Ground Regolith Unit – A Solution to Lunar Infrastructure using ISRU

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As the frontier of space exploration continues to be pushed forward, the Moon represents an essential steppingstone for the future of space travel. In the past decades, the sights of NASA have been set on the Moon as a potential hub in interplanetary space travel. Building a space hub on the moon requires a level of infrastructure and construction never before accomplished in space. To make this level of infrastructure feasible, utilizing natural materials found on the Moon is ideal as transporting raw materials from earth is exorbitantly expensive. The first step of using lunar material is collection. The Ground Regolith Unit (G.R.U.) is a proposed concept for a lunar material collection vehicle. It is designed to dig up the top layer of sand-like lunar regolith and transport it to a processing site. The G.R.U. will utilize a bucketwheel style digging head and supported by a modified Rocker-Bogie suspension system. It will operate semi-autonomously, equipped with onboard cameras and sensors to navigate its environment. This concept has been designed in accordance with the design requirements and limitations of the C3 COSMIC Capstone Challenge. The G.R.U represents the first step in establishing a new era of space exploration.

I. Introduction

The idea for a permanent base on the Moon dates as far back as 1985 within the United States Air Force [1]. Since then, multiple missions to the Moon have been conducted with the Apollo program, providing invaluable data from the lunar surface and furthering our understanding of the harsh environment. With a new space race on the horizon, the possibility of a lunar base has shifted from the realm of science fiction to the focus of countless industries. Modern-day missions, such as the NASA Artemis program, plan to return to the Moon by late 2028 to expand the next frontier, coupled with yearly visits to build on existing infrastructure [2].

A glaring concern with developing a base on the lunar surface is the exorbitant costs to transport materials from Earth. Current projections by SpaceX price the cost of sending one kilogram to the lunar surface at $100,000 [3]. One popular solution to material limitation is the use of In-SITU Resource Utilization or ISRU. Lunar regolith has become a popular choice for the first step in ISRU because of its abundance and rich material properties [4]. Simple fabrication methods such as laser sintering, additive manufacturing, and freeze casting are the first steps in creating basic infrastructure that will be a steppingstone for early pioneers on the moon. [4].

To effectively utilize lunar regolith for infrastructure, a method to efficiently collect, organize, and distribute the base material is key. Our team proposes the Ground Regolith Unit 1.0 (G.R.U.), a semi-autonomous rover to effectively collect and move lunar regolith. During development, our group identified and focused on researching the technologies most important to gathering lunar regolith with our excavation head and supporting systems taking precedent. Our design of other components such as the wheels, suspension system, conveyer belt, and electronic housing was all created with the focus of increasing the efficiency of gathering and transporting lunar regolith.

II. Technological Outline and Limitations

Before designing G.R.U. specifications and limitations were developed. Specs follow the C3 Cosmic Capstone Challenge: Lunar Operations Track, which gave brief technical limitations. The most rigid outline pertained to the transportation of the device to the Moon. According to the challenge handbook, the device would be transported on the Astrobotic Griffin Lander [5]. In accordance with the Griffin Lander, the following details and limitations were provided.

Table 1 Size, limitations, and assumptions of the Griffin Lander [5]

Factor	Description
Size	The Astrobotic Griffin Lander has a maximum payload size of 40.5 m^3. This included a maximum height of 2.0 meters, and a max length and width of 4.5 meters. Our payload must be smaller than 75% of the lander's volume or 30.375 m^3.
Weight restrictions	The rover developed may weigh no more than 200 [kg] before launch.
Provided electrical components	• 5kWe solar power • Inductive wireless charger • 80W battery (70W for lander system + 10W for construction system) • 8kWhr for each night • 5G relay at 60Mbps

As shown in Table 1, we will be able to utilize solar energy from panels on the Griffin Lander to supply the energy needs of our rover. Our rover will operate by traversing the lunar surface and gathering regolith until its battery has been nearly depleted, at which point the rover will return to the Griffin Lander for recharging. We will have onboard sensors to track how far away from the lander our rover has travelled and calculate how much power our rover will need to safely return to the lander at any given time. As outlined in Appendix A, a potential mode of failure relying solely on the Griffin Lander for our power supply is GRU 1.0's battery depleting and being left stranded. To accommodate this, there will be a solar panel on board which will be utilized in such a scenario. Additionally, a solar panel will extend the rover's operating time. Our final design will use Spectrolab space solar panels with a surface area of 1.419 m^2, which at beginning of life will produce 489.56 W-h [6].

An additional constraint is the actual manufacturing window. G.R.U. 1.0 should enter and exit production within a two-year time frame [5]. This means that any technology incorporated in our design or to be used in manufacturing must already exist or be able to be reasonably developed within two years. Even with this time constraint, it was found there were some features that may rely on technologies designed but not tested.

When examining ways the rover system may fail prior to starting our design process, the following failure methods for the rover were identified in Table 2 in appendix A. One solution for each failure is provided which was further implemented in the design process of the rover.

With these failure methods identified, it became critical for each aspect of our design to introduce the proper solutions to prevent or minimize the chance of failure occurring. In each part and systems design review, the failure methods above were key factors to be addressed before reaching the final design proposal.

III. System Prototyping

A. Digging and Conveyer System

The bucket wheel design is intended to transfer regolith on the ground and into the chassis. The digging design takes inspiration from earth excavators - specifically bucket wheel excavators. Initial prototypes consisted of three different designs with variations in profile and diameter. However, subsequent testing showed that a bucket wheel design was the best option. The chosen design incorporates several modified bucket wheels in parallel to excavate and conveyor the regolith into the main body of the rover. One profile has a greater diameter of 22.75 centimeters and a thickness of 5.2 centimeters. Each individual profile is extruded with ten buckets with roughly 29.8 cubic centimeters of volumetric capacity, meaning one full rotation of the digging bar can collect up to 7151.5 cubic centimeters of regolith per rotation although further testing showed that additional material was excavated. The minor diameter is hollowed out to save material and mass while ensuring strength requirements are met. The full bar of the digging system is separated into three even segments, each containing eight bucket profiles staggered in orientation. The staggered orientation ensures that constant force is being applied against the system so that dynamic loading is avoided. The material of the profiles is made of Ti-6Al-4V although future iterations may incorporate space grade carbon fiber to conserve mass and increase stiffness. A total of 24 of these profiles will be fitted onto the drum motor that will be attached to the top of the chassis by two holder bars that split the entire digging bar into even thirds.

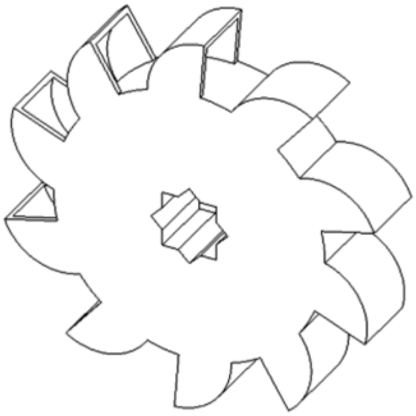

Figure 1: Single bucket profile of digging head.

The regolith dug by the profiles will be transported by a conveyor belt system. The conveyor system will consist of two conveyor belts. The first will be an inclined conveyor belt positioned right behind the digging head.

The regolith will get deposited from the digging head onto this conveyor belt and be transported up to the secondary conveyor belt. The secondary belt is horizontal and spans the remaining length of the chassis. As the regolith is deposited onto the secondary conveyor belt, it moves back further in steps as the front of the belt fills with regolith. This process continues until the entire secondary conveyor belt is filled with regolith. To unload the regolith from the rover, the back hatch opens up and the secondary conveyor belt simply moves all the regolith out through the open hatch.

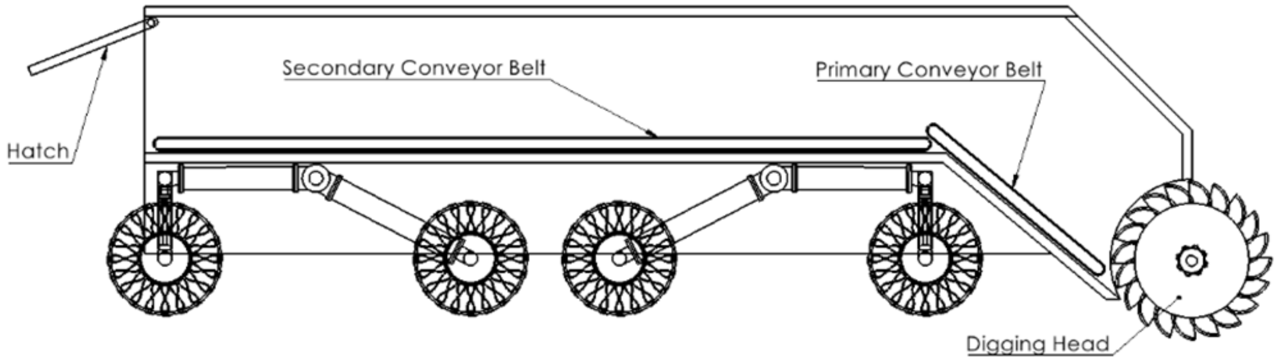

Figure 2: Schematic of conveyor belt system.

B. Suspension and Tires

Damper-spring and Rocker-Bogie suspensions were considered as preliminary options for the suspension system. With a damper-spring suspension, the chassis could move dynamically through its environment and keep all wheels touching the surface. Dampers have a fluid inside that, when compressed, slows motion down and dissipates energy. This makes it ideal when in high speed/high stress environments; however, these suspensions run the risk of fluid leaks and require maintenance [7]. The Rocker-Bogie suspension also provides dynamic movement, but rather than using springs or dampers it relies on a 6-wheel distribution. To stabilize itself, it has a differentiator that keeps the rover from tipping on either side of its main pivot joint. The Rocker-Bogie suspension removes the complexity of hydraulics to remain stable on the ground; however, it is important to note that the Rocker-Bogie suspension is ideal in low-speed environments that do not generate a lot of reactionary forces as it cannot dissipate energy like a spring-damper suspension [8].

Because of the potential for fluid leaks and the environment being low-speed, a modified Rocker-Bogie model was designed. To allow the digging system to contact the lunar surface, the suspension was designed to raise and lower itself without the use of hydraulics or chains as seen below.

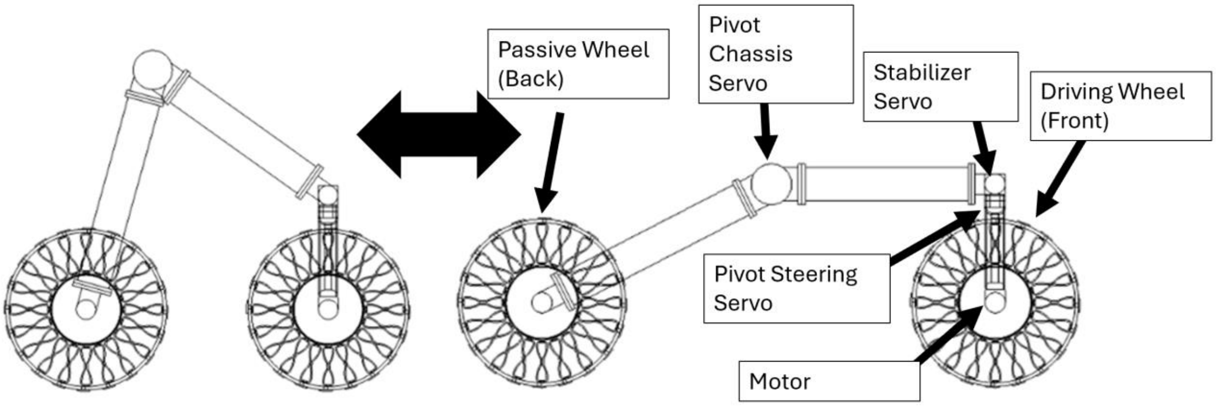

Figure 3: Suspension in raised (left) and lowered (right) positions (Front of rover).

Four pivot points exist on the chassis that connect to a freely rotating subassembly. On the front of the rover, the front driving wheels have an independent motor to move the rover forward and backward. Additionally, there is a pivot servo motor to steer the rover left or right. Connecting to the pivot is another servo motor that serves to stabilize the wheel during chassis raising and lowering. Lastly, the final servo motor at the pivot point connecting to the chassis moves the passive back wheel forward to raise the rover, or backward to lower the rover. This configuration allows the rover to move 13 [cm] vertically. The back of the rover is a mirrored version of the front.

To design the wheels, a trade study was conducted to determine the best style based on durability, weight, complexity to manufacture, and price. The three wheels compared were Bridgestone's second-generation lunar rover tire, NASA’s Spring tire, and a traditional tire with a solid metal contact patch [9]. Each wheel was given a score between one and ten and then multiplied by a weighted score between one and five based on the significance of the given factor. Table X in appendix B reviews the trade study performed for the different tire options.

The Bridgestone second generation lunar rover tire was chosen due to the durability of the design and minimal weight over the Spring Tire and traditional. When looking at the spring tires specifically, the durability over the mission life span became a critical factor in deciding away from the option as the spring tire faced deformations on the Martian terrain track at NASA’s Jet Propulsion Laboratory [9]. With this concern for the spring tire and comparing the possible weight distribution, lifetime of mission, and terrain requirements, it was decided it would be better to follow a concept similar to previous rovers with the Bridgestone tire.

Following the Bridgestone lunar tire design philosophy, we modeled a new tire to fit the design specifications and needs of G.R.U. The wheel was designed to fit the rover's specifications, leading to a diameter of 166.00 mm and width of 133.00 mm. A focus was put on the spokes, adding slight curvature to allow evenly distribution of force among the length of the spokes. The first modeled prototype featured sixty unique contact points for the surface with gaps between, allowing for the tire to comfortably conform with changing weight in the bay of the rover.

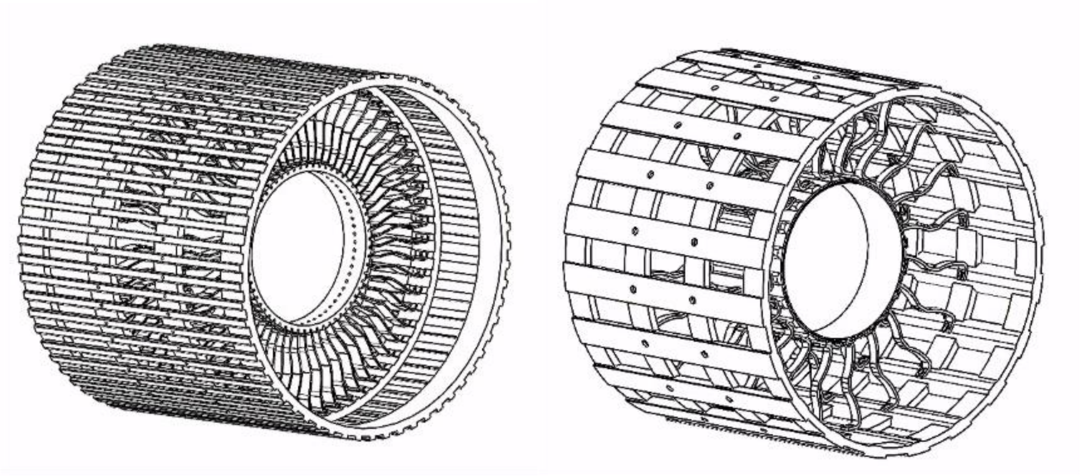

Figure 4: Prototype one (Left) and prototype two (Right).

The first prototype wheel although meeting the needed design requirements, ended up having multiple concerns before strength simulations began. The most major of these concerns was that traditional bolts would be unable to hold down the spokes due to a lack of clearance between each set of spokes. Because of this concern, a second prototype was made, reducing the number of contact points to twenty while increasing the size of each contact point as well as the gap size between.

With the second prototype, all concerns were taken care of, and the prototype passed the initial design phase. Following this, the prototype was simulated using a finite element analysis to confirm its structural integrity. The wheel material was selected to be 7075 Al T6 Wrought, one of the leading candidate materials for the wheel. The following simulation was created using the worst conditions possible to guarantee the functionality of the wheel. The following conditions were calculated and assumed. The complete simulation can be found in Appendix B.

From the simulation we were able to retrieve that with a factor of 2.0 applied to the maximum weight and a factor of safety of 1.5 applied to the maximum torque, we were able to get a maximum stress less than the maximum for 7075 Al T6 Wrought. More details can be found in the appendix on the setup and result of the simulation.

IV. Material Selection

There were many property requirements and failure considerations when it came to the material selection process. We initially identified potential sources of material failure to narrow down usable materials. These sources of failure include fatigue and creep onset due to extreme cyclical changes in temperature, ionizing radiation from solar wind, degradation from electrostatically charged and jagged lunar regolith particles, and outgassing of volatile contents in low-pressure environments. Additionally, all of our materials must meet the flight requirements for our mission. Our rover has been designed to be semi-autonomous, so it is important that our materials are able to hold up structurally for a long period of time without regular maintenance. We must also consider material cost and aim to minimize these costs without sacrificing functionality. All parts inevitably will fail. It is our goal, however, to design our rover so that it can operate semi-autonomously for a substantial amount of time until a permanent lunar base can be established. The landing site of our rover is on the lunar south pole which has extreme temperature changes depending on the location of operation. Permanently shaded regions of the south pole can reach extreme temperatures as low as -250 degrees Celsius while the sunlit regions can reach up to 60 degrees Celsius [10]. Certain alloys used can be made to better withstand this harsh environment through the use of specific tempering techniques and the use of protective ceramic coatings.

Material selection for lunar environments is typically based upon previous lunar missions as the lunar environment is nearly impossible to accurately simulate here on Earth. The materials selected for the parts on our rover will be based upon what has been successfully used in other lunar missions. We conducted principal stress tests on our parts using simulation software to check selection and part design. The tests that our team conducted serve to then influence design changes of our rover and make sure that our system is structurally sound with the materials that have been selected. The following tables contain important properties of potential materials for rover structural components, the digging head, and conveyer belt. The tables found in Appendix D were used to select materials for each of our components. Trade studies based on these tables were used to make initial material selection for key rover components.

For the frame of our rover, having a high yield strength while also staying lightweight was most important for our material selection. Abrasion resistance is not as much of a concern for our frame as it is not directly exposed to the lunar environment. We also want a relatively high thermal conductivity to help dissipate heat away from electronic components and wiring. For these reasons, we selected 7075 grade aluminum for our frame. It has the highest yield strength among aluminum alloys analyzed, a low density compared to titanium and stainless steel, and a much higher thermal conductivity compared to titanium and stainless steel. The panels of our rover which are fastened to the frame and exposed directly to the lunar environment need to have high abrasion resistance as well as be extremely lightweight. We settled on 6061 aluminum as it has a higher fracture toughness and lower density than 7075 aluminum. Additionally, it is cheaper to manufacture as it is easier to form into sheets. 6061 aluminum's lower strength isn't a liability for structural cladding.

The wheels and suspension of our rover require closer consideration as their operations are critical to the success of G.R.U. The suspension system as seen in Figure 3 will need to support the full load of our rover. Additionally, it needs to be able be able to withstand the bending stress associated with raising and lowering the rover. The wheels similarly need to be able to support the full load of our rover with the added requirement of a very high abrasion resistance. The outer shell of our wheel is making direct contact with the lunar surface and will degrade far quicker than previously mentioned parts. We selected 7075 aluminum for our suspension as well as the wheel hub. For the outer shell of the wheel, we will use titanium 3Al-2.5V as it has a high fracture toughness and a much higher yield strength than aluminum and the other titanium alloy we looked at. One concern with using 7075 aluminum for these systems is the alloy's susceptibility to stress corrosion cracking. Even though there is no moisture on the Moon, high thermal cycling can cause propagation of cracks at grain boundaries under high stress conditions. One way to mitigate this is to use alternative tempering paths. For example, the T73 temper is far more resistant to stress corrosion cracking than T6.

When selecting materials for our digging head as seen in Table 6, we looked at carbon fiber, titanium, stainless steel, and aluminum. The current design for our digging head as seen in Figure 1 will be cast/formed out of one solid material. The material chosen will experience high compressive and shear loads as the bucket shears through the ground as well as cyclic loading on the lip of the bucket. We were able to rule out carbon fiber as a viable material as lunar regolith particles would erode the epoxy matrix over time and cut through an exposed carbon fiber surface relatively quickly. This delamination would be catastrophic for our rover's operation.

Ultimately, we decided to use titanium 6Al-4V for its high strength and abrasion resistance. A concern with using titanium for our entire drill head is the added weight that would create. In future design iterations, carbon fiber can be incorporated as a structural shell with titanium surrounding that shell and contacting the regolith.

As seen in Table 7 PTFE film, PTFE-coated glass fabric, Kapton HN film, and Mylar PET film were all considered for our conveyer belt. All these materials are fabrics or films and would be pulled in tension over our conveyer belt system, so it is important that our selection has a high tensile strength. Most importantly, our selection must have a service temperature that is sufficient for the extreme cold and hot conditions. At a first glance at the table, it would seem that Kapton film is the best choice for this operation however it is highly possible that a thin film like this would be susceptible to tearing or even puncture during operation. PTFE film will be used for the conveyer belt because Teflon has comparable service temperature with the added benefit of having a low coefficient of friction. One concern with using Teflon is the high triboelectric charging of the material. Without a way to mitigate this, the finer electrostatically charged regolith particles would stick to the conveyer belt and degrade the system over time. All of the possible materials for the conveyer belt are non-ideal but PTFE film if the triboelectric effect can be mitigated by coatings or by weaving the Teflon with a glass fabric.

It must be noted that these are initial material selections and upon the continuation of this project further, more rigorous testing would need to be carried out to confirm material choice. As the design of G.R.U. continues to evolve, the material selection will need to be re-evaluated. For G.R.U. 1.0 material selection was made for our key operating systems (the frame, panels, wheels, suspension, digging head, and conveyer belt). Further material selection will need to be done for bolts, fasteners, bearings, wiring, etc.

V. Electronical Components

The electrical systems will be responsible for moving the rover, allowing for autonomous and semi-autonomous movement, while also allowing for the main function, scooping up the regolith and allowing for the conveyor belt to carry it into the body, storage, of the rover. Other features of the rovers include multiple cameras, lights, solar panels, batteries, and communications.

C. Communications

Communications are the brains of the rover, allowing for movement, and full functionality. TTC (Telemetry, Tracking, and Command) subsystem is responsible for keeping connection between the rover and earth, where TTC will receive commands from earth and forward them to the computer onboard. TTC uses the three main functions, telemetry, tracking, and command, to communicate with the rover. The telemetry is used for the transmission of system data, like battery health, temperature, and any other instruments on the rover. The tracking function sends information about where the rover is on the lunar surface, and finally the command function receives the encoded instructions and sends them to the computer on the rover [11]. The subsystems, and the supporting architecture, for the TTC will be altitude supported by an antenna, data handling controlled by buses clocks, and two-way comm requirements, electrical power subsystem, thermal made possible by heat dissipation and sinks, and payload, RF and EMC interface, and modulation [11]. C&DH (command and data handling) will be the main computer onboard the rover receiving the communication from TTC, this will be where the data and instructions will be sent to.

The movement of the rover will be mainly autonomous with very little manual control, most of the movement will come from waypoint commands, which are commands sent to the rover to signify where the rover should travel to next after the previous command was carried out. Autonomous navigation will be controlled by the LN1 (Lunar Node-1) [12], as of March 2026 is still being experimented with, is a radio beacon used for precise geolocation and to confirm the location on the mood which can be sent to the C&DH. The LN-1 relies on MAPS (multi-spacecraft autonomous positioning system), which allows for autonomous movement. [13]

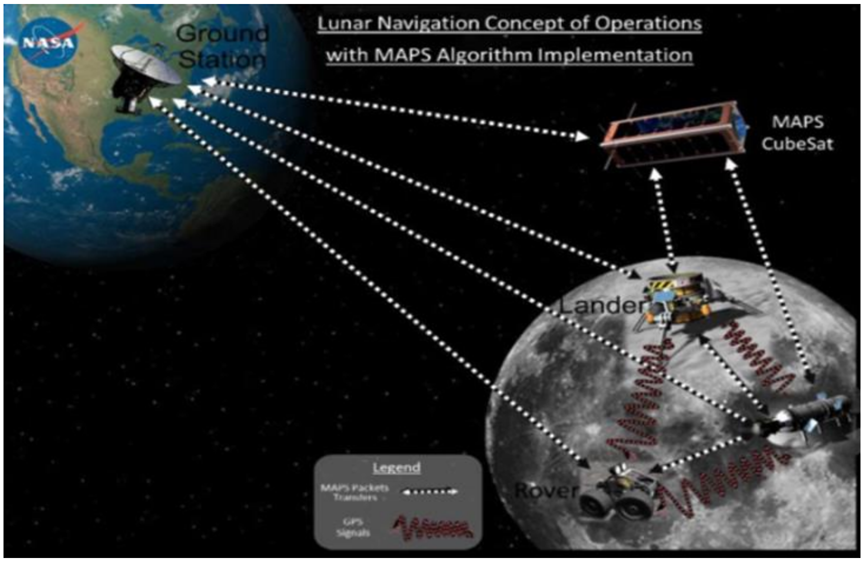

Figure 5: MAPS demonstration.

The figure above demonstrates MAPS fully implemented, which demonstrates two-way communication between the station on earth and the rover and lander on the lunar surface. MAPS is an efficient implementation that substitutes for any manual control from earth, which is needed due to the delay of communications from earth to the lunar surface. The accuracy of the MAPS system is accurate depending only on the truth simulation coordinator, which is the role of either a human or system, that checks the accuracy of the data that the TTC is sending back to earth. The timing, to minimize delays between communications, is dependent on the timing coordinator, which controls the clocks to ensure that they are at the correct timing.

D. Batteries, Charging, Cameras, and Lights

The batteries that will be used on the rover are classified as “High Performance Lithium-Ion Batteries” [14], which are used frequently in many commercial products and even on prior lunar missions. These batteries are rechargeable, crucial for longer missions, but therefore do not have the greatest battery life. The maximum energy density that it outputs is 350 Wh/kg, and if run at that number risk overheating and other problems, 200-250 Wh/kg will be the chosen range. With 20kg available for the battery, one 20 kg batteries will be used which puts the outage at 20(100 - 250) = 2 – 2.5 kWh, with no power dissipation, but about 1.6 – 2 kWh assuming 80% power dissipation. Charging will be done by using solar panels that will provide 489.55 Wh.

E. Motors

The motors that will be used are AK 80-9 v3.0 robotic actuator, which has a rated wattage at 368 W, AK 10-9 v2.0 robotic actuator, whose rated wattage is 430W, AKH 70-48 v1.0 Hollow Shaft Planetary Actuator, at 217 W, and another robotic actuator which is still under development. The first motor will have a set which will be ran at 55 minutes out of the hour, and there will be another set of the same motor ran at 3 minutes out of the hour. The second motor mentioned above will be ran 3 minutes out of the hour, then the last motor will be ran for 57 minutes out of the hour. After calculations the total energy used will be 588.1 Wh, when ran on a 1.6kWh battery uses about 36.8 percent of the battery, lasting about 2.7 hours. After applying the solar panel, charging the battery at a rate of 489.55 Wh, the total energy loss will be 98.55 Wh. This minimal loss will give the battery a total life of about 16 hours.

VI. Technological Gaps and Limitations

While G.R.U. is designed to successfully operate using current technologies available, there are some developing technologies that can improve the rover efficiency, longevity, and supporting systems. One key challenge with creating a long-term system on the lunar surface is the degradation of materials from jagged and electrostatically charged regolith particles. G.R.U. is only the first stage of creating infrastructure on the Moon. Supporting systems for filtering, storing, casting, and sintering of regolith all need to be developed thoroughly otherwise gathering mass quantities of regolith is not a worthwhile endeavor. A developing technology that was briefly mentioned in the section IV is wear resistant ceramic coatings. By coating titanium and aluminum alloys with a compatible ceramic by chemical vapor deposition, the underlying metallic substrate can remain protected from lunar dust [15]. Coating ceramic materials include alumina, boron carbide, and chromium oxide.

VII. Conclusion

G.R.U. 1.0 will stand as an example on what is possible on the lunar front. With the renewed interest of not only revisiting the Moon, but using the Moon to further mankind forward, developing technologies to build the foundations needed is a key with projects like G.R.U. The team also understand the many shortfalls found in G.R.U. such as the small regolith bay and low lifetime between charges, however, the team believes developments in the digging system as well as the suspension and wheel system are strong areas to focus further research and development on.

The digging system utilized by G.R.U. represents a further development on the focus of utilizing lunar regolith. The digging system maximizes the use of earth-based designs while repurposing them for lunar development. The suspension and wheel system take inspiration from previously designed systems while advancing and repurposing them for regolith mining. The advantages found with the redesigned rocker bogie suspension system and changing heights can be used in multiple applications of rover design. The wheel designs strength on the lunar surface proves simplified design philosophy can help further mobility on the lunar surface.

The developments of G.R.U. hope to further humanity’s goals on the lunar surface by minimizing transportation costs of materials by utilizing materials provided on the Moon. The technologies developed through the G.R.U. project thus far will continue to be studied by the group in the upcoming months with goals to continue testing.

Appendix A

Table 2: Design Failure Mode Analysis

Failure Mode	Severity Level (1–10)	Fixability (1–10)	Description	Solution
Battery depletion to zero	10	10	When the rover is operating away from the Griffin lander, the battery reaches a point where it is unable to return to its charging station.	Adding a solar panel to the rover will prevent complete battery failure and allow the rover to recharge and return in an emergency scenario.
Rover becomes beached	10	10	During the collection of lunar regolith, the rover ends up in a spot where it is unable to move due to the body being stuck in the ground.	The rover's suspension system can raise and lower, which will prevent beaching while mining regolith.
Communication channel failure	5	10	Methods of communication to the rover fail due to disruptions to the system.	A relay satellite serves as a backup communication system while storing data when communications are disrupted, syncing upon reconnection.
Particle blockage	3	5	Lunar regolith becomes stuck inside the moving belt, causing the system to jam or block.	Tighten seals on the conveyor and incorporate a shaking mechanism to clear blockages.
Motor failure	5	0	A motor on a wheel experiences an unexpected failure.	Multiple wheels are given motors to reduce reliance on any single unit. Rover code can be updated to adjust movement calculations in the event of a failure.
Code failure	3	7	Code sends incorrect signals due to high-energy particles from cosmic rays flipping a bit.	Three redundant code storage systems are used. Two run simultaneously and cross-check before each movement; if they disagree, a third arbitrates and resets the faulty system.
Electronic degradation	4	0	Materials such as copper used in electronic components will diffuse during elevated daytime temperatures on the Moon due to the lack of an oxide passivation layer.	—

Appendix B

For each trade study multiple potential designs were considered in which key factors were weighted against each other and then compared between models. For both of the studies, the design with the most weighted point accumulated was selected as the final candidate. For the digger head, the study was composed after results from initial prototypes were finalized. For the tire design, two proposed tire designs, the NASA spring tire [9] and the Bridgestone second-generation lunar rover tire [HH Z] were tested as previously developed designs while a traditional full metal wheel was used as a control variable.

Table 3: Digger head design trade study

Factor	**Weight**	**Four Spoke**		**Three Spoke**		**Bucket Wheel**	
		Raw Score	**Weighted**	**Raw Score**	**Weighted**	**Raw Score**	**Weighted**
Volume Excavated	4	3	12	2	8	4	16
Volume Retained	2	3	6	1	2	4	8
Mass of Wheel	1	2	2	4	4	1	1
Score			**20**		**14**		**25**

Table 4: Tire design trade study

Factor	**Weight**	**Bridgestone**		**Spring Tire**		**Traditional**	
		Raw Score	**Weighted Score**	**Raw Score**	**Weighted Score**	**Raw Score**	**Weighted Score**
Durability	5	7	35	5	25	3	15
Weight	3	7	21	10	30	3	9
Complexity	2	5	10	2	4	10	20
Price	1	5	5	2	2	7	7
Score			**71**		**61**		**51**

Appendix C

To begin the Ansys [10] simulation the previously developed SolidWorks model of the wheel was placed inside static structural. The outer shell of the wheel was assigned Ti-3Al-2.5V while the spokes and wheel hub were selected to be Al 7075 T6 wrought.

After these materials were assigned to their respective parts, body sizing was placed across the model. Due to the goal of the test being for simple verification of strength and not to find the exact maximum strength, the mesh sizes used were larger than normal to speed up the simulation process. The outer shell of the wheel was assigned a mesh sizing of 1 mm while the spokes and inner hub were given a mesh sizing of 0.05 mm. Further analysis is required with mesh sizing focusing on stress concentrated points to confirm the tests results, however, the eventual maximum stress found was well below the material limit giving the group confidence in the tires strength.

Following the mesh sizing, three static structural properties were added to the model. The first added feature was a zero-displacement boundary at the bottom most contact point of the tire. This boundary condition represents the worst case scenario where the wheel is placed on a hard surface that it cannot dig into and push for some stress relief. The second boundary condition was a force of 410.54 newton on the top section of the inner hub. This force represents two times the maximum expected force to be placed on the tire at any given time. The final boundary condition was a 13.5 newton meter torque in the center of the wheel hub to represent 1.5 times the expected torque needed to get the wheel moving from a stopped position. The torque needed to begin movement was calculated prior to simulation. Following these boundary conditions and simulation, it was found that a possible maximum stress on the wheel was less than the maximum yield stress of Al 7075 T6 Wrought. The stresses were most concentrated in the center of the spokes which preliminary review brought as the main concern for the design.

Appendix D

Table 5: Comparison of Material Properties and Costs for Structural Systems

Material	Density, g/cm^3	Cost, \$ kg^{-1}	Yield Strength, MPa	Fracture Toughness, MPa m$^{1/2}$	Thermal Conductivity, W m^{-1} K^{-1}
Al 2024-T3	2.78	2-4	345	23-41	121
Al 6061-T6	2.70	2-4	276	29-38	167
Al 7075-T6	2.81	3-6	503	22-33	130

Ti-6Al-4V	4.43	30-60	880	75-110	6.7
Ti-3Al-2.5V	4.48	25-50	1000-1100	70-90	7.5
SS 316L	8.00	3.6	290	100-200	16.3

Table 6: Comparison of Material Properties and Costs for Digging Head

Material	Density, g/cm^3	Cost, \$ kg^{-1}	Yield Strength, MPa	Fracture Toughness, MPa m$^{1/2}$	Fracture Toughness G-IC Mode, J m^{-2}	Thermal Conductivity, W m^{-1} K^{-1}
CF T700SC	1.8	20-35	2550	x	150-250	9.8
CF T1000GB	1.8	80-150	6370	x	400-600	9.6
Ti-6Al-4V	4.43	30-60	880	75-110	x	6.7
SS 17-4PH	7.78	15-25	1170-1310	50-95	x	18.3
SS 440C	7.65	8-15	1900-2000	14-25	x	18.4
Al 7075-T6	2.81	3-6	503	22-33	x	130

Table 7: Comparison of Material Properties and Costs for Conveyer Belt

Material	Density, g/cm^3	Cost, \$ kg^{-1}	Tensile Strength, MPa	Elongation to Failure, %	Coefficient of Friction (dry)	Service Temperature Range, ºC
PTFE film	2.15-2.20	30-80	20-35	200-400	0.04-0.10	-260 to +260
PTFE-coated glass fabric	1.80-2.00	40-120	100-300	3-5	0.05-0.15	-70 to +260
Kapton HN film	1.42	200-800	165-185	70-100	0.45-0.60	-269 to +400
Mylar PET film	1.38-1.40	5-20	170-210	60-165	0.25-0.50	-70 to +150

Appendix E

Table 8: Weight budget for G.R.U. 1.0

Weight Rover	Weight [kg]	Quantity	Total Weight [kg]	Percent Weight
Suspension	3.32	4	13.28	6.6400%
Frame	97.16	1	97.16	48.5800%
Solar Panel	2.497	1	2.497	1.2485%
Motors	17.672	1	17.672	8.8360%
Camera Sensors	9.391	1	9.391	4.6955%
Conveyor System	14	1	14.00	7.0000%
Battery	20	1	20.00	10.0000%
Digging Head	26	1	26.00	13.0000%
Total Weight			**200.00**	**100.0000%**

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