires two 22 to 15 pin camera adapters to connect to the Pi. A large number of GPIO pins are required for just these systems, leading to the selection of a GPIO extension board.



Figure 27: Raspberry Pi 5

Feature	Specification
RAM	8 GB
CPU Speed	2.4 GHz
USB Ports	2 × USB 3.0, 2 × USB 2.0
Camera Ports	Two 22-pin camera ports
Connectivity	Bluetooth, Dual-band Wi-Fi, Ethernet
Storage	microSD card slot
Power Requirement	5V DC
GPIO	40-pin GPIO header

Table 8: Raspberry Pi 5 Specifications

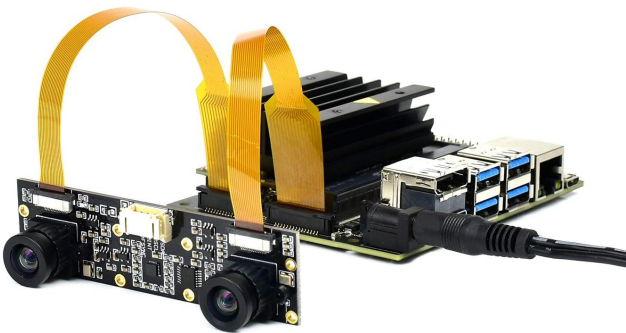


Figure 28: Waveshare Binocular Stereo Camera

Feature	Specification
Lens Diameter	60 mm
Resolution	3280 × 2464
Focal Length	2.6 mm
Field of View	83°
Distortion	1%

Table 9: Waveshare Binocular Camera Specifications



Figure 29: Buck-boost Converter

This buck-boost converter will be used to decrease voltage and adjust current to enable lower level electronics to operate on the same power source as higher draw components, such as motors. This is necessary to ensure the operability and safety of REHT's design.

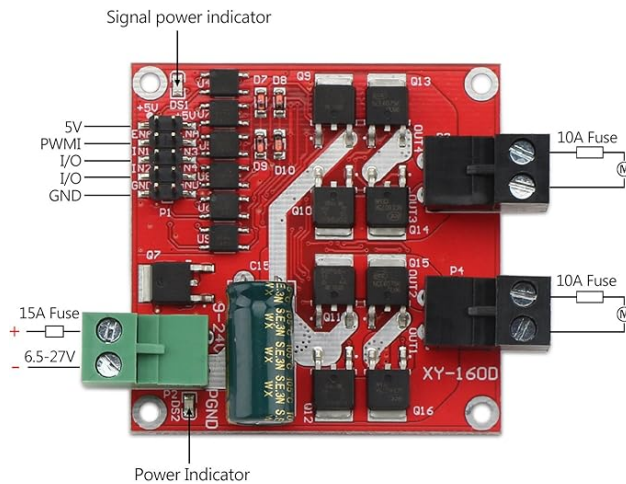


Figure 30: DROK DC Motor Driver

The DROK DC L298 dual bridge motor controller is capable of sustaining motors up to 27V and 7A which meets the requirements for our motors. Motor drivers are required to provide power and signal to the motors as the Raspberry Pi can not draw enough voltage to manage this on its own. Each of these motor drivers is capable of powering two motors at once, meaning that 3 will be needed to power the wheels motors, and the remaining motors can be powered by lower level drivers already in Pack7's possession.

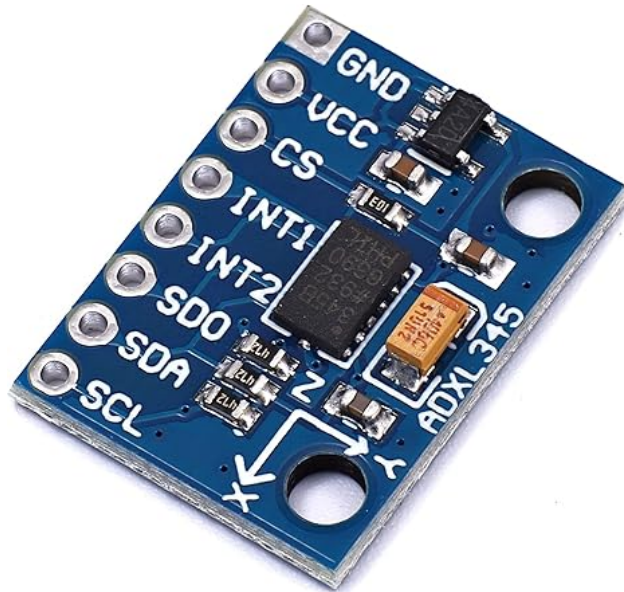


Figure 31: Teyleten GY-291 ADXL345 Accelerometer

An IMU is a key component of any rover, enabling determination of velocity and its relative direction as well as rotation. It will enable REHT to keep its path if communication with ground station is interrupted. This IMU is capable of interfacing directly with the Raspberry Pi using a number of its GPIO pins.

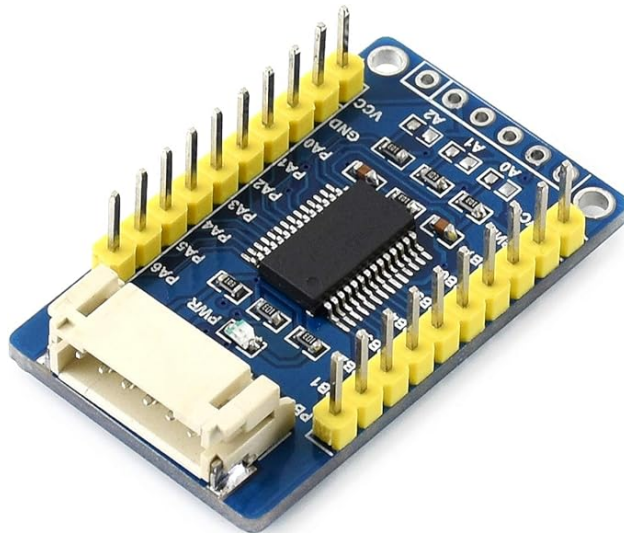


Figure 32: GPIO Expander Board

This expander board is used to significantly increase the number of GPIO pins available by a factor of four. This is necessary due to the number of components that need to be run off of our Raspberry Pi, including over a dozen motors, cameras, sensors, etc. As a result, the standard 40 pin configuration does not provide enough connectivity to meet REHT's demand. This board will be connected to the Raspberry Pi 5's GPIO pins 2 and 3 which can still be used providing a net 16 increase over the base 26 per board. To meet total requirement, two of these boards will be used.

Several of these components are likely to experience significant heat, specifically the Raspberry Pi, buck-boost converters, and motor drivers. To account for this, active thermal systems in the form of electronic coolers will be used to keep temperatures down. Further information on these systems can be found in the thermal systems subsection of the design.

III.2.2.3. Navigation

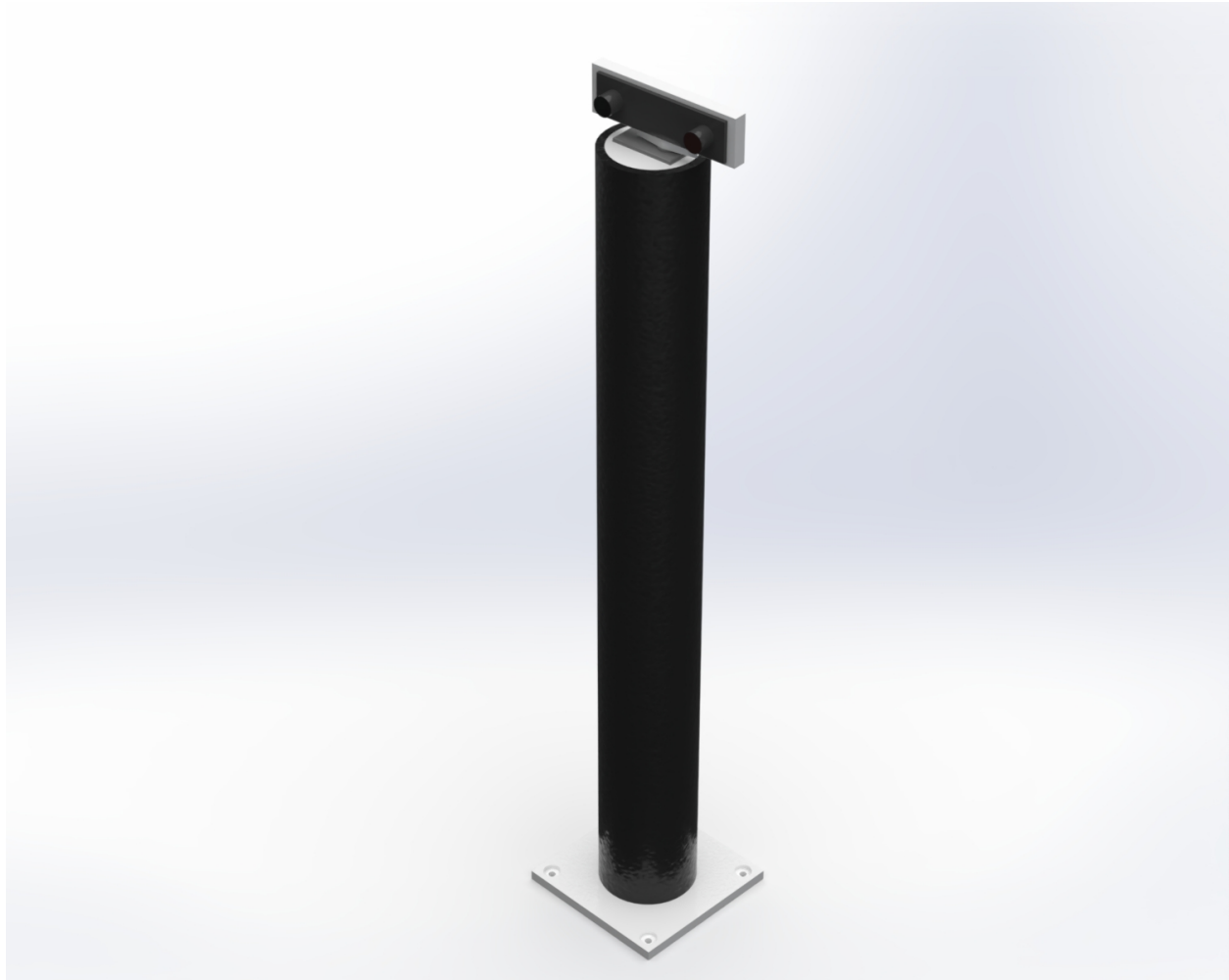


Figure 33: Stereo Camera Configuration for REHT Navigation

The image above shows the rotating camera configuration what will be used for object detection and terrain mapping for REHT. It features a stereo camera powered by a servo motor to enable the location of objects to be determined across a range of angles. This is then mounted on a piece of PVC pipe to raise the camera above other components and system so that it can effectively view the terrain without obstructions. The stereo camera will be connected to the Raspberry Pi via two twenty two to fifteen pin adapter cables, and the servo will be connected to the 5V positive and negative lines, with another connection to a GPIO pin on the Raspberry Pi. This configuration will then be mounted to the top of the rover through the use of a specifically designed adapter.

The selected camera is a Waveshare Binocular Camera Module, this was chosen due to its compatibility

with the Raspberry Pi 5, its high resolution, and the balanced field of view it has at 83° . This enables a good range of detection while still producing accurate results. Distortion is also rated as less than 1% for this product further emphasizing its accuracy which will be critical for the success of this system. At full scale a more sophisticated camera configuration will be used such as the Mastcam-z which was used on the perseverance rover providing longer range, and more specialized capacity.

III.2.2.4. Object Detection

Object detection is a key component of any modern rover design, enabling important features to be detected and identified, and serving as one of the foundations for terrain mapping. Out of the various available object detection software available, SSD MobileNet utilizing the OpenCV library was chosen for its comparatively low computational requirements and high speed making it ideal for our prototype as it does not require an AI accelerator to achieve its maximum performance on the Pi 5. SSD MobileNet is a lightweight, open source, object detection software well known for its reliable performance with low computational power. While its accuracy is not as high as competing software such as You Only Look Once (YOLO), it will still provide high enough accuracy for the expected tests. At full scale, YOLO would be a much better choice, based on its higher accuracy and fidelity when not constrained by processing power, however OpenCV remains one of the best libraries, and would likely still be used.

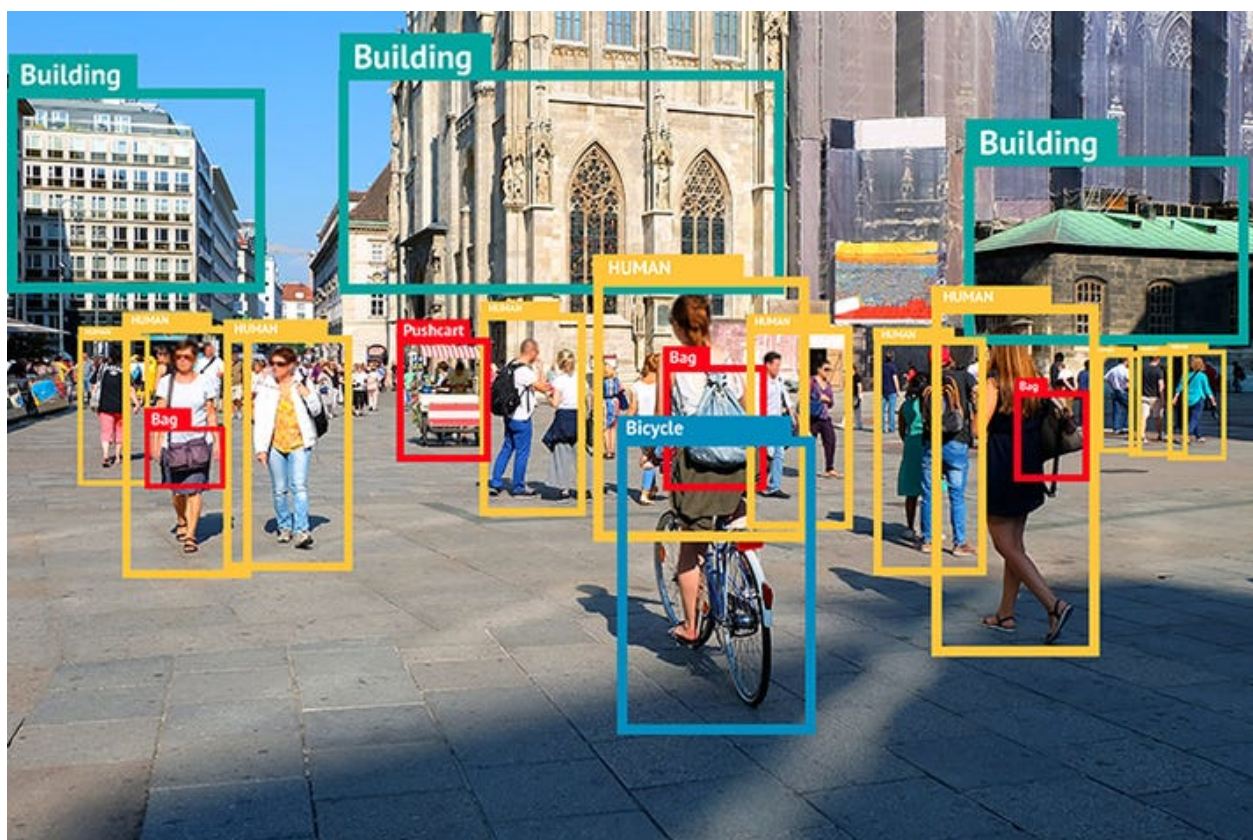


Figure 34: SSD MobileNet Perspective

On REHT's prototype, object detection will be used to navigate the areas surrounding the MAE senior design lab, and several other parts of NCSU's campus to test its performance and ability to reach target locations. This software will be used to recognize obstacles and impediments, paths it can follow such as

doors, and potential hazards such as cars. At full scale, this software will be used to detect debris blocking the rovers path, potential formations of interest, identify unstable terrain, and help identify its path.

III.2.2.5. Terrain Mapping

Terrain mapping software generally uses a combination of object detection, accelerometer and gyroscope data, and LiDAR in order to identify its position with respect to surrounding objects and terrain features. For REHT's prototype, Robot Operating System 2 (ROS2) was chosen as it is lightweight and can be run effectively on a Raspberry Pi 5. This will be run on a docker container utilizing Ubuntu OS to make the most out of this software's capabilities. This will enable REHT to identify its surroundings, avoiding obstacles and charting the optimal path at both the prototype and full scales.

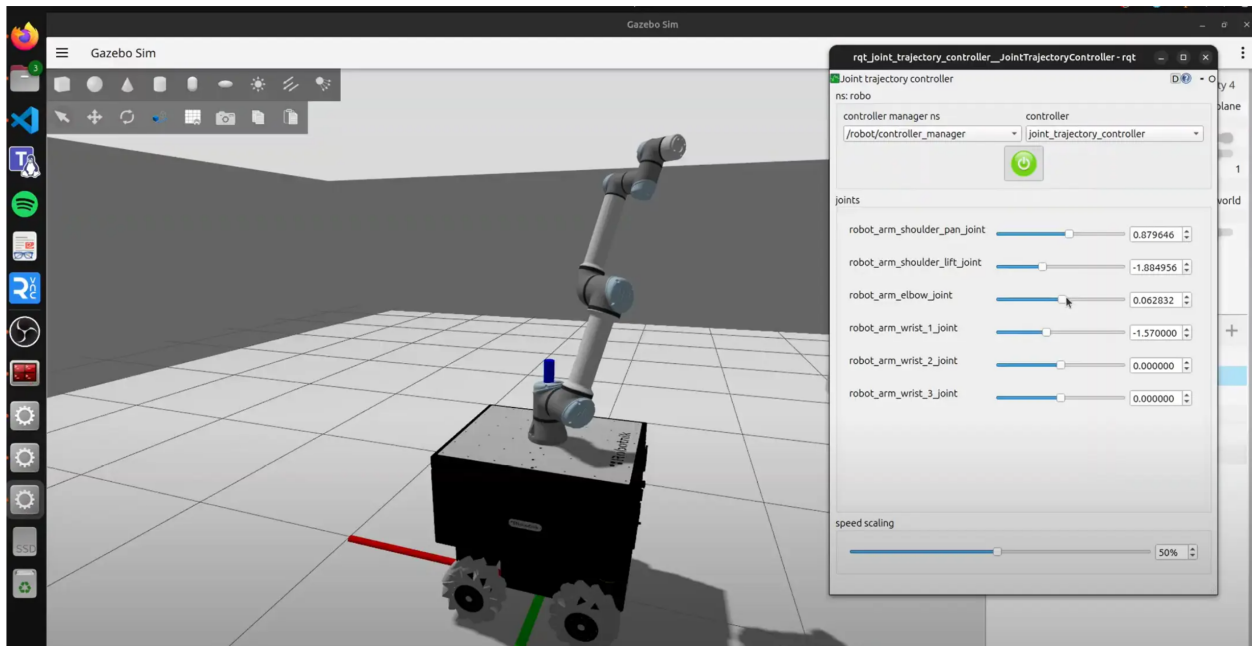


Figure 35: ROS2 Software Example

III.2.3. Motor

REHT uses a six wheel drive train, with each wheel having its own motor for maximum efficiency. As discussed in VIII.1.1., the REHT prototype will require motors that can produce 10 Nm of torque (for each wheel). Motors come in a thousand different shapes, sizes, and types. For situations where one needs high torque and a compact size, the best choice is an electric gear motor.

Electric gear motors use a series of gears to upgrade a relatively low torque motor to higher and higher torques. This comes at a cost, as gears increase, so does the final speed (revolutions per minute, or RPM). Thankfully, REHT does not require high RPMs, as the rover does not need to travel at high rates of speed.

REHT will use a 24V planetary gear motor with a maximum torque output of 11Nm at 37 RPM. It was selected due to it's size, strength, and affordability. This motor will allow the rover to operate at slopes of up to 30 degrees.

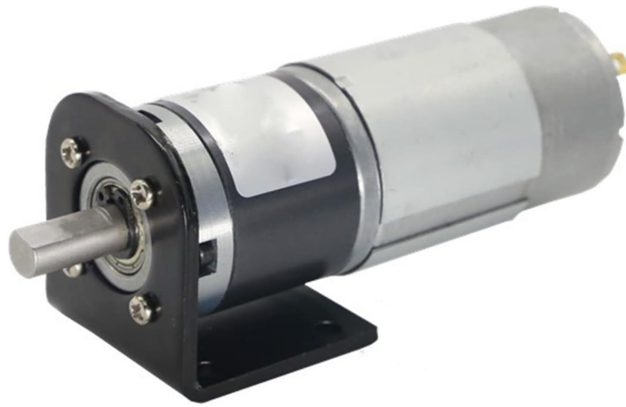


Figure 36: Planetary Gear Motor

III.3. Structures and Mechanisms

III.3.1. Chassis Configuration

Through the chassis configuration trade study and the Pugh matrix, a modular design was selected as the baseline chassis design for the REHT. This design was chosen because of its superior performance in criteria such as the simplicity of fabrication, and adaptability for subsystem integration. The modular layout allows individual sections of the rover to be independently assembled, modified, or replaced without affecting the entire structure, improving accessibility during manufacturing and integration. This chassis will fit well within the design and weight requirement, while also providing exceptional support to the rest of the subsystems.

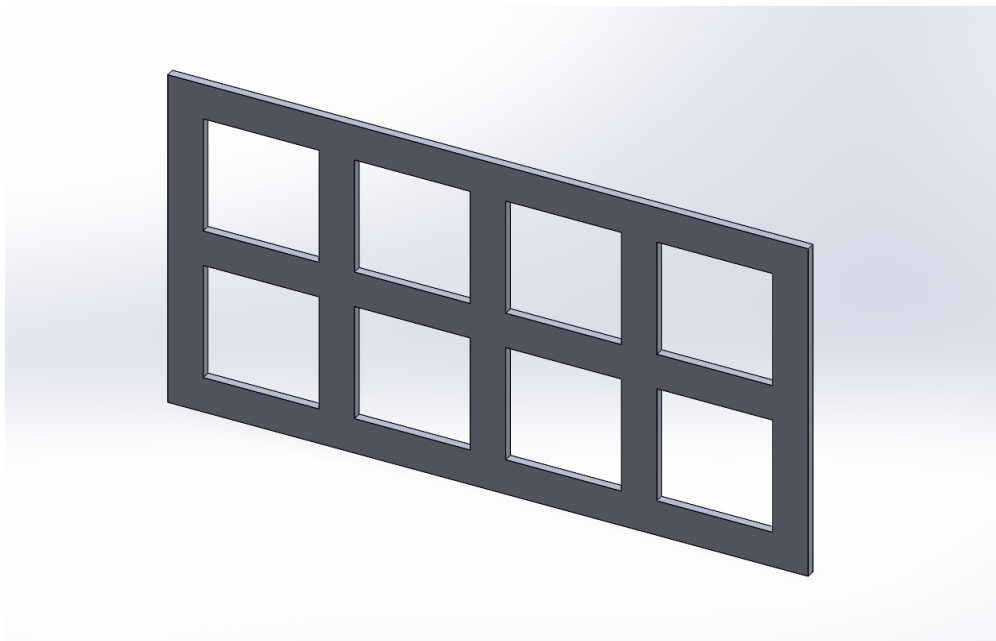


Figure 37: Isometric View of REHT's Chassis

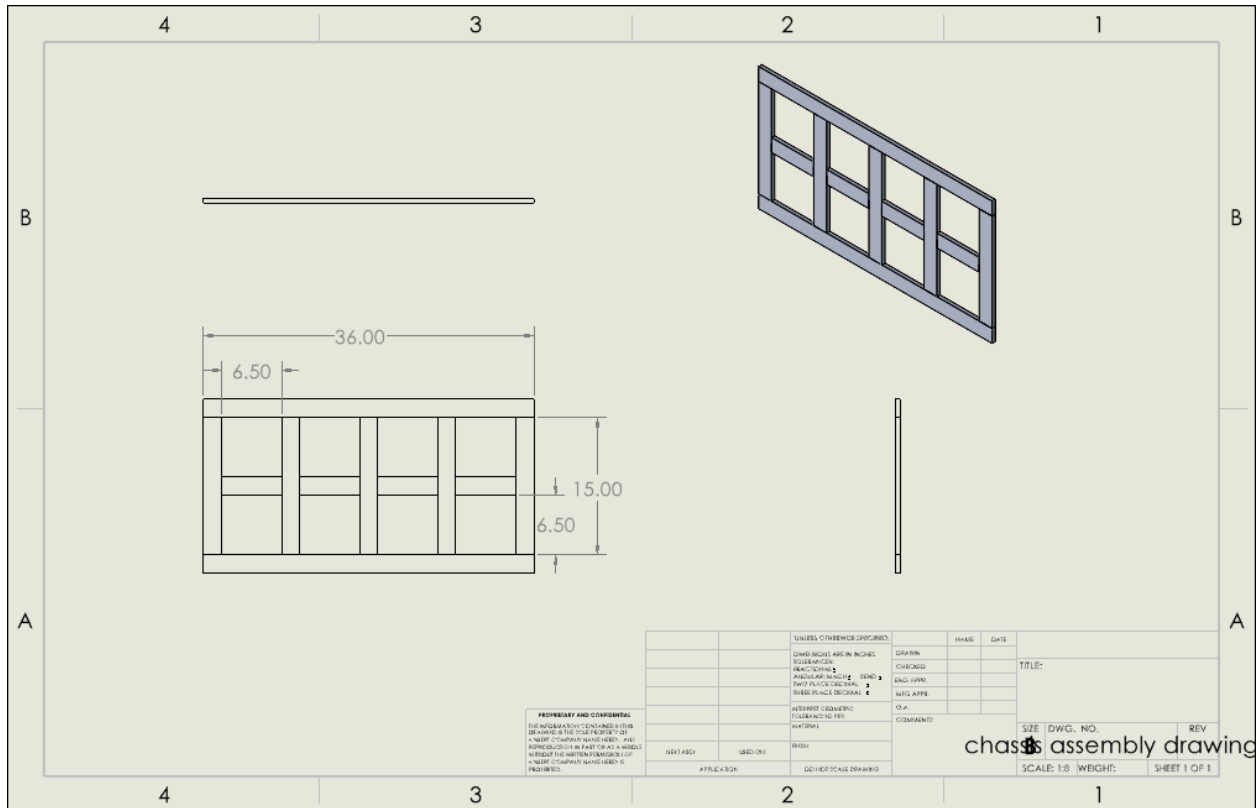


Figure 38: REHT's Chassis Drawing

The modular chassis selected for REHT not only supports the mechanical subsystems such as the rocker-bogie suspension, but it also provides the structural backbone required for the rover's navigation and electronic control systems. The chassis configuration must ensure all mechanical loads transmitted through the suspension while also providing mounting points for sensors, cameras, processors, and power electronics.

In addition to mechanical requirements, the chassis must house and protect the navigation and autonomy components, such as the Raspberry Pi 5, motor drivers, buck-boost converters, and GNSS receiver. A modular interior arrangement allows isolated compartments for the motor systems and computing hardware, which reduces the electromagnetic interference that could affect object detection, depth calculations, and spectrometer abilities. The large flat upper deck in the modular concept is also advantageous, providing a stable mounting location for the rotating stereo-camera mast that enables ROS2 terrain mapping and SSD MobileNet object detection.

Cable routing considerations were also an important factor in the chassis design. Channels and opening within the modular structure allows power and signal wires to run efficiently from the electronics bay to the six wheel motors, the accelerometer, the cameras, and the servo motor without significant disruption and interference. This is an essential aspect of mobility performance as navigation tasks can be completed effectively. The modular configuration also simplifies maintenance. Individual sections of the chassis can be removed to access wiring harnesses or replace any malfunctioning sensors without fully disassembling the rover.

Structurally, the chassis is designed to distribute loads associated with the differential bar, rocker joints, and bogie arms while maintaining low deflection values. Through the usage of ANSYS Workbench and finite

element analysis, it is shown that stresses remain well below the material limits for the chosen aluminum alloys, even when accounting for dynamic loads during obstacle traversal. Maintaining stability is important for the entirety of the system. Stability is critical for accurate sensor readings, mainly for stereo-vision and inertial navigation, because excessive chassis flex would most likely result in misalignment of camera baselines or accelerometer drift.

Overall, the integration of structural, mechanical, and electronic considerations reinforces the selection of the rectangular, modular chassis. Its adaptability allows for iterative upgrades to navigation sensors, computing modules, or suspension components without having to completely overhaul the current design. This makes the chassis design not only structurally sound, but also highly compatible with the evolving control, navigation, and drilling requirements of REHT.

III.3.2. Chassis Material

Through the chassis material trade study and the Pugh matrix, Aluminum Alloy 7075 was selected as the baseline material for the primary structure of the full-scale rover. However, for the prototype, Aluminum 6063 would be utilized as the baseline material. Aluminum 6063 demonstrated the best overall balance of cost, corrosion resistance, and manufacturability, while also maintaining a favorable mass density. With a density of 2.70 g/cm^3 and a tensile strength of approximately 190 MPa, this alloy provides sufficient strength for lightweight lunar surface operations while remaining easy to machine and extrude. It also offers excellent surface finish quality and broad commercial availability, enabling efficient in-house fabrication of structural components. Aluminum 6063 provided the most practical and cost-effective solution for REHT's structural and manufacturing requirements and gave plenty of reason for its selection.



Figure 39: Aluminum 6063

III.4. Drill

After a thorough analysis of potential options for a sub-scale Earth model of a rotary percussive drill, a final design was decided upon. This design seeks to minimize complexity as much as possible without sacrificing critical functionality. The full lunar rover drill design will be highly complex, having to collect samples from 0 to 2 meters deep, including everything from loose lunar regolith to incredibly hard rock. It must be able to break off rock cores while also holding loose regolith that can slide out of tiny cracks. It then needs to transport that material to a storage container and push the material out on demand. This, although simple in theory, becomes quite complex when dealing with the various soil types that would be encountered on Earth. On the moon there is no moisture, limiting the types of soils that can be found. However, the Earth has a wide variety of soil types that drastically change soil mechanical properties, making a drill that

can collect all of these types adequately quite difficult. Thus, a target material was set for the design to focus on that would then be expandable to the largest variety of materials. The best design was deemed to be a hammer drill design to cut through rock. Not only does this match our mission profile of drilling down deep, it is also functional for cohesive rock, clay, and soil. The following design review will outline the critical components that allow the drill to cut a core, transport it, and deposit it inside the rover storage system. Where possible, the design was chosen to reduce complexity and increase manufacturability. Any electric components were minimized by increasing the number of tasks a single electric part can do. All designs were made such that they could be manufactured in the EB3 machine shop using tools such as lathes, CNC machines, and welders. This analysis will discuss parts in order of the drilling process. Thus, the drill and cutting bit will be discussed first. The drill selected for this design is the **BAUER 20V Brushless Cordless 1/2 in. SDS-PLUS Rotary Hammer Drill**. Its relevant specifications are shown in Table 10.

Table 10: Specifications of Selected BAUER Rotary Hammer Drill

Property	Value
Maximum Speed	1300 RPM
Impact Rate	4600 BPM
Torque	65 N·m
Product Length	12 in.
Product Weight	4.9 lb



Figure 40: Bauer Drill

This should be able to handle the designed loading that will be experienced from the friction on the drill bit from the soil. The drill bit itself has been designed to take out six inch core segments at a time but can be extended to a larger size.

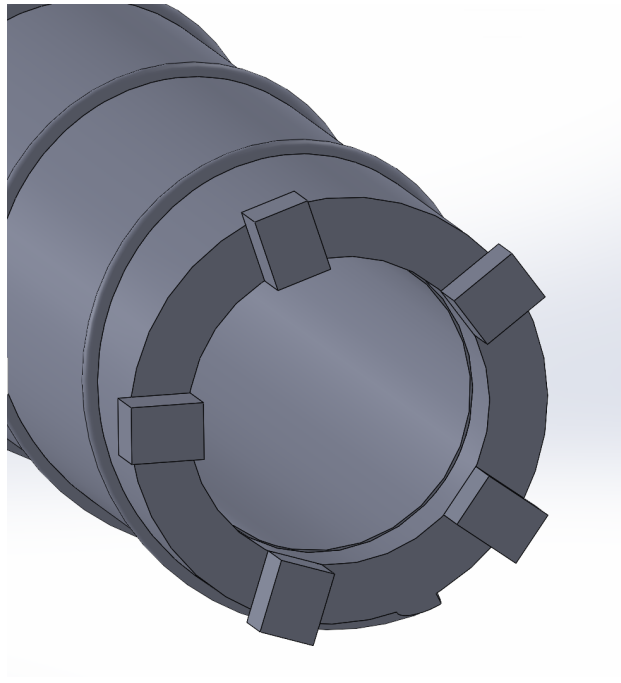


Figure 42: Aligned inner and outer tubes.

A carbide-tipped cutting head (Fig. 41) uses five cutting teeth and a helical outer flute to remove debris. When the desired drilling depth is reached, an internal mechanism disengages the inner and outer tubes, allowing relative rotation. Because the inner tube is intentionally non-concentric, rotation induces shear that fractures the core from bedrock.

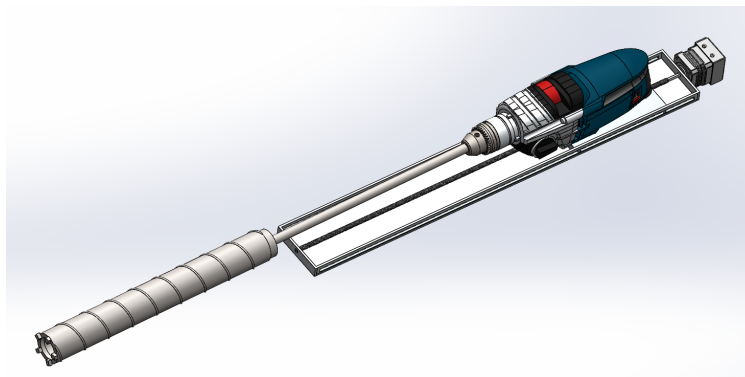


Figure 41: Cutting bit and drill assembly.

Two tube states—aligned and misaligned—are shown in Fig. ??.

A screw-driven internal motor actuates a translational “core pusher” (Fig. 50). When retracted, it engages a locking pin for drilling; during core breaking, it advances slightly to disengage the pin. Once the core is fractured and contained, the drill retracts to its storage position. A storage-tube arm then prevents outer-tube rotation while the drill realigns the tubes. Finally, the same pusher motor ejects the core into the storage system.

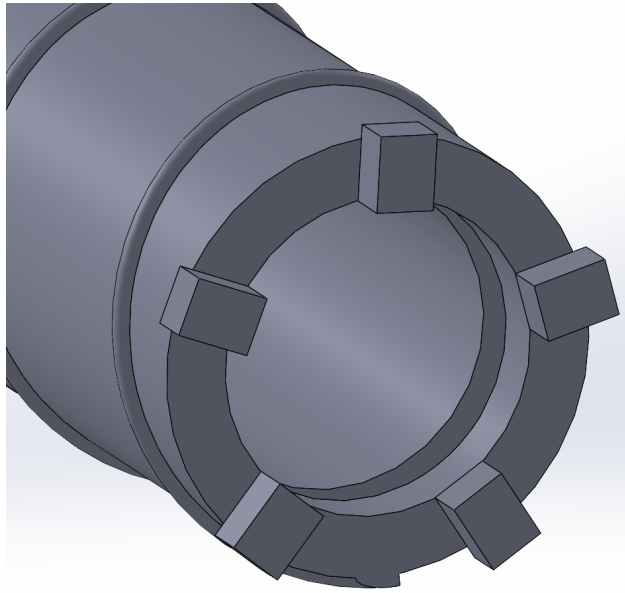


Figure 43: Misaligned tubes for shearing the core.

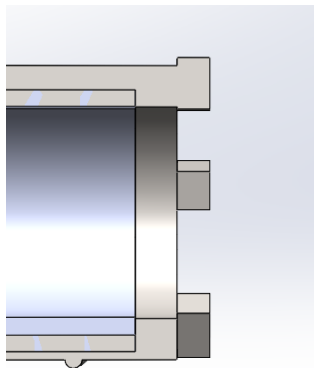


Figure 44: Aligned inner and outer tubes.

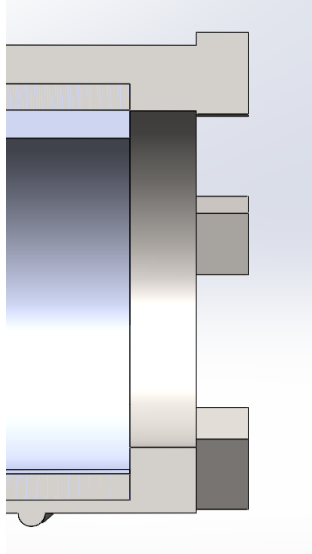


Figure 45: Misaligned tubes for shearing the core.

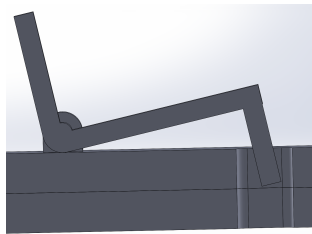


Figure 46: Unengaged Pin

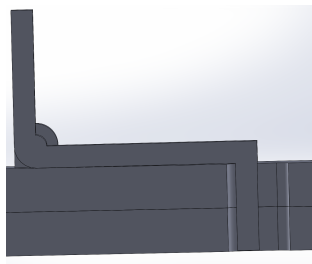


Figure 47: Engaged Pin

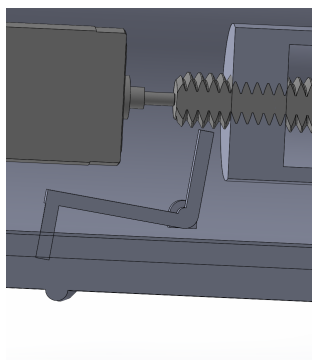


Figure 48: Unengaged Pin in Assembly

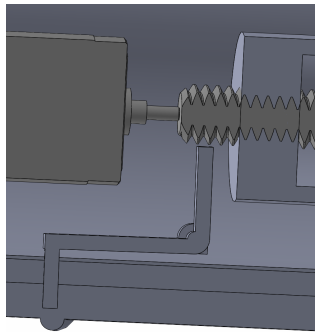
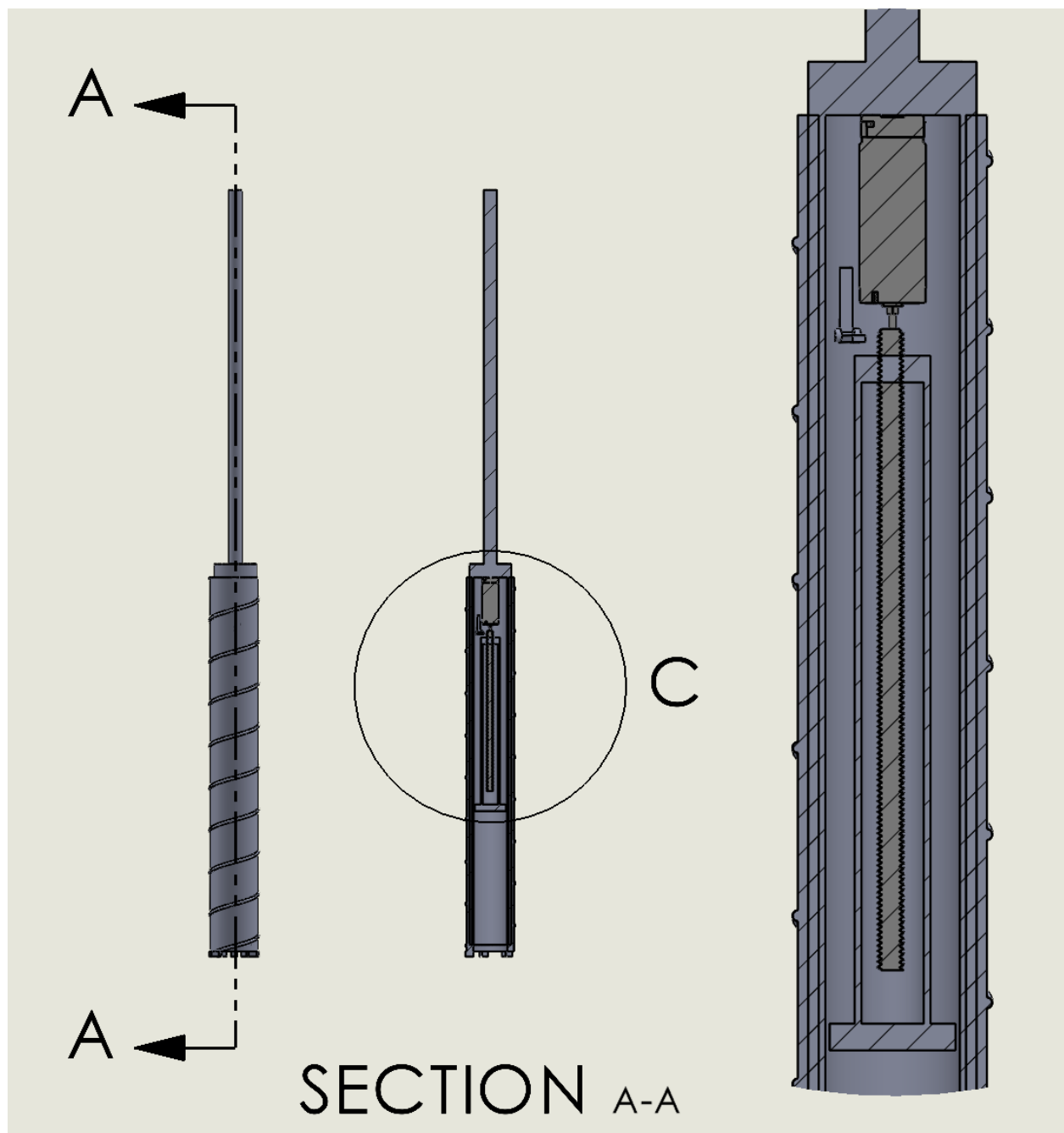


Figure 49: Engaged Pin in Assembly



Expected drilling torque must remain below the drill’s supply torque and material strength limits. Lunar regolith data from the literature were used to estimate loads; ranges and best estimates are shown in Table 11.

Table 11: Representative Lunar Regolith Mechanical Properties

	Property	Range	Best Estimate
[29]	Porosity	35–38%	36.5%
	Void Ratio	0.54–0.61	0.58
	Density (g/cm ³)	1.92–2.01	1.97
	Friction Angle (deg)	47.5–51.5	49.5
	Cohesion (kN/m ²)	0.98–1.02	1.00

The drill torque consists of four components:

- 1. Cutting screw conveyance
- 2. Cuttings extrusion
- 3. Cuttings bulldozing
- 4. In-situ simulant cutting

Penetrating speed v_p /(mm·min ⁻¹)	Rotary speed n /(r·min ⁻¹)	Weight on bit F_w /N			Rotary torque T /(N·m)		
		Experiments	Average	Model	Experiments	Average	Model
85	60	61.6–83.6	72.1	71.3	1.13–1.45	1.31	1.05
85	80	32.0–41.9	37.7	39.0	0.70–0.88	0.78	0.54
85	100	21.2–28.2	25.6	24.2	0.52–0.59	0.55	0.33
85	120	15.8–22.2	18.4	15.8	0.33–0.43	0.37	0.21
85	140	9.2–17.5	12.7	11.6	0.22–0.29	0.26	0.15
85	200	6.6–10.0	7.8	6.7	0.08–0.16	0.12	0.09
10	10	32.5–42.0	37	39.0	0.61–0.8	0.69	0.54
60	60	36.2–41.9	40	39.0	0.68–0.78	0.76	0.54
70	70	34.3–49.5	39	39.0	0.62–0.80	0.73	0.54
200	200	32.1–41.5	38	39.0	0.68–0.72	0.70	0.54

Figure 51: Table from Qi-Quan Quan [30]

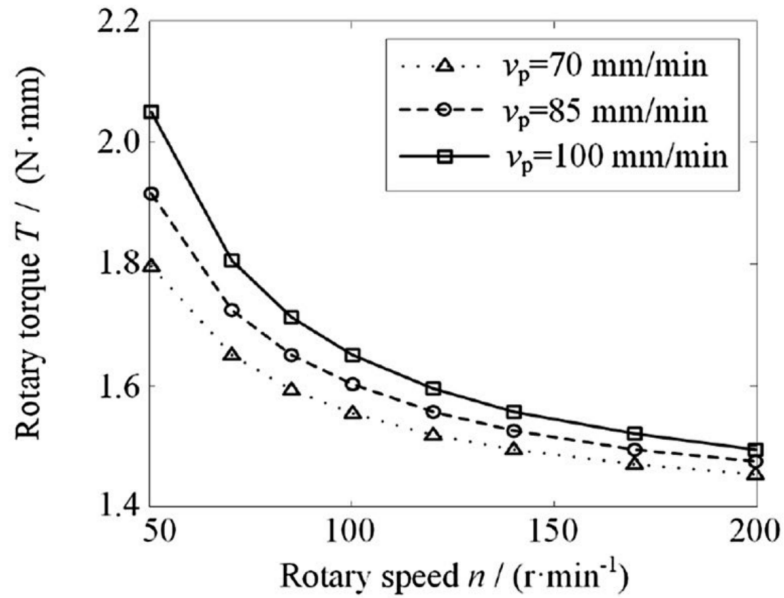


Figure 52: Variation in Torque with various parameters [30]

A MATLAB implementation of these models yielded:

$$\text{Torque} = 5.131 \text{ N}\cdot\text{m}, \quad \text{Safety Factor} = 3$$

Additional calculated loading results:

$$\begin{aligned} \text{Force on wheels} &= 7.70 \text{ N} \\ \text{Max friction force} &= 8.18 \text{ N} \\ \text{Stress in solid shaft} &= 12.76 \text{ MPa} \\ \text{Stress in inner tube} &= 0.60 \text{ MPa} \\ \text{Stress in outer tube} &= 0.28 \text{ MPa} \\ \text{Stress in pin} &= 8.10 \text{ MPa} \end{aligned}$$

Static structural simulations in ANSYS were conducted to include off-axis mass effects in the drill head (Fig. 53).

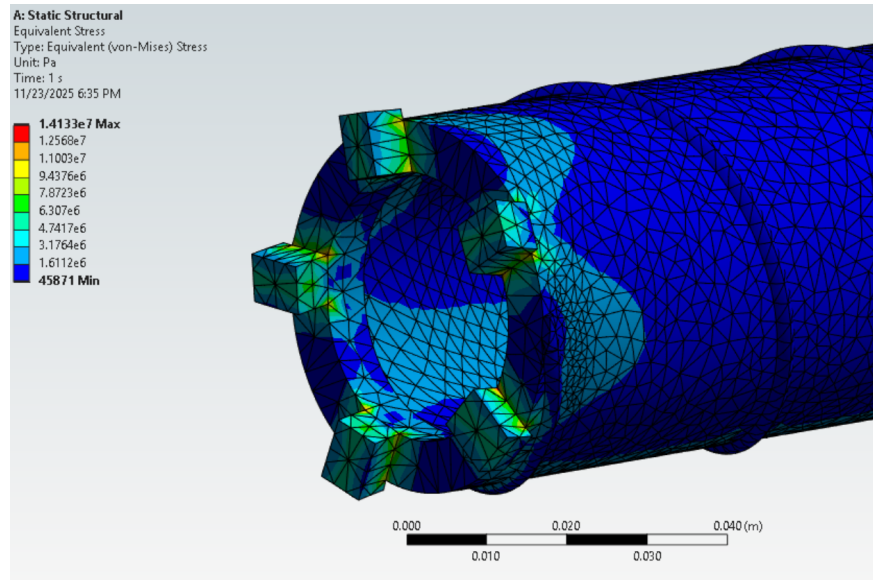


Figure 53: ANSYS simulation showing stress distribution in outer bit under 900 RPM and 100 N per carbide tooth.

Results indicated:

- Maximum stress in outer bit: **14 MPa**, well below steel yield strength.
- Reducing carbide cutter height would further reduce stress.

A separate analysis of the inner tube (Fig. 54) showed:

- Maximum stress: **102 MPa**, caused by intentional off-axis rotation geometry.
- Still significantly below steel yield strength.

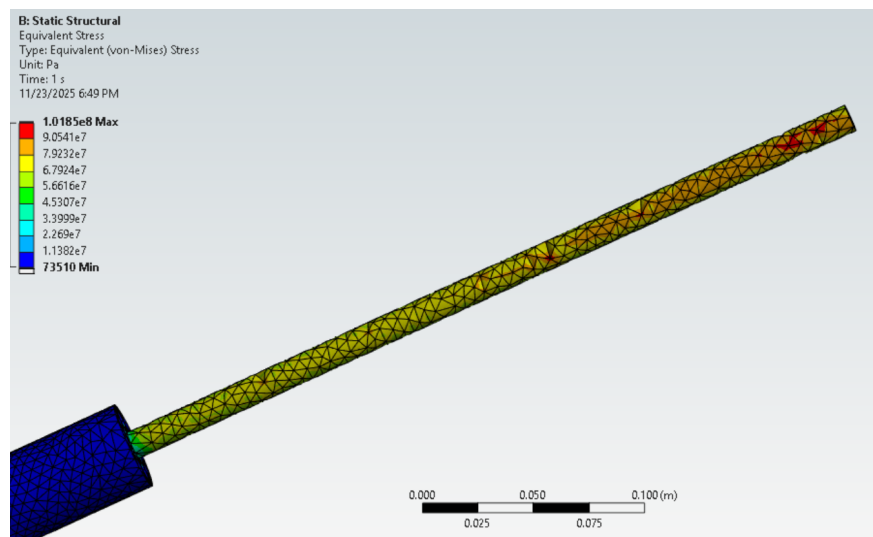


Figure 54: ANSYS simulation of inner tube showing stress concentration from eccentric rotation.

Based on these simulations, the material chosen for the drill is A36 Steel, which has a yield stress of 250 MPa. It is readily available, inexpensive, and able to handle the loads for the task. Additionally, steel has a fatigue limit, whereas aluminum does not, meaning the drill will be able to last through more hours of drilling.

III.5. Payload

III.5.1. Storage

III.5.1.1. Motivation

There are multiple reasons why this was chosen over the ALSRC. First is the hermetic seal, which prevents any pressure or gas from escaping once the sample is stored. This allows the sample to remain in a constant state. This is especially useful for our main desired sample, Helium-3. Though its concentration is stored within the lunar soil, there's no telling how its properties may change over time after its extraction or return to Earth. If the Helium-3 were to be expelled within the tube as a gas, it is still properly stored within the tube.

Next is its separation by materials and temperature. Given its much smaller volume when compared to the ALSRC, it's much easier to separate samples between different tubes, be they marked by material or temperature. Their compact nature also makes them easier to handle with the drill, such as being able to extract the sample from the drill bit and store it after a sample tube is brought over through a conveyor system.

Though the main reason comes from the base motivation of each design. The ALSRC was designed for manned missions, garnering multiple hinges and latches to keep the container closed while maintaining a bulkier volume meant for human interaction. Sample tubes were designed with unmanned missions in mind. It's much simpler in design, only really having a storage compartment, a storage-release compartment, and a seal. As such, it's easier to integrate autonomously with the more complicated subsystems REHT utilizes. The sample tubes shown below are those used on the Perseverance Rover back in 2020. The designs for REHT's sample tubes will be a simplified version of these.

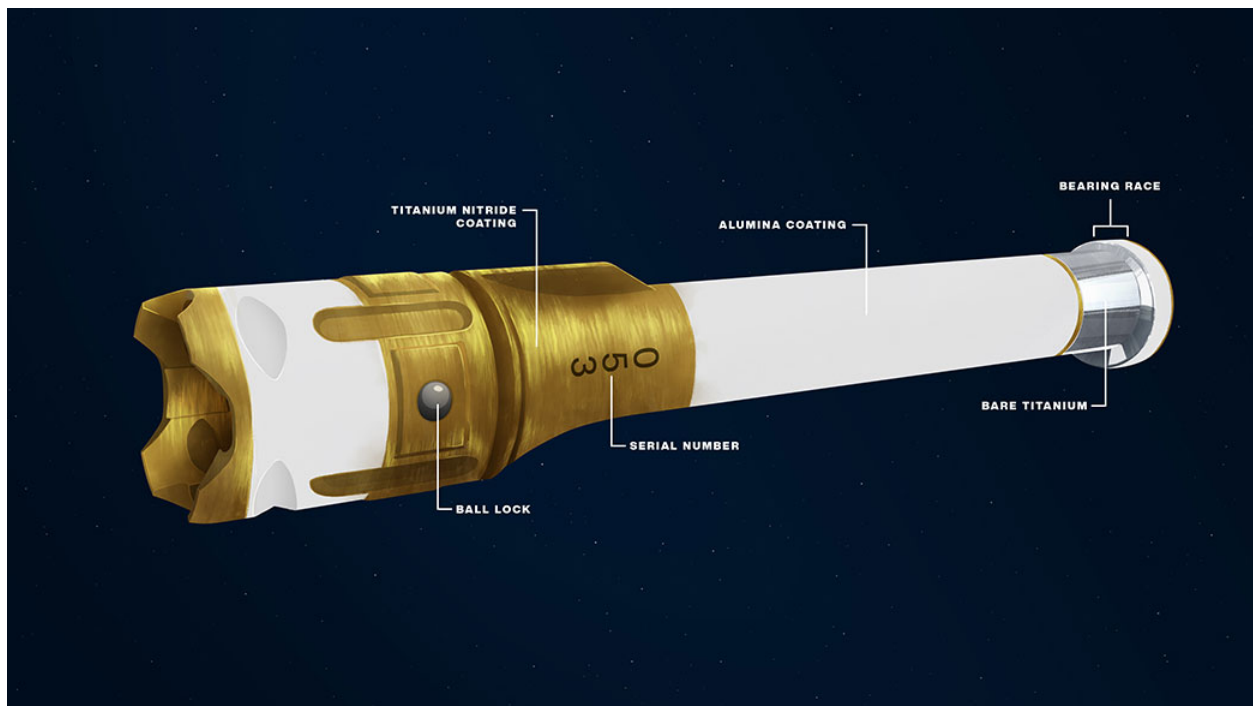


Figure 55: Outside View of Perseverance Rover Sample Tube [5]

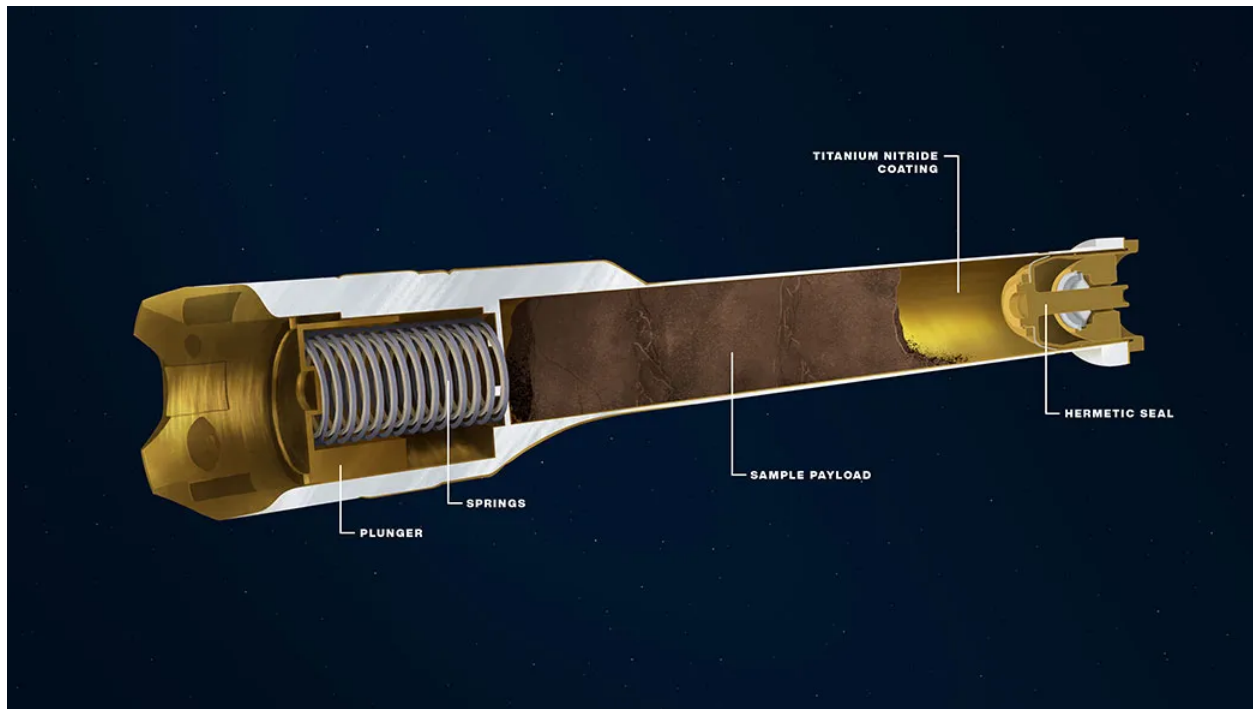


Figure 56: Inside View of Perseverance Rover Sample Tube [6]

III.5.1.2. Sample Collection

Since REHT will need to make multiple trips upon sample collection, the storage system must be designed with that in mind. Additionally, considering the mission is unmanned, the collection and storage process must be completely automated. Lastly, since there are different storage compartments (one with control samples and another with refrigerated samples), there must be a way of separating these samples.

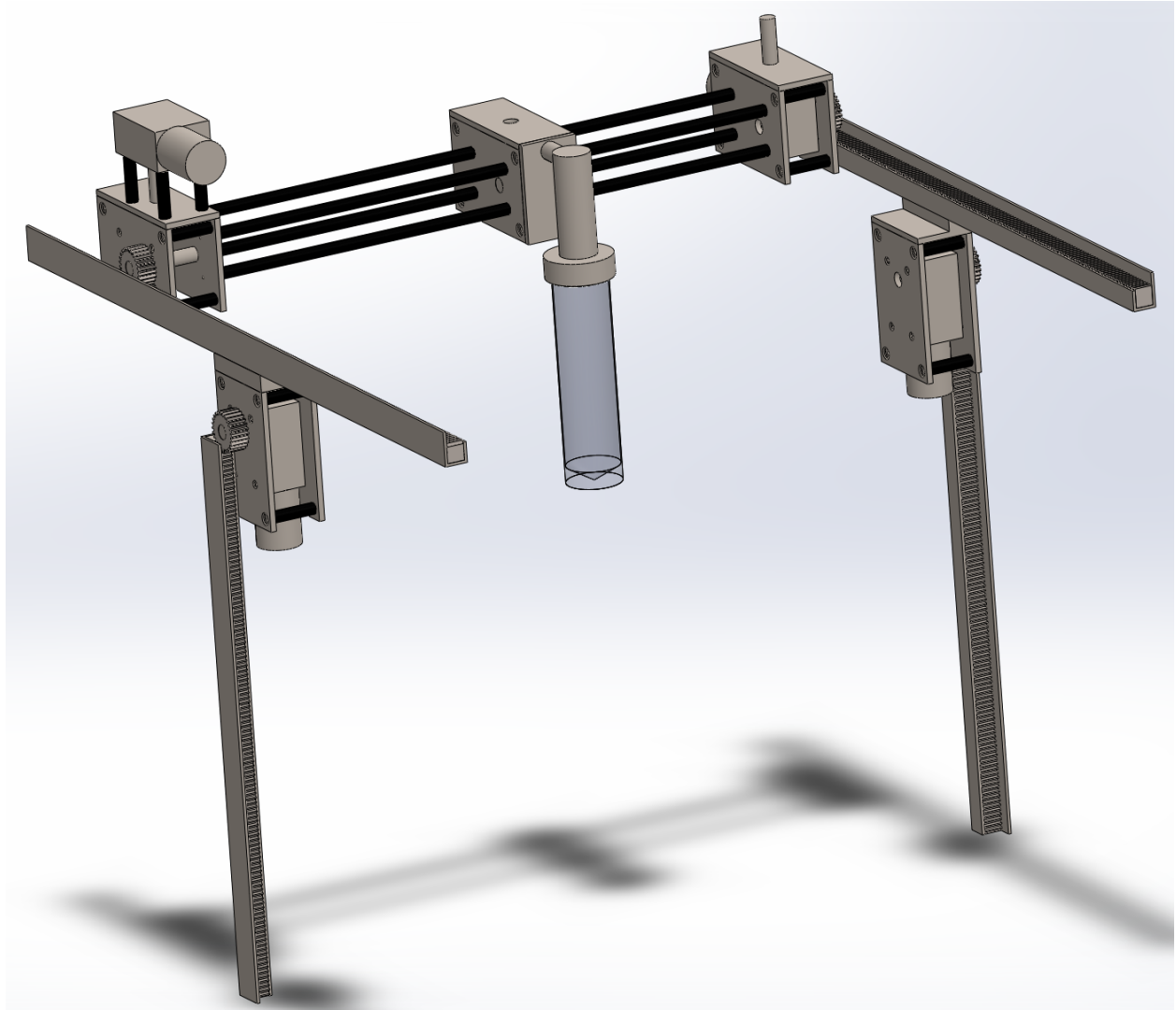


Figure 57: Storage Module CAD with Storage Module

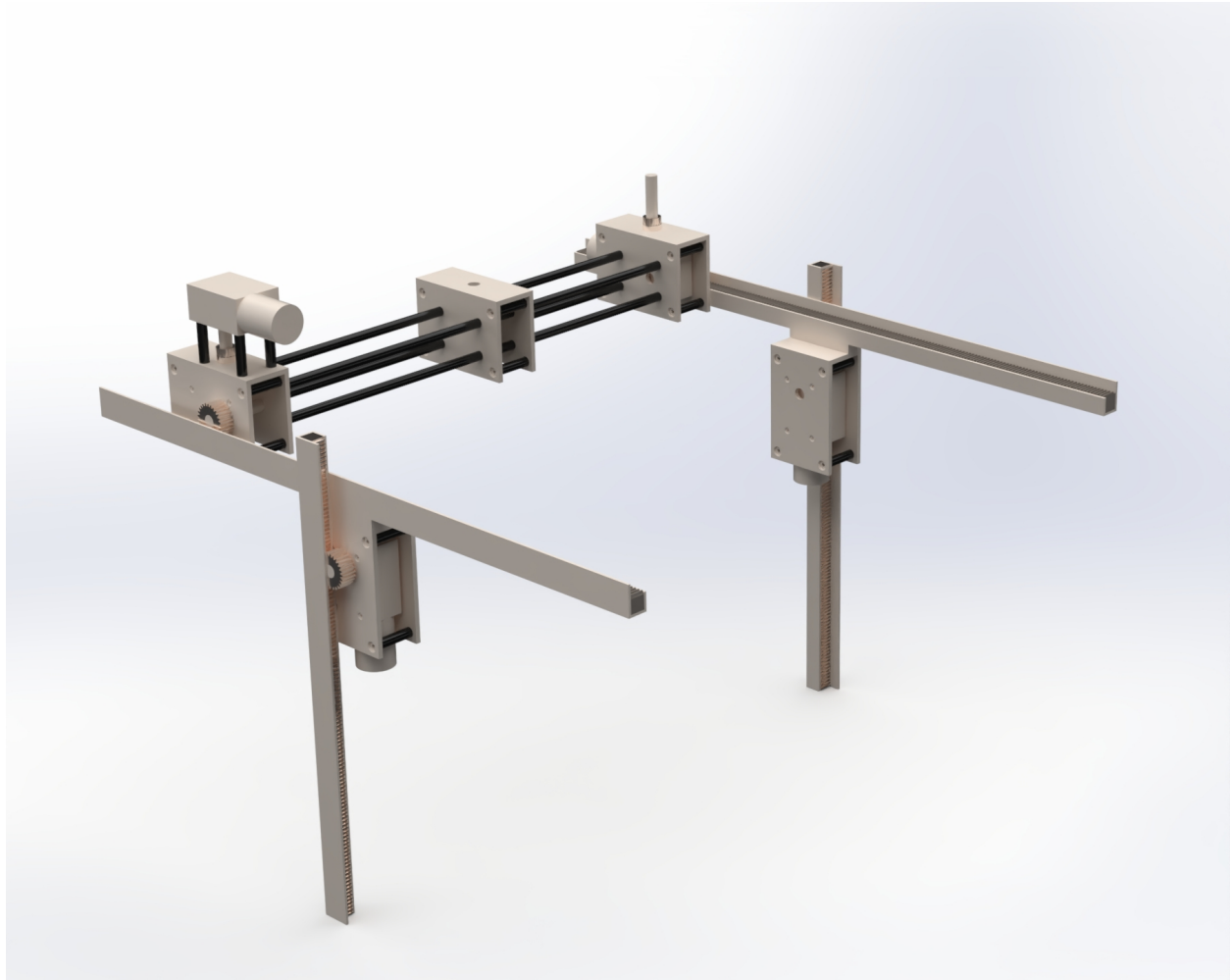


Figure 58: Storage Module CAD Rendering

The solution to this is a modular grabber system. This system is made up through a variety of bars, gears, and motors. At the center of the system is the storage module, made for picking up the sample tubes by twisting their caps onto them and pulling them up. When a sample tube would be released, the storage module would loosen it's grip on the cap while keeping the cap hermetically sealed onto the sample. Once the sample tube is released, the storage module would collect another cap and repeat the process.

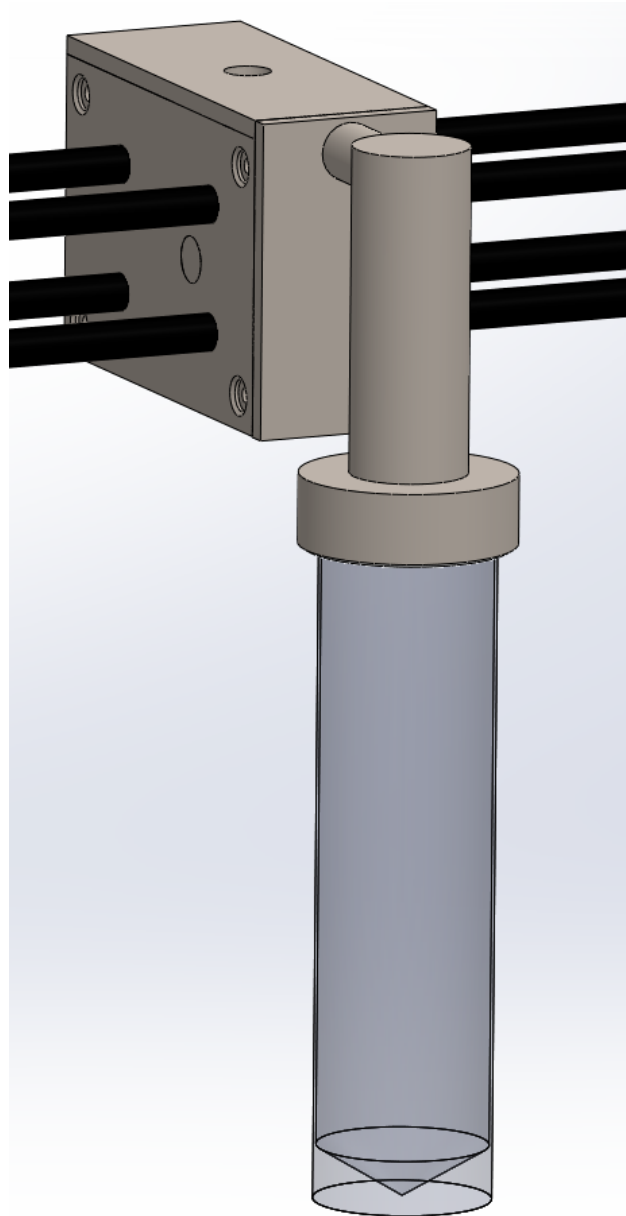


Figure 59: Baseline Storage Grabber CAD

Far as transporting the tubes, the aforementioned bars, gears, and motors influence where the sample tube is placed. Along the edges of REHT's interior are two bars, one on each side. They both have a motor and a gear which determines the vertical movement of the storage module. There are two more horizontal bars along the top as well. These two each have a motor and two gears which determine the horizontal movement of the storage module.

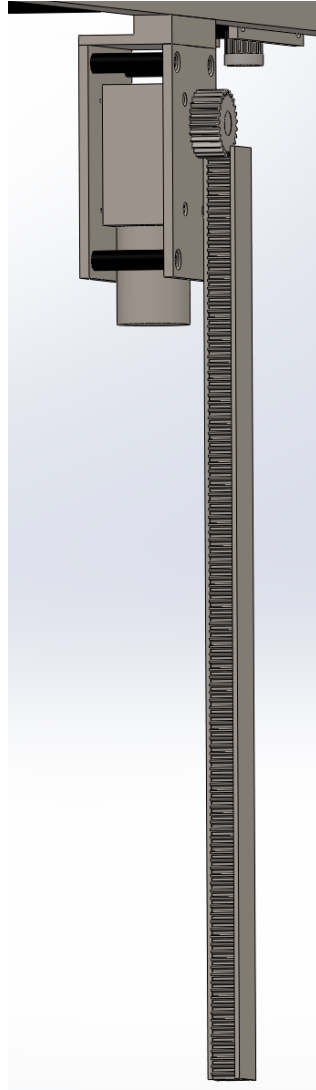


Figure 60: Vertical Belt CAD

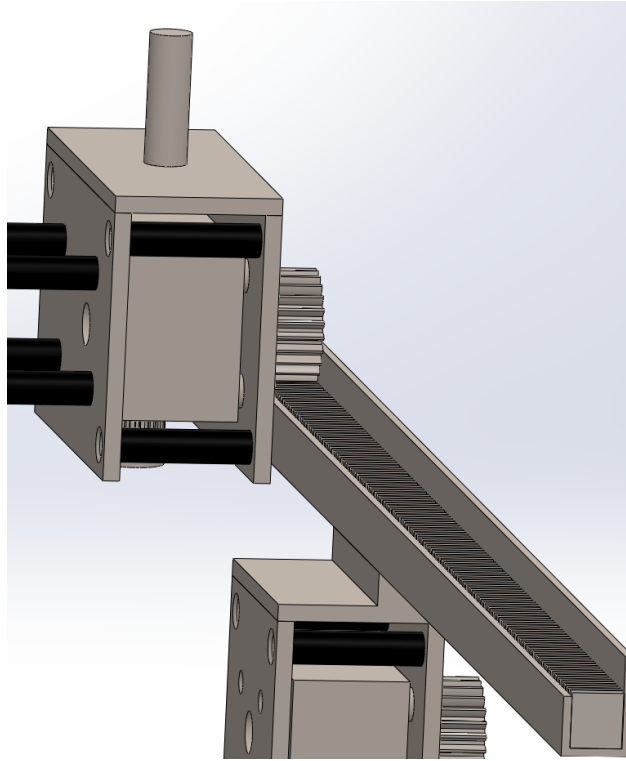


Figure 61: Horizontal Belt CAD

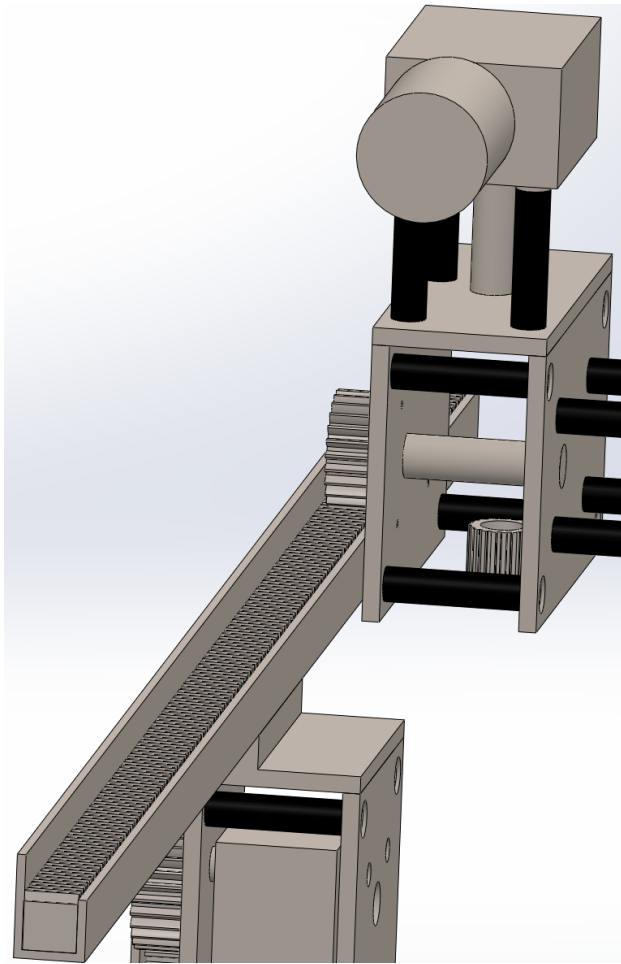


Figure 62: Horizontal Belt CAD

The system starts out having 75 empty sample tubes in the middle compartment of the REHT. As the drill begins drilling into the lunar surface, it will extract the desired material through the drill bit. During this process, an opened and empty sample tube will be carried from a storage module towards a designated area on REHT for sample collection. The drill bit will carry the extracted dust to the sample tube and pour the lunar regolith into the container. As the drill bit extends back out onto the lunar surface, the cap of the sample tube is hermetically sealed on top of the container, effectively containing the sample in a pressurized container.

Depending on the regolith concentration, the sample tube will either be carried to the control sample compartment or the refrigerated compartment by means of the transport system. After the cap is sealed, the sample tube will hang by the storage module. The storage module will transport the tube to its respective storage section. At the end of the system, the tube will be lowered onto a storage rack in its respective unit, the storage module twisting the cap just enough where it let's go of the tube.

This process will continue until all 75 sample tubes on-board the rover are filled. From here, REHT will return to the launch vehicle and deposit the sample tubes on board. It will do this by opening the storage section, pulling the racks of sample tubes out and collecting said samples with an on-board collection method. Though the design of said collection method between REHT and the launch vehicle is outside the scope of

this design, it is likely to be another automated rack which grabs all sample tubes at once and pulls them into the launch vehicle. Once the sample tubes have been collected will the racks be pushed back into the rover.

Likewise, a new set of empty sample tubes from the launch vehicle will be inserted in the sample collection section in a process which mirrors the collection. With the samples collected and REHT restocked can REHT continue it's mission until the desired amount of lunar regolith is collected.

III.5.1.3. Sub-Scale Dimensions

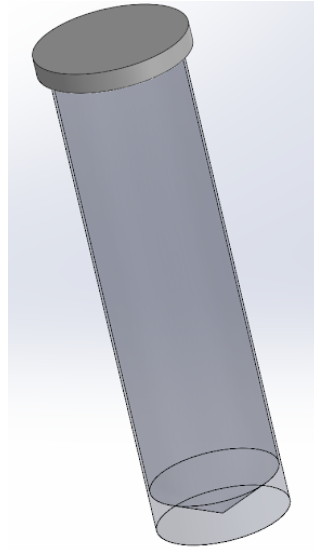


Figure 63: CAD Model of Sample Tube

Based on the dimensions of the rest of the subscale chassis and the standard measurements of all typical sample tubes, the storage has the following dimensions:

- Tube: 30 mm in diameter, 115 mm in height. 25 mm dowel hole at bottom of the tube.
- Cap: 35 mm in diameter, 4.6 mm in height. Inner diameter of 31 mm sunk 3.6 mm.
- Total: 50 mL in measurement.

The dimensions and the design were made to determine the sample tubes ordered for the subscale. The following trade study was conducted to determine the best option available.

Subscale Storage Study		Self-Standing Test Tube		SPL Conical Tube		Glass Sample Vial	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Usage	25	-	-	-	-	-	-
Ease of Storage	6.25	1	6.25	1	6.25	0	0
Drill Application	6.25	1	6.25	1	6.25	-1	-6.25
Spectrometer Application	12.5	1	12.5	1	12.5	1	12.5
Transportation	20						
Dimensions	5	-1	-5	1	5	0	0
Conveyor Application	15	1	15	-1	-15	-1	-15
Affordability	5	-	-	-	-	-	-
Upfront Cost	5	1	5	0	0	-1	-5
Storage	15	-	-	-	-	-	-
Storage Capability in g	5	1	5	1	5	1	5
Total Weight in g	5	0	0	1	5	1	5
Measurability	5	1	5	1	5	-1	-5
Temperature	15	-	-	-	-	-	-
Constant Temperature	7.5	0	0	0	0	1	7.5
Refrigeration	7.5	1	7.5	1	7.5	1	7.5
Sample Preservation	20	-	-	-	-	-	-
Sealing	10	0	0	1	10	-1	-10
Sterile	10	1	10	1	10	0	0
Total Score			67.5		57.5		-3.75
Rank			1		2		3

Figure 64: Trade Study for Subscale Sample Tube

The trade study above illustrates how the self-standing test tube is the best choice for the subscale storage containers. There are three main deciding factors which differed between the three choices. First is it's cost. The self-standing test tubes were cheaper than the other two options, allowing for an adequate amount of storage given its cost. Second is the material used. The self-standing test tube and the SPL conical tubes are made of high quality polypropylene material (a type of plastic) whereas the other sample vial is made of glass. Not only are the polypropylene tubes more sterile because of this, they are unlikely to break. Finally, is their integration with the sample collection process. Because of the shape of the self-standing tubes, these fit best with the conveyor system outlined above. Thus, the Kashi 50 mL self-standing test tube is the container of choice for the subscale's storage. Given budget constraints, 25 of these tubes of these tubes will be ordered.



Figure 65: Kashi 50 mL Self-Standing Test Tube

Additionally, three sets of sample tube racks will be ordered as well; one for each storage unit. Each rack can hold ten 50 mL tubes.

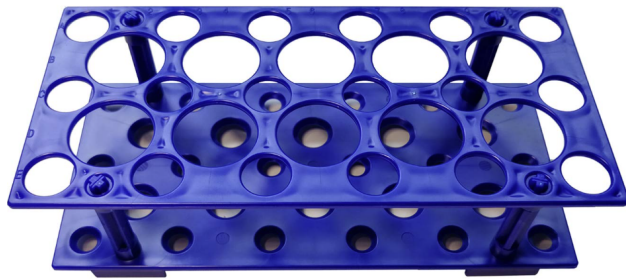


Figure 66: Test Tube Rack

III.5.2. Spectrometer

III.5.2.1. Full-scale Spectrometer Selection

Based on the trade study, the most practical and feasible choice of spectrometer is the Laser Induced Breakdown Spectrometer. There are multiple reasons why LIBS is the best spectrometer for REHT. Starting from the sampling compatibility, LIBS has the capability to remotely measure and detect the presence of various elements. Mounted on top of the REHT LIBS, it can first analyze the Lunar surface before drilling and collecting samples. LIBS has a range of up to 7m, making it highly compatible with the REHT's core drilling sampling method. A mass spectrometer, on the other hand, requires a separate sampling method, where it analyzes the samples inside the rover before taking a final core sample, making it incompatible with REHT's core drilling sampling method. Similarly, an APXS requires it to be placed extremely close to the targeted sample location for it to work. This does not require a separate sampling method, but it makes it so that REHT requires a separate arm to operate an APXS properly.

A neutron spectrometer and a near-infrared spectrometer are highly compatible with REHT's sampling method due to their remote measuring capabilities, similar to LIBS. However, a neutron spectrometer is mostly used to detect the presence of Hydrogen and Iron. Similarly, a near-infrared spectrometer is excellent only at detecting Hydrogen molecules like water and Hydroxide, whereas an APXS is used to detect elements with an atomic number higher than 11. Despite being useful in detecting water, they are not capable of detecting the presence of Helium-3 on the lunar surface. A mass spectrometer, unlike others, can detect the presence of Helium-3 directly. However, it requires pyrolysis to be performed on the sample, which not only makes the design of REHT complicated but also makes it less feasible. Although LIBS is not capable of detecting Helium-3 presence directly, it can easily detect the presence of elements and minerals like Ilmenite and Titanium, which have a high probability of containing trapped Helium-3.

Moving on to sensitivity and resolution, the mass spectrometer is the best out of them all. However, a mass spectrometer is heavier compared to others and, as mentioned earlier, requires the implementation of a complicated design for REHT, making it a highly unfeasible option. A LIBS performs similarly in terms of resolution and sensitivity while being more feasible for REHT. A neutron spectrometer is just as sensitive as a mass spectrometer, detecting the slightest presence of elements; however, it struggles to differentiate between similar elements because it has a very low resolution. Lastly, the near-infrared spectrometer and the APXS lack sensitivity and have moderate resolution, making their results comparatively less accurate.

Apart from performance criteria there are several constraints that REHT has, according to which selecting an ideal spectrometer is essential. The mass spectrometer and LIBS perform the worst in this category. A mass spectrometer has a high power usage and occupies a very large volume. This is because it requires analyzing samples from within as opposed to remotely, like other types of spectrometers. Not to mention, even commercially available mass spectrometers are some of the most expensive spectrometer types in the world. A custom-built mass spectrometer for space operations could cost more than 5 million dollars, eating up a big chunk of the budget. LIBS, on the other hand, is less expensive as compared to a mass spectrometer and occupies much less volume; however, due to its pulsating laser, it consumes an extreme amount of energy that is more than all other spectrometers. A near-infrared spectrometer occupies a similar volume and uses moderate power; however, its costs can range up to a few million dollars, making it very expensive. An APXS and a neutron spectrometer consume less power and occupy the least amount of space, with the APXS being relatively very cheap as compared to others. However, these spectrometers do not perform as well as compared to LIBS or a mass spectrometer, making them a latter preference.

As mentioned earlier, the temperature on the surface of the Moon can vary anywhere from 120°C to about -250°C during the span of the day, depending upon the location. This makes it extremely difficult for instruments such as a spectrometer to operate in such conditions. As a result, no spectrometer can operate in such a wide range of temperature, with APXS and mass spectrometers being the most temperature sensitive out of them all. LIBS, on the other hand, cannot operate in such harsh temperature conditions; however, it can be designed and manufactured in such a way that the spectrometer can keep itself safe at extreme temperatures. This can be done by insulating the spectrometer and also by providing it with both active and passive temperature regulation mechanisms, allowing the spectrometer to operate properly in such conditions.

One of the most important factors about operational capabilities is the regolith tolerance of instruments. Being loose, fragmented, and unconsolidated lunar regolith is an extremely hard thing to deal with. Moreover, the lunar regolith is extremely abrasive due to the presence of sharp and jagged glass-like particles. During past lunar missions this has proven to be an issue, causing damage to equipment and instruments. Hence, it is important to select and design spectrometers and other instruments in a fashion that they are tolerant to the lunar regolith and retain as little damage as possible. LIBS is one of the best options for this, as its remote detection capabilities allow it to analyze regolith from a safe distance, preventing it from getting inside the spectrometer equipment and damaging it. Despite this, there is a chance of getting lunar dust or other soil particles on the laser and detector lenses. If there are particles on the lens while the laser is fired, the particles could burn and get stuck on the lens, ruining the instrument. However, this can be prevented with a specific design and manufacturing of the spectrometer and its shielding. Some of the ideas are having compressed gas to clean the lens every time before firing, having a lid to secure the spectrometer when not in use, and lastly having a rotating lens, preventing any dust from settling on the lens. A neutron spectrometer and an infrared spectrometer are similar because of their remote sensing capabilities. An APXS, on the other hand, is at a high risk of getting damaged due to the abrasive capabilities of the lunar regolith. Hence, using an APXS and analyzing samples from a close distance poses a risk of damaging the instrument, preventing it from providing accurate results. Similarly, a mass spectrometer is at an even higher risk of damage due to regolith because it is required to analyze samples inside the spectrometer, making it highly probable of getting the lunar dust in the spectrometer. This makes LIBS an ideal choice for this criterion.

Because of a lack of atmosphere, the Moon's surface is exposed to constant solar and cosmic radiation, which can be ionizing and can damage a spectrometer, gradually lessening its life span. Optics, electronic detectors, and supporting electronics are the most susceptible to radiation. Over time, due to the radiation, these instruments record faulty readings by getting a permanent noise within them. APXS and neutron spectrometers are most tolerant to radiation. APXS itself houses Curium-244, which is a radioactive element, whereas a neutron spectrometer is used to detect neutrons due to cosmic rays. Their specific uses allow manufacturers to design them with extremely radiation-tolerant materials. LIBS and all the other spectrometers are susceptible to radiation damage over time. However, this can be mitigated and lessened through radiation hardening and the use of dense materials like Tungsten and Lead to shield the spectrometers.

Lastly, measuring the speed of these spectrometers is important. A higher measuring speed allows REHT to explore more areas of the Moon and saves a lot of time. A slow measuring speed would mean that REHT will have to wait for a long time before collecting core samples and will have to stay at the same location for a very long time. As a result, REHT would not be able to explore more locations on the Moon for a similar amount of time. In permanently shadowed regions of the Moon, staying at one location for a long time could mean taking a risk of running out of power completely, leading to mission failure. LIBS and near infrared spectrometers are extremely fast at measuring and analyzing samples, taking from seconds to

a few minutes to analyze targeted samples properly. This is because of their natural operation by detecting wavelengths of light. APXS is capable of detecting major elements in a few minutes. However, detecting trace elements could take a few hours for a complete analysis. A neutron spectrometer has a similar speed, taking hours to detect elements completely in a sample. This is because a neutron spectrometer requires a sufficient build-up of information from neutrons reflecting on the detector before concluding the presence of various elements. Lastly, a mass spectrometer is the slowest, requiring more than an Earth day to analyze solid samples. This is because it requires a separate sample preparation, which requires the samples to go through pyrolysis if isotopes like Helium-3 are required to be detected.

Overall, from the trade study, it is clear that LIBS is the best choice of spectrometer for REHT because of its performance and feasibility. A neutron spectrometer, despite being close to LIBS, is not the correct choice because of its lack of high resolution and it being unable to detect or predict the presence of Helium-3 on the lunar surface.

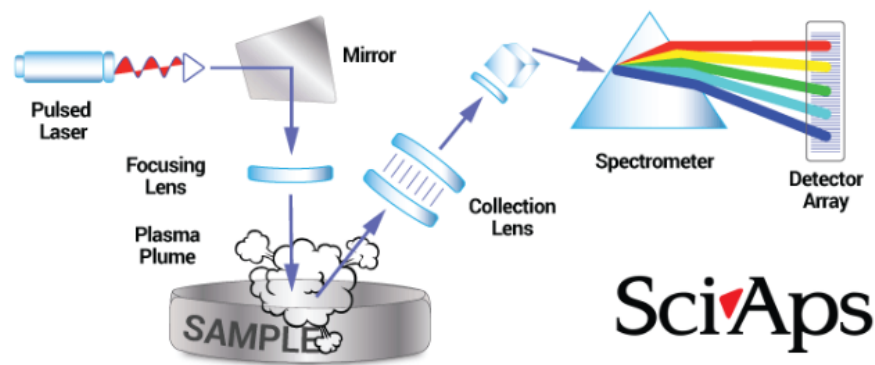


Figure 67: Laser Induced Breakdown Spectrometer Function Diagram

III.5.2.2. Design

To mimic the LIBS spectrometer for the model prototype, a Raspberry Pi camera module will be used along with an ultrasonic sensor module to sense distances. The Raspberry Pi camera module permits a live camera feed that will be displayed on a remote device that is able to control the REHT from a distance. The camera module using Raspberry Pi is also capable of using object detection software known as SSD MobileNet. Using this software, the camera module would be capable of detecting different surfaces and objects. This allows REHT to monitor its surroundings and locate promising drill sites for sample collection.

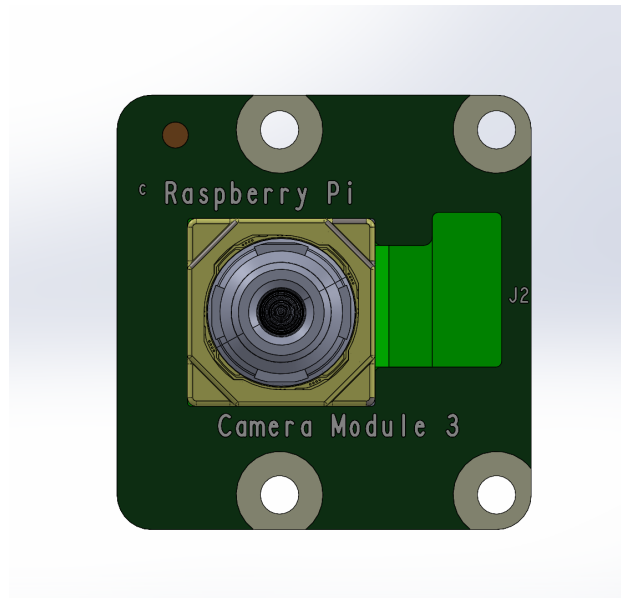


Figure 68: CAD of Raspberry Pi Camera Module 3

Feature	Specification
Resolution	11.9 megapixels
Sensor size	7.4 mm
Dimensions	25 × 24 × 11.5mm
Ribbon Cable	200mm
Diagonal field of view	75 degrees

Table 12: Raspberry Pi Camera Module 3 Specifications

The REHT prototype will be using an HC-SR04 Ultrasonic sensor module for object detection and measuring distance. The module produces sound waves at a specific frequency that travel through the air and reflect back after hitting an object, allowing the module to sense distances. It will be crucial in obstacle detection and collision avoidance.



Figure 69: HC-SR04 Ultrasonic sensor module

Feature	Specification
Operating Voltage	5V DC
Operating Current	15mA
Measuring Angle	15 degrees
Range	0.02m to 4m

Table 13: Raspberry Pi Camera Module 3 Specifications

The CAD for the spectrometer component housing features a hollow design for the fixed arm that will house the electronics and wires, along with a servo motor. The box design would house the small battery for the servo motor, the Raspberry Pi 3B+, a motor driver, and the communication equipment like the LORA transceiver. On top of the box there will be a servo motor with the camera and ultrasonic sensor mount allowing the servo arm to rotate 180 degrees. The hollow design of the box with openings up front and at the bottom for the wiring to pass through without being visible is really useful and feasible. The entire spectrometer box would be 3D printed to save costs, machining time, weight, and to get rapid prototypes.

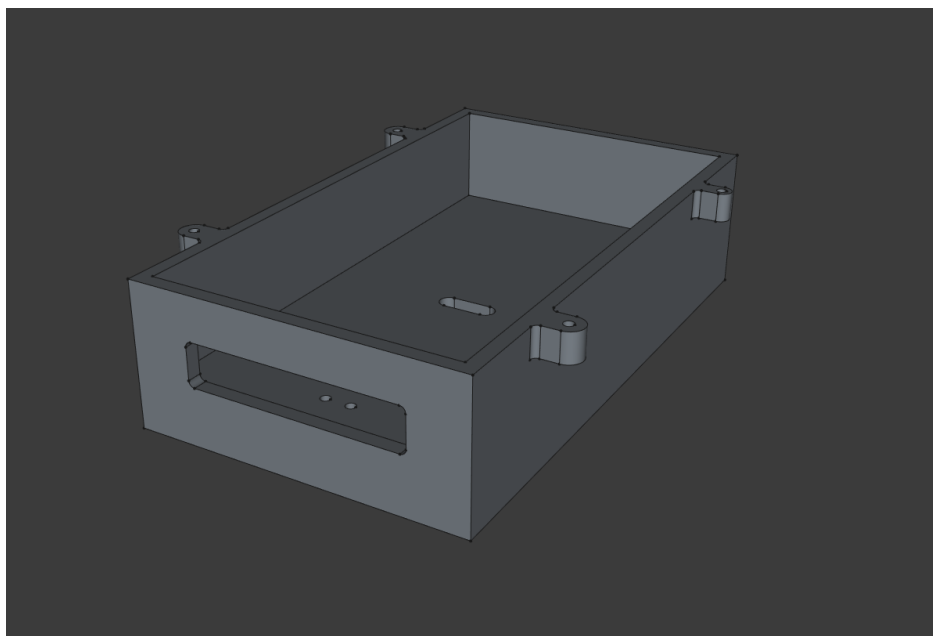


Figure 70: CAD of Spectrometer Housing Top Part

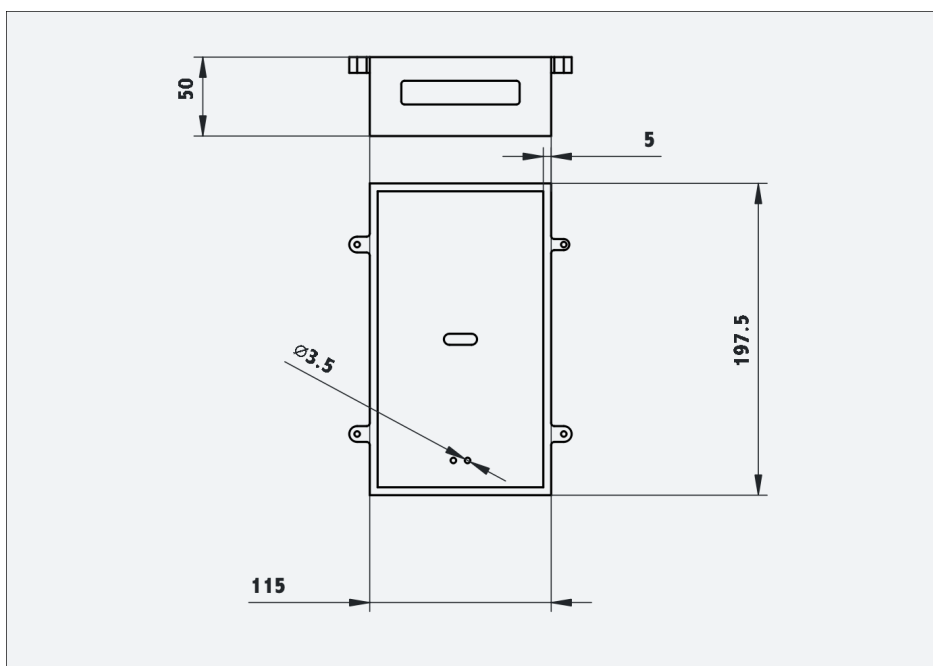


Figure 71: Drawing of Spectrometer Housing Top Part

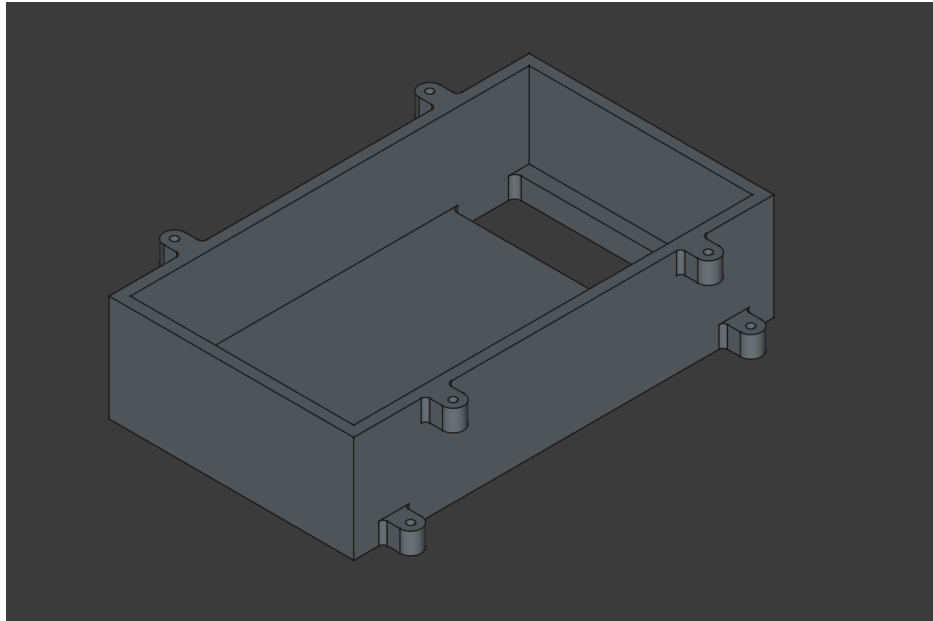


Figure 72: CAD of Spectrometer Housing Bottom Part

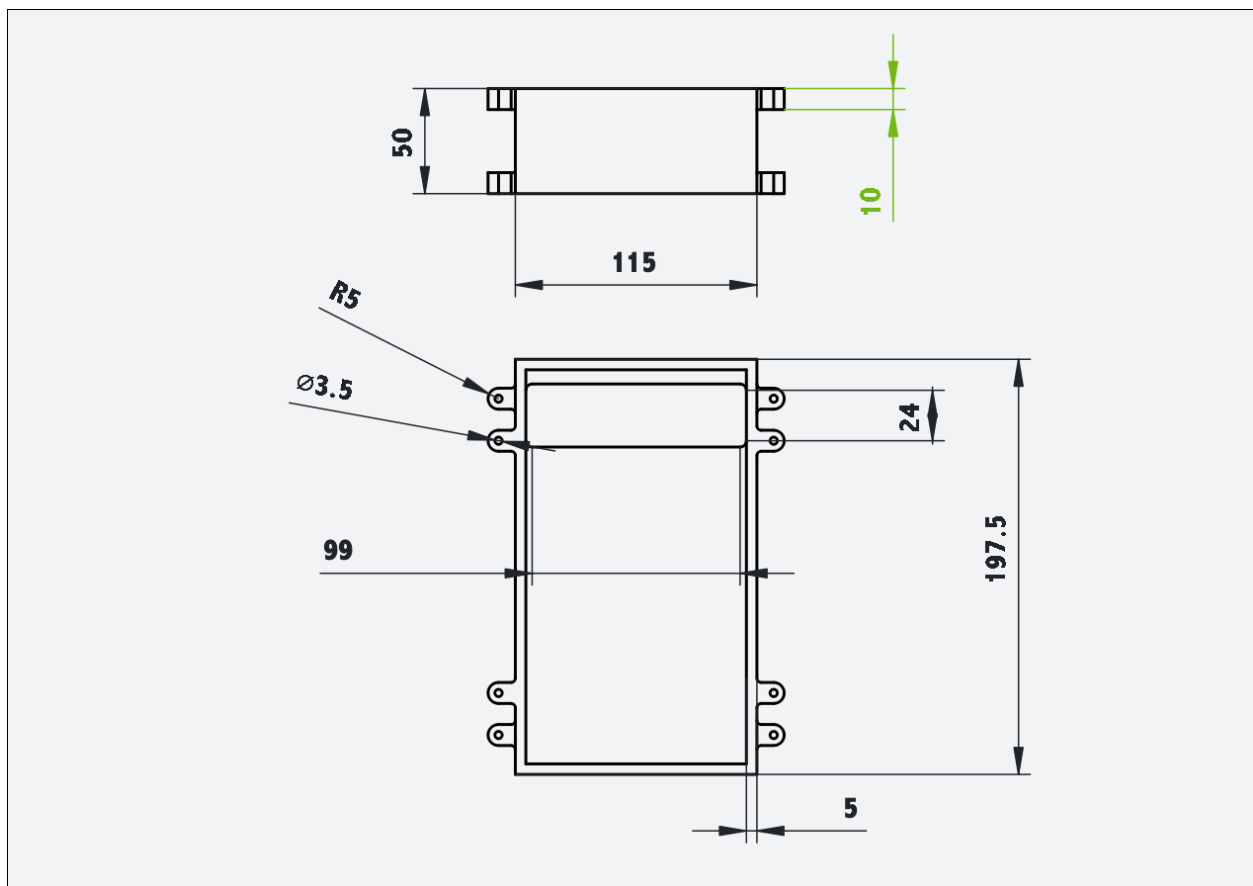


Figure 73: Drawing of Spectrometer Arm Bottom Part

Due to budget limitations, full-scale rover hardware and technologies cannot be implemented in the prototype. However, the prototype design for the spectrometer can be replicated with the full-scale concept of REHT. For the full-scale rover, REHT will be using a LIBS as mentioned earlier. This would allow REHT to analyse the lunar regolith and predict the presence of Helium-3 in the lunar regolith. Furthermore, sensors like LIDAR, along with multiple cameras, can be used for the full-scale version for measuring distance, obstacle detection, and obstacle avoidance.

III.6. Power and Electrical

III.6.1. Batteries

III.6.1.1. Motivation

REHT will use lithium-ion batteries. Firstly, silver-zinc is inferior to lithium-ion and nickel-cadmium in nearly every way. Its specific energy is significantly lower, it doesn't last long, and it isn't rechargeable. Though used for the Apollo lunar missions back in the late sixties [31], silver-zinc is obsolete in terms of battery power, thus quickly disregarded in its potential use for REHT.

The main deciding factor for the use of lithium-ion batteries was their specific energy. Though lithium-ion and nickel cadmium have similar power outputs, nickel cadmium remains much heavier [32], thus significantly lowering its specific energy and leaving less space on board the rover. As will be discussed in section VII.4.1, lithium's specific energy allows it to last for months to even years, far past the one-year mission time set aside for REHT.

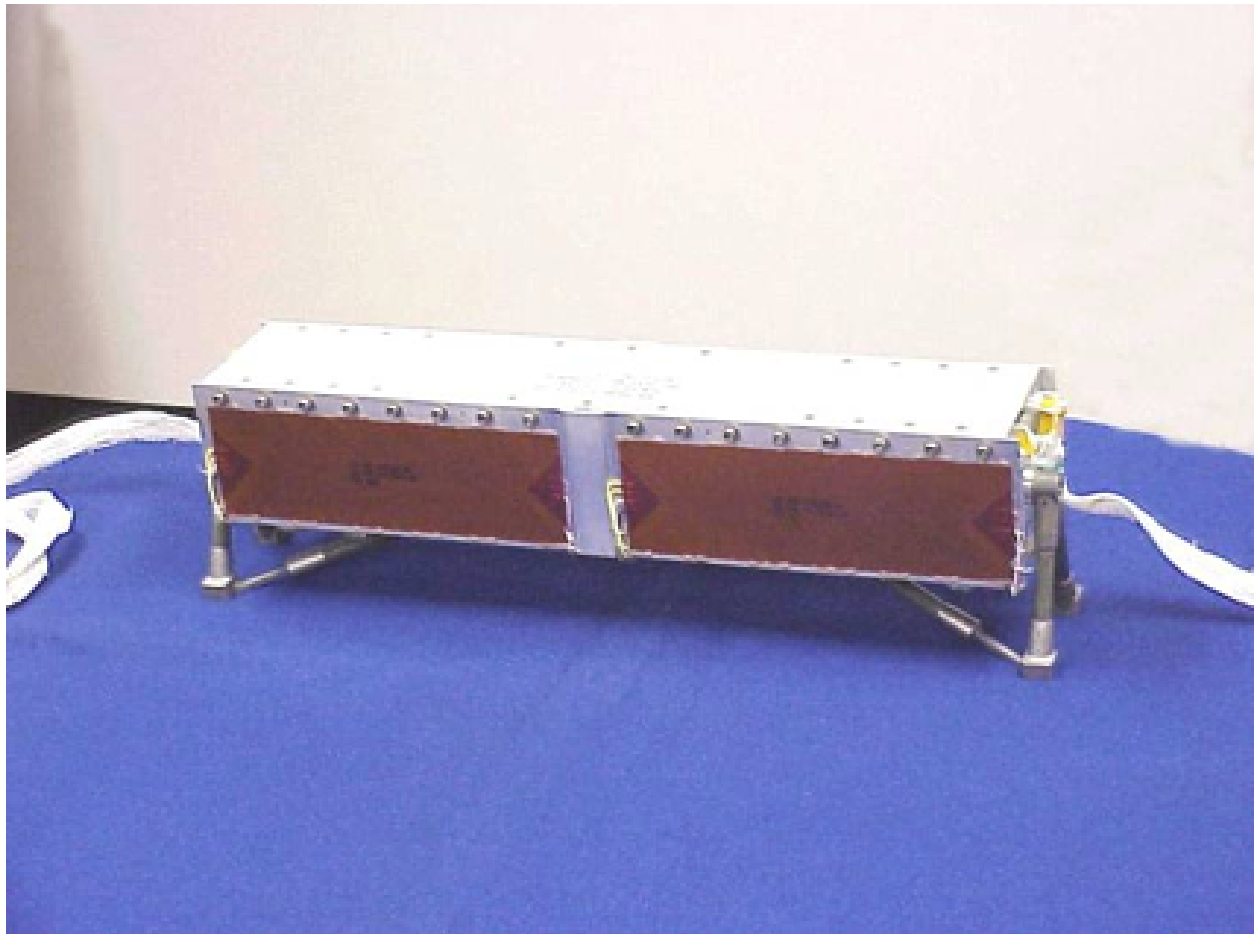


Figure 74: Lithium Ion Battery [7]

III.6.1.2. Sub-Scale

Lithium Ion Battery Study		KBT 24V-8Ah		Fryzonix 24V-10Ah		Lithium Hellas 24V-10Ah		Mspalocell 24V-4Ah	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Capacity	30	0	0	1	30	1	30	-1	-30
Durability	20	1	20	0	0	1	20	1	20
Rechargeability	20	0	0	1	20	1	20	1	20
Weight	10	0	0	0	0	0	0	1	10
Dimensions	5	0	0	-1	-5	-1	-5	-1	-5
Cost	15	0	0	1	15	1	15	-1	-15
Total Score		20		60		80		0	
Rank		3		2		1		4	

Figure 75: Subscale Lithium Ion Battery Trade Study

The trade study above illustrates how the Lithium Hellas 24V-10Ah battery was the best fit for REHT's subscale model. For starters, nearly all electrical components for the subscale model require 12 to 24 volts, so that at least was kept constant between all batteries considered. The Mspalocell 24V-4Ah battery was nearly immediately scrapped in terms of its low power output and high cost compared to all other batteries. The KBT 24V-8 Ah battery was also only briefly considered, as its only notable quality is its durability.

The decision came down to the Fryzonix 24V-10Ah and the Lithium Hellas 24V-10Ah batteries. Both were nearly identical in most aspects. Both had around the same power output, rates of rechargeability, weight, measurements, and even cost. The biggest difference was their durability. Though both have the same level of cyclic charges, the Lithium Hellas battery proves safer with safeguards which protect against over-current and short circuiting utilizing multi-layer safety. Thus, the Lithium Hellas battery is better in terms of long-term performance, ensuring its usage upon the REHT subscale model.

Listed below are the properties of the battery:

- Capacity - 240 Wh
- Durability - Over 1000 charge cycles while maintaining over 80% capacity.
- Rechargeability - Takes 9 - 10 hours for full charge. Charger operates at 29.4 volts at 1 ampere.
- Weight - 1400 grams
- Dimensions - 160 x 60 x 100 mm



Figure 76: Lithium Hellas 24V-10Ah Battery

III.7. Thermal Systems

III.7.0.1. Full Scale Thermal System Selection

Thermal systems are an integral part of REHT and provide temperature control for optimal functioning of all its subsystems. REHT requires a combination of multiple heating and cooling systems to control the temperature of various subsystems. Hence, we cannot rely on just trade studies and have a single thermal system for a subsystem or the rover. The trade studies can instead be used to identify strengths and weaknesses of thermal systems allowing for an efficient combination of systems for perfect temperature control. For the LIBS spectrometer, it faces challenges like generating heat when firing laser, sensitivity to thermal noise, and long term outside exposure. This can be solved with a combination of MLI, vacuum enclosure, TEC, and PCMs. MLI provides it with insulation from cold temperatures at night whereas vacuum enclosure and TEC provide an instant solution to heat generated due to laser and thermal noise. Lastly PCM acts as a buffer not allowing rapid temperature change for spectrometers causing damage to the instrument.

Drill on the other hand generates high heat when operating and requires heat for maintaining proper lubrication when idle. This can be solved through a combination resistive heater and MLI which insulate the drill mechanism and its internal unit while heating it before operation for ideal performance. Additionally, heat pipes could be used to make a waste heat capture system where operational heat from the drill can be provided to components like batteries and electronics during cold nights. Batteries and electronics on the other hand are susceptible to both heat and cold temperatures. They cannot attain peak performance during extremely cold temperatures and can easily overheat short during high temperatures. Hence, a combination of heat pipes, MLI, and PCMs could solve this problem. PCMs act as a buffer preventing immediate temperature changes whereas heat pipes provide heat from heat generating sources during cold nights. Lastly, MLI insulates the batteries and electronics, retaining heat generated by them.

The storage unit though is the most important subsystem of the whole rover. Helium-3 samples and all the other samples must be temperature controlled and refrigerated depending upon need. Hence, a combination of MLI along with a resistive heater and a TEC could maintain the temperature of the storage units and even refrigerate or heat them actively when needed. PCMs could be added to the mix to provide a temperature buffer while the active thermal systems kick in. Lastly, a combination of louvers, radiators, and heat pipes over rover chassis can aid all other thermal systems in maintaining temperature of their respective subsystems.

III.7.0.2. Thermocouple

For the prototype of REHT, a commercially available thermocouple will be used that is compatible with Raspberry Pi directly. However, the below mentioned CAD design and drawing were created to get a basic sense of the size of the thermocouple probe.



Figure 77: CAD of Thermocouple

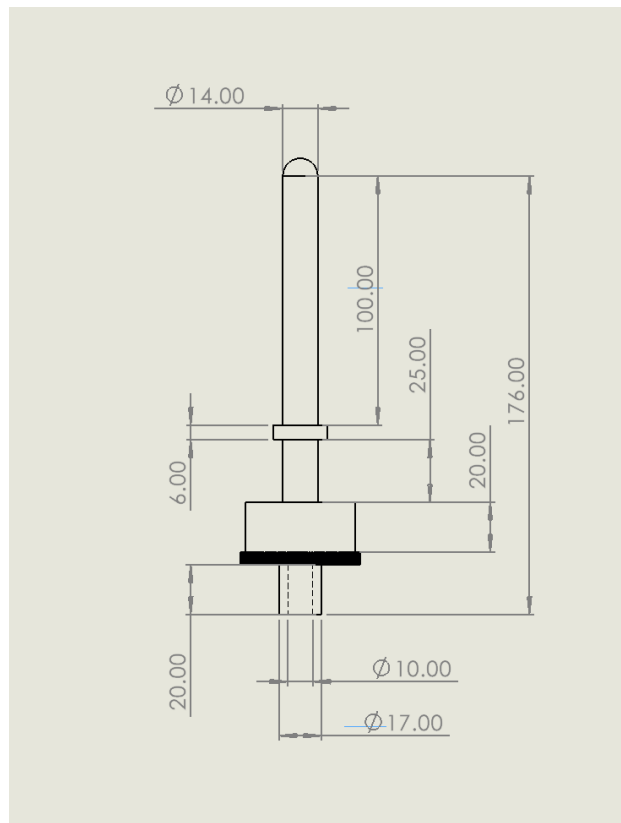


Figure 78: Dimensions of Thermocouple

REHT prototype will utilize a DS18B20 Temperature Sensor that allows temperature measurement. This will be used to detect temperature changes throughout the various subsystems on board REHT. With the measurements gleaned from the thermocouple can be used by the active thermal systems to adjust the necessary temperatures to keep each subsystem running optimally and prevent failure through thermal loading. This will be especially helpful for determining the current temperatures of both the control sample and the refrigerated storage systems.

The metal used for the thermocouple allows for the detection of a wider range of temperatures. The temperature sensor is capable of measuring temperatures ranging from -55°C to 125°C . With this information being fed directly to the Raspberry Pi, the microcontroller will be able to turn on and off the active thermal systems, regulating the temperature as precisely as possible.



Figure 79: DS18B20 Temperature Sensor

III.7.0.3. Prototype Thermal Systems

For the REHT prototype, radiators and insulation materials will be used to conserve the heat and regulate the rover's temperature passively. The aluminized heat shield will be used to cover REHT externally, which will allow the rover to reflect the incoming heat. The heat shield also contains fiberglass that will aid in heat reflection and make it water and dust-resistant protecting the internals of REHT. Combined with that, ceramic fiber insulation will be used to cover walls of separate subsystems to insulate them and have a passive heating system. The ceramic fiber insulation is capable of withstanding heating upwards of 2600°F .



Figure 80: Aluminized Fiberglass Heat Shield



Figure 81: Ceramic Fiber Insulation

For the cooling systems, the REHT prototype will be using peltiers or thermo-electric coolers for various subsystems. The peltiers will be connected to a microcontroller, which will command the coolers to switch on and off based on the desired temperature range. The TECs are cooling pads which will be mounted on the walls of various systems throughout the rover aiding in temperature regulation.



Figure 82: TEC1-12706 Peltier Cooler

In order to make sure that these thermal systems are powered correctly without drawing up too much power from the battery or the other circuitry, a buck boost will be used to reduce and control the voltage. Furthermore, a 5V 4 channel relay model will be used to automatically turn the peltier coolers on and off based on the temperatures measured by the temperature probes. All of this will be controlled by the Raspberry Pi 3B+.

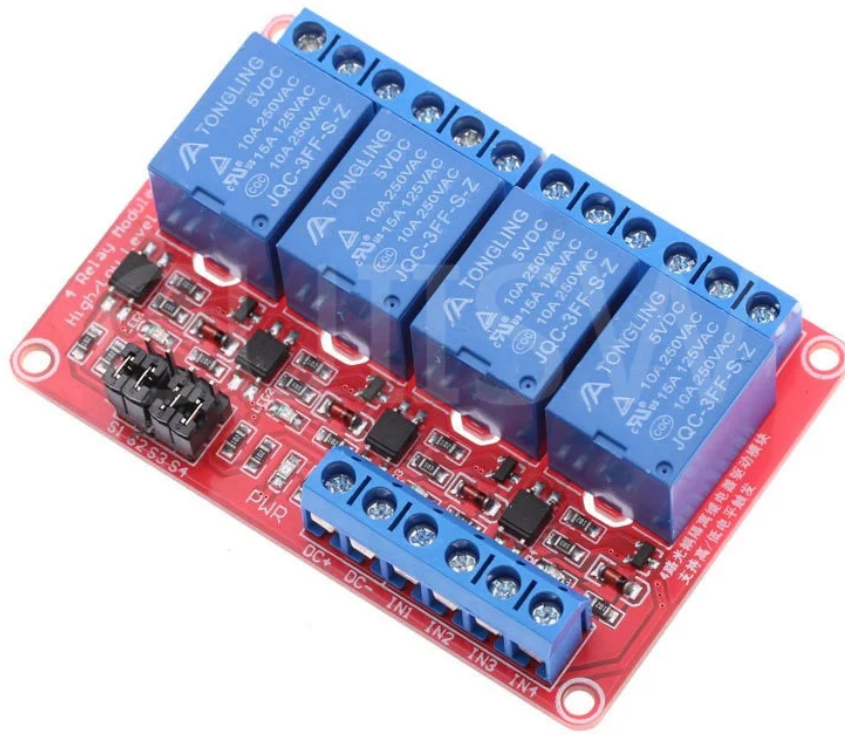


Figure 83: 5 Volt 4-channel relay module

These thermal systems can be scaled up to the full-scale version of REHT. For the full-scale version, REHT would utilize Mylar insulation along with resistive heaters to heat up the rover and regulate the temperature of the sample storage, along with other subsystems and electronics. Thermo-electric coolers come in different sizes, along with different temperature ranges, allowing their use in cooling components like the drill, battery, sample tubes, and microchips on the full-scale design effectively. Having been proven with many other previous spacecraft, these thermal systems work great when combined to regulate the temperatures of various components of the rover.

Additionally, on the full-scale REHT design, PCMs or phase change materials can be used. PCMs would act as an effective buffer, mitigating the risk of damaging components or compromising samples due to sudden temperature changes in the environment.

III.8. Ground Station

III.8.1. Ground Station Integration System

For the Ground Station to be able to communicate with RHET, the selected micro controller needs to have a space grade memory system to allow various functions. It first needs to be able to store the operating system and store information the rover collects while not in communication with the Ground Station.

III.8.2. Ground Station Design Solution

III.8.2.1. Selected Ground Station Network

The easiest and simplest communication network for our mission is the Near Earth Network. It's a proven network that reliably communications with object on the lunar surface already and doesn't require RHET to have specialized equipment like using the Space Network or Deep Space Network would. It should be noted that if the RHET design were to be integrated into Martian exploration, it would then require the use of the Deep Space Network. The use of the Network would be limited to sending commands to the rover and monitoring the rover's health.

III.8.2.2. Data Storage

The selected Data storage is a micro-sd card as it works with the Raspberry Pi micro-controller we chose for our design. Our full scale model will include higher storage capacity but due to budgetary constraints, our prototype rover will only include 128 gigabytes of storage.



Figure 84: Micro-SD Card

III.9. Communications and Data Handling Systems

The communication system for RHET includes an on-board computer, an S-band transmitter and receiver, and both polarized and patch antennas. These components form the core of the rover's ability to send and receive information during surface operations.

The on-board computer is modeled after a commercial Raspberry Pi that would be adapted for space use so it can reliably interface with the rover's other subsystems. The transmitter and receiver are based on commercial S-band communication units from Endurosat for our full-scale rover. For our prototype rover,

III.9.1. Transmitter and Receiver

The RHET Rover's communication architecture uses an S-band transmitter paired with an S-band receiver. The transmitter provides a data rate of 20 Mbps and includes 32 GB of internal memory for storing and buffering data. Together, the transmitter and receiver have a combined mass of 470 g. These units were selected to deliver dependable communication performance while satisfying the mission's mass, power, and

reliability requirements.



Figure 85: S-Band Transmitter and Receiver

III.9.2. Antenna

The RHET Rover communication system incorporates an S-band patch antenna as its primary surface communications radiator. The patch antenna was selected for its low mass, compact geometry, and stable radiation pattern, which make it well suited for lunar surface operations where the rover may frequently change orientation while driving or drilling.

The antenna design is modeled after Endurosat's commercial S-band patch antenna[33], which provides consistent performance across the standard 2 to 4 GHz S-band frequency range used by the Near Earth Network and other NASA communication assets. The antenna has a mass of 64 g and operates with a typical gain of approximately 6 to 7 dBi, allowing the RHET Rover to maintain a reliable link with the lander relay system during nominal mission phases.

The patch antenna's wide beamwidth is a key advantage for RHET because it reduces pointing sensitivity. This allows the rover to maintain communications without relying on a gimbaled mount or active steering, which simplifies the overall mechanical design and decreases power consumption. Its planar structure also makes it easy to integrate into the rover chassis while maintaining protection against dust and mechanical interference during drilling operations.

The combination of stable gain, low mass, and mechanical simplicity makes the S-band patch antenna an effective solution for RHET's communication requirements, ensuring dependable data transmission whenever the rover has access to the relay through the Near Earth Network.

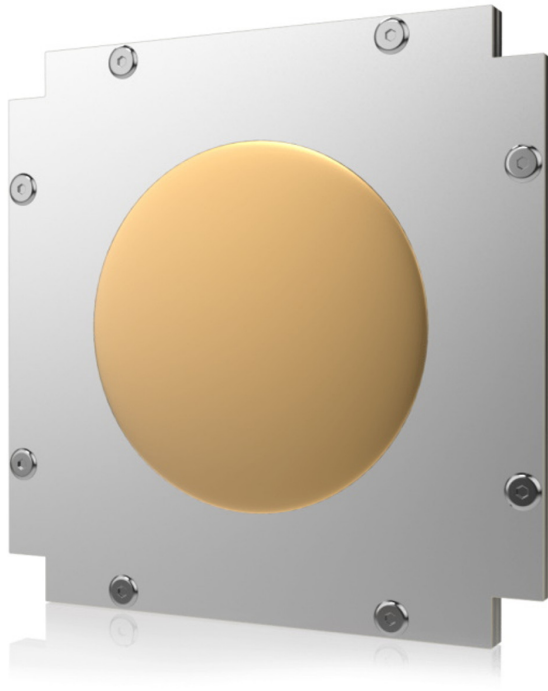


Figure 86: S-Band Antenna

III.10. Finalized Baseline CAD Design

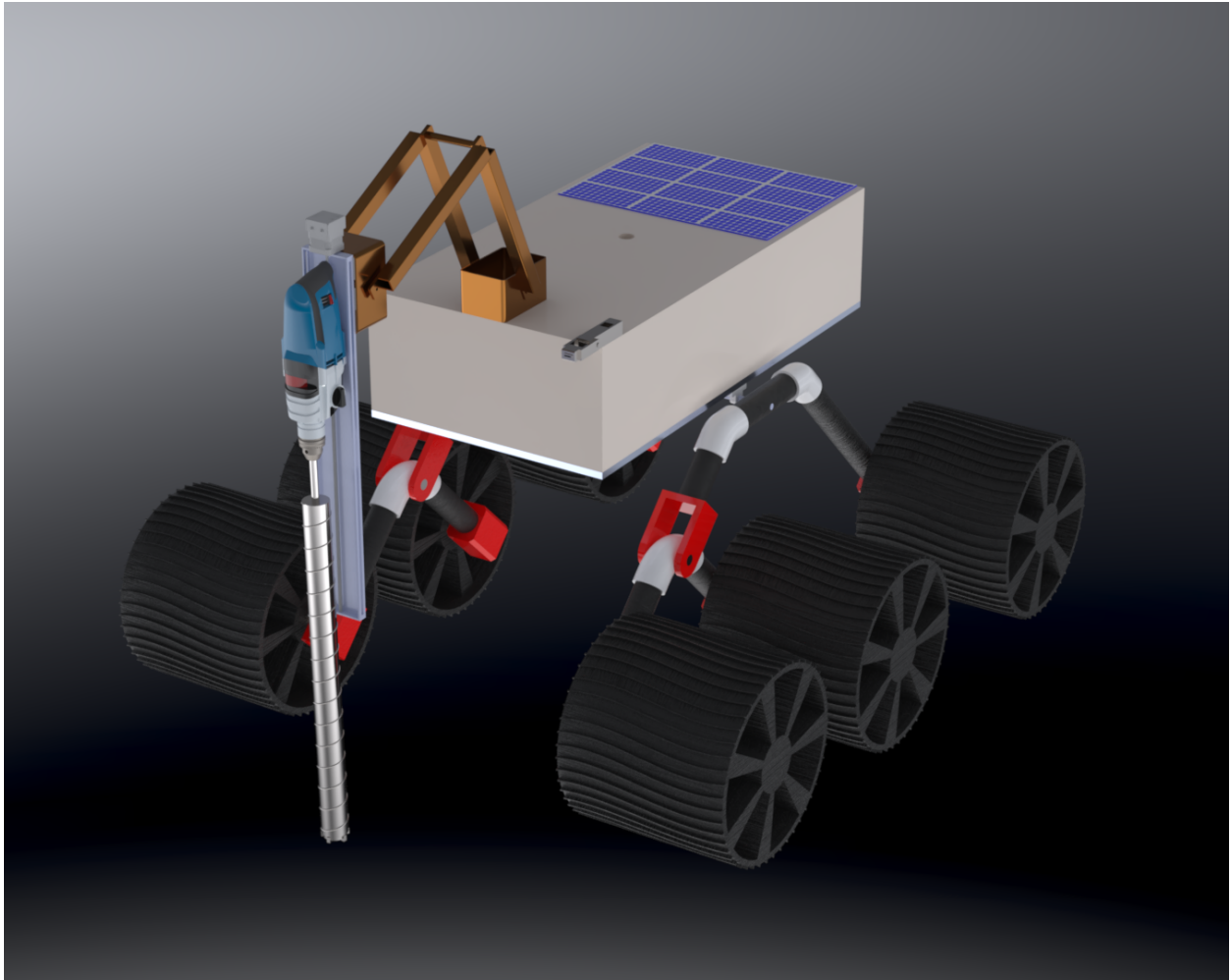


Figure 87: Finalized CAD Design

The finalized mass of our rover was 77.52 lb, mostly coming from the rover body, the drill, and the suspension system. This is above the initial value that was set for the mass, however as progress was made, it was determined that it was unrealistic. The impact that this increase has will be minimal as no components were close to failure even with oversized loads. The volume of the rover came in at 8441.48 cubic inches. This value is significantly larger than what is expected due to unrealistic infills in several components and the CAD models including the rover body. In reality it is expected to be closer to 1200 cubic inches.

IV. Manufacturing

IV.1. Guidance Navigation and Controls

IV.1.1. Differential Mechanism

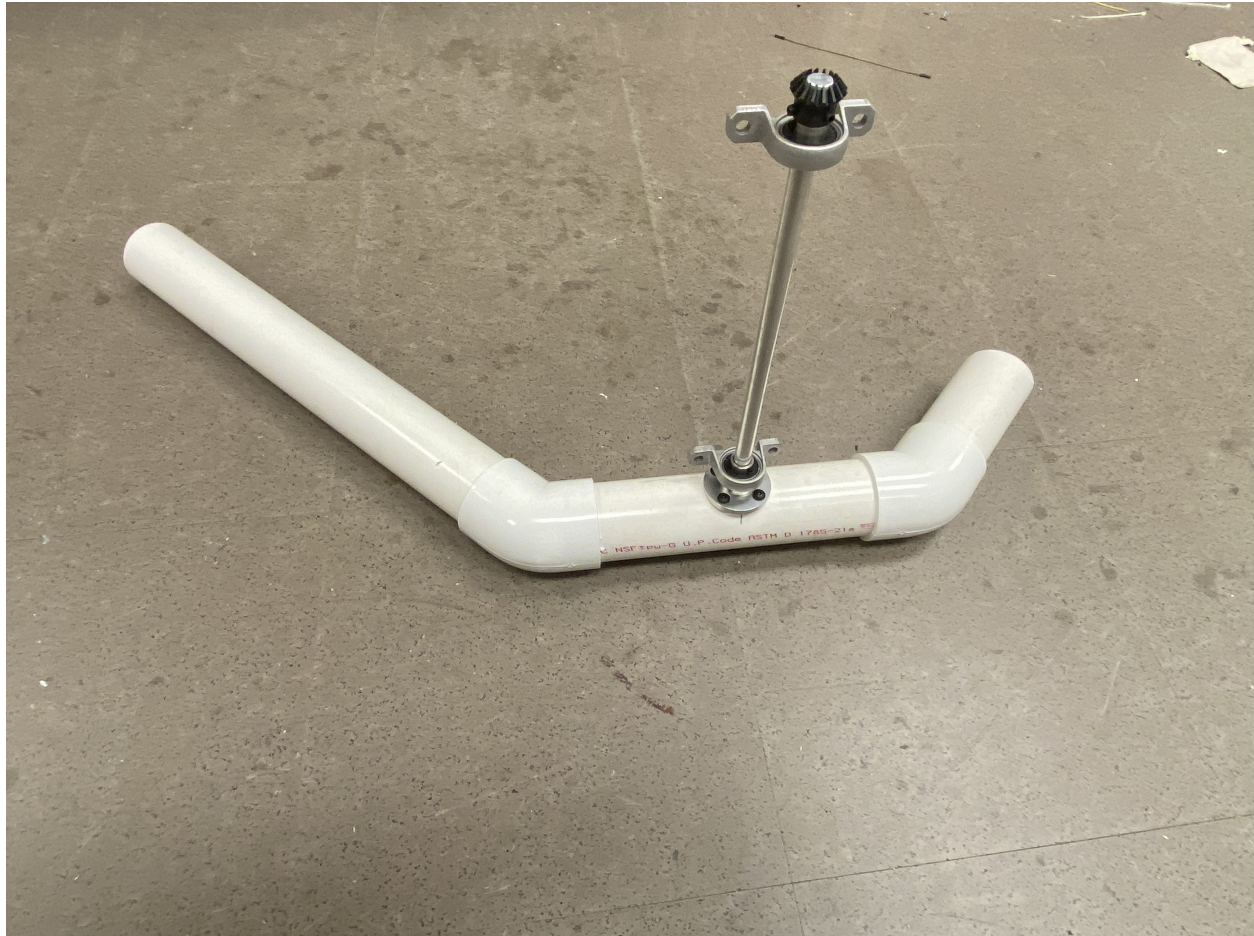


Figure 88: First Side of Differential on Rocker

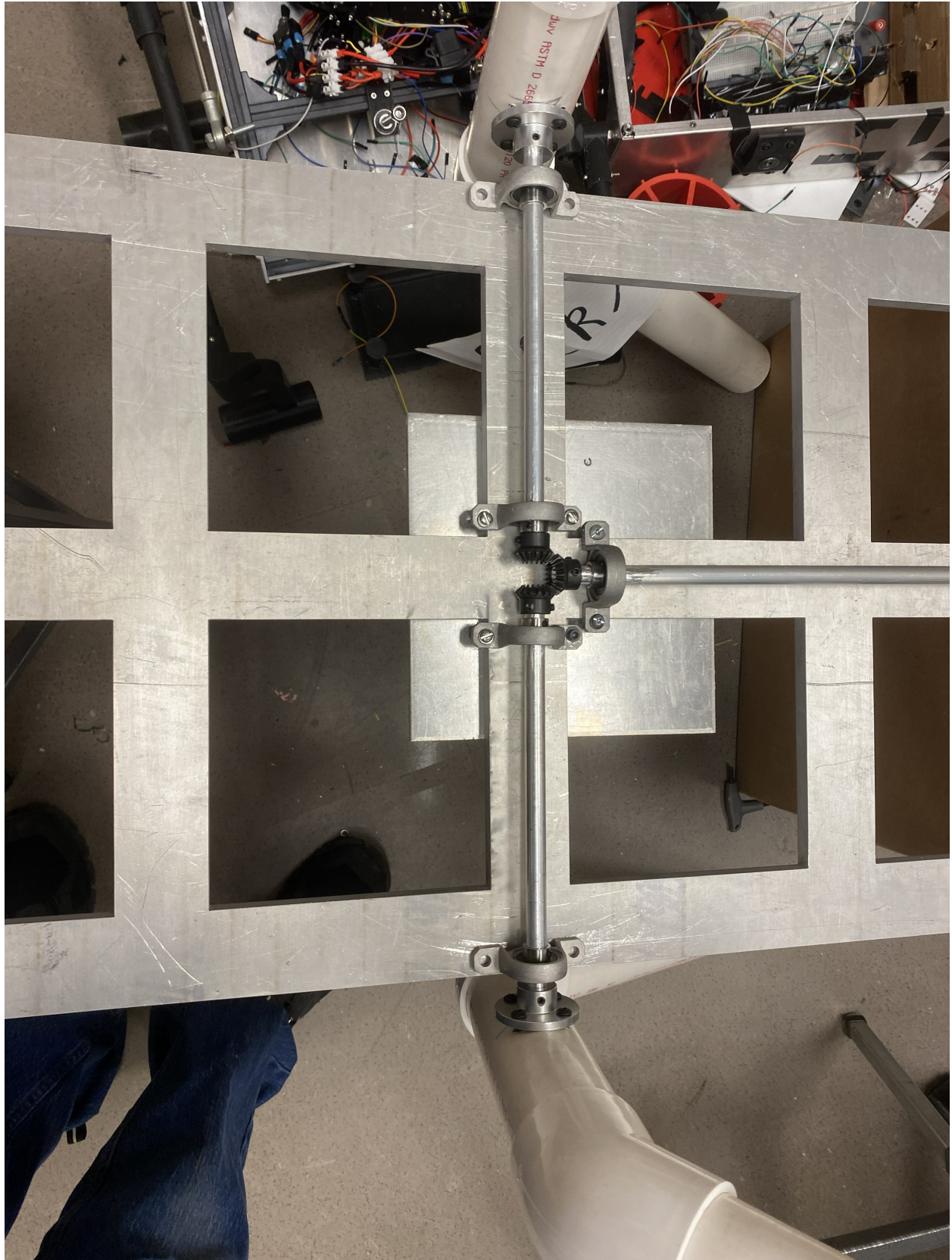


Figure 89: Version 1 of Differential

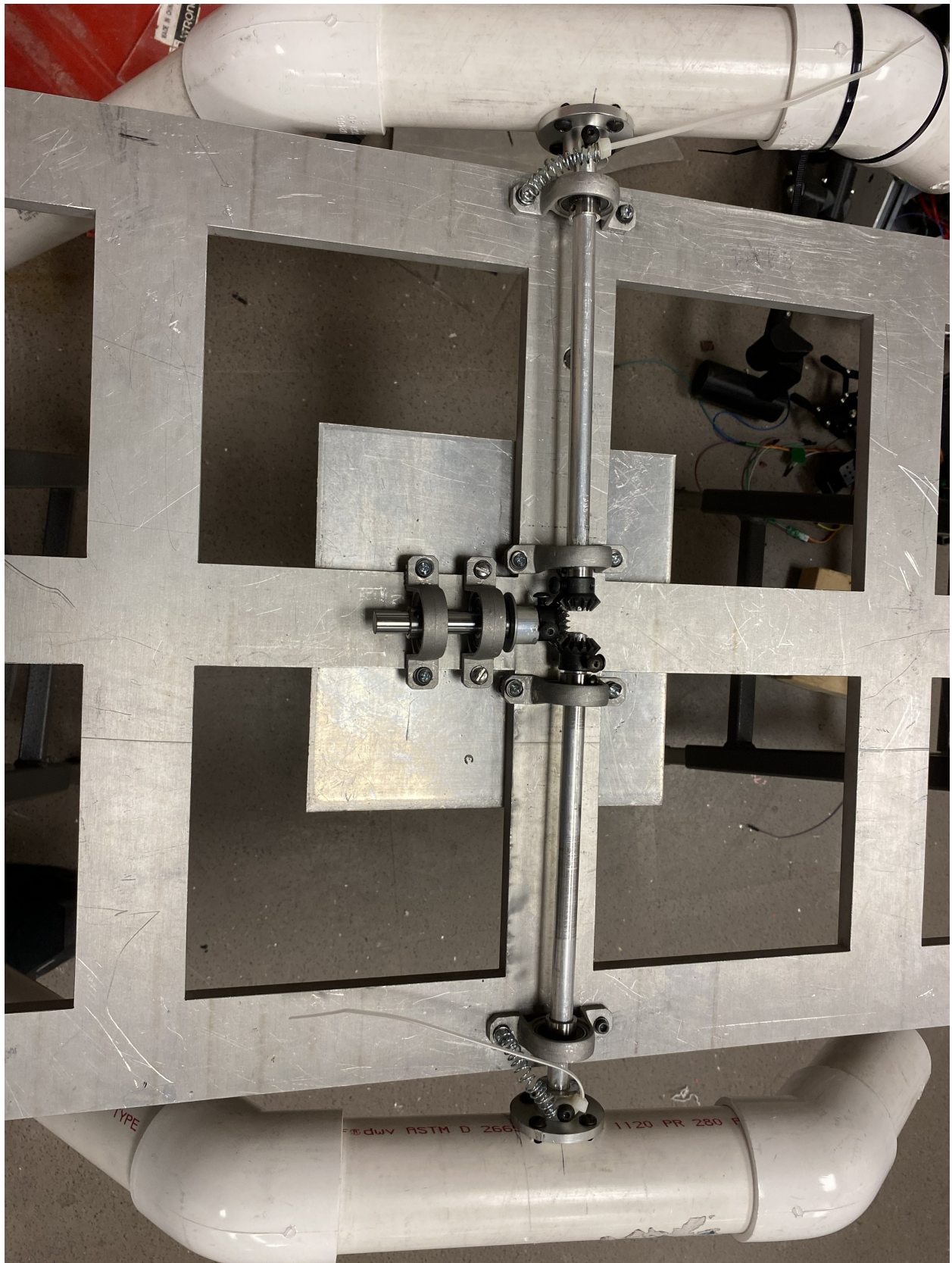


Figure 90: Finalized Differential Mechanism

Objective: Prevent rover tilt and reduce severity of roll by raising one side when the other is lowed and vice versa.

Procedure: The first step of manufacturing the differential mechanism was to file down the ends of the aluminum shafts as only one was within the tolerance needed to fit into the bearings. This was done using a steel file to remove excess material. Once this was done. The pillow block bearings were attached to the shaft at the desired locations, and the bevel gears and connectors were attached and locked in place using grub nuts and Allen keys. Because the pillow block bearings were larger than originally expected, they could not be attached directly to the chassis for the central bearings. To attach them, holes were drilled at the required locations in an aluminum plate using the drill press at NCSU's aerospace senior design lab. The plate was mounted to the opposite side of the chassis to the differential, and screws were run through the holes to the bearings to hold them in place. Holes were then drilled in the sides of the chassis by NCSU's machine shop for the outer bearings to be added. The outer bearings were then attached to the chassis. This resulted in the first version of the differential being completed. After testing this, substantial amounts of slippage was noted in the bevel gears, both relative to the shafts and to each other, substantial flexure was also noted in the central aluminum shaft. Several approaches were take to reduce slippage in the gears including adding a spacer to the central bevel gear between it and the bearing to prevent flexure, part of the aluminum shafts were flattened for the grub nuts to bear on, and grub nuts were replaced with small bolts to increase their hold. After these steps were taken, another test was run, resulting in the central aluminum shaft bending, likely due to it receiving a much higher moment due to both of the other gears acting on it. To prevent this from happening in the future, and to reduce flexure increasing stability, the 300mm aluminum shaft was replaced with a 100mm steel shaft. Because the bevel gears were still slipping relative to the aluminum shafts at this point while under load, holes were drilled in the ends of the aluminum shafts using a hand drill for the bolts to go in, resulting in almost no slippage for future tests and finalizing the differential mechanism. Following the second flight test, the differential was overloaded and some components sustained damage. To account for this two springs were added between the rear end of the chassis and the correspond end of the rocker. This counteracted the moment produced by the drill restabilizing the rover.

Facility: NCSU EB3 Senior Design Lab

Equipment Used: File, hand drill, drill press, Dremel, screw drivers, Allen keys, channel wrench, vice.

Status: 100% complete

Challenges / Interface Issues: Bearings used were larger than the chassis rib width requiring redesign. Getting bevel gears correctly aligned was challenging with redesign. Natural backlash in gears allowed some oscillation. Overloading system caused bending, slippage, and component damage.

IV.1.2. Rocker

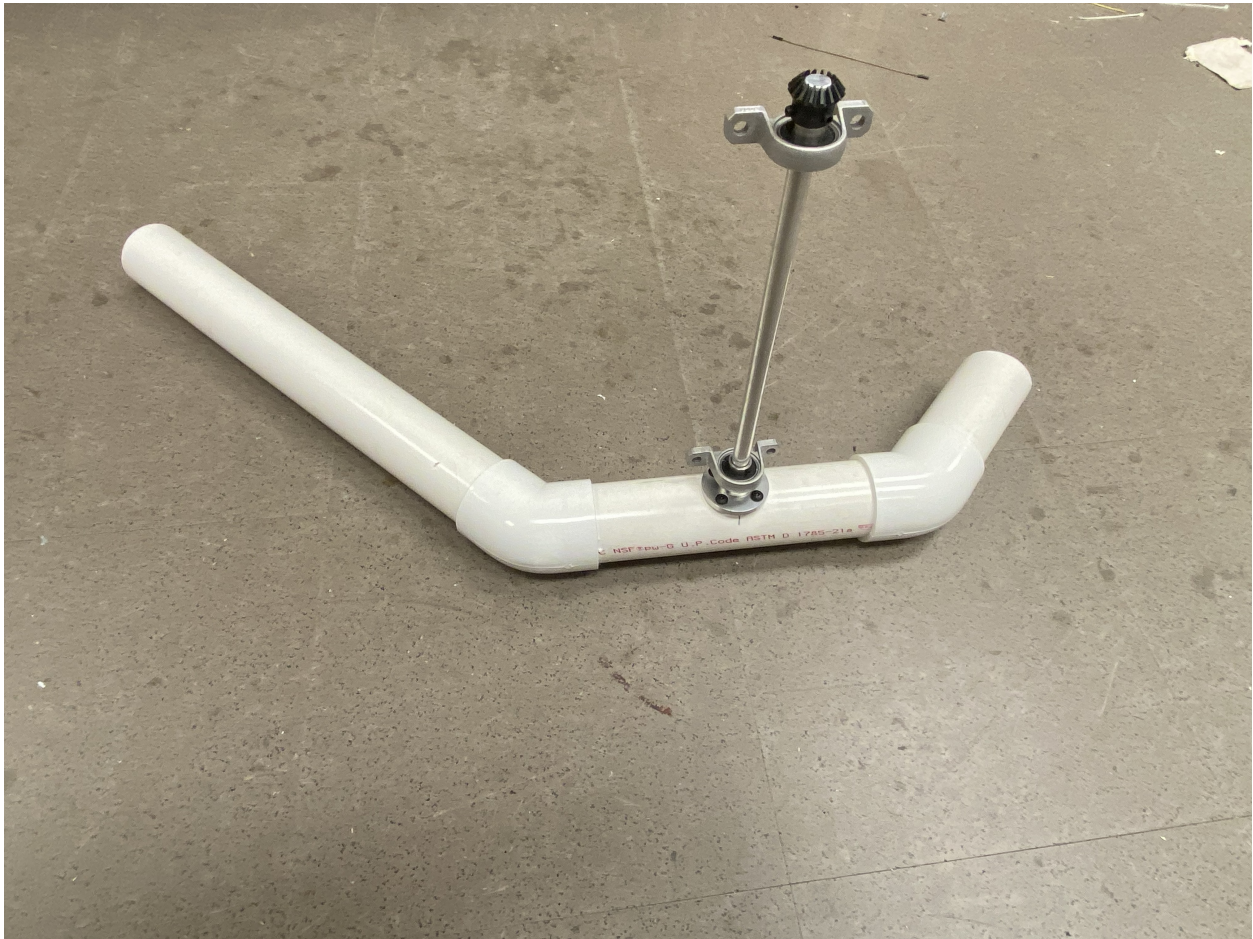


Figure 91: Bogie Assembly

Objective: Rotate relative to the rover body to accommodate obstacles and uneven surfaces.

Fabrication Procedure/Process:

- PVC segments were cut with 10" (2x), 18" (2x), and 5" (2x) arms using a saw.
- Arms were connected using 45° PVC connectors to form both rockers.
- Four holes were drilled at the center of the central 10" segment, spaced 1 inch apart in a square pattern.
- A slot was then cut in the opposite side of this section to allow access to the screws.

Facility: NCSU EB3 Senior Design Lab

Equipment Used:

- File
- Drill

-
- Vice
 - Saw
 - Drill Press

Status: 100% Complete

Challenges / Interface Issues: Positioning the holes correctly required several practice attempts to achieve proper alignment.

IV.1.3. Bogie



Figure 92: Bogie Assembly



Figure 93: Bogie with Hole Drilled

Objective: Rotate relative to the rocker arm to overcome obstructions.

Fabrication Procedure/Process:

- PVC segments were cut to 8" lengths (4x).
- Bogie arms were connected using 90° PVC connectors.
- A hole was drilled through the center of the connectors.

Facility: NCSU EB3 Senior Design Lab

Equipment Used:

- File
- Drill
- Vice
- Saw

Status: 100% Complete

Challenges / Interface Issues: Connecting the rocker and bogie was challenging, the initial design utilized a 3D printed component, however with the infill available and other design modifications it was unable to achieve the needed strength. The modified connection saw the bogie placed on the outside edge of the rocker. This produced a moment in the suspension that caused a certain amount of bending in the system.

IV.1.4. Navigation

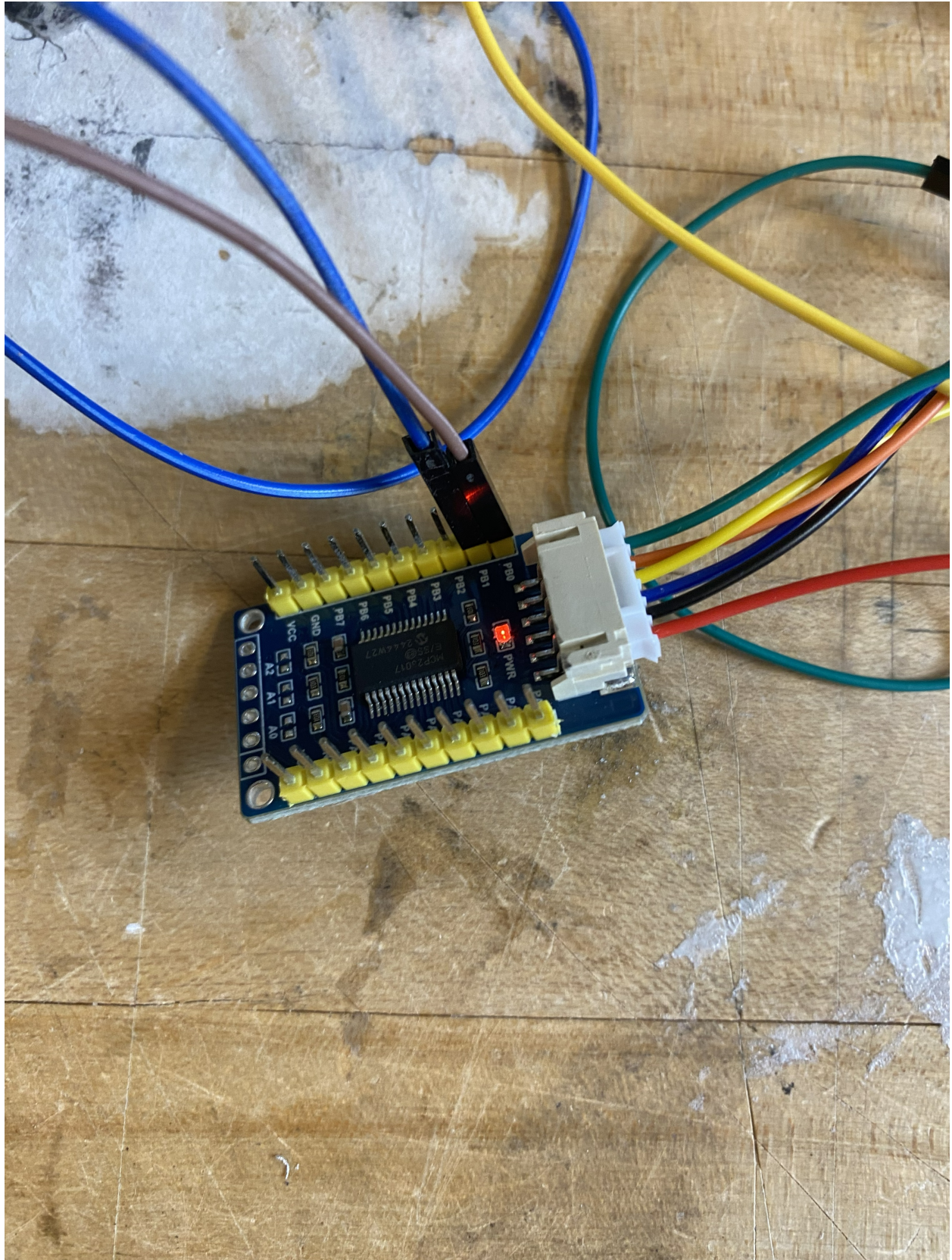


Figure 94: Expander Board
120 of 237

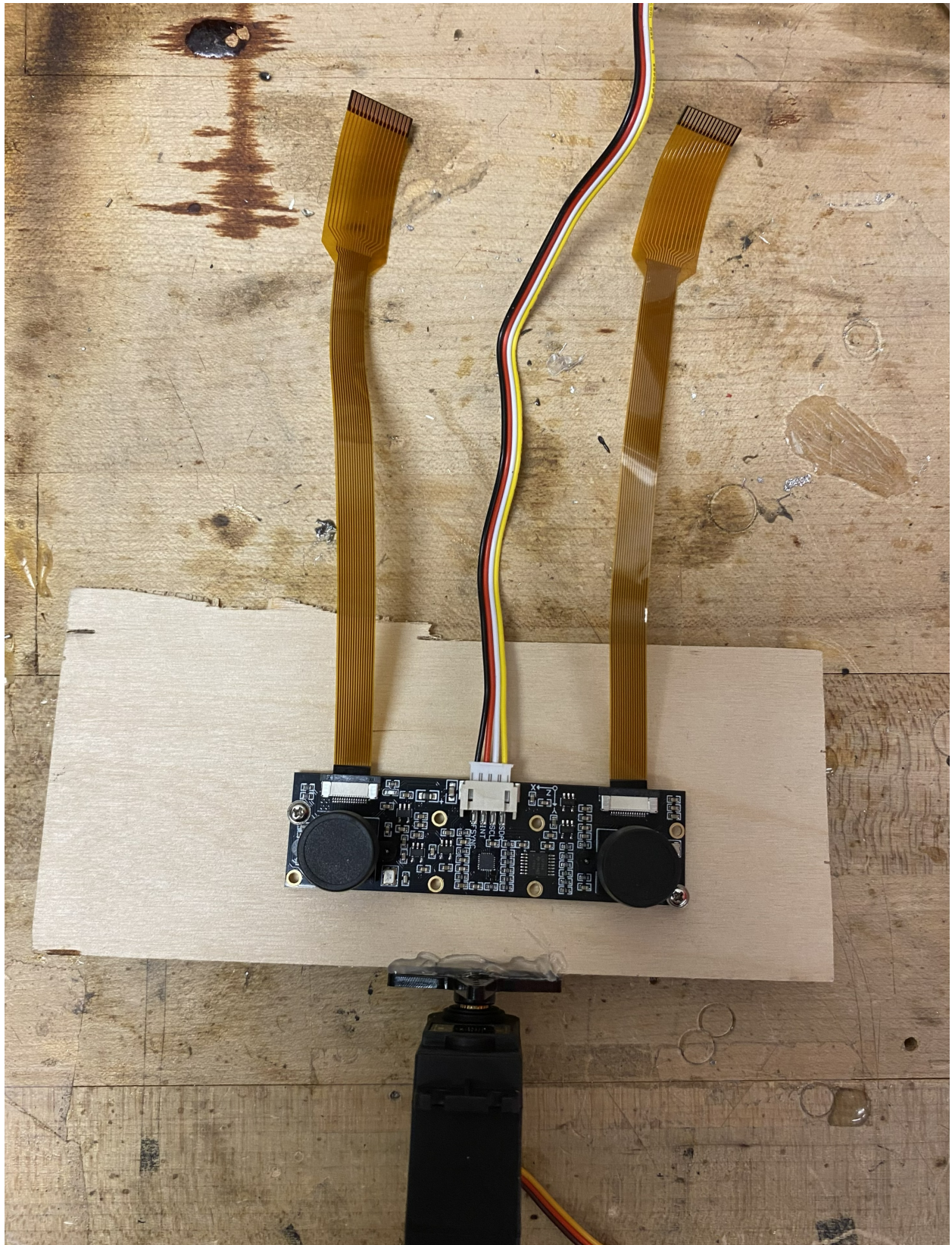


Figure 95: Stereo Camera and Servo Configuration

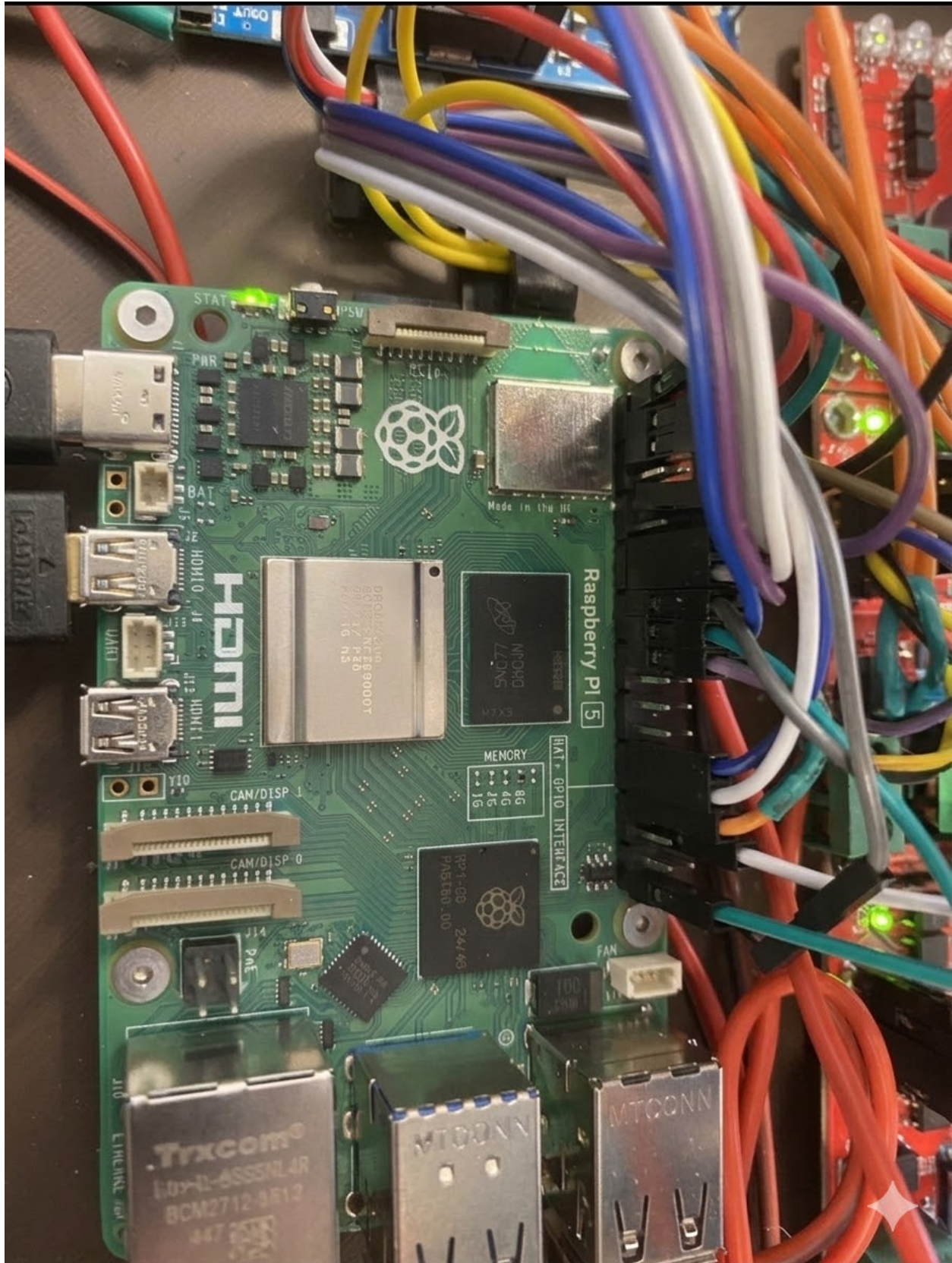


Figure 96: Raspberry Pi Wiring

Objective: Determine the locations of obstacles and avoid them.

Fabrication Procedure/Process:

- Set up the software interface in a Docker container for ROS2 and OpenSSD.
- Integrate the object detection program.
- Use collected sensor data to map terrain within ROS2.
- Mounted the stereo camera to the front of the rover
- Connected the expander board to the Raspberry Pi 5 by connecting wires to SDA, SCL, 3.3V, GND, GPIO 17, and GPIO 27.
- Connected the stereo camera to the expander board and Raspberry Pi 5 via SDA/SCL lines and B0/B1 pins on the expander board.
- Created python script to collect accelerometer and gyroscope data and convert to position over short time intervals

Facility: NCSU EB3 Senior Design Lab

Equipment Used:

- Raspberry Pi 5
- Computer
- Stereo Camera
- Servo Motor
- Expander Board
- Soldering Iron
- Hand drill

Status: 100% Complete

Challenges / Interface Issues: Type-B ribbon cables were the only cables available capable of interfacing with the original stereo camera. This made interfacing impossible and required switching stereo cameras.

IV.2. Propulsion

IV.2.1. Integration

The propulsion system manufacturing process involved both additive manufacturing and electrical assembly to create a functional motor control platform. A custom enclosure for the three Drok L298N motor drivers and Raspberry Pi 5 was designed and 3D printed to protect the electronics while providing ventilation and cable management. The six rover wheels were 3D printed with tread patterns optimized for traction,

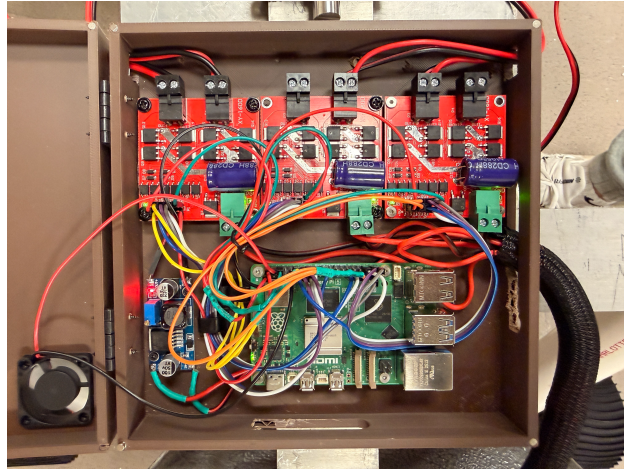


Figure 97: Motor Drive System

and custom motor shaft couplings were additively manufactured to securely connect the 24V DC motors to the wheel axles, ensuring proper torque transfer and alignment. Electrical assembly included soldering power and signal wires to the motor driver terminals, crimping Dupont connectors for GPIO interfacing with the Raspberry Pi, and routing wire harnesses throughout the chassis to connect all six motors to their respective driver outputs. Heat-shrink tubing and cable ties were used to organize and protect the wiring from mechanical wear during operation. The motor drivers were mounted to the 3D printed enclosure using standoffs to prevent short circuits, and all electrical connections were tested for continuity and proper polarity before final integration. This combination of additive manufacturing and hands-on electrical assembly resulted in a robust, modular propulsion system ready for verification testing.

IV.3. Structures and Mechanisms

IV.3.1. Chassis

The manufacturing process for REHT's chassis began with ordering two aluminum bars, with dimensions of 0.5x2x96 inches. Through consultations with technicians at NC State's MAE Machine Shop, methods for fabricating the chassis were discussed. Initially, the chassis design consisted of multiple aluminum bar components that would be cut and welded together. However, after discussing options with the machine shop staff, it was determined that a more efficient approach would be to waterjet the chassis profile directly from a single aluminum sheet they had in their scrap metal collection. This method provides more strength and stability than the welded option and, therefore, this process was chosen.



Figure 98: Purchased Aluminum Bars

Following this discussion, the chassis design was adapted to accommodate waterjet manufacturing. A flat pattern of the chassis frame was created in CAD and exported as a compatible file format for the waterjet cutting system. The aluminum sheet stock was then selected to match the required thickness and structural requirements for the rover frame. The aluminum sheet stock was placed in the waterjet cutting system, and the machine precisely cut out the dimensions defined in the CAD model. This process produced the chassis frame in an efficient manner that significantly reduced the number of separate components that would have otherwise needed to be machined and welded.

After the waterjet cutting process was completed, dimensions were verified to ensure the chassis was cut fabricated correctly. This led to minor finishing operations, such as buffing the edges and cleaning the cut surfaces. This was important for safe handling and proper fitment of other components and subsystems. With the chassis completed, secondary components such as brackets, plates, and drilling holes were installed into the structure. These components are perfect for the modular assembly of the chassis and allows for easier subsystem integration.

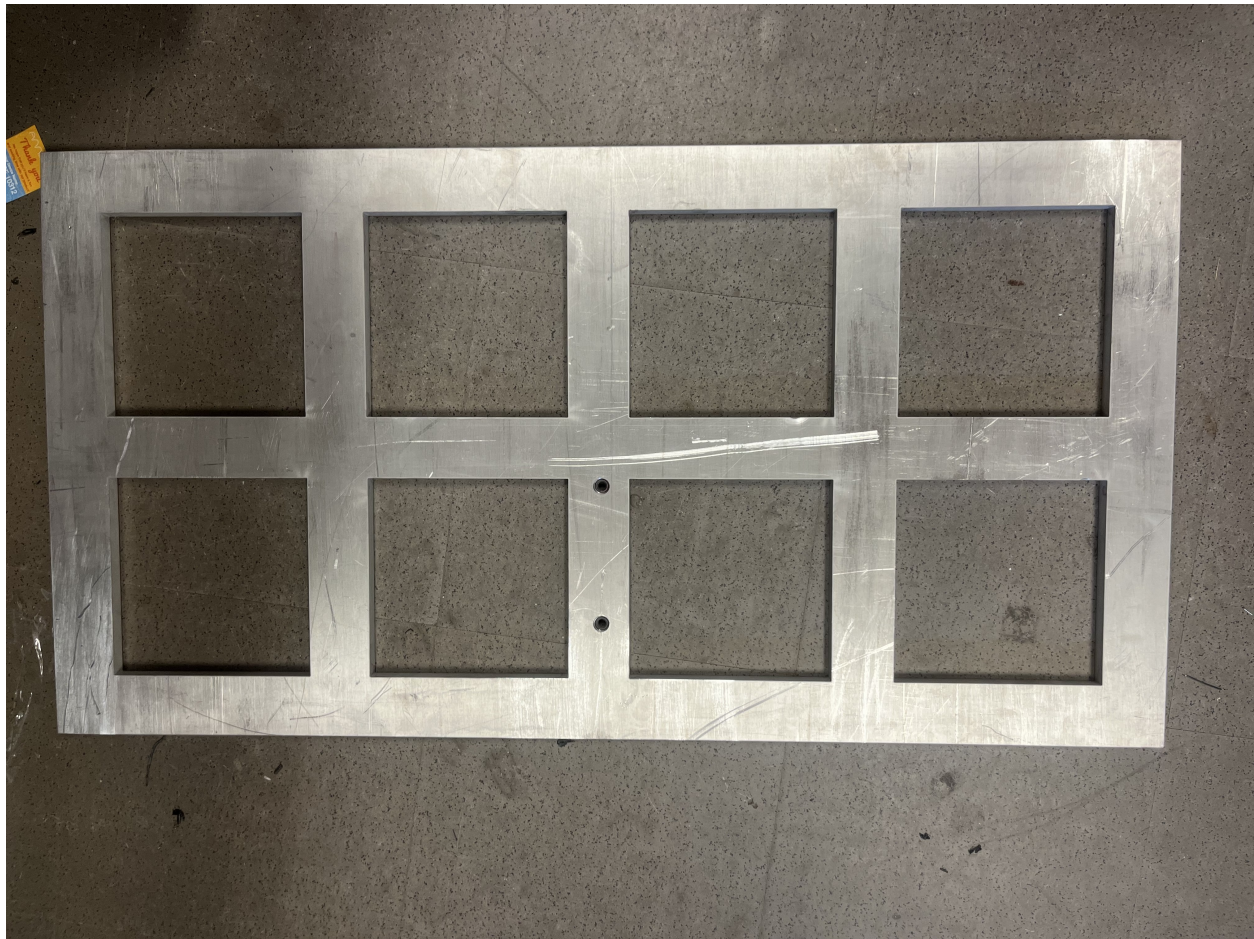


Figure 99: REHT's Chassis

By working with the MAE Machine Shop and utilizing their expertise in waterjet cutting, the manufacturing was simplified immensely. Fabrication time was greatly reduced, the need for welding was minimized, and the chassis was still produced in a strong manner.

IV.4. Drill

The drill manufacturing process was simplified by implementing available technology for the hammer drilling process. A commercially available hammer drill was purchased, and verification and validation was conducted on this system to verify its operability. The manufacturing for the rest of the drill system can be broken down into 3 main categories. The first is the drill carriage system, the second is the coring bit, and the third is all of the sub-components that are connected to these systems. Manufacturing for the drill carriage system was designed to be simple, reliable, easy to manufacture, and adjustable. Thus, a rail system made of half slot channel struts was chosen. This is easy to purchase, easy to modify, and able to complete the needed tasks. Two parallel tracts were bolted next to each other with a third, shorter segment that could slide along the length of them. Next, a lead screw was mounted along the length, which acts to move the smaller segment up and down. A geared down motor was mounted to the top, parallel to the lead screw. A gear was placed on the motor and on the lead screw shaft, allowing motor power to be transmitted to the lead screw.



Figure 100: C-slot rail used for mounting and linear guidance.

To actually make this, the tools needed were an angle grinder, a drill, and various hand tools in the senior design shop. There were no problems in the manufacturing of this part. The second system that needed to be manufactured was the core bit. This system is by far the most difficult to manufacture. During the design phase of this part, it was assumed that we would have access to the lathe in eb3. However, this was incorrect, and this information was not found out until all of the parts were already ordered. In addition to this, the parts delivered were not the parts that were ordered, so the drill had to be redesigned to fit the real parts. This redesign on its own took a week to figure out how to work with the parts we had ordered. Because the price of the material was expensive, it was unfeasible to buy the new parts within the constraints of the budget. The new part was made by cutting the core bit length in half, providing the requisite material needed to make the functional bit. To verify fit and work, the core bit was 3d printed full scale. The next phase of the design involved getting the drill to an acceptable design for the machine shop to be able to make it. Because the drill was designed with the thought that we could put many hours of machine time into it, it would take many hours to machine it. Because of this, the machinists asked for the design to be simplified. Thus, the next two weeks were spent discussing with the machinist, coming up with a new design, and then re-discussing. Eventually a new design was decided upon that we agreed was acceptable. This involved compromising the core break-off mechanism, meaning there was more uncertainty in the operability of this core bit on rock. However, there are techniques available that still allow it to work. The design was submitted to be machined, but it has not yet been manufactured due to wait times. The final parts that were machined were the sub-components, such as the core pusher mechanism. This involved multiple 3d prints, and creating the mechanism to attach the lead screw to the motor. A spacer had to be printed so that the motor could be flushly mounted in the core tube. Additionally, an adapter to go from the threaded bit to the lead screw to the core pusher tube had to be printed (see figure below). . The



Figure 101: Drill Carriage with Drill

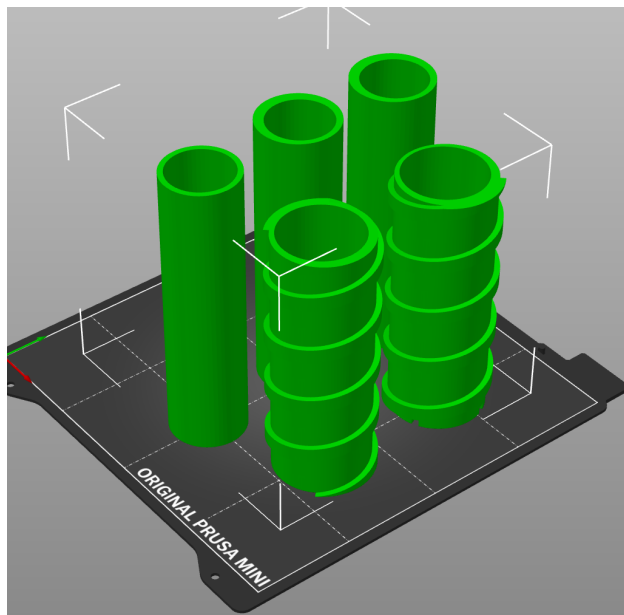


Figure 102: Prusa Drill model

sub-component manufacturing went incredibly well, with components fitting well and operating with more capability than expected.

IV.5. Payload

IV.5.1. Automated Conveyor System

IV.5.1.1. Structural

Starting out the manufacturing process for the structural parts of the system. Much of the structure keeping the system in place (between the railings and the motor brackets) are made of aluminum 6061. As such, these couldn't be casually cut with the tools available in the senior design shop. So, after the CAD was finalized on 1/26/2026 and the SolidWorks part drawings done on 1/28/2026, the following orders were given to the MAE machine shop on 1/29/2026.

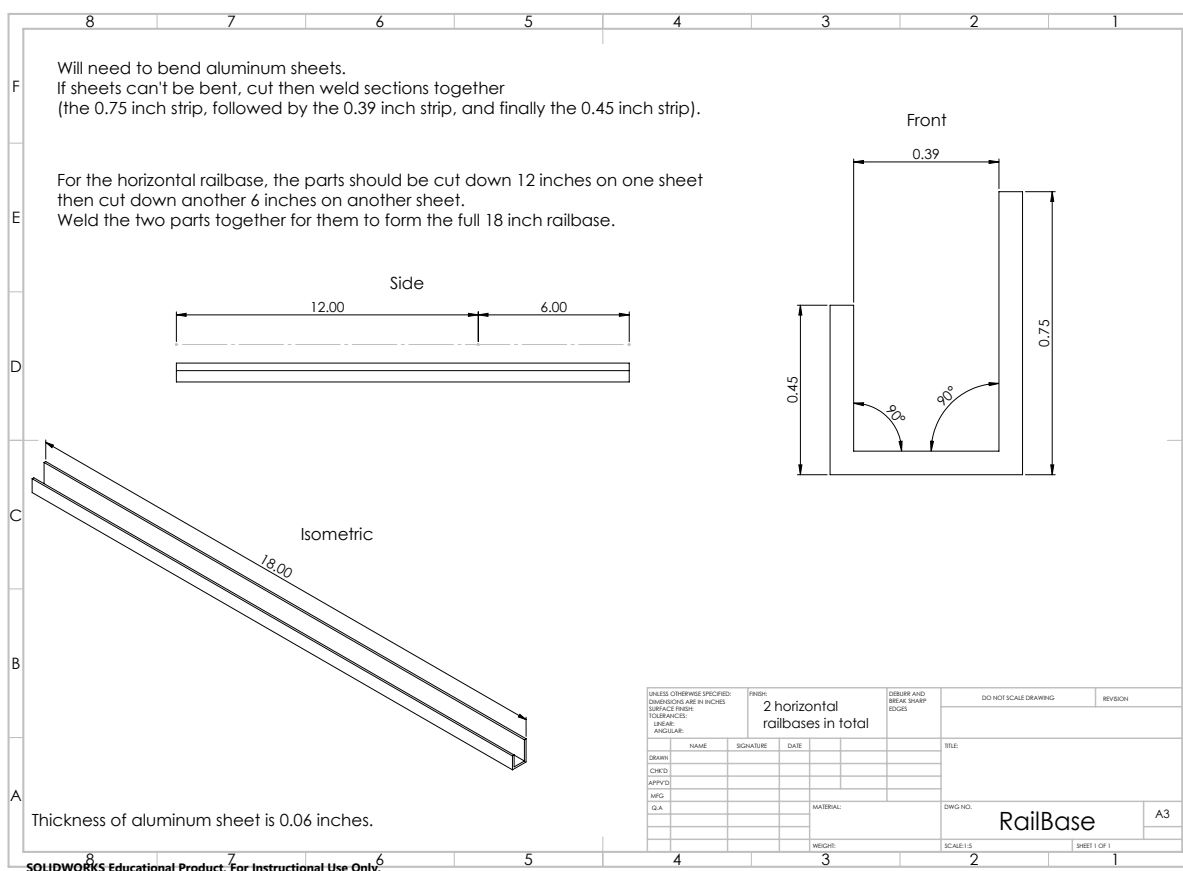


Figure 105: Horizontal Rail base for Storage SolidWorks Drawing

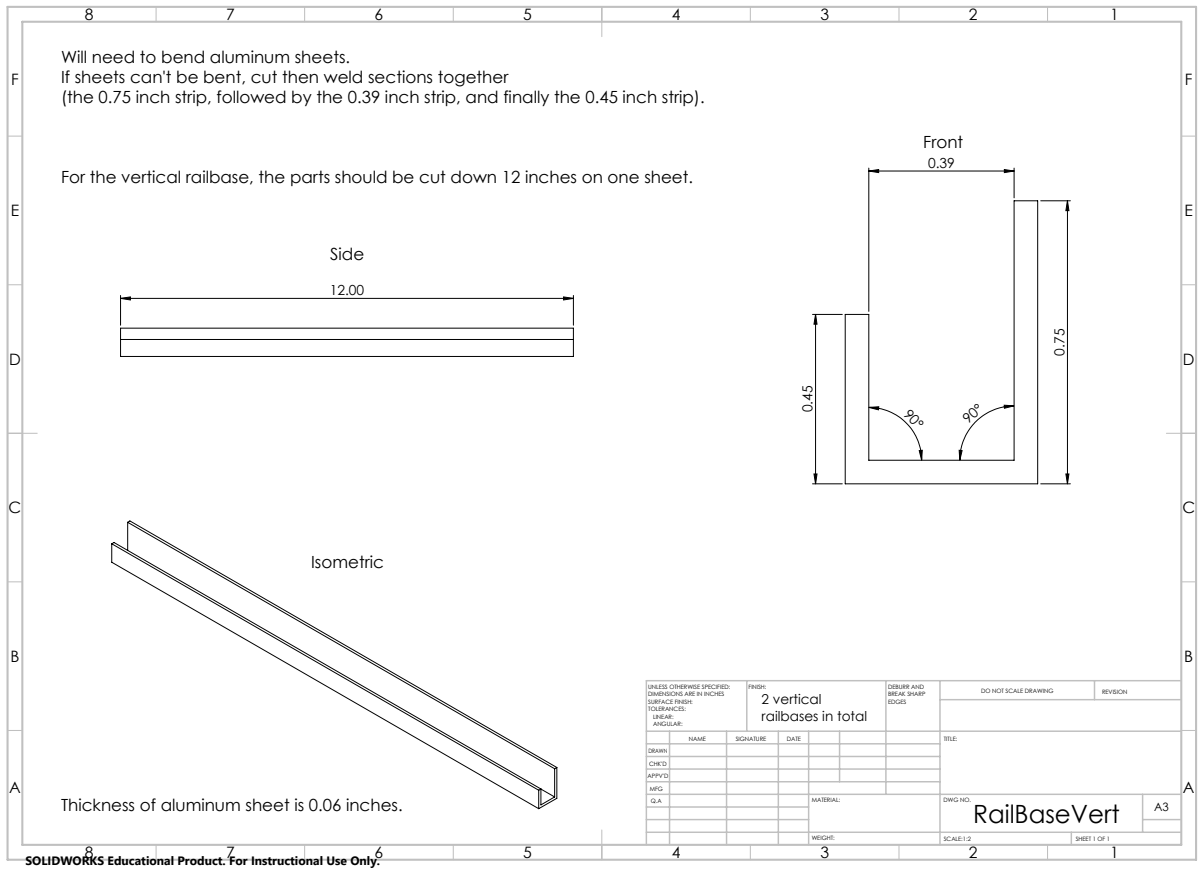


Figure 106: Horizontal Rail Base for Storage SolidWorks Drawing

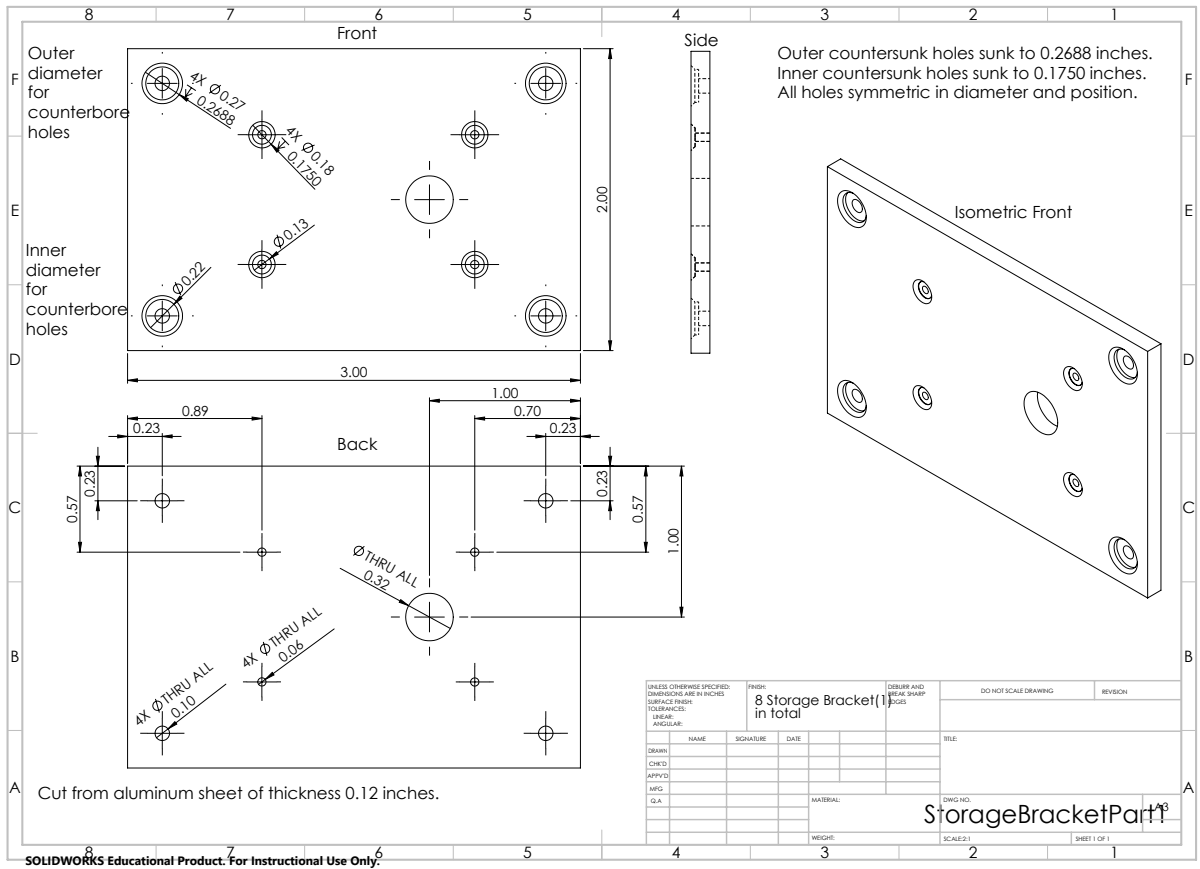


Figure 107: Outer Motor Storage Bracket SolidWorks Drawing

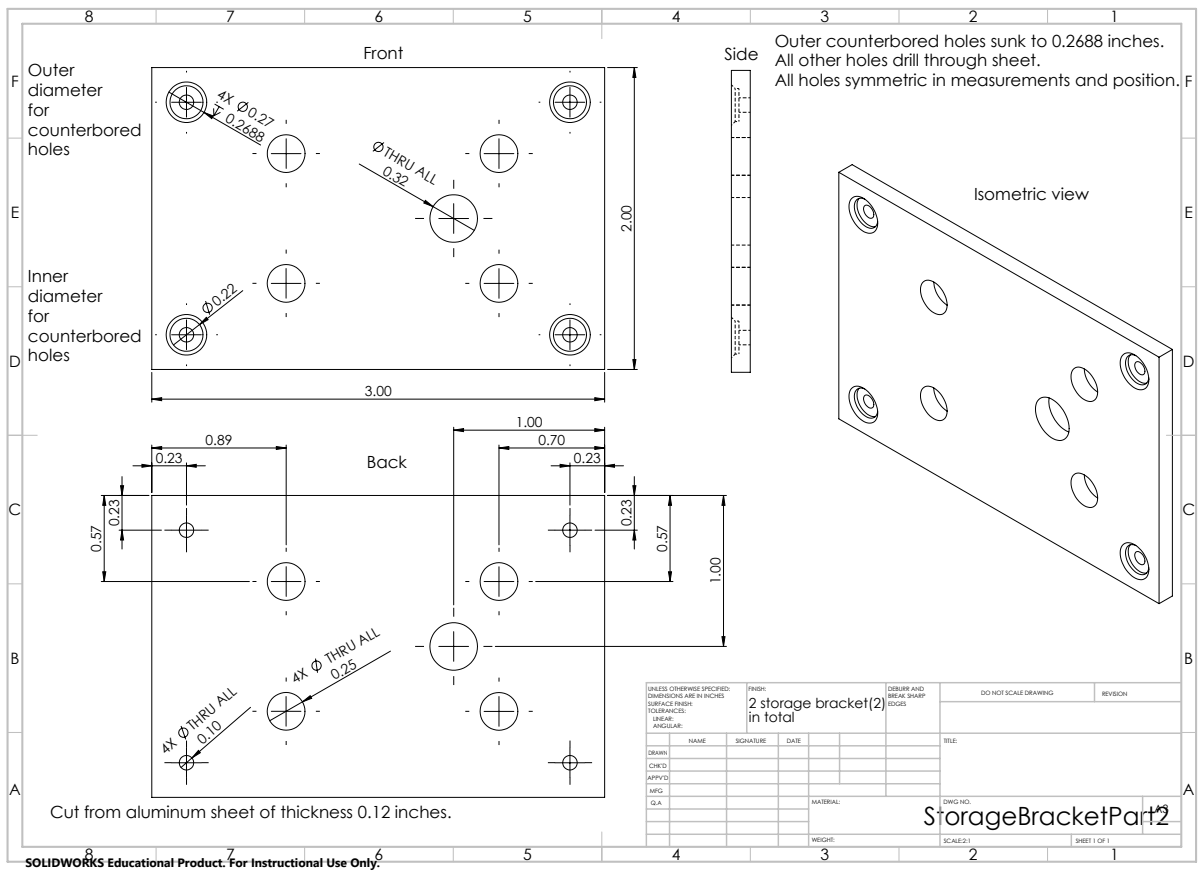


Figure 108: Inner Motor Storage Bracket SolidWorks Drawing

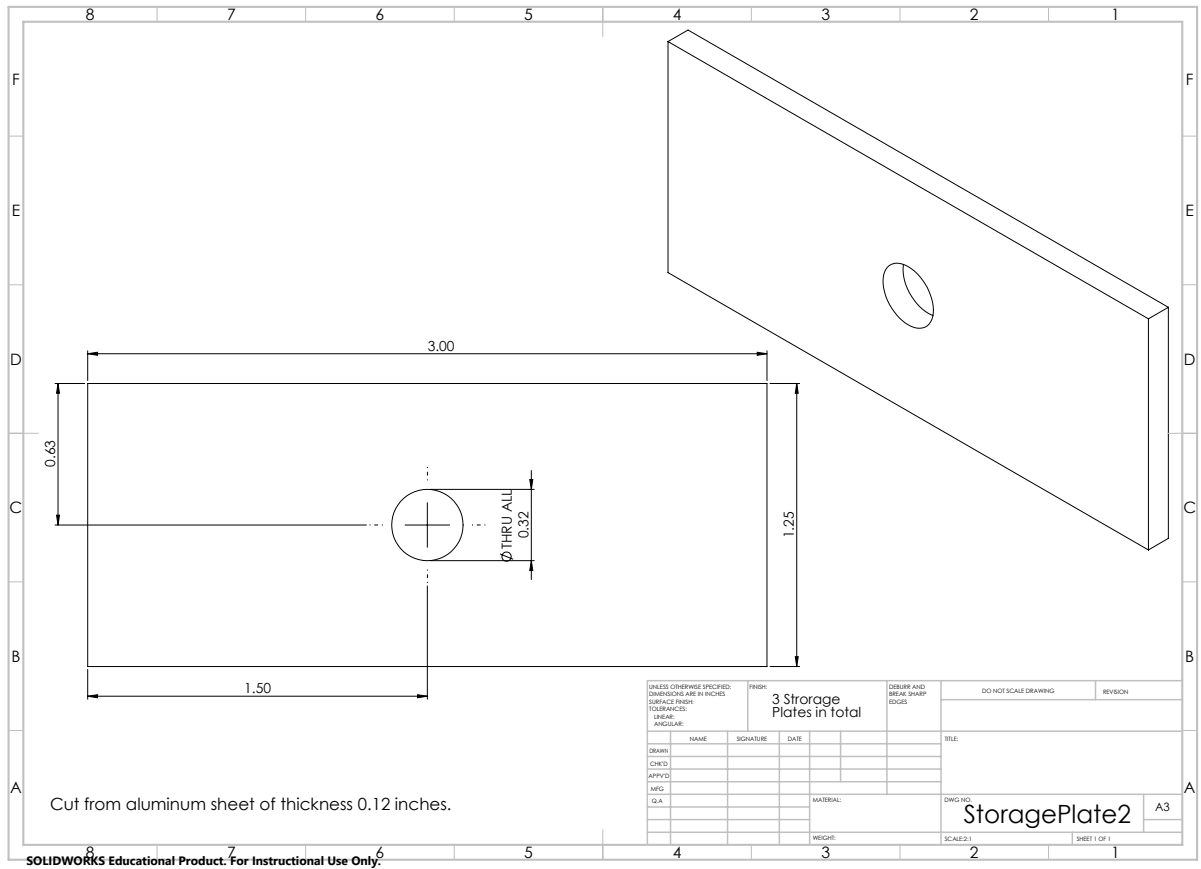


Figure 109: Storage Plate SolidWorks Drawing

Using a 0.12 inch thick aluminum sheet of dimensions 12 x 12 inches would the storage plates and storage brackets be cut out drilled through. Specifically:

- Three 3 x 1.25 inch storage plates with one 0.32 inch diameter hole in the middle.
- Two 3 x 2 inch storage brackets used for the inner section of the storage system with holes meant to be held through the centerpiece and counterbored holes to hold the bracket together.
- Eight 3 x 2 inch storage brackets used for the outer section of the storage system with holes meant to hold the 12 V motors and counterbored holes to hold the bracket together.
- One 2.13 x 1.25 inch aluminum plate

These plates were cut out of the aluminum sheet using a water jet. The holes cut through the plates were also cut through using a water jet. Only the counterbored holes were drilled through.

Then there were the aluminum rail bases to add some structural integrity to the conveyors themselves. The intention for these was for them to be cut out of a 0.06 inch, 6 x 12 inch aluminum sheet. The walls were either bent or cut out and then welded together. Additionally, given the length of the horizontal base in particular, that needed to be cut out in sections then welded together (one section of 12 inches, another of 6 inches).

This is where the first manufacturing issue arose. Because of the rigidity of the aluminum, it couldn't be bent without snapping. So, that left the walls to be made through welding. Unfortunately, due to the thickness of the aluminum (or rather, lack thereof), they could not be welded either without risking melting a good portion of the structure. As such, the rail bases could not be manufactured as is.

Fortunately, the experts at the machine shop had an alternative. Searching online at McMaster-Carr was a aluminum 6061 u-channel that nearly exactly fit the desired measurements of the railbases needed. So, two of these 3 foot u-channels were ordered on 2/16/2026. The reason why it was late after the initial machine shop order is the fact the machine shop was only able to get to the order on that date due to the influx of jobs they had backed up from the rest of the university. The 3-foot u-channels arrived on 2/23/2026. Another machine shop order was placed to cut it down using the waterjet at specific ranges. Where the u-channels were cut is listed in the SolidWorks drawing below.

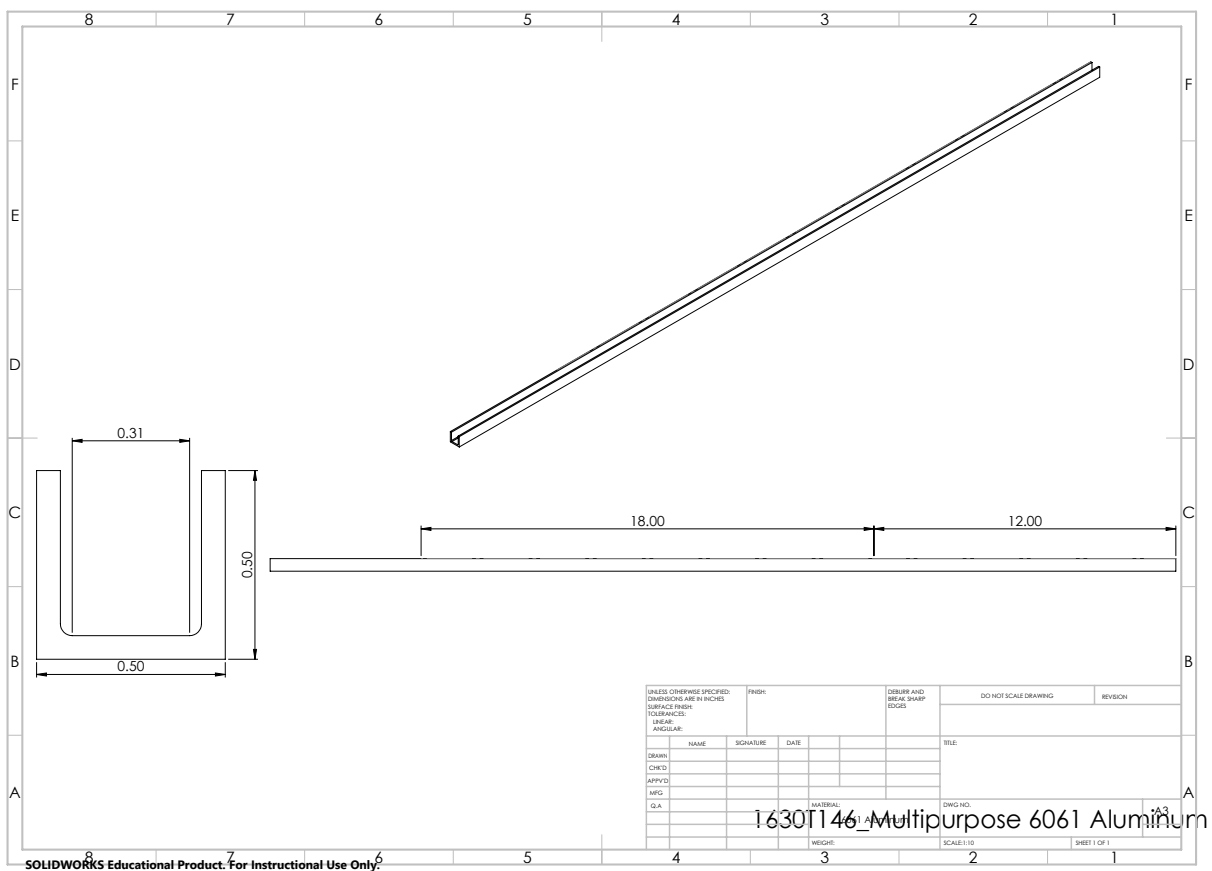


Figure 110: Aluminum U-Channel SolidWorks Drawing

With the two u-channels cut at 12 inches and 18 inches were the railbases and all of the other items in the machine shop finally finished on 2/25/2026.

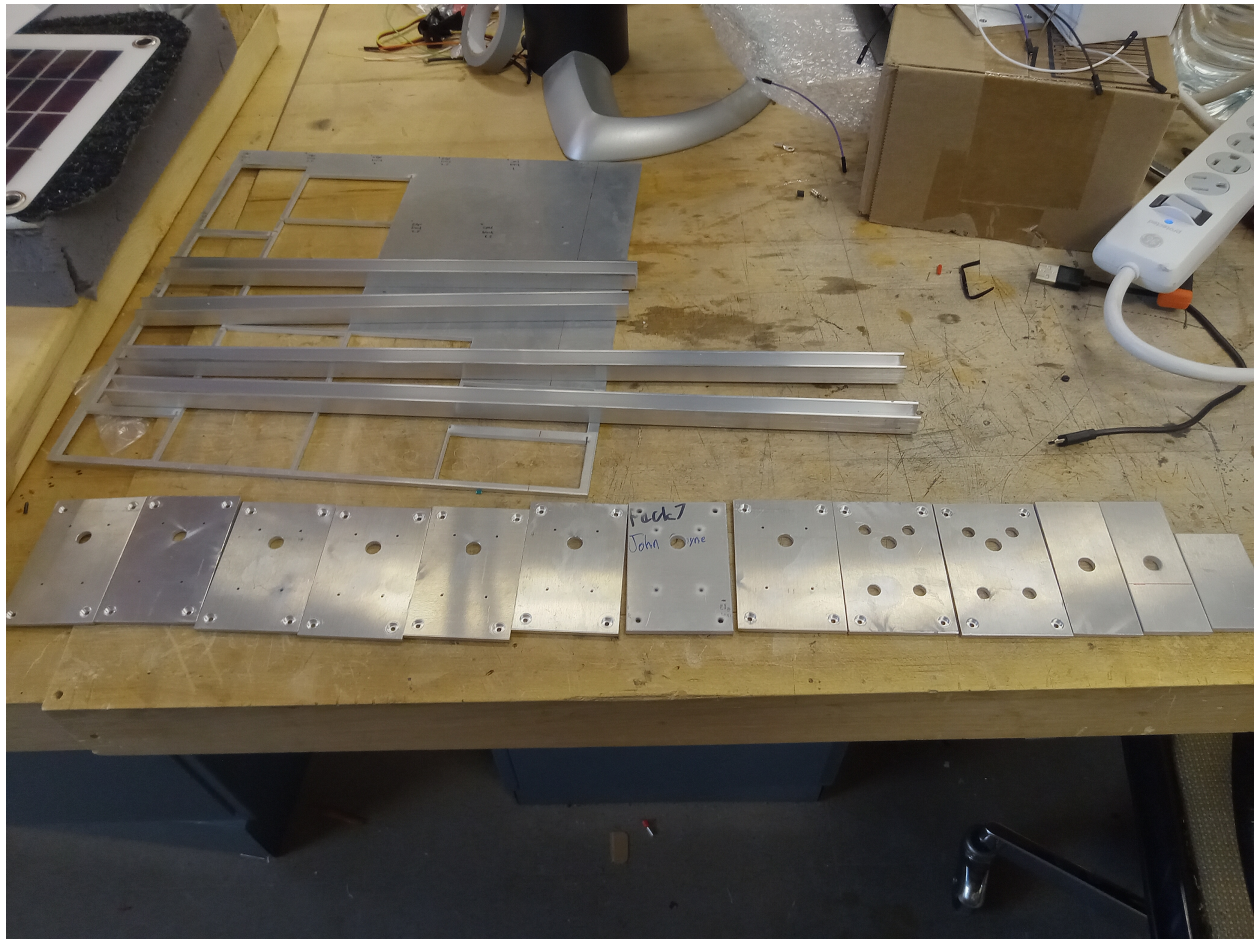


Figure 111: Machine Shop Order Finished

IV.5.1.2. Storage Motor Brackets

With the machine shop orders finished were all of the motor bracket plates acquired. Unfortunately, there were some errors with the order. All cut through holes with the water jet (aside from the center) were just barely thin enough to prevent the screws from fitting inside. Additionally, the center holes didn't line up with the motor mountings. Thus, did they need to be drilled through.

The outer holes were simple enough to drill through, as the counterbored holes were already in the correct positions. The center holes needed to be remeasured to line up with the motor mountings, which took a little more work. Fortunately, only four of the eight outer storage brackets needed to be lined up with the motor mountings, so there was some room for error.

With all of the necessary changes made were the motor mounts able to be screwed in. First, the motor itself was screwed onto the plates with the four motor mountings. The center torque fits through the center hole of each plate to allow for rotation of the gears on the storage belts. With the motor screwed onto the plates, were two of the plates screwed together through the counterbored holes.

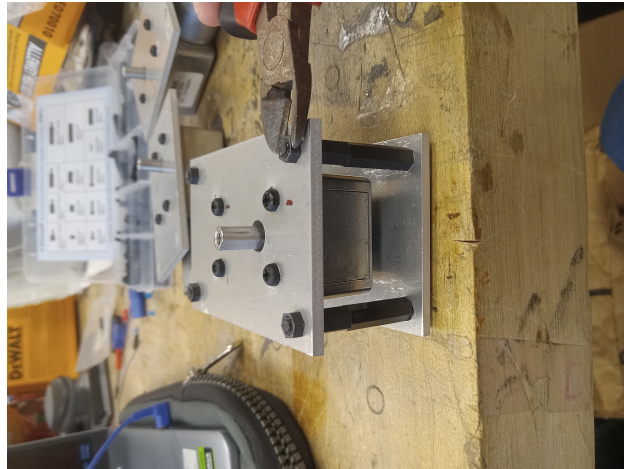


Figure 112: Storage Motor Bracket Being Constructed

Though two of the motor brackets needed to be reassembled with screws that had a higher structural integrity, eventually four motor brackets were assembled. These were all made using the senior design lab.

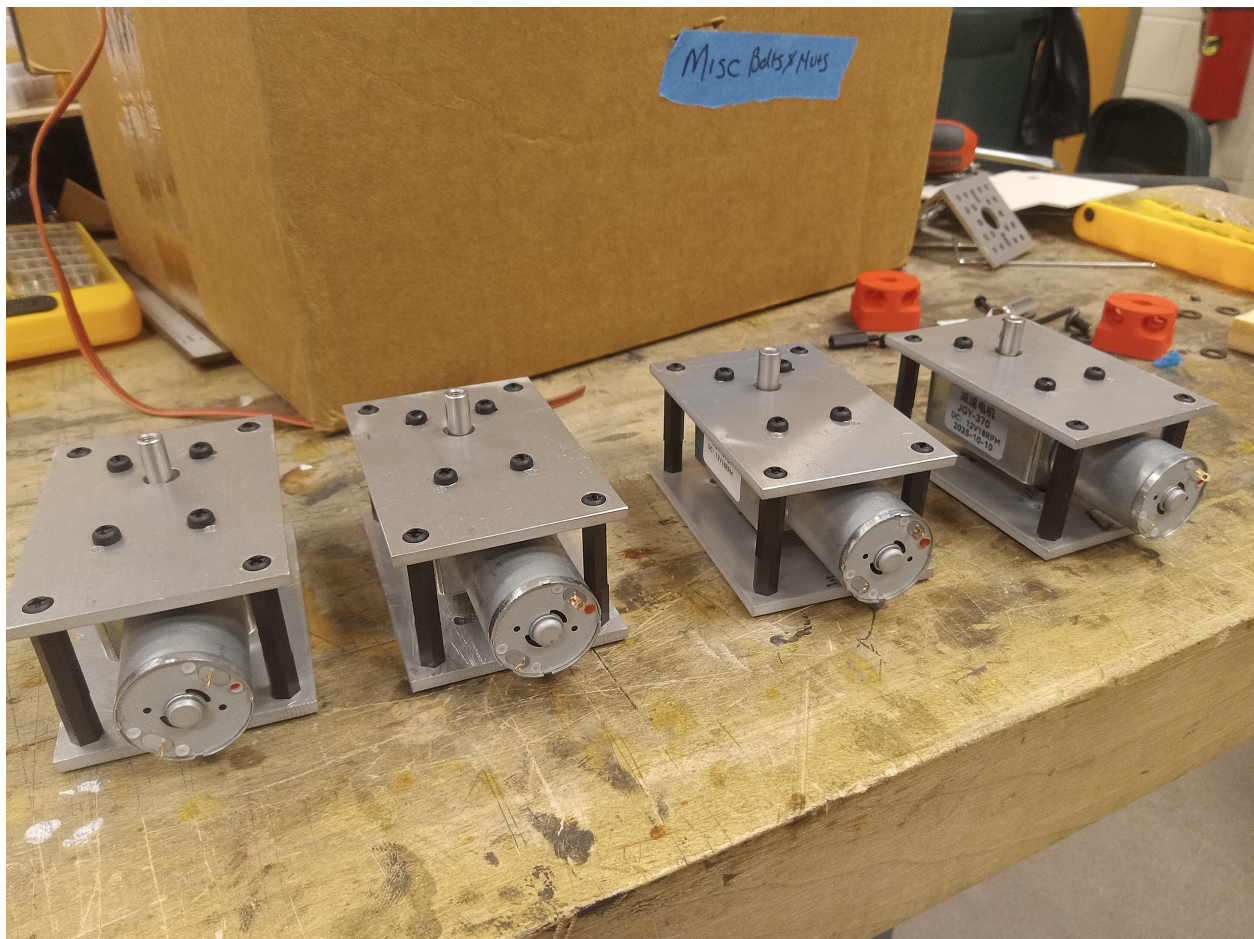


Figure 113: Motor Storage Brackets Assembled

IV.5.1.3. Storage Belts

Next came the storage belts. First, the racks which act as the base for the conveyors needed to be cut down to the same lengths the aluminum bars were cut at (12 inches and 18 inches, respectively). So, the four steel racks of 19.68 x 0.39 x 0.39 inches were cut down to the above lengths using a vise and a dremel. Below are the cut down belts.

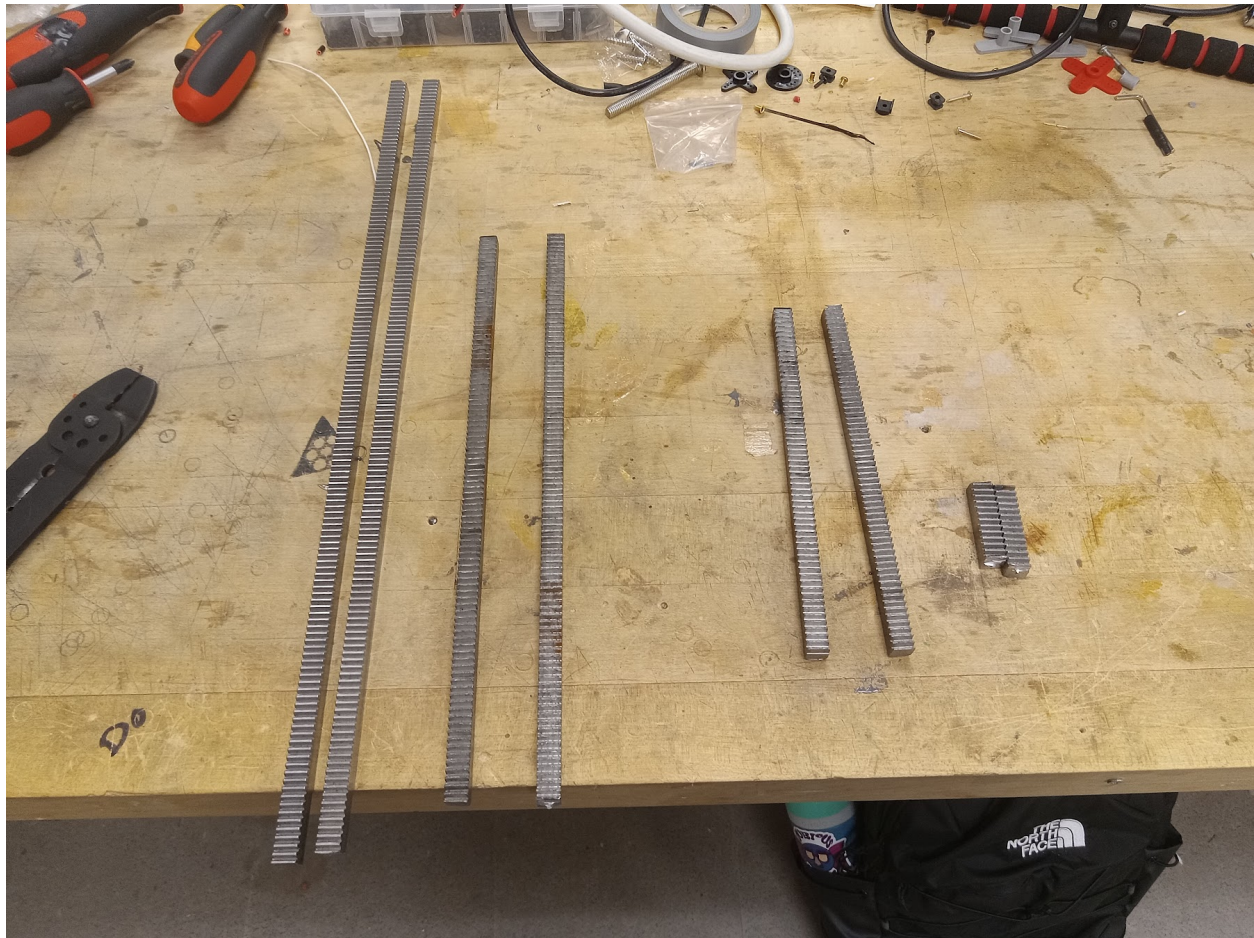


Figure 114: Manufactured Rack (on left) and Extra Length (on right)

From there, the aluminum bars can be attached to the racks to provide structural support. But, one oversight made when ordering these aluminum bars is the measurements of the base. The aluminum bars measure with a base of 0.374 inches while the racks measure to a base of 0.39 inches. Even when attempting to fit the racks either through thermally expanding the aluminum bars or hammering in the racks, neither option worked. Thus, will the racks be without the aluminum bars. Fortunately, these can be reused in another section, as discussed in the design solution.

The last point of manufacturing to the storage belts is based around the pinions. After receiving our parts, only one of four of said pinions arrived. As such, new ones had to be made. From the initial SolidWorks design, the gears used there were 3D-Printed in the Engineering Garage. These gears have a diameter of 0.875 inches with a thickness of 0.39 inches. Four of these gears were printed in case the remaining pinion wasn't apt for this design.

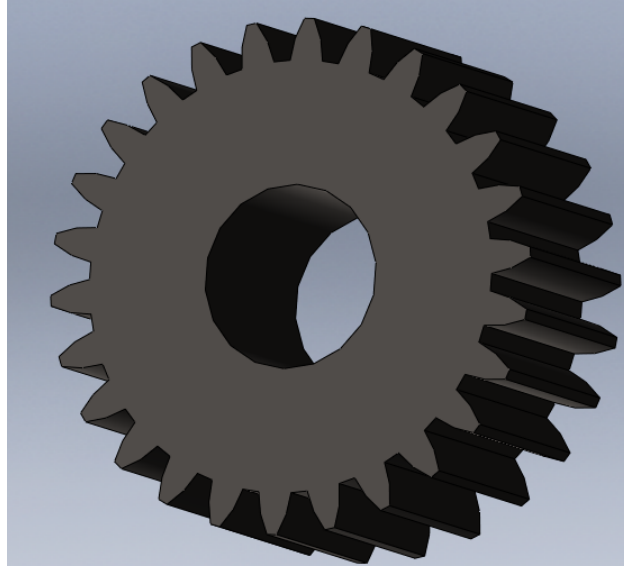


Figure 115: CAD Model of Storage Gears

IV.5.1.4. Missing Parts and Brainstorming

With most necessary parts obtained could the entire system start to be put together. Unfortunately, there were some issues with the current parts. For one, the racks couldn't fit onto the u-channels due to mismeasurements in said u-channels. Additionally, there were multiple missing parts that couldn't be assembled. These were the shafts that were to be connected to the belt in order for the system to move laterally.

Thus, with parts missing to keep the system stable and towards lateral movement, a new design needed to be devised based on what was available. This is pertaining to the parts received through ordering, 3D printing any necessary parts, and any scrap from the senior design lab to be used for structural support.

IV.5.1.5. Conveyor Assembly

The idea for the horizontal movement of the system remained largely the same, utilizing two motors parallel to each other on a set of conveyors. Biggest difference was this was now the base of the system, instead of being at the top. The conveyor belts and leftover aluminum u-channels were combined using a mixture of metal-curing epoxy with a layer of hot glue on top. As far as connected some of the smaller parts of the system together, that is the adhesive which was used.

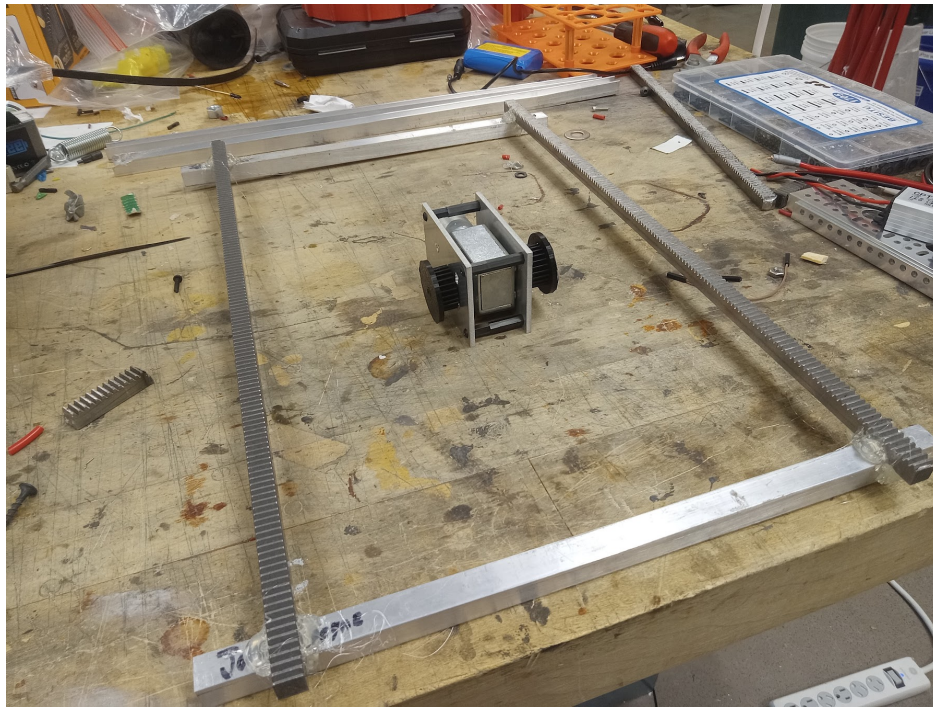


Figure 116: Conveyor Base of Storage System

Next came the lateral conveyor. This was the second major change to the design. Due to the limited power which could be supplied to the system and the missing parts, the lateral needed to be simplified when compared to the original design. The solution for this was to have two conveyors attached to the top of the horizontal motors parallel to each other. The lateral motion of the system would then be controlled by one lone motor as it moves along both conveyor belts.

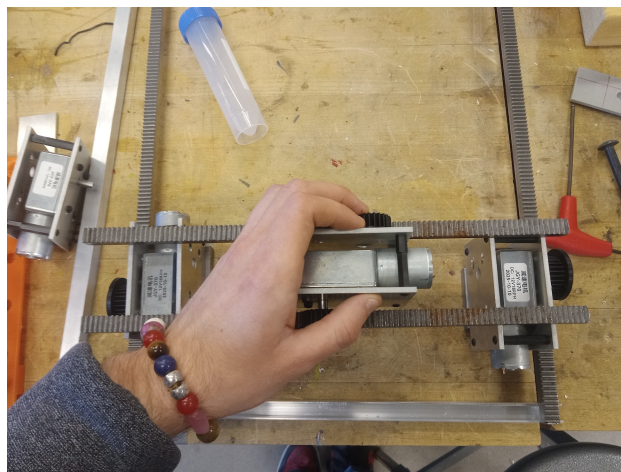


Figure 117: Theoretical Design of Lateral Storage Conveyor

When constructing it, there were some slight changes to the design in order for better stability. One of the gears was replaced with a 3D printed wheel, and the rack was replaced with a leftover L-channel in the senior design lab. This change made it easier for the side of the motor bracket not attached to the motor

shaft to roll along parallel of the gear. Thus, after some adhesive was applied to the L-channel and rack on top of the horizontal moving motors could the lateral motor balance on the conveyor without any other necessary supports aside from a small counterweight.

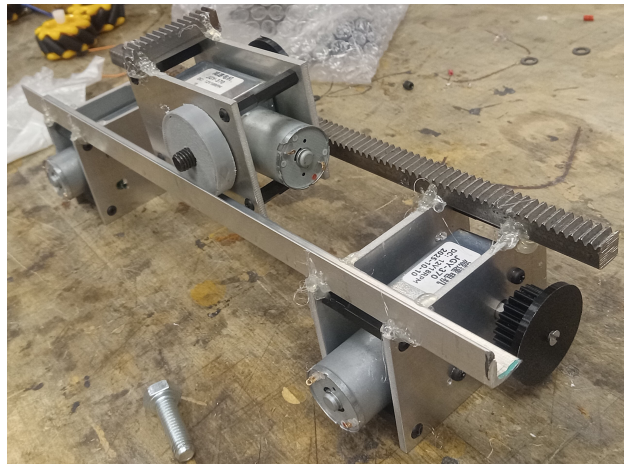


Figure 118: Lateral Storage Conveyor

The last part was the vertical system. Since this system was built around the horizontal and lateral systems in the early design, their new designs heavily influenced how this system would turn out. This new theoretical design would be stationed on top of the lateral motor, where the vertical motor-bracket would roll vertically between two conveyor belts parallel to a counterweight. In-between said counterweight and beneath the lateral motor would be one last motor which would be stationed vertically to carry the sample tubes. Said motor would be attached to an aluminum bracket and move with the vertical conveyor motor.

With a broad design in mind came the manufacturing. First was the part which would hold the vertical motor meant to carry the sample tubes. A motor bracket with a gear attached to it and an empty motor bracket were attached to a metal bracket, utilizing a mixture of the epoxy and hot-glue adhesive and screws to firmly attach them together.

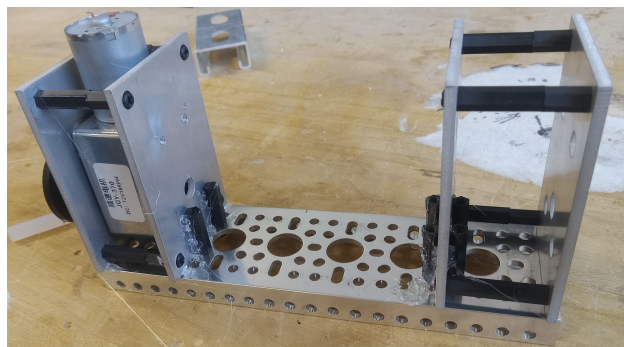


Figure 119: Sample Tube Grabber Mount

Afterwards came creating the conveyor which would be attached to the lateral motor. First, the lateral motor was epoxied to another metal bracket. Next were the conveyors added. Two were needed to be able to firmly grasp the vertical gear while still having enough room for it to move. To act as a counter weight, a

L-bracket was fastened to the metal bracket to even out the weight distribution of the system. Finally, were the sample tube grabber mount and the vertical conveyor part combined using the aforementioned adhesive and additional fastening. Below is the result. Note that the vertical motor wasn't added yet, as that would be among the final parts to the system.

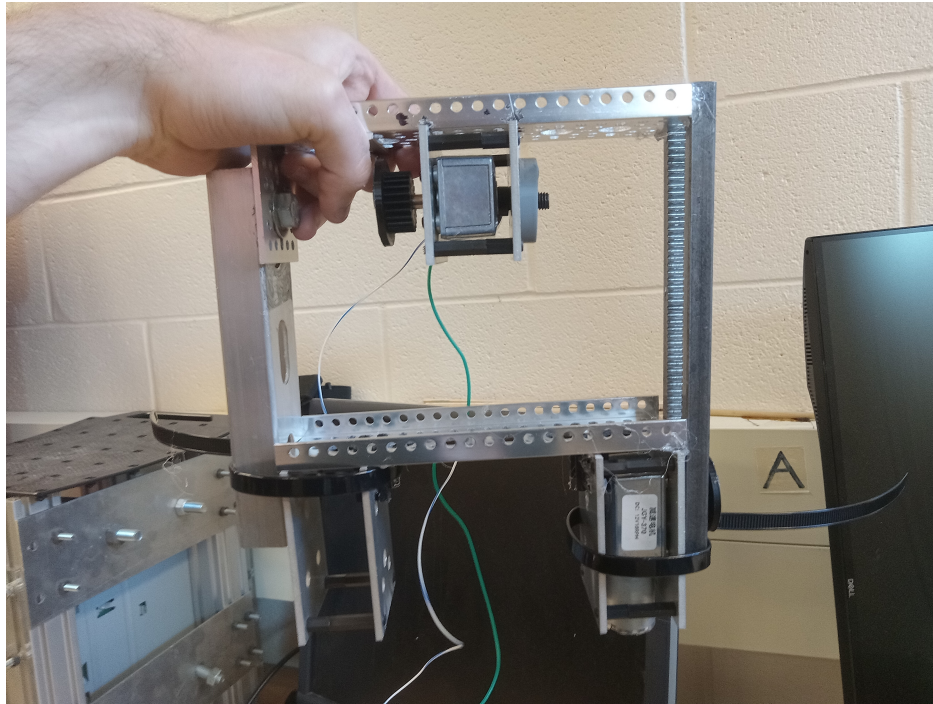


Figure 120: Vertical Conveyor System

IV.5.1.6. Structural Assembly and Collapse

After constructing the different conveyor parts and soldering the wires to the motors, could the assembly of the structure start. The whole structure was slated to sit atop a wall of wood roughly half a foot tall. This serves multiple purposes. The first is that the sample tube holders would be placed at the base of this system with the coolers underneath them. The wooden walls would act as separation between the storage system and all of the other subsystems, gaining a better temperature reading within an isolated area. This is further supported through the insulation which would be cast around the edges. Finally, the height of the walls allows for the system to adequately transport the sample tubes about a three-dimensional axis with enough room to move horizontally, laterally, and vertically.

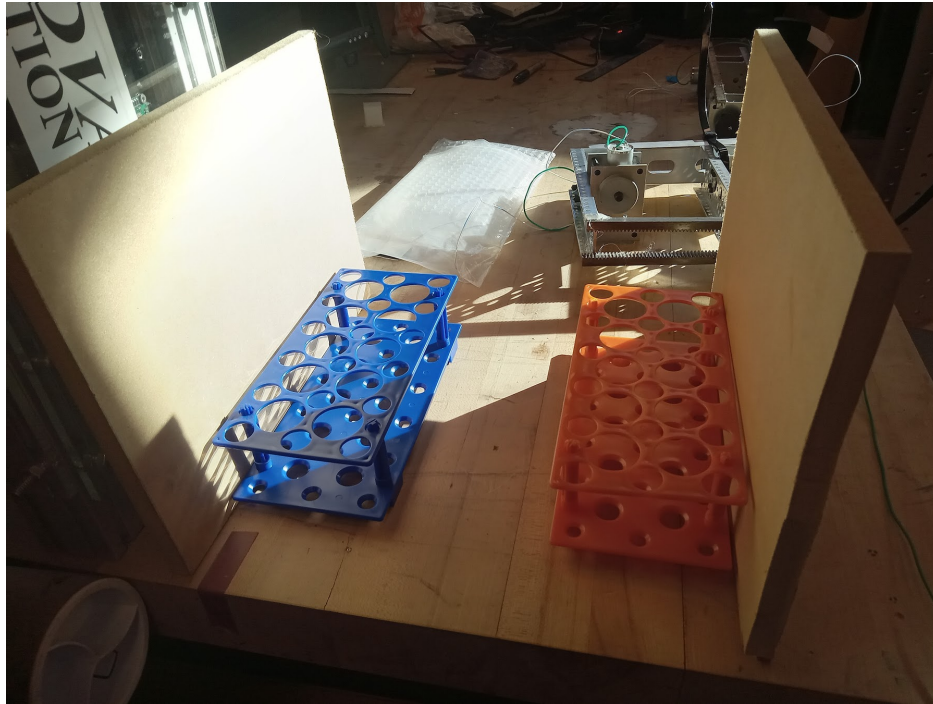


Figure 121: Theoretical Design of Storage System Base

Unfortunately, when assembling the system, a shift in the wood caused the whole system to collapse, effectively undoing all of the epoxy used to hold the conveyor system together. Due to time constraints, the new design of the storage system could not be completed, as it required at least three separate days to apply a recoat of epoxy to all of the different parts. Some parts of the design were salvageable, as the horizontal conveyor base was rebuilt by drilling holes into the metal and screwing the parts together. Yet, it was infeasible to apply such a strategy to rebuild the small motor brackets. Thus, without any time to either rebuild the system or devise a new design which wouldn't add more unnecessary weight to REHT, the storage conveyor system unfortunately was not finished in time for the senior symposium.

IV.5.1.7. Storage and Thermal Integration

Fortunately, there was one aspect of the system which was salvageable: the storage itself. Since the thermal systems were running well, that could be easily integrated with what remained of the storage system. It started by placing the Peltier coolers on top of an aluminum sheet with the same measurements of the width and length of the horizontal conveyor base. Said aluminum sheet was to act as the heat sink for the coolers, expelling any heat they emit onto the sheet and out of REHT. Another, smaller aluminum sheet was placed on top of it with the sample tube container epoxied onto it. This sheet was meant to conduct the thermal regulation the coolers put out, thus cooling the sample tubes which were to be housed in the compartment.

In terms of isolating the compartment, four walls made of PCB were cut out and attached to the inside of REHT around the base of the storage. Small gaps were left in the walls in order for the wiring and the temperature probes to fit through. Lastly, to keep the wires hidden and the compartment's temperature regulated, insulation was placed along the inner wall.



Figure 122: Final Storage System

Despite the many setbacks in constructing the storage system between lost/mismeasured parts, impromptu designing, time constraints, and the collapse of the conveyor system mere days before the senior symposium, the storage system was at least well integrated with the thermal systems. This accomplishes the design goal of being able to store refrigerated samples onboard REHT.

IV.5.2. Spectrometer

As mentioned earlier, spectrometer manufacturing mostly consisted of 3D printing and assembling the whole system. The equipment used in manufacturing the spectrometer system is the Raspberry Pi 3B+, Pi camera module, prebuilt servo motor and link arm, motor driver, 12V battery, a breadboard, and 3D printed components.

The first step in manufacturing the system was to use TensorFlow Lite image recognizing models and training them to recognize mission specific requirements like water, sand, grass, and if it doesn't recognize anything, unknown. Writing a python code to live feed what the camera sees and recognize the objects in front of it at the same time. However, upon completion despite the system working perfectly, a lot of lag was observed due to limited processing power of the Pi, keeping that in mind, the code was changed to capture an image and only display the results of what the camera recognizes in front of it saving a lot of processing power for other components of the system.

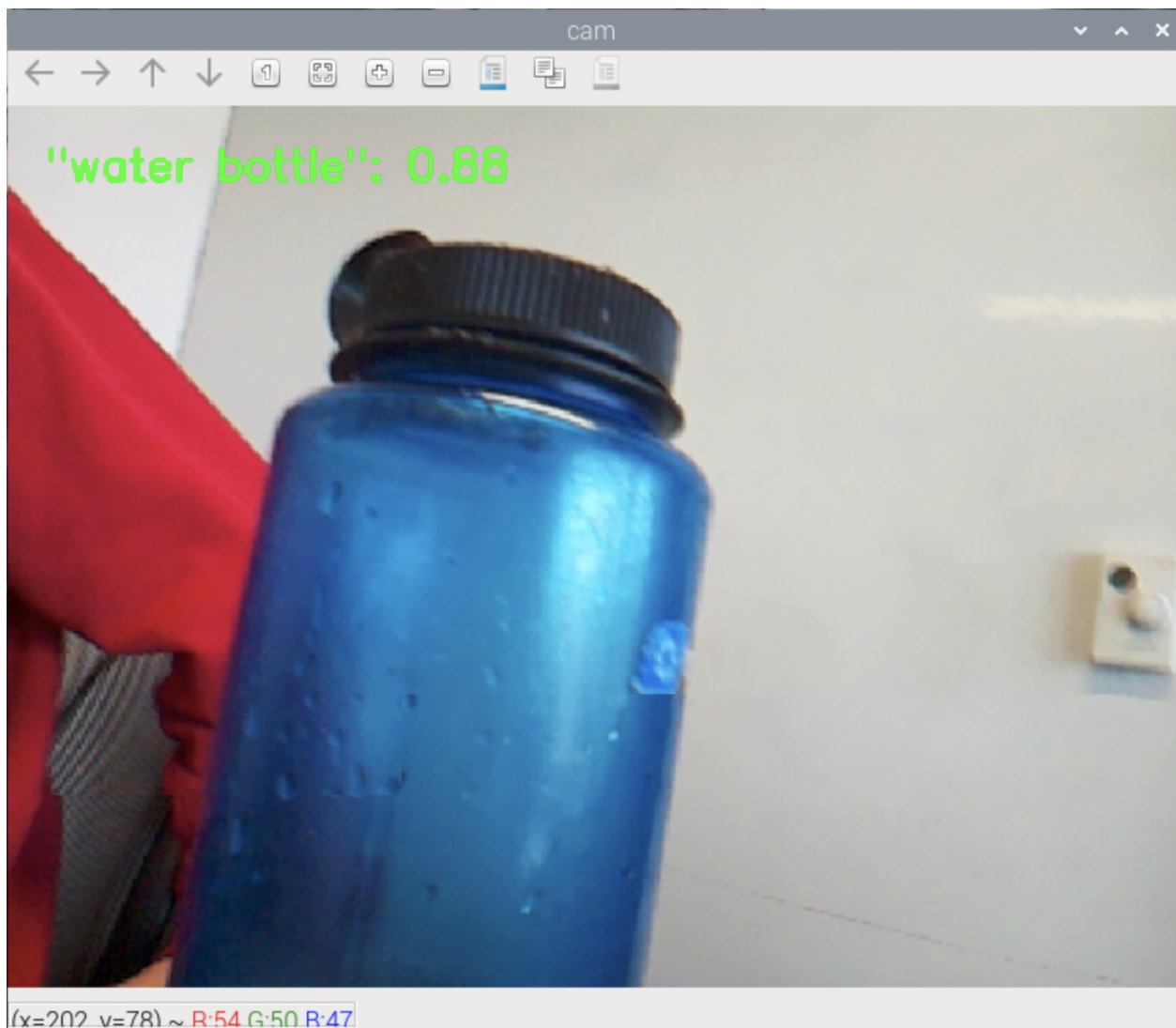


Figure 123: Test program recognizing a bottle

The next step was to program the servo motor. Using the breadboard and the Pi GPIO pins, the servo was programmed such that it can be remotely controlled using keyboard keys. The prebuilt mount and the pink and link configuration allowed the servo to rotate the link based on remote commands making it feasible for long distance and remote communication. At the same time, the ultrasonic sensor module was programmed to accurately measure the distance in front of it and print out the distance periodically. This would allow it to be controlled remotely via LORA communications module without consuming too much bandwidth. A breadboard was utilized to do attach jumper wires and connect them to the required Pi GPIO pins.

After that, the final step was to design a box to house the electronics and mount the motor onto and to design a custom mount capable of holding the camera and ultrasonic sensor module. These designs were made and 3D printed as mentioned in the design solutions section and as seen in image below.

With this the spectrometer system is completely built and functional at the present time. Next steps in the process include modifying the code for the servo motor and the ultrasonic sensor module to make it compatible with the LORA communication system in order to communicate and control the system remotely through the use of the Pi and to connect the Pi power supply via a buck boost to regulate the voltage provided by the battery. An additional step would be to connect both the Raspberry Pi 3B+ and the Pi 5 along with the transceiver module. The final step would be to place the system on top of the rover body and the breadboard within the rover body along with extending the wires after the rover body manufacturing is complete.

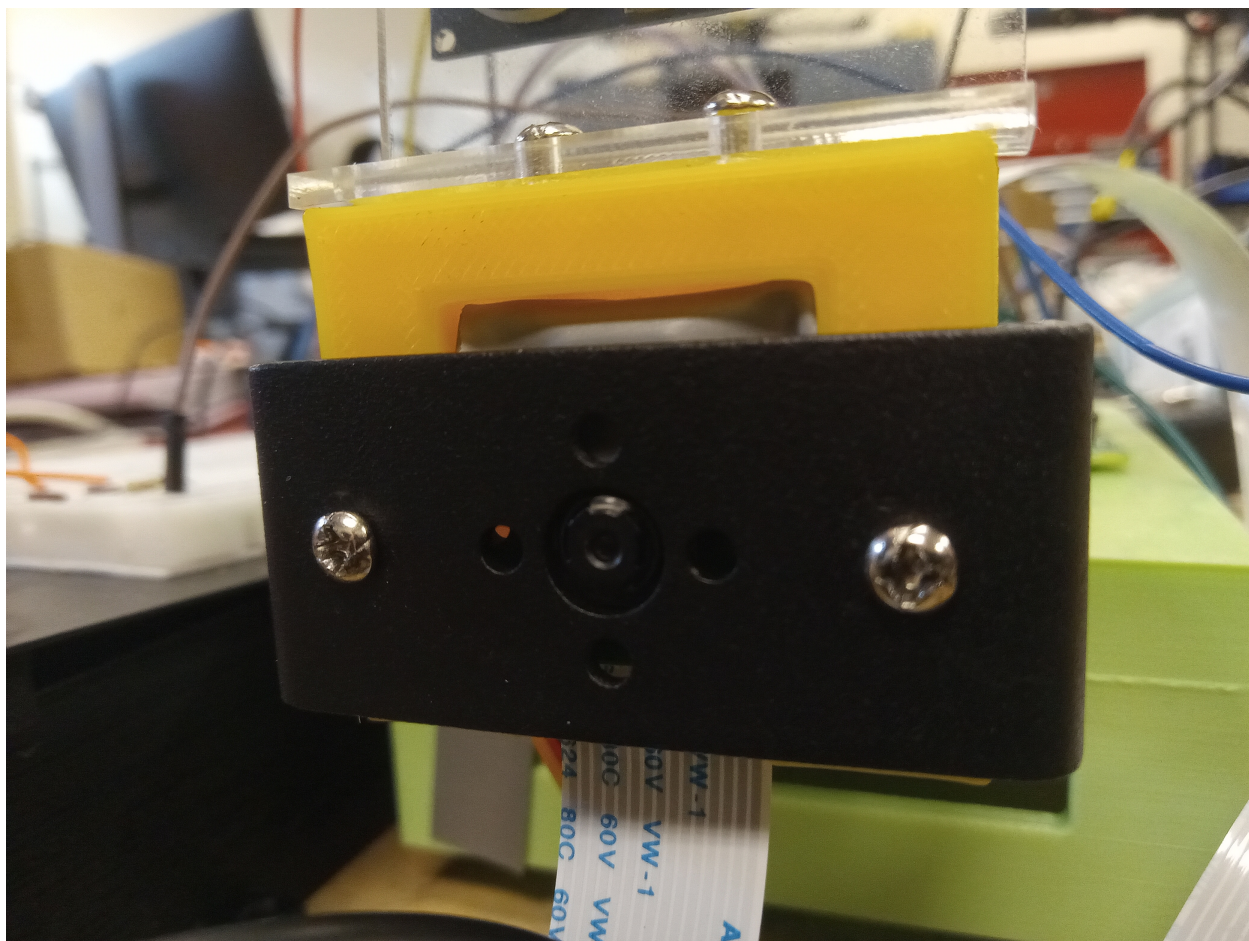


Figure 124: Raspberry Pi Camera Attached to Spectrometer Arm

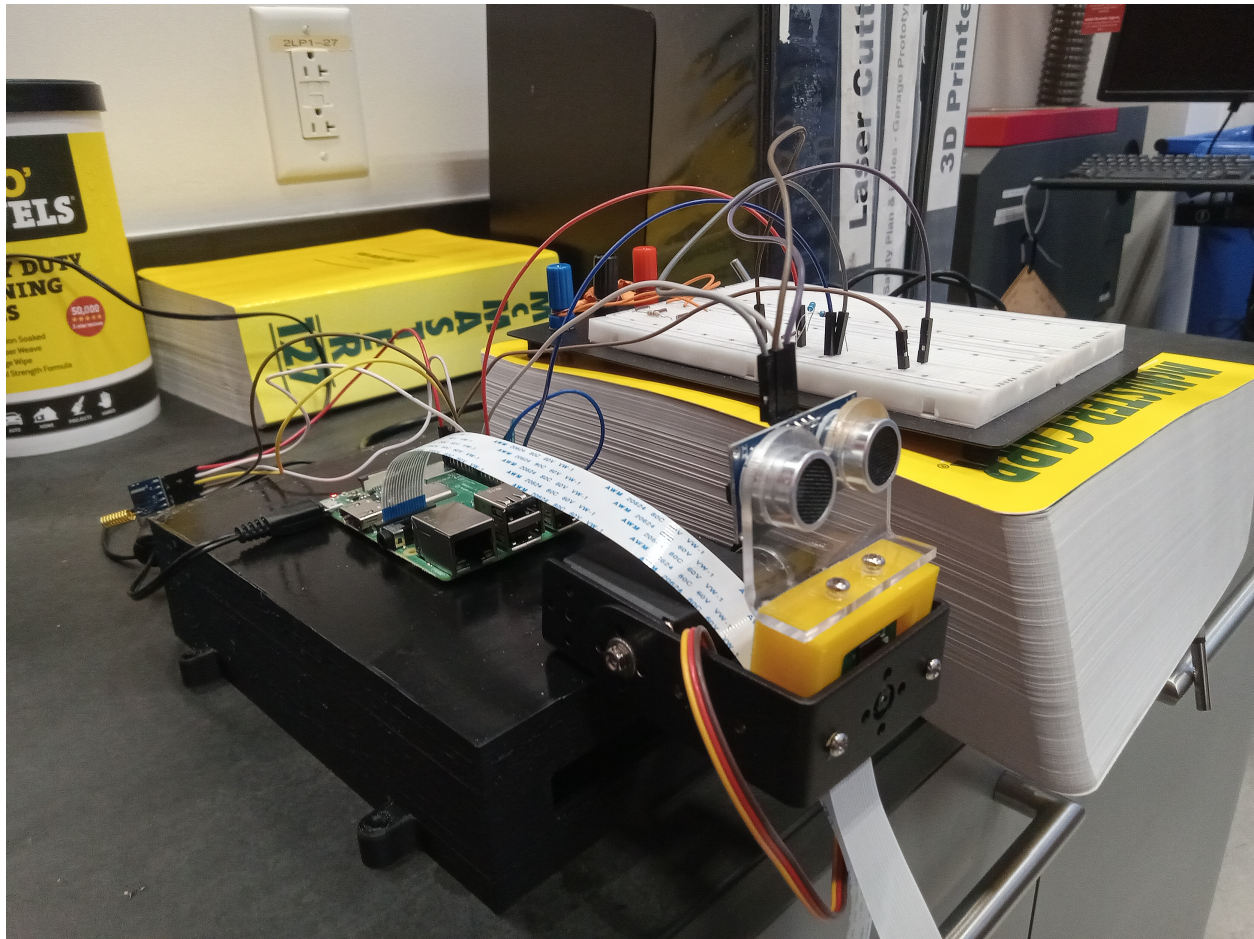


Figure 125: Full Spectrometer System

IV.6. Power and Electrical

IV.6.1. Systems Integration

Powering and integrating the subsystems was the biggest difference between the CDR and this Final report. We housed three different 24 volt batteries on the rear of the rover that would each power individual subsystems. One battery powered the GNC, Raspberry pi 5, and all six motors. Another battery powered the Raspberry Pi 3, thermal system, spectrometer systems, and communications systems. Finally, the last battery powered the drill systems.



Figure 126: power Supply

The Thermal, raspberry pi 3, and communications system all ran off one 24 volt battery. The difficulty of integrating this system was finding a way to step down the voltage for each individual component. Luckily, the thermal coolers, and fan ran off of 12 volts so therefore all we need to do was step down 24 volts to 12 volts which was accomplished through a custom buck converter found inside the senior design lab. Next we need to find a way to power the raspberry pi 3, communications and spectrometer. Luckily these components mostly need 5 and 3 volt inputs. Our raspberry pi 3 comes installed with 3 and 5 volt pins which is helpful to us as we used a breadboard to extend those connections to power all of our components. The five volt line consisted of the spectrometer arm servo motor and the drill servo motor. The 3 volt line consisted of the temperature probes and communication chips. Below is the final picture of the entire system.



Figure 127: Thermal Power Circuit

IV.7. Thermal Systems

There isn't a major change in the design of the thermal systems since the Critical Design Review document except the inclusion of the 5V 4-channel relay module. The equipment utilized in manufacturing the system is the peltier coolers, power supply, aluminum base plate, 5V 4-channel relay module, Raspberry Pi 3B+ (same Pi shared with the spectrometer system), breadboard (shared with the spectrometer), and the temperature probes.

The first step in this process was to connect the DS18B20 temperature probes with the Raspberry Pi 3B+ using the breadboard. The 3.3V pin on the Pi powers the temperature probes. Connecting them and writing a python program to recognize the probes, number, read temperatures from the probe, and print them on the terminal of the Pi. The same program also included the code to activate and deactivate the numbered peltier coolers that are recognized based on the Pi GPIO pins.

The next step was to connect the peltier coolers with the pi. In order to do that, the 5V 4-channel relay module was included in the system. GPIO pins from the Pi corresponding to the peltier cooler pins on the code were connected to the IN slots of the relay module. The 5V pin and the ground pin from the Pi was also connected to the relay module DC+ and DC- slots. These pins would allow the pi to switch the relay on and off turning the cooler on and off based on the set temperature range being measured by the temperature

probes. The COM slot of the relay module was connected to the positive terminal of the power supply and the Normally Open slot was connected to the positive terminal of the peltier coolers. The negative terminal of the power source and coolers were then connected completing the circuit. An aluminum plate was placed beneath the coolers to act as a heat sink and absorb the heat generated by the coolers. With the the Pi was automatically able to turn the coolers on and off based on the temperatures measured by the temperature probes and the range set in the code.

The next steps in the process include placing the coolers in the and temperature probes in their designated location inside REHT storage system, extending wires to reach to the breadboard in order to complete the circuit, and to modify the program for the thermal system to make it compatible with the LORA communication system. The passive thermal systems that include the aluminized heat shield and the insulation would be installed after the manufacturing of the rover body and installation of other subsystems.

```

1 import tkinter as tk
2 from W1ThermSensor import W1ThermSensor
3 import RPi.GPIO as GPIO
4
5 # --- CONFIGURATION ---
6 # Mapping of your specific Sensor Serial Numbers to BCM GPIO Pins
7 ZONE_MAP = {
8     "000000718a8c": [17], # Probe 1 -> Relay 1 (Pin 11)
9     "0000006e410c": [27], # Probe 2 -> Relay 2 (Pin 13)
10    "0000006ce74c": [22], # Probe 3 -> Relay 3 (Pin 15)
11    "0000006f19fd": [23] # Probe 4 -> Relay 4 (Pin 16)
12 }
13
14 # Temperature Thresholds
15 # Set low for testing; once verified, change to 25.0 and 20.0
16 MAX_TEMP = 27.0 # Turn ON cooling above this
17 MIN_TEMP = 25.0 # Turn OFF cooling below this
18 UPDATE_INTERVAL = 1000 # Refresh every 1 second (1000ms)
19
20 # GPIO Setup
21 GPIO.setwarnings(False)
22 GPIO.setmode(GPIO.BCM)
23 pins_to_setup = [17, 27, 22, 23]
24 for pin in pins_to_setup:
25     GPIO.setup(pin, GPIO.OUT)
26     GPIO.output(pin, GPIO.LOW) # Start with everything OFF
27
28 class TempMonitorApp:
29     def __init__(self, root):
30         self.root = root
31         self.root.title("4-Zone Peltier Control System")
32         self.root.geometry("500x600")
33         self.root.configure(bg="#2c3e50")
34
35         # Header
36         tk.Label(root, text="System Temperature Monitor", font=("Arial", 18, "bold"),
37                 bg="#2c3e50", fg="white").pack(pady=20)
38
39         # Initialize Sensors
40         try:
41             self.sensors = W1ThermSensor.get_available_sensors()
42             print(f"System: Found {len(self.sensors)} DS18B20 sensors.")
43         except Exception as e:
44             print(f"Error: {e}")
45
46     def update_temps(self):
47         # Update temperature readings and relay status
48         # ... (code for updating sensors and relays) ...
49
50     def start(self):
51         self.update_temps()
52         self.root.after(UPDATE_INTERVAL, self.update_temps)
53
54 if __name__ == "__main__":
55     root = tk.Tk()
56     app = TempMonitorApp(root)
57     app.start()
58     root.mainloop()

```

System Temperature Monitor

Zone	Temperature	Status
Zone 1 (ID: 000000718a8c)	30.1°C	COOLING
Zone 2 (ID: 0000006e410c)	21.0°C	STABLE
Zone 3 (ID: 0000006ce74c)	21.6°C	STABLE
Zone 4 (ID: 0000006f19fd)	21.3°C	STABLE

Figure 128: Thermal System Pi Code Display

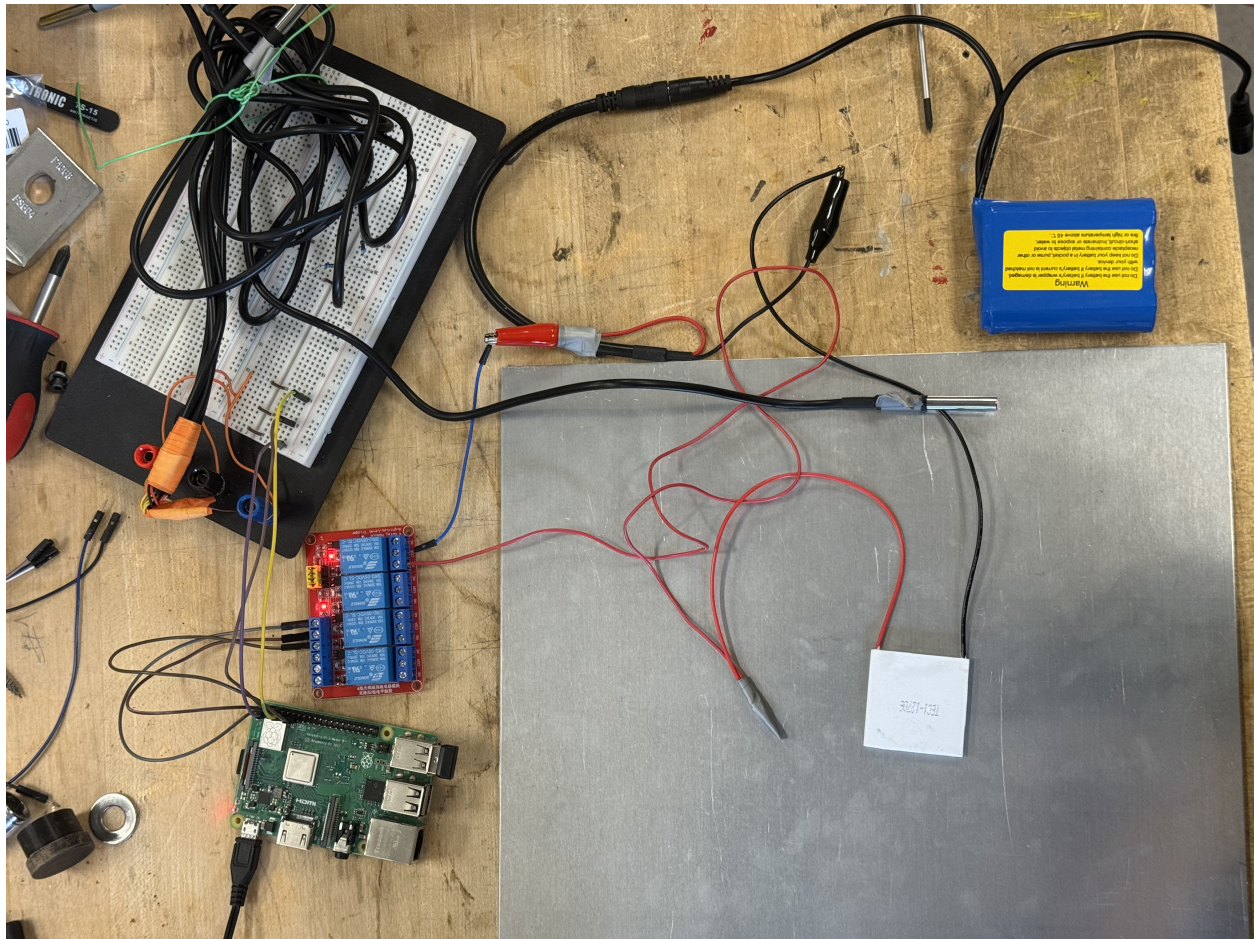


Figure 129: Full Active Thermal System Design

IV.8. Ground Station/Communications

IV.8.1. Ground Station Antenna/Transceiver

The ground station communication hardware required manual assembly prior to system integration. The Raspberry Pi Pico and SX1278 LoRa transceiver module were initially supplied without pre-attached header pins. In order to enable electrical connections between the components, header pins were manually soldered onto both the Raspberry Pi Pico and the SX1278 module using a soldering iron and lead-free solder. Care was taken to ensure proper pin alignment and strong electrical joints to prevent intermittent connections during operation.

After soldering the headers, jumper wires were used to establish the necessary electrical connections between the Raspberry Pi Pico and the SX1278 LoRa module. These jumper cables connected the required power, ground, and communication pins to allow the microcontroller to interface with the LoRa transceiver.

To enable wireless signal transmission, an external antenna was connected to the SX1278 module. This required the use of a specialized antenna cable adapter connected to the module's antenna port. The LoRa antenna was then attached to the opposite end of the adapter cable, completing the radio frequency transmission path. Once assembled, the system was powered and verified to ensure proper electrical connectivity

and successful LoRa signal transmission.

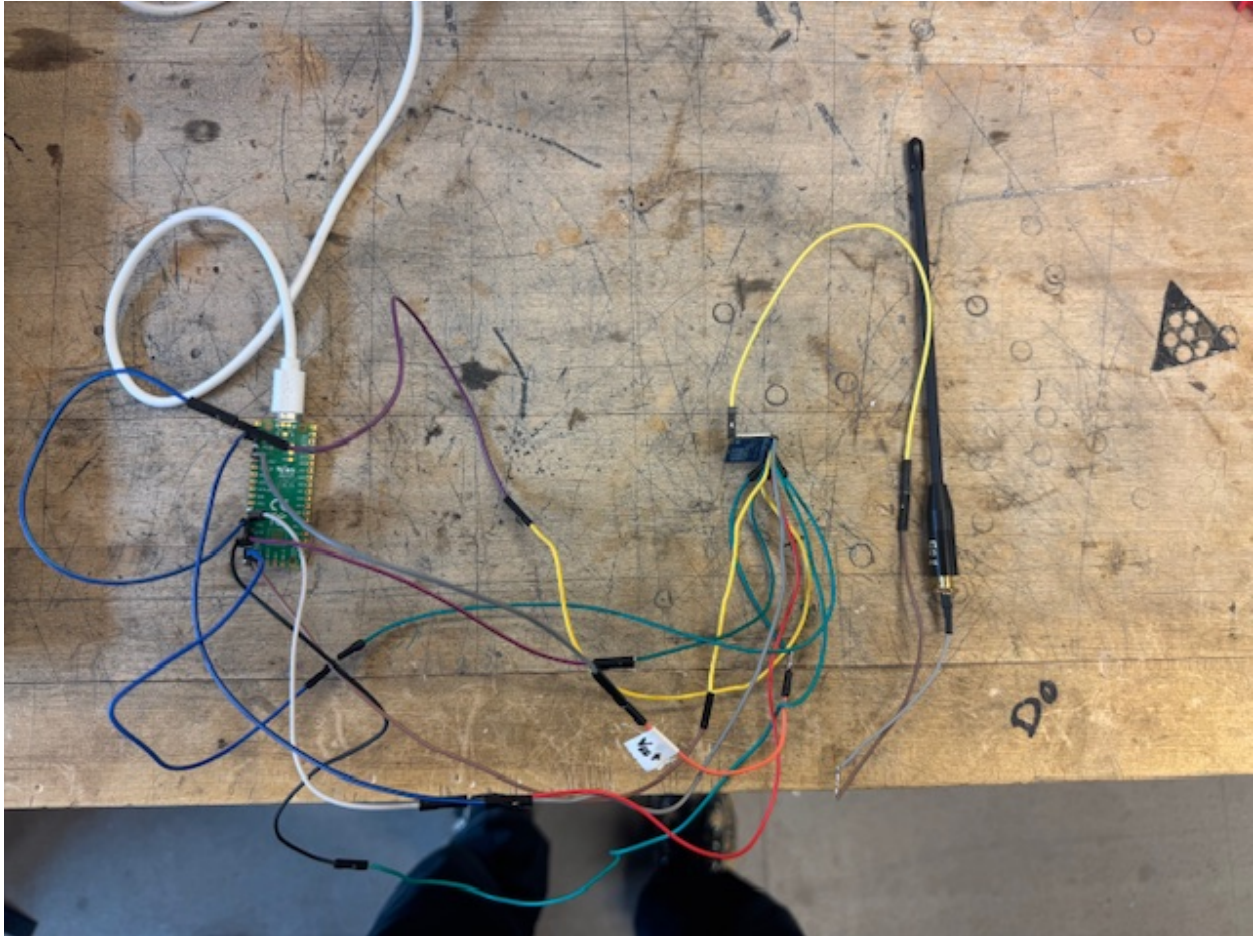


Figure 130: Ground Station System

IV.8.2. Rover Side Antenna/Transceiver

In contrast to the Pico transmitter assembly, the receiver-side hardware required minimal physical preparation. The RYLR998 LoRa module was interfaced directly with the Raspberry Pi 3 through its GPIO header. The module was equipped with standard header pins that allowed it to be connected to the Raspberry Pi 3 using jumper wires. These connections provided power, ground, and UART communication lines required for serial data exchange between the LoRa module and the Raspberry Pi. Once the pins were connected to the appropriate GPIO and power terminals on the Raspberry Pi 3, the receiver system was ready for software configuration and communication testing. This simplified integration reduced assembly complexity for the ground station receiver while still enabling reliable LoRa packet reception.

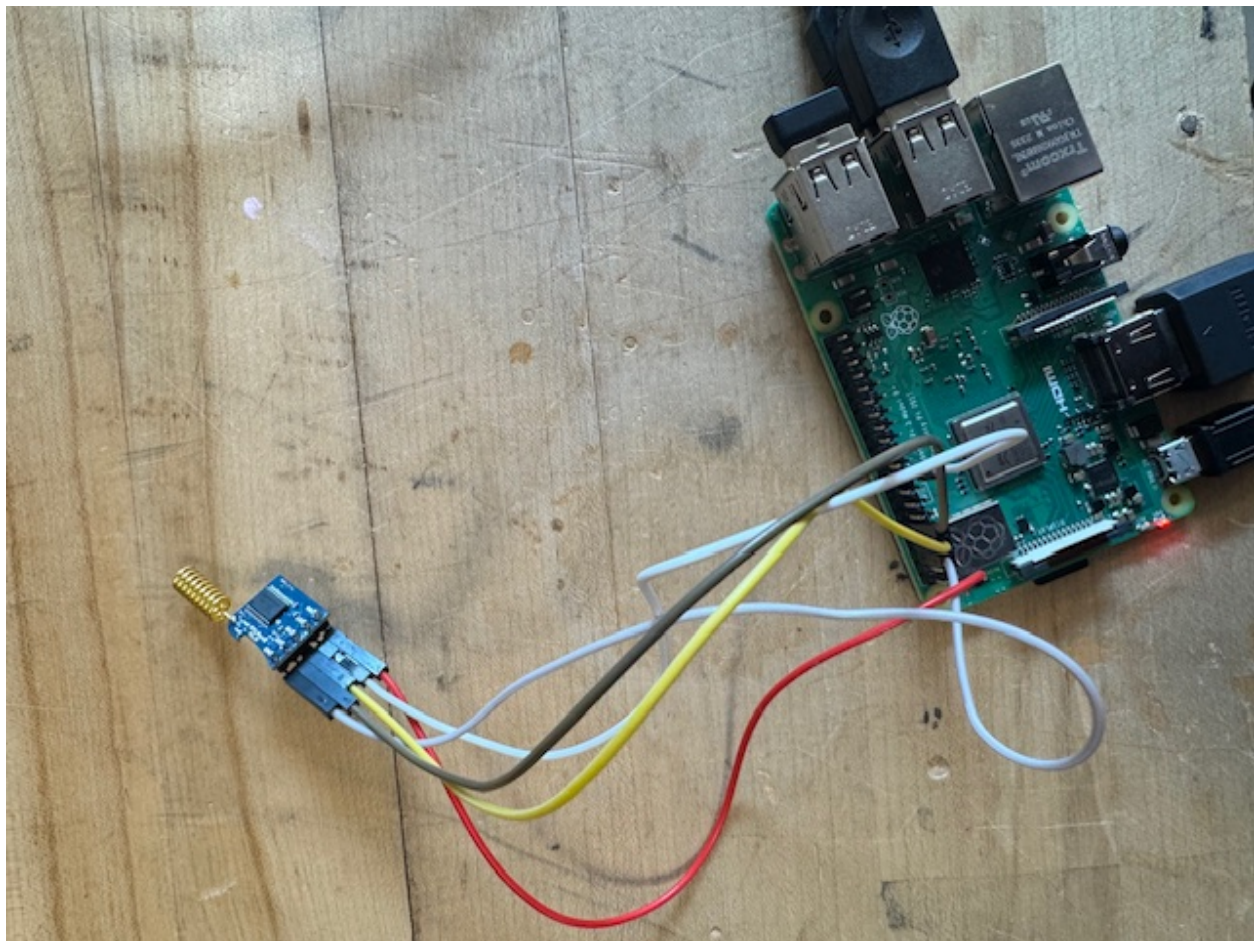


Figure 131: Rylr998 Attached to the Raspberry Pi 3

IV.8.3. System Intergration

Not much has changed since the CDR document, but the biggest difference is the fact that the entire subsystem is now encased in a shell. This shell lays ontop of the Plexiglass of the outer layer of the rover. This shell houses the antenna, the spectrometer servo and motor driver, and the RYLR998 communication chip.

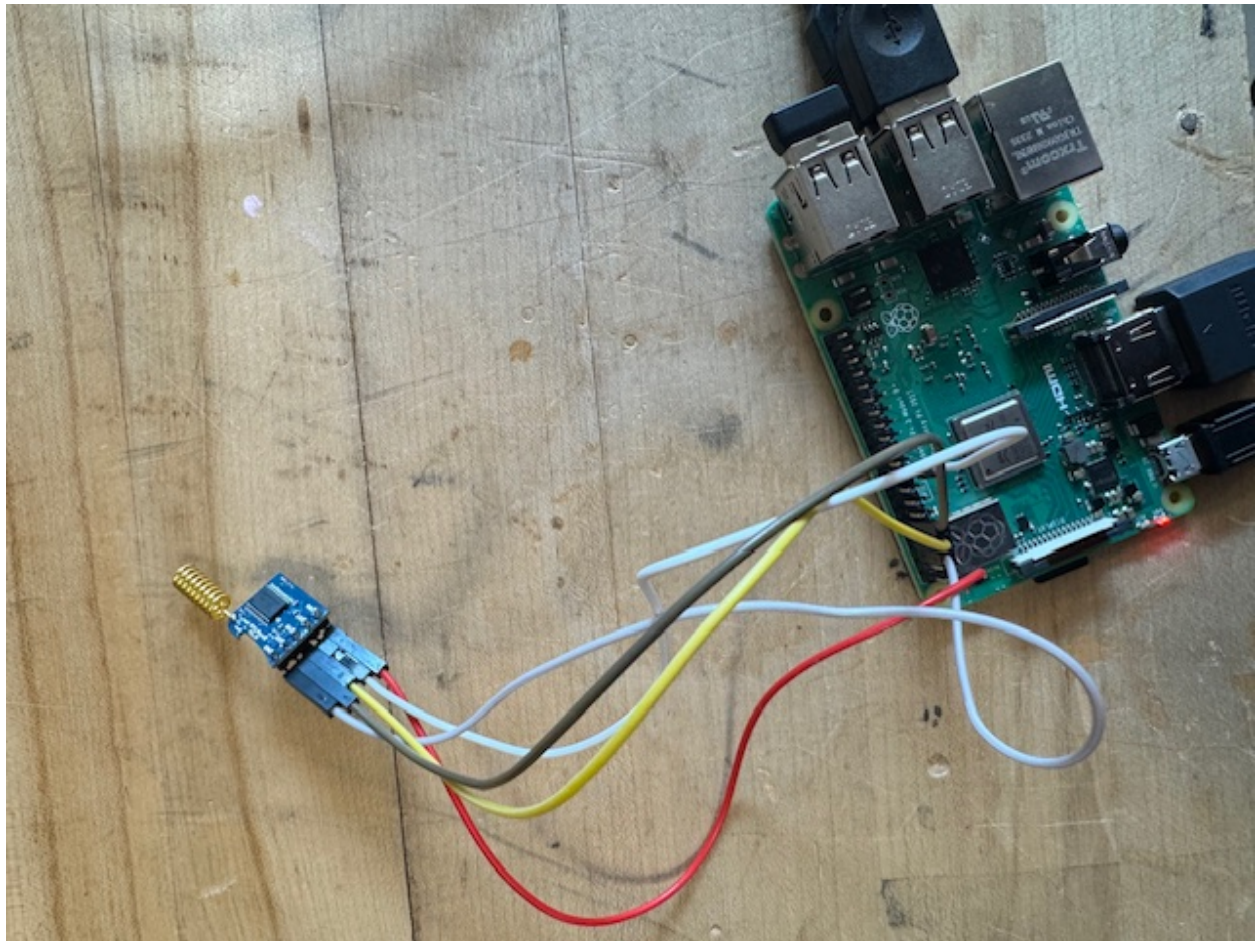


Figure 132: Ryli998 Attached to the Raspberry Pi 3

IV.9. Final Prototype

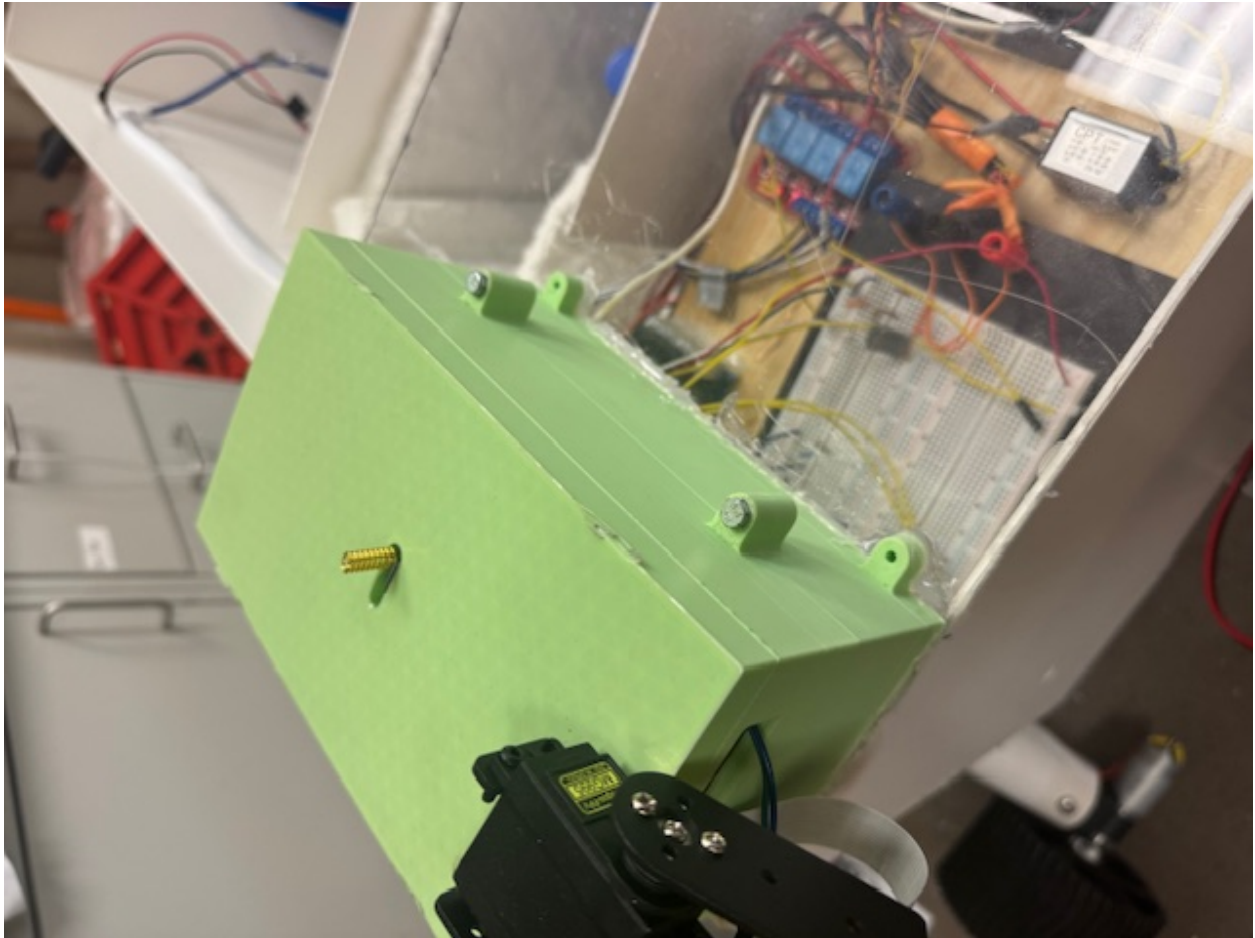


Figure 133: Final Prototype Model

Above is the result of the manufacturing process. The dimensions and weight of the subscale REHT were roughly the same as the model designed, only being about a couple pounds lighter as it was closer to 70 pounds. PCB was used for the walls while plexiglass was used for the ceiling, having a latched opening in case any additional work on the system needed to be done. Some additional springs were added on the back of the suspension system as well to counteract the moment caused by the drill at the front and the lithium ion batteries in the back. The green compartment on top of the plexiglass is the spectrometer system, with all of its wiring housed within the 3D printed box. All other subsystems are found within the subscale rover itself, such as the storage system, navigations and controls wiring, propulsion motor drivers, and thermal system.

V. Validation, Verification, and Testing

V.1. Navigation and Controls

V.1.1. Dead Reckoning Navigation Test

Test Explanation The rover's IMU will be moved at least 5 feet in under 2 seconds in a straight line before turning and traveling another 5 feet in the same time period.

Test Procedure Two sets of markings will be placed 5 feet from each other at right angles. The box containing the IMU and Raspberry Pi will be picked up and carried from the initial marking to the second, and then from the second mark to the third; a stopwatch will be used to confirm this occurs in under the specified time.

Objective This is needed to allow REHT to operate with minimal supervision over extended periods of time, as well as account for communication time between Earth and the lunar surface.

Driving Requirement [FR.1]: REHT shall be capable of autonomously traversing the distance between sites of interest.

Method Experiment.

Facility/Location NCSU EB3 Senior Design Lab.

Equipment/Machines Raspberry Pi 5, Computer, Stereo Camera, and IMU.

Schedule 3/04/2026 (presented), 3/-/2026 (will perform when camera ribbon adapter order arrives).

Level of Success This test is considered a success if position measurements are taken at less than 6 inches from the final measured location.

Test Explanation	The rover's IMU will be moved at least 5 feet in under 2 seconds in a straight line before turning and traveling another 5 feet in the same time period.
Test Procedure	Two sets of markings will be placed 5 feet from each other at right angles. The box containing the IMU and Raspberry Pi will be picked up and carried from the initial marking to the second, and then from the second mark to the third; a stopwatch will be used to confirm this occurs in under the specified time.
Objective	This is needed to allow REHT to operate with minimal supervision over extended periods of time, as well as account for communication time between Earth and the lunar surface.
Driving Requirement	[FR.1]: REHT shall be capable of autonomously traversing the distance between sites of interest.
Method	Experiment.
Facility/Location	NCSU EB3 Senior Design Lab.
Equipment/Machines	Raspberry Pi 5, Computer, Stereo Camera, and IMU.
Schedule	3/04/2026 (presented), 3/-/2026 (will perform when camera ribbon adapter order arrives)
Level of Success	This test is considered a success if position measurements are taken at less than 6 inches from the final measured location.

V.1.2. Differential Moment Simulation

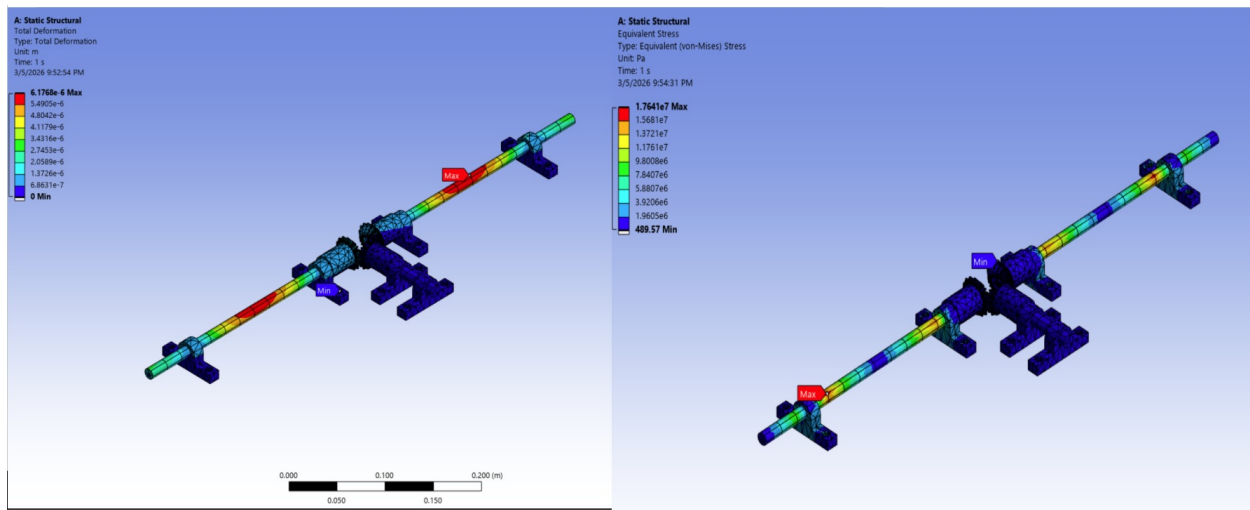


Figure 134: Differential Simulation

Test Explanation: An Ansys simulation was performed in order to determine if the differential mechanisms shaft and bevel gears can sustain high loads.

Objective: Suspension is needed to overcome the obstacles and debris that will be present on the lunar surface. While larger objects can be avoided, smaller obstructions and terrain inconsistencies will have to be overcome. This requires a differential mechanism to reduce the rovers roll when driving over obstacles.

Driving Requirement: [FR.1]: REHT shall be capable of autonomously traversing the distance between sites of interest.

Method: Simulation

Facility/Location: N/A

Equipment/Machines: Laptop, ANSYS Student

Schedule: 3/5/2026

Level of Success: Very successful, stress and deformation were well below the level that would cause damage or system failure.

Test Explanation	An Ansys simulation was performed in order to determine if the differential mechanisms shaft and bevel gears can sustain high loads.
Objective	Suspension is needed to overcome the obstacles and debris that will be present on the lunar surface. While larger objects can be avoided, smaller obstructions and terrain inconsistencies will have to be overcome. This requires a differential mechanism to reduce the rovers roll when driving over obstacles.
Driving Requirement	[FR.1]: REHT shall be capable of autonomously traversing the distance between sites of interest.
Method	Simulation
Facility/Location	N/A
Equipment/Machines	Laptop, ANSYS Student
Schedule	3/5/2026
Level of Success	Very successful

V.1.3. Rocker Bogie Obstacle Test

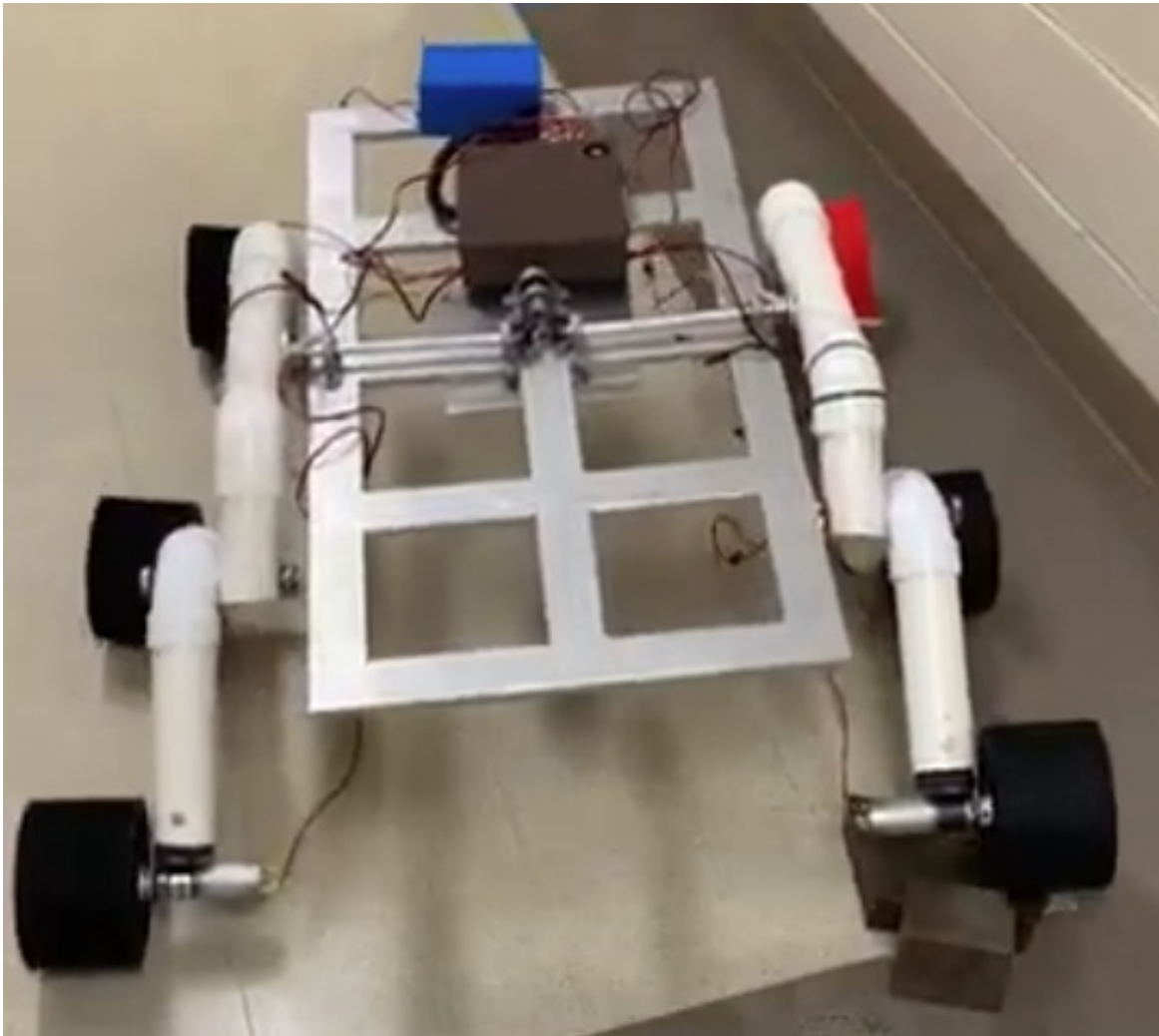


Figure 135: Rocker Bogie Obstacle Test

Test Explanation: An obstruction of known height will be placed in front of one side of the rover. Under its own power it will drive over the obstacle and the results will be recorded.

Test Procedure: A set of two steel blocks were placed back to back, one with a height of 2 inches and the other with a height of 4 inches. The rover was then directed to drive over them, and it was ensured that all three wheels on the side of the obstacle passed over it.

Objective: Suspension is needed to overcome the obstacles and debris that will be present on the lunar surface. While larger objects can be avoided, smaller obstructions and terrain inconsistencies will have to be overcome. This requires a series of rocker and bogie that can shift in response to obstacles while minimizing roll and ensuring all wheels remain in contact with the ground at any given time.

Driving Requirement: [FR.1]: REHT shall be capable of autonomously traversing the distance between sites of interest.

Method: Experiment

Facility/Location: NCSU Engineering Building 3 Hallway

Equipment/Machines: 2" and 4" Steel blocks

Schedule: 3/5/2026

Level of Success: Successful, all objectives were met, there is still slightly more oscillation than optimal but it is within acceptable levels.

Test Explanation	An obstruction of known height will be placed in front of one side of the rover. Under its own power it will drive over the obstacle and the results will be recorded.
Test Procedure	A set of two steel blocks were placed back to back, one with a height of 2 inches and the other with a height of 4 inches. The rover was then directed to drive over them, and it was ensured that all three wheels on the side of the obstacle passed over it.
Objective	Suspension is needed to overcome the obstacles and debris that will be present on the lunar surface. While larger objects can be avoided, smaller obstructions and terrain inconsistencies will have to be overcome. This requires a series of rocker and bogie that can shift in response to obstacles while minimizing roll and ensuring all wheels remain in contact with the ground at any given time.
Driving Requirement	[FR.1]: REHT shall be capable of autonomously traversing the distance between sites of interest.
Method	Experiment
Facility/Location	NCSU Engineering Building 3 Hallway
Equipment/Machines	2" and 4" Steel blocks
Schedule	3/5/2026
Level of Success	Successful, all objectives were met, there is still slightly more oscillation than optimal but it is within acceptable levels.

V.2. Propulsion

V.2.1. Motor Drive System Test

Purpose:

The purpose of this verification and validation test is to:

1. **Verify** that the three L298N motor driver modules (U1, U2, U3) correctly interface with the Raspberry Pi 5 GPIO control system
2. **Validate** that all six 24V DC motors receive proper power and directional control as designed
3. **Confirm** that the complete wiring implementation matches the electrical schematic and provides reliable motor operation
4. **Demonstrate** bidirectional control (forward/reverse) for all motors with correct skid-steer turning functionality

Subsystem/CPE Overview:

This test focuses on the REHT Propulsion system, which is the hub for controlling all activity of the motor drivers. The system consists of three L298N motor driver modules, raspberry pi 5, buck converter, 24V battery, and six 24V planetary gear motors.

Equipment:

- Motor Driver Box
- 6 24V Motors
- 3 L298N Motor Drivers
- 24V Battery
- Raspberry Pi 5
- Buck Converter

Facilities: This test will be conducted in the senior design lab.

Procedure:

Pre-Test Setup

1. Verify all wiring connections match the electrical schematic
2. Confirm 24V power supply voltage using multimeter
3. Verify 3.3V logic power to driver control circuits
4. Ensure Raspberry Pi GPIO pins are correctly mapped to driver inputs
5. Confirm ground connections between Pi, drivers, and power supply

Individual Motor Tests For each motor (M1 through M6):

1. Execute forward command via GPIO control
2. Measure motor terminal voltage (expected: $\sim 24\text{V}$)
3. Verify motor rotation direction
4. Execute reverse command
5. Measure motor terminal voltage during reverse
6. Verify motor reverses direction
7. Execute stop command and verify motor stops

Integrated System Tests

1. **Full Forward Test:** Command all six motors forward simultaneously
2. **Full Reverse Test:** Command all six motors reverse simultaneously
3. **Right Turn Test:** Right motors reverse, left motors forward (skid steer)
4. **Left Turn Test:** Left motors reverse, right motors forward (skid steer)
5. **Emergency Stop Test:** Verify all motors stop on command from any operational state

Voltage Validation Using a multimeter, measure and record:

- Motor terminal voltages during operation
- GPIO output voltages (HIGH = 3.3V, LOW = $\sim 0\text{V}$)
- Driver input terminal voltages
- Confirm voltage levels match design specifications

Level of Success:

Test Results Summary (Success Criteria Met!)

Motor Voltage Tests:

- All motors received design voltage ($24\text{V} \pm 0.5\text{V}$)
- GPIO control signals verified at 3.3V logic levels
- Driver logic power confirmed at 3.3V (critical discovery: required matching GPIO voltage)

Directional Control:

- All six motors demonstrated bidirectional control

-
- Forward/reverse commands executed correctly
 - Motor direction matched intended behavior

Integrated Functionality:

- Synchronized forward motion achieved
- Synchronized reverse motion achieved
- Skid-steer turning (left and right) operational
- Emergency stop function verified

Wiring Verification:

- All connections matched schematic
- No shorts or open circuits detected
- Signal integrity confirmed across all GPIO connections

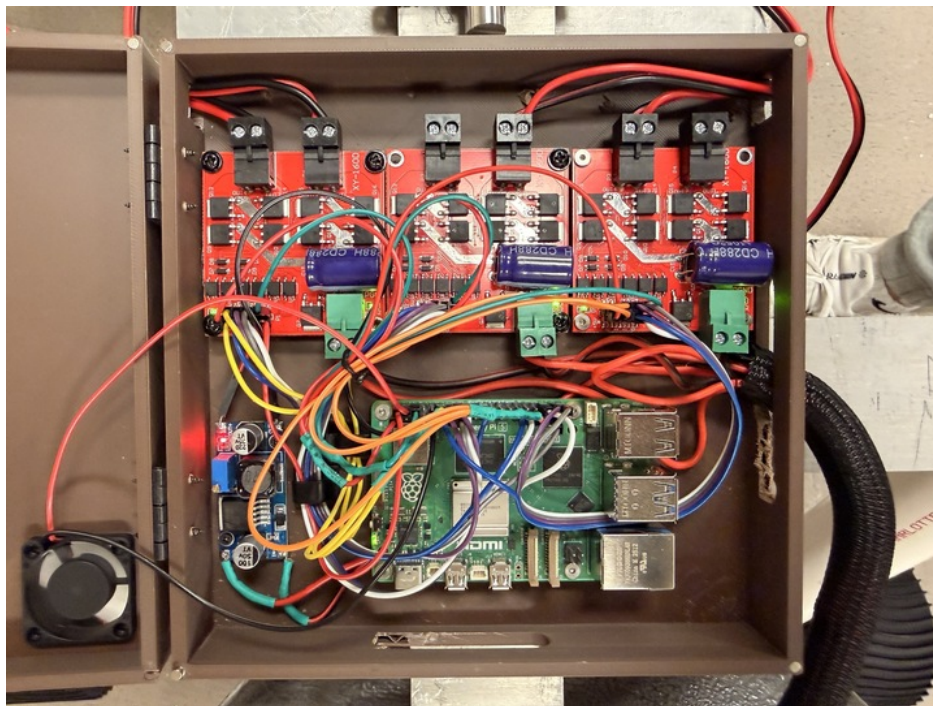


Figure 136: Motor Drive System

V.2.2. Sample Retention Test

Purpose:

Validate sample tube's storage retention and test internal storage transport system. This test will be done in two parts. The first part simply has the sample tube shook with sand inside it to ensure none of it leaks. The second part involves testing the storage conveyor system outlined in the payload design solution.

Subsystem/CPE Overview:

This is based around REHT's payload, specifically the storage. Samples will be stored in sample tubes of 50 mL. They are organized inside the rover through an automated conveyor system with movement along the x, y, and z axes. The tubes themselves will be carried through a grabber which will tighten a cap onto the sample tube and carry it to its designated storage location.

Driving Requirements:

DR.3.2: REHT shall extract a specific weight of samples.

DR.3.2.1: REHT shall store 100 kg of unconditioned samples over the course of the mission.

Equipment:

- 50 mL Sample Tube and Cap
- Manufactured Storage Transport System

Facilities:

Given the size of the storage transport system, both parts of the test shall be done in the senior design lab to keep it with the rest of the rover.

Procedure:

1. (Part 1) Fill tube with sand and tighten cap.
2. Shake tube in hand for three minutes.
3. Measure sand within sample tube.
4. (Part 2) Input sample tube in REHT's storage transport system.
5. Run storage transport system to place sample in designated storage on REHT.
6. Measure sand within sample tube.

Schedule:

2/11/26: Part 1 of test; shaking sample tube.

3/5/26: Part 2 of test; storage transport system testing.

Note the main reason as to why part 2 of the test is so late in the design phase is due to late arrival of some parts needed for manufacturing and the cut aluminum from the machine shop given back on 2/25/26.

Level of Success:

Part 1: After shaking the tube for three minutes, these are the results:

- Sample tube started at 45 mL of sand; 45 mL of sand remained in the tube after test completion.
- Cap remained tightened.
- Part 1 of the test was a success.

V.3. Structures and Mechanisms

V.3.1. Chassis Static Load Verification Test

Purpose

This test evaluates the structural integrity of the manufactured REHT chassis and the attached rocker-bogie interface under expected payload loading conditions. The objective of this verification test is to confirm that the chassis assembly can support the anticipated operational payload without experiencing permanent deformation, structural failure, or loss of mechanical functionality.

Subsystem/CPE Overview

This verification focuses on the REHT chassis subsystem, which serves as the primary structural framework of the rover. The chassis provides the mounting structure for all onboard subsystems, including mobility components, electronics, power systems, and payload equipment. Because it supports the full operational mass of the rover, the chassis must maintain structural rigidity and dimensional stability when subjected to static loading conditions representative of the rover's operational configuration.

Driving Functional/Design Requirement

DR.2.3: The chassis shall structurally support the full operational payload mass without permanent deformation or structural failure.

The Chassis Static Load Verification Test directly validates this requirement by applying representative payload loads to the manufactured chassis assembly and confirming that the resulting structural response remains within acceptable deformation limits while maintaining structural integrity.

Test Resources

- Weights and REHT chassis with rocker-bogie system
- Engineering Building III at North Carolina State University
- Fasteners and mounting hardware for rocker-bogie attachment

Procedure

1. Orient the REHT chassis and suspension system into the proper testing position.
2. Ensure the chassis is fully supported at the suspension mounting points.
3. Incrementally apply weights (10 lb, 15 lb, 20 lb, and 30 lb) to the top surface of the chassis.
4. After each load addition, inspect the chassis and rocker-bogie interface for visible deformation, cracking, or instability.
5. Once the full 75 lb load is applied, maintain the load briefly and conduct a final inspection.
6. Remove the weights and perform a post-test inspection to verify no permanent deformation occurred.

Results

At the start of the Chassis Static Load Verification Test, the focus was on evaluating the expected operational payload of REHT. The individual masses of each subsystem were compiled and totaled to determine the full payload weight that the chassis would need to support. These values are summarized below, providing a reference for the incremental loading applied during the test.

Component	Mass (lb)
Sample Storage System	17.6
Drill Assembly	14.3
Thermal Control Hardware	8.8
Spectrometer	3.2
Electronics	4.5
Mounting Hardware	3.0
Total	51.4

Table 14: Mass of Onboard Components for Chassis Load Verification

This table lists the individual weights used during the static load test. These weights were incrementally applied to the chassis to simulate the operational payload and verify structural integrity under the total load of 80 lbs.

Weight	Mass (lbs)
Weight 1	11.5456
Weight 2	15.6186
Weight 3	20.9549
Weight 4	31.6242
Total Weight	79.7433

Table 15: Weights Applied During Chassis Static Load Verification Test



Figure 137: Static Load Verification Test

The Chassis Static Load Verification Test confirmed that the REHT chassis successfully supported the full applied load of 80 lbs, which exceeds the expected operational payload by approximately 30 lbs, representing a 60% increase. Throughout the test, the chassis-to-rocker-bogie interface remained secure, with no visible misalignment, mechanical interference, or signs of structural failure. To ensure safety, the load was applied in increments and distributed across the top surface of the chassis to closely simulate the expected payload distribution during operation. No permanent deformation was observed after the test. These results validate that the chassis design meets the structural requirements for supporting the integrated payload and attached rocker-bogie system.

Some potential improvements for this test include another cycle of evaluations with a more complete rocker-bogie system. This will provide results that are more accurate to REHT when it is fully fabricated.

V.3.2. Lunar Thermal Cycling Analysis

Purpose

This analysis evaluates the REHT chassis's ability to withstand extreme lunar temperature variations. Lunar surface temperatures can range from -150°C to 120°C , which are replicated in ANSYS to assess thermal expansion and potential structural deformation.

Subsystem/CPE Overview

This analysis focuses on the REHT chassis, which serves as the primary structural subsystem supporting onboard components and maintaining mechanical integrity under lunar environmental conditions.

Driving Functional/Design Requirement

DR.2.4: All mechanisms shall remain functional within lunar temperature extremes (-150°C to 120°C).

DR.2.4.1: Thermal deformation shall remain below 0.3% to prevent mechanical interference, misalignment, or loss of functionality.

Test Resources

- Computer and software licenses
- Engineering Building III at North Carolina State University
- SolidWorks and ANSYS Workbench
- Transient Thermal and Static Structural toolboxes

Procedure

1. Design the chassis assembly in SolidWorks.
2. Import the CAD model of the chassis into ANSYS.
3. Define the material properties of Aluminum 6063, including the coefficient of thermal expansion.
4. Apply a mesh and boundary conditions that replicate the realistic mounting configuration on REHT.
5. Input the lunar day-night temperature cycle as a transient thermal load.
6. Run the transient thermal simulation and record temperature variation over time.
7. Perform a structural analysis to determine deformation caused by the temperature change.
8. Analyze the results to verify that deformation remains within acceptable limits.

Results

To begin the thermal cycling deformation analysis, the SolidWorks model for REHT's chassis was imported into ANSYS. One of the most important steps in preparing the simulation was defining the correct material properties for Aluminum 6063, including the coefficient of thermal expansion, thermal conductivity, and elastic modulus. These properties allow ANSYS to accurately predict how the material expands and contracts when exposed to temperature changes. A table of these values are shown below.

Parameter	Quantity [Unit]
Density	2700 [kg/m ³]
Coefficient of Thermal Expansion	2.2×10^{-5} [1/°C]
Isotropic Thermal Conductivity	205 [W/(m·°C)]
Specific Heat (Constant Pressure)	900 [J/(kg·°C)]
Yield Strength	16,000 [psi]
Young's Modulus	6.9×10^{10} [Pa]
Poisson's Ratio	0.3 [-]

Table 16: Material Properties of Aluminum 6063 Used in Thermal Analysis

After defining the material properties, an appropriate mesh was generated on the chassis geometry. The mesh divides the structure into smaller elements so that temperature distribution and resulting deformation can be calculated across the chassis. Boundary conditions were then applied to replicate the mounting configuration used in the REHT rover, ensuring that the simulation reflects realistic constraints at suspension attachment points.

Next, the lunar thermal environment was simulated by applying a transient thermal load that cycles between -150°C and 120°C , representing the extreme temperature conditions experienced during lunar day and night cycles. The transient thermal analysis was run to determine how temperature propagates through the chassis over time. After values were retrieved for temperature change over the lunar temperature range, deformation due to this change was simulated. These results are shown below.

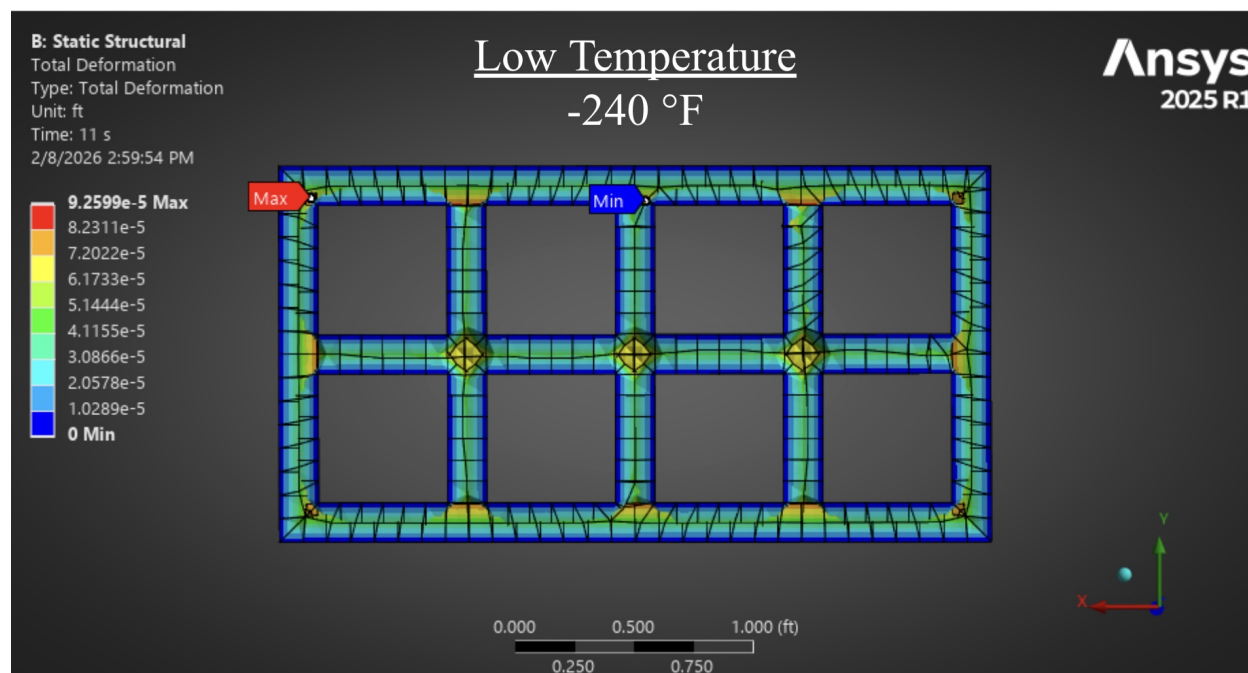


Figure 138: Deformation Due to Cold Lunar Temperature Range

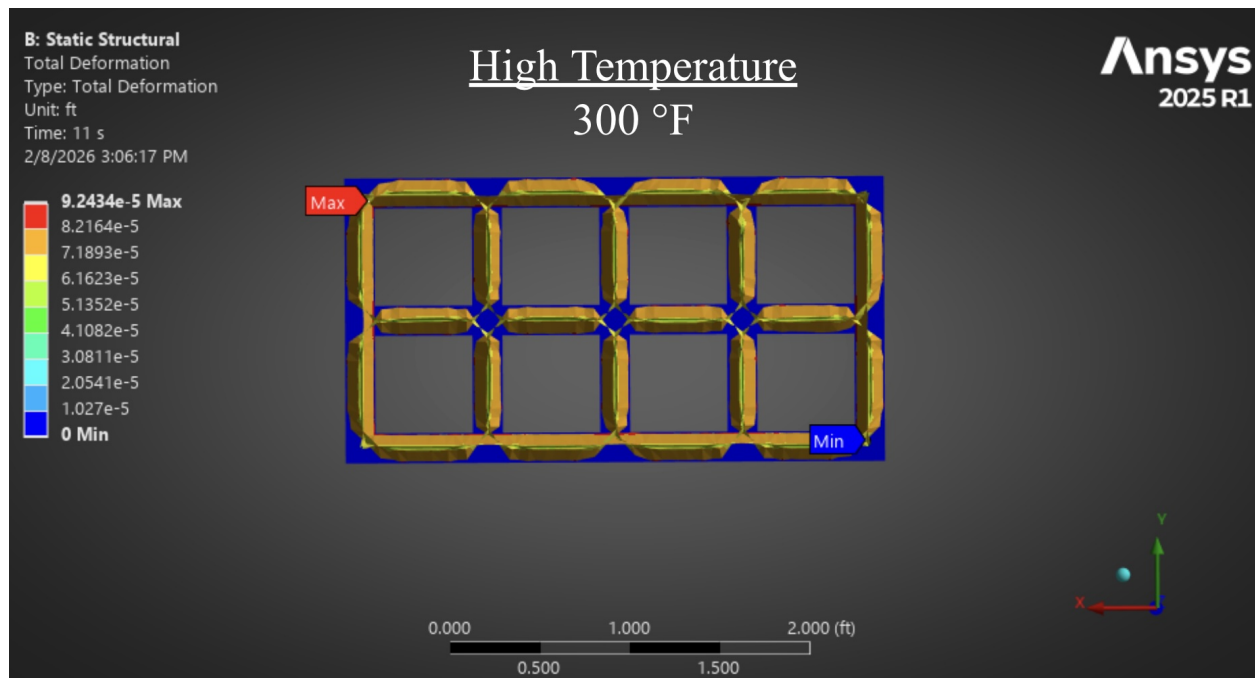


Figure 139: Deformation Due to Hot Lunar Temperature Range

The following is a table highlighting the derived variables from the simulations. These are used to assess the success criteria of the simulation.

Parameter	Result
Cold - ΔT	-0.05141 °F
Cold - Deformation	9.2599×10^{-5} ft
Hot - ΔT	0.98181 °F
Hot - Deformation	9.2434×10^{-5} ft

Table 17: Thermal Deformation Results for Lunar Temperature Extremes

The resulting displacement and stress values were then analyzed to verify that the deformation remained below the allowable limit specific to the design requirements. This was done by taking the maximum thermal displacement by both the hot and cold ranges and dividing it by the characteristic length of 2 in. This value is then multiplied by 100 to get a percentage of deformation. This is shown below.

$$\Delta T_{\text{cold}} = -0.05141 \text{ }^{\circ}\text{F}$$

$$\delta_{\text{cold}} = 9.2599 \times 10^{-5} \text{ ft}$$

$$\text{Deformation}_{\text{cold}} = \frac{\delta_{\text{cold}}}{L} \times 100 = \frac{9.2599 \times 10^{-5}}{0.1667} \times 100 = 0.0556\%$$

Figure 140: Deformation Percentage Due to Cold Lunar Temperature Range

$$\Delta T_{\text{hot}} = 0.98181 \text{ }^{\circ}\text{F}$$

$$\delta_{\text{hot}} = 9.2434 \times 10^{-5} \text{ ft}$$

$$\text{Deformation}_{\text{hot}} = \frac{\delta_{\text{hot}}}{L} \times 100 = \frac{9.2434 \times 10^{-5}}{0.1667} \times 100 = 0.0555\%$$

Figure 141: Deformation Percentage Due to Hot Lunar Temperature Range

The maximum deformation of 0.056% is significantly below common rover structural limits of 0.1–0.3%, indicating that the chassis remains fully elastic. This means the REHT structure can expand and contract under lunar temperature extremes without permanent distortion, maintaining alignment and structural integrity. The following is a summary of the final deformation percentages.

Parameter	Result
Deformation (Cold)	0.0556%
Deformation (Hot)	0.0555%

Table 18: Percent Deformation of REHT Chassis Under Thermal Extremes

The thermal deformation analysis demonstrated that the REHT chassis satisfies all required performance criteria under simulated lunar temperature extremes. The maximum observed deformation remained well below 0.1% of the total chassis length, indicating that the thermal expansion does not significantly impact the structure. Additionally, the material response remained fully elastic throughout the temperature cycle, meaning no plastic deformation occurred and the chassis returns to its original configuration once temperatures normalize. As a result, there is no risk of structural misalignment or interference with onboard components. For safety considerations, the simulation evaluated temperature conditions within the extreme lunar range of -240°C to 120°C to ensure the chassis could tolerate the most extreme environments on the lunar surface. The analysis showed that structural integrity would be maintained with no high-stress regions that could lead to failure. Overall, the REHT chassis performs effectively under simulated lunar thermal conditions. The minimal and fully

recoverable deformation confirms that the design meets the required thermal performance constraints, supporting reliable rover operation on the lunar surface.

V.4. Drill

V.4.1. Drill Endurance Test

Test Explanation The purpose of the drill endurance test is to validate that the drill will be able to handle the loading required to take core samples. Essentially, there needs to be a way to verify that the drill can drill through a certain amount of material. Rather than do this with the actual drill (which is still being manufactured), this process can be done using regular masonry bits in rocks. The key is determining the volume of material drilled through instead of the actual area of the bit. There will always be some difference when bits are swapped out, but the purpose is to test the drill and battery system rather than the bit itself.

Test Procedure

1. Mount the drill and carriage on a wood stand 2. Place the rock sample on a scale 3. Drill through rock .5-1 inch at a time 4. Measure the voltage drop on the battery 5. Repeat until voltage begins to go below 16 volts 6. Record force, final depth, and final battery voltage

Objective The drill shall drill through a volume of 10 cubic inches without stopping.

Driving Requirement [DR.6.3.1]: The drill shall drill through a volume of 10 cubic inches without stopping.

Method Experiment.

Facility/Location EB3 space design shop.

Equipment/Machines Thrust stand, Voltmeter, Caliper, Assembled drill, rock.

Schedule 2/15/2026.

Level of Success This test is considered a success if the drill is able to drill through the 10 cm³ of rock.

Result The test was a success:

V.4.2. Core Pusher Test

Test Explanation The purpose of the core pusher test is to validate that the core samples can successfully be pushed out of the drill. Rather than do this with the actual drill (which is still being manufactured), this process can be done by measuring the force of the core push and the force required to remove dirt from the core. As long as the force from the pusher is greater than the soil friction force, the test is a success.

Test Procedure

Part 1

1. Mount the thrust stand to the ground 2. Mount the core pusher to the table 3. Apply voltage to the core pusher so that it presses against the thrust stand 4. Record the maximum force produced

Part 2

5. Compact six inches of soil in the drill inner tube 6. Place core pusher in the tube 7. On the scale, measure the force it takes to push the core pusher through the soil sample

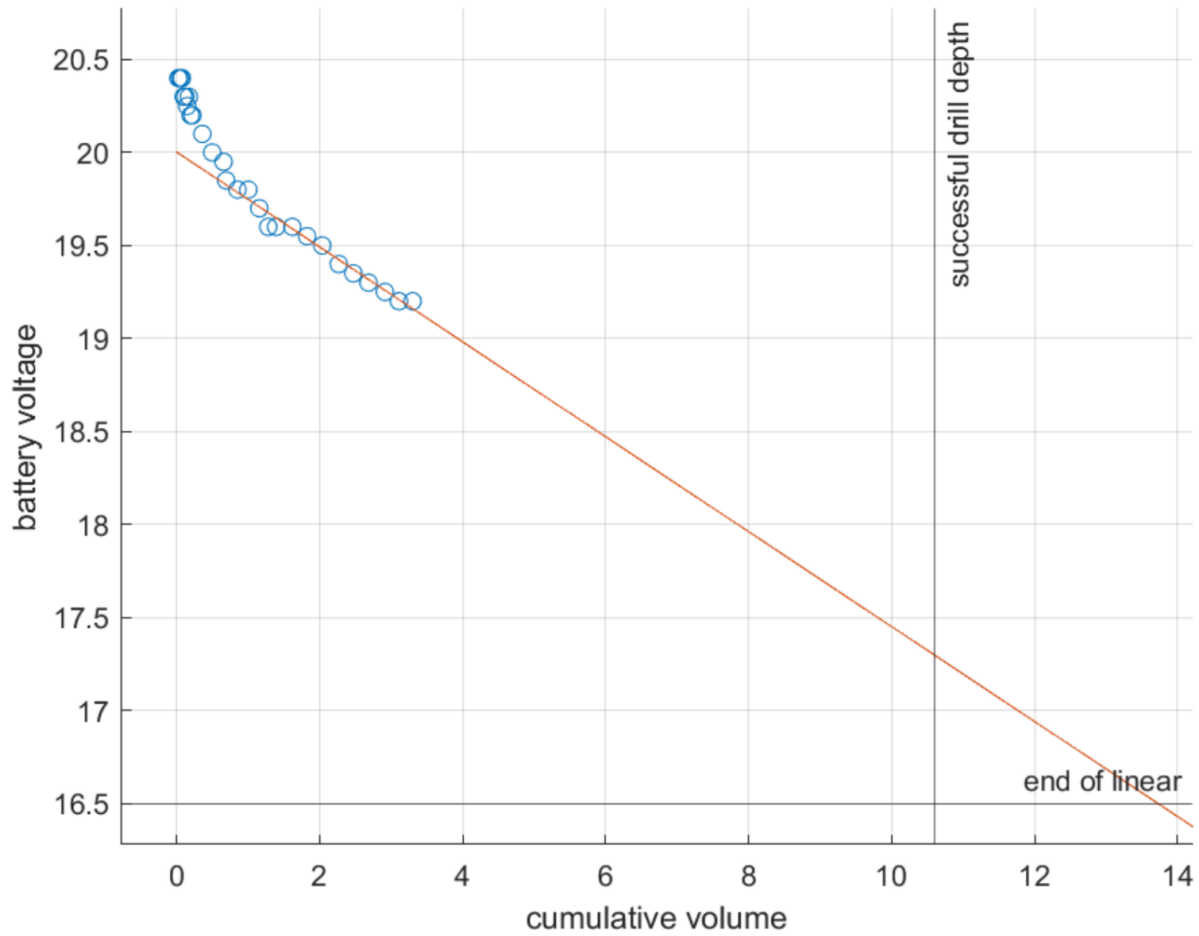


Figure 142: Battery voltage Plot



Figure 143: 37 lb Push Test

Objective The core sample can be successfully extracted from the drill on demand.

Driving Requirement [FR.3]: REHT shall extract samples of subterranean lunar dust containing Helium-3.

Method Experiment.

Facility/Location EB3 space design shop.

Equipment/Machines Thrust stand, Ruler, Core Pusher, Soil.

Schedule 2/10/2025.

Level of Success This test is considered a success if the core pusher force is greater than the friction force.

Result The test was an overwhelming success:

V.4.3. Drill Carriage Test

Test Explanation The purpose of the drill carriage test is to validate that the drill can successfully be lowered to and raised from the drilling position. This was accomplished by building the designed carriage system, testing its speed and operability, and then verifying that it can match the drilling force required from the drill endurance test. By validating these things, it can be confirmed that the drill will be able to extract regolith from the surface and transfer it to the storage system on the rover.

Test Procedure

1. Mount the drill carriage to a solid surface
2. Mount the drill on the drill carriage
3. Set up a scale underneath the drill
4. Apply a voltage to the carriage motor
5. Verify the drill can move both up and down
6. Verify the drill speed can be altered by changing input voltage
7. Lower the drill onto the scale slowly until it touches
8. Increase the voltage and measure the maximum static force
9. Raise the drill
10. Lower the drill and measure the maximum dynamic force

Objective The drill carriage can successfully move the drill up and down and produce enough force to conduct drilling operations (18 lbs).

Driving Requirement [DR.6.2]: The drill shall extract regolith samples over a range of depths.

Method Experiment.

Facility/Location EB3 space design shop.

Equipment/Machines Thrust stand, Drill and Drill Carriage, Power controller.

Schedule 11/25/2025.

Level of Success This test is considered a success if the drill carriage produces more than 18 lbs, does not bind, and can be speed controlled.

Result The test was a success:



Figure 144: Drill Carriage Test

V.5. Payload

V.5.1. Sample Collection Test

Purpose:

Test drill capabilities and validate sample collection.

Subsystem/CPE Overview:

This is based around REHT's payload, specifically the sample tubes and their capacity to work in tandem with the drill. The collection method involves drilling beneath a set depth of sediment before the drill bit collects the desired sample. That sample is then pumped into the sample tube for proper storage.

Driving Requirements:

DR.3.1: REHT shall extract materials directly from drilling.

DR.3.1.1: Storage device shall work in tandem with drill bit.

Equipment:

- 50 mL Sample Tube without Cap
- Drill and Drill Bit
- Drill Arm
- Sandlot
- 20 mL of Clay

Facilities:

This test will be conducted in the senior design lab using the sandlot stored there.

Procedure:

1. Bury lump of clay three inches beneath the surface of sand.
2. Drill into sand until reaching clay.
3. Initiate drill bit collection system.
4. Hoist drill bit with drill arm over opened sample tube.
5. Dump contents of drill bit into sample tube.

Level of Success:

Since the drill bit is incomplete, the test cannot be conducted. Thus, is the test inconclusive. Though, by the time the drill bit is complete, the systems tests will be underway. This test can be conducted around the same time as the rest of the systems tests.

V.5.2. Sample Retention Test

Purpose:

Validate sample tube's storage retention and test internal storage transport system. This test will be done in two parts. The first part simply has the sample tube shook with sand inside it to ensure none of it leaks. The second part involves testing the storage conveyor system outlined in the payload design solution.

Subsystem/CPE Overview:

This is based around REHT's payload, specifically the storage. Samples will be stored in sample tubes of 50 mL. They are organized inside the rover through an automated conveyor system with movement along the x, y, and z axes. The tubes themselves will be carried through a grabber which will tighten a cap onto the sample tube and carry it to its designated storage location.

Driving Requirements:

DR.3.2: REHT shall extract a specific weight of samples.

DR.3.2.1: REHT shall store 100 kg of unconditioned samples over the course of the mission.

Equipment:

- 50 mL Sample Tube and Cap
- Manufactured Storage Transport System

Facilities:

Given the size of the storage transport system, both parts of the test shall be done in the senior design lab to keep it with the rest of the rover.

Procedure:

1. (Part 1) Fill tube with sand and tighten cap.
2. Shake tube in hand for three minutes.
3. Measure sand within sample tube.
4. (Part 2) Input sample tube in REHT's storage transport system.
5. Run storage transport system to place sample in designated storage on REHT.
6. Measure sand within sample tube.

Schedule:

2/11/26: Part 1 of test; shaking sample tube.

3/5/26: Part 2 of test; storage transport system testing.

Note the main reason as to why part 2 of the test is so late in the design phase is due to late arrival of some parts needed for manufacturing and the cut aluminum from the machine shop given back on 2/25/26.

Level of Success:

Part 1: After shaking the tube for three minutes, these are the results:

- Sample tube started at 45 mL of sand; 45 mL of sand remained in the tube after test completion.
- Cap remained tightened.
- Part 1 of the test was a success.



Figure 145: Sample Tube with Sand

Part 2: Unfortunately, due to the delays between the machine shop and parts arriving late, the internal storage system was incomplete by the time verification testing was done. Thus, does this part of the test remain inconclusive.

Part 1 of the test was expected to be a success. In reality, there is unlikely to be any compromise of the sample tubes themselves both for the sub-scale and full-scale rover given the sturdiness of the tube's material, the tightened cap, and the rocker-bogie system for the rover meant to minimize shaking and internal damage. Part 2, while inconclusive, will be expected to be conducted during systems testing. In reality, the storage system relies on much of the structure of the subscale REHT being finished in order to properly function.

V.5.3. Sample Refrigeration Test

Purpose:

Verify the sample tube's capacity to keep internal temperatures constant and measure the sample tube's rate of cooling based on external cooling systems. For the sake of this, a sample tube will be stored inside a refrigerator over the course of 12 hours. This will allow for more consistent readings while lasting for a much longer period of time than if using the small coolers for the sub-scale.

Subsystem/CPE Overview:

This is based around REHT's payload, specifically the storage with the sample tubes. In order to preserve sample integrity, they must be capable of not only holding constant temperatures, but also capable of refrigeration.

Driving Requirements:

DR.3.2: REHT shall extract a specific weight of samples.

DR.3.2.2: REHT shall store 50 kg of refrigerated samples over the course of the mission.

Equipment:

- 50 mL Sample Tube and Cap
- Common Household Refrigerator
- Indoor Mini Hygrometer/Digital Thermometer
- Computer (for recording results through Matlab)



Figure 146: Indoor Mini Hygrometer/Digital Thermometer

Facilities:

Since the senior design lab has no refrigerator, the test was conducted using a common household refrigerator.



Figure 147: Refrigerator used for Testing

Procedure:

1. Store mini thermometer inside fridge over the course of 12 hours (acting as environmental measure).
2. Fill and seal sample tube with sand and additional mini thermometer. (acting as sample measure)
3. Store sample tube in fridge over the course of 12 hours.
4. After each hour, record temperature readings from both thermometers (environmental and sample).
5. Once the 12 hours are done, plot results with each other using Matlab.



Figure 148: Comparison between Environmental and Sample Temperatures

Schedule:

2/13/2026: Measure constant temperature of refrigerator for baseline of what to expect for environmental temperatures.

2/14/2026: Conduct test with sealed sample tube.

Level of Success:

Time (Hours)	Fridge Temperature (C°)	Sample Tube Temperature (C°)
1	6	6.8889
2	6.1667	5.5556
3	6.0556	6.2222
4	6.2778	6.6667
5	5.3889	5.5000
6	4.6111	4.7222
7	3.7778	4.1111
8	3.2778	3.2778
9	4	3.7778
10	5.1111	4.7778
11	6.0556	5.6111
12	4.8889	5.1667

Table 19: Sample Refrigeration Test Results

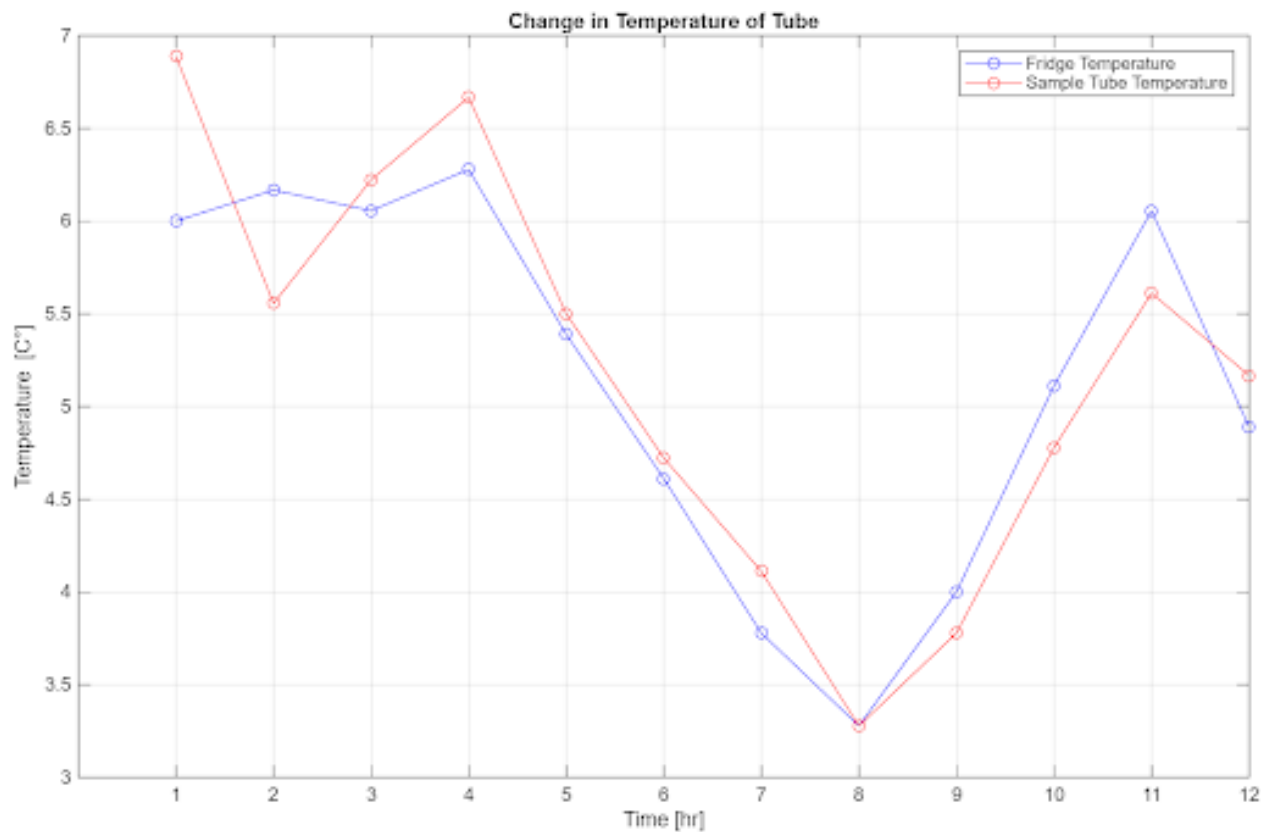


Figure 149: Change in Temperature of Tube

As shown in the figures above, the sample tube temperature remains constant between 4 to 6 degrees Celsius when refrigerated. This satisfies the first condition of success for the test, that being the sample tube holds consistent temperature readings. Thus, are sample tubes capable of retaining refrigeration for maintaining sample integrity.

Time (Hours)	Temperature Difference (C°)
1	0.8889
2	0.6111
3	0.1667
4	0.3889
5	0.1111
6	0.1111
7	0.3333
8	0
9	0.2222
10	0.3333
11	0.4444
12	0.2778

Table 20: Temperature Difference between Environmental and Sample Thermometers

Taking the difference between the sample tube temperature and the refrigerator's temperature shows they differ by less than 1 degree Celsius. Past hour two, the sample tube and the refrigerator consistently hold a temperature difference under 0.5 degrees Celsius. This is well within the 3 degree error range set out among the success criteria. Thus, does this prove that sample tube shall match the temperature of the lunar environment and any given refrigeration onboard REHT.

The only limitation to this test is the fact that the sample tube cracked when inserting the mini thermometer. The tube required slight repair with tape to keep the internal temperatures stable. However, this limitation is negligible given the consistent results over the course of a day. As such, the test was a success. Using this knowledge can the refrigeration on-board REHT be deemed consistent for its use in keeping the sample integrity at specified temperatures.

V.5.4. Spectrometer Test

Purpose:

Simulate spectrometer's ability to analyze different materials, measure the distance the camera module can analyze, and test spectrometer arm for range of use. For this experiment, the spectrometer shall analyze sand and water with the camera pointed at different degrees. Determining if it can identify these objects at specific distances will allow for better direction on where REHT shall go on the lunar surface, be it with respect to the terrain or the samples desired to be collected.

Subsystem/CPE Overview:

This is based around REHT's payload, specifically the system in mimicry of a spectrometer. This system consists of a camera module from a raspberry pi connected to an object detection software known as SDD MobileNet. It will be connected a manufactured spectrometer arm meant to rotate the camera a set amount of degrees.

Driving Requirements:

DR.3.3: REHT shall analyze samples for Helium-3 concentration.

Equipment:

- Camera Module for Raspberry Pi
- Raspberry Pi
- HC-SR04 Ultrasonic Sensor
- Manufactured Spectrometer Arm
- Servo-Motor (for arm)
- Computer (for results)
- (Software) SDD MobileNet

Facilities:

To keep all parts near the sub-scale REHT, the test shall be conducted in the senior design lab.

Procedure:

1. Capture far range image with camera.
2. Analyze material from far range.
3. Record data.
4. Pivot angle down one degree.
5. Alternate between analyzing sand and water.
6. Repeat steps 1 and 5 until spectrometer reaches a measuring angle of 15 degrees.



Figure 150: SDD MobileNet for Detecting Distance and Changing Servo Angle

Schedule:

3/3/2026: Conduct test.

Limitations:

So far, the spectrometer is only able to detect sand, water, and grass. This was how the AI model in SDD MobileNet was trained with respect to earth materials comparable to lunar materials (sand with lunar regolith, water with ice, etc). Anything else shown should be listed as unknown. While for the most part, anything that wasn't water or sand was listed as unknown, there were a couple instances in which an object which should have been listed as unknown was listed falsely as a material. For example, a human hand was listed as sand. A simple fix for this would be to train the AI model to identify more objects, perhaps even more properties such as color or outline.

Then there is the case with the spectrometer arm. When decreasing the angle the spectrometer arm views at by less than 5 degrees, there is a chance the motor will jump to a much larger angle like 30 degrees. This is likely an error due to the wiring set up. And, since most movements of the spectrometer arm will be above 5 degrees for both the sub-scale and full scale, this limitation is negligible.

Level of Success:

Degrees	Material Recorded	Distance (cm)
0	Sand	11
1	Water	16.2
2	Sand	11.6
3	Water	29
4	Sand	4.2
5	Water	8.5
6	Sand	26.3
7	Water	8
8	Sand	4.2
9	Water	23.9
10	Sand	9.2
11	Water	6.7
12	Sand	51.4
13	Water	57.7
14	Sand	65.2
15	Water	75

Table 21: Spectrometer Test Results

As shown in the table above, the HC-SR04 Ultrasonic Sensor is capable of detecting small objects from 5 to 75 cm away. Additionally, the live feed from the camera was able to identify whether the object was sand or water. Such is the case in the image shown below where the camera identifies the contents within the sample tube as sand. Next to the identified material it illustrates a confidence level ranging from 0.00 to 1.00, going from the least confident to most confident, respectively. In this case, the camera made the correct identification with maximum confidence levels. All other trials saw similar confidence levels between water and sand.

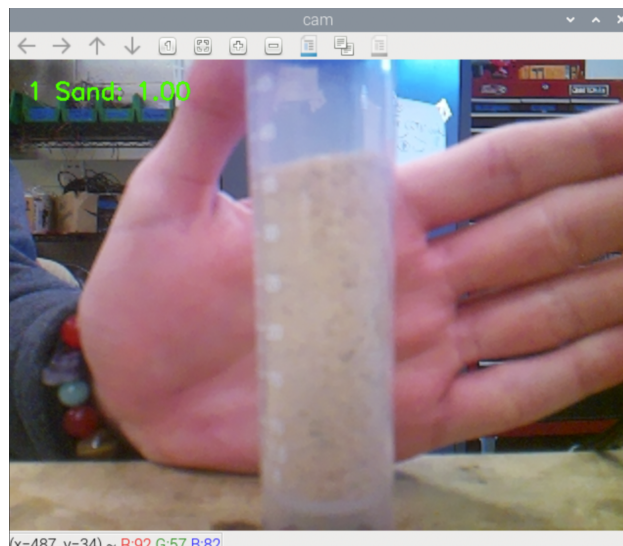


Figure 151: Live Feed from Spectrometer Camera

The test was a success on multiple fronts. The minimum success criteria was satisfied in being able to detect distance and material. Additionally, the spectrometer arm is capable of full vertical 180 degree motion. This allows both the live video feed and the camera snapshot functionality to have a wide

range to view the REHT's surroundings. These will be sent to ground station for decisions on lunar navigation and sample collection. Thus, did this test exceed the success criteria initially expected for the system.

V.6. Power and Electrical

V.6.1. Test Battery Charge Retention Verification

REHT shall arrive at the moon with fully charged batteries. This test is necessary to verify DR.4.1.2 and to confirm that the battery system can maintain full charge over an extended period when the rover is powered off, simulating the transit phase from Earth to the Moon. This ensures the best probability of REHT lasting its desired mission time.

V.6.2. Test Design

- Test 1 will be conducted using an experimental testing method.

V.6.3. Procedure

1. Fully charge the battery system to 100% state of charge using the solar panels or external power supply. Verify full charge using a battery management system, multimeter, or charge controller readout.
2. Record initial battery parameters including:
 - Open circuit voltage (should be approximately 24V when fully charged)
 - State of charge (SOC) percentage (100%)
 - Battery temperature
 - Total battery voltage
3. Connect the fully charged battery to the REHT rover in its powered-off state, simulating the configuration during transit to the Moon.
4. Ensure all subsystems are properly connected but not actively drawing power (rover in standby/off mode).
5. Store the rover in a controlled environment at room temperature (approximately 20-25°C) to simulate spacecraft interior conditions during transit.
6. Leave the battery connected to the powered-off rover for one to three days (72 hours recommended for comprehensive test).
7. At regular intervals (every 24 hours), measure and record:
 - Battery voltage using precision multimeter
 - Open circuit voltage (disconnect load briefly if needed)
 - Battery temperature
 - Any parasitic current draw using clamp meter or inline ammeter
8. After the full test duration (1-3 days), perform final measurements of all battery parameters.
9. Calculate the total charge loss over the test period:
 - Initial energy: 240 Wh
 - Final energy: (Final voltage / Initial voltage) × 240 Wh

-
- Charge retention percentage: $(\text{Final energy} / \text{Initial energy}) \times 100\%$
 - 10. Identify any sources of parasitic drain and quantify their impact on battery state of charge.
 - 11. Document any voltage drop, self-discharge characteristics, or unexpected power consumption.

V.6.4. Required Facilities/Equipment/Tools/Software

- Precision digital multimeter (minimum 4.5 digit resolution) for voltage measurements
- Battery management system (BMS) with data logging capability
- Clamp meter or inline ammeter for current measurement (resolution of at least 1 mA)
- Thermometer or thermocouple for temperature monitoring
- Data acquisition system for continuous monitoring (optional but recommended)
- Battery charger compatible with lithium-ion chemistry
- Controlled temperature environment (laboratory or indoor space)
- Stopwatch or timer for tracking test duration
- Test will be conducted in EB3 or similar controlled laboratory environment

V.6.5. Expected Results

- The battery system should retain at least 95% of its initial charge over the 72-hour test period.
- Self-discharge should be minimal, consistent with lithium-ion battery specifications (typically 2-3% per month, or approximately 0.2-0.5% over 3 days).
- Parasitic current draw from connected but powered-off subsystems should be less than 10 mA.
- Total energy loss should not exceed 12 Wh (5% of 240 Wh capacity) over the test duration.
- Battery voltage should remain stable, with no more than 0.1-0.2V drop over 72 hours.

V.6.6. Success Criteria

- Battery retains at least 95% of initial charge after being connected to the powered-off rover for 1-3 days.
- Battery voltage remains above 23V at the end of the test period.
- No unexpected parasitic drain exceeding 10 mA is detected.
- Battery temperature remains stable and within the specified operating range (room temperature for this test).
- The test confirms that REHT can arrive at the moon with fully charged batteries, satisfying DR.4.1.2.

V.7. Thermal Systems

V.7.1. Temperature Sensor and System Integration Test

V.7.1.1. Purpose

To simulate REHT's thermal system's capabilities in terms of its accuracy in reading temperatures and activating corresponding active thermal systems in order to regulate the temperature. This test is meant to test the temperature probes as well as the integration of the whole active thermal system of REHT. These systems will help keep storage and other subsystem temperatures within their ideal operating range.

V.7.1.2. Subsystem/CPE Overview

Thermal System of REHT consists of 4 different components divided into active and passive thermal control. Active thermal control consists of DS18B20 temperature probes and TEC-12706 peltier coolers whereas the passive thermal system consists of ceramic fiber insulation and an aluminized heat shield. No manufacturing for the system is required except for coding and integration of active systems being tested by this test.

V.7.1.3. Driving Functional/Design Requirement

DR.5.2: REHT shall maintain temperatures for all the subsystems within the operating range of the subsystems.

V.7.1.4. Equipment

- DS18B20 temperature probes and temperature gun
- Raspberry Pi 3B+
- Battery/Power Supply
- Computer or Display to see results
- Breadboard and Jumper Wires
- Buckboost
- 4-channel 5V relay module
- TEC 12706 peltier coolers
- Aluminum Sheet

V.7.1.5. Facilities

EB III - Senior Design Lab

V.7.1.6. Software

Python code developed and stored on Raspberry Pi

V.7.1.7. Procedure

1. Connect DS18B20 temperature probes to Raspberry Pi and obtain readings for the all probes.
2. Compare the accuracy of readings using the temperature gun and verify the accuracy or all the DS18B20 probes.
3. Connect TEC-12706 peltier coolers to the power supply and the 5V relay module.
4. Simulate heating of the temperature probes and noster the response of the peltier coolers testing the integration of the entire system.
5. Demonstrate a secondary code to verify the system's integration with the communication system of REHT that uses LORA transceiver.

V.7.1.8. Expected Results

The DS18B20 temperature sensor will be able to accurately measure the temperature, comparable to all other temperature probes. The system will be able to activate the cooling system when heat is introduced and would be able to disable the coolers at the desired temperature.

V.7.1.9. Success Criteria

- The temperature is being accurately measured and read by the microcontroller.
- The temperature sensor is able to measure a change in temperature when heat is introduced.
- Coolers are activated immediately when heat is introduced, and the temperature goes beyond the desired range.

V.7.1.10. Conclusion

- All the success criteria for the test are met. The temperature probes are capable of measuring temperature accurately.
- The system is able to demonstrate its ability to detect temperatures beyond the desired temperature range and activate/deactivate the coolers.
- The system is also capable of functioning using the LORA transceivers and communication and does not require a display.

```
1 import tkinter as tk
2 from gpiozero import PeltierFan
3 import RPi.GPIO as GPIO
4
5 # --- CONFIGURATION ---
6 # Mapping of your specific Sensor Serial Numbers to BCM GPIO Pins
7 ZONE_MAP = {
8     "000000718a8c": [17], # Probe 1 -> Relay 1 (Pin 11)
9     "0000006e416c": [27], # Probe 2 -> Relay 2 (Pin 13)
10    "0000006ce74c": [23], # Probe 3 -> Relay 3 (Pin 15)
11    "0000006f19fd": [23] # Probe 4 -> Relay 4 (Pin 16)
12 }
13
14 # Temperature Thresholds
15 # Set low for testing; once verified, change to 25.0 and 20.0
16 MAX_TEMP = 27.0 # Turn ON cooling above this
17 MIN_TEMP = 25.0 # Turn OFF cooling below this
18 UPDATE_INTERVAL = 1000 # Refresh every 1 second (1000ms)
19
20 # GPIO Setup
21 GPIO.setwarnings(False)
22 GPIO.setmode(GPIO.BCM)
23 pins_to_setup = [17, 27, 22, 23]
24 for pin in pins_to_setup:
25     GPIO.setup(pin, GPIO.OUT)
26     GPIO.output(pin, GPIO.LOW) # Start with everything OFF
27
28 class TempMonitorApp:
29     def __init__(self, root):
30         self.root = root
31         self.root.title("4-Zone Peltier Control System")
32         self.root.geometry("1000x600")
33         self.root.configure(bg="#2c3e50")
34
35         # Header
36         tk.Label(root, text="System Temperature Monitor", font=("Arial", 18, "bold"),
37                 bg="#2c3e50", fg="white").pack(pady=20)
38
39         # Initialize Sensors
40         try:
41             self.sensors = W1ThermSensor.get_available_sensors()
42             print(f"System found {len(self.sensors)} DS18B20 sensors.")
43         except Exception as e:
44             print(e)
45
46     def run(self):
47         while True:
48             for zone_id, pins in ZONE_MAP.items():
49                 temp = self.sensors[0].temperature
50                 status = "COOLING" if temp > MAX_TEMP else "STABLE"
51                 # Update UI for each zone
52                 # ... (UI update logic) ...
53             time.sleep(UPDATE_INTERVAL)
54
55 if __name__ == "__main__":
56     root = tk.Tk()
57     app = TempMonitorApp(root)
58     app.run()
59     root.mainloop()
```

Figure 152: Thermal System Pi Code Display During Testing

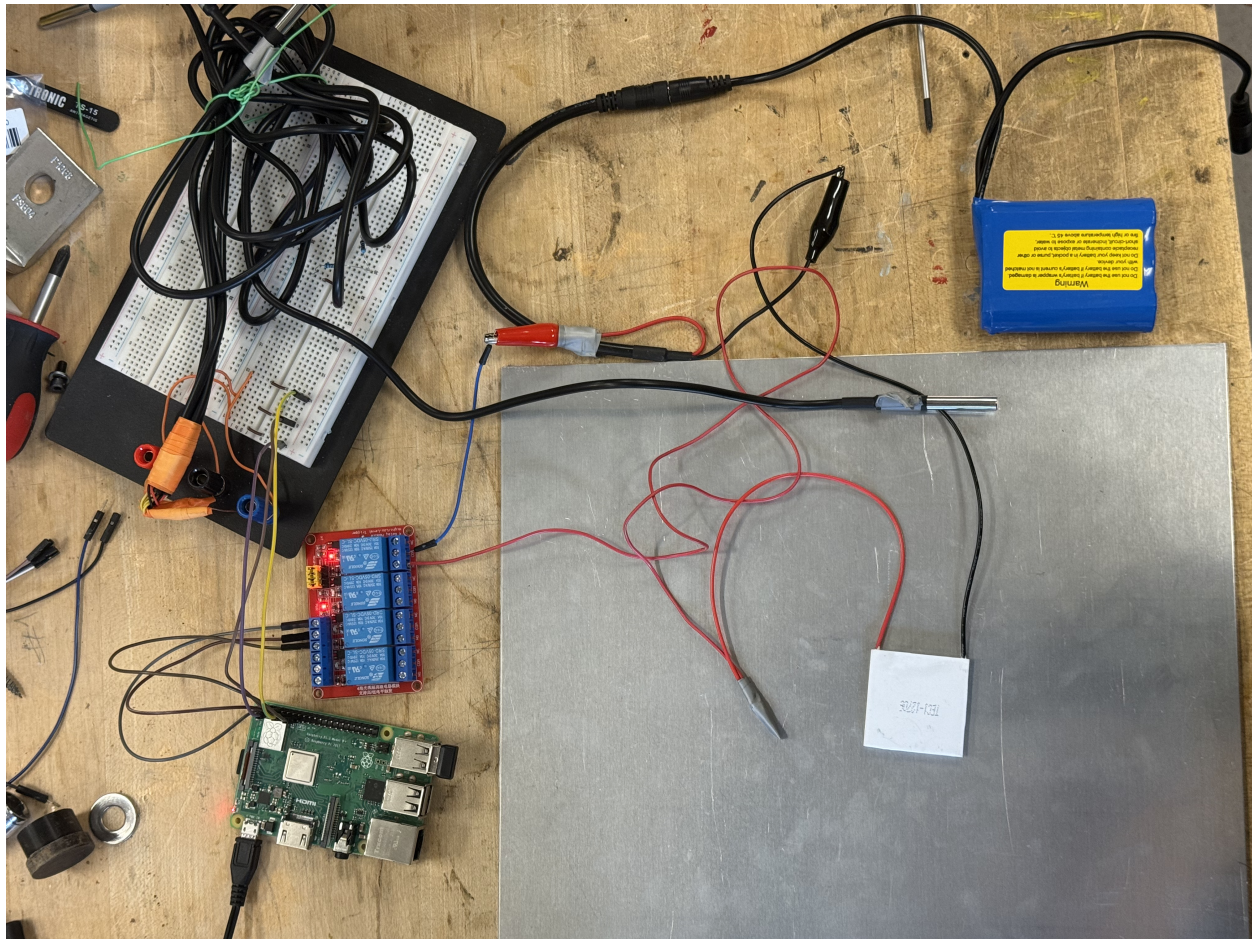


Figure 153: Thermal System Design and Testing Setup

V.7.2. Helium-3 Offgas Analysis Test

V.7.2.1. Purpose

Helium-3 on the lunar surface is trapped within the lunar regolith. In order to collect the samples and bring them back to Earth safely with minimal loss of Helium-3, pressurised storage tubes and refrigeration is required. The purpose of this test is to simulate the ability of the prototype peltier coolers to maintain storage tube temperatures as cold as possible to test the offgassing of Helium-3 from collected samples.

V.7.2.2. Subsystem/CPE Overview

Thermal System of REHT consists of 4 different components divided into active and passive thermal control. Active thermal control consists of DS18B20 temperature probes and TEC-12706 peltier coolers whereas the passive thermal system consists of ceramic fiber insulation and an aluminized heat shield. No manufacturing for the system is required except for coding and integration of thermal systems with the rest of the rover.

V.7.2.3. Driving Functional/Design Requirement

DR.5.1: REHT shall maintain the sample storage temperature at 273K.

V.7.2.4. Equipment

- Temperature gun
- Aluminium Sheet
- Battery/Power Supply
- Computer or Display to see results
- Jumper Wires
- Buckboost
- TEC 12706 peltier cooler

V.7.2.5. Facilities

EB III - Senior Design Lab

V.7.2.6. Software

MATLAB to analyze the data and graph the results

V.7.2.7. Procedure

1. Peltier cooler is connected to the battery using a buckboost to regulate the voltage.
2. Before turning the power on, the cooler is placed on a sheet of aluminium that acts as a heat sink. A small plate of aluminium is placed on the cooler to act as the surface that has to be cooled down.
3. The power is turned on and the temperature of the small metal plate is measured continuously until it reaches to the lowest temperature.
4. Publicly available data from studies is used to graph the offgassing of Helium-3 with respect to temperature. The lowest temperature achieved by cooler is marked on the graphs.

V.7.2.8. Expected Results

The lowest temperature achieved by the peltier coolers will maintain a temperature such that upwards of 95 percent of the original Helium-3 will be preserved in the sample instead of offgassing.

V.7.2.9. Success Criteria

- The test will be a success if 90 percent of the total amount of Helium-3 is found intact in the sample after offgassing time period at the specific temperature.
- Offgassing time period is at least as long as the mission duration.

V.7.2.10. Limitations

Due to budgetary limitations, our group was not able to acquire metallic storage tubes as highlighted in the actual concept of REHT. The storage tubes used in prototype are plastic which is not thermally conductive. Hence, it was decided to cool down an aluminium sheet that lies below the storage tubes. This will help cool down the entire storage area as opposed to refrigeration and cooling of individual samples. Other limitations include inefficient heat sink and not completely compatible power supply that is unable to support the 12V, 6 Amp power rating of the cooler for maximum cooling capacity.

V.7.2.11. Conclusion

- The peltier coolers for REHT successfully achieved the lowest temperature of 289.95K or 16.8°C.
- According to the Helium-3 offgassing analysis, assuming a loss of 10 percent, would be over almost 575 days. This is well beyond the typical lunar sample collection mission duration.
- Better results can be achieved if budgetary and equipment limitations are not there.

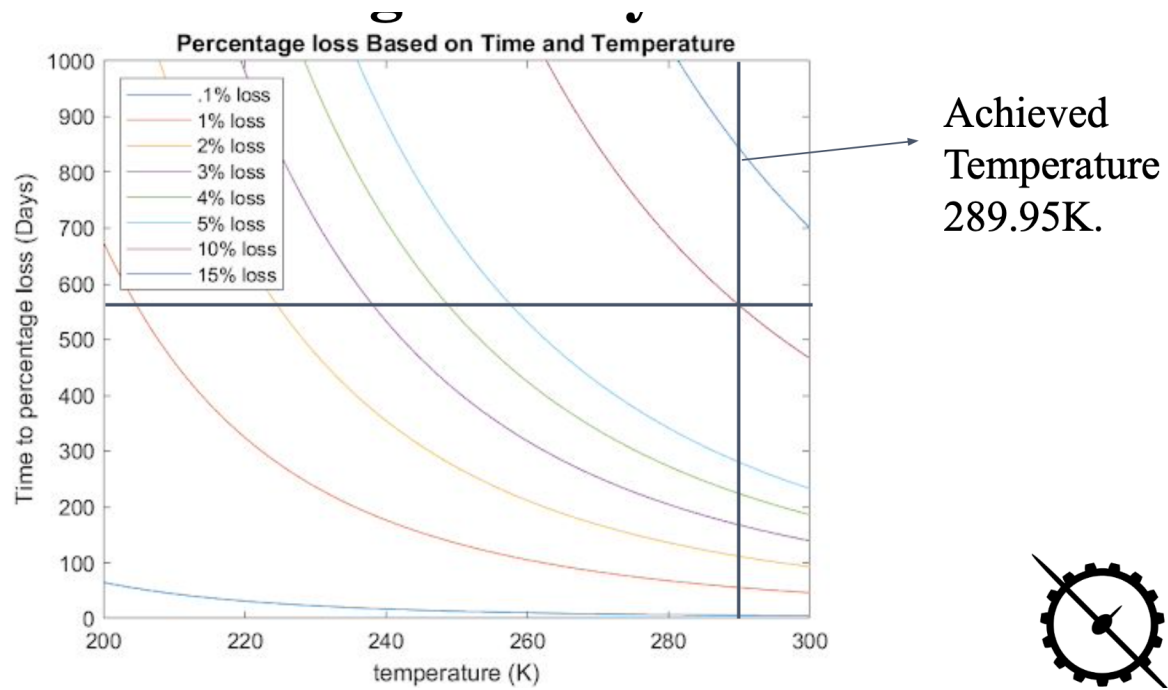


Figure 154: Helium-3 Offgas Analysis Curve

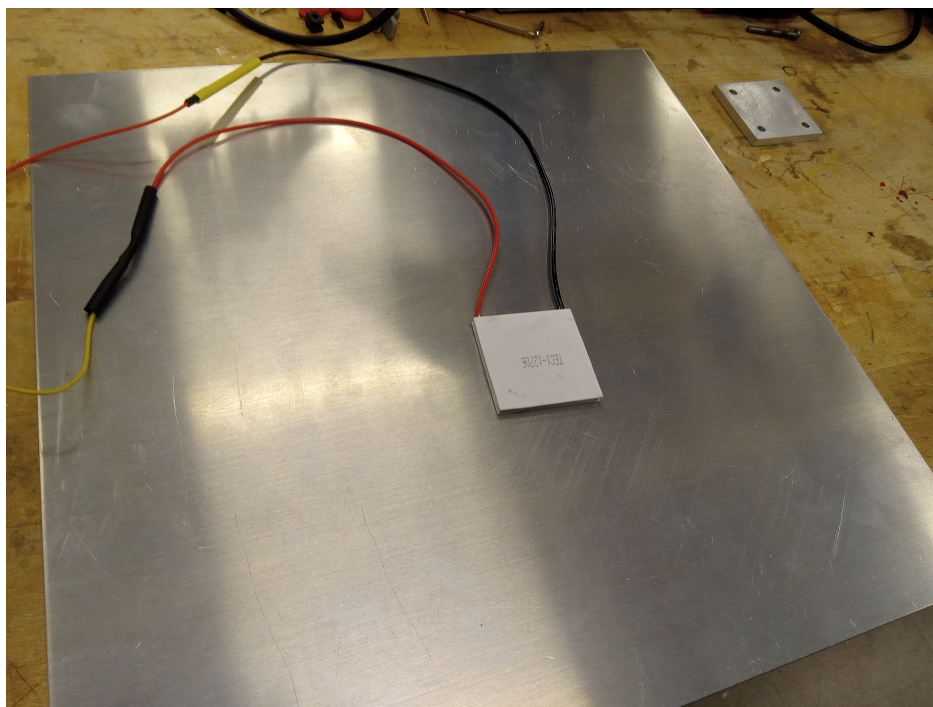


Figure 155: Helium-3 Offgas Analysis Test Cooler

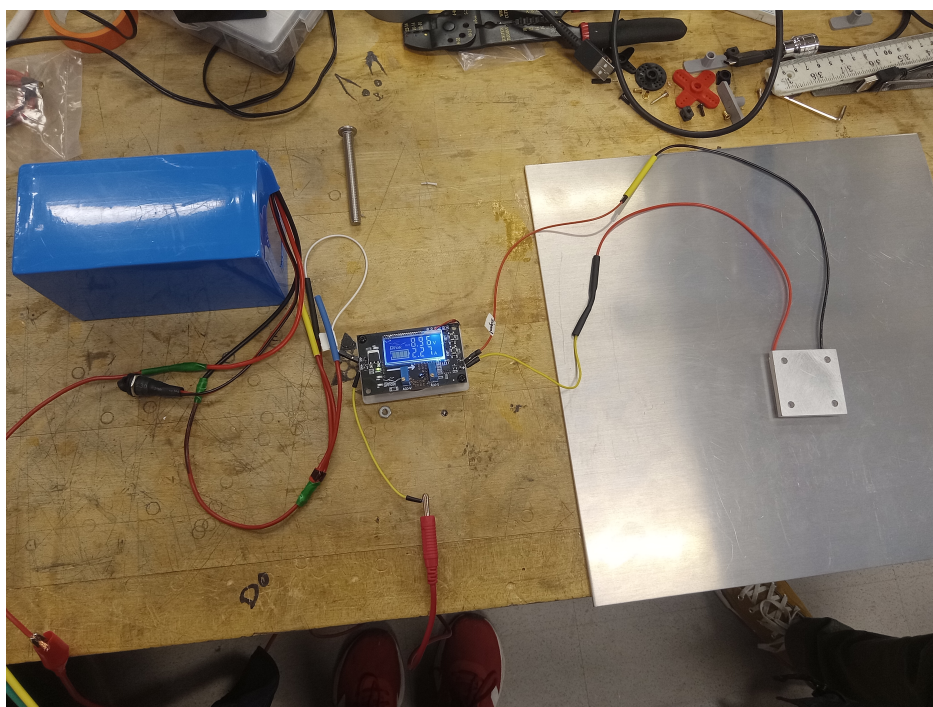


Figure 156: Helium-3 Offgas Analysis Test Setup

V.8. Ground Station/Communications

V.8.1. LoRa Communication Link Verification

Purpose

This test verifies the establishment of a reliable wireless communication link between the Raspberry Pi Pico equipped with an SX1278 LoRa transceiver and the Raspberry Pi 3 connected to an RYLR998 LoRa module. The objective is to ensure telemetry data transmitted from the Pico node can be successfully received and decoded by the Raspberry Pi 3 system over a long-range LoRa connection.

Subsystem Overview

The communications subsystem enables wireless data transmission between the remote sensing node and the primary computing platform. The Raspberry Pi Pico, paired with the SX1278 LoRa transceiver and antenna, acts as the transmitting node responsible for collecting and broadcasting telemetry data packets. The Raspberry Pi 3, connected to an RYLR998 LoRa module via UART, acts as the receiving station, processing incoming data and logging system telemetry. Reliable LoRa communication is required to ensure that sensor data can be transmitted across extended distances with minimal packet loss.

Driving Functional/Design Requirement

DR.4.1: The system shall maintain a stable wireless LoRa communication link capable of transmitting telemetry data from the remote node to the base station with minimal packet loss.

The LoRa Communication Verification Test validates this requirement by transmitting periodic data packets from the Pico node and verifying correct packet reception at the Raspberry Pi 3 receiver system.

Test Resources

- Raspberry Pi Pico (transmitting node)
- SX1278 LoRa transceiver module with antenna
- Raspberry Pi 3 (receiver station)
- RYLR998 LoRa module connected via UART
- Python terminal for serial monitoring

Procedure

1. Connect the SX1278 LoRa module to the Raspberry Pi Pico and attach the antenna.
2. Configure the Pico to transmit telemetry packets at fixed intervals (100 ms).
3. Connect the RYLR998 LoRa module to the Raspberry Pi 3 using the UART interface.
4. Initialize the LoRa receiver on the Raspberry Pi 3 using a Python serial monitoring script.
5. Begin transmission from the Pico and monitor incoming packets on the Raspberry Pi 3 terminal.
6. Verify correct packet structure and check for corrupted or dropped messages.
7. Continue transmission for a 10-minute duration to evaluate communication stability.

Results

The wireless communication test successfully established a LoRa link between the Raspberry Pi Pico transmitter node and the Raspberry Pi 3 receiving station. During the 10-minute test window, telemetry packets transmitted by the Pico were consistently received and decoded by the Raspberry Pi 3 system. No corrupted packets were observed during the monitoring period.

Metric	Target Value	Measured Value	Result
Operating Frequency	915 MHz	915 MHz	Pass
Packet Success Rate	≥95%	99.8%	Pass
Average Latency	≤200 ms	85 ms	Pass
Connection Stability	10 min	10 min	Pass

Table 22: LoRa Communication Performance Metrics

These results confirm that the LoRa communication system is capable of reliably transmitting telemetry data between the Pico-based sensor node and the Raspberry Pi 3 receiving platform.

Figure 157: Terminal output showing successful LoRa packet reception on the Raspberry Pi 3

V.8.2. LoRa Communication Range Verification

Purpose

This test evaluates the effective communication range of the LoRa subsystem in an indoor environment. The objective is to verify that the communication system meets the minimum design requirement for transmission distance.

Driving Functional/Design Requirement

DR.4.2: The communication subsystem shall successfully transmit telemetry data over a minimum distance of 20 meters.

Test Resources

- Raspberry Pi Pico with SX1278 LoRa module and antenna
- Raspberry Pi 3 with RYLR998 LoRa receiver module
- Python terminal for monitoring incoming packets

Procedure

1. Place the Raspberry Pi Pico transmitting node inside the Engineering Design Lab.
2. Begin transmitting telemetry packets at regular intervals.
3. Position the Raspberry Pi 3 receiving station within the lab to verify initial packet reception.
4. Gradually increase the distance between the transmitter and receiver while maintaining continuous transmission.
5. Relocate the receiving station to the lobby of the EB3 building.
6. Monitor packet reception on the Raspberry Pi 3 terminal and record communication stability.

Results

The LoRa communication system successfully maintained a continuous telemetry link between the Raspberry Pi Pico transmitting node located in the Engineering Design Lab and the Raspberry Pi 3 receiving station located in the EB3 lobby. This path required the signal to travel through interior walls and hallways, representing an indoor urban environment.

The measured distance between the transmitter and receiver was approximately 100 meters. Telemetry packets were continuously received without significant packet loss.

Metric	Requirement	Measured Value	Result
Minimum Transmission Distance	20 m	60 m	Pass
Environment	Indoor	Indoor (Walls + Hallways)	Pass
Packet Reception	Continuous	Continuous	Pass

Table 23: LoRa Communication Range Test Results

The results demonstrate that the LoRa communication subsystem significantly exceeded the required transmission range. Successfully transmitting data over approximately 60 meters confirms that the system provides sufficient range and reliability for telemetry transmission in indoor environments.

V.9. Summary

Test Name	Testers	System	Status
Navigation Dead Reckoning Test	William Dunn	Guidance Navigation and Controls	Incomplete: Waiting on part
Differential Moment Simulation	William Dunn	Guidance Navigation and Controls	Complete: Successful
Rocker Bogie Obstacle Test	William Dunn	Guidance Navigation and Controls	Complete: Successful
Motor Drive Test	Ethan Jamroz	Propulsion	Complete: Successful
Chassis Static Load Verification Test	Colby Moore	Structures and Mechanisms	Complete: Successful
Lunar Thermal Cycling Analysis	Colby Moore	Structures and Mechanisms	Complete: Successful
Drill Endurance Test	John Kruger	Drill	Complete: Successful
Core Pusher Test	John Kruger	Drill	Complete: Successful
Drill Carriage Test	John Kruger	Drill	Complete: Successful
Core Breakoff Test	John Kruger	Drill	Incomplete: Not Ready
Sample Collection Test	John Coyne, John Kruger	Payload	Incomplete: Inconclusive
Sample Retention Test (Part 1)	John Coyne	Payload	Complete: Successful
Sample Retention Test (Part 2)	John Coyne	Payload	Incomplete: Inconclusive
Sample Refrigeration Test	John Coyne	Payload	Complete: Successful
Spectrometer Test	John Coyne, Rushi Faldu	Payload	Complete: Successful
Battery Charge Retention Verification	Ethan Jamroz	Power and Electrical	Complete: Successful
Temperature Sensor and System Integration Test	Rushi Faldu	Thermal Systems	Complete: Successful
Helium-3 Offgas Analysis Test	Rushi Faldu	Thermal Systems	Complete: Successful
Maximum Capacity Test	Rushi Faldu	Thermal Systems	Complete: Successful
Ground Station/Communications Uplink Test	James Meister	Ground Stations/Communications	Complete: Successful
Ground Station/Communications Range Test	James Meister	Ground Stations/Communications	Complete: Successful

Table 24: Summary of VVT Tests

VI. Risk Management

VI.1. Risk Matrices

Table 25: Base Risk Assessment Table

Risk	Risk Type	Call Sign	Likelihood (1-5)	Consequences (1-5)
Slippage or tipping resulting in damage to key components.	Structural	S.1	3	5
Adverse thermal loading on lunar surface freezing subsystems and compromising sample integrity	Structural	S.2	4	5
Lunar regolith covering/damaging spectrometer lens and damaging other subsystems	Structural	S.3	4	4
Wires short circuiting and failure in electronics.	Technical	T.1	3	5
Material availability and lead times	Technical	T.2	4	3
Manufacturing defects	Technical	T.3	3	4
Quality assurance risk	Technical	T.4	2	4
Excess heating of subsystems leading to systems failure	Technical	T.5	3	4
Radiation causing damage to spectrometer detection capability	Technical	T.6	5	1
Ordered part doesn't arrive	Schedule	D.1	2	3
Ordered part incorrect	Cost	C.1	1	2
Ordered part breaks/broken	Cost	C.2	2	3

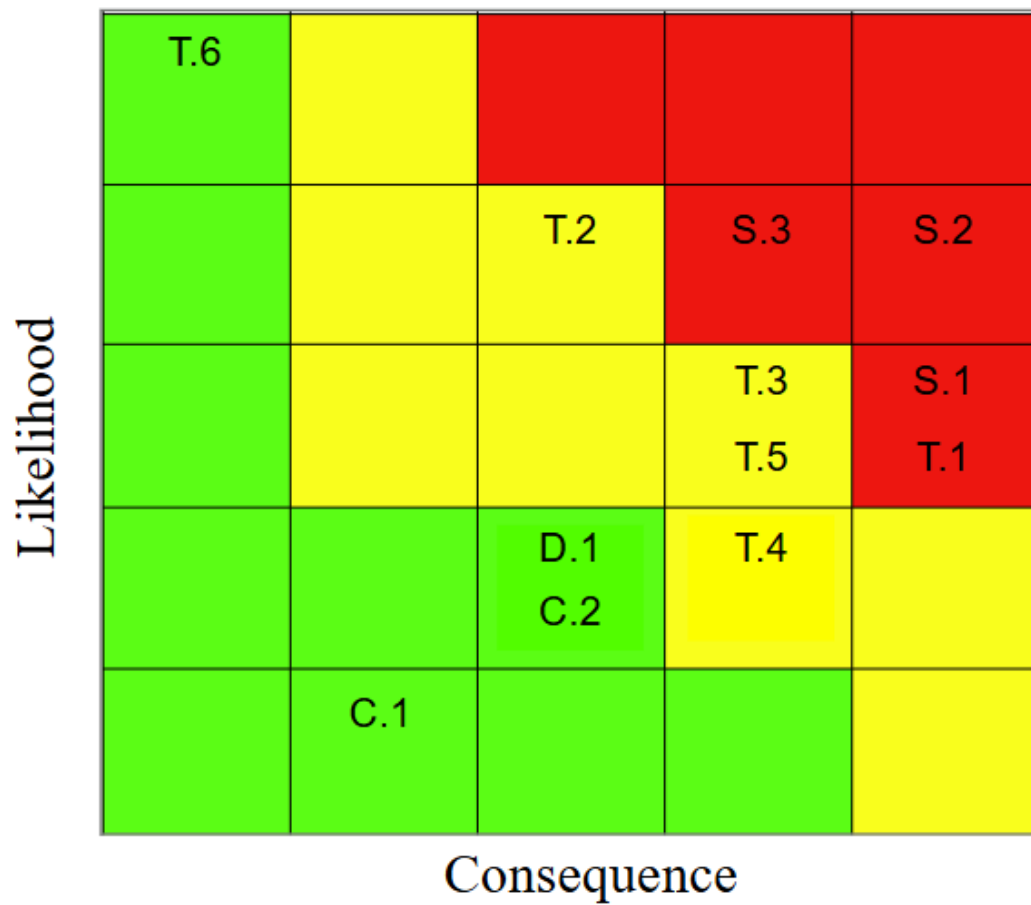


Figure 158: Base Risk Assessment

Table 26: Risk Assessment Table with Mitigation

Risk Mitigation	Call Sign	Likelihood (1-5)	Consequences (1-5)
- You Only Look Once software on raspberry pi	S.1	2	4
- Resistive heater for heating of storage - Combination of louvers, radiators, and heat pipes for heating structure and other subsystems - Phase change material and multi-layer insulation for keeping temperature constant	S.2	1	4
- Lens cover on spectrometer - Drill arm	S.3	3	3
- Proper insulation and wire management. - Heat shrink usage.	T.1	2	2
- Identify multiple suppliers. - Place orders early and confirm lead times.	T.2	2	3
- Implement strict fabrication inspections. - Use validated machinists and processes. - Perform test runs on prototypes.	T.3	2	3
- Ensure suppliers have favorable feedback. - Conduct material inspections.	T.4	1	3
- Use mechanisms (drill and spectrometer) in intervals - Thermo-electric cooler for refrigeration of storage - Phase change material and multi-layer insulation for keeping temperature constant	T.5	1	2
- Insulative coating on spectrometer	T.6	3	1
- Contact manufacturer - Find/manufacture alternative	D.1	2	2
- Contact manufacturer - Find/manufacture alternative	C.1	1	1
- Handle objects safely to prevent destruction	C.2	1	3

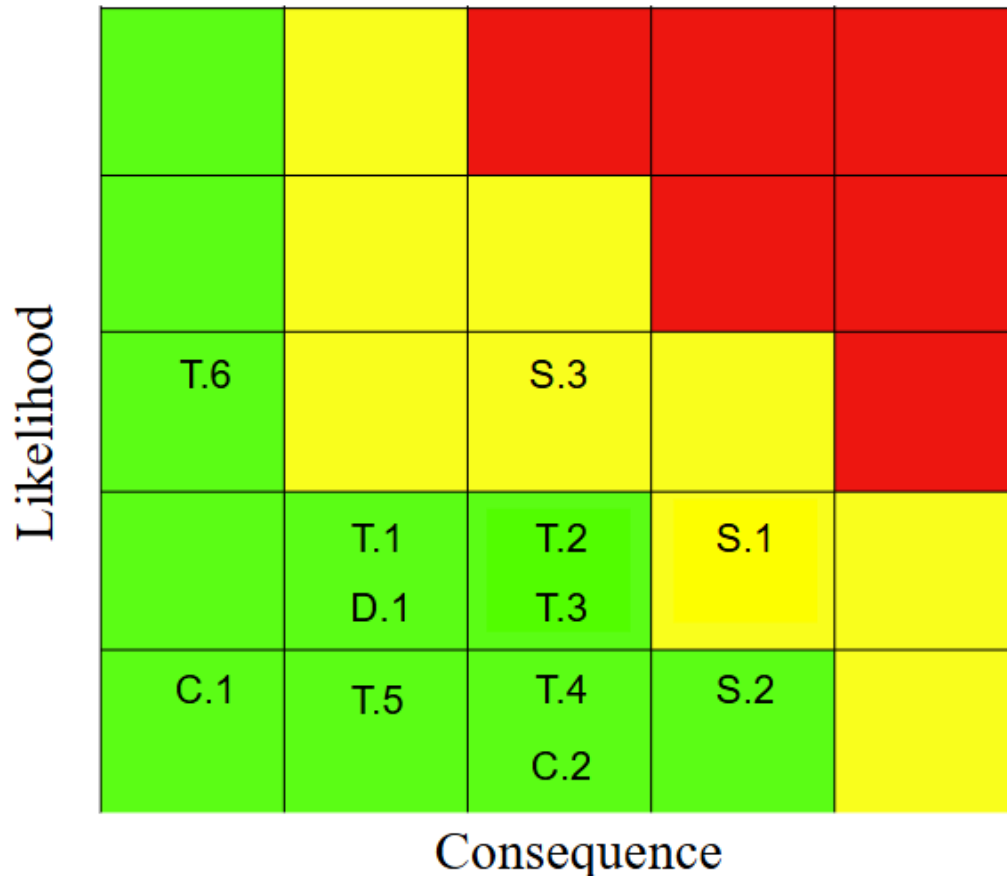


Figure 159: Risk Assessment with Mitigation

VI.2. Navigation and Controls

1. Given that the severity of the terrain exceeds the maximum displacement of the rocker bogie system, there is a high probability of slippage or tipping resulting in damage to key components. This will be mitigated by utilizing You Only Look Once software run on the raspberry pi in conjunction with a camera and ultrasonics to analyze terrain and navigate around obstacles.

Extent Realized: This risk was not realized, no tipping or slippage occurred at any point on any obstacles or slopes traversed.

2. Given that two wires come in contact with each other there is a high probability of a short occurring, resulting in potential failure of electronics and inability to complete mission. This will be mitigated by utilizing appropriate insulation and wire management, as well as heat shrink or similar over any exposed wires.

Extent Realized: Over the course of the project, only one short occurred causing damage to a motor driver when it was set directly on the chassis. This prevented autonomous operation of the drill.

3. Given that the moment applied to the differential exceeds safe limits, there is a high probability of slippage in, or damage to components. This will be mitigated by simulating the maximum expected moment in ANSYS in order to ensure that component failure will not occur. To mitigate slipping, all components should be as tight as possible.

Extent Realized: This issue was realized to a significant extent, applied moment exceeded expected and simulated values resulting in slippage and material failures in the bevel gears.

VI.3. Propulsion

1. Given the weight of the subscale REHT and the diameter of the wheels, increasing the torque on the motors beyond what the propulsion system is capable of handling will cause the wheels to snap. This can be mitigated by manually controlling the RPM at which the wheels rotate to a slow speed.

Extent Realized: The mitigation was a success after having the RPM around a consistent 1 to 1.5 MPH. Only one wheel snapped during testing, but it caused no damage to either the motor attached or the propulsion system. Said wheel was soon replaced and the propulsion system never experienced the same issue again.

2. Likewise, due to the moment caused by the subscale body, turning puts additional strain upon the front wheels. Turning while moving forward is likely to cause the wheels to snap at a high enough torque. This can be mitigated by only having the subscale rover turn after it comes to a stop.

Extent Realized: The mitigation was mostly a success. Having the rover turn only after stopping puts less strain on the wheels and prevents them from snapping, at least upon smooth ground. When operating on sand though, having the wheels turn for an extensive period of time runs the risk of them sinking into the sand and snapping under continual movement. While this didn't occur outright, there was one test in which it appeared it would had we not turned off the propulsion system and kept it running for a couple more seconds.

VI.4. Structures and Mechanisms

1. Since there is uneven and unpredictable surface topography, there is a moderate chance of tipping or sliding (S.1) that will cause damage to the structures and mounted subsystems. Mitigation involved

careful designing of the chassis through maintaining a low center of gravity, wide wheelbase, strong mounts, and working together with navigational technology to steer clear of hazardous surface areas.

Extent Realized: The possibility was marginally met as there was some tipping and slippage happened during the tests.

2. Considering that the environment is very hot, the probability of adverse thermal loading is high (S.2). Such loading might cause material deformation, strain in the structure, and subsystem malfunctions. Mitigation of the risk involved designing the structure taking into consideration its thermal loading characteristics.

Extent Realized: The risk was not of any significant issue as there were no failures of any structures or materials owing to temperatures during testing.

3. Fabrication of the structure has an inherent chance of errors or defects (T.3) that may have consequences on structural soundness and assembly of subsystems. Such risks were mitigated by repeated prototyping and inspecting the process used in fabrication.

Extent Realized: There was an issue regarding fitment and alignment while assembling the structural frame, but it was overcome without compromising the structure.

VI.5. Drill

1. The weight of the drill and its components meant that the drill carriage had to carry more weight than predicted. When the voltage was dropped down by the buckboost converter to twelve volts, it was no longer able to return to the up position. To mitigate this, the power from the 24v battery was wired directly to the drill components, allowing it to have sufficient power to rise.

Extent Realized: The 24v was sufficient to give the drill carriage power to rise, and the only result was movement slightly faster than in original testing. The higher voltage may put more load on the electric motors, leading to a higher likelihood of degradation over time.

2. The largest risk of the drill system was its integration with the computer on board RHET. Due to the lack of computing power and storage, along with lack of physical pins on the Raspberry Pi's, the wiring was done, but there was risk of the computer overloading. To mitigate this, other subsystems would need to minimize their power draw during drill operation.

Extent Realized: This did cause issues on the coding side, and it limited the autonomous capabilities of the drill.

3. The drill needed power transmitted to the internal motor, which needed to spin. Initially this proved a challenge because the graphite brushes were not able to handle the vibration and bumps on the surface. This was mitigated in two ways. First, a stabilizer was added to the drill to keep it from vibrating, and a new copper brush was built.

Extent Realized: The problem was successfully mitigated by these solutions, and there were no issues in transmitting power.

VI.6. Payload

1. Given the height and length of the storage conveyor system, the use of epoxy for structural support, and the moment applied on the subscale REHT, there is a high probability of system collapse. This can be mitigated by adding additional supports to the bottom of the storage system as well as the base

of the conveyor system. Though, doing so will also increase the moment in which the subscale REHT experiences due to the added weight.

Extent Realized: System collapsed before additional support could be added.

2. Given the different aspects of the spectrometer (I.E. the camera and the ultrasonic sensor in tandem with the raspberry pi), these all needed wiring that didn't interfere with each other. If one of the wires were to disconnect or short-circuit, the system wouldn't run. To mitigate this, a small 3D printed box was constructed to house all the wiring.

Extent Realized: With the creation of the 3D printed box, all wiring was neatly held together for the spectrometer system, allowing for everything to run nominally.

3. Given the limited bandwidth of the communications system, some functionality of the spectrometer (such as the snapshot feature and the live camera feed), it is infeasible for the spectrometer to run commands over a long period of time outside the basic bandwidth of the communications system. This can be mitigated by limiting the commands sent by the communications system and the outputs they run, such as limiting the snapshot feature to only taking one photo at a time.

Extent Realized: At first, there were some issues getting the spectrometer running in tandem with the communications system even with the mitigated commands. But after redoing some of the code on both to be more efficient, the mitigation was a success.

VI.7. Ground Station

1. Given the exposed nature of the Raspberry pi Pico and the LoRa chip and antenna, there was risk that being exposed to the elements could damage or mess up the rover's communication.

Extent Realized: Throughout the course of the project, the ground station components needed to be resoldered/rewired multiple times. We printed out a chamber to house the micro-controller and that heavily reduced the issues with the ground station.

VI.8. Communications

1. The biggest risk associated with the communications system was going over the allowed data limit that can transfer over the 915 Mhz radio waves we were utilizing. Therefore large dataset such as images, which were very important to our project, wouldn't be able to be transferred over our connection. We managed to mitigate this by sending the image in smaller bites so that we could transfer all of the data.

Extent Realized: Throughout the course of the project, the ground station components needed to be resoldered/rewired multiple times. We printed out a chamber to house the micro-controller and that heavily reduced the issues with the ground station.

2. Another risk of the communications system was drawing too much power from the raspberry pi 3 and causing a short

VI.9. Thermal and Survivability

1. The peltier coolers only have about a minute or two of activation time before the cooling functionality wears off. Beyond that activation time and the cooler runs the risk of being permanently inoperable. This is mitigated through multiple means. First, is through having four different peltier coolers and only activating one at a time. The cooling extent remains the same given the aluminum plate which

conducts the thermal properties to the sample tubes. Second is the temperature probes. It is set where if the surrounding area reaches above 25 degrees Celsius, the cooler will turn on. When the area reaches below 25 degrees Celsius, the cooler would turn off.

Extent Realized: Due to the temperature probes and the layout of the active cooling system, all coolers remained intact throughout the course of the project

2. Given the peltier coolers expel heat from the bottom, this runs the risk of counteracting the thermal regulation desired from them within the storage compartment. This can be mitigated by placing them on top of a separate aluminum sheet which lays just on top of the chassis. Said aluminum plate will act as a heat sink, expelling any excess heat out of the subscale REHT.

Extent Realized: The heat sink was a success. The excess heat built up did not interfere with the storage cooling and was expelled through the heat sink.

3. Given the flammable material of the insulation, if any sparks were to occur within the subscale REHT (such as faulty wiring), the insulation would quickly catch fire and burn down the rest of REHT. This is mitigated by having the storage compartment along the center of REHT separated by PCB walls.

Extent Realized: Mitigation procedures were proficient enough for the insulation nor REHT ever caught fire.

VI.10. Power and Electrical

1. Due to the voltage of the lithium ion batteries, connecting the two leads together would cause a variety of problems such as causing sparks, draining the power of the battery, and potentially causing a fire. This can be mitigated through the use of electrical tape in two ways. Before the whole subscale was built, the leads would be tied up, only untied when the battery was in use (which, for most subscale verification testing was rare). When the subscale was built, the leads would be taped at opposite ends along the inner wall of the subscale REHT.

Extent Realized: Mitigation procedures were a success, as none of the above issues occurred when applying electrical tape to the lithium ion batteries.

VII. Project Management

VII.1. Timeline

Below is the general timeline PACK7 is following throughout the course of senior design. Phase 1 and 2 are already completed, having finished during the fall semester and over winter break, respectively.

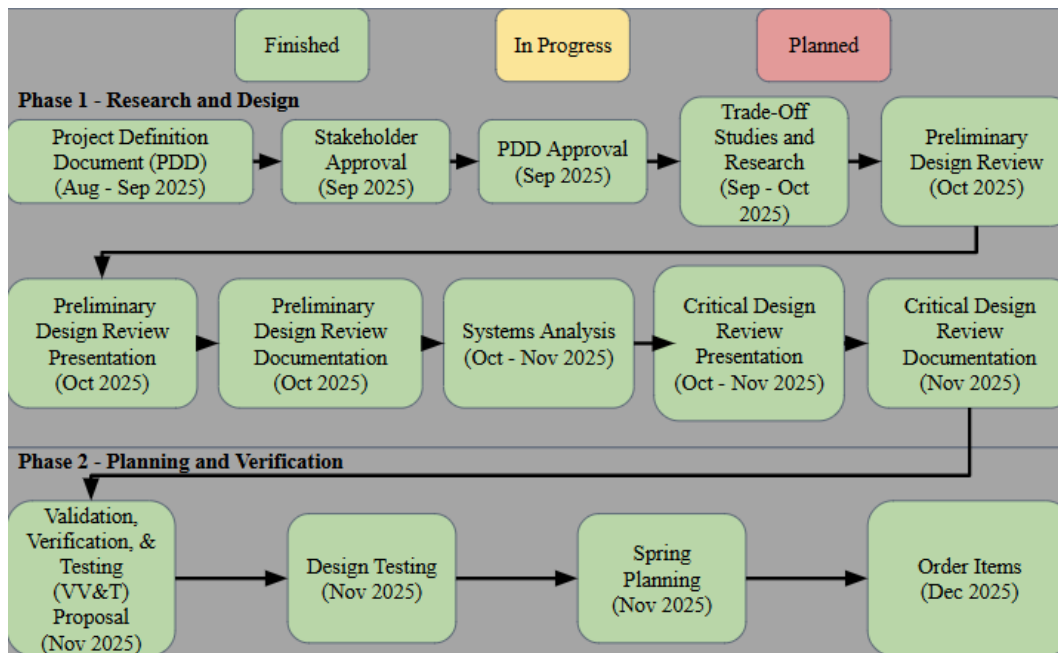


Figure 160: 2025 Fall Schedule

With our items ordered did phase 3 finally begin; the manufacturing and presenting phase. This phase will last entirely through the spring semester. Fabrication started as soon as stakeholder approval was gleaned.. In January, this fabrication mainly focused on subsystems and trying to get specific systems to work with each other (such as the power train working in tandem with communications or payload working in tandem with the drill). Further CAD work was done determining how each subsystem connected to the rover as a whole, particularly in terms of the wheels and the propulsion system. Come February, the CAD was finished and the subsystems were being fabricated so their testing can start. Finishing these steps leads to the manufacturing review on how far the REHT subscale has come to that point.

This leads to the subscale of REHT in it's final stages of manufacturing. The necessary changes listed in the design solution are were conducted given the feedback from the manufacturing review, any missing parts, and the findings during the verification testing. Fabrication with these changes was be done by the end of march, where the systems tests of REHT started. Though, due to some setbacks in the systems tests, there were some additional points in which the systems needed to be redone, such as an overhaul for the suspension system. When those were finished was REHT finally presented with the senior symposium acting as a physical test for REHT's capabilities. All which remains now is the final report where all of our findings are compiled. As how the report is now.

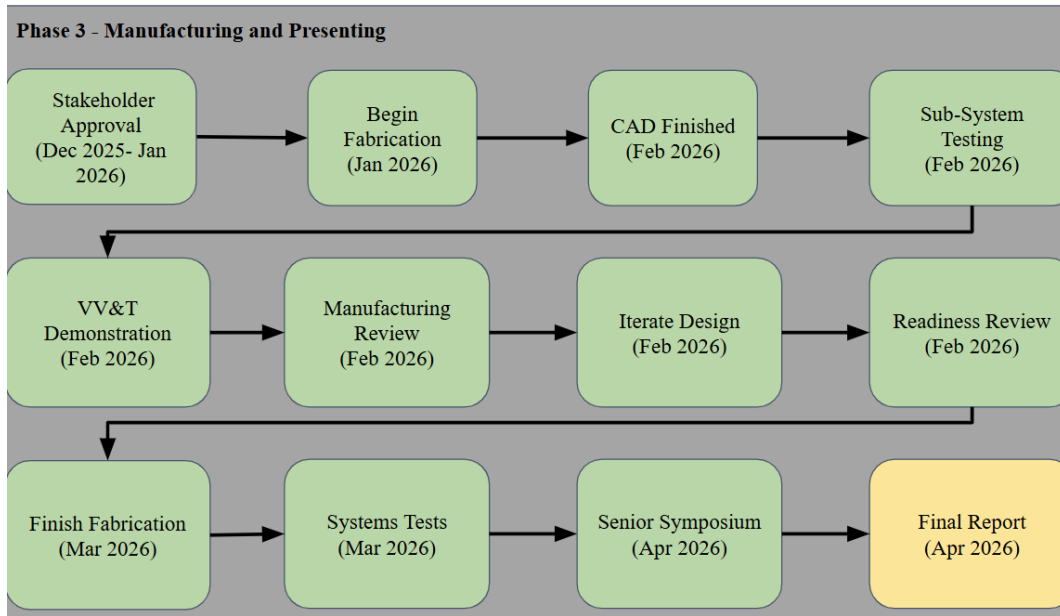


Figure 161: 2026 Spring Schedule

VII.2. Work Breakdown Structure

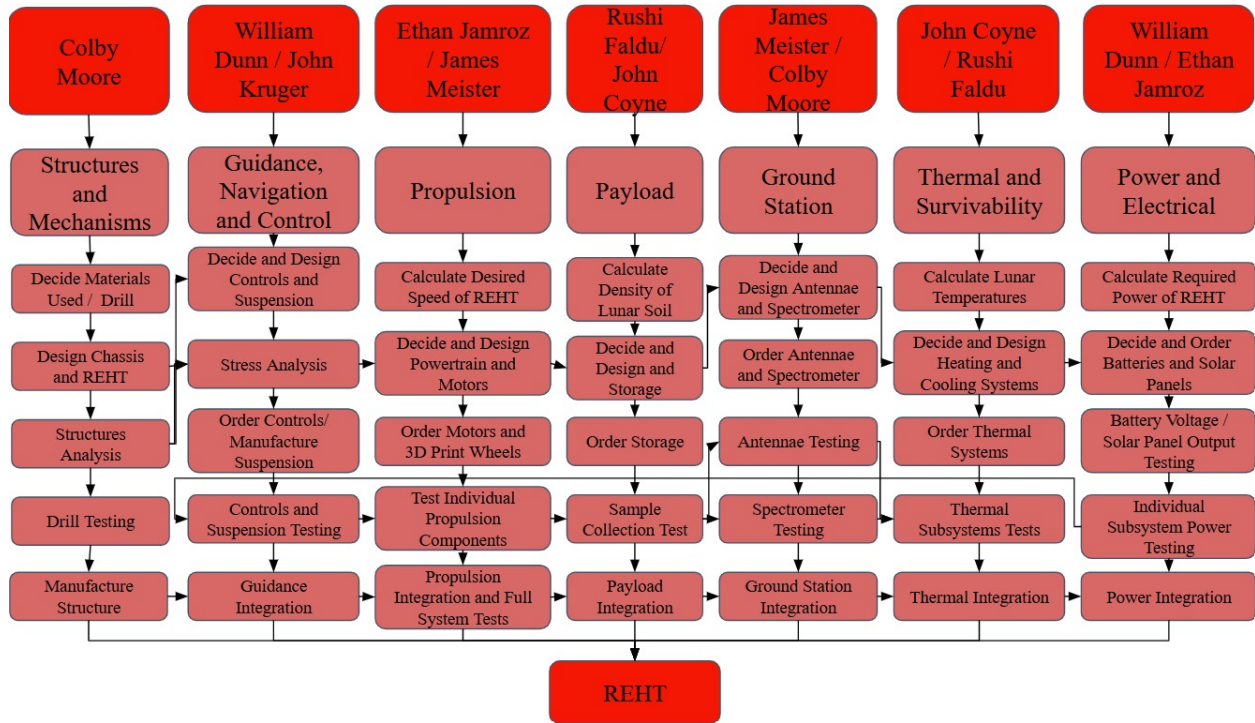


Figure 162: Work Breakdown Schedule

Shown above is the work breakdown structure. Here, it is split up between all of the different subsystems of the rover.

VII.2.1. Structures and Mechanisms

Focuses largely on the framework of REHT and the main tools used in it's mission. For this case, it's the drill. Starting out, Pack7 will decide upon the materials used for the chassis and frame of the rover as well as the drill to be used. From there comes the design work of the framing and the basic structure of REHT itself done primarily through Solidworks CAD. With each design shall a structure analysis be conducted to determine the total deformation and stress upon the chassis using ANSYS.

The structure analysis is a key point in the process. That is due to the fact it directly determines the design for the rest of the subsystems and thus their own components. As such, the structures analysis and the design of the structure is an iterative process, needing to redo the chassis design however many times are needed to minimize the deformation and stress induced upon the structure. As it stands, Pack7 is currently undergoing this process.

When this process is complete shall the needed materials and drill be ordered. Additionally, completing this process will soon allow all of the other subsystems to definitively decide upon their respective design and components. Starting here will the manufacturing and testing phase start. More specifically, the drill will be tested while the chassis and framing are constructed with their respective designs. Once both have reached an acceptable standard based on their respective verification tests, REHT will start to be fully assembled. The chassis, frame, and drill will be the first parts of REHT fully

manufactured and assembled, thus allowing all other subsystems easier integration.

VII.2.2. Guidance, Navigation, and Control

This subsystem focuses primarily on the navigation systems of REHT, I.E. how it moves and what controls said movement. First the different components are decided upon and designed with respect to the rover. Electrical components to consider include motor drivers, raspberry pi, and arduino's. For the navigation, a rocker-bogie system will be used for the suspension system. Like with the structures and mechanisms, a stress analysis will be taken on the suspension system. Based on the deformation induced within the system will the design be altered to minimize the induced stress. The design chosen here will directly influence the drivetrain and motors used for the propulsion subsystem.

Once the design was finalized can the proper components be ordered. By this point, there will be two different tasks on making this subsystem run. The first will be coding the arduino and the respective controls of the subscale rover, ensuring it runs a proper image processing software. The other will be manufacturing the rocker-bogie system. Subsequent testing will be conducted between both the code and the suspension system. Once the two individual components have conducted their respective verification tests can they be integrated into the overall design of the rover. The rocker-bogie system will be connected to the bottom of the frame and the electronics will be implemented sub-sequentially with what systems they control (such as the controls for the payload being implemented when the payload is first made).

VII.2.3. Propulsion

The propulsion subsystem focuses on the movement of the rover as it works in tandem with the navigation subsystem. Starting out, the desired speed of REHT is calculated under various circumstances, such as the speed of the rover under standard conditions and it's rate of climb up slopes of varying degrees. Such calculations are instrumental to determine the ideal powertrain used for the rover I.E. the wheels and their respective motors. The wheels will be designed using Solidworks with respect to the dimensions of the rocker-bogie system and the aforementioned speed calculations. The motors will be chosen based off the dimensions of the wheels and their required torque.

Once the wheels have been designed can they be manufactured through use of a 3D printer. Likewise, the motors can now be ordered. With the motors and the wheels both obtained can they be tested individually, such as witnessing the output of the motor drivers to the motors and measuring the rate of rotation for the wheels under the motor torques. Once the individual components have been properly tested can they be integrated into the rest of REHT, adding any other parts to the powertrain if need be. The wheels will be added to the rocker-bogie system while the motors are connected to the electronics on-board the rover. Once the electrical subsystem is connected to the propulsion can further tests be made regarding the maneuverability of REHT. These tests shall include directional movement, turning corners, and climbing slopes of varying degrees.

VII.2.4. Payload

The payload subsystem focuses primarily on what REHT will be transporting as per mission requirements. Since the desired mission is the return of 150 kg of lunar dust containing concentration of helium-3, the storage devices used for sample collection will be the main payload. First, to determine

how much lunar regolith can fit inside a pressurized container, the density of the lunar regolith had to be calculated to find the desired volume of the storage. Based off the dimensions of REHT's structure will the storage container's dimensions be decided upon. The same can be said for how many storage containers will fit on-board REHT.

With the storage decided upon for REHT can they be ordered. With the storage obtained can various sample collection tests be conducted. These include storing lunar dust-like material (sand) in the containers and putting them under various conditions (thermal or physical loading) to test the redundancy of said containers. Additional tests shall be conducted collecting samples in conjunction with the drill bit. Once said tests have been conducted will the payload system be fully integrated into REHT. It's full integration will involve the manufacturing of a conveyor system as a means to collect samples in conjunction with the drill.

VII.2.5. Ground Station

The ground station subsystem is based around how REHT communicates and interacts with the ground system designed for this mission. Since it is not a critical design element compared to the other subsystems, it's integration with REHT ties into the other subsystems. More specifically the antennae used to communicate with the ground station on Earth ties into navigations and controls. Additionally, the spectrometer used for analysis of regolith ties into the payload subsystem. Based on the selected storage and the electronics used, the antennae and spectrometer will be decided, designed, and subsequently ordered.

With the parts ordered can their respective verification tests be conducted. The antenna tests will be conducted in tandem with the overall structure of REHT and it's electrical systems, testing the range of said antenna given a specified power output. Additional tests shall be taken in tandem with the spectrometer in analyzing material within the storage as per payload requirements. If all verification tests are conducted can the ground station parts be integrated with the rest of the design.

VII.2.6. Thermal and Survivability

The thermal and survivability subsystem ensures REHT does not undergo adverse thermal or physical loading. Given how this subsystem is supposed to protect nearly every other subsystem from these effects, it is one of the last to be worked on. First, the temperatures of all previous subsystems are conducted with respect to the lunar temperatures. In accordance to these findings and the desired efficiency of each subsystem is the appropriate thermal system decided upon. For example, payload will require an active cooling system to keep some samples refrigerated while the navigation systems would require a passive heating system to keep them running. Each system will be designed with either an active or passive thermal system, be it heating or cooling.

Once these systems are decided, designed, ordered, and received can their respective verification tests be conducted. As opposed to previous subsystems verification tests, these verification tests will need to be repeated per subsystem. In order to best conduct these experiments, many of these subsystems will be tested at or close to full power to measure the extent these thermal systems protect against thermal loading. Once tested and obtained satisfactory results will the thermal systems be fully integrated into REHT.

VII.2.7. Power and Electrical

Last is the power and electrical section subsystem. This is made to ensure REHT itself has enough power to function. Since the first task done here is to calculate said power for each subsystem, the progression of the work here heavily ties to the rest of the system. As such, much of the work for this subsystem is done before the rest. Given the power calculations can one decide and order the required batteries and solar panels to be used for the subscale rover.

Once these items are obtained can they be properly tested. First, the batteries are tested to measure their voltage and output. The same is done for the solar panels. Another test will be conducted connecting the solar panel to the battery to measure the rechargeability of the two. With the individual tests finished can the tests for the other subsystems be done. Thus, the power testing occurs with all other experimental tests for REHT (aside from drill testing). Once all of the tests are done can the power and electrical subsystem be integrated with REHT alongside the rest of the subsystems.

VII.3. Gantt Charts

When analyzing the gantt charts below, they are split up into the following sections:

- Project Definition Document (Phase 1): Yellow
- Preliminary Design Review (Phase 1): Green
- Critical Design Review (Phase 1): Cyan
- Validation, Verification, and Testing Proposal (Phase 2): Blue
- Manufacturing Planning (Phase 2): Purple
- Manufacturing and Fabrication (Phase 3): Pink
- Physical Testing (Phase 3): Red
- Manufacturing Reports (Phase 3): Orange

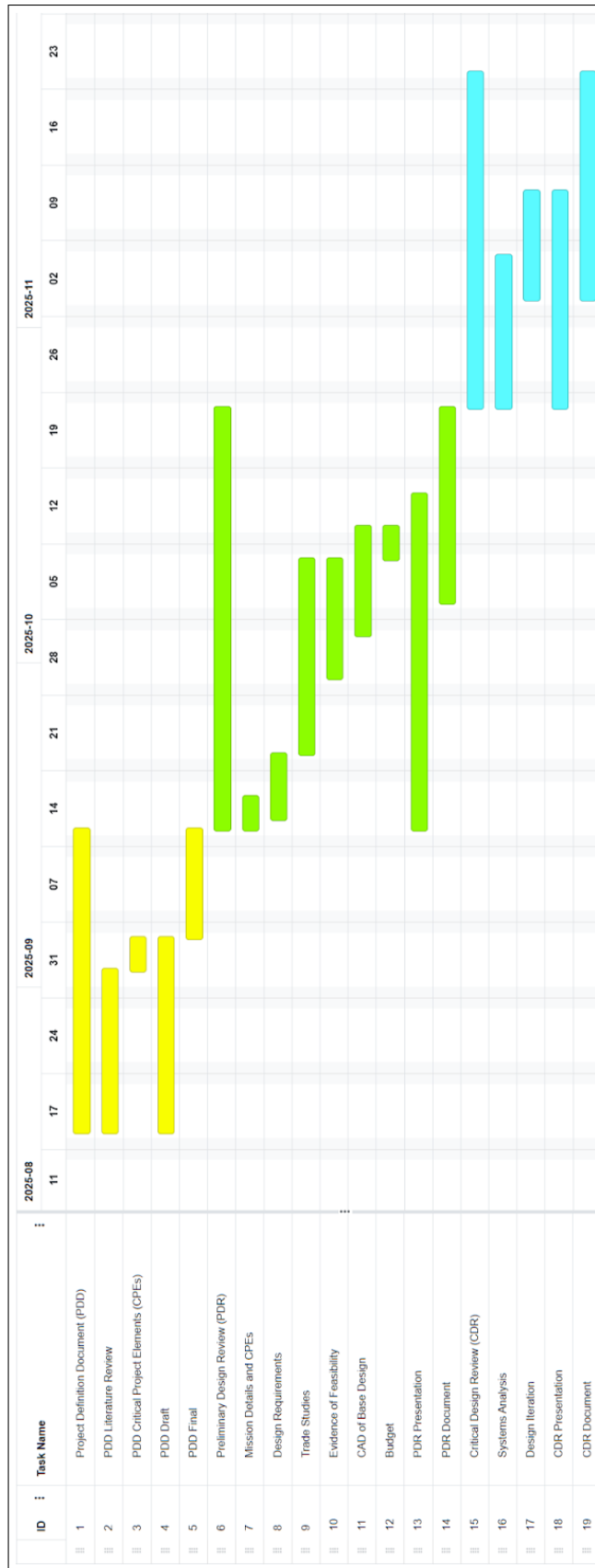


Figure 163: Gantt Chart Phase 1

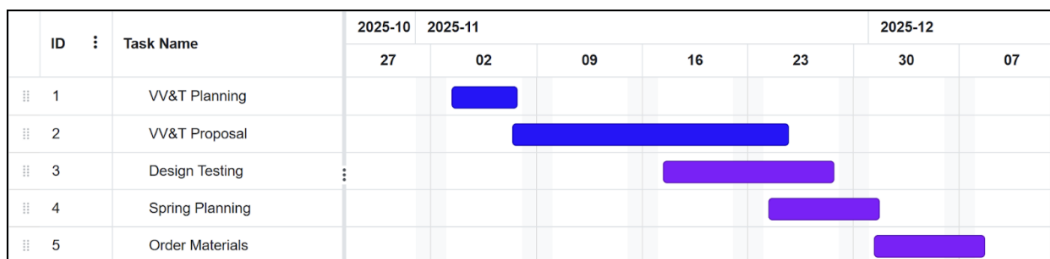


Figure 164: Gantt Chart Phase 2

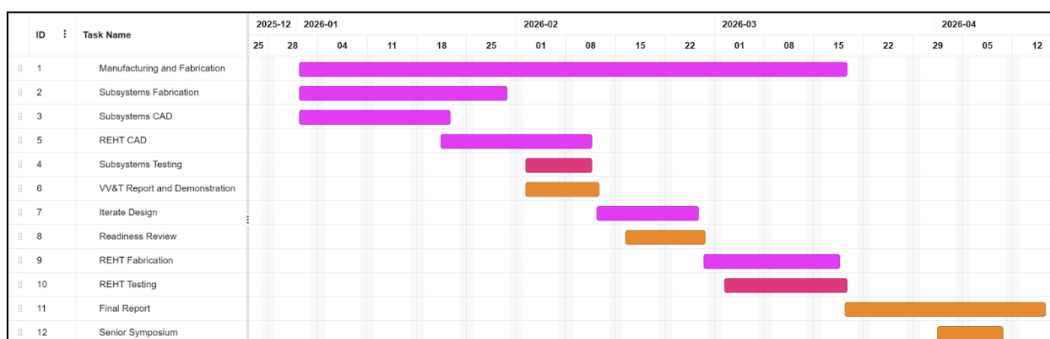


Figure 165: Gantt Chart Phase 3

VII.4. Budget Breakdown

VII.4.1. Cost Estimate

The estimated cost of REHT's prototype is \$1765.67 which makes up a large portion of the total budget for this project. When factoring taxes, there are about \$100 left available to spend offering enough flex room for small modifications if required. For the full scale, the material and launch cost is estimated to be \$3,055,526, however this is excluding research and development costs, along with personnel required for the mission. Assuming that these additional costs are twice the total cost of the material and the launch price, the overall cost estimate becomes \$91,665,780.

longtable

Prototype Parts List Table and Cost Estimate

Category	Item	Cost	Qty
Control Electronics			
	Raspberry Pi 5	99	1
	Stereo Camera	58	1
	Buck Boost Converter	16	2
	Wire	9.99	1
	Motor Drivers	24.99	3
	Camera Adapter Wire	8.29	2
	GPS	48.49	1

Category	Item	Cost	Qty
	Accelerometer	9.99	1
	Servo Motors	17	1
	Buck-boost 2	13	1
	GPIO Expander Board	12	2
	Buck Boost 3	10	1
	Total:	413.02	
Suspension			
	Pillow Block Bearings	15	
	90 Degree Connectors	18.99	1
	45 Degree Connectors	18.99	1
	Bevel Gears	19.59	1
	Aluminum Shaft	11.99	1
	PVC	14.36	1
	3D Printed Components		
	Shaft Couplings	15	1
	Total:	113.92	
Ground Station			
	Micro SD Card	67.50	1
	Total:	67.50	
Communications			
	Transceiver	22.27	1
	Antenna	12.50	1
	Total:	34.77	
Payload			
	50 mL Test Tubes (set 25)	14.99	1
	Test Tube Rack (10 tubes)	29.97	3
	Total:	104.90	
Spectrometer			
	Ultrasonic Sensor	6.99	1
	Servo Motor	11.99	1
	Total:	18.98	
Thermal Systems			
	Temperature Probe	9.99	1
	Peltier	9.79	1
	Radiator	9.99	2
	Insulation Material	13.99	1
	Total:	43.76	
Structures and Mechanisms			
	Aluminum 7075 Sheet (36×19×0.5)	519.54	1
	Total:	519.54	
Storage Mechanism			
	Limit Switches	9	1

Category	Item	Cost	Qty
	Rack and Pinion	35	1
	Aluminum	13	1
	Aluminum Shaft	8	1
	Motors	20	2
	6mm to 8mm Adapter	10	1
	More Aluminum	16	2
	Standoffs	7.3	1
	Pulley	7	1
	Belt	10	1
	Total:	152.30	
Drill			
	Inner Motor	11	1
	Bauer Drill	70	1
	Battery	50	1
	Inner Tube	30	1
	Outer Tube	67	1
	Shaft	5	1
	Brushes	10	1
	Carbide Bits	25	1
	Mount Bit	10	1
	Half Slot Channel	35	1
	Bolts	8	1
	YellowJacket Motor	50	1
	Lead Screw	17	1
	Threaded Rod	5	1
	Clamping Collar	5	1
	Gear	12	2
	Aluminum tube	2	1
	Total:	412	

Full Scale Cost Estimate Table

longtable

Component	Cost
Navigation and Controls	
Microprocessor	\$200,000.00
Motor	\$600,000.00
Wheels	\$60,000.00
Structures and Mechanisms	
Materials	\$50,000.00
Carbon Fiber	\$21,600.00
Drill	\$10,000,000.00

Component	Cost
Payload	
Witness Tubes	\$11,410.00
Spectrometer	\$5,000,000.00
Power and Electrical	
Electronics	\$100,000.00
Batteries	\$10,000.00
Solar Panel	\$13,935,250.00
Thermal Survivability	
Components	\$1,000,000.00
Travel	
Travel	\$567,000.00
Total	\$30,988,260.00

VII.4.2. Pie Chart

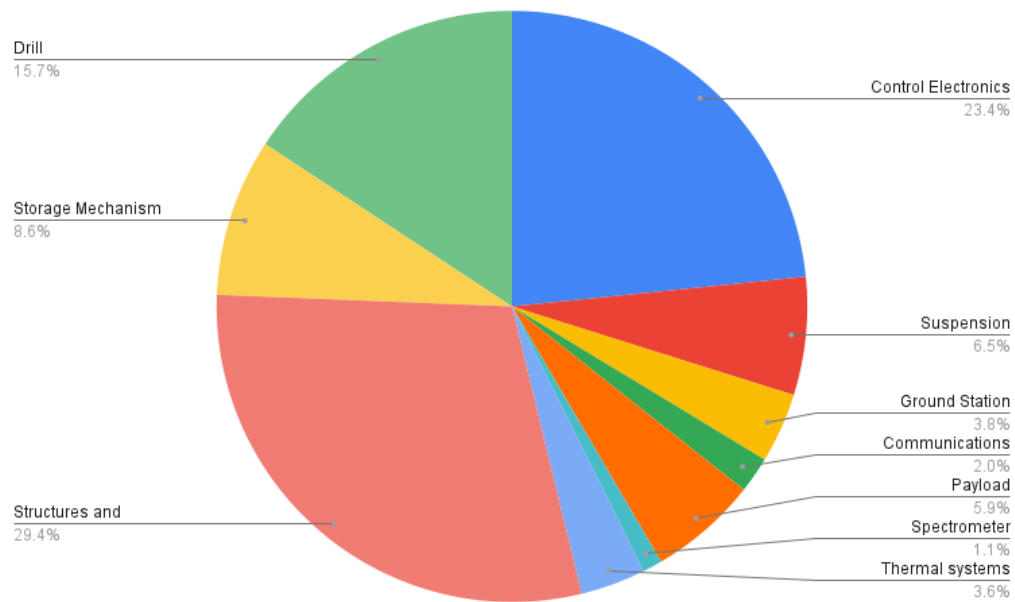


Figure 166: Budget Breakdown for Prototype

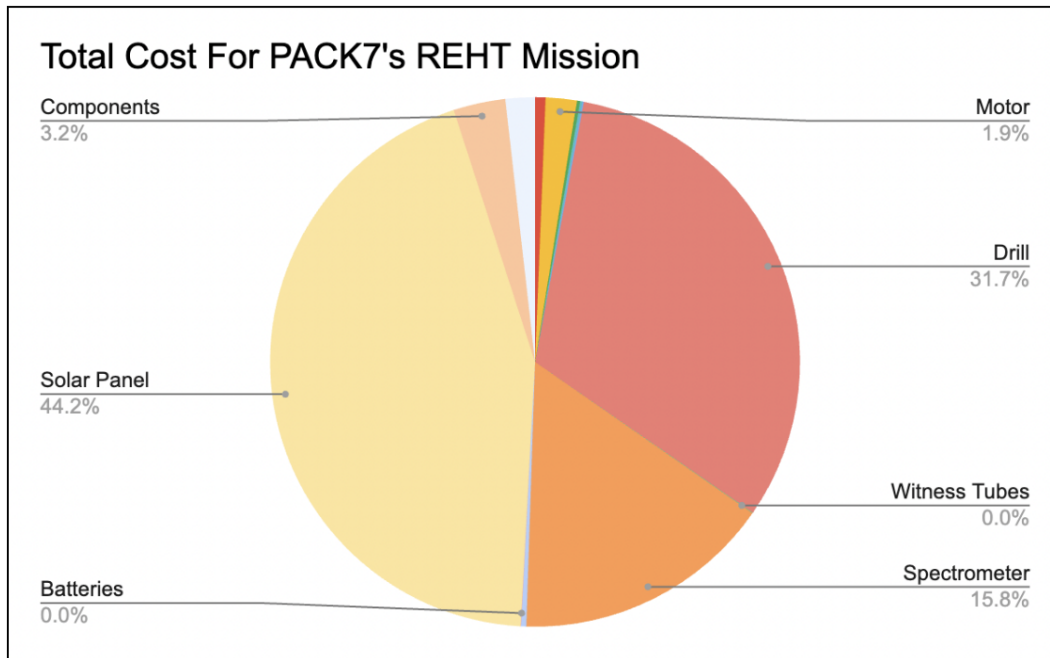


Figure 167: Budget Breakdown for Full-Scale Rover

VII.5. Tasks and Activities

VII.5.1. Navigation and Controls

Table 29: Electronics Manufacturing Schedule

Date	Task	Completion of Task
1/12/26	Receive ordered parts, check that all are working	Parts ordered and inspected
1/13/26 – 1/14/26	Wire motors to motor drivers, and motor drivers to Raspberry Pi; requires wire cutters, soldering iron, crimping tools, and insulation	Wired and insulated motor system
1/15/26	Connect battery to buck-boost converters 1-3 in senior design lab and set them to desired output; requires wire cutters, soldering iron, crimp tools, and insulation	Battery system connected
1/16/26	Connect USB-based components to Raspberry Pi and mount all electronics in electronics tray	Electronics mounted in tray
1/19/26	Connect buck-boost to Pi, test motors, and verify full operability	Motor and electronics testing completed
1/20/26 – end	Program and configure Raspberry Pi	Software configuration completed

Table 30: Navigation Manufacturing Schedule

Date	Task	Completion of Task
1/12/26	Receive ordered parts, check that all are working	Parts ordered and inspected
1/13/26 – 1/17/26	3D print camera base and servo holder; requires access to 3D printer	3D printed base and holder
1/15/26	Mount PVC pipe on base and servo holder to the top of the pipe with the hole facing up; this will require 2 part epoxy	Stand assembled
1/16/26	Place servo motor in holder and attach wires, connect servo to camera back (flat plate); this will require wire cutters and a crimp	Servo mounted and connected
1/19/26	Mount stereo camera to camera back using screws, will require screwdriver, drill, and tap	Motor and electronics testing completed
1/20/26 – end	Program and configure the object detection and terrain mapping softwares	Software configuration completed

VII.5.2. Structures and Mechanisms

Table 31 highlights the plan for manufacturing of the Chassis.

Table 31: Chassis Manufacturing Schedule

Date	Task	Completion of Task
1/12/26	Receive and inspect raw materials; verify aluminum stock, brackets, and hardware	Materials received and cleared for machining
1/13/26 – 1/17/26	CNC machine primary chassis components using manual CNC in the senior design lab; verify all tolerances against CAD	Chassis plates and mounting features machined and checked
1/19/26 – 1/23/26	TIG weld chassis frame structure; ensure proper fit-up and weld continuity in the senior design lab	Chassis frame welded and inspected
2/02/26 – 2/05/26	Install machined brackets, motor housings, and fittings onto the welded chassis using fasteners	Brackets and housings installed and aligned
2/09/26 – 2/13/26	Perform full chassis integration and alignment check; verify motors, shafts, and gears alignment	Chassis fully integrated and verified for subsystem assembly

The chassis manufacturing schedule is structured to ensure that all the machining, welding, and integration steps are completed in a controlled manner. After receiving and verifying that the aluminum sheets are within the correct dimensions, machining can ensue. Through the utilization of the CNC equipment in the senior design lab, all of the primary chassis components can be produced within the required tolerances. Once the machined components are acquired, the frame is assembled and TIG welded. Following welding, all brackets, motor housings, and mounting features are installed and mechanically fastened to the chassis. A full alignment check is then performed to validate proper positioning of motors, shafts, and gears, which ultimately ensures that the rest of the subsystems can be integrated efficiently. This schedule provides a realistic path that ensures the chassis is fabricated accurately and will be prepared for the final assembly.

VII.5.3. Drill

Much work was done to make sure the design was feasible not only for stresses but also for machinability. To begin, the drill will be made from an off-centered tube inside another off-center tube. This is the most technically difficult part to machine. To manufacture this, the tube will be cut into 3, six inch segments. Starting with a wall thickness greater than the final design, the wall will be machined down using the cnc machine to get the off-centered circle. This will allow for bits of 3 inches to be used, which is standard in machine shops. Next, the 3 segments will be welded together to obtain the full length tube. The outer tube will be made in the same way, except the outer wall must be cut down on the lathe to create the helical exterior auger. This is a feasible process, as threads, a much more precise shape, can be created on a lathe. The internal motor has the difficulty of receiving power while rotating in the main drill. This is a common problem and has a known solution. Electric graphite brushes can transmit power through the rotating shaft in a similar way to DC motors. There are also internal pin mechanisms that are difficult to put into place. However, these issues can be mitigated by assembling the internal mechanisms before welding the pipe together, allowing easier access to the parts.

Drill Manufacturing Schedule	Date	Task	Completion of
	1/22/26	Receive and inspect raw materials;	The wrong mater ered.
	1/22/26 – 3/21/26	Redesign of the drill main body due to wrong parts and machining limitations	The final drill des upon and selected
	1/29/26 – 3/5/26	VV&T Testing of the drill subcomponents	The core pusher, drill endurance t pleted.
	3/21/26 – 4/01/26	Construction and Integration of Drill subsys-tem	The drill carriage bit were all moun to the rover.

VII.5.4. Payload

Storage:

By the time manufacturing starts in the spring, the 50 mL self-standing test tubes and all other parts shall have already been ordered. This shipment should arrive by 12th of January, though it is likely to arrive even earlier. Only after ensuring the packages arrive safely, accounting for the correct dimensions , and testing the motors can the manufacturing for the storage system be conducted.

As mentioned in the design solution, the subscale of REHT shall utilize an internal transport system to transport the 25 sample tubes throughout the different sections of the rover. As the rover's dimensions are finalized in the first two full weeks of January, so is the CAD model for the system. Like with all of the other models for REHT, the transport system shall be done in Solidworks. With the CAD finished can the framework of the transport system start to be shaped appropriately to the dimensions of the model. The sheet metal ordered will be shaped using a bending brick, allowing the structural aluminum rigidity.

As the frame is construction can the preparations for it's integration be made. By the end of the third or week of January, the basic frame of REHT shall be constructed. As such, three flaps will be cut into the rear end of the frame where the storage sections are divided if it has not already been done so. By the time

Table 32: Storage Manufacturing Schedule

Date	Task	Completion of Task
1/5/26 - 1/16/26	CAD Design for Storage System Finalized	Solidworks
1/12/26	Receive Ordered Parts	Ordered Through Amazon
1/16/26 - 1/23/26	Cut Flaps in Back of REHT for Storage Integration	Cut with Senior Design Saw
1/16/26 - 1/23/26	Shaping of Sheet Metal	Bending Brick
1/23/26 - 1/30/26	Integrate Framing into Rover Design	Screwing in Bolts; Fastening Framing; Utilize Two-Component Epoxy if Needed
1/30/26 - 2/5/26	Integration of Belt and Gears	Connected through Frame; Dremel and Drill Holes into Conveyor Belt Fasteners; Fasten Belt through said Fasteners with Screws
2/5/26 - 2/12/26	Integration of Motors	Motor Frames Cut with Senior Design Saw then Screwed Plates Together; Connected through Frame

this finishes will the shaping also be done.

The last week of January and the first week of February can the frame of the system start to be implemented into the sub-scale rover. First, the frame itself will be attached to the subscale of REHT. This will be done in the third full week of January by drilling and screwing the framing down while fastening it. Two-component epoxy may be used here if needed, though this will only serve as a temporary fix and should be avoided unless absolutely necessary.

Next, in the first week of February will the belt and gears be implemented into the framing. These will be done mainly through conveyor belt fasteners used to fasten the belts into the frames. These fasteners will need to be altered through use of a drill and dremel in order to gain the proper dimensions needed to fit on the belt. Once the fasteners are made can they be screwed into the framing and the belt be fastened onto the frame along with the gears.

The last task is connecting the motors to the system. This will be done in the second week of February, potentially earlier if time allows. The motor frames would need to be constructed first. This will be done using the senior design saw to get the proper dimensions before screwing the plates together. Then can the motors be placed inside said frames and connected to the belts.

Spectrometer:

VII.5.5. Power and Electrical

VII.5.6. Thermal Systems

Table 33: Spectrometer Manufacturing Schedule

Date	Task	Completion of Task
1/5/26 - 1/16/26	Finalizing the CAD models for the spectrometer housing and spectrometer arm	Solidworks
1/12/26	Receive Ordered Parts	Ordered Through Amazon
1/16/26 - 1/30/26	Integrate the ultrasonic sensor modules and the camera with the servo motor	Use wires and programming
1/16/26 - 1/25/26	3D printing spectrometer housing components	Using LAB 3D printer
02/1/26 - 02/5/26	Integrate the spectrometer arm with the rover and attach wiring to the microcontroller	Fastening the arm to the rover body and using drill and screws
02/5/26 - 2/10/26	Test the code and object detection capabilities of the camera	through programming and testing

Table 34: thermal system Manufacturing Schedule

Date	Task	Completion of Task
01/12/26	Receive Ordered Parts	Ordered Through Amazon
01/12/26 - 01/20/26	Programming the temperature probes to give the correct reading	Use Raspberry Pi and programming
01/20/26 - 01/25/26	Integrating the active cooling systems with the temperature probe and Raspberry Pi	Use Raspberry Pi and programming
01/25/26 - 01/31/26	Integrating the wires and cooling systems with the rover and other subsystems	Attaching and fastening the cables and TEC pads
01/31/26 - 02/10/26	Test the code, temperature detection, and switching on and off of cooling pads	through programming and testing
02/10/26 - 02/20/26	Putting the insulation and aluminized heat shield on the rover after all other subsystems are completed	gluing and fastening the insulation and heat shield

VIII. Course Reflection

VIII.1. Key Lessons Learned

Learning to Work on Systems with No Prior Knowledge:

This is easily the biggest lesson learned during the course of this project, and varies between each group

member depending on the subsystem. Despite being a part of the Aerospace Capstone Project, much of the manufacturing was mechanical engineering based, and even involved some aspects of computer science. Among the different topics learned, these were the standouts:

- **Electrical and Wiring:** The only class in which aerospace engineers take which pertains to this subsystem is Principles of Automatic Controls. Even so, said class is only offered during the same time this project was conducted. Thus, our knowledge on wiring and electronics was limited before starting the subscale REHT. Fortunately, when it came time to construct the subscale, our group had enough basic knowledge behind the system to easily learn any other details needed to efficiently connect the different systems to the raspberry pi and the propulsion to the motor drivers.
- **Simulations:** Between the feasibility analysis conducted in the fall and the verification tests conducted in the spring, the use of various simulation programs were needed to analyze aspects of REHT we otherwise wouldn't be able to discern. These include MATLAB, SolidWorks, and ANSYS. Though each of us have used these programs before, they were not as extensive as required for the verification on this project (particularly with ANSYS). Fortunately, said basic knowledge also made it simple to learn the extent of these programs in terms of finding various loadings upon the suspension and chassis.
- **Coding:** This was by far the most difficult aspect to learn, as none of us had little to no prior knowledge for the coding languages and programs used for this project. These include coding the Raspberry Pi for the controls and navigation, Thonny for the ground station, python for thermal systems, and others in terms of integration with the main Raspberry Pi. Every system which had some automated process needed to be coded one way or another. Learning these different coding languages was arguably the most time consuming aspect of the manufacturing process.

Undertaking these tasks and subsystems with limited knowledge simply meant we had to learn it as we went along with the project. Of course, when one member had more experience in a topic than another, the less-experienced would learn from the other. Yet, there were many instances (especially in coding) when none of us had any experience with it, thus needing to resort to outside sources and using ample time just to learn said topics. Though it was desirable to have prior classes which dealt with these unknown topics, ultimately, learning them while designing and manufacturing REHT both made it easier to apply in the moment and gives us a better idea of how future engineering work might be.

Unexpectancy in Working with Third Parties:

Though much of the work on REHT was largely done in the confines of Pack7, there were a couple instances in which we needed to rely on other parties for the manufacturing.

The obvious one is the supplier, or suppliers in this case. Those in which all materials were gained. Much of our materials arrived on time, though there were some in which either arrived late or didn't arrive at all. In those instances, we needed to count the inventory we did have, reorder what wasn't delivered, and work on what we could in the meantime. And in the instances in which something was missing and it was too late to order, we had to make do with what we had.

The other is needing to work with the MAE machine shop in order to do all machining for the metal. Here we needed to give precise specifications towards what needed to be done and be open for communication in case there were any issues in the order. Due to some inexperience in how to handle some materials, most notably aluminum, some of the specifications were infeasible to conduct (such as welding metal which is too small or bending metal too rigid). Thus did we need to alter our designs of not only the parts manufactured but also the design of the REHT based off the recommendations of the machine shop. We also needed to

work around the time constraints as well, given how long it took for some orders to be finished. Ultimately, instances like these required adaptability to keep the manufacturing process on schedule.

Keeping Track of Changing Designs:

Another key lesson learned over the course of this project was to keep better track of the effects of changing multiples parts. The method of connecting the differential had to be redesigned in a suboptimal way because both the bearings used and chassis underwent redesigns at different points in the design. While the original bearings would have worked with the new chassis, the updated ones would not. Because the bearings were not updated in the CAD model, the change in design caused a conflict that was not noticed in time.

In Depth Reserach on Component Interfacing:

Another key lesson learned was to check component interfaces on a much deeper level when dealing with unfamiliar systems and components. Because there was minimal prior experience using ribbon cables, several mistakes were made in component selection that became massive time sinks and ultimately prevented the initial stereo camera from being brought online. Doing more in depth research into this connection method ahead of hand, especially on cable pitching and type, would have resulted in a vastly superior final product as more time would have been available for refining and troubleshooting.

VIII.2. Wishes in Hindsight

Knowledge on Machining and Reliance on MAE Machine Shop:

Our group was under the idea that with the manufacturing process, we would be doing all of the manufacturing ourselves. This includes metal working, such as machining, cutting, welding, etc. We expected we would either be trained to do the machining ourselves or work directly with the MAE machine shop. Unfortunately, the former was not the case. Though the latter did occur, it was to a much lesser degree than we had hoped for.

What ended up occurring was we would submit whatever work order we had with the machine shop with the given materials and specifications on what they should be made into. This needed to be done specifically with the chassis, storage system, and the drill. Hypothetically, the orders were to take a maximum of two weeks. Though cumbersome, since the orders were made early in the semester they were expected to be done by beginning of February. Said orders ended up being finished late February to early March.

This was due to the fact that every other senior design group also needed to rely on the MAE machine shop as well, thus causing a large backlog of orders for them to complete. Due to said influx of orders and the strain caused by it, even the orders finished didn't come out to exact specifications, requiring for changes in the design of the chassis, storage system, and drill.

Hypothetically, there were other means of getting some of the results expected, such as utilizing the water jet training for one of the makerspaces on Centennial Campus of North Carolina State University. Yet, we were not made aware of said resources, nor made aware of the full extent the machine shop would take.

As such, knowing the heavy constraints placed upon the MAE machine shop before the semester started and how much we were to rely on it for machining is among one of the details our group wished we knew before manufacturing. Knowing the constraints would have encouraged us to get in those orders right as the semester started. At the very least, as explained above, it simulates the unexpectancies which may arise in working with other parties.

Resources Available:

Building off of the previous topic, we went into the manufacturing process expecting that practically any tools we needed to manufacture REHT were readily available within the senior design lab. Though there was an ample amount of basic equipment (such as allen keys/screw drivers, wrenches, scissors, drills) and some higher end equipment (drill press, soldering irons, hot glue guns), there were other pieces of equipment that felt like they were needed that weren't present. One big example are dremels, in which it was either required someone bring in their own or to go to another makerspace. The 3D printer wasn't readily available either. Additionally, some basic materials promised such as screws, nuts, and bolts were difficult to find within the lab without proper organization.

Additionally, even though most of them are not tied to the project, it would have been a boon to know of the other facilities available to us as students. These include other makerspaces and machine shops. It would have allowed us to figure out alternative designs quicker. Fortunately, we had access to the Entrepreneurship Building's Engineering Garage, which had much of what the Senior Design Lab lacked such as a set of dremels and a multitude of 3D printers. Yet, even so, our work was limited in spaces such as these as it made transporting manufactured parts more difficult. Ultimately, it would have been desired to know what the Senior Design Lab had and what it lacked in order to make a better plan of manufacturing.

Prioritizing Simplicity when Possible:

Many aspects of the REHT's design were significantly more complicated and intensive than needed for a prototype. Because of this fact, combined with tight time table, it became incredibly difficult to get all systems completed and integrated to the desired level of quality and a number of mistakes and failures occurred that could otherwise have been prevented by scaling down, better component selection, or having fewer moving parts. While a full scale rover would require this level of complexity and more, it is infeasible on the budget and schedule available to be ambitious with your design as you might like.

VIII.3. Advice for Rising Seniors

There are plenty of recommendations which can be made. For simplicities sake, we'll list them out by aspect.

Documentation:

For starters, use Overleaf. Though it may be frustrating to learn at first, the amount of time it saves in terms of formatting reports and saving parts such as images or citations save much more time than one expects. Also make sure to build off of previous documents rather than just blatantly copy and paste sections that need to be repeated. Taking the time to reread over some details can help out in determining how to proceed with the project later down the line. This is especially the case during the fall semester when most of the semester is documentation. Lastly, make sure to take plenty of pictures of brainstormed designs or steps done during manufacturing. Doing so will cut down on the writing needed for the documents, presentations, and the engineering notebook.

Presentations:

There isn't much which can be said for the presentations. The main piece of advice we can give is just to try and use the slides as a reminder of what you need to say rather than just directly reading from them. Especially when it gets to the point of manufacturing when it's easier to remember the information, it allows the presentations to flow more naturally. Additionally, time yourselves during the presentations. They go by quicker for the presenters and slower for the audience, so make sure each section is well paced.

Communication:

For most communication, either use text or discord. This comes down to personal preference, but steer away from anything which can be easily ignored (like Gmail or most social media) or deleted after a set amount of time (like Snapchat or the free version of Slack). Don't be afraid to speak up in terms of any issues or questions which arise, as chances are someone else in the group has that same issue/question. Lastly, and arguably most importantly, check in on each other. Not only just to see how everyone's progress is on their respective subsections or if they need help, but just in general. Keeping tabs on how everyone is doing and ensuring everyone is in a good state of mind just allows everything to flow more naturally. After all, it's easier to work on a yearlong project with friends instead of perpetual strangers.

Design work and manufacturing:

Though there should be subsystem leads, that doesn't mean everyone should only work on "their" subsystem. Ultimately, the team should work together on most (if not all) aspects of the project, or at least to the extent they can. Because there are two eventualities: the first is that the subsystem lead will run into problems and need help in finding out how to resolve said problems. The second is that all of these subsystems will eventually be integrated together for the overall project. If no one knows how each others systems work, chances are the integration will fail, leading to the failure of the project as a whole. Thus, it's important that everyone helps with each subsystem when they can (especially the ones unfamiliar to MAE majors such as electrical or coding aspects).

Start early:

Do not wait until last minute to do things. Yes, that can be said about practically anything, but take priority in senior design over all other classes. Though the classes are listed as three-credit hours, its one of those courses where that isn't very accurate. It will take a long time to write each report. It will take a long time to manufacture or get assistance with manufacturing. It will take a long time to troubleshoot issues. The earlier you start, the earlier you find potential issues and the more you can work around everyone's schedules. The earlier you start, the more you can pace out the project to ensure everyone isn't in a state of perpetual stress. Out of all the advice here, even though it is the most general, it is the most important. Start early.

Ensure Complete Compatibility Before Ordering:

By ensuring that all your components and designs are entirely compatible in terms of dimensions, electrical interfaces, screw sizes and threading, weight, power draw, voltage requirements, and other key factors future teams can avoid many significant issues. Even minor compatibility issues can cause cascading effects that prompt significant system redesign taking up valuable time and resulting in a suboptimal design.

IX. Individual Contributions

IX.1. William Dunn

As Guidance, Navigation, and Controls lead, designed significant portions of the electrical system including Raspberry Pi 5 selection, stereo camera selection, buck-boost choices, motor driver selection, expander board selection, and servo motors. Designed, selected parts for, and manufactured rocker-bogie suspension system including differential. Redesigned for part incompatibilities and material failures that occurred in manufacturing. Implemented spring system to counteract full integration overload. Designed and implemented basic control system using ROS2 and basic machine learning to simulate navigation methods used on full scale rovers including dead reckoning through IMU data combined with stereo camera reset to counteract drift caused by sensor error and double integration of acceleration. Utilized this data to track position

over time and created framework to allow autonomous control based on this principle. Troubleshoot several interface issues with stereo camera/IMU connection finding method to bring inbuilt IMU online despite inability to get camera feed with components available. Performed extensive testing and refinement on all GNC systems to improve performance and reduce risk of failure. These included oscillation and obstacle tests on the suspension, and movement tests for navigation. Also contributed to design and assembly of rover shell. Wrote all GNC sections in this report, wrote portions of risk management, lessons learned, and conclusion. Also created full scale estimated budget.

IX.2. John Kruger

As the system engineer and drill lead, he was responsible for the design, construction, and testing of the drill, along with its integration with the other systems. Because the drill is the main tool for completing the mission task of collecting samples at various locations, it was critical that this component would be functional. After a number of redesigns to make the drill more compatible with the available tools, he machined the drill himself, along with the welding and metal cutting required to make the part functional. This subsystem included complex wiring to transmit power to the internal motor while the drill was spinning, as well as structures to ensure the drill would remain stable while spinning a large weight. A drill carriage was also constructed to move the drill up and down into its drilling position. Verification and validation testing was conducted on the components of this drill, ensuring proper operation once it was integrated into the rover. Work was done with the machine shop to tig weld the aluminum structures on the drill carriage. Assisted in other construction tasks, helping with the rover body and top, as well as wiring batteries.

IX.3. Colby Moore

As the structures and mechanisms lead and systems engineer, he was responsible for designing and building the main chassis and structure of the vehicle. This was done in efforts to optimize strength and weight while considering the needs of subsystem integration. Assisted in the mechanical design from ideation to manufacturing, including selecting appropriate materials, structuring the chassis, and developing an effective build strategy. Performed mechanical system integration on the rover's chassis, ensuring all systems work together effectively by interfacing mechanical, electrical, and propulsion components. Collaborated closely with team leads to resolve fitment, mounting, and load distribution challenges during assembly. Conducted structural validation through iterative testing and refinement, ensuring the rover could withstand operational loads and terrain interactions. Documented chassis and body design decisions, fabrication processes, and system integration procedures to support future design improvements.

IX.4. Ethan Jamroz

As propulsion lead, designed and implemented the complete six-wheel motor control system for the REHT rover, including electrical integration of three Drok L298N motor drivers with the Raspberry Pi 5 GPIO interface. Discovered and resolved the critical 3.3V logic power requirement that enabled reliable motor operation. Developed Python control software using the lgpio library for bidirectional motor control and skid-steer differential steering. Conducted comprehensive verification and validation testing, including individual motor function tests, integrated mobility demonstrations, and obstacle traversal experiments. Documented complete motor control system architecture, GPIO pin mappings, and inverted logic behavior through experimental testing.

IX.5. Rushi Faldu

As the thermal lead, his main focus was on designing and manufacturing both the active and passive thermal systems. He did the coding to get the Peltier coolers to run automatically in tandem with a temperature probe. Additionally, he manufactured and coded the spectrometer functionality for the payload subsystem. He worked on the Raspberry Pi 3B+, the Pi camera module, spectrometer arm assembly, and the ultrasonic sensor. All verification, writing portions for the spectrometer, and thermal sections were also all written by him. Lastly, he assisted with some of the coding and verification for the ground station/communications subsystem and the design and manufacturing of a part of the storage system.

IX.6. John Coyne

As payload lead, his main focus was on manufacturing the storage system. Other subsystem manufacturing includes assisting with systems adjacent to storage, such as the spectrometer and the thermal systems, though was not the lead for said systems. Conducted the verification tests for storage and assisted with the tests for the spectrometer, thermal systems, and ground station as well. Lastly, alongside writing for the storage section deliverables for both reports and presentations, wrote much of the additional sections such as project purpose, work breakdown, schedule, budget, risk management, and the course reflection. Assisted in writing other sections and deliverable formatting as well when time permitted.

IX.7. James Meister

As Communication and Ground Station lead, his main focus was the manufacturing, implementation, and coding of the two way communication system between Reht and a student laptop. He accomplished this by using public 915 Mhz radio waves and two LoRa (Long range network) chips to establish the connection. He then needed to write code so that the two chips could recognize and talk to one another. Finally to establish full control over the rover, he needed to connect the Raspberry Pi 3 to the Raspberry pi 5 through an ethernet connection while allowing the two SSID's to have full access to each other. This system would contribute as the main link between all of the other subsystem on the rover and give the students a way to peer into the rovers actions from a distance. This require heavy collaboration between the payload, thermal, and propulsion team leads.

X. Conclusion

X.1. Summary

To conclude, the Rover for Extraction of Helium Three is a multi-faceted system designed to be capable of surviving and navigating on the lunar surface for extended periods of time by utilizing solar power and lithium ion batteries. It will use state of the art technology such as a laser induced breakdown spectrometer and rotary percussive drill system in order to detect hotspots for Helium-3 across the lunar surface, and take samples at up to 3 meters in order to broaden our understanding of where this key resource is located across the moon. These samples will then be stored at freezing conditions using a witness tube system with passive and active thermal regulation in order to ensure minimum off-gassing. Throughout this process REHT will be in regular communication with earth through connections to lunar satellites, sending updates and data, and receiving updated instructions and terrain data. Using this, in conjunction with stereo vision and accelerometer data, REHT will map its surroundings and chose the best path to reach its destination.

Once the mission is completed, REHT will return to the ascent vehicle, store its samples, and repeat until all desired sites have been sampled, then make its final trip to the ascent vehicle and return to earth for more detailed analysis.

The subscale of REHT showcased much of the functionality the fullscale is meant to exhibit. Between the navigation and controls, propulsion and suspension, drill, storage, spectrometer, ground station, thermal regulation, and power, much of the subscale REHT's systems were well integrated with each other. Even those that weren't, given some additional time and some changes to the design can they run in tangential with each other. Thus, may REHT serve as a baseline for future terrestrial lunar missions.

X.2. Acknowledgments

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XI. Appendix

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