C3 COSMIC Track 2: REV-LE (Regolith Excavation Vehicle for Lunar Exploration)

Final Technical Report

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Table of Contents

Abbreviations

CAD	Computer Aided Design
C&DH	Command and Data Handling
COM	Communications
dBm	Decibel Milliwatts
DC	Direct Current
DMM	Digital Multimeter
ESA	European Space Agency
EMI	Electromagnetic Interference
EPS	Electrical and Power Subsystem
FOS	Factor of Safety
GB	Gigabyte
GHz	Gigahertz
GLL	Griffin Lunar Lander
GNC	Guidance, Navigation, and Controls
GPR	Ground Penetrating Radar
ISAM	In-space Servicing, Assembly, and Manufacturing
ISRO	Indian Space Research Organisation
JAXA	Japan Aerospace Exploration Agency
LCL	Latching Current Limiter
LiDAR	Light Detection and Ranging
Mbps	Megabits per second
NASA	National Aeronautics and Space Administration
NASA JPL	NASA Jet Propulsion Laboratory
psi	Pounds per Square Inch
REV-LE	Regolith Excavation Vehicle for Lunar Exploration
SG	System Goal
SN	Stakeholder Need
TB	Terabyte
TMS	Thermal/Mechanical Structures
3D	Three Dimensional
COTS	Commercial-off-the-shelf

1 Mission and Design Overview

1.a. Background and Motivation

As NASA and other international allies work to establish a sustainable lunar habitation system with the Artemis program, infrastructure needs have become one of the top engineering priorities. Power systems, habitats, modes of mobility, and scientific establishments cannot be deployed on the lunar surface without proper preparation, safety measures, and increased usability. The root of the issues on the Moon is lunar regolith, a combination of fragmented rock and moon dust that is loosely compacted on the surface and highly damaging to emerging technologies. Without any process to bind these particles or manage the dust contamination, the regolith remains easily mobilized and destructive to lunar operations. During landings and ascents, rocket plumes propel loose regolith particles at high speeds, which can destroy scientific instruments, deteriorate seals and joints, and cause dust dispersion through significant distances.

Uneven regolith and moon rocks on the surface provide a secondary challenge to future infrastructure on the Moon by making systems vulnerable to slight variations in slope, crater distribution, and boulder fields. Rover mobility faces these challenges, as well as potential traction loss and thermal problems. A lack of flat, compact terrain could slow down operations, notably in the colder, icy areas of the surface. Current lunar rovers, including those used in the Apollo missions, were designed for the exploration of new terrain rather than to establish a more permanent outpost on the Moon. This technology lacks the mass, means, and ability, as well as the necessary tools and, ideally, autonomy for activities such as clearing or ground compaction.

While emerging infrastructure ideas, such as regolith-based manufacturing, have great potential, they assume the presence of prepared and stable surfaces. These construction methods are ineffective when not adapted for lunar conditions. These restrictions create a capability gap; existing spacecraft or rover capabilities cannot adequately influence the lunar environment for prolonged human or robotic exploration. Developing an autonomous site-preparation system is an important and necessary requirement for the future of large-scale lunar infrastructure. REV-LE addresses the limitations of current technologies by removing surface obstacles, compacting regolith, minimizing dust uplift, and establishing verified sites to be occupied by a number of lunar outposts and infrastructure. By enabling safe missions to the lunar surface, this rover directly supports several space exploration objectives by maintaining an indefinite presence on the Moon, setting the stage for future commercial activity and human settlement.

1.b. Design Process Overview

The engineering design process of the REV-LE site-preparation rover was planned based on an iterative, structured approach aligned to stakeholder requirements, mission constraints, and a disciplined trade-study approach. The System Concept Review (SCR), System Requirements Review (SRR), and System Design Review (SDR) were developed in the earlier phases to establish the mission context and identify requirements and key stakeholders. These efforts led to the selection of the site-preparation rover as the baseline concept based on feasibility, mission value, and system complexity.

The overarching challenge is updating technologies to produce flat, compacted, dust-controlled surfaces on the Moon. Stakeholder interests were translated into specific system goals, operational constraints, and quantifiable performance measurements. This phase set the context of the mission and ensured a traceable flow between user needs and the system. After design requirements were identified, the subsequent System Design Review (SDR) involved investigating a large number of possible payload concepts addressing mission requirements. Concepts such as regolith-based additive manufacturing, modular robotics, lunar resource extraction, charging stations, and site-preparation rovers were generated and tested for technical feasibility, fit on the Griffin lander, scientific and commercial utility, system complexity, and group capability.

In this exploratory effort, a feasible design space was defined, and the architectural characteristics critically important to lunar infrastructure support were defined, such as terrain leveling, obstacle removal, regolith compaction, and dust mitigation. REV-LE was introduced as the baseline payload and demonstrated the first integrated system concept, including a high-level ConOps, top-level subsystem definitions, and refined system goals and success criteria that aligned with stakeholder needs. This formalized the rover's role as an enabling technology for future lunar infrastructure and set the stage for subsystem-level engineering. The initial design was then modified to be more realistic to produce as a functional prototype while maintaining the basic intended functionality.

This phase represents the critical transition from design to implementation. Verification planning has been developed to support future prototype testing, and parts have been ordered, allowing construction to commence promptly. During assembly, the focus will fall on physical subsystem integration, mechanical assembly, and validation of the rover's mechanical abilities. These efforts should highlight early identification of integration challenges and performance limitations, providing potential design improvements.

2 Stakeholders, Needs, Goals, Assumptions, and Constraints

2.a. Stakeholders

Primary Stakeholders	
Stakeholder	Need Statement
Lunar lander companies using launch pads prepared by system (SpaceX, Blue Origin, Intuitive Machines, Firefly, Future Systems, etc.)	SN 1.1 The system produces flat enough sites to be landed on reliably in locations of scientific or commercial interest.

	SN 1.2. The flat sites produced for launch pads are capable of being landed on with minimal dust displacement from surface into the surrounding space.
Lunar mobility companies using roads prepared by system (Lunar Outpost, Intuitive Machines, Astrolab, NASA JPL, etc.)	SN 2.0. The system produces flat enough roads to allow enhanced mobility near locations of scientific or commercial interest.
Lunar habitat companies using habitat sites prepared by system (ICON, Sierra Space, Lockheed Martin, Boeing, Northrop Grumman, etc.)	SN 3.0. The system produces sites accessible for humans or other infrastructure building robots to construct habitats near locations of scientific or commercial robots.
End operator of system (Internal team or NASA)	SN 4.1. The system is capable of a mixture of autonomy and remote controlled operations.
	SN 4.2. The system contains sufficient safety procedures and considerations to ensure reliable continued operations.
Lander provider (Astrobotic)	SN 5.1. The system will be capable of being safely deployed to the surface by the Griffin lander.
	SN 5.2. The system will be compatible with the Griffin lander's communication and power interfaces.
NASA & Other International Space Agencies (JAXA, ESA, ISRO, etc.)	SN 6.0. The system will provide and enable critical infrastructure for sustained life and scientific exploration on the moon.
Federal Communications Commission (FCC)	SN 7.0. The system will comply with FCC regulations surrounding radio communication.
Federal Aviation Administration (FAA)	SN 8.0. The system will comply with FAA regulations surrounding vehicle launch.

Table 1: *Primary stakeholders driving mission decisions*

Secondary Stakeholders	
Stakeholder	Need Statement
United States Department of War and International Defense Allies	SN 8.0. The system will increase access to the moon in a way that preserves or promotes the United States' and its allies' defense needs.
United States Department of State and Space Policy Organizations and Various International	SN 9.0. The environmental impact of the system will be positive enough to allow international

Government Organizations	accessibility to the moon as outlined by the Artemis Accords.
Private Space Organizations Investing in Lunar Exploration and Infrastructure	SN 10.0. The system will make the lunar economy more economically viable.
Subcontractors for electronics	SN 11.0. The system will be compatible with the components or subsystems provided by subcontractors.

Table 2: *Secondary stakeholders with potential interest in mission*

The primary stakeholders were identified by considering the entire concept of operations and determining the interfacing companies and agencies that would require a certain performance or usability as well as determining the necessary regulatory bodies that would require compliance. The secondary stakeholders were also identified as a precautionary measure to consider the wide reaching effects of the system, allowing early identification of threats to mission success and of opportunities for future growth and system use cases.

2.b. System Goals

Goal ID	System Goals	Priority	Needs Satisfied
Criteria 1: Site Preparation			
SG 1.1	The system must ensure that debris rock above the desired compaction plane can be pushed by the dozer blade out of the site borders.	Critical	SN 1.1, SN 1.2, SN 2.0, SN 3.0, SN 6.0
SG 1.2	The system must be able to compact the ground sufficiently to achieve a density suitable for building lunar infrastructure on top.	Critical	SN 1.1, SN 1.2, SN 2.0, SN 3.0, SN 6.0, SN 7.0
Criteria 2: Griffin Lunar Lander Restrictions			
SG 2.1	The system must fit inside half of the payload volume envelope provided by the Griffin Lunar Lander.	Critical	SN 5.1, SN 10.0
SG 2.2	The system must meet the mass requirements of the Griffin Lunar Lander.	Critical	SN 5.1, SN 9.0, SN 10.0
Criteria 3: Set up and Tear down			
SG 3	The system should be deployed from the lander with minimal human intervention.	Important	SN 4.1, SN 5.1
Criteria 4: System Performance			
SG 4.1	The system might be capable of traveling from the lander to a	Desirable	SN 5.2, SN 9,

	compaction site and back before battery depletion.		SN 10.0
SG 4.2	The system might be able to fully prepare a sufficient area of standard site per lunar day.	Desirable	SN 6.0, SN 7.0, SN 9.0
SG 4.3	The system might be able to complete operations within an acceptable time frame.	Desirable	SN 1.1, SN 1.2, SN 2.0, SN 3.0, SN 6.0, SN 9.0, SN 10.0
Criteria 5: Site Scanning and Identification			
SG 5	The system must have geography scanning LiDAR capabilities capable of measuring ground heights with sufficient accuracy.	Critical	SN 1.1, SN 1.2, SN 2.0, SN 3.0, SN 6.0, SN 9.0, SN 10.0
Criteria 6: Autonomy			
SG 6	The system might operate with minimal human intervention.	Important	SN 4.1
Criteria 7: System Durability			
SG 7	The system must survive all possible environmental challenges of operating on the lunar surface for greater than 14 days.	Critical	SN 5.2
Criteria 8: Communications			
SG 8	The system shall be able to communicate with the Griffin Lunar Lander within its maximum operable range.	Critical	SN 5.2
Criteria 9: Environmental Impact			
SG 9	The system must have a positive enough impact to allow for increased lunar transportation and economic viability whilst also not causing significant damage to nearby lunar site environments.	Critical	SN 9.0, SN 8.0

Table 3: *Systems goals and success criteria*

3 System Architecture

3.a. Concept of Operations

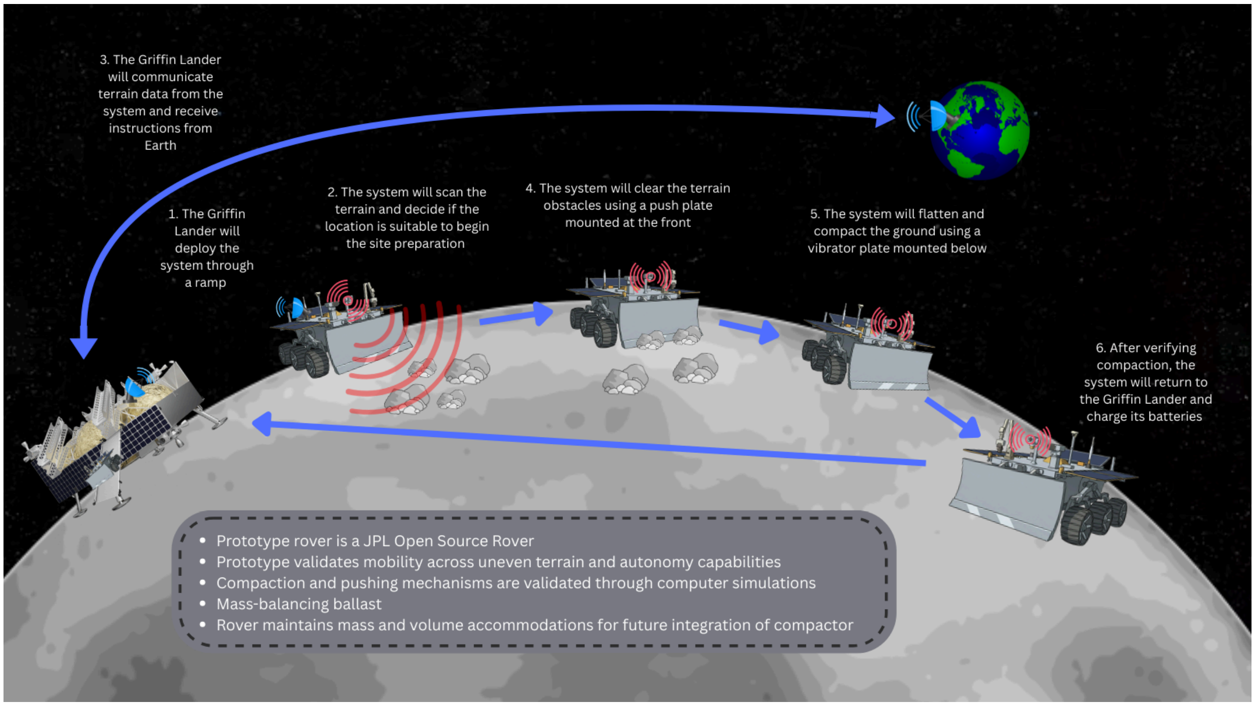


Figure 1: *REV-LE concept of operations depicting phases 1-6 of the mission*

3.b. Functional Flow Block Diagram

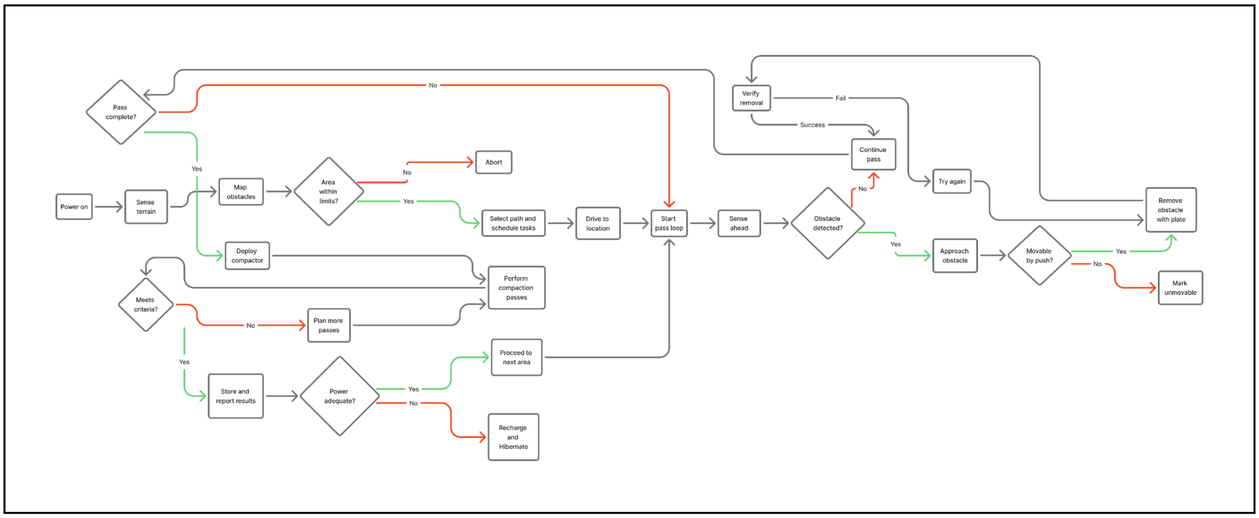


Figure 2: *REV-LE functional flow block diagram*

3.c. System Decomposition Diagram

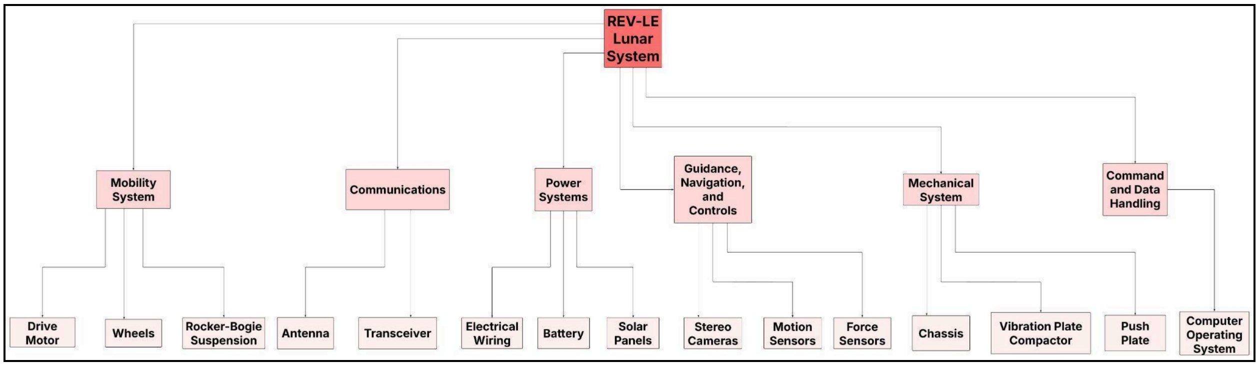


Figure 3: *REV-LE system decomposition diagram*

The System Decomposition Diagram illustrates the subsystems and its components.

Mobility System - Enables the system to maneuver through uneven lunar terrain and reach its desired destination safely.

- Drive Motor - Convert electrical energy to mechanical energy to move the wheels
- Wheels - Provide traction and propels the system forward
- Rocker-Bogie Suspension - Ensures mobility over rocks and irregular terrain

Communications - Allows reliable communication and data exchange between the rover and Griffin Lander.

- Antenna - Handles transmission and reception of communication signals
- Transceiver - Converts digital messages into radio signals and vice versa

Power Systems - Provides electrical power for mobility, sensing, computing, and compaction

- Electrical Wiring - Distributes power across all subsystems
- Battery - Stores energy during operations and powers high demand components
- Solar Panels - Recharge the batteries during daytime and extend mission endurance.

Guidance, Navigation, and Controls - Enables the system's autonomy, obstacle detection, localization, and perception of the environment.

- Stereo Cameras - Provide 3D scene reconstruction for terrain mapping and identifying obstacles
- Motion Sensors - Used to estimate the system's position and velocity
- Force Sensors - Monitor loads on the push plate and compactor, helps assess the mobility of an obstacle and verification of compaction

Mechanical System - Perform the physical work of clearing obstacles and compacting regolith

- Chassis - Protects and holds all components, supports loads during obstacle pushing and compaction
- Vibration Plate Compactor - Compacts the lunar regolith to achieve a specified density and flatness
- Push Plate - Removes rocks and debris from the terrain

Command and Data Handling - Provides computational autonomy and control

- Computer Operating System - Runs the system's autonomy software, sensor processing, path-planning algorithms, and communication protocols

4 Requirements

4.a. System-Level Requirements

REVLE System-Level Requirements			
System Requirement ID and traceability	**Requirement Statement**	**Rationale**	**Verification Method**
REVLE-001 SG 2.2	The system shall have a mass less than or equal to 200 kilograms at launch.	The system must meet the payload mass requirements to be considered for further development.	The system's mass will be measured using a scale, which can be achieved by breaking the system into components and adding the individual masses to determine the system's total mass.
REVLE-002 SG 2.1	The system shall have dimensions less than or equal 1.7 m by 1.75 m by 2.5 m in launch configuration.	The system must meet the payload size requirements to be safely attached to the Griffin Lander and to be considered for further development.	The system's volume will be analyzed by calculating and adding the individual component volumes using the geometry defined in CAD.
REVLE-003 SG 5	The system shall have LiDAR capabilities capable of scanning geography and measuring ground heights with an accuracy of ±20 mm.	The system must be able to accurately measure terrain height for site identification and for ensuring level surfaces for site preparation.	The system's LiDAR capabilities will be tested on lunar regolith simulant with known reference heights to compare with the system's measurements and ensure accuracy.
REVLE-004 SG 6	The system shall autonomously navigate and determine its position and orientation within the lunar environment.	The system must be able to autonomously maneuver the lunar landscape to complete its tasks with minimal human input.	The system's autonomous movement will be verified by testing its navigation on a simulated lunar environment. Performance can be assessed by comparing the planned path and the actual path.
REVLE-005 SG 4.2	The system shall compact and clear greater than or equal to 150 m^2 of surface per operational lunar day.	The system must be able to perform tasks and prepare sites within an appropriate timeframe, considering the mission's lifetime.	The system will be tested by running a site preparation sequence on a lunar regolith simulant and measuring the area it prepares within a lunar

			daylight period (approximately 14 Earth days).
REVLE-006 SG 8	The system shall have a communication range greater than or equal to 500 meters in sight of the lander.	The system must be able to receive and transmit data to the Griffin Lander from its site preparation location.	The system's communication range will be tested in a field test simulating the lunar environment by measuring the connection stability.
REVLE-007 SG 4.3, SG 8	The system shall have a bit error rate less than or equal to 10^{-6} during navigation and site preparation tasks.	The system must be able to receive commands and transmit telemetry and site preparation data safely.	The system's bit error rate will be determined by simulating a site preparation task and transmitting known data, which will then be used to evaluate the number of received bits and identify the number of errors.
REVLE-008 SG 1.2	The system shall measure the density of landing sites after preparation and ensure the bulk density is greater than or equal to 1.40 g/cm^3.	The system must be able to ensure the effectiveness of its site preparation by measuring the density of the regolith. The regolith must be dense enough to house infrastructure such as landing pads.	The system's tool for measuring density will be tested on Earth after the system does its compaction operations on lunar regolith simulant to verify accurate measurements.
REVLE-009 SG 7	The system shall limit regolith particle concentration above the surface to less than or equal to 255 μg/m^3 during operation.	The system must be able to minimize regolith dust generation to maintain operations, minimize part degradation, and survive the entire mission duration.	The system's regolith particle generation will be measured with optical instruments during site preparation tasks on a lunar regolith simulant.
REVLE-010 SG 7	The system shall comply with the requirements for active payloads with antennas as defined in the Requirements for the Control of Electromagnetic Interference	The system must comply with electromagnetic emissions standards to prevent degradation of communication and performance in the Griffin Lander.	The necessary system-level testing to ensure compliance with EMI standards is found in MIL-STD-461G (Requirements CE102, CS101, CS114, CS115, CS116, RE102, RS103).

	Emissions and Susceptibility (MIL-STD-461G) document.		
REVLE-011 SG 5, SG 8	The system shall process and store mission data at a rate sufficient to allow for continuous navigation and site preparation operations without exceeding storage limits.	Site preparation tasks can not be completed if the system cannot process and store the necessary amount of data.	The system's site preparation tasks can be simulated to determine whether they can be performed with minimal human input, demonstrating that the system has the necessary storage and processing power.
REVLE-012 SG 9	The system shall adhere to the Outer Space Treaty RES 2222 (XXI).	Debris and damage could interfere with lunar ISAM operations and scientific interests.	On earth testing and post-operations observation and analysis of selected site and surrounding environment.
REVLE-013 SN 1.1, SN 1.2, SN 2.0, SN 3.0, SN 6.0	The system shall be capable of traversing lunar surface terrain without causing damage to the rover or compromising compaction performance.	Traversal to and from the GLL is necessary for site identification, site preparation, and recharge.	Mobility envelope, multi-body simulations, and prototype testing.
REVLE-014 SN 4.2, SN 6, SN 5.1	The system shall deploy and pass all post landing tests (Power-on-self test, telemetry link test, Mobility test, Power/thermal test, and Nav sensor test) and require no in-situ maintenance.	Lunar operations preclude field servicing, robustness is essential in avoiding mission disturbances and interruptions	Prototype testing, designing no maintenance parts (ie seals, joints, dry lubes, hardware).

Table 4: *System-level requirements, rationale, and verification*

4.b. Subsystem Requirements

4.b.1 Communications (COM) Subsystem Requirements

REVLE System-Level Requirements			
System Requirement ID and traceability	**Requirement Statement**	**Rationale**	**Verification Method**
REVLE-COM-001 SG 8	The system shall be capable of transceiving communication from the Griffin Lander of signal strengths -100 to -10 dBm.	The ability to transceive the wide range of signal strengths expected to and from the Griffin lander enables constant connection for critical communication in the wide range of mission conditions.	The transceivers sourced from subcontractors will come with verified specifications.
REVLE-COM-002 SG 8, REVLE-003	The system shall be capable of transceiving communication from the Griffin Lander of bandwidths 5-15 Mbps.	The communication bandwidth must enable video stream to the Griffin lander to be relayed back to Earth during mission critical anomaly handling situations.	The transceivers sourced from subcontractors will come with verified specifications.

Table 5: *Communications (COM) subsystem-level requirements, rationale, and verification*

4.b.2 Electrical Power (EPS) Subsystem Requirements

REVLE System-Level Requirements			
System Requirement ID and traceability	**Requirement Statement**	**Rationale**	**Verification Method**
REVLE-EPS-001 SG 1.1, SG 1.2, REVLE-005	The EPS shall provide a continuous power output of 500-1000 W for a duration of 4 hours during peak site-preparation operations, including operation of the roller compaction mechanism and bulldozing mechanism.	Defining explicit power (W) requirements ensures the rover can meet all operational demands without premature depletion.	Test & Analysis: During integrated system testing, the EPS will be instrumented to measure bus power output under a simulated peak site-preparation load of 500 W for the specified 4-hour operation profile. Analytical modeling of power profiles will supplement the tests to

			confirm margin across worst-case scenarios.
REVLE-EPS-002 SG 1.1, SG 1.2, SG 4.1, SG 4.2, SG 4.3, REVLE-005	The EPS shall store 2.0-10.0 kWh of usable energy, enabling the rover to complete one full worst-case site-preparation cycle.	Defining energy capacity (Wh) requirements ensures the rover can meet all operational demands without premature depletion. The metric in the requirement enables the rover to complete a worst-case system operation cycle (4 hours active operation plus 2 hours travers), and still maintain a state-of-charge ≥15% of total usable capacity at the time of redocking to charge at the Griffin lander. This reserve margin provides operational robustness against performance degradation (battery aging, thermal effects, dust-reduced solar charging) and unexpected load increases.	Test & Analysis: During integrated system testing, the EPS will be instrumented to measure bus power output under a simulated peak site-preparation load of 500 W for the specified 4-hour operation and 2-hour traverse profile. Battery energy capacity (≥2.5 kWh usable) and reserve state-of-charge (≥15%) will be verified by discharge testing against a representative duty cycle. Survival loads (≤50 W) will be monitored to confirm continuous support. Analytical modeling of power profiles and thermal effects will supplement the tests to confirm margin across worst-case scenarios.
REVLE-EPS-003 SG 1.1, SG 1.2	The EPS shall protect against electrical faults by maintaining bus voltage within 28 V ± 2 V during normal operation and disconnecting loads if the bus exceeds 30 V or falls below 26 V.	Explicit trip thresholds and voltage ranges ensure that the EPS can be verified in test and analysis, preventing damage from overloads and shorts.	Test & Analysis: On a bench with a programmable DC bus supply, oscilloscope, and precision DMM, operate the EPS through the worst-case “normal operation” load profile. Induce controlled excursions: step the input so the internal bus attempts to exceed 30.0 V and then below 26.0 V.
REVLE-EPS-004 SG 1.1, SG 1.2	The EPS shall protect against electrical faults by tripping per-channel latching current limiters	Explicit trip thresholds and ensure that the EPS can be verified in test and analysis, preventing	Test & Analysis: On a bench with a programmable DC bus supply, oscilloscope, and precision DMM, operate

	(LCLs) at 1.5x nominal load current, with up to 3 autonomous retries before latching off.	damage from overloads and shorts.	each EPS output channel through its nominal load current. Use a programmable electronic load to pull 1.5x the nominal load, and capture current/voltage/time data.

Table 6: *Electrical Power (EPS) subsystem-level requirements, rationale, and verification*

4.b.3 Guidance, Navigation, and Controls (GNC) Subsystem Requirements

REVLE System-Level Requirements			
System Requirement ID and traceability	**Requirement Statement**	**Rationale**	**Verification Method**
REVLE-GNC-001 SG 4.1, SG 6, REVLE-004	The guidance subsystem shall identify its local 3D position within 0.25 meters.	The rover must be able to track its position with high enough accuracy to map 3D environments with high fidelity and enable closed loop control for path following, and avoiding obstacles.	The positional accuracy of the guidance subsystem can be modeled using the propagated error of the sensors utilized to produce a 3D position estimate.
REVLE-GNC-002 SG 4.1, SG 6, REVLE-003, REVLE-004	The guidance subsystem shall identify its 3D orientation within 2 degrees.	The rover must be able to track its orientation with high enough accuracy to map 3D environments with high fidelity and enable closed loop control for path following, and avoiding obstacles.	The orientation accuracy of the guidance subsystem can be modeled using the propagated error of the sensors utilized to produce a 3D orientation estimate.
REVLE-GNC-003 SG 4.1, SG 6, REVLE-004	The navigation subsystem shall be able to continuously update path planning algorithms within 3 seconds of a new terrain information package.	It is necessary for the robot to be able to dynamically move through an unmapped terrain and react to unexpected obstacles autonomously to allow autonomous mapping for determining site locations in quick enough time to complete site preparation tasks in	The robot’s path planning algorithm can be tested in a simulation environment then in a physical environment replicating the moon’s environment on Earth.

		the allotted time before system failure.	
REVLE-GNC-004 SG 4.1, SG 6, REVLE-004	The control subsystem shall navigate the robot through the desired path within 0.25 meters accuracy.	It is necessary for the robot to be near its desired path to avoid unintended obstacles and optimize trajectories for performance in the shortest amount of time.	The control system utilized on the robot can be tested in first simulation then in a physical environment replicating the moon's environment on Earth.

Table 7: *Guidance, Navigation, and Controls (GNC) subsystem-level requirements, rationale, and verification*

4.b.4 Thermal/Mechanical Structures (TMS) Subsystem Requirements

REVLE System-Level Requirements			
System Requirement ID and traceability	**Requirement Statement**	**Rationale**	**Verification Method**
REVLE-TMS-001 REVLE-001	The TMS system of REVLE shall have a mass between 100 and 180 kg.	The TMS system needs to adhere to the weight constraints of the Griffin Lander and also adhere to the system requirements that govern it.	The TMS system's individual components can be weighed on Earth and added up to find the total weight of the system. This mass of the system can then be calculated using the total weight.
REVLE-TMS-002 REVLE-002	The TMS system's bulldozing mechanism shall be able to withstand between 40.5 and 65 N of resistive normal force on the blade without yielding or buckling with a FOS between 1.5 and 250.	The TMS system should not fail under its operating conditions. The operating conditions are defined by the system's ability to overcome the static frictional force generated by pushing a 50 kg rock on lunar regolith.	Test REVLE on Earth by letting it push an equivalent load and measure the strains developed on the mechanism's parts using a strain gauge.
REVLE-TMS-003 SG 7	The TMS system shall be able to withstand temperatures ranging from -208 to 250°C.	The failure mechanisms of yielding and buckling are dependent on material properties (yield strength and elastic	Perform analysis by simulating yielding and buckling on the TMS mechanisms and the

		modulus) that are dependent on the temperature of the body.	extremes of the temperature ranges.
REVLE-TMS-004 SG 1.2	The TMS system's vibration compaction mechanism shall be capable of producing greater than or equal to 2.8 kpa of compaction pressure.	The vibration mechanism needs to be able to compact the regolith to enough density that lunar infrastructure can be built on top of the prepared site. A dense ground is required to prevent buildings from sinking into the soil.	Test the prototyped compaction system on a simulation and ensure its meeting the density requirement.

Table 7: *Thermal/Mechanical Structures (TMS) subsystem-level requirements, rationale, and verification*

4.b.5 Command and Data Handling (C&DH) Subsystem Requirements

REVLE System-Level Requirements			
System Requirement ID and traceability	**Requirement Statement**	**Rationale**	**Verification Method**
REVLE-C&DH-001 SG 4.1, SG 6, REVLE-003, REVLE-011	The on-board processor shall contain 4-8 cores operating at 2-5 GHz.	The speed necessary for 3D map generation and path planning requires significant central processing unit clock speed and parallel processing capabilities.	The processor sourced from subcontractors will come with verified processor specifications.
REVLE-C&DH-002 SG 4.1, SG 6, REVLE-003, REVLE-011	The data handling system shall contain 4-16 GB of random-access memory.	The system will need to have active path planning, obstacle avoidance, and control systems programs and tasks that require fast access to short-term memory.	The random access memory sourced from subcontractors will come with verified specifications.
REVLE-C&DH-003 SG 4.1, SG 6, REVLE-003, REVLE-011	The data handling system shall contain 1-2 TB of internal storage.	The system will be taking in considerable amounts of data that require storage before completing necessary computations and	The internal storage sourced from subcontractors will come with verified specifications.

		discarding through erasure or uplink.	

Table 8: *Command and data handling (C&DH) subsystem-level requirements, rationale, and verification*

4.b.6 Mobility (MOB) Subsystem Requirements

REVLE System-Level Requirements			
System Requirement ID and traceability	**Requirement Statement**	**Rationale**	**Verification Method**
REVLE-MOB-001 SN 1.1, SN 1.2, SN 2.0, SN 3.0, SN 6.0, SN 4.1, SN 4.2	The system shall traverse slopes up to 20 degrees without exceeding 20% wheel slip or loss of traction.	This ensures the rover maintains forward motion and control on an inclined slope if encountered in traversal of lunar terrain.	Ramp testing verification of prototype, slip ratio computation, odometry data during 20 degree ascent.
REVLE-MOB-002 SN 1.1, SN 1.2, SN 2.0, SN 3.0, SN 6.0, SN 4.1, SN 4.2	The mobility subsystem shall traverse obstacles up to 20 cm in height without high-centering or loss of stability.	This guarantees the rover can negotiate uneven terrain, rocks, and crevasses within its operational region.	Physical obstacle course prototype testing on simulant, verify that all 6 wheels make ground contact when clearing a 0.2 m step.
REVLE-MOB-003 SN 1.1, SN 2.0, SN 3.0, SN 6.0, SN 4.2	The system's wheel sinkage shall not exceed 10 mm under nominal lunar gravity loading.	Prevents loss of traction and minimizes energy loss.	Wheel simulation and prototype testing.
REVLE-MOB-004 SN 1.1, SN 1.2, SN 2.0, SN 3.0	The system shall maintain static stability on slopes up to 35 degrees in both longitudinal and lateral directions without tipping.	Tip over is a critical consequence, this requirement sets a 15 degree margin beyond operational gradeability to ensure safety during traversal.	Tilt-table prototype testing and CAD analysis.

Table 9: *Mobility (MOB) subsystem-level requirements, rationale, and verification*

5 System Design (Full-Scale Flight Model Rover)

5.b. Plate Compactor

Key subsystem Requirements driving the design of the payload/compaction plate: REVLE-002, REVLE-005, REVLE-TMS-001, and REVLE-TMS-004. The plate compaction design process began with rough calculations to determine the plate's dimensions and the force produced by the vibratory motor. Since our rover needs to prepare a certain area per day, the plate's surface area must be large enough to meet that requirement. The plate is 21.625 inches long, 14.5 inches wide, and 0.35 inches thick. A36 steel was the material chosen for several reasons. The material's high density will increase the force of compaction the surface regolith experiences due to the mass it adds to the overall compaction system. Additionally, steel is a strong, stiff alloy that can withstand yielding while transferring vibrational force to the surface.

Once the plate dimensions were chosen, the centrifugal force that the motor needs to produce could be found by working backwards from the compaction pressure requirement, a value of 2.8 kPa outlined in REVLE-TMS-004. Until further analysis of the effects of implementing a motor that produces a large vibratory force on our chassis is conducted, a target pressure of 3.0 kPa was set. Since the area of the plate is 0.202 m^2, the compaction system should produce roughly 600 N of force. The plate will weigh 26.7 N on the moon, so the motor must produce around 575 N of centrifugal force. Based on this criterion, an electrical micro vibration motor - VY 60 by Miksan Motor was chosen. This motor produces 579 N of centrifugal force, has a mass of 2.70 kg, and operates at 50 Hz. This subsystem now adheres to the REVLE-002, REVLE-005, REVLE-TMS-001, and REVLE-TMS-004 requirements.

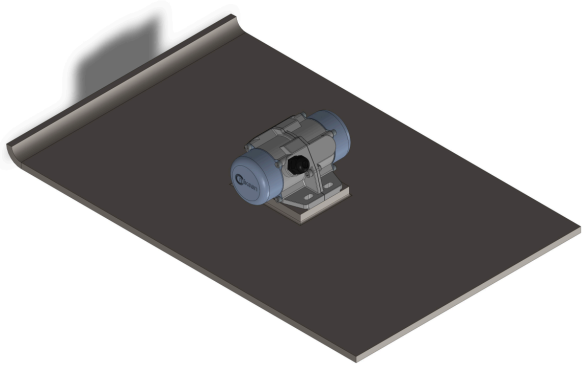


Figure 5: CAD Model of the Plate Compactor

FEA analysis was performed on the compaction plate to ensure that it did not yield from the applied vibratory force from the motor. The locations where the plate was connected to the rover assembly were assumed to be elastically supported, since, as later mentioned, they were connected by shock dampers. The load condition was a 600 N force applied to the rotor mount. Below is the resulting Von Mises stress figure, showing that the plate is not close to yielding.

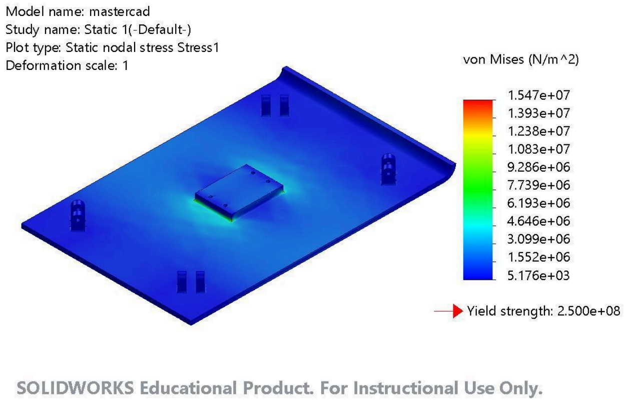
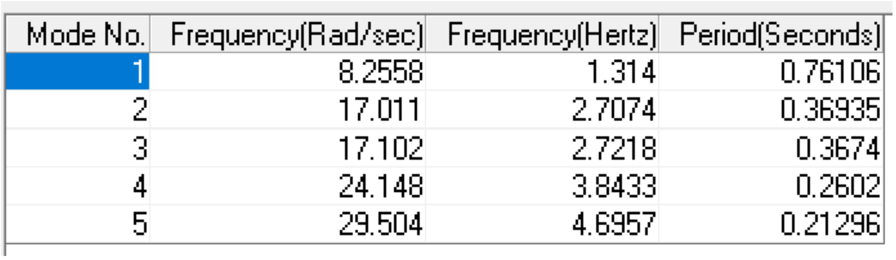


Figure 6: Von Mises Stress Figure

The last analysis done on the plate compaction subsystem was a modal analysis. It was important to determine the frequencies of the modes to ensure they did not match or come close to the motor's frequency, 50 Hz, or else resonance would occur and damage the system. The total mass of the plate and motor is 18 kg. Below is the modal analysis, which shows that the subsystem does not resonate.



Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	8.2558	1.314	0.76106
2	17.011	2.7074	0.36935
3	17.102	2.7218	0.3674
4	24.148	3.8433	0.2602
5	29.504	4.6957	0.21296

Figure 7: Results of Frequency Testing

5.b.2 Plate Compactor integration with chassis

An interface plate was created that would connect the compaction plate system to the chassis. The compaction plate is connected to the interface plate through four axial coilover shock damps. These shock damps will help direct the motion of the vibrating plate vertically, minimizing horizontal movement and directing the force downwards. Additionally, the shock damps will help minimize the vibrational forces the chassis will feel from the motor. A screw jack mechanism is implemented to translate the compaction plate up and down relative to the chassis. It will be retracted, translated upwards, during rover mobility maneuvers, and then extruded for compaction. The compaction subsystem will be prototyped and tested on regolith simulants to ensure it is meeting system reuse requirements and stakeholder needs.

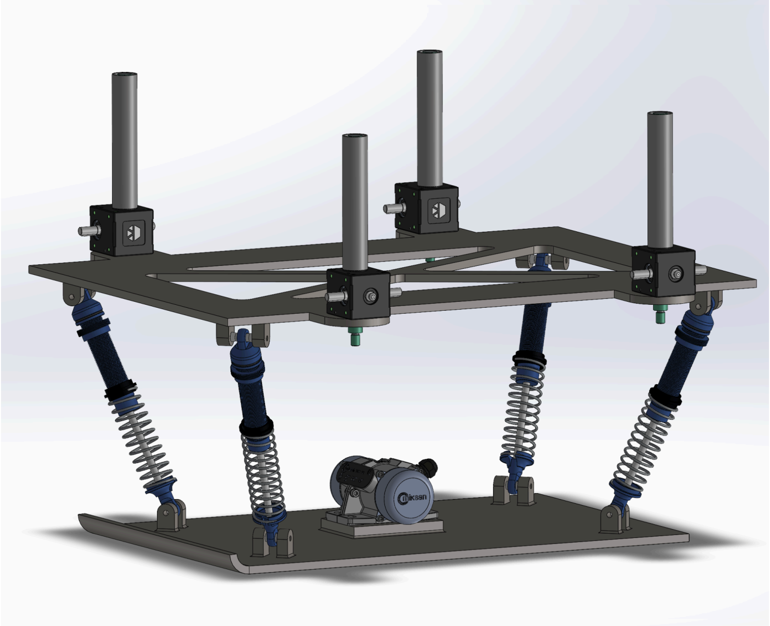


Figure 8: CAD Model of Plate Compactor and its Connection to the Chassis

5.b.3 Density Analysis

The method for measuring regolith post-compaction is a digital static cone penetrometer. The Humboldt HS-4210 is a device used to measure compaction and load-bearing capacity. This specific model has been cited in the literature and used for lunar missions. Although the device cannot directly measure density, a relationship between load-bearing capacity and density can be established by testing lunar simulants. Calibration of the device will be performed by mimicking the environment in which it will be used to ensure the relationship between load-bearing capacity and density is accurate. Other options such as a nuclear density gauge were considered, but the penetrometer allows for easy implementation. Once calibrated, tests can be performed to ensure that the tool can meet system requirements and measure density of sites accurately.

5.c. Power:

The power subsystem provides continuous electrical power to all other subsystems. It will primarily consist of solar panels and a battery.. The primary design drivers are REVLE-EPS-00, which states that the EPS shall provide a continuous power output of 500-1000 W for a duration of 4 hours during peak site-preparation operations, including operation of the roller compaction mechanism and bulldozing mechanism, as well as REVLE-EPS-002, which says that the EPS shall store 2.0-10.0 kWh of usable energy, enabling the rover to complete one full worst-case site-preparation cycle. In the case that the battery level reaches a critical level before the mission is completed, the system automatically aborts and drives to the Griffin Lander to recharge.

5.c.1 Power Budget

Component	Bus Voltage (V)	Average Power (W)	Capacity (Wh) (over 4 hours)
Wheel Hub Motors	48	400	1600

Screw Jack Motors (for plate assembly)	24	100	400
Vibratory Motor	230	21	84
Flight Computer	3.3	20	80
Communication Transceiver	3.3	5	20
IMU	3.3	0.1	0.4
Stereo Cameras	5	8	32
Temp. & Pressure Sensors	3.3	0.05	0.2
Displacement Sensor	5	1	4
Load Cell	5	0.2	0.8
Navigation Sensor	12	10	40
Total:	-	565.35	2261.4

Table 4: REV-LE Power Consumption

The total average power estimate is 565.35 W, with a capacity of 2261.4 Wh to sustain power for 4 hours during high demand operations. These values fall within the ranges stated in the requirements. The solar panels and battery were designed to support this energy demand with margins of safety. The solar panels will generate 700 W and the battery will store 3 kWh of usable energy.

5.c.2 Battery

A Lithium-ion battery was chosen due to its high gravimetric energy density and ability to deliver high peak currents to motor loads. A 3 kWh battery provides usable energy of 2.4 kWh at 80% DoD for safety margin. This accounts for battery degradation, depth of discharge limits, and other inefficiencies in power conversion. A 48 V battery is a practical choice for this system due to its low currents for kW-class loads. Lower current ensures that the wiring can be thinner and has lower losses, which is important for mass-constrained lunar hardware. A 3 kWh of usable energy with a 48 W battery indicates 62.5 Ah for the battery. This is calculated by dividing the nominal energy of 3000 Wh by the 48 V. It is estimated that a battery of these characteristics weighs between 20-40 kg.

5.c.3 Solar Panels

Spectrolab triple-junction Gallium Arsenide solar panels were chosen for its high efficiency of 30% and reliability in space. These panels are commonly used in other space applications due to their radiation tolerance and low mass, which is important in the lunar environment that REV-LE will be exposed to. In order to obtain 700 W of power with 80% DoD margin, the system needs 2.14 m^2 of GaAs solar panels. These panels will weigh an estimated 3-4 kg for the size needed.

Solar Panel Area Calculation where A is the area of solar panels, E is nominal energy, G is solar irradiance of the moon, and sigma is panel efficiency:

$$A = \frac{E}{(G \cdot \sigma \cdot 0.8)} = \frac{700\ \text{W}}{(1361\ \text{W/m}^2 \cdot 0.3 \cdot 0.8)} = 2.14\ \text{m}^2$$

5.c.4 Power Verification Methods

To verify that the Electrical Power System meets the mission requirements, a series of hardware and analytical tests will be conducted to validate both power delivery and energy storage performance. The battery will undergo controlled charge-discharge testing to confirm usable energy output and confirm that the system can sustain a continuous 700 W load for the required four hours at peak operations. Thermal and electrical measurements during these load tests will verify that voltages and currents remain within safe operating ranges. The power management hardware will also be tested in a vacuum with lunar conditions to verify that all components can maintain performance under lunar temperatures and pressure.

The solar array will also be validated through illumination testing to confirm it can produce the expected power generation and charging rates. Additional tests will monitor the panel's sensitivity to dust and panel angle, which will account for inefficiencies similar to those in the lunar environment. This test will ensure that the solar panels have sufficient safety margins for the battery recharge requirements.

5.d. Rover Mobility

The rover mobility subsystem can be broken down into 3 components: the wheels, suspension, and the drive motor system. This system will be capable of traversing moderate to severe difficulty lunar terrain obstacles. Assumptions made for lunar environment parameters in calculations and design parameters are given in the appendix along with sources/rationale for each value.

Slope Traversal Calculation

The ability of the rover to climb or traverse inclined terrain depends on whether the available traction force is greater than the forces acting downslope. Up-slope the force of traction (F_{req}) is required to maintain wheel mobility and must not be exceeded by downslope forces. If $F_{avail} > F_{req}$ the rover will successfully climb the slope, if $F_{avail} < F_{req}$, the wheels will slip or stall. The governing equations experienced by the rover during slope ascension are the following:

$$F_{req} = W\sin\theta + F_{rr}$$

$$F_{rr} = c_{rr}W\cos(\theta)$$

$$F_{avail} = \mu W\cos\theta$$

In which W is the rover weight, θ being the slope angle in degrees, c_{rr} being the rolling resistance coefficient, and μ being friction between wheel and regolith. F_{rr} is the energy loss due to wheel deformation and internal resistance to rolling, F_{avail} represents the maximum possible traction force the wheels can generate before slip occurs. For a slope traversal of 20°, values of W=283.5 N, θ = 20°, μ = 0.7, and c_{rr} = 0.05 were used which resulted in the following values:

$$F_{avail} = (0.7*283.5*\cos(20)) = 186.48\ \text{N}$$

$$F_{rr} = c_{rr}N = 0.05 * 283.5 * \cos(20) = 13.32\ N$$

$F_{req} = 283.5N * sin(20) + 13.32 = 110.28\, N$

Since F_{req} = 110.28 N and $F_{avail} = 186.48\, N$, this makes the ratio of required force to available force 1.69 which is acceptable for our gradeability requirement REVLE-MOB-001.

Gradeability Bound

The rover's gradeability represents the steepest slope it can ascend without slipping or losing traction. During slope ascension, the available traction force generated by the wheels must be greater than the sum of the forces acting downslope, therefore the minimum condition for maintaining traction is given by the following equation

$tan(\theta_{max}) \approx \mu - c_{rr} = 0.70 - 0.05 = 0.65\, rads \approx 33°$

Where μ is the coefficient of friction between the wheel and the regolith, c_{rr} is the rolling resistance coefficient, and θ_{max} is the maximum climbable slope angle in radians. Once our assumed values are calculated we receive a θ_{max} value of 33 degrees which greatly surpasses our the REVLE-MOB-001 requirement with a margin of 13°. This will ensure safe slope operation with a comfortable safety margin for operational uncertainties such as variations such as soil cohesion, uneven wheel loading, localized slip, or wheel sinkage.

Sinkage

To determine the sinkage of the rover wheels into the lunar regolith, we use the Bekker pressure-sinkage relationship. For this equation we assume a value of with k_c being the cohesive modulus of deformation, k_ϕ being the frictional modulus of deformation, z being sinkage depth, b as wheel width, and n as the sinkage exponent.

$p = (\frac{k_c}{b} + k_\phi)z^{n} = (\frac{1400}{0.08} + 820,000)z$

Since this equation has 2 unknowns, we must find another equation to solve for z, so we use the normal force of the wheel is equal to both the weight distributed per wheel and the contact pressure multiplied by the contact area touching the ground.

$N_{wheel} = p * A_c = W/6 = 47.25\, N$

$N_{wheel} = 47.25\, N = (\frac{1400}{0.08} + 820,000)z * A_c$

$A_c = b * l$

$l = 2\sqrt{rz}$, plugging the known values in we get $z = 9.19\, mm$ which meets REVLE-MOB-003 since sinkage does not exceed 10 mm. We can also calculate the ground pressure resulting from this and we get approximate 7.70 kPa which can be useful later in the design for understanding our maneuverability capabilities.

Obstacle Clearance

The rover's ability to climb over surface obstacles is primarily governed by its suspension geometry and wheel radius. The empirical suspension step-climbing capacity for rocker bogie within the range of 1.3 to 1.5 times the wheel radius, for our calculations we will use the lower bound to ensure we meet our minimum clearance requirement in worst case scenarios. $h_{max} \approx (1.3) * r = 0.208\, m$

This means the rover can theoretically climb obstacles up to 0.208 meters in height in nominal traction conditions. However, the anti-high-centering criterion is $H_c > \frac{h_{req}}{2}$ which is an acceptable approximation for now. The value for h_{req} is the maximum required obstacle height and H_c is the chassis ground clearanceSince our obstacle height clearance as outlined in REVLE-MOB-002 is $h_{req} = 0.20\,m = 200\,mm$, H_c is 0.12 m which is is an acceptable value to satisfy this requirement since it is greater than $\frac{h_{req}}{2}$.

Static Stability (Tip over Analysis)

The static stability of the rover determines the maximum slope or tilt angle it can experience before its center of gravity passes beyond the polygon of support formed by the wheel contact points which will cause tip over. To evaluate tip-over limits we need assume the chassis behaves as a quasi-rigid body which allows body flexing and dynamic effects are negligible and we rely solely on geometry. The governing equations using the polygon of support criterion are as follows:

$$\theta_{tip,\,long} = tan^{-1}\left(\frac{L/2}{h}\right) = tan^{-1}\left(\frac{0.90/2}{0.25}\right) = 61°$$

$$\theta_{tip,\,lat} = tan^{-1}\left(\frac{T/2}{h}\right) = tan^{-1}\left(\frac{0.60/2}{0.25}\right) = 50°$$

Plugging in our values for L = 0.90 m, T = 0.60 m, h = 0.25 m, we end up getting $\theta_{\text{tip, long}}$=61°, $\theta_{\text{tip, lat}}$=50°. Since both $\theta_{\text{tip, long}}$ and $\theta_{\text{tip, lat}}$ are much greater than 35 this meets the stability requirement with a large margin which satisfies REVLE-MOB-004. This means that the rover will remain stable beyond its maximum operating slope of 20 degrees.

5.d.1 Wheels

Trade studies conducted showed that machined aluminum wheels with curved titanium spokes and S curve shaped grousers, inspired by the Perseverance rover, allowed for the best traction, durability, lightest mass, and reduced slippage for our use case.

5.d.2 Suspension

Trade study showed that the Rocker-Bogie suspension system was the superior option when compared against active, independent, and solid axle suspension systems. They were evaluated using selection criteria of Mobility & obstacle clearance, stability, mass, power consumption, simplicity, and robustness. Plans to manufacture the chosen suspension system include a combination of both COTS and team machined components. Parts bought off the shelf are the differential joint and rocker joint. Whereas the rocker arm, forward bogie arm, and aft bogie arm will be machined using 4130 steel.

5.d.3 Wheel Motors

Assumping a forward speed of about 0.1 m/s and known radius r = 0.16 m, we can calculate the angular frequency per wheel using $\omega = v/r = 0.625\,rad/s$, this combined with the slope force requirement REVLE-MOB-001, electric power P_{elec} would equal roughly 29 W. Motors at peak 10 N per wheel which gives a 2x margin over the 20 degree torque requirement.

$$P_{mech} = F_{req}v = 22\,W$$

$$P_{elec} = P_{mech}/\eta = 22/0.75 = 29.3\,W$$

For our use case, a COTS dust-sealed brushless DC wheel motor similar to the ones used in Perseverance are the optimal choice for wheel motors due to their superior compatibility with our chosen suspension design, robustness, and for its low speed, high power specialized functions.

5.e. Communications:

All communication to and from REV-LE is conducted through a telemetry link between REV-LE and the Griffin Lander. Communication with the ground station will be handled by the Griffin Lander and relayed to REV-LE. Consequently, the communications subsystem of REV-LE has 3 major system and subsystem requirements driving its design. System requirement REVLE-006 states that the communication range must be greater than or equal to 500 meters in sight of the lander. Subsystem requirement REVLE-COM-001 states that the system shall be capable of transceiving communication from the Griffin Lander of signal strengths -100 to -10 dBm. Subsystem requirement REVLE-COM-002 states that the system shall be capable of transceiving communication from the Griffin Lander of bandwidths 5-15 Mbps.

Initially 4 different types of communication architecture were considered feasible for the mission, and then were further analyzed in a trade study. These options are UHF/S-band narrowband RF link, 2.4 GHz Wi-Fi industrial module, Sub-GHz LoRa spread-spectrum radio, and optical or laser line-of-sight link. The optical and laser line-of-sight connections were screened out early in the design process due to their highly directional nature, which would require rotating hardware and therefore added complexity to ensure a connection regardless of rover orientation.

Of these options, the major criteria were receiver sensitivity (dBm) as key link-closing factor, EIRP (dBm) based on transmitter power + antenna gain, and sustained user data rate (kbps) relative to imagery requirements. Additionally, other minor criteria were considered, which were energy efficiency and idle draw (mW) for EPS impact and environmental robustness and TRL for lunar survivability.

Ultimately the trade study resulted in pursuing a design for a UHF band communication architecture. This option had the highest TRL, robust to pointing, best sensitivity, with a still adequate data rate. While Wi-Fi was also an adequate option for its high data rate, it was deemed as a second-rate due to its poor link margin, high idle draw, and low TRL for lunar vacuum. LoRa architecture was deemed as inferior due to its insufficient data rate.

The final pieces of selected hardware for REV-LE's communication system is the SpaceQuest TRX-U UHF Transceiver and UHF Antenna III.

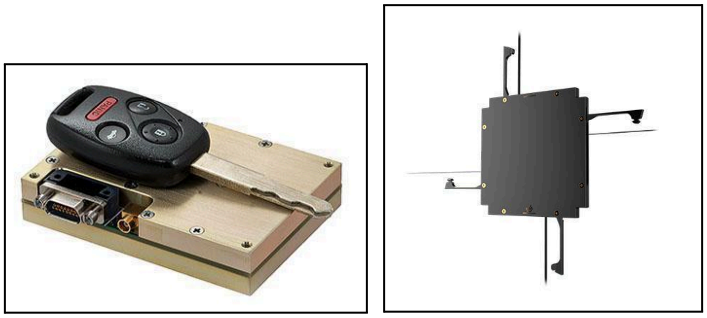


Figure 9: SpaceQuest TRX-U UHF Transceiver and UHF Antenna III

SpaceQuest TRX-U UHF Transceiver

- 24–32 dBm configurable TX power
- RX sensitivity in −110 to −120 dBm class
- ~250 mW RX-only power consumption
- Proven CubeSat/planetary heritage
- TRL-9

UHF Antenna III

- Near-omnidirectional pattern for rover motion
- Circular polarization for multipath tolerance
- Compact mounting footprint
- TRL-9

The final decision to pursue the use of a UHF-band communication architecture for REV-LE is driven by its superior balance of reliability, link performance, environmental survivability, and operational simplicity when compared to the other architectures considered. These pieces of hardware demonstrate the strongest ability to maintain a robust telemetry link with the Griffin Lander while REV-LE is in motion. This is partially due to its near-omnidirectional radiation pattern and lack of dependence on precise pointing or alignment, a feature produced by the 4 oppositely pointing wire antennas. The UHF architecture also provides the best receiver sensitivity and link margin among the evaluated options, ensuring that the subsystem comfortably satisfies the 500-meter communication requirement even under worst-case rover orientations, terrain effects, and lunar dust interference. In addition to the performance of the RF hardware, both components have extensive flight heritage at TRL-9, which is important for reducing risk and ensuring compatibility with the Moon's environment.

There are three verification and validation tests that should be performed on the RF communication subsystem to ensure their functionality before the rover is launched. The first is a link budget test, which assesses the full TX/RX chain using calibrated signal sources to verify margin ≥ 10 dB at 500 m equivalent path loss. Secondly is environmental qualification where both pieces of hardware are placed into a thermal vacuum chamber, and tested for both survivability and functionality at the extreme temperatures defined in requirement REVLE-TMS-003. In addition to thermal vacuum testing, vibration testing should also be performed to ensure structural integrity. Finally, a functional field test should be conducted which involves placing the RF hardware into a simulated lunar terrain field, and trials verifying consistent telemetry and command link of at least 500 m.

5.f. AODCS (Autonomy):

The attitude determination and autonomy stack can be broken into five subsections: command & data handling (C&DH) hardware, sensor hardware, mapping the terrain, localization / pose estimation within the terrain, and path planning. Final specifications, analysis, assumptions, and verification methods are discussed in the subsections below.

5.f.1 C&DH Hardware

The requirements to be met for C&DH Hardware include REVLE-C&DH-001, 002, and 003. The requirements are for a computer with at least 4 cores, 4 GB of RAM, and 1TB of storage. These requirements were set based on the verification method of proven analogous autonomous systems on Earth with constrained data relay environments. In addition, the computer and data storage management systems need to be properly rated for the deep space radiation and thermal environment. The hardware systems chosen include two redundant, cross-strapped Aitech SP1 flight computers and one Aitech S993 1TB memory card [18 & 19]. Both pieces of hardware are deep space rated and capable of handling a reasonable electronics bay temperature on the moon of -40 to 85 degrees Centigrade. The SP1 and S993 are designed specifically for deep space autonomy, with radiation tolerant FPGAs as well as watchdogs for safe operations and anomaly handling from bit flips due to the radiation environment. Together the C&DH package consumes less than 105W and weighs less than 2.5 kg. The C&DH system meets all compute, memory, storage, and extreme environment requirements, verified by the manufacturer.

5.f.2 Sensor Hardware

The pose estimation and site preparation verification sensor suite includes two visible light cameras, two inertial measurement units (IMU), and a radio frequency communication device. The radio frequency communication device is discussed in Section 5.5. The requirements set for sensors are downstream from the requirements set to be able to identify local position within 0.25m and orientation within 2 degrees (REVLE-GNC-001 & 002). To validate that the sensors chosen are sufficient for propagating an estimate with a reasonable pose estimation the team will draw analogy to a similar Earth system that met requirements utilizing similar sensor suite specs and accessible software. The University of Delaware's RPNG Multisensor-aided Inertial Navigation System (MINS) software is an open source software that is rated for local pose estimation well within the orientation and position estimate error floors [23]. The IMU chosen for the space system was the LN200S by Northrop Grumman [21]. This IMU has flight heritage on the Mars Rovers, an accelerometer with 300 micro-g bias repeatability and 100 ppm scale factor accuracy, and a gyroscope with a .15 degree / hr bias repeatability and 50 ppm scale factor accuracy. The cameras chosen are the RGB 3DCS4M by 3D Plus featuring 2048X2048 pixel resolution, 6 fps frame rate, and an 80 degree field of view [17]. The camera comes with a reconfigurable FPGA and has a built-in watchdog and reliability software suite to handle deep space radiation bit flips. The camera's resolution, framerate, and field of view all rival analogous Earth systems such as that used in the RPNG MINS study, verifying its ability to produce pose estimation within requirements.

5.f.3 Mapping the Terrain & Localization / Pose Estimation

The process chosen for simultaneous localization and mapping (SLAM) is a variation of the software provided in an open source format by the University of Delaware's RPNG Lab. The software package, MINS, provides a modular architecture to accept pose estimation data from stereo cameras, Lidar, GNSS, IMU, and wheel encoders and applies a Kalman filter to find an optimized probable pose. For the sensor suite chosen in the above subsection, the code, modular in nature, will use just the stereo vision, IMU, and a modified GNSS input. While there is no GNSS pose estimation present in the system, the time of flight from the lander to the rover gives a high confidence filter of possible rover positions that can be utilized to filter bad pose estimations. In addition, while the code is not designed to be compatible with NASA's flight software standards, it is designed to perform on embedded systems, and contains proper robust practices to ensure safe operations. Covariance matrix accessibility and redundant sensing allows an external watchdog to determine trust in an output pose and restart the software in bit flip or uncaught exceptions cases. In addition, the software's modular nature allows the code to seamlessly switch to a lower degree of freedom pose estimation method when a sensor produces bad or no data, allowing continuous operation in lunar operations. Finally, the software's pose estimation method utilizes a dynamic variable for the sensor calibration parameter, adding it to the state vector in optimization calculation. This allows the system to handle small displacements in the sensor's positions or timings and dynamically calibrate. This robust set of software procedures has been verified to meet the pose estimation requirements for an Earth system, and can be slightly modified with a watchdog and GNSS to time of flight measurement to meet REVLE's system requirements with high confidence.

5.f.4 Path Planning

Requirement REVLE-GNC-003 defines a maximum path planning time to be 3 seconds from receiving a new state package. The necessary pieces of information embedded in a state matrix is the position and orientation of the rover and a cost map of the local terrain based on a defined goal and within physical constraints. The process of gaining each of these pieces of information are detailed in the subsections below.

5.f.4.1 Defining Constraints

The constraints for the rover include maximum relative terrain slope before tipping in each direction and clearance for non-wheel body members. Geometric constraints are measured from the 3D model of the rover. More complex constraints will be calculated by utilizing Unity Game Engine as a physics simulator with custom moon gravity.

5.f.4.2 Defining Goals

Goals are the endpoints of the rover's position. During site identification phase, the goals will be pre-defined in code with prior knowledge of potential points of interest for the rover. Following a site choice, the operator in the loop will choose goal locations to perform site preparation.

5.f.4.3 Cost Map

The cost map is essentially a measure of how safe a rover is if translated to a particular location. This is an important input into a path planning algorithm that allows the rover to optimize safety in mobility. Isaac ROS NvBlox will be used to translate the point cloud developed by the SLAM algorithm into a mesh and then translate constraints into a cost map. Its performance and robustness has been verified on embedded systems on Earth.

5.f.4.4 Pose Estimation

Pose estimation will be calculated using the methods discussed in Section 5.6.3.

5.f.4.5 Path Planning

The path planning algorithm chosen was BIT*, an optimization algorithm that allows a preset optimization duration, producing the most optimal option in a predictable time. While inherently stochastic, the deterministic nature of the return time allows the robust operation necessary for a space software system. An open source BIT* package from Open Motion Planning Library (OMPL) will be used to turn a pose estimation and cost map into an optimal path to be executed by a control algorithm.

5.f.4.6 Decision Tree

A decision tree is a final check before executing a path that ensures the safety of a rover in its planned path. This will be custom programmed as a safety mechanism.

5.f.4.7 Control Algorithm

The control algorithm chosen for the mobility to match the path planned with BIT* is known as Pure Pursuit, supplied in an open source format [20]. The package utilizes PID control to control robot speed, and is verified to follow a path plan within .1 meters, well within the 0.25 meters mandated by REVLE-GNC-004.

5.g. Thermal/Mechanical Structures

5.g.1 Chassis

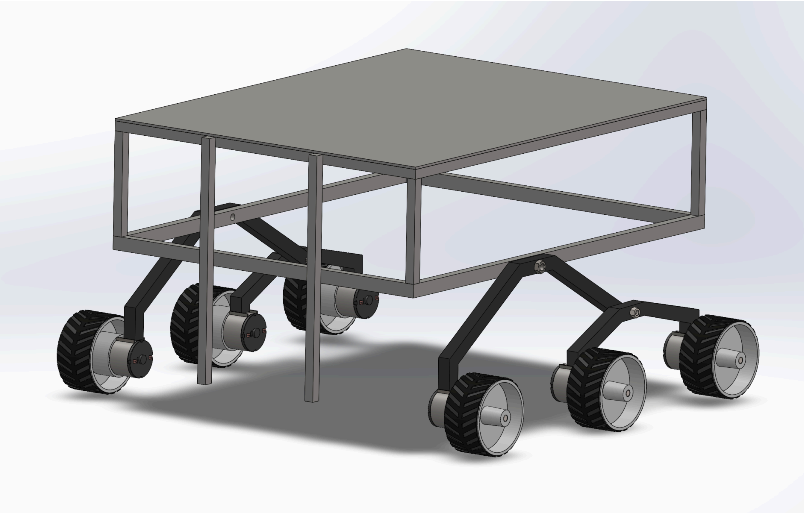


Figure 10: REV-LE Structural 3D CAD Model

The Chassis of REV-LE provides the main structure for each subsystem's hardware to mount to. As specified in REVLE-002, the chassis conforms to the Griffin Lander's payload volume restrictions. It also conforms to both REVLE-TMS-001 and REVLE-001 to adhere to the mass requirements.

The main components of the chassis consist of 1" x 1" OD, 1/16" thick square 4130 Steel tubing, and a 28" x 36" OD, 3/16" thick cut of A36 Steel sheet metal. Several trade studies were performed to decide on the component base materials. The rocker-bogie suspension system also makes use of the same type of steel tubing.

1" x 1" OD square steel tubing was chosen due to its manufacturability and cost. 4130 Steel was chosen as the material for the tubing mainly due to its manufacturability and strength at high temperatures. The main manufacturing method chosen for the chassis was welding. 1/16" was chosen as the wall thickness dimension as that is the thinnest value that is consistently weldable at a reasonable skill level and easy to procure.

A36 Steel was also chosen for similar reasons. Its weldability makes it easy to integrate with the rest of the system. Sheet metal provides a large flat surface that is extremely easy to mount componentry to. It can also be easily waterjetted to the required dimensions.

The combined weight of the sheet metal and tubing is estimated to be 98 lbs.

To ensure that REVLE’s chassis meets its functional expectations and satisfies the system and subsystem requirements, the subsystem should undergo a series of verification and validation tests representative of its loads and lunar environment. The first of these tests is thermal-vacuum cycling to simulate extreme temperature swings and vacuum conditions. In accordance with the subsystem requirement REVLE-TMS-003, the chassis should be tested to withstand -208 to 250°C while still being fully capable of its function of supporting all of the rover’s components. Additionally, vibration testing is necessary to confirm structural integrity in all expected load cases. The rover experiences strong vibration loads, from the launch, orbital transport, and from the rover’s vibratory compaction during operation. To ensure that these cannot cause structural damage or failure, each of these load cases should have their vibration profile applied to the structure to check for displacement limits, mechanical loosening, cracks, and connectors.

5.g.2 Bulldozer plate

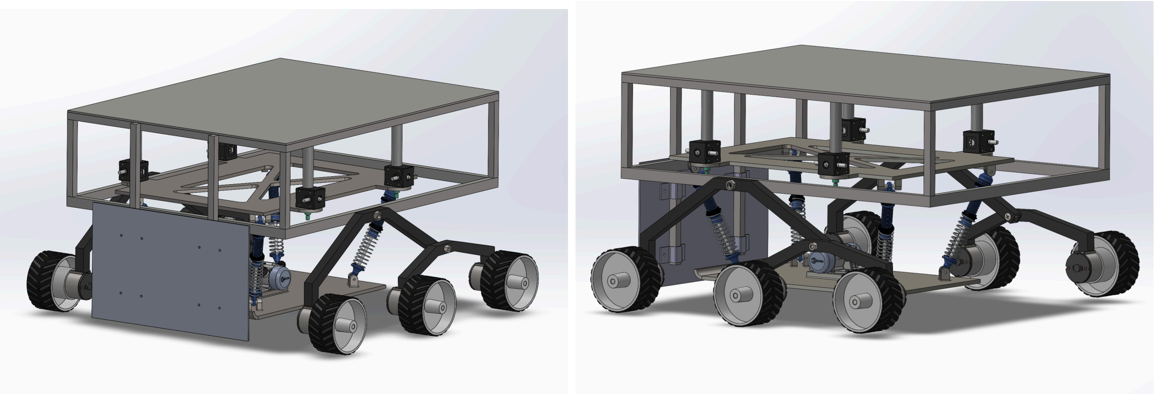


Figure 11: CAD Model of Bulldozer mounted to the Chassis

The bulldozer assembly is mounted to the front of the chassis as seen in the figures above.

The bulldozer assembly exists to excavate areas of interest by pushing large lunar rocks off of the construction site. It fulfils REVLE-005 by clearing large obstructions before the compaction system can start condensing the regolith. Another requirement that it is required to address is REVLE-TMS-002. The forces in this requirement were based on the normal/pushing force required to overcome the static frictional force between a large 50 kg lunar rock and regolith under the Moon’s gravitational field. The calculation for this upper bound can be seen below:

$$F_W = m \; * \; g_{moon} = 50\,kg \; * \; 1.6\,m/s^2$$

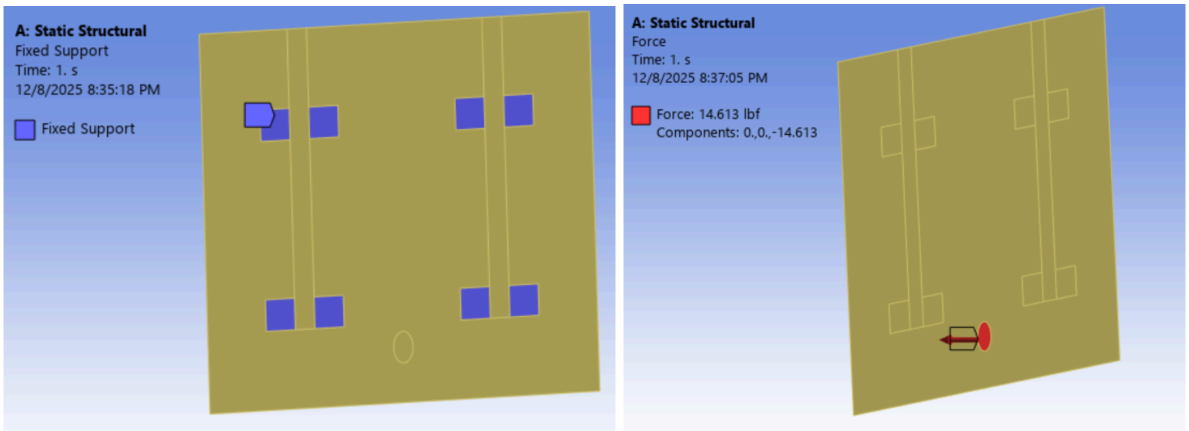
$$F_{f_{static}} = F_N \mu_{static} = F_W \mu_{static}$$

$$F_{f_{static}} = 50\,kg \; * \; 1.625\,m/s^2 \; * \; 0.8 \; = \; 65\,N$$

The bulldozer plate assembly is made out of Al-7075-T6. This was mainly due to its specific strength. The assembly consists of a 7 gauge thick, 20” x 12” sheet metal. The mounting brackets are made of ⅛” thick 1” x 3” sheet metal. These parts are then assembled using fasteners due to the risks associated with welding aluminum. Although the vertical riser on the chassis that this system is attached to is made of steel, this dissimilar metal configuration is extremely unlikely to cause any concerns involving galvanic corrosion due to the nature of the lunar atmosphere. However, while the system is being built or stored on Earth, caution needs to be taken to ensure that the aluminum and steel are not in contact with each other when in damp conditions.

In order to size the thickness of the plate, a finite element model of the bulldozer plate was made and simulated. The plate was modeled as a 2D shell element with a quadrilateral dominated mesh control. The thickness assigned to the shell was 7 gauge (.1443 inches) and linear elastic material properties for Al-7075-T6 were applied to the geometry.

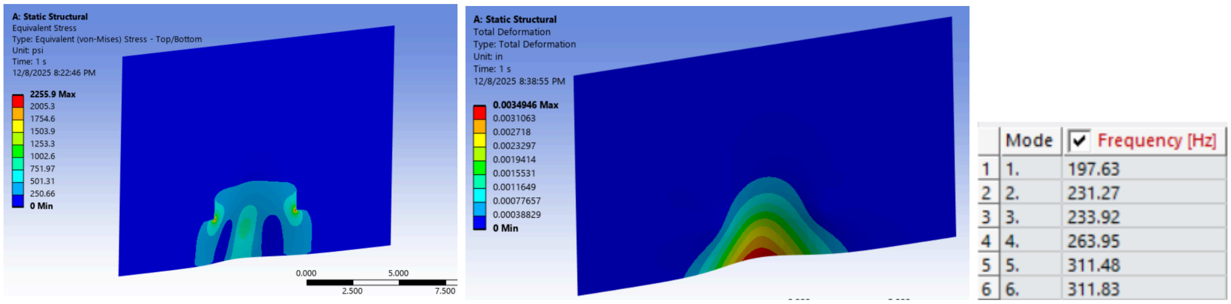
The estimated mass of the bulldozer assembly is 4.4 lbs.


A: Static Structural
Fixed Support
Time: 1. s
12/8/2025 8:35:18 PM

A: Static Structural
Force
Time: 1. s
12/8/2025 8:37:05 PM

Figure 12: Visual of Plate Load and Boundary Conditions

The load and boundary conditions can be seen in the figures above. A mesh convergence study was performed to ensure that the mesh was sufficiently fine and the results converged to the solutions shown below.


A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress - Top/Bottom
Unit: psi
Time: 1 s
12/8/2025 8:22:46 PM

A: Static Structural
Total Deformation
Type: Total Deformation
Unit: in
Time: 1 s
12/8/2025 8:38:55 PM

	Mode	☑ Frequency [Hz]
1	1.	197.63
2	2.	231.27
3	3.	233.92
4	4.	263.95
5	5.	311.48
6	6.	311.83

Figure 13: Results of Static Structural and Modal Analysis

Although the factor of safety of the plate against yielding exceeds 29, the thickness of the plate shall not go below 7 gauge. This is primarily due to manufacturing and assembly concerns.

Along with the static structural simulation, a modal analysis was performed on the plate to predict the resonance modes of the plate. This was done to ensure that the operating frequency of the plate compactor motor does not match any resonant frequencies of the bulldozer plate. The first six resonance frequencies can be seen above.

Similar to the chassis, the bulldozer plate must also undergo verification and validation testing to ensure its structural integrity meets the subsystem requirements and functionality expectations. A series of functional tests must be performed to ensure that the system survives and performs adequately during operation. Likewise to the chassis, thermal-vacuum cycling should be conducted to simulate extreme temperature conditions and vacuum conditions from REVLE-TMS-003. Vibration testing is also necessary to confirm structural integrity from the launch, orbital transport, and from the rover’s vibratory compaction during operation.

In addition to testing the environment through thermal vacuum and vibration, a hammer test should be performed. This test involves placing accelerometers onto the bulldozer plate and then striking the plate with a hammer. The accelerations can be recorded in the accelerometers and Fourier Analysis can be performed on the extracted data to output the resonant frequencies of the bulldozer plate. In the event that these frequencies coincide with the operating frequency of the compaction plate motor, the bulldozer plate’s mounting hardware can include high temperature rubber washers and/or weights for vibration damping.

5.g.3 Thermal Protection Systems

The requirement driving the thermal protection system is REVLE-TMS-003, which states that the TMS subsystem shall be able to withstand temperatures ranging from -208 to 250 degrees celsius.

The mechanism through which REVLE will radiate heat away is through radiator panels. These panels create a large surface area on top of the vehicle through which heat produced by various electronic components can be dissipated into space. These components are connected to the radiator panel using thermal straps that conduct the heat from the heat producing componentry to the panel. Additionally, the full structure will be coated with radiative paint to help minimize heat absorption through radiation. These three components of the thermal protection system will help ensure the system is meeting the REVLE-001 and REVLE-TMS-003 requirements.

6 System Design (Proof-of-Concept Prototype Rover)

As a proof-of-concept prototype system, the team used the NASA JPL Open Source Rover. The main purpose of this vehicle was to design to validate suspension and mobility, as well as giving a test stand for the development of the system’s autonomous perception. This vehicle has a similar 6 motor 6 wheel rocker-bogie suspension. Certain aspects of the main system design were omitted in the consideration of this prototype, including the thermal protection, dust mitigation, bulldozer plate, and communication.

6.a. Plate Compactor

The prototyped rover will not physically display the compaction mechanism due to budgetary constraints. However, the subsystem will be fully designed and simulated, and its integration with the rest of the rover will be discussed to demonstrate its capabilities. The updated requirements for the compaction subsystem prototype were derived from a NASA paper that measured the bulk density of regolith simulants after conducting a static compaction pressure test. The method demonstrated in the paper is what our prototype will utilize, where the rover uses its weight to generate compaction pressure through the plate, in addition to dynamic pressure generated by the vibratory motor. The design requirements obtained from the paper that will drive the compaction subsystem design are a minimum of 7000 Pa of static pressure and 4000 Pa of vibratory pressure [25].

The dimensions of the prototype compaction plate were determined by selecting values that would satisfy the design requirements while accounting for the JPL rover's reduced weight and undercarriage size compared to the full-sized model. The first iteration of the compaction plate has dimensions of 0.152 x 0.152 x 0.008 meters and is made of Aluminum 6061-T6. This results in a plate area of 0.0232 m^2, which is used to determine the forces required to meet the static and dynamic pressure requirements.

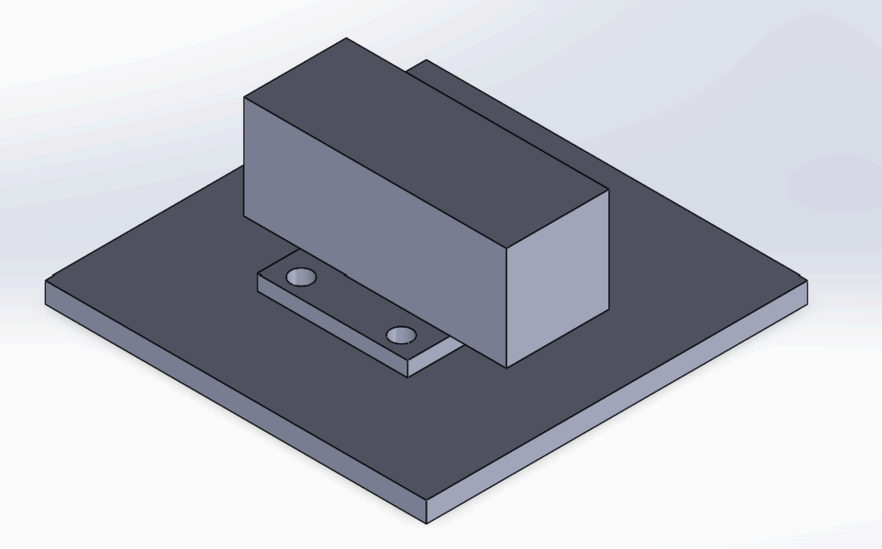


Figure 14: *REV-LE compaction plate CAD*

A static force of 162.54 N and a vibratory force of 92.88 N are the minimum values required to meet the subsystem requirements. The JPL rover's weight will be approximately 13.5 kilograms, so adding additional mass to the rover will help achieve the required static force. A single-mass vibration motor was selected based on the criterion that it generates close to 89 N at peak force and that it fits the dimensions of the prototype plate. To test in simulation, the selected motor is the ATO-MVB20DCB12-1, which is capable of generating up to 103 N of vibratory force.

Simulations of the plate compactor model were performed using MATLAB Simulink, with block logic shown in Figure 15. The plate model was developed based on the selected geometry and material properties and includes gravitational effects, as well as internal mechanics based on the dampers used in the design. A sinusoidal force was applied to the plate, with amplitude and frequency values taken from the ATO motor specifications. For this simulation, the soil was assumed to be linearly elastic with parameters representative of loose sand [26], requiring reasonable estimates for stiffness and damping coefficients. As the plate penetrates the sand, the soil exerts a reaction force that alters the plate's dynamics. This reaction force is the primary quantity of interest, as it determines the resulting compaction pressure. The soil force was modeled as shown below, where J is a soil parameter, x′ is the plate velocity, and x is the penetration distance:

$$F_{soil} = kx + kxJ * x'$$

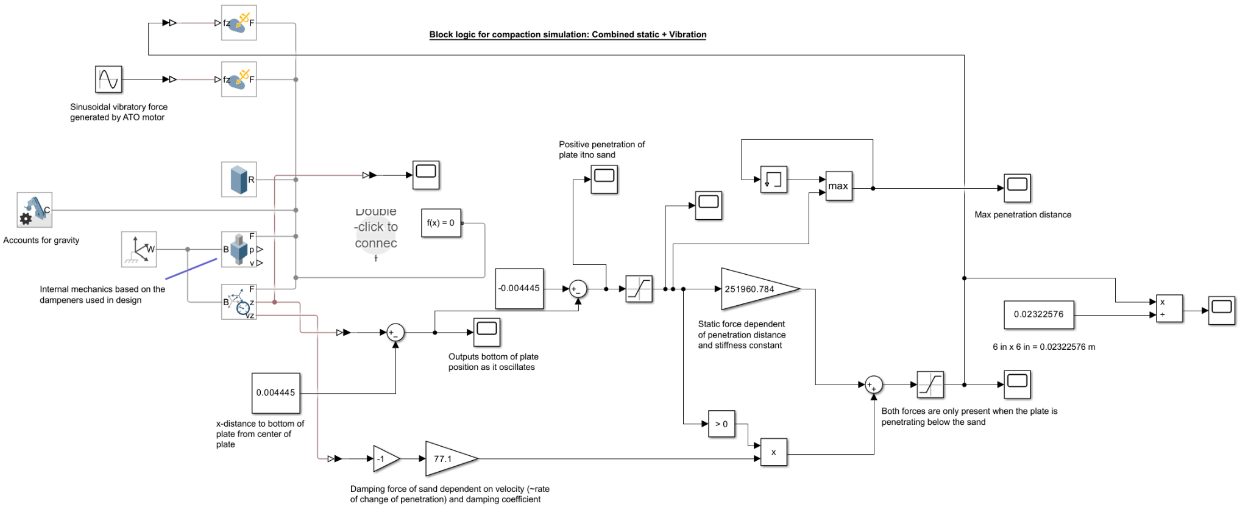
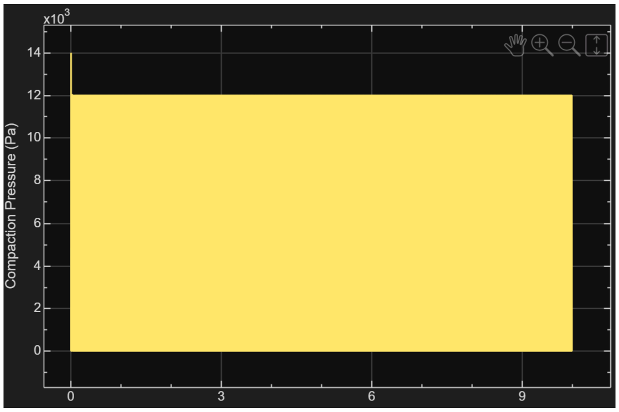


Figure 15: *REV-LE compaction plate simulation logic*

The purpose of this simulation was to validate the feasibility of REVLE’s compaction pressure requirements. The first iteration of the simulation resulted in the total compaction pressure, including contributions from the motor and rover weight, to be approximately 6,000 Pa, which is significantly lower than the combined 11,000 Pa system requirement. Additionally, the measured dynamic pressure was approximately 1,500 Pa, which is below the target of 4,000 Pa. Although the simulation demonstrated the feasibility of the compaction mechanism, either a motor with greater force output or a reduction in plate area is required to meet system requirements.

To meet system requirements, a new motor was selected while maintaining the same plate geometry. The ATO-35DCBVM-244 motor provides a peak force of 560 N at a frequency of 4700 RPM. Simulating with these updated parameters resulted in compaction pressures that meet system requirements, as shown in Figures 16 and 17.



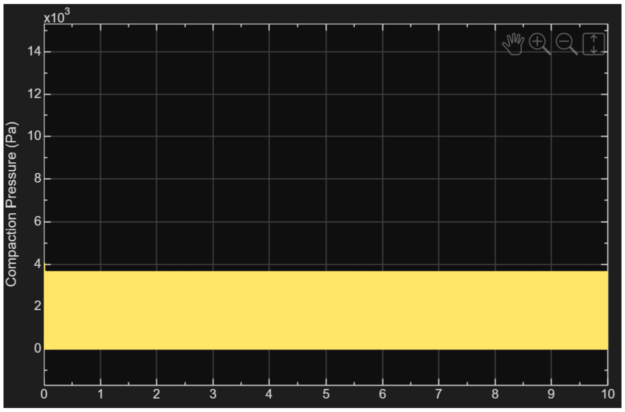


Figure 16: *Static + dynamic pressure*

Figure 17: *Dynamic pressure*

6.b. Electrical and Power

The proof-of-concept rover uses the NASA JPL Open Source Rover electrical architecture as a low-cost, modular hardware backbone. The electronics system is responsible for four main functions: distributing battery power, commanding wheel and steering actuators, reading health and status data, and interfacing with higher-level control software. The Open Source Rover control board uses a 14.8 V input bus and generates regulated 12 V, 5 V, and 3.3 V rails for the various subsystems. It also supports digital current and voltage sensing through an INA260 power monitor and uses a PCA9685 PWM generator for actuator control. This makes the prototype especially useful for demonstrating practical rover integration issues such as power distribution, wiring management, actuator interfacing, and system troubleshooting.

6.c. Communications

The communications architecture of the proof-of-concept rover is intentionally simpler than the REV-LE flight model concept, but it preserves the same command-and-telemetry structure. In the REV-LE mission architecture, the rover communicates with the Griffin lander, which then relays information to Earth. In the prototype, the rover instead communicates directly with a nearby ground station control (GSC) operator station over terrestrial links. The Open Source Rover platform is built around a Raspberry Pi that contains built-in WiFi. This functionality is used to create a Wifi communication link between the Raspberry Pi and the GSC computer. A USB gamepad or remote controller is connected to the GSC computer for teleoperation.

6.d. Guidance, Navigation, and Control

The prototype rover will demonstrate the ability to autonomously map a terrain and localize with stereo vision and IMU technology analogous to those available on the final system. The process will happen in a simulated lunar environment, complete with sand analogous to lunar regolith and similar lighting conditions. The rover will also demonstrate the ability to plan paths in a 3D environment, utilizing a 3D cost map. Finally, the rover will demonstrate the ability to complete autonomous decision making, carrying out a control system to follow a path. The autonomous capabilities being demonstrated are critical in showing the feasibility of the system in a lunar environment, with remote control having necessarily high latency from Earth.

The fidelity of the simulated environment is reasonably high for demonstrating the autonomous capability. Although the low gravity and exact regolith response is tough to model, the autonomous systems will not alter significantly in a lunar environment. Thus, the prototype will show the system's ability to perform autonomy, a critical capability, in a simulated environment analogous to the deployed lunar environment.

6.e. Prototype Mobility Validation Testing

REV-LE Prototype Mobility Validation		
System Requirement ID and traceability	**Requirement Statement**	**Test PASS/FAIL**

REVLE-MOB-001	The system shall traverse slopes up to 20 degrees without exceeding 20% wheel slip or loss of traction.	PASS
REVLE-MOB-002	The mobility subsystem shall traverse obstacles up to 20 cm in height without high-centering or loss of stability.	PASS
REVLE-MOB-003	The system's wheel sinkage shall not exceed 10 mm under nominal lunar gravity loading.	PASS
REVLE-MOB-004	The system shall maintain static stability on slopes up to 35 degrees in both longitudinal and lateral directions without tipping.	PASS

Figure 18: *REV-LE prototype mobility testing: MOB-001, MOB-002, MOB-003*

Figure 19: *REV-LE prototype handling test*

7 Risk Assessment

7.a. Risk Assessment Matrix

Consequence

		1	2	3	4	5
Likelihood	5	Wheel Traction Loss (1.4)	Ice in Rover Crevasses (9.1)	Power system overload (3.1)	Error in Autonomy (5.1)	Dust Contamination (1.1)
	4	Clearance blade wear reduces performance (4.2)	Deployment Mechanism fails to release (10.1)	Immovable Rock on compaction site (1.7)	Lidar or Navigation Sensor Failure (2.1)	Suspension Failure due to uneven terrain (1.5)
	3	Sun glare affecting optical Sensors (2.2)	Density Verification Sensor Drift (4.3)	Solar Array Dust accumulation (3.4)	Failure of Rover Deployment (10.1)	Complex Terrain causing tip over (1.3)
	2	Time Sync Errors (5.4)	Fault Management misclassification (5.3)	Loss of Comms (2.2)	Compaction Tool Failure (4.1)	Power Depletion before mission complete (3.2)
	1	Failure of Hibernation Cycle (3.7)	Overcooling of electronics (3.6)	Rover Exceeds SWaP (6.1)	Rover cannot withstand landing (10.2)	System Overload from Actuators (3.1)

8 Cost Assessment

Life cycle cost estimation for the REV-LE lunar site-preparation rover has been made by making analogous estimates for similar costs. This relies on real-world historical costs for NASA and private lunar missions, scaling those same resources according to the mass, functionality, environmental complexity, and sub-system design that the rover is scaled similarly against due to its closest similarity. All costs are presented in constant dollars and encompass the full mission life cycle from concept, through landing on the surface, all the way through sustaining engineering.

In comparing REV-LE to analogs including the VIPER and Curiosity lunar rovers, the latter has been found to be the most analogous to REV-LE in terms of mechanical and environmental complexity, autonomous mobility capabilities, sensors, and the harsh regolith environment and extreme thermal cycles. Its life cycle cost is estimated to be about $433.5 million. As REV-LE has a lower complexity level and mass, its corresponding cost will be lower than that of VIPER. Based on previous cost experience with rovers, the space segment hardware cost for REV-LE can be estimated at $110-130 million.

Payload subsystems for site preparation will incorporate payloads such as the plate compactor and the bulldozer plate. The payloads will have been developed to operate in highly abrasive regolith. The corresponding analogs to these payloads would be the excavation equipment used by planetary analog robots and other heavy-duty payloads such as those used on previous missions. Payload subsystem costs generally make up a considerable fraction but a lower fraction of the total mission cost compared to the cost of other spacecraft subsystems. Payload subsystem costs for the mission are estimated to be about $20–$30 million, taking into account previous mission costs, design, manufacturing, environmental conditioning, structural tests, and integration into the rover chassis.

Costs for software and autonomy are estimated by analogy as well. Software that would be included in a mission to Mars includes flight software that controls the robot’s mobility and autonomy functions that detect hazards, monitor systems, and communicate in delayed times. Cost estimates for the software and autonomy subsystems of REV-LE are about $10-15 million.

Programmatic and oversight costs, which encompass systems engineering, program management, safety, mission assurance, and I&T, are estimated via similar fractional estimates from prior NASA missions. For example, referring to ratios obtained historically through rover missions, the systems engineering and program management costs of the REV-LE mission will fall in the range of $35-45 million. In contrast, integration and testing costs, which include vibration testing, thermal vacuum testing, end-to-end functionality tests, and deployments verification tests, may cost $25-35 million.

Similarly, the mission operation and ground segment costs will follow the analogous behaviors seen by robotics-based missions on the surface. For example, the mission operation costs will reflect the behaviors exhibited during the initial lunar rover missions and Mars surface missions in regards to navigation, data processing, communications, and anomalies. Therefore, considering these similar robotics-based missions, we can estimate that the total mission operation costs will cost between $40-60 million while sustaining engineering costs are $30-50 million.

Historical NASA missions of similar maturity levels (PDR) usually have a margin of 20-25%. Using the historical margins for missions of equivalent maturity level, the margin for REV-LE's development cost would be approximately $40-60 million, which is consistent with the observed right-skewed cost uncertainty distribution. Adding up all elements of the WBS including space-segment hardware, payload mechanisms, software & autonomy, systems engineering/program management, integration and test, launch and delivery, mission operations, sustaining support, and reserves yields an estimated total cost of $550 million, with a plausible range of uncertainty between $500-700 million. The entire estimation is purely based on historical missions that have similar characteristics. At this stage, it can provide a credible cost baseline for decision-makers.

9 References

[1] *Weather on the Moon*. (2025, May 21). NASA Science. Retrieved September 17, 2025, from https://science.nasa.gov/moon/weather-on-the-moon/

[2] Lunar Retroreflectors. (2010). Ucsd.edu. https://tmurphy.physics.ucsd.edu/apollo/lrrr.html

[3] Sviatoslavsky, I. (2025, September 18). The Challenge of Mining He-3 on the Lunar Surface: How All the Parts Fit Together. Archive.org. https://web.archive.org/web/20190120035522/http://fti.neep.wisc.edu/pdf/wcsar9311-2.pdf

[4] Howell, E. (2019, July 11). Why Is the Apollo Reflector Experiment Still Operating, 50 Years Later? Space.com; Space. https://www.space.com/apollo-retroreflector-experiment-still-going-50-years-later.html

[5] Moonquakes - NASA Science. Nasa.gov. Published November 13, 2024. https://science.nasa.gov/moon/moonquakes/

[6] Astronika Sp. Z O. O. (2022, , September 10). *Energy-efficient regolith compactor for surface construction.* The European Space Agency. https://activities.esa.int/4000134104

[7] Kaczmarek, S. *Positioning on the moon without global positioning system (GPS).* https://sylvesterkaczmarek.com/blog/positioning-on-the-moon-without-global-positioning-system-gps/

[8] Sands, K. (2021, Nov 19). *Fission system to power exploration on the moon's surface and beyond.* NASA. https://www.nasa.gov/humans-in-space/fission-system-to-power-exploration-on-the-moons-surface-and-beyond/

[9] *Thermal solutions for planetary rovers* . Advanced Cooling Techniques. https://www.1-act.com/resources/blog/thermal-solutions-for-planetary-rovers/

[10] Zanon, P., Dunn, M., & Brooks, G. (2023). Current lunar dust mitigation techniques and future directions. *Acta Astronautica, 213*, 627–644. https://10.1016/j.actaastro.2023.09.031

[11] Deepak Bapna, Martin, M., & Whittaker, W. (2003, April 11). Earth-Moon Communication from a Moving Lunar Rover. ResearchGate; unknown. https://www.researchgate.net/publication/2566438_Earth-Moon_Communication_from_a_Moving_Lunar_Rover

[12] Bapna, D., Martin, M., & Whittaker, W. (2003). Earth-moon communication from a moving lunar rover. https://www.researchgate.net/publication/2566438_Earth-Moon_Communication_from_a_Moving_Lunar_Rover

[13] *Griffin lander* . Astrobotic. https://www.astrobotic.com/lunar-delivery/landers/griffin-lander/

[14] *Department of Defense. (2015).* MIL-STD-461G: Requirements for the control of electromagnetic interference characteristics of subsystems and equipment.

[15] The Planetary Society. *Every NASA Budget Rquest, from 1961 to Now. Every NASA Budget Request, from 1961 to Now | The Planetary Society*

[16] Bell, E. A., Kemmerer, B. W., Gelino, N. J., Sibille, L., Holmgren, G. M., Flowers, P. F., & Rao-Aourpally, V. (2025, May). Vibratory Plate Compaction of BP-1 & LHS-1 Utilizing the Planetary Automated Compaction Tool (PACT). NASA Technical Memorandum 20250005172.

https://ntrs.nasa.gov/api/citations/20250005172/downloads/Vibratory%20Plate%20Compaction%20of%20BP1%20LHS1.pdf

[17] CASPEX 4M Space Camera Head. (n.d.). 3D PLUS. https://www.3d-plus.com/products/caspex-4mpx-space-camera-heads/

[18] S993 | 3U CompactPCI Non-Volatile Memory Board. (n.d.). Aitech Systems. https://aitechsystems.com/product/s993-3u-compactpci-non-volatile-memory-board/

[19] SP1 | Radiation Tolerant 3U SpaceVPX SBC. (n.d.). Aitech Systems. https://aitechsystems.com/product/sp1-radiation-tolerant-3u-openvpx-sbc/

[20] Sakai, A. (n.d.). PythonRobotics: Python sample codes and textbook for robotics algorithms. GitHub. https://github.com/AtsushiSakai/PythonRobotics/tree/master

[21] LN-200S & LN-200HPS Inertial Measurement Units. (n.d.). Northrop Grumman. https://cdn.northropgrumman.com/-/media/Project/Northrop-Grumman/ngc/what-we-do/mission-solutions/assured-navigation/ln-200s-ln-200hps-imu/LN-200S-LN-200HPS-inertial-measurement-unit-imu-datasheet.pdf?rev=3cb767f4f3fd43c59631fcd464027787

[22] Barrett, T. J., Ariza Pardo, A., & Blanc, A. (2024). Physical Properties of Lunar Regolith Analogue at a Cinder Lake Crater Field, Arizona. 55th Lunar and Planetary Science Conference, Abstract 1352. https://www.hou.usra.edu/meetings/lpsc2024/pdf/1352.pdf

[23] Lee, W., Geneva, P., Chen, C., & Huang, G. (2025). MINS: Efficient and robust multisensor‑aided inertial navigation system. *Journal of Field Robotics, 42*(7), 3252–3284. https://doi.org/10.1002/rob.22546

[24] E. B. Sperling (1970), Basic and Mechanical Properties of the Lunar Soil Estimated From Surveyor Touchdown Data. JPL Technical Memorandum 33-443, Jet Propulsion Laboratory, California Institute of Technology; National Aeronautics and Space Administration, https://ntrs.nasa.gov/api/citations/19700014154/downloads/19700014154.pdf

[25] NASA. (2025). *Vibratory Plate Compaction of BP-1 Lunar Simulant*. NASA Technical Reports Server (NTRS). https://ntrs.nasa.gov/api/citations/20250005172/downloads/Vibratory%20Plate%20Compaction%20of%20BP-1%20LHS1.pdf

[26] Texas Transportation Institute. (n.d.). *Soil Properties and Engineering Characteristics*. Texas A&M University. https://static.tti.tamu.edu/tti.tamu.edu/documents/125-1.pdf

10 Appendix

Parameter	symbol	Assumed Value
Wheel radius	r	0.16 m

Wheel Width	b	0.08 m
Wheelbase (front-rear)	L	0.90 m
Track width (left-right)	T	0.60 m
Ground clearance	H_c	0.12 m
Center of gravity height	h	0.25 m
Rover total mass	m	175 kg

Table 7: Mobility Subsystem Dimensions.

Environmental Parameter	symbol	Assumed Value	Source
Lunar Gravity	g_{moon}	1.62 m/s^2	Used for lunar operations
Earth Gravity (testing)	g_{earth}	9.81 m/s^2	Used for Earth test case
Slope angle (gradeability test)	θ	20	Target slope for requirement check

Table 8: Environmental Effects.

Parameter	Symbol	Assumed Value	Source
Rolling Resistance Coefficient	c_{rr}	0.05	Highly variable, for purpose of initial design, this is chosen
Coefficient of friction	μ	0.7	NASA CR 109410, 1970
Cohesion strength	c	170 N/m^2	NASA Terramechanics for LTV Modeling and simulation
Internal Friction angle	ϕ	35°	NASA NTRS 20100000019, 2010
Shear deformation Modulus	K	1.78 cm	NASA NTRS 20100000019, 2010
Modulus of cohesion	k_c	1400 N/m^2	NASA Terramechanics for LTV

			Modeling and simulation
Modulus of friction	k_ϕ	820,000 N/m^3	NASA Terramechanics for LTV Modeling and simulation
Exponent of sinkage	n	1.0	NASA Terramechanics for LTV Modeling and simulation
Max allowable ground pressure	p_{max}	10 kPa	Max limit in which the energy consumed by wheeled vehicles can be estimated [NASA-CR-192033]

Table 9: Regolith Parameters

It is worth noting that the rolling resistance coefficient for rover wheels is highly variable, and this number is an approximation.

Parameter	Symbol	Assumed Value	Source
Drive wheel torque (peak)	$\tau_{\text{max, wheel}}$	10 N*m	Chosen
Drivetrain efficiency	η_{drive}	0.75	Chosen
Desired linear velocity	v	0.10 m/s	Chosen
Number of driven wheels	N_w	6	Chosen

Table 10: Drive System/Performance.

Parameter	Symbol	Assumed Value	Source
Obstacle height requirement	h_{req}	20 cm	Chosen
Max Slope angle	N/A	25°	NASA TR R-401
Required tip-over margin	θ_{req}	35°	Based off of LRV and Curiosity longitudinal and lateral tip angles [NASA Apollo 15-16 post mission mobility report] and [NASA JPL Mobility design notes, 2011-2020]
Obstacle climb factor	N/A	1.3 * 1.5 * r	Definition
Slip threshold	N/A	20%	Near the efficient traction plateau

			on regolith

Table 11: Rover Specifications.

Table 12: Table of Identified Risks

Risk ID	Risk Description	Likel-ihood	Conse-quence	Risk Level (LxC)	Classifica-tion	Mitigation Strategy
1.1	Dust contamination on moving parts	5	4	20	High	Apply dust-sealed joints and electrostatic shielding.
1.2	Failure of suspension system due to uneven regolith terrain	4	5	20	High	Implement suspension prototype testing and redundancy in actuators.
1.3	Rover gets tipped over by complex terrain	3	5	15	High	Integrate path mapping to avoid steep slopes that could tip the rover.
1.4	Wheel Traction loss	5	1	5	Low	Implement suspension prototype testing and redundancy in actuators
1.5	Suspension failure	3	5	15	High	Labyrinth seals, periodic joint exercises, dry-film lubes
1.6	Structural Crack in frame under load	2	4	8	Medium	FEA, add fillet at stress points, load test
1.7	Immovable Rock on compaction site	3	3	9	Medium	Obstacle detection logic, adjustable blade height
2.1	Lidar or navigation sensor malfunction	3	4	12	Medium	Integrate sensor redundancy; add self-check diagnostics.
2.2	Intermittent Comms loss with Lander	2	3	6	Low	Communications redundancy
2.3	Camera Lens obscured by dust	4	3	12	Medium	Add shutters/film
2.4	Sun glare of optical sensors	3	1	3	Low	HDR/exposure control
3.1	Power system overload from	3	5	15	High	Perform testing of electrical system and sensor suite.

	multiple actuators					
3.2	Power depletion before mission tasks complete	2	5	10	Medium	Add solar array optimization and energy budgeting.
3.3	Battery runaway or cell degradation	2	5	10	Medium	Add BMS monitoring, thermal isolation
3.4	Solar Array dust accumulation reduces rover lifespan	3	3	9	Medium	Panel tilt when idle, passive dust shielding
3.5	Powerboard failure	2	4	8	Medium	Thermal test, redundant power rails, derate components
3.6	Overcooling of electronics during lunar night	1	2	2	Low	Thermal straps/heaters, thermostat to monitor temp drops
3.7	Failure of Hibernation cycle	1	1	1	Medium	Perform testing of rover hibernation cycle and include redundancy in power to reduce possibility of mission failure in this instance
4.1	Compaction tool failure or jamming	3	4	12	Medium	Run fatigue simulations and include quick-disengage mechanism.
4.2	Clearance blade wear reduces performance	4	1	4	Low	Coatings, heat treatments, inspection after missions
4.3	Density Verification Sensor Drift	2	3	6	Low	Calibrate before and after compaction
4.4	Obstacle Clearing blade stuck on embedded rock	2	4	8	Medium	retreat/retry logic
4.5	Large Divot in the ground prevents uniform compaction	3	3	9	Medium	Ground profiling scan, rover re-compaction protocol
5.1	Software control	3	5	15	High	Implement

	logic error in autonomous navigation					simulation-in-the-loop testing and code verification.
5.2	Map divergence/SLAM inconsistency	3	4	12	Medium	Loop-closure validation
5.3	Fault Management missclassification	2	2	4	Medium	Confusion matrix analysis, fault-injection testing
5.4	Time sync errors causing data misalignment	3	3	9	Medium	Timestamp verification
6.1	Rover mass exceeds SWaP	1	3	3	Low	Maintain mass budget
6.2	Power/connector mismatch at lander interface	2	4	8	Medium	IDD verification
6.3	EMI/EMC coupling into comms or sensors	2	4	8	Medium	cable shielding
7.1	Long-lead component delaying integration schedule	4	3	12	Medium	Order critical parts early and identify alternates, maintain buffer between integration and testing
7.2	Test facility unavailability	3	3	9	Medium	Reserve test slots early, plan backup lab
7.3	Key personnel turnover	3	3	9	Medium	Maintain documentation, assign backups
8.1	Operational error during testing or deployment	3	3	9	Medium	Checklists, rehearsal runs, full autonomy stack, detailed documentation
8.2	ESD damages electronics during integration/testing	2	4	8	Medium	Write straps and training
9.1	Ice in Rover Crevasses	5	2	10	Medium	Use hydrophobic coatings, thermal cycling before mission

9.2	Radiation induced single-event upset in electronics	3	3	9	Medium	add ECC memory, selective shielding
10.1	Deployment mechanism fails to release rover	2	4	8	Medium	deployment testing, redundant release mechanism
10.2	Landing causes damage to rover	2	4	8	Medium	Perform fit checks, test vibrational loads in landing
10.3	Rover arrives and does not have power	2	5	10	Medium	Telemetry port to monitor the vitals of the rover