Singapore Space Challenge 2020-2021
Team Lunarage Mission Report

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1. Mission Objective

The objective outlined in the Singapore Space Challenge of 2020 is to create a rover that is capable of lunar exploration and excavation. In this paper we detailed our proposed lunar rover design that responds effectively to this objective.

The primary objective of the lunar rover is the extraction and collection of research samples at deep-ground without contamination, allowing for efficient and effective analysis. The topsoil of the lunar is primarily composed of fine particles of dust several hundred thousand years old. Layers of the soil are relatively undisturbed, therefore layers are logically ordered by their time period. The deeper the samples are collected, the older the samples would be. As such, samples from a range of layers can help construct a geological timeline of the Moon and other surrounding celestial bodies that may have interacted with it.

Excavation should dig an adequate amount below the surface, without distributing dust and other "waste" that could potentially reduce vision of the target or set on critical components such as the wheels, reducing maximum speed, and or the solar panels. After excavation has been performed, a full sample needs to be collected. To provide a fair assessment of the location, the sample retrieved should be as much as possible. The lunar surface is not a constant: there may be impurities that are unable to be processed by the excavation modules. Objects that are too large or tough for the claws must either be avoided properly or broken down. Finally, a collected sample should be transferred to its container for storage whilst minimizing the amount of the sample lost. The container should be sealed well, with minimum potential for the sample to leak out. Depending on the objective of the mission, the amount and specificity of the samples collected may change. Our design should overcome these three base challenges before focusing deeper on performing extremely well on one of them. We believe that our design does so. Below are additional, more specific objectives we aim to achieve.

1.1 Efficient Sample Collection

A question that arises when considering how to tackle the problem of excavating lunar material is whether or not a priority should be given to excavating materials efficiently. Having a rover that is capable of efficient sample collection enables less resources to be expended when collecting resources the same amount of material but often comes at the cost of other goals or metrics. Efficiency is especially important in lunar excavation and exploration as resources that can be transported and used on the Moon are limited severely by the maximum payload of the mode of transportation.

1.2 Precise Sample Collection

Precise sample collection proves to be a challenging task for any excavation technique as targeted areas are often surrounded or covered by other samples that may contaminate the area of collection. Many traditional collection methods involve excavating the surrounding region, to access the desired region which often takes excessive time and resources. A precise mechanism that would target a region with pinpoint accuracy without the need to disturb large amounts of surrounding material would be most ideal for excavation.

2. Lunar Conditions

The Moon is theorized to have been formed from the collision of the Earth and a planetesimal, with a thorough mixing of the colliding bodies. Since the collision and the formation of both the Earth and Moon, the Moon has gradually been drifting away from the Earth.

Team Lunarage intends to deploy the lunar rover at the Northern rim of the Peary crater, which is located 88.5 degrees North and 30 degrees East. It is the closest crater to the Northern pole of the Moon. Because of this, in conjunction with the angle of the Moon's tilt, it receives constant illumination, thus providing a continual supply of solar power for the rover and a lunar base. Solar energy can be harnessed in different ways, such as use for In-Situ Resource Utilization (ISRU) mechanisms.

2.1 Lunar Topology

The lack of wind results in a relatively flat lunar surface with few sharp edges. As such, the lunar surface is comparably smooth and less arduous to traverse. Large craters are scattered around because of the numerous impacts from asteroids the Moon has endured.

2.2 Lunar Geological Makeup

The lunar soil on the surface is composed primarily of several elements, including: silica, alumina, lime, iron (II) oxide, and magnesia. Recently, patches of water have been confirmed to be in several regions of the Moon that are under sufficient shade from the LCROSS satellite data as shown in Figure 1.

2.3 Lunar Weather

There is a distinct lack of an atmosphere on the lunar surface. Because of this,wind currents are nonexistent, contributing to the relatively flat, smooth surface. Temperatures on the Moon vary between -180 to 100 degrees Celsius. The drastic difference exists because unlike the Earth, the Moon lacks greenhouse gases and an atmosphere, as well as effective ways of absorbing the solar energy. The temperature range found in the target deployment location is from -50 to 100 degrees Celsius. Research performed found that, in the Peary crater, the average area is between 69.5 and 82.5 percent lit up.

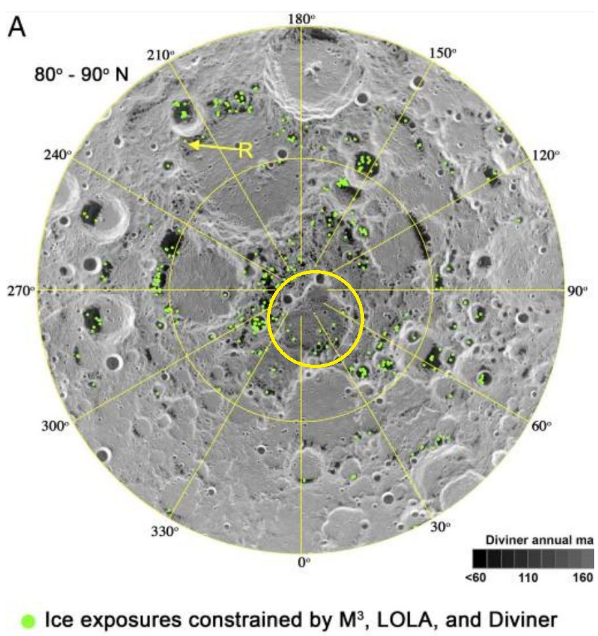

Figure 1. Water Detected On Moon (Li et al, 2018).

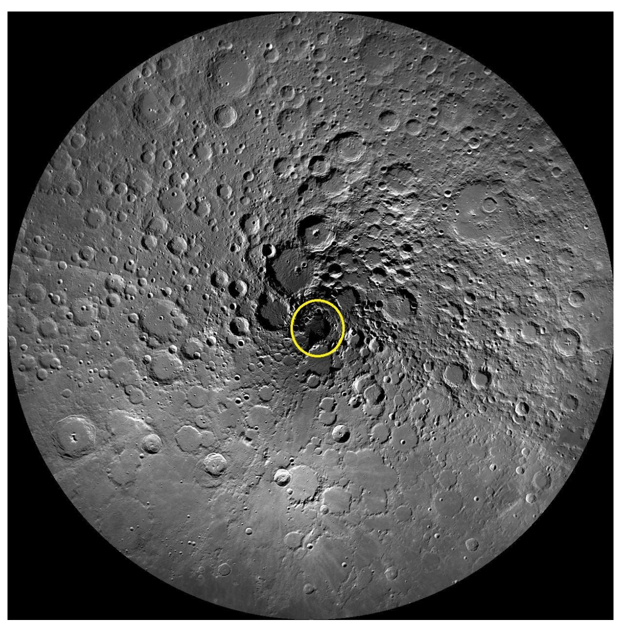

Figure 2. Peary Crater (NASA, 2017)

3. Mission Proposal

3.1 Overview

3.1.1 Design Overview

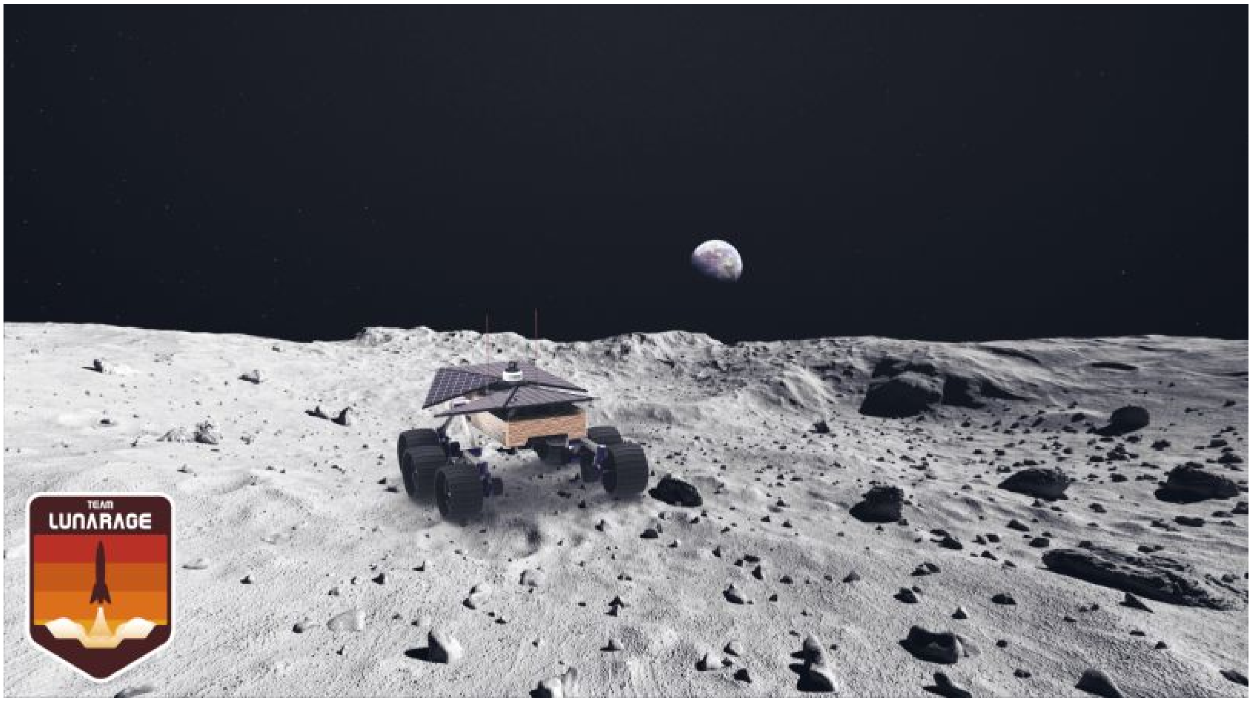

Figure 3. Rover in Lunar Environment.

To accomplish the main objective, Team Lunarage proposes a lunar rover (Fig. 3) with a flexible, unique mechanism for excavation and sample collection inspired by moles. Differing from traditional excavation mechanisms, this design would dig and traverse around the lunar environment similar to how a mole would. This mechanism enables a wider range of motion when excavating into the dirt, allowing for more difficult sample collection to be achieved while being as precise and efficient as possible. Furthermore, because of its extensibility, samples can be collected from a great range of depths from the surface without having to disturb large amounts of surrounding material. This paper introduces the aforementioned mechanism, and details of the other components that comprise the lunar rover that allow for maximum efficiency to be gained with sample collection.

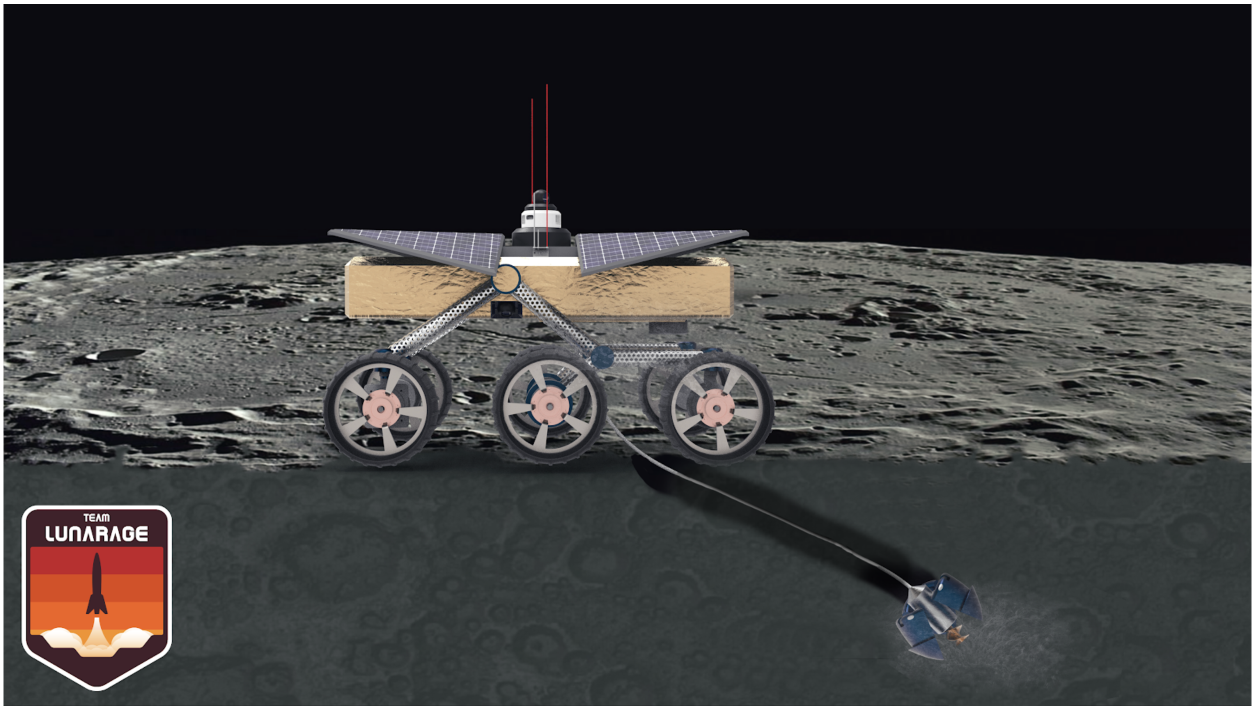

Figure 4. Excavation Mechanism Deployment.

The prompt for this competition asks competitors to create a rover that is capable of excavation or ISRU missions. This team chose against doing ISRU onboard the rover due to the given size restraints (1m x 1m x 1m) and the missions system we planned to integrate made having built in ISRU inefficient and interfered with other mechanisms. Many ISRU modules require large amounts of energy and space to properly extract, purify and utilize said resource, with water being a key example. We did not, however, let these constraints limit us, and modified our excavation mechanism to be able to excavate beyond those constraints (Fig. 4 and 5).

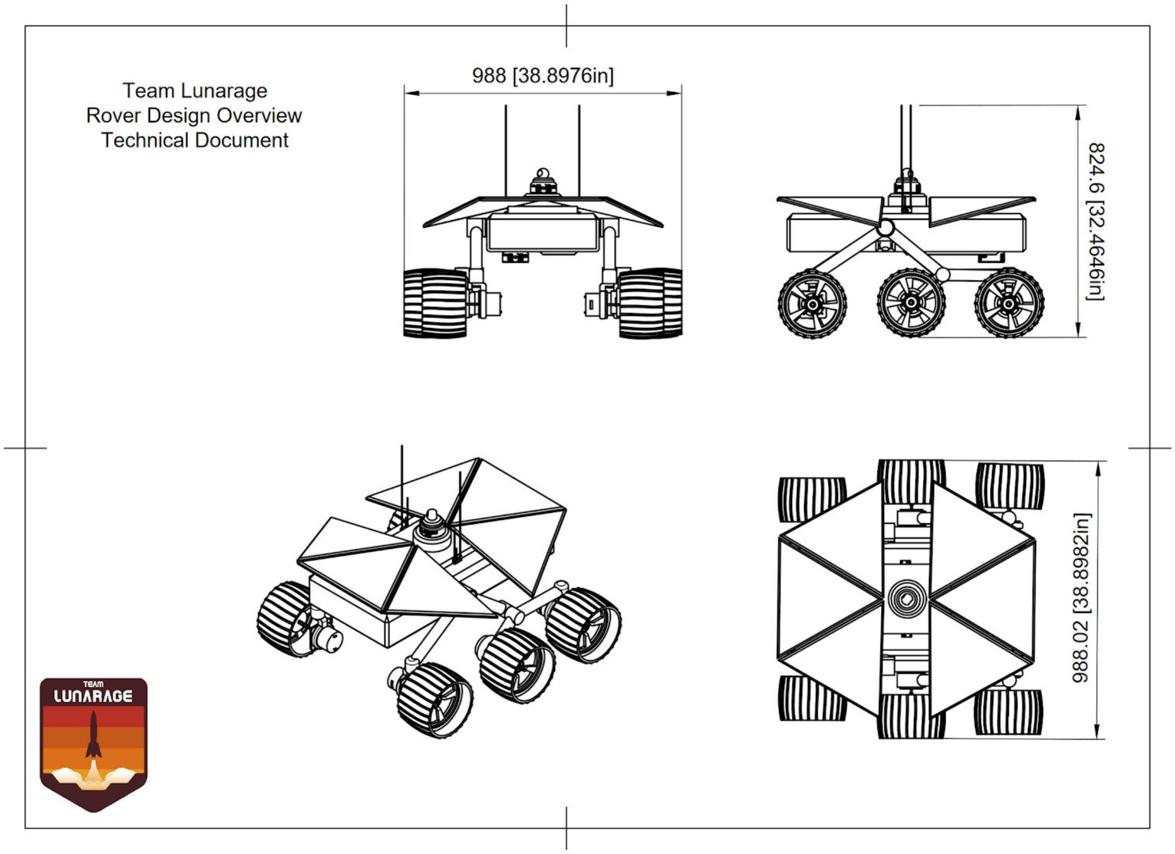

Figure 5. Rover Design Overview Technical Document

In particular, we aim to focus on excavation that allows for the collection of samples for scientific research purposes such as water, ice, and soil samples. Water is a resource of increasing importance, and with the relatively recent confirmation of the presence of water on the Moon, it is critical that analysis be performed on the water samples. Doing so would provide a greater understanding of the resource's availability and quality on the Moon. Water additionally can be used as a consumable resource to further the mission, whether it be restocking the lunar base's water supply or generating hydrogen fuel through electrolysis.

Understanding the elemental composition of the differing layers of lunar soil would also provide insight into the geological development of the lunar surface. It is imperative to record the changes of elemental composition in the different layers, as it may help point towards key events in the Moon's history.

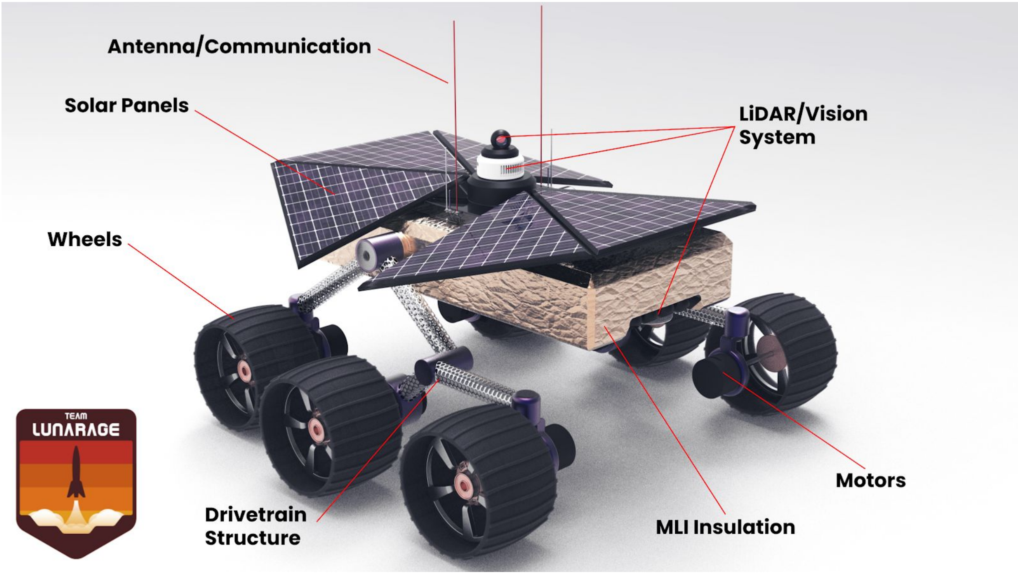

Figure 6. Rover Overview.

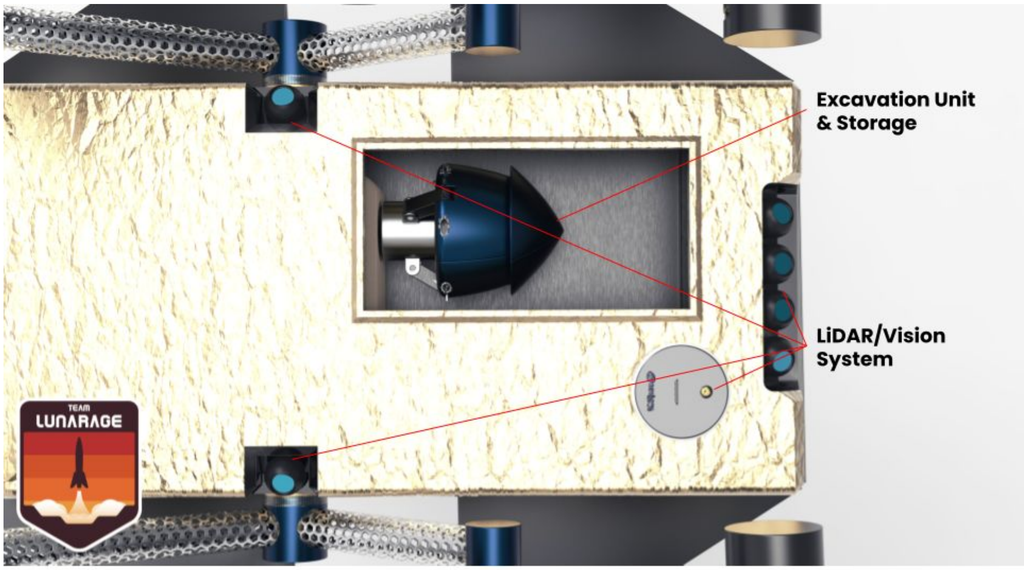

Figure 7. Rover Underside Overview

3.1.2 Costs

Material and Manufacturing Cost Analysis excluding Research and Development costs

System	Material/Raw Cost	Fabrication/Manufacturing Cost
Excavation/Sample Handling	$9,320	$9,850
Main Body	$16,800	$5,400
Power System	$6,500	$500
Vision/Sensing System	$4,000	$200,000

Computing/Communications System	$8,000	$300,000
Subtotals	$44,620	$515,750

Estimated Total Cost of Rover: $560,370 SGD

3.1.3 Weight Analysis/Breakdown

System	Weight
Drive	6kg
Main Body	21kg
Power System	25kg
Vision/Sensing System	2kg
Computing and Communication	0.6kg
Misc.	<2kg

Estimated Total Weight: 56.6kg

3.2 Excavation

3.2.1 Overview

The subsystem responsible for excavation and sample collection is a tethered claw combined with an integrated capsule that doubles as the method to collect samples and store samples. The design of the claw was inspired by not only the shape of a moles claw, but also the motions that accompany it. It works on the principle of excavating and compacting lunar soil around the claw in order to burrow into the soil and navigate in all 3 axis of movement. The total estimated cost of the subsystem is located below.

Module	Material Cost	Manufacturing Cost
Custom Milled Titanium Claw and Case	$3,000	$7,000
6x Intake and Sample Collection Capsule	$300	$600
3D Printed Intake and Sample Collection Capsule	$20	$50
Tendon and Intake Motors	$2,000	$0
Kevlar reinforced PTFE Flexible arm Tubing	$1,500	$200
Misc.	$2,500	$2,000
Subtotals	$9,320	$9,850

Note. Costs calculated in $SGD and are a rough estimate of the final costs.

3.2.2 Biological Inspiration

To further understand the function of our excavation subsystem, it is critical that moles, the inspiration of the subsystem, are understood.

Moles are organisms whose forelimbs provide them the specialized function of burrowing deep into dirt. Because of the structure and motion range of their forelimbs, moles have the ability to burrow through dirt that is both compact and loose, digging as deep as 40 inches, and as fast as 15 inches per hour. As such, they are adapted to a wider variety of earth's surfaces. Team Lunarage takes inspiration from the specialized burrowing function of moles to design the proposed rover's excavation mechanism.

The biological design of moles' forelimbs allows them to burrow through dirt almost as if they were swimming through water. Moles are able to generate a digging force equivalent to more than 30 times their body weight. This is enabled by the situation of their forelimbs closer to the rostrum region, with their palms facing laterally. Their elongated nails help sink their forelimbs into the dirt, and the added surface area to their forelimbs allows for more dirt to be displaced. The muscle which controls wrist movements in mammals facilitates the transmission of force from the humerus bone to the widened palm. Furthermore, because of the structure of their short and wide humerus, the teres major muscle has a larger attachment area, contributing to about 75% of a mole's forelimb muscle volume. These biological specializations empowers the mole to have the impressive function of efficient burrowing.

Moles use their hands to plow out soil and navigate through the environment as shown in Figure 8. Their claws create a gliding motion that pushes material to the sides and allows their bodies to move towards an inner location.

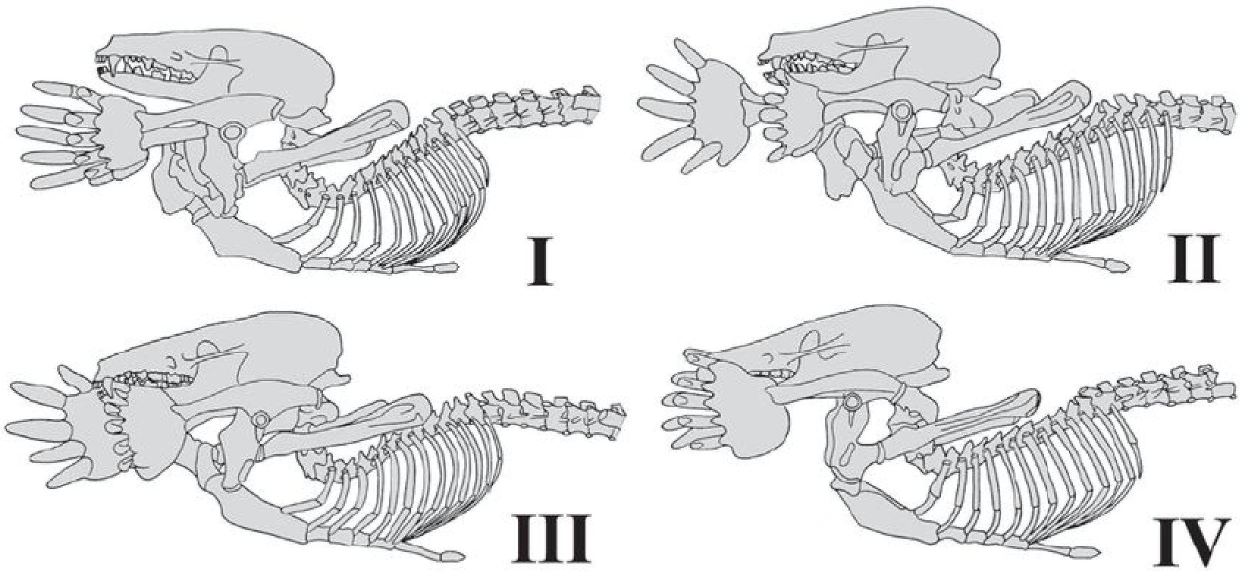

Figure 8. Mole Digging Sequence. (Lin et al, 2017)

The higher the porosity of the soil, the more efficient moles are at burrowing through dirt. Since the porosity of the lunar soil below the surface is measured to be roughly 50%, creating an excavation mechanism similar to moles's forelimbs would result in more rapid excavation. The style of the tunnels that moles excavate is dependent on the compactness of the soil. Since only surface excavations will be performed, the compactness of the soil on the lunar surface is relatively loose. In looser substrates, moles perform "elevating strokes" with their forelimbs. Elevating strokes are executed with a lower velocity than strokes from more compact substrates, with about 14 cm/s for the former and 21 cm/s for strokes for the latter. Elevating strokes were also performed at a lower frequency at 1.91 strokes per second compared to 3.39 strokes per second at more compact substrokes. To emulate moles's excavation functions at looser soil substrates as found on the Moon, strokes should be less frequent and have a lower velocity.

Using a similar system, we can replicate a moles excavation techniques with a synthetic arm that can be pulled in and out. This can be achieved with a flexible membrane with a set of tendon wires similar to those in the main arm. Through this, efficient and precise excavation and extraction of samples from the lunar soil can be achieved.

3.2.3 Claw Design

Our team's design was inspired by the specialized burrowing function of moles. After thoroughly studying the way moles performed efficient and precise excavation, we conceptualized several different ideations that would allow us to perform similar functions on the lunar surface. Our selected design, shown in Figure 9 and Figure 10, has undergone several major developments, evolving to be as efficient, precise, and fault tolerant as possible. The objective of the claw is to excavate through dirt such that the arm is able to reach the desired location for sample location, as well as help navigate the arm in tougher environments.

Figure 9. Claw Design Front View.

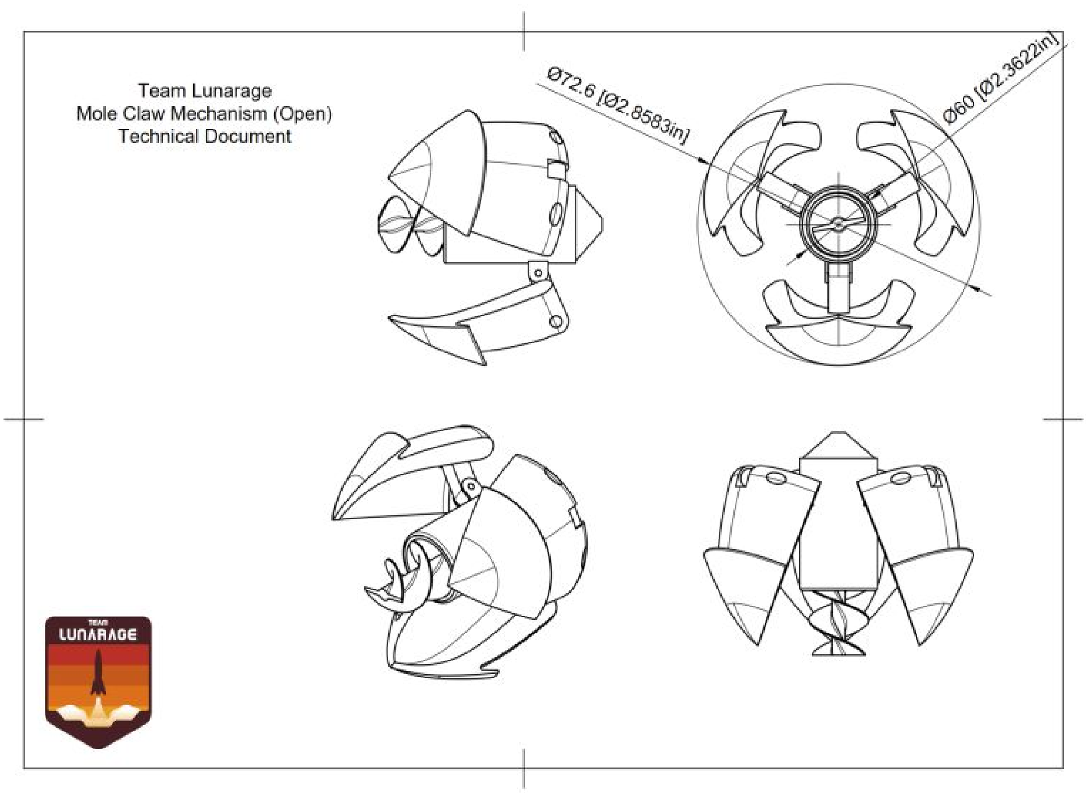

Figure 10. Claw Mechanism Technical Document.

Since there are differing environmental variables between the Earth's surface (particularly where moles occupy) and the lunar surface, there were several design considerations the team concentrated on. One such consideration was the porosity of the soil, which is roughly measured at 50% on the lunar surface. As revealed earlier, the looser the soil, the less frequent moles perform strokes, as well as the lower the velocity of the performed strokes. The statistics derived from this fact prompted us to likewise use relatively lower frequencies and velocities of strokes.

Moles have palms which are disproportionately sized to the rest of their body and forelimbs. These palms, in addition to their nails, provide them the surface area required to push dirt. When considering the length of the forearm relative to the rest of the forelimbs, the design of the claw that was adopted for our design has a longer forearm. While we took inspiration from the nature-developed mechanism of moles, we were constrained by our lack of technical skill, and thus were unable to create a design that fully mimicked the moles' mechanism. We created a design that "compromised", following nature as closely as possible whilst injecting our own mechanical flavours.

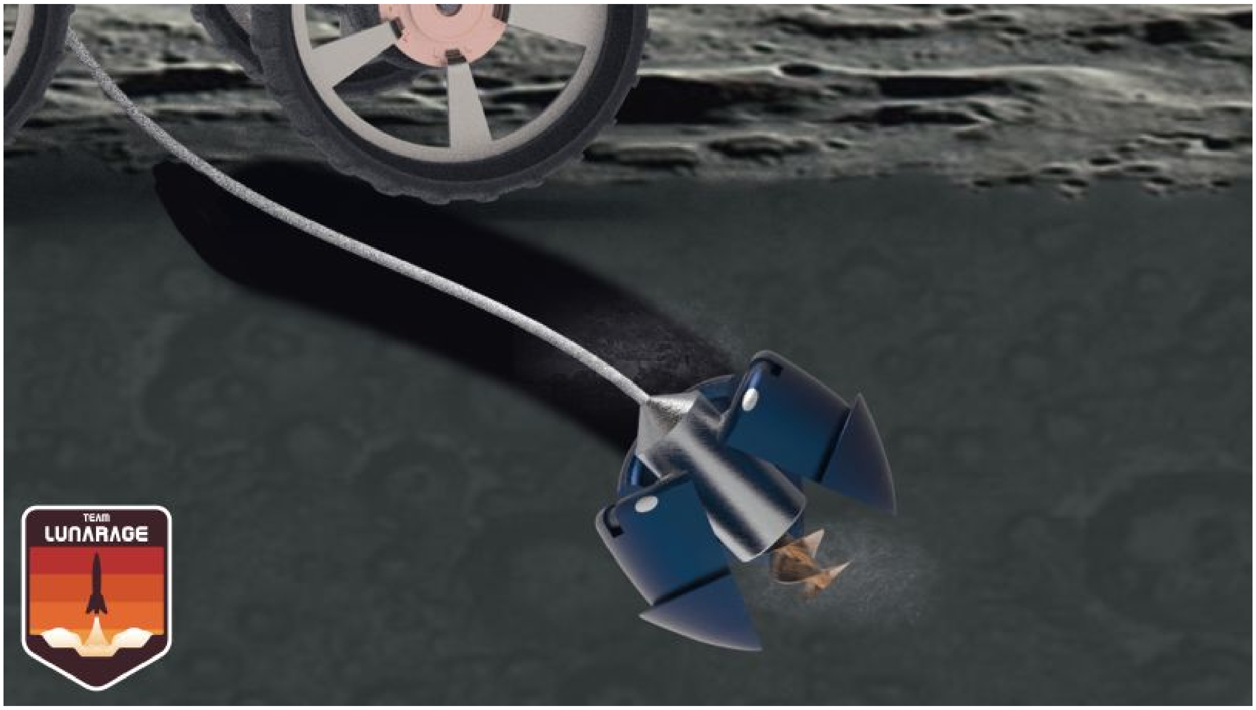

Figure 11. Render of excavation system in use.

Excavation was broken up into two main motions. First is scratching, where the claws initially loosen and dislodge the soil. Once the soil has been displaced to the sides, compression is performed to harden the walls of the tunnel. The mechanical design of our claw utilizes this process for excavation to manipulate its path. A render of this is shown above in Figure 11.

The excavation mechanism, the claw, works in conjunction with the sample-collection mechanism, the arm, to provide the best results in sample collection as possible. The claw has two responsibilities when working with the arm: first, acting as a cap or cover for the archimedes screw; second, serving its role in excavation. When the claws are in a closed position, it provides an almost airtight seal over the arm and Archimedes screw such that it is difficult for the samples to escape. This enables the mechanism to capture the sample and store it, doubly acting as the sample storage. The geometrical structure of an individual claw maximizes as much surface area as possible. During scratching, when the dirt has been adequately dislodged, the claws push back the dislodged dirt for the compression stage.

The arm is furthermore designed to be relatively short. The claws are required to reach the tip of the archimedes screw in a closed position. If the arm was longer, then the claws would likewise be longer, costing significantly more surface area. Since the surface area would be much greater, the force necessary to displace dirt would likewise be greater, costing more energy. As such, the arm was shortened as much as possible, whilst maintaining a length suitable for sample collection.

The design of the arm contains an extruding camera to aid with sample collection. More specifically, it allows the crew operating the lunar rover to determine the location of choice during sample collection, as well as guide the arm towards preferred regions. With the use of infitted gyroscope and accelerometer sensors into the arm, the precise location of the arm and excavation mechanism can be mathematically determined to provide more information to the operating crew.

3.2.4 Intake/Sample Collection

The intake/sample collection mechanism chosen is most well suited for smaller scale precise sample collection for research purposes. In this configuration a screw based container connected to the main rigid head acts as both the main sample collection unit and intake mechanism. Each capsule acts as an independent sample capsule that can be replaced by another capsule by detaching it from the attached threads. The sample collection and intake mechanism is shown in Figure 12 and 13.

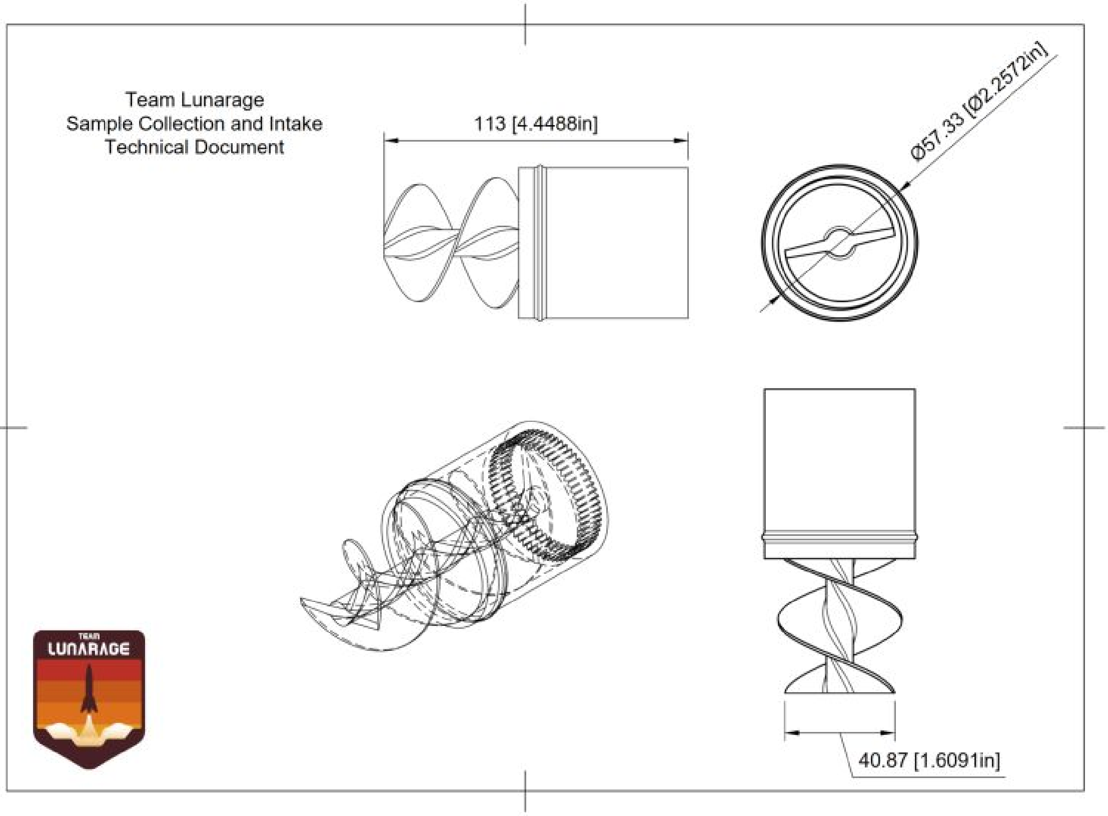

Figure 12. Technical drawing of replaceable Archimedes screw module.

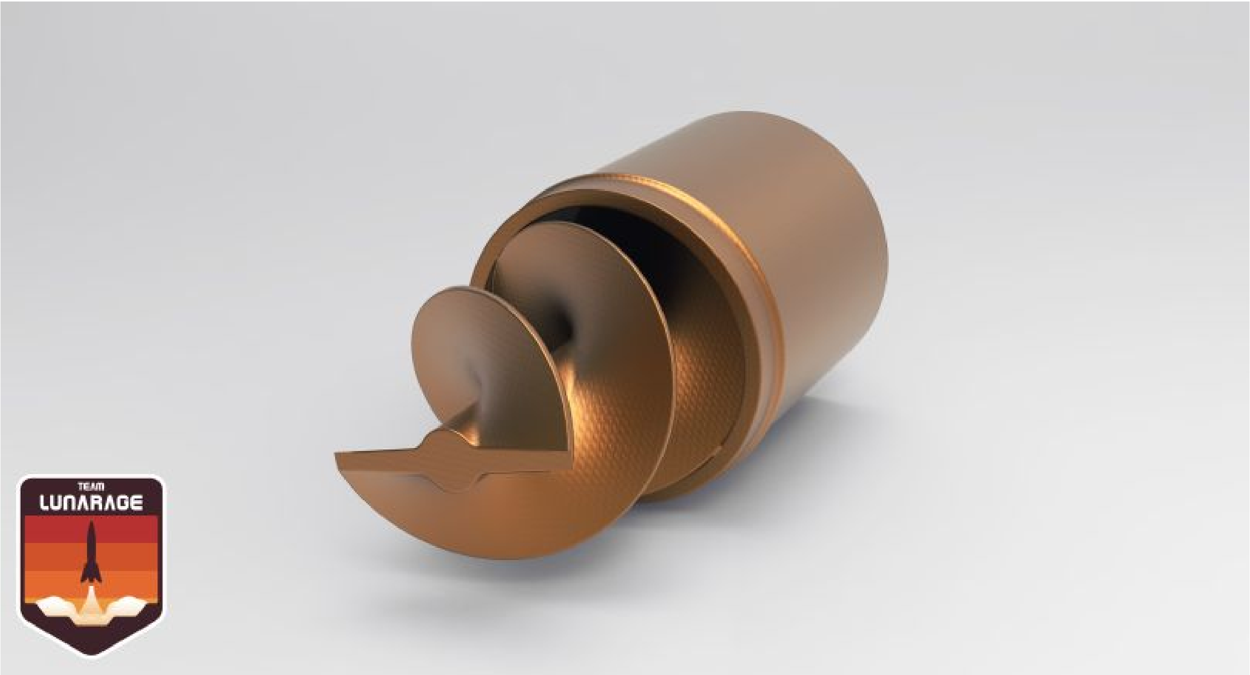

Figure 13. Render of replaceable Archimedes screw module.

The main intake of the excavation mechanism uses a screw that uses the principle of an archimedes screw to transfer materials from the targeted area into itself. The screw is driven by an onboard motor that connects to it with a 3-1 gear ratio allowing for higher torque for the materials to be translated inside. When the motor is turned on, the spinning Archimedes screw would lift the samples onto the main screw and would be moved up from the motion which would lead either to a collection system or other tubing as shown below in Figure 14.

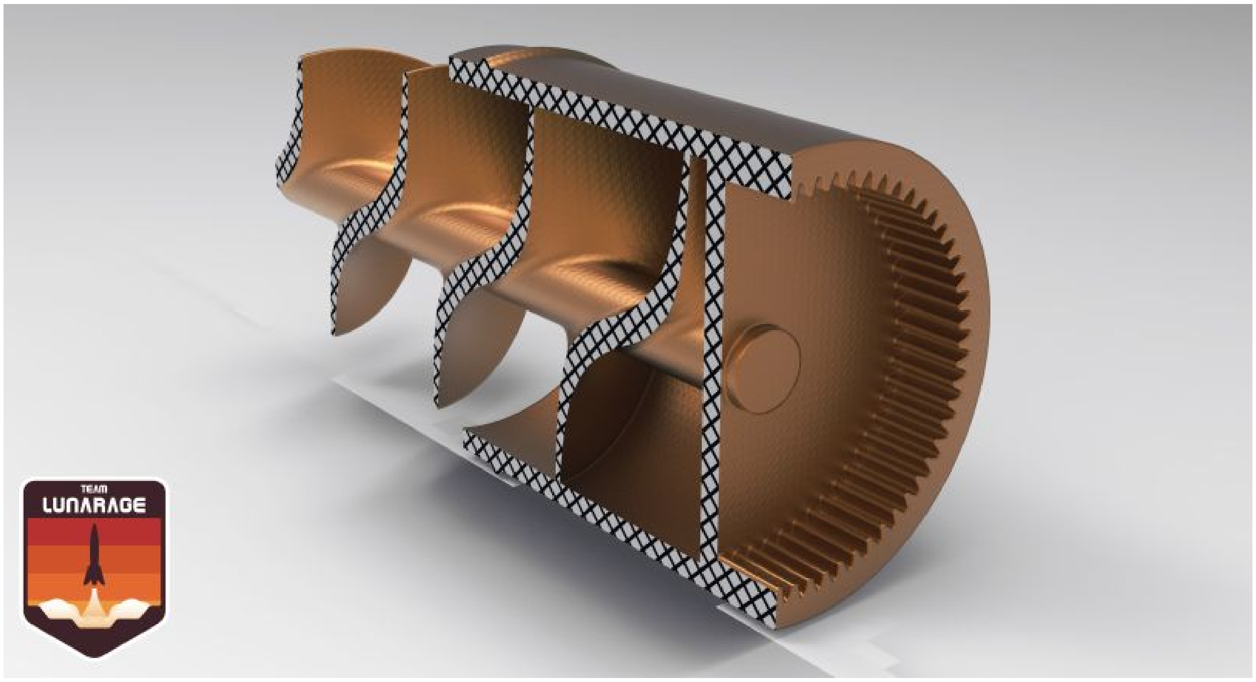

Figure 14. Cross-section of replaceable Archimedes screw module.

When initially configured before samples are collected, a thin disposable polymer shield covers the screw during transportation to the desired location to prevent contaminants from entering the collection system. Once the desired location is reached, the film is retracted using an onboard tendon arm connected to the main gearbox.

Additionally, additional capsules can be created using 3d printing technology if more capsules are required during missions. Low-cost and easily replaceable 3d printed capsules are advantageous in that they can be manufactured on the Moon, resulting in less concern over protection during transportation.

3.2.5 Flexible Arm and Internal Gearbox

A flexible arm connects the claw mechanism to the main body for power and sample collection and moves around in conjunction for excavation purposes. The arm is primarily made of two layers of Kevlar Reinforced Hardened flexible PTFE Tubing with one placed within another.

Acting as a tether of sorts, the arm is configured within the rover where it is able to be deployed or retracted. Internally, the arm is folded in a tape measure like fashion and is able to be drawn out with an internal winch motor. If needed to extend, the motor turns the system and the arm is extruded and vice versa for retraction. A pair of roller wheels help to further guide the flexible arm out during deployment and retraction when needed. This design allows for variable length of the arm without further stress put on the mole claw mechanism and the depth at which samples can be mined at is only limited by the amount of slack tubing. Given the size and current configuration of the rover, the flexible arm would allow excavation up to a meter deep into the lunar environment. An isolated view of the winch system and the claw mechanism is shown in Figure 15.

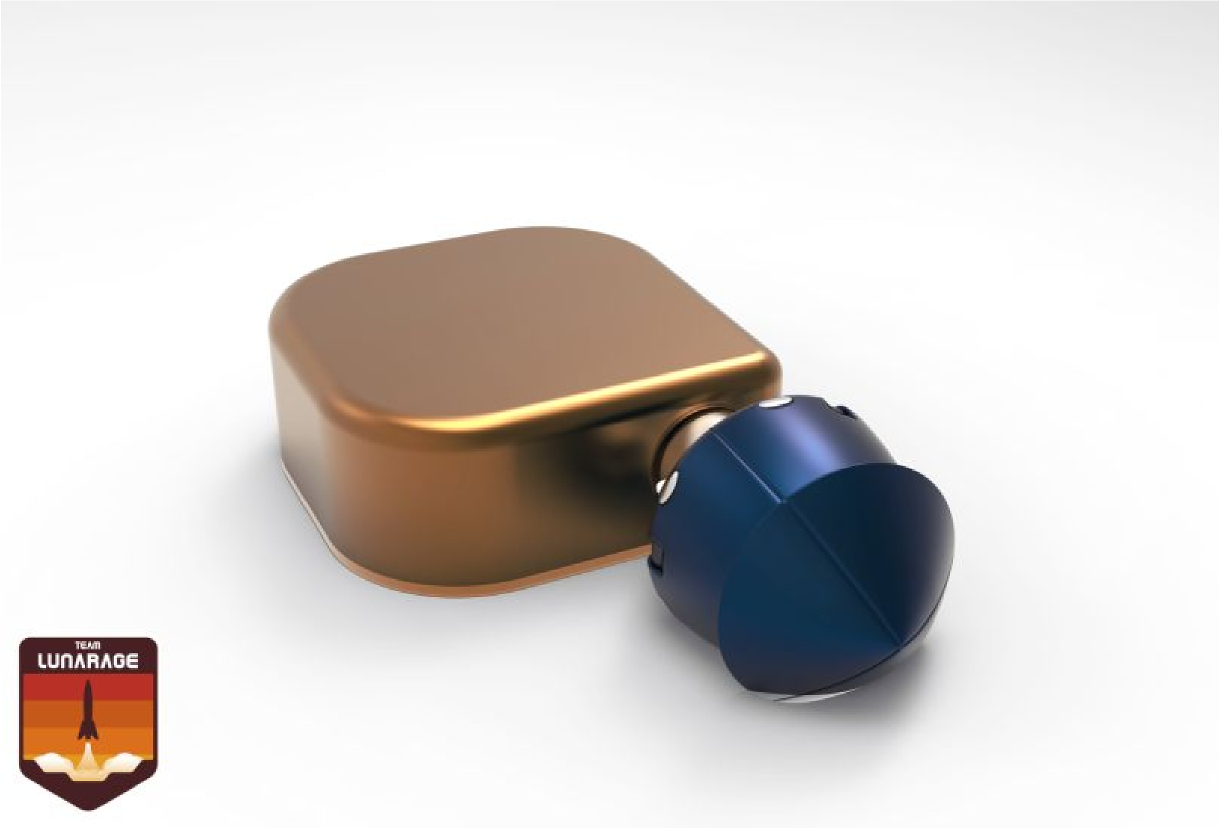

Figure 15. Render of excavation winch module.

3.2.6 Operation

Several stages comprise the sample collection process. Excavation is performed to allow for the collection of harder-to-reach samples deeper beneath the surface. The excavation mechanism, the claw, works in conjunction with the sample-collection mechanism, the arm, to provide the best results in sample collection as possible. Figure 16 shows a 3-dimensional demonstration of the movement achieved by the mole claw mechanism.

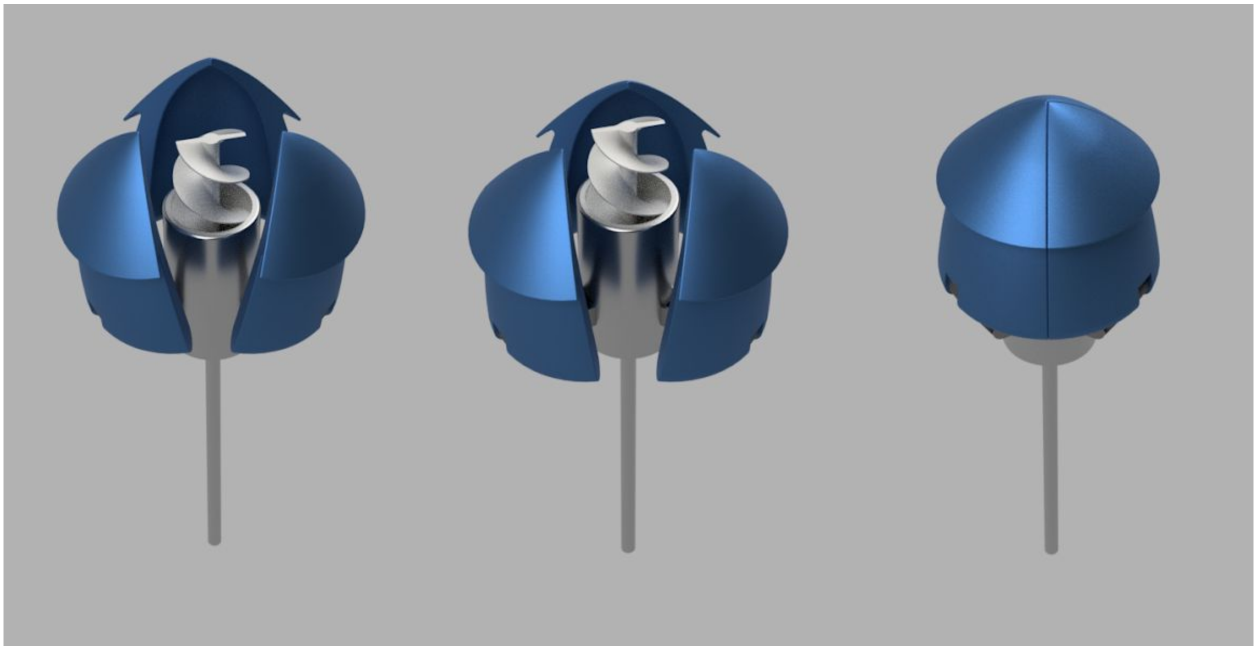

Figure 16. Stages of claw kinematics. Animation can be found here

Stage 1 (Extension)

Prior to performing the sample collection process, the claws are aimed toward the center, partially covering the arm. When the area of excavation has been selected, the mechanism extends towards the selected region. Once the mechanism makes contact with the ground, the claws push outward, dislodging the initial layer of topsoil.

Stage 2 (Compression)

With the assistance of additional sensors and cameras located on the arm of the mechanism, the operating crew has the ability to determine more desirable regions for excavation. Since the maneuvering of the arm beneath the soil is a result of manipulating tendons connected to the arm, the operating crew can direct the arm towards preferable locations. The integration of sensors such as gyroscopes and accelerometers enable the operating crew to be aware of the mechanism's position relative to the target region.

While approaching the location, the claws continuously displace the lunar soil. Each individual moves in a circular motion: pushing dirt away with a stroke and retracting backwards, then returning to its original position. Because this function has to be performed at a certain frequency, a sizable amount of power will be consumed whilst excavating towards the target location. Once the target location has been reached, the collection process is initiated.

Stage 3 (Collection)

When the arm is in contact with the target samples (fig 17), the Archimedes screw activates. Because of the texture of the screw, the samples get caught because of friction as the screw rotates. The rotation continues until the container storing the samples has been adequately filled. At that point, the rover retracts its arm and proceeds to leave the targeted area. To prevent samples from falling out, the claw fully extends out, covering the screw.

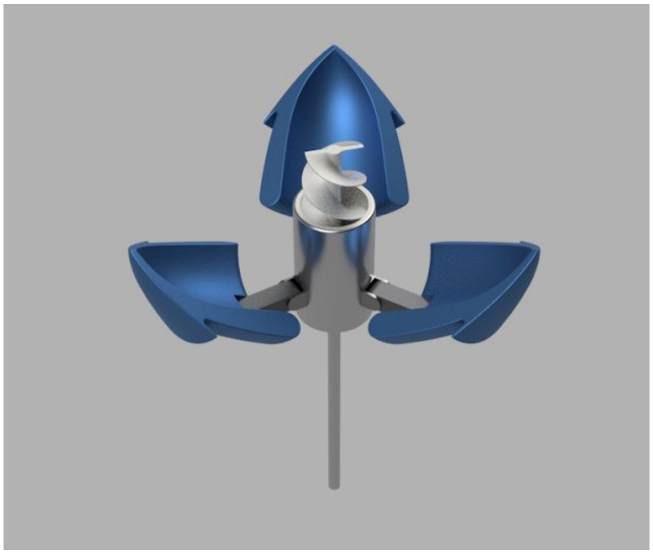

Figure 17. Stage 3 visualized

3.3 Body and Drive

A large metallic main body contains most inner mechanical components of the rover including most motors used in the excavation system,navigation sensors, communication, and computing equipment. Connected to the main body of the rover is the 6 wheel rocker style drivetrain that allows for travel across the majority of environments that the rover will have to travel through (fig 18).

Figure 18. Render of rover drivetrain.

3.3.1 Main Body

The body's main job is to provide protection to the internal components from the Moon's harsh environment, whether it be the surface temperature or radiation exposure. The main body is covered in layers of radiation and heat shielding film that give the base layer of passive protection. Inside the rover body include geiger meters and temperature probes to monitor temperatures and either heat or cool using the contained heating elements. It also provides a structure for our internal components such as the rover control module, kevlar tubing storage, and our rover's batteries.

3.3.2 Drive

This team's rover design is driven by a 6 wheel rocker type drivetrain (Fig. 19) made of aluminum to save weight. Utilizing this drive type allows for maneuverability across bumpy or hazardous terrain. The rover’s wheels (Fig. 20) are made of a strong titanium and nickel alloy called nitinol that are used for long term usage and durability. The drivetrain also makes use of low power DC brushless motors capable of traversing the lunar landscape with minimal power consumption.

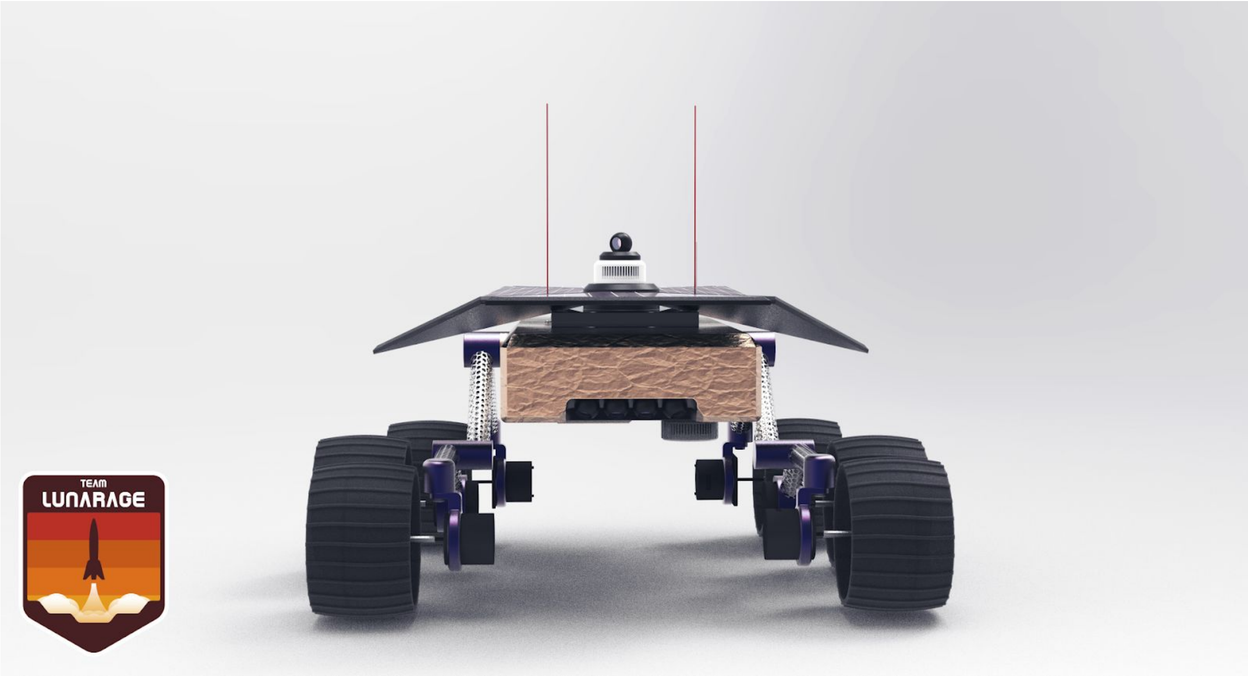

Figure 19. Front view of rover drivetrain.

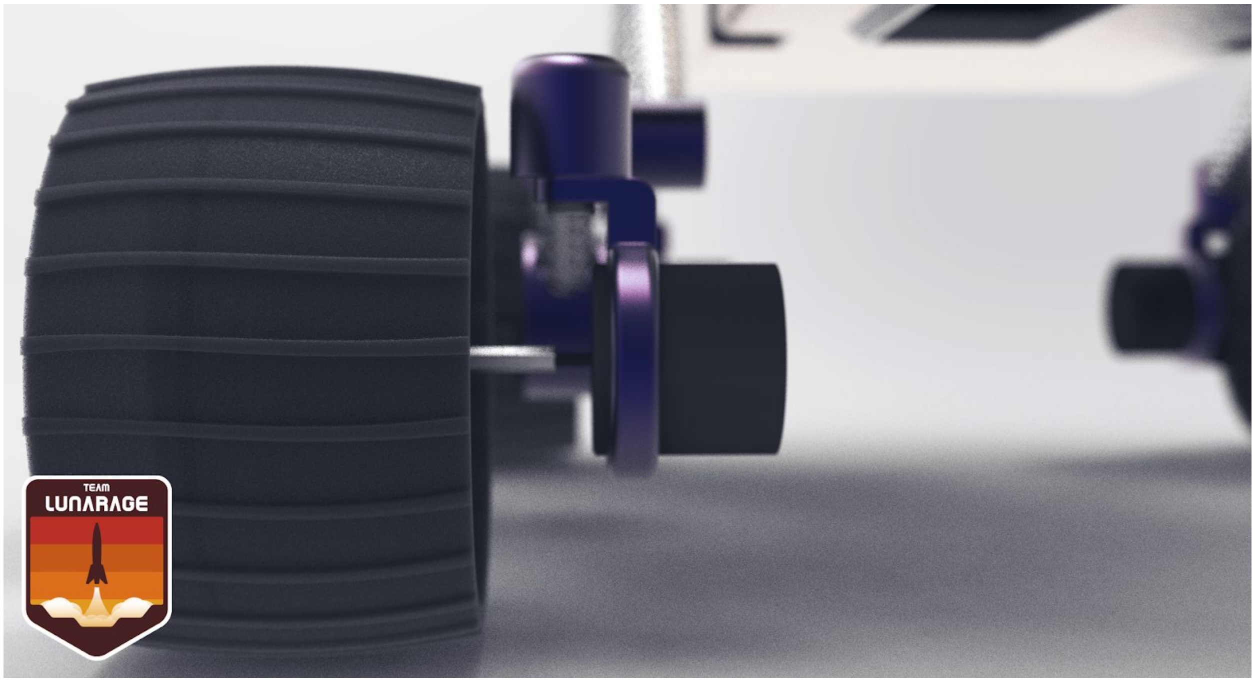

Figure 20. Front render of rover wheel.

3.4 Vision/Sensing

Cameras and sensors enable the rover and engineers maneuvering the rover to gain a stronger grasp over their environment and the various variables that they need to take into consideration. By strategically placing numerous cameras and sensors of differing types, we can increase the overall information collection of a rover's surroundings. When coupled with a strong autonomous driving system, cameras and sensors allow for more efficient data collection and terrain traversal. In this section, Team Lunarage outlines the various types of cameras and sensors, and their selected placement.

With the Vision/Sensor Subsystem, Team Lunarage aims to reduce the technical specifics required to navigate rough terrain. Such specifics can require human effort that could be better invested elsewhere. By constructing a solid Vision/Sensor Subsystem that handles the insignificant details, more effort can be spent on the process of sample collection and analysis.

3.4.1 Camera

In order to achieve autonomous navigation, a rover and its supporting crew need to be aware of the immediate surroundings. More specifically, they need to be wary of any obstacles, such as larger rocks or depressions in the soil.

The most important area that needs to be taken into account is the direct surface in front of the rover, as that is where the rover will logically travel to. Team Lunarage's rover installs a series of four front-facing hazard cameras, horizontally aligned, as shown in Figure 21. These cameras have the same angle of rotation to the ground, but have different angles from the center of the rover, as shown. Because of these differing angles from the center of the rover, engineers are able to better estimate the size of obstacles and have better depth, similar to how humans have two eyes.

Figure 21. Render of LiDAR and vision system.

The area behind the back of the rover is another space to take into consideration. Team Lunarage's rover also places a series of back-facing hazard cameras to the rover on the rear, to allow for precise reverse-driving.

Hazard cameras in the front and back enable the rover and its crew to effectively traverse rough terrain by providing visuals that allow the crew to identify obstacles in the rover's immediate vicinity. Team Lunarage also installs fixed navigation cameras that allow the crew to view the surroundings up to a long distance.

A navigation camera is installed at a higher position on the lunar rover than the hazard cameras, allowing the operating crew to have a better view of the surroundings. There are fixed navigation cameras installed on the right and left of the lunar rover, as shown in Figure 22.

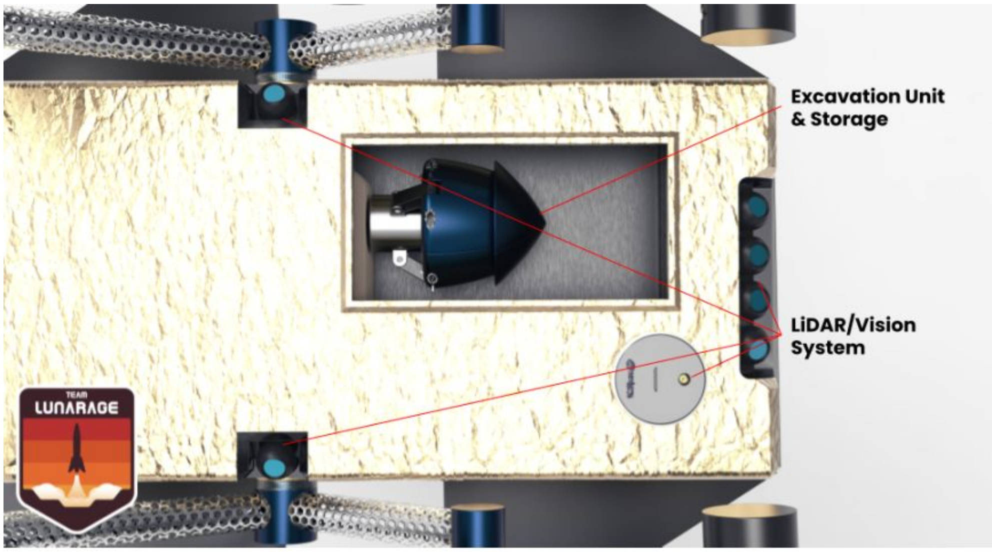

Figure 22. Render diagram of key rover functions.

Two fixed navigation cameras are installed per side to allow for increased fault tolerance; if one navigation camera were to fail, there would be another one to rely on. As such, only one fixed navigation camera per side needs to be active. An additional navigation camera with a swivel mechanism allows the crew to view the surroundings at a specific angle. Furthermore, this additional navigation camera is extensible, allowing it to alter its height to provide greater information and visibility. This camera is atop an additional LiDAR module and is shown in Figure 23.

Figure 23. Render of central LiDAR and vision tracking system.

When the rover is actively navigating terrain, the crew is able to plot its future path with the visual information accrued from the navigation cameras. Thereafter, the rover follows the designated path, autonomously making adjustments with the obstacle information collected from the hazard cameras. This combination of hazard and navigation cameras allow for the rover to focus on reaching its destination, and not the miniscule details of terrain traversal. Thus, the majority of effort is invested in sample collection rather than navigation.

3.4.2 LiDAR

Team Lunarage also installs LiDAR at the front of the rover. Continuous data collection from the LiDAR sensor enables engineers to construct a 3D approximation of the lunar terrain, which is useful for scientific analysis. Furthermore, in low light conditions, LiDAR can aid in navigation, when the navigation cameras and hazard cameras are less effective.

Figure 24. Render of Intel® Realsense™ L515 LiDAR Camera.

LiDAR is conventionally used in indoor, bounded locations, where it is relatively easy to construct a 3D model of the surroundings. In open, unbounded terrains, such as the surface of the Moon, generating 3D models of the surroundings requires a much different method than locations with well-defined boundaries, such as the rooms of a building. As such, a distinct method must be used with LiDAR; instead of generating the model from the entire 360 degree surroundings, Team Lunarage's rover uses LiDAR to dynamically scan only the region of the traversal path. The regions to the side and the rear of the lunar rover are irrelevant for autonomously determining the path of the lunar rover, and thus no data collection is necessary for these regions. LiDAR is used in this scenario to get to a destination faster, through the use of dynamic and autonomous data collection on the region.

The rover uses radiation hardened Intel® Realsense™ L515 LiDAR Camera because of its esteemed efficiency and lower power consumption. Since it is the world's most power-efficient, high-resolution LiDAR, it is advantageous relative to other LiDAR products. Information collected on the terrain is considerably more accurate, allowing for more definite identification of obstacles. Since its power consumption is moderate, the utilization of multiple LiDAR units will not have a significant impact on cumulative power consumption.

The generated 3D model should represent a topographic map of the regions which the rover has traversed and is about to traverse. With a topographic map, the rover gains the ability to autonomously identify obstacles such as larger rocks or troughs in the soil.

Because LiDAR uses lasers to collect information on the distance of objects, it is able to function in low light conditions. This is especially critical in situations where the lunar rover is in a location lacking sunlight, and needs to continue travelling to a destination. With the implementation of LiDAR on the lunar rover, navigating to destinations is overall more efficient.

3.4.3 Spectrometers/Motion Sensors

A series of motion sensors around the body of the rover and onboard the main computation unit help the rover find its exact orientation and tilt. By using this information the rover can far more accurately determine its position and different materials located around the rover. Having a spectrometer to gather this information would be significantly useful when looking for micro cold traps of ice on the Moon. Having a gyroscopic sensor array on the excavation mechanism itself would be particularly helpful in finding and positioning it when it is digging underground. These sensors could allow us to heavily increase the accuracy in samples that we retrieve as we could more precisely select the location in which they are dug.

Module	Material/Raw Cost	Fabrication/Manufacturing Cost
Radiation Hardened Intel® Realsense™ L515 LiDAR Camera	$5,000	$20,000
Hazard and Navigation Cameras, Lens etc.	$2,000	$4,000
Gyroscopes	$400	$500
Spectrometer	$4,500	$1,300

3.5 Computing and Communication

3.5.1 Computing

Rover SBC	Radiation-hardened Custom Fabricated Blackbird VL-EPU-4562
Processor	AMD Ryzen™ Embedded V1202b Dual Core/quad Thread @ 2.3ghz (3.2ghz Boost)
Graphics	AMD Radeon™ Vega 3 Graphics
Memory	DDR4 Dual-channel 64-bit 32Gb 2400Mhz
Power Consumption	15 Watts

Used for onboard image processing, running and controlling mechanisms electrically and maintaining rover homeostasis with onboard sensors to properly address issues. It was decided to use the Blackbird VL-EPU-4562 made by VersaLogic for its small size, low power consumption, and specific design towards military and aerospace applications. These computers will be custom fabricated specifically for the rover. Radiation hardening will be performed to increase the reliability of the computer when it is deployed on the Moon. These computers also have the option for dedicated graphical processing, which is integral to the usability of our extensive LiDAR and vision system. Most importantly however, it was selected because of its rated power consumption of an incredibly minimal 15 watts, aiding with the limited amount of power available when active on a mission.

3.5.2 Communication

Communication onboard the rover includes receiver (Rx) and transmitter (Tx) modules between the rover and the lunar base, as well as the rover and the earth base. The rover primarily uses the communication channel between it and the lunar base. The lunar base transmits information between the rover and the earth base through the use of NASA's DSN (Deep Space Network), which helps facilitate communication with critical space missions. To communicate, ultra-high frequency antennae (Fig. 25) are installed on both the lunar rover and the lunar base. This ensures that the volume of information able to be transmitted is very high.

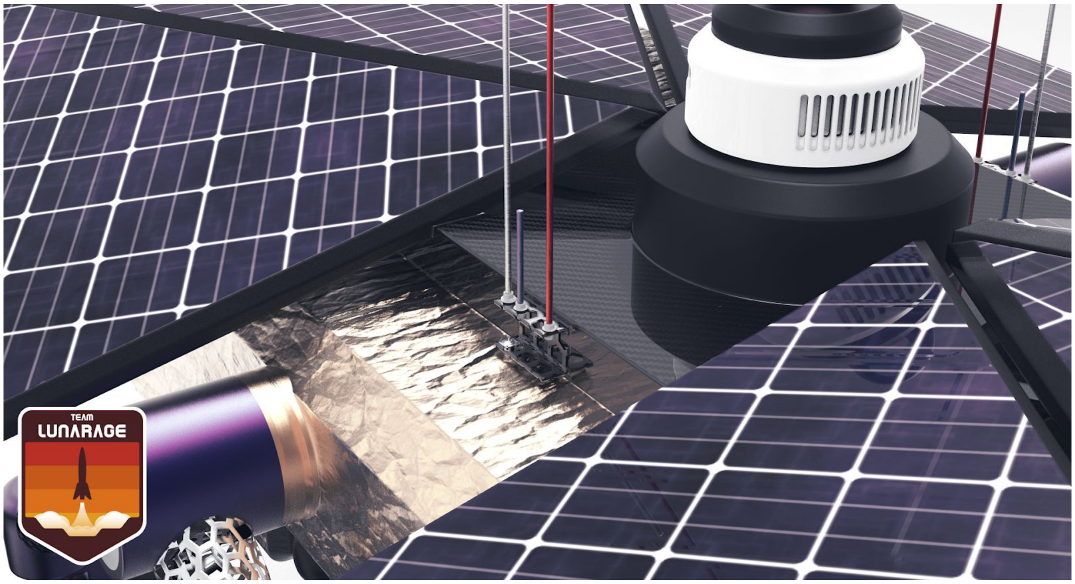

Figure 25. Render of antenna/communications system.

For situations where the lunar base loses its capability to communicate with the base on earth, the lunar rover can autonomously establish connection with the base on earth. If connection between the rover and the lunar base has been dropped for a certain period of time, it will assume independent responsibility to establish that connection.

3.6 Power

3.6.1 Solar Array

The rover's main electrical input comes from a solar panel array housed on the top of the rover that gives a constant source of energy when exposed to the sun. The solar panels onboard the rover are gallium arsenide base panels that can achieve up to 25% efficiency with minimal loss of efficiency over time. Given the total surface area of the solar panels (0.43 meters squared) and efficiency, it is predicted that the proposed rover will generate a peak of 108 watts of power while within sunlight. The solar panel array layout is shown in Figure 26.

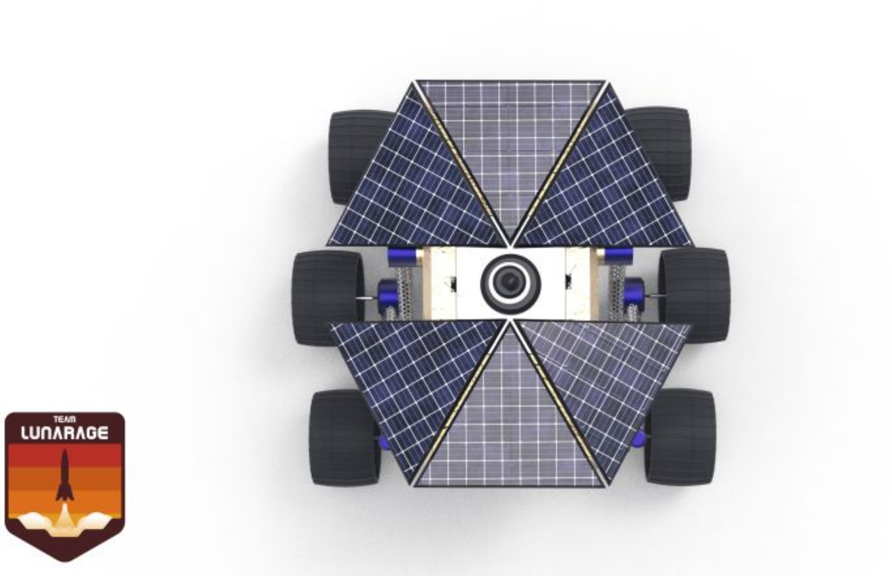

Figure 26. Top down render of rover/solar array.

Ideally, procedural maintenance should be performed at regular intervals. Extra solar panels should be stored on the lunar base in case of a solar panel failing. Every return trip to the lunar base should remove any excess lunar dust or sediment located on top of the solar panels; dust can block a significant amount of energy collection.

Figure 27. Render of rover solar panel.

3.6.2 Battery

Located on the rear inner side of the rover, lithium ion batteries hold power for the rover's operations and allow for constant electrical output when needed. Included within each rover is a main and backup battery both rated for 330 watt hours. These batteries combined with the MLI insulation are also capable of withstanding the temperatures and radiation present on the Moon. The battery module is shown in Figure 28.

Figure 28. Render of rover Li-ion battery module.

A charging connector similar to an electric car is placed onboard the backside of the rover and can be used to charge the battery externally. Additional power can be supplied through connecting with the lunar base while also charging with the solar cells at the same time. The base would ideally be in an area with more solar energy and would have more reserved power.

3.6.3 Power Consumption

System	Avg. Power Consumption during operation (Watt)	Peak Power Consumption (Watt)
Drive	40	50
Claw Mechanism	12	30
Cameras and LiDAR	5	6
Computing/Communications Unit	10	15

4. Direction For Future Implementation

This team acknowledges that improvements can be made to our current design and that the current rover we have proposed is in no way perfect. Given that our team is composed of high school students who have somewhat limited knowledge and experience in this field of study could leave room for improvement in future designs. With more time and resources, further steps would include designing a more efficient sample collection system and a better archimedes screw cover design.

We could also possibly implement a better system for containing our samples in the mechanism once they have been excavated. As of now the only way that the material can stay in the capsule is based off of the tension strength of the claw cables. This has not fully been tested and could lead to material falling out when shaken. Our design could also benefit from more insight into the biological functionality of mola and how their digging behaviour works. This could be used to further optimize our designs efficiency when excavating. Moreover, having a more streamlined design for the rover would allow use to optimize many of the structural and technological aspects of our design. Furthermore as outlined in our other sample collection methods we could possibly implement a new sample collection method into our current design from the ones that we have previously researched.

4.1 Comparison to Alternatives

4.1.1 Alternative Sample Collection Mechanism

An alternative design for sample collection that showed potential was one that prioritized large amounts of collection over smaller scale scientific excavation. This configuration would be ideal for mining or large scale excavation operations for ISRU or other less scientific purposes, but would come at the cost of accuracy due to the large buffer area between the arm and the final collection point and the inability to sort collected materials when shifting. Because of those drawbacks, the team ultimately opted not to use this excavation method. In this configuration, the Archimedes screw would be directly connected to the main flexible arm tube which would lead into the rover body. Although this design was ultimately not chosen for the final design, it could be easily integrated if larger scale excavation is required for any mission in the form of a minor modification to the rigid head and collection system.

A sample collection bag is located at the end of the hollow inner center of the arm for large scale sample collection usage and can be accessed from the bottom of the rover by a human or other operator. Utilizing a flexible folding collection system, this configuration would allow for a large amount of material to be collected at once before needing to be emptied.

4.1.2 Flexible Tube Coring

Potential alternative designs to mole inspired excavation

The alternative design our team saw had the most potential besides our mole claw mechanism was excavation using Flexible Tube Coring. Utilizing a similar intake mechanism to our current mechanism, the coring drill gathered material by drilling material and then capturing the material at the end and storing it inside the coring drill tube. However, our current design allows for more precise and targeted collection of resources without large scale changes to the surrounding environment.

4.1.3 Pneumatic Solution

This team researched a pneumatic solution to lunar excavation that utilized shooting jets of compressed gas into the ground and funnelling shifted samples into a collection system. Because of the large amount of stored gas needed to effectively collect samples and the inaccuracies involved in collection the team decided against using such a mechanism.

4.1.4 Barrel Drum

A barrel drum design would've allowed us to collect large lunar samples as well as store them in the rover. What we realised when testing the feasibility of the design was that it would've been quite inaccurate as well as being considerably bigger and power hungry than the competition's restrictions would allow.

4.1.5 Fracking

Allows for large amounts of material to be collected. However current technology only allows for liquids to be processed through this means of excavation meaning most of the samples we wished to collect would be unavailable. Fracking also proved to be an environmentally harmful process and had the potential to change the well preserved lunar surface.

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