C3 Cosmic Design Report

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This document covers the work done so far by the War Eagle Lunar Team in the design of the CLEAR Lunar Grading System. The Primary and Secondary objectives that guided design are covered followed by a review of each major subsystem of the C.L.E.A.R. Rover. The document concludes with a risk assessment that is followed by an evaluation of the next steps required to progress the project.

I. Introduction

In order to establish a permanent lunar presence, there is wide array of tasks that need to be performed. Bases need to clear ground, construct structures, establish communication networks and many other tasks. One of first that needs to be done is the clearing and leveling of ground, or grading. All buildings have an acceptable grade, even without intermittent weather conditions like here on earth. Two especially important structures, roads and landing pads, critically need to be leveled.

In cooperation with AULUNA, C.L.E.A.R. forms the first stage of autonomous lunar base construction. Grading surfaces, clearing large obstacles and creating dump zones where spare regolith can be easily accessed.

A. Similar Systems

In preparation of the design process for the C.L.E.A.R. Rover we looked at several previous projects similar to the one discussed in this document. We first looked at a project done by students at Florida Atlantic University called R.O.V.E.R.. This vehicle's mission was similar to our in that its purpose is to excavate lunar regolith. No sizing of their system was provided in their report. We looked into this project to hopefully find a mechanism that would be ideal for excavating lunar regolith. This project was a major inspiration for our choice of using a dozer blade subsystem to do the excavating and grading of lunar regolith. This project also gave us inspiration for what our rover's prototype should eventually look like when completed.

Secondly, the team looked at a project done by previous Auburn students back in the summer of 2009. Their project was called the "Lunar Regolith Excavator" which had a similar mission to ours which was to excavate lunar regolith. This system is a 38 in x 48 in lunar excavator. This team used a kind digger arm system to excavate regolith as well as a track system for its wheels, very similar to an excavator that you would see at a construction site today. We looked into this project in hopes of finding details of what our teams reports should look like. We were able to access this team's final report which gave us inspiration on how to structure our reports and talk about our individual subsystems. This team's work gave a guideline of how to fully go about completing our project with out leaving any important details out.

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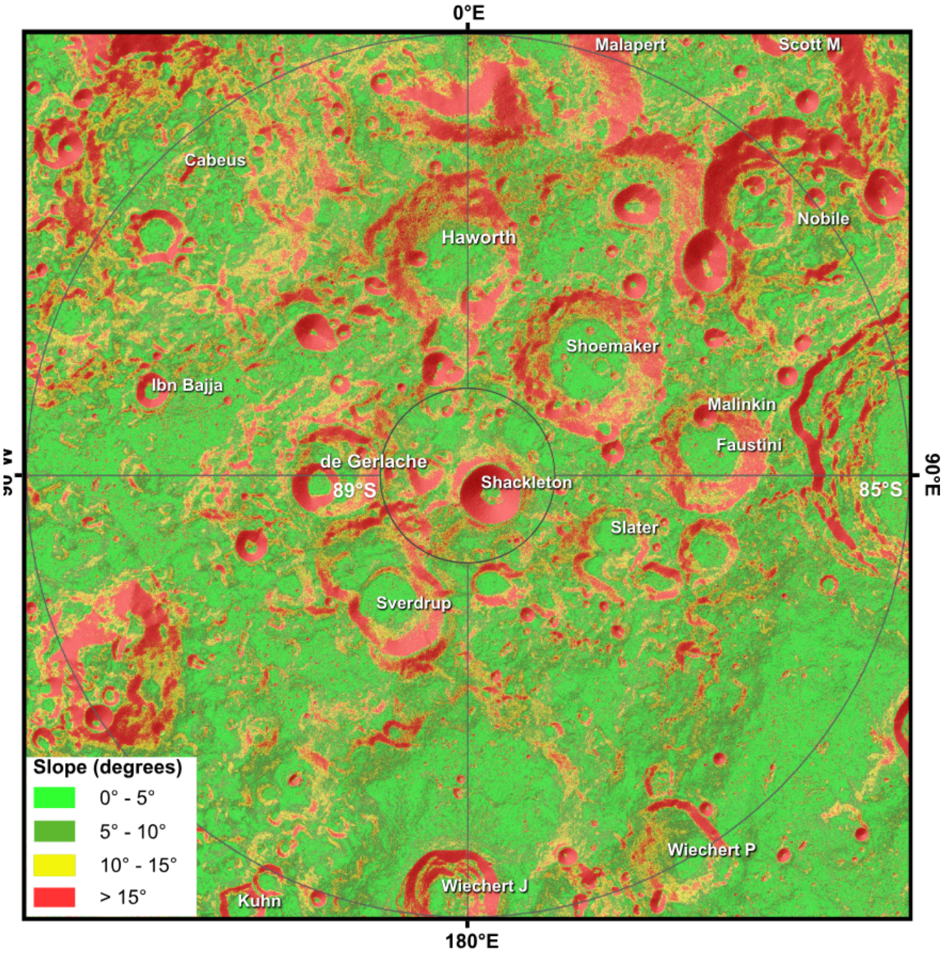


Fig. 1 Slope Map of the Lunar South Pole, showing variety in grades

II. System Overview

The C.L.E.A.R. Rover's Grading System is designed with the two following primary objectives:

PO1 Grade Lunar Regolith ahead of other Lunar Infrastucture systems.
PO2 Be capable of manuevering the Lunar South Pole terrain.

The first primary objective is considered to be fulfilled if the system is capable of grading slopes of up to fifteen percent. The secondary primary objective is similar, being fulfilled if the system is capable of manuevering over slopes of fifteeen percent. This shared requirement for both is due to South Pole topography, were most slopes do not exceed a fifteen percent grade. Excluding extreme terrain features such as craters, which are not chosen for base sites.

From these several secondary objectives are dervied:

SO1 The System must be able to communicate its progress
SO2 The System must be able to determine that grading has been completed.
SO3 The System must be able to manage heat as to prevent damage it its own componenets.

The first of these secondary objectives will be considered fulfilled if the rover can regularly update Mission Command of its progress at the end of every lunar day. Due to the low data requirement of this, only needing a simple check-in message and operational status, a data rate of 2 Mb/s from the communications system is considered adequate. The second is considered fulfilled if the System's sensor system is capable of grade differences of 0.5% and the Controls system is capable of storing, reading and utilizing topographical information collected by the sensor system. The Third secondary objective is considered fulfilled if a Heat Balance verifies the design choices made for Heat Balancing.

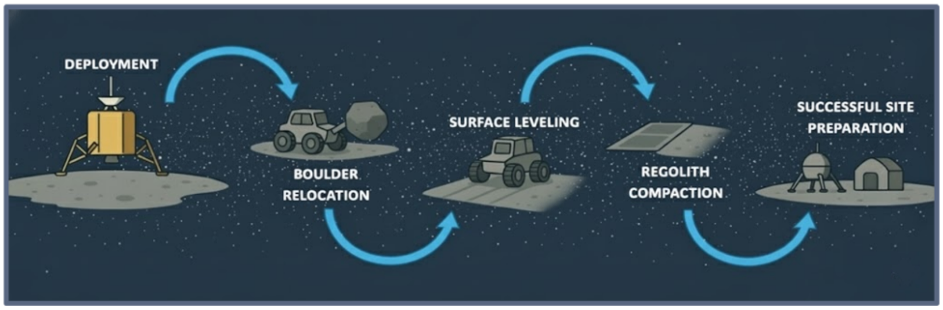


Fig. 2 Concept of Operations.

A. Concept of Operations

The Concept of Operations is shown here, the System will be delivered by the Griffin Lunar Lander. Then it will begin boulder relocation of the given site. Next it will grade the site to the provided levels. Then the Regolith can be compacted, this System is not capable of performing this task however it is intended that it work closely with other systems who can such as the AULUNA Sintering Device. Finally the site has been successfully prepared and the System can be disassembled or reused for other sites depending on its operational capacity.

B. Frame Requirements

The frame of the C.L.E.A.R. rover is responsible for resisting structural strain while also needing to stay within our mass budget of 200 kg. The frame serves as the primary load bearing structure and forms the structural backbone of the grading system. It provides mechanical support for all major subsystems, including the dozer blade, power system, avionics, and mobility components, while maintaining geometric alignment during excavation and traversal operations. In addition to supporting the subsystem mass on slopes up to 9–15 percent, the frame must efficiently transmit blade reaction forces, resist torsional deformation during uneven terrain traversal, and withstand load cases from takeoff.

Because the rover is constrained to a total system mass of 200 kg, the frame must achieve a high structural stiffness and strength while minimizing mass. The design must also be able to withstand the lunar South Pole's thermal environment and maintain sufficient stability for operations on slopes up to 9–15 percent. The following subsections describe the material selection, structural architecture,and sizing used to develop the C.L.E.A.R. rover's frame design.

1. Frame Materials

The C.L.E.A.R. rover chassis material will be made of aluminum alloy due to its high strength to mass ratio. The primary load-carrying members are designed in 6061-T6 aluminum to provide toughness and stable mechanical properties in the lunar thermal environment. 6061-T6 aluminum has an ultimate tensile strength of 310 MPa. High-load attachment regions such as the blade interface and wheel mounts will use 7075-T6 bolted hardpoints to reduce local bearing stresses and prevent joint deformation while maintaining a low overall structural mass. 7075-T6 aluminum has an ultimate tensile strength of 572 MPa. A bolted construction approach is preferred for the rover frame to avoid reductions in weld strength affected by heat in critical load paths.

2. Frame Architecture

The C.L.E.A.R. rover uses a box-frame chassis constructed from rectangular structural members arranged in two primary longitudinal rails connected by multiple transverse crossmembers. A box-frame was selected because it provides high torsional rigidity for uneven lunar terrain traversal while also creating a structurally efficient mounting platform for the wheels, battery pack, avionics, and dozer blade assembly. Compared to an open ladder frame or truss style space frame, the box frame offers a stronger resistance to chassis twist, improves blade alignment stability during grading, and simplifies manufacturing and assembly through straight members and repeatable joints.

3. Frame Sizing

The C.L.E.A.R. rover chassis was sized to an overall envelope of 7 ft (2.13 m) length by 5 ft (1.52 m) width. This footprint was selected to provide sufficient longitudinal space for the blade mounting bulkhead, protected internal packaging of the battery and avionics, and to provide a wide track for increased stability and torsional resistance when traversing uneven lunar South Pole terrain. A static stability check indicates that for a conservative center-of-gravity height on the order of 0.45–0.60 m, the rover's lateral tip-over angle exceeds 50°, which is well above the expected operational slope range (9–15 percent). Therefore, chassis sizing is expected to be governed by traction and mobility constraints rather than geometric stability limits.

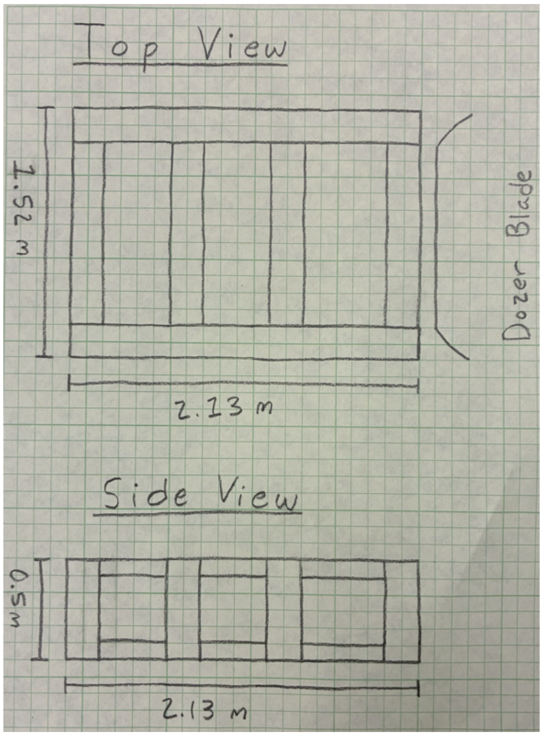


Fig. 3 Frame Dimensions

C. Implement Design

The implement attachment at the front of the C.L.E.A.R. rover would be the primary component in successful excavation. While choosing this attachment, three different implement types were considered, namely the front bucket, the roller, and the dozer blade. After comparing the advantages and disadvantages of each type, the team ultimately decided on the dozer blade attachment, due to it providing the highest excavating and control capabilities. Further research led to the selection of a semi-universal (or SU-type) dozer blade, which combined a flat center with slightly angled side wings to hold material during excavation, which would allow regolith to be transported more easily.

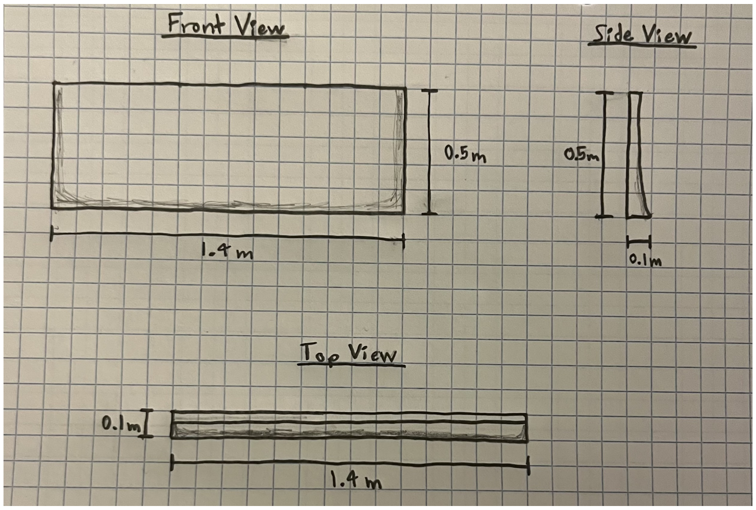


Fig. 4 Implement Dimensions

1. Implement Sizing

Following the decision of the dozer blade type, the specific dimensions of the implement attachment were determined based on the previously concluded frame dimensions. These values came out to be about 4.59 ft (1.4 m) for blade width, about 1.64 ft (0.5 m) for blade height, and about 0.33 ft (0.1 m) in depth. Additionally, the implement was determined to have an overall mass close to 30 kg, allowing the bulk of the 200 kg mass to be carried by other components of the rover.

2. Implement Materials

The team decided that, for the prototype design, the dozer blade attachment would be fixed to the front of the rover; however, the possibility of the blade having degrees of freedom for the full 200-kg rover design is still being considered. As a result, two different versions of the dozer blade were analyzed when determining its structural design: one with movement capabilities, and one without. Both versions would have a blade body and side wings composed of 6061-T6-Al, as well as a cutting edge (or wear strip) of carbide-coated steel. The blade mounting bracket (whether fixed or articulated) would be composed of aerospace aluminum, the structural reinforcements would be aerospace aluminum alloy, and the fasteners would be either stainless steel or titanium.

As for actuation and motor control, any and all high-force actuators, motor drivers, position encoders, and harnessing and connectors would need to be composed of space-rated, radiation-tolerant materials. These components would not apply should the implement attachment be fixed to the C.L.E.A.R. rover. Similarly, any force/torque sensors would also be made of proper space-rated materials, so as to withstand the harsh lunar environment. Custom dust seals and covers would be implemented as needed, along with any thermal control elements such as heaters or multi-layer insulation (MLI) to help with temperature regulation.

3. Excavating Capabilities

For a previous trade study, the team determined a range of possible excavation rates for the 200-kg rover by proportionalizing the mass and rate with those of two past Auburn University experiments which included similar rover designs and operation concepts. These rovers were about 1/6th the size of the full 200-kg rover for this project. The resulting values and range can be seen in the figure below.

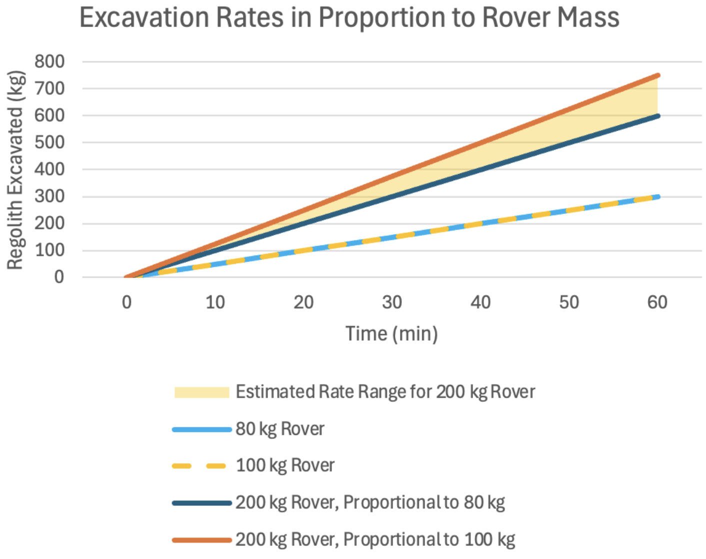


Fig. 5 Excavation Rates in Proportion to Rover Mass

With the completion of the Lunar Excavation MATLAB simulation, the team was then able to take the average of ten varying simulated results to determine an actual estimated excavation rate for the 200-kg rover; this value came out to be around 5570.758 kg/hr, close to six times larger than the predetermined rate range, as expected. The plot below shows this exact rate in comparison to those determined during the trade study.

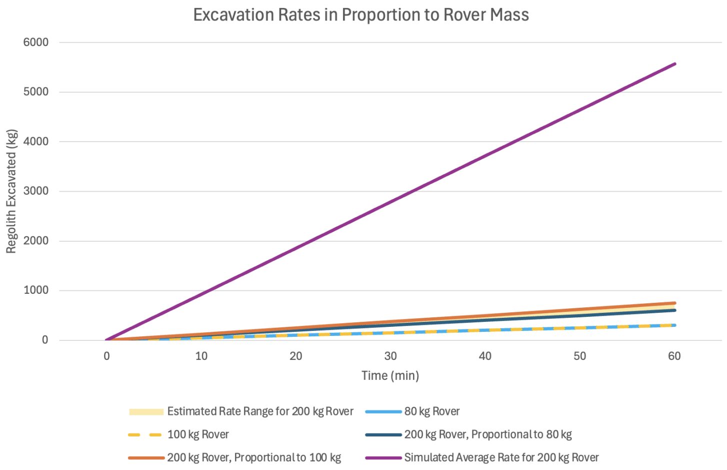


Fig. 6 Excavation Rates in Proportion to Rover Mass, Simulation Rate Included

Additionally, the following figure displays the average simulated rate scaled down to 1/6 its actual value, for easier comparison with the previous rates.

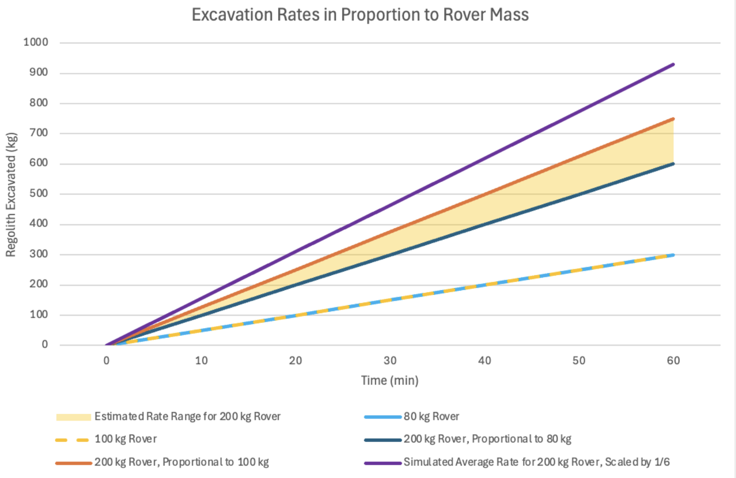


Fig. 7 Excavation Rates in Proportion to Rover Mass, Simulation Rate Included (Scaled to 1/6 Actual Value

D. Wheel Design

The full-scale C.L.E.A.R. rover wheel system is designed to maintain traction and mobility while grading regolith on slopes up to 9–15%. Because lunar environments preclude pneumatic tires due to vacuum exposure, abrasive dust, and extreme thermal cycling, heritage lunar and Mars rover missions employ metallic wheel structures with integrated tread features. The Apollo Lunar Roving Vehicle demonstrated the effectiveness of non-pneumatic metallic wheels using mesh and chevron treads for dust tolerance and compliance. Mars rovers such as Curiosity and Perseverance further validated rigid aluminum wheels with grousers as a durable and predictable solution for mixed terrain, while highlighting the importance of structural reinforcement to prevent fatigue and puncture damage.

Based on this heritage, the C.L.E.A.R. baseline wheel design consists of a rigid metallic rim with evenly spaced grousers to reduce sinkage and increase shear resistance during blade engagement. The structure includes a thin outer skin for continuous ground contact and a stiffened hub/spoke assembly to transmit torque without local buckling. Controlled compliance may be introduced through flexure spokes or localized tread flexibility while maintaining a fully metallic external surface to prevent dust intrusion. The primary wheel material is flight-grade aluminum (6061-T6 or

7075-T6) for high strength-to-mass efficiency, with titanium or hardened steel wear strips at grouser edges to mitigate abrasion.

Fig. 8 Skeletal aluminum rover wheel with integrated grousers and reinforced hub structure.

1. *Suspension System*

The suspension system is designed to maintain continuous wheel-ground contact and balanced load distribution during excavation and grade climbing up to 15%. Because the rover operates at low speeds under sustained traction loads, the suspension prioritizes passive articulation and structural stiffness over dynamic damping.

A four-wheel passive rocker configuration is selected as the baseline architecture. Each side of the rover incorporates a rocker arm supporting front and rear wheels, allowing vertical articulation over uneven terrain. The left and right rockers are linked by a central differential mechanism that averages chassis roll and maintains uniform normal force across all wheels. This geometry reduces wheel unloading during slope traversal, improves traction in loose regolith, and supports stable grading operations.

E. Power Design

The power system for the C.L.E.A.R. rover is responsible for supplying sufficient energy to support mobility, excavation, communication, sensing, and thermal management while operating in the extreme lunar South Pole environment. Because the rover's primary mission is to grade terrain at a rate of 600–750 kg/hr while traversing slopes up to 9%–15%, the power subsystem must sustain continuous mechanical loading during active excavation and mobility phases. Additionally, the system must operate for a minimum of 8 hours per lunar day on internal battery power alone, with no solar input, and recharge during peak daylight conditions.

1. *Power System Contraints*

The primary constraint impacting power design is the total system mass limit of 200 kg and volume limit of 9 m^2 imposed by Griffin Lander compatibility. This forces optimization between energy density, reliability, and total system weight. In addition, the solar array, if implemented, must generate an average of at least 250 W under peak lunar daylight conditions to sustain operations and recharge the batteries. Another critical constraint is battery depth of discharge. The battery system shall not exceed a depth of discharge of 75–80% during nominal operations to preserve battery longevity in the lunar thermal environment. Finally, the power system must operate within the lunar temperature range of approximately negative 163C to 54C.

2. *Solar Power Considerations*

The initial trade study compared solar panels and RTGs as primary power sources, evaluating energy density, reliability, and power output. Although RTGs offer continuous power independent of lunar night and higher energy density, their lower peak power output (110 W) makes them less suitable for high-load excavation operations. In contrast, solar panels can deliver significantly higher peak power (500 W), which aligns more closely with rover operational needs.

However, solar power introduces operational constraints. Solar arrays generate no power during lunar night and experience reduced output if dust accumulates on panel surfaces. At the lunar South Pole, prolonged shadowing may further reduce effective charging time. Therefore, even if solar panels are included, the rover must still be capable of operating solely on battery power for at least 8 hours.

Currently, the design is still assessing whether a solar array is necessary or if a battery-dominant architecture is sufficient for mission duration. Including solar panels reduces required battery mass, but increases structural complexity, surface area exposure to dust, and overall system mass. Excluding solar panels simplifies design but requires significantly higher onboard energy storage, which directly impacts the 200 kg mass constraint.

3. Battery System Design

The battery subsystem forms the foundation of the rover's power architecture, providing energy storage for both operational and survival phases. A trade study was conducted to evaluate lithium-ion, solid-state, and lithium-sulfur chemistries based on energy density, thermal resilience, cost, cycle life, and technology maturity. Lithium-ion batteries were selected as the baseline configuration due to their proven reliability, well-characterized thermal behavior, widespread availability, and compatibility with space-relevant operating conditions. Although alternative chemistries offer higher theoretical energy densities, lithium-ion systems provide predictable cycle life performance and align well with the required 75–80% depth-of-discharge constraint.

The rover requires approximately 414–420 W to support simultaneous excavation and maneuvering during the 8-hour battery-only operational phase. During no-sun conditions, an additional 131 W is required to maintain thermal survival, including both heater power and internal survival electronics. Integrating these loads over the operational and survival periods results in a usable energy requirement of approximately 5.41 kWh. Enforcing the 75–80% depth-of-discharge limit increases the total installed battery capacity to approximately 6.8–7.2 kWh. Based on an assumed lithium-ion energy density of 190 Wh/kg and including packaging and battery management overhead, this corresponds to an estimated battery system mass of 43–49 kg, maintaining compatibility with the 200 kg mass constraint imposed by the Griffin Lander.

F. Controls

The C.L.E.A.R. system utilizes an altered Dozing algorithim of the one developed by Bettemir in his paper [25]. This algorithim prioritizes grading from high points in the terrain, allowing the system to use gravity to its advantage and reduce energy costs. In order to do this, the C.L.E.A.R. system will be equipped with a LIDAR sensor array that allows it to map the terrain of its work site. The Algorithim from this developed map will then determine the highest point and from there begin its grading.

The Algorithim also designates dump sites at the edge of the work area. These dump sites produce reserves of Regolith that will allow future systems to have easy access to supplies of regolith for fabrication of materials on-site.

III. Risk Assessment

A risk assessment was conducted to identify potential mission failure points and broader impacts associated with the rover's excavation operations on the lunar surface.

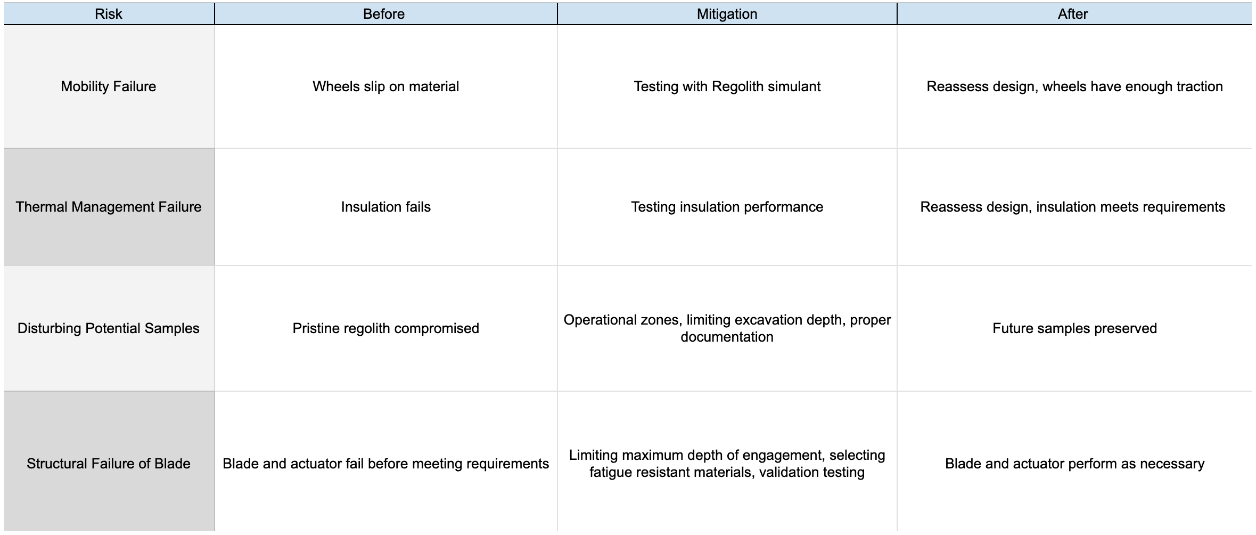
One primary risk involves mobility failure due to interaction with lunar regolith. The lunar surface consists of loose, fine-grained material that can lead to wheel sinkage, slippage, and reduced traction. Because lunar gravity is approximately one-sixth of Earth's gravity, the normal force acting on the rover's wheels is reduced, which directly decreases the available friction force.

A second significant risk is thermal management failure. The lunar environment experiences extreme temperature fluctuations. These conditions can negatively affect batteries, motors, structural components, and onboard electronics. Excessive heat may degrade battery performance, while extreme cold can reduce battery capacity and impair startup capability.

A third risk concerns the disturbance of future scientific sampling sites. The lunar regolith contains valuable information regarding solar wind implantation and early solar system processes. Excavation activities may unintentionally disturb or contaminate pristine regolith layers that could otherwise be used for future scientific investigations.

Finally, structural failure of the blade or actuation system presents an additional risk. Although the lunar regolith is fine-grained, resistive forces during excavation can still produce repeated mechanical loading on the blade assembly. Over time, these loads can cause fatigue or actuator failure.

All mitigation strategies can be seen in the table below.



Risk	Before	Mitigation	After
Mobility Failure	Wheels slip on material	Testing with Regolith simulant	Reassess design, wheels have enough traction
Thermal Management Failure	Insulation fails	Testing insulation performance	Reassess design, insulation meets requirements
Disturbing Potential Samples	Pristine regolith compromised	Operational zones, limiting excavation depth, proper documentation	Future samples preserved
Structural Failure of Blade	Blade and actuator fail before meeting requirements	Limiting maximum depth of engagement, selecting fatigue resistant materials, validation testing	Blade and actuator perform as necessary

IV. Conclusion and next steps

The C.L.E.A.R. Design provides a simple but effective design for autonomous grading on the Lunar Surface. Using a combination of NASA rover technology and modern dozer technology, the C.L.E.A.R. system can prepare sites ahead of other lunar infrastucture systems. With a Frame and Wheel design that emphasizes practicality and dust mitigation, a Power System that would allow the System to complete its mission objectives without outside support and a Dozer implement that can grade and create dump zones to lay the foundation for future operations. The next steps required to progress are a test in earth like conditions to identify present weak points. Once these present weak points are considered the design can move to adjusting the Frame design to consider the lunar environment outside of dust mitigation. With these adjustments further tests will be needed to bring the design up to standard in simulated lunar environments. Finally if the design meets these tests it can move to production and accompany other lunar infrastucture systems to begin laying site groundwork.

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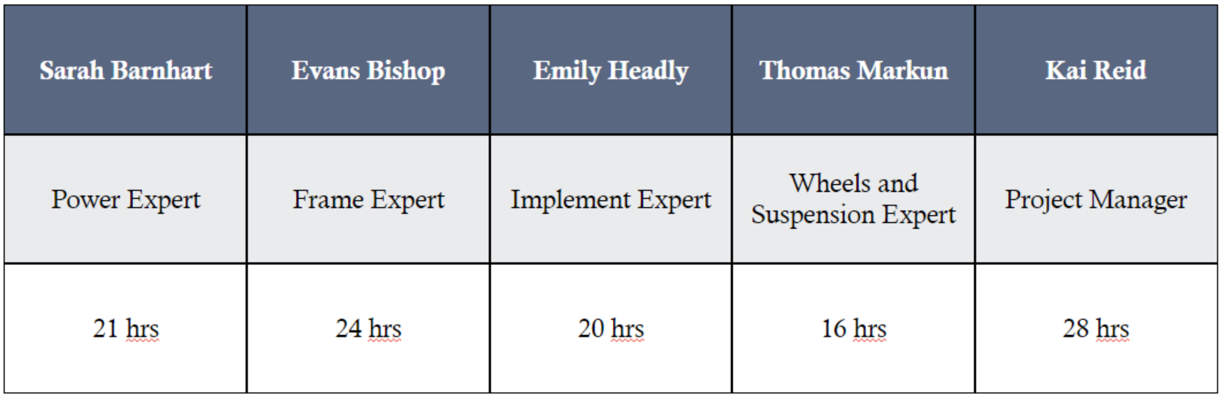
32) https://www.lpi.usra.edu/lunar/lunar-south-pole-atlas/

V. Addendum

A. Budget Discussion

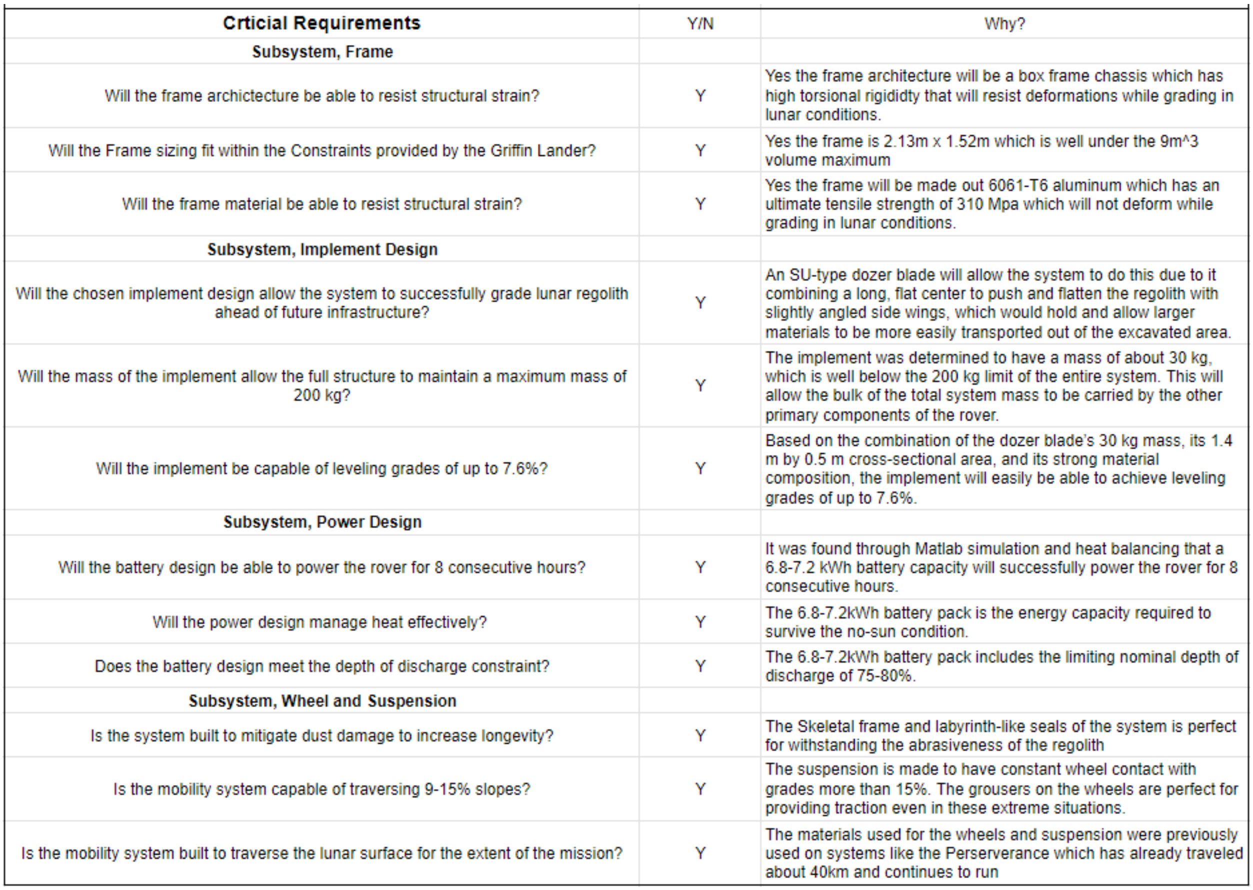
The Team has not purchased anything for the project thus far.

DESIGN TEAM ROLES AND HOURS



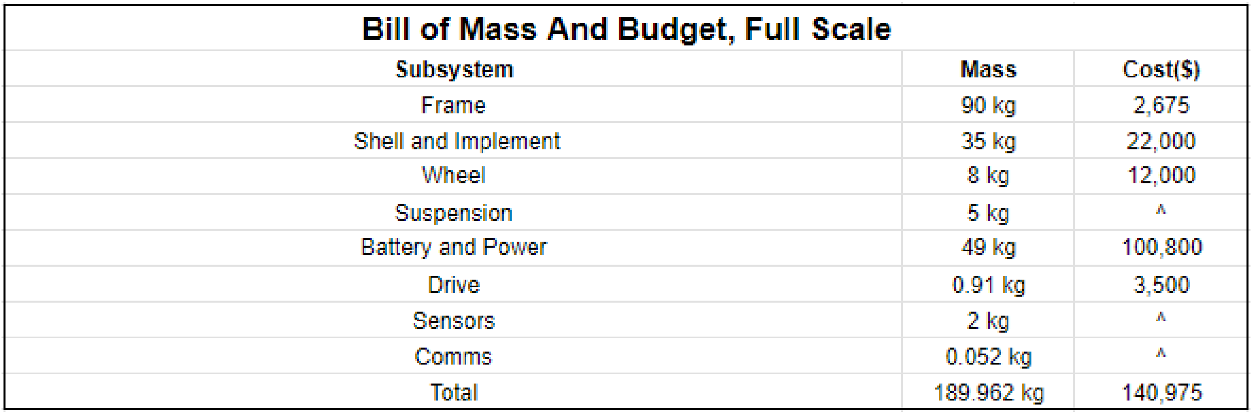
Sarah Barnhart	Evans Bishop	Emily Headly	Thomas Markun	Kai Reid
Power Expert	Frame Expert	Implement Expert	Wheels and Suspension Expert	Project Manager
21 hrs	24 hrs	20 hrs	16 hrs	28 hrs

Fig. 9 Hours and Roles



Crticial Requirements	Y/N	Why?
Subsystem, Frame		
Will the frame archictecture be able to resist structural strain?	Y	Yes the frame architecture will be a box frame chassis which has high torsional rigididty that will resist deformations while grading in lunar conditions.
Will the Frame sizing fit within the Constraints provided by the Griffin Lander?	Y	Yes the frame is 2.13m x 1.52m which is well under the 9m^3 volume maximum
Will the frame material be able to resist structural strain?	Y	Yes the frame will be made out 6061-T6 aluminum which has an ultimate tensile strength of 310 Mpa which will not deform while grading in lunar conditions.
Subsystem, Implement Design		
Will the chosen implement design allow the system to successfully grade lunar regolith ahead of future infrastructure?	Y	An SU-type dozer blade will allow the system to do this due to it combining a long, flat center to push and flatten the regolith with slightly angled side wings, which would hold and allow larger materials to be more easily transported out of the excavated area.
Will the mass of the implement allow the full structure to maintain a maximum mass of 200 kg?	Y	The implement was determined to have a mass of about 30 kg, which is well below the 200 kg limit of the entire system. This will allow the bulk of the total system mass to be carried by the other primary components of the rover.
Will the implement be capable of leveling grades of up to 7.6%?	Y	Based on the combination of the dozer blade's 30 kg mass, its 1.4 m by 0.5 m cross-sectional area, and its strong material composition, the implement will easily be able to achieve leveling grades of up to 7.6%.
Subsystem, Power Design		
Will the battery design be able to power the rover for 8 consecutive hours?	Y	It was found through Matlab simulation and heat balancing that a 6.8-7.2 kWh battery capacity will successfully power the rover for 8 consecutive hours.
Will the power design manage heat effectively?	Y	The 6.8-7.2kWh battery pack is the energy capacity required to survive the no-sun condition.
Does the battery design meet the depth of discharge constraint?	Y	The 6.8-7.2kWh battery pack includes the limiting nominal depth of discharge of 75-80%.
Subsystem, Wheel and Suspension		
Is the system built to mitigate dust damage to increase longevity?	Y	The Skeletal frame and labyrinth-like seals of the system is perfect for withstanding the abrasiveness of the regolith
Is the mobility system capable of traversing 9-15% slopes?	Y	The suspension is made to have constant wheel contact with grades more than 15%. The grousers on the wheels are perfect for providing traction even in these extreme situations.
Is the mobility system built to traverse the lunar surface for the extent of the mission?	Y	The materials used for the wheels and suspension were previously used on systems like the Perserverance which has already traveled about 40km and continues to run

Fig. 10 Requirements Table



Bill of Mass And Budget, Full Scale

Subsystem	Mass	Cost($)
Frame	90 kg	2,675
Shell and Implement	35 kg	22,000
Wheel	8 kg	12,000
Suspension	5 kg	^
Battery and Power	49 kg	100,800
Drive	0.91 kg	3,500
Sensors	2 kg	^
Comms	0.052 kg	^
Total	189.962 kg	140,975

Fig. 11 -