

Lunar Utilization and Novel Assembly via Regolith Integrated Systems

Hugo E. Vega*

California State University, Northridge, CA

Brendan M. Williamson[†]

California State University, Northridge, CA

Nico A. Hornquist[‡]

California State University, Northridge, CA

Albert S. Chamoun[§]

California State University, Northridge, CA

The development of sustainable infrastructure is essential for enabling long-term human presence on the Moon. Transporting construction materials from Earth is constrained by mass and launch costs, motivating the use of ISRU technologies that leverage locally available lunar regolith. This paper presents the design, analysis, and preliminary validation of an autonomous rover system capable of excavating, processing, and manufacturing structural components using SLS.

The proposed system integrates excavation, material handling, additive manufacturing, power distribution, thermal management, and autonomous control within a single mobile platform deployed via the Griffin lunar lander. A systems-level approach is used to ensure compatibility between subsystems, particularly in delivering process-ready regolith feedstock for manufacturing. Structural modeling and finite element analysis were conducted to evaluate chassis performance, and prototype testing was performed to validate subsystem functionality.

Results demonstrate the feasibility of an integrated ISRU-based construction system capable of producing building materials under representative conditions. This work advances the development of autonomous lunar construction systems and supports future mission architectures for sustained extraterrestrial operations.

Nomenclature

EDS = Electrodynamic Dust Shield

ISAM = In-Space Servicing, Assembly, and Manufacturing

ISRU = In-Situ Resource Utilization

SLS = Selective Laser Sintering

I. Introduction

The need for sustained lunar missions from NASA Artemis campaign has emphasized the need for solutions in the construction of scalable infrastructure to support a permanent human presence on the Moon. NASA has already made a big push to build an outpost on the moon following the cancellation of the original Gateway mission and instead repurposed the station in a construction of 20 billion dollar moon base. Transporting construction materials from Earth is very expensive due to mass and launch constraints, therefore motivating the development of ISRU technologies that leverage the use of locally available materials on the moon[1]. Using Lunar Regolith as powder feedstock for additive SLS manufacturing has emerged as a promising approach to enabling the autonomous construction of infrastructure directly on the lunar surface[2, 3].

The lunar environment presents significant challenges for construction systems however. Extreme temperature variations, high vacuum conditions, abrasive and electrostatically regolith, and limited power availability impose strict design constraints on robotic solutions. Additionally, low-gravity conditions affect excavation efficiency, material flow, and structural stability, making conventional terrestrial construction approaches unsuitable for lunar applications.

Current robotic systems have demonstrated key capabilities relevant to lunar operations. Excavation platforms such as NASA's RASSOR and prior planetary rover systems have demonstrated reliable mobility and regolith interaction capabilities under extraterrestrial conditions [4]. There is a great heritage of planetary rovers demonstrating reliable mobility across terrestrial terrain. In parallel, there is already research into using regolith in SLS to create construction blocks. However, these efforts are typically developed as isolated subsystems and are often limited to controlled or stationary environments.

A critical gap remains in the development of an integrated, autonomous system capable of performing the complete construction workflow. Integration of excavation and dispensing regolith. The lack of such systems limits the feasibility of scalable, on-site infrastructure development for future lunar missions. This paper presents the design and analysis of a rover demonstrates the capability to autonomously create fundamental building blocks from lunar regolith using advanced additive manufacturing technologies. Landed by the Griffin lunar lander, the mission will efficiently create infrastructure essential for establishing a permanent lunar outpost.

The primary contributions of this work include:

- development of a SLS additive manufacturing subsystem printing on lunar surface as printing bed with regolith as the powder feedstock
- the design of a multi-functional rover incorporating excavation and additive manufacturing capabilities
- and advances the feasibility of autonomous lunar construction with machine learning artificial intelligence.

II. Background

Sustained lunar exploration requires the development of infrastructure to support long-term human presence. Transporting construction materials from Earth is highly constrained by launch mass and cost, motivating the use of ISRU technologies that leverage locally available lunar regolith as a construction material[1]. Current regolith-based construction approaches can be broadly categorized into direct forming methods, which rely solely on local materials, and indirect methods that require additional binders transported from Earth [2].

SLS has emerged as a promising method for converting regolith into structural components. In this process, regolith is used as a powder feedstock and fused layer-by-layer using a high-energy laser to form solid structures. However, unlike terrestrial materials used in conventional SLS systems, lunar regolith is a poorly sorted granular material with a wide particle size distribution, ranging from fine dust to coarse particles. Experimental studies have demonstrated compressive strengths exceeding 31 MPa in regolith-based components produced via laser powder bed fusion, indicating the feasibility of structural applications [3].

This variability presents significant challenges for additive manufacturing. Oversized particles can lead to incomplete bonding and rough surface finishes, while extremely fine particles reduce material flow and promote agglomeration. As a result, regolith must be processed to achieve a more consistent particle size distribution suitable for reliable layer deposition and energy absorption.

The lunar surface environment imposes strict constraints on system design. Surface temperatures can range from approximately 170 K to over 390 K depending on solar exposure and terrain [5]. At the lunar south pole, permanently shadowed regions can reach temperatures below 100 K [6]. Extreme temperature cycling, high vacuum conditions, abrasive and electrostatically charged dust, and reduced gravity all influence excavation, material handling, and structural performance. These conditions limit the effectiveness of conventional terrestrial construction methods and require specialized robotic solutions.

Existing technologies have demonstrated key capabilities relevant to lunar operations, including regolith excavation, planetary mobility, and laboratory-scale regolith sintering. However, these capabilities are typically developed as separate systems and are often limited to controlled environments.

A critical gap remains in the development of integrated systems capable of performing the complete construction workflow. This work addresses that gap through the development of a mobile system capable of excavating, conditioning, and manufacturing structural components directly on the lunar surface. By integrating excavation, material handling, and additive manufacturing into one platform, the system enables construction using locally available resources.

III. Assumptions and Constraints

The following assumptions define the operational scope and boundary conditions for the proposed system. These assumptions are based on existing lunar mission architectures, prior experimental work, and concept-level design

constraints. These assumptions are intended to constrain the design space while maintaining consistency with current lunar exploration architectures and technology readiness levels.

A. Mission and Deployment Assumptions

The ISAM rover is assumed to be delivered to the lunar surface via the *Griffin* lunar lander and to deploy nominally following landing operations. The landing site is assumed to be within the lunar south polar region, consistent with current exploration priorities. Sufficient mission duration is assumed to enable excavation, material handling, and additive manufacturing operations within a defined operational zone. The total mass of the payload, the rover, will be under 200 kg and will take up a volume no greater than three quarters of of 1.7 X 1.75 X 2.5 m³ volume.

B. Environmental Assumptions

Lunar surface conditions are assumed to fall within established bounds for the south polar environment. Regolith properties, including particle size distribution, bulk density, and thermal characteristics, are assumed to be consistent with widely used lunar simulant. The terrain is assumed to be traversable within the rover's mobility capabilities, and environmental effects such as dust accumulation are assumed to be present but manageable within system design limits.

C. Thermal and Power Assumptions

The thermal control approach is assumed to be comparable to that demonstrated by NASA's *VIPER* rover, providing sufficient protection against extreme temperature variations. The power system is assumed to support all primary subsystems, including mobility, sensing, communications, and laser-based manufacturing, within the defined operational duty cycle.

D. Communications and Autonomy Assumptions

The communications architecture is assumed to be consistent with existing lunar robotic mission concepts, enabling periodic data transmission and supervisory control. Due to communication latency and potential signal interruptions, the rover is assumed to operate with a level of onboard autonomy sufficient to perform navigation, excavation, and manufacturing tasks with limited real-time intervention.

E. Manufacturing Process Assumptions

Lunar regolith is assumed to be a viable feedstock for laser-based sintering without reliance on significant imported binding materials. The additive manufacturing process is assumed to be capable of producing structurally meaningful components under lunar conditions. Regolith collection, delivery, and deposition processes are assumed to achieve sufficient consistency for repeatable manufacturing operations. The system is intended to demonstrate proof-of-concept construction capability rather than full-scale infrastructure deployment.

F. Modeling and Scope Assumptions

Subsystem designs informed by prior lunar missions are treated as reference heritage rather than exact replications. The system is evaluated at a concept and prototype level, and full flight qualification is beyond the scope of this work. Long-term degradation effects due to radiation, dust abrasion, and thermal cycling are acknowledged but not fully characterized within this study.

IV. System Overview

Planetary rover systems require tight integration of mobility, thermal, power, and control subsystems to operate in extreme environments [4]. The proposed system is an autonomous mobile platform designed to perform ISRU through excavation, material processing, and additive manufacturing. The rover traverses to a construction site, collects regolith, processes it, and fabricates structures in situ.

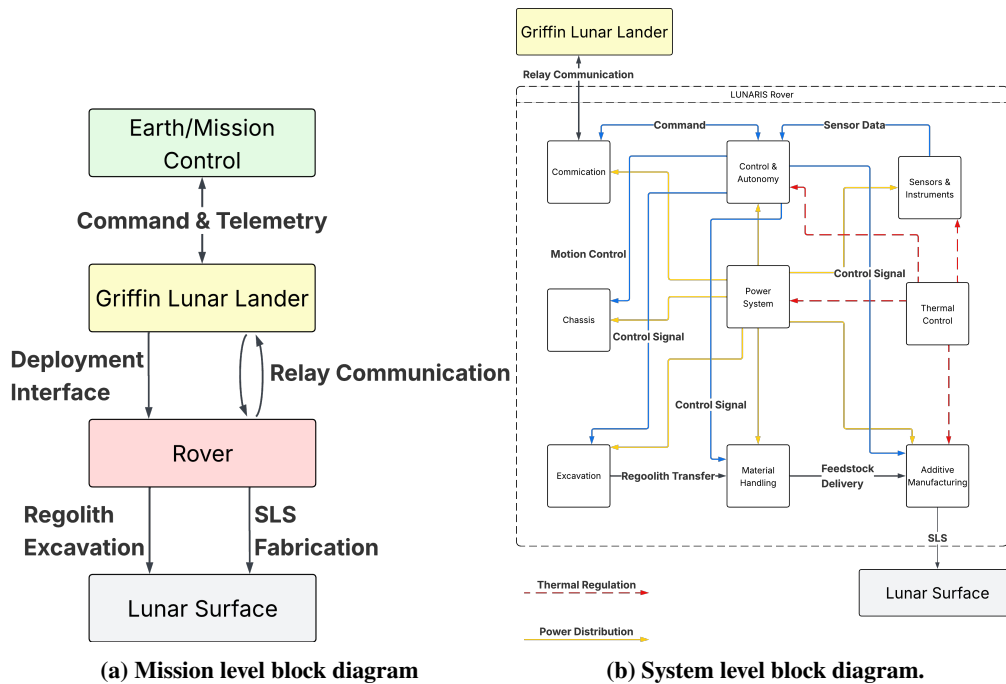


Fig. 1 Block diagrams of (a) mission and (b) system

The system consists of five primary subsystems:

- Excavation and Material Handling
- Additive Manufacturing
- Power System
- Thermal Control
- Control and Autonomy

These subsystems are integrated within a six-wheel mobile chassis designed for stability and mobility. The excavation

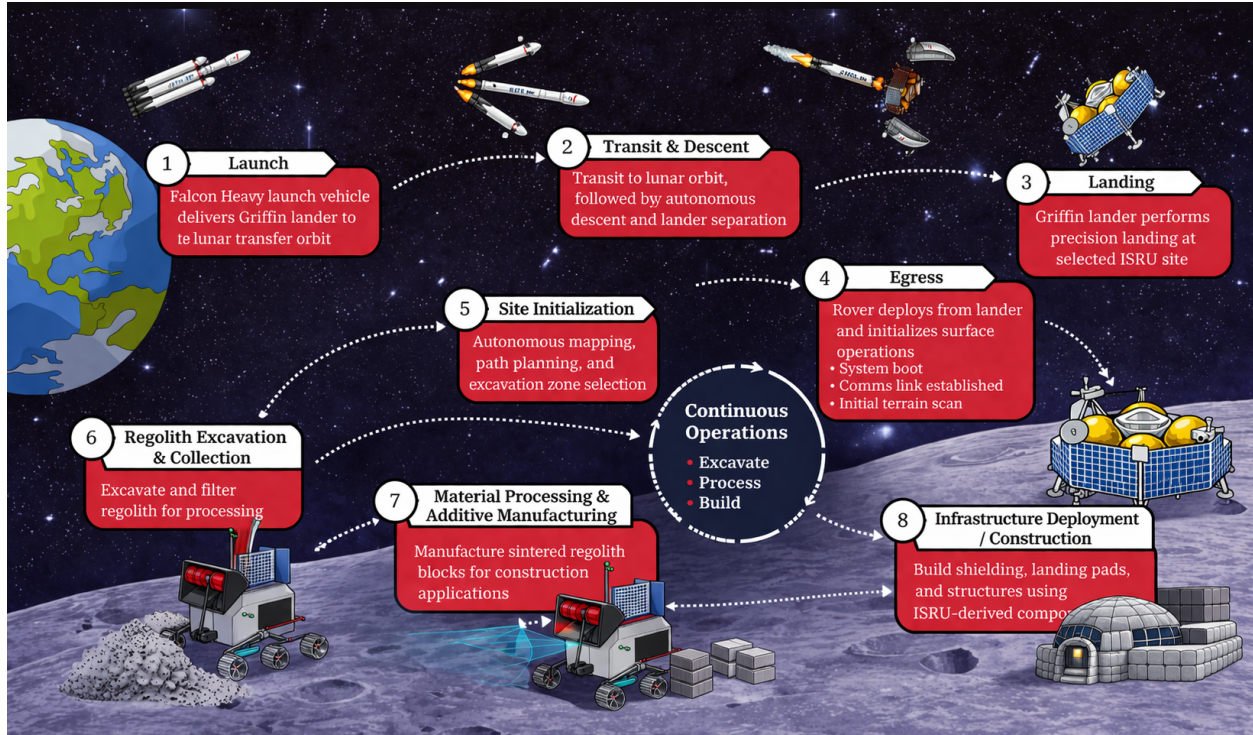


Fig. 2 Concept of operations of conceptual design.

subsystem is designed as a continuous material preparation process. Regolith is excavated, transferred, sieved, and delivered to the manufacturing subsystem.

The concept of operations begins with the rover traversing to a target location. A front mounted excavation subsystem collects regolith optimized for low-gravity environments. The collected material is transferred to an onboard storage and handling system, where it is metered and delivered to the additive manufacturing subsystem. A SLS additive manufacturing system processes the regolith and deposits material layer-by-layer to form structural components directly on the lunar surface. The system is designed to operate autonomously, with supervisory control provided through a machine learning AI control architecture. The high level view is shown on Fig. 5.

The high level view of the system architecture consists of five primary subsystems: excavation, thermal, additive manufacturing, power, and control. These subsystems are integrated within a six-wheel mobile chassis designed for stability and mobility across uneven lunar terrain. Power is supplied through a hybrid energy system and distributed to all subsystems, while onboard computation manages navigation, actuation, and process control.

V. Subsystem Design

A. Chassis

The chassis serves as the primary structural framework of the rover and provides mounting interfaces for all subsystems, including the harvesting system, additive manufacturing unit, power system, and control electronics. The design is based on a six-wheel rocker-bogie configuration to maximize stability, terrain adaptability, and load distribution across uneven lunar surfaces. The chassis frame is designed to:

- Distribute loads from all subsystems
- Maintain structural integrity throughout launch and landing
- Egress safely from the Griffin Lunar Lander
- Provide stable mounting points for mechanical and electrical components and subassemblies
- Support skid steering through independent drive on each side
- Simplify mechanical assemblies to minimize moving components
- Withstand the harsh lunar environment

The chassis interfaces directly with multiple subsystems and plays a central role in system integration. Load paths originate from subsystem masses and are transferred through the chassis to the release ring during launch and to through the suspension/wheels to the ground. Proper placement of components within the chassis is critical to maintaining a low center of gravity, which will improve stability during traversal of obstacles, reducing the risk of tipping on inclined surfaces. Additionally, choosing a flight-proven configuration of a six-wheel rocker bogie design also decreases potential for failure, further reducing the total mission risks.

B. Excavation and Material Handling

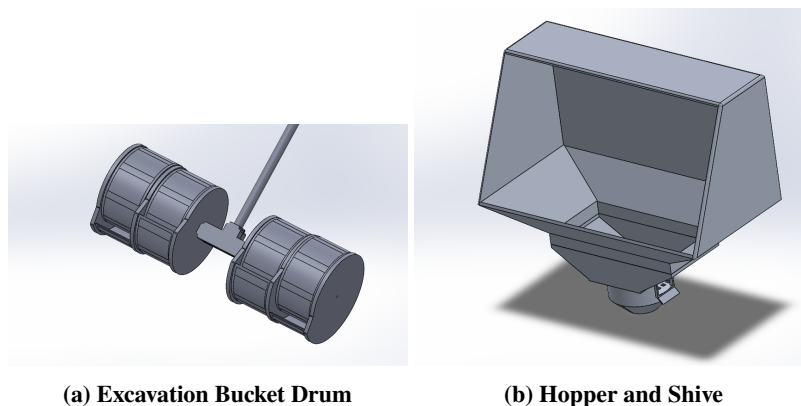


Fig. 3 CAD of (a) Bucket Drum and (a) Hopper

The current excavation subsystem, as shown in Fig. 3 are organized around a mobile chassis. The sieve and discharge channel are mounted below the hopper mouth. This design reflects an important systems level decision: excavation and

delivery are being treated as one continuous material handling process rather than as isolated functions. Material is excavated, transferred into onboard storage, sieved and finally dispensed in a controlled manner to the next subsystem. Traditional terrestrial selective laser sintering systems rely on powders with a narrow and well controlled particle size distribution, this is often in the range of 25–60 μm because that range supports uniform powder spreading, stable layer deposition, efficient packing and more consistent laser energy absorption. In contrast, lunar regolith is more broadly distributed, containing material from sub-micron dust to coarse particles and small rocks. Regolith is generally described as a poorly sorted granular material rather than a print ready powder[1]. Noble notes that lunar regolith spans sizes from large boulders down to sub micron dust, while typical lunar soils commonly fall in the broader 40–800 μm range, with most samples clustering around 45–100 μm . Connolly and Carrier describe lunar soil as poorly sorted, with a median particle size of 40–130 μm and roughly 10 % to 20 % of the material is finer than 20 μm . Raw lunar regolith is not directly compatible with conventional SLS requirements: oversize particles can produce rough layers and incomplete melting, while extremely fine particles can reduce flow ability and promote clumping. For this reason our sintering process targets a particle-size range of 20–80 μm and this serves as a compromise between the tight powder control used in terrestrial SLS and the broad particle distribution of lunar regolith, while still remaining achievable through mechanical sieving.

C. Additive Manufacturing

Following the mission goal of producing building materials through an ISRU process, the additive manufacturing module uses harvested regolith to generate structural components through a combination of SLS and powder-bed printing processes.

To accomplish this, the system prints directly on the lunar surface, eliminating the need for a traditional print bed and reducing overall system complexity at the cost of a negligible reduction in dimensional accuracy. The process consists of preparing a leveled workspace, sintering an initial layer using laser heating, and dispensing regolith to form subsequent layers until the final structure is completed.

Laser-based additive manufacturing of regolith requires careful control of process parameters such as laser power, scan speed, and layer thickness to ensure sufficient bonding and structural integrity [1, 3]. The subsystem consists of three primary components: a three-axis gantry system used to control the position and focus of a high-power laser, a recoater mechanism with adjustable height to prepare each layer of material, and a laser power control system to regulate energy input during the sintering process.

D. Controls

A companion effort within focus on development of autonomy and control architecture for lunar operations for additive manufacturing and harvesting of regolith [7]. This work informed the integration of sensing, safety, and decision-

making subsystems within the overall rover design including dynamic autonomy and learning-based manipulation for uncertain, contact-rich tasks, in-space assembly and manufacturing context motivating modular autonomy stacks, edge AI and onboard learning under power/compute constraints; and planetary material identification context relevant to regolith-oriented perception.

Enabling autonomous mission execution through a modular architecture integrating perception, decision-making, and safety supervision, the system supports multi-modal sensing through camera and LiDAR fusion, enhanced by machine learning-based perception for environment classification. A safety-governed autonomy framework allows real-time hazard detection, action override, and health-aware degraded operation. A hardware based interlock provides redundant safety enforcement. The system is capable of autonomous navigation, task execution, and manipulation, while maintaining full traceability through per-frame telemetry and logging. Simulation-based testing and a hybrid execution architecture further enable robust validation prior to full hardware deployment.

VI. Design Methodology

A. Chassis Design Requirements

The chassis design is driven by a combination of environmental, structural, and mission requirements that govern material selection, structural configuration, and mobility architecture. These requirements ensure reliable operation in the harsh lunar environment while supporting all integrated subsystems.

A. Environmental Requirements

The chassis must operate in a vacuum environment, withstand extreme thermal cycling, and resist abrasion from fine, electrostatically charged lunar regolith[5, 6]. These conditions drive the selection of materials and surface treatments to mitigate wear, thermal stress, and degradation over time.

B. Structural Requirements

The chassis is required to support the total rover mass and payload while maintaining structural integrity under launch, landing, and operational loading conditions. The dynamic loads induced during the traversal of uneven terrain are considered in the design. Critical components are designed to meet a minimum factor of safety of 1.5 to ensure reliability throughout the mission lifecycle.

C. Mission Requirements

The rover must traverse uneven and sloped terrain while maintaining stability and traction. To meet these requirements, the chassis supports a skid-steering configuration with independent drive on each side of the drivetrain. Stability considerations further drive the design toward a low center-of-gravity configuration and even load distribution across all wheels.

These requirements collectively inform the selection of a six-wheel rocker-bogie suspension system, which provides

enhanced terrain adaptability, passive load distribution, and improved stability without the need for complex active suspension components. The resulting chassis architecture serves as the foundational platform for subsystem integration, directly supporting the excavation and additive manufacturing systems described in the following sections.

B. Excavation System Design Requirements

The Excavation team has a set of design requirements that align with increasing efficiency and reliability in our system. The main one being is reducing the number of moving parts coming into contact with lunar regolith, this is in order to reduce wear and tear. We also have a requirement to be able to store 25 kg of regolith in the rover in order to allow the printing of almost six bricks without returning to a harvesting location. the final requirement is to refine / filter the regolith into a powder roughly 20 to 80 μm in order to increase the efficiency and consistency of the sintering process.

C. Additive Manufacturing Unit Design Requirements

The primary function of the additive manufacturing module is the reliable conversion of raw, filtered lunar regolith into structural components through a modified SLS process. As a metric for a successful mission, the hardware must be able to complete the production of at least 100 uniform products capable of demonstrating compressive strengths exceeding 31 MPa.

Operationally, the system requires a precise repetitive cycle consisting of surface preparation done in precise intervals, sustained high-power laser exposure resulting in near complete material liquidation and bonding between 1300 °C to 1600 °C, and the expulsion of excess heat generated by the hardware in a vacuum.

D. Chassis Trade Study

Three trade studies were conducted to evaluate key aspects of the chassis subsystem: (1) suspension configuration, (2) drivetrain configuration, and (3) deployment mechanism selection. These studies ensure the selected architecture meets mission requirements for mobility, stability, and system integration.

A. Suspension Configuration Trade Study

A trade study was conducted to evaluate candidate suspension architectures, including fixed chassis, rocker-bogie suspension, and independent suspension systems. Evaluation criteria included traction, obstacle climbing capability, operational stability, mechanical complexity, and technology readiness level (TRL).

The rocker-bogie suspension demonstrates superior obstacle traversal capability, maintaining wheel contact over obstacles up to approximately 70–80% of the wheel diameter, compared to 50–60% for independent suspension and 30–40% for fixed chassis systems. Additionally, the rocker-bogie system provides passive load distribution and high stability without requiring active suspension components.

Table 2 Suspension Configuration Trade Study

Criteria	Fixed	Rocker-Bogie	Independent
Traction	-	+	+
Obstacle Climbing	-	+	+
Operational Stability	+	+	+
Low Complexity	+	+	-
High TRL/Heritage	+	+	+
Selected		✓	

B. Drivetrain Configuration Trade Study

A trade study was conducted to compare four-wheel independent drive and six-wheel differential drive configurations. Evaluation criteria included load distribution, traction, stability, and system complexity.

Table 3 Drivetrain Configuration Trade Study

Criteria	4-Wheel	6-Wheel
Load Distribution	Low	High
Traction	Moderate	High
Stability	Moderate	High
Mechanical Complexity	Low	Moderate
Redundancy	Low	High
Selected		✓

The six-wheel configuration improves traction and reduces ground pressure by distributing the rover mass across additional contact points. It also provides redundancy, allowing continued operation in the event of partial system failure.

C. Deployment Mechanism Trade Study

A trade study was conducted to evaluate candidate deployment mechanisms for rover release from the Griffin lunar lander. The mechanisms considered include the EBAD NEA PRR-15, Rocket Lab Motorized Lightband MkII, and EBAD NEA PRM 9103 multi-point release system.

Table 4 Deployment Mechanism Trade Study [8–10]

Criteria	PRR-15	MLB MkII	PRM 9103
Volume (m ³)	0.00967	0.00783	0.009
Mass (kg)	2.9	2.63	6.53
Mechanical Simplicity	High	Moderate	Moderate
Selected	✓		

The PRR-15 provides a balanced combination of moderate mass, compact volume, and high mechanical simplicity. Although the MLB MkII offers slightly lower mass and volume, it introduces increased complexity due to motorized

actuation. The PRM 9103 system provides distributed load release but incurs a significant mass penalty and increased integration complexity.

Based on the results of these trade studies, the selected chassis architecture consists of a six-wheel rocker-bogie suspension system with differential skid steering and an EBAD NEA PRR-15 deployment mechanism.

E. Excavation Trade Study

The excavation subsystem interfaces directly with the larger lunar construction mission. Its output is not an end product, but a prepared input for selective laser sintering of regolith bricks. Important interface variables include delivered mass flow rate, retained hopper volume, particle size window after sieving, discharge consistency, and contamination or segregation during transport. This interface driven view is consistent with broader lunar manufacturing research. Powder properties such as reflectance, flow ability, and particle size distribution directly affect energy absorption and build consistency[11], which means regolith preparation cannot be understated. In practical terms, the excavation team improves the probability of successful sintering when it delivers a narrower, more repeatable powder stream. A well designed excavation subsystem reduces risk in two ways. First it provides the additive manufacturing team with a more uniform feedstock. Second, it protects the rest of the system from the most problematic regolith fractions, especially the finest dust that is likely to adhere, infiltrate and degrade hardware.

For those reasons we have chosen to use a vibratory sieve to filter the regolith into a target range of 20-80 μm [12], and the bucket drum harvesting system reduces the number of moving parts coming into contact with lunar regolith while also allowing us to use the harvester as a storage container capable of carrying almost 25kg of lunar regolith.

F. Additive Manufacturing Trade Study

A trade study was conducted to evaluate key design choices for the additive manufacturing subsystem, including gantry motion systems, recoater mechanisms, laser types, and regolith protection strategies [13]. Each option was evaluated based on mechanical complexity, power requirements, reliability, and compatibility with lunar environmental conditions.

The selected configuration utilizes a belt and pinion-driven gantry system, a roller-based recoater mechanism, and a diode laser system operating with continuous point exposure. An electrodynamic dust shield (EDS) was incorporated to mitigate the effects of fine regolith particles on sensitive components.

Alternative configurations were considered but were determined to be less suitable due to increased system complexity, reduced durability, or higher power consumption. The selected design provides a balance between performance, simplicity, and robustness for operation in the lunar environment.

G. Chassis Key Design Decisions

The final chassis configuration incorporates several design features to support mobility, stability, and subsystem integration.

A six-wheel rocker-bogie suspension system was implemented to enable passive articulation and continuous wheel-ground contact during traversal [14]. This configuration allows the chassis to conform to uneven terrain while maintaining stability without the use of active suspension components.

The chassis geometry was designed with a low-profile structure to maintain a low center of gravity, improving resistance to tipping during operation on uneven or sloped terrain. A symmetric structural layout was adopted to ensure balanced load distribution across all wheels and minimize structural asymmetry.

The design also incorporates modular mounting interfaces to support integration of the excavation system, additive manufacturing unit, and power subsystem. These interfaces allow for efficient subsystem placement while minimizing additional structural complexity.

H. Excavation Key Design Decisions

The excavation subsystem is driven by four main requirements: reliable collection, stable transport, temporary storage, and controlled dispensing. These requirements arise from both lunar surface conditions and the needs of the additive manufacturing process. On the Moon, excavation hardware must operate in reduced gravity, where available normal force and traction are limited. At the same time, the system must survive repeated contact with abrasive regolith and avoid excessive complexity or mass growth. NASA reviews of extraterrestrial excavation emphasize that these constraints strongly shape machine configuration, force management, and material transfer strategy[15]. For the excavation team, the design goal is not simply to maximize how much regolith can be moved per cycle. Instead, the more important metric is usable regolith delivered to the manufacturing subsystem. That distinction matters because bulk throughput alone does not guarantee process-ready feedstock. A subsystem that excavates quickly but delivers poorly graded or poorly flowing material can still bottleneck the overall mission. This is especially relevant for laser-based regolith manufacturing, where powder characteristics influence spreading, absorption of laser energy, and the stability of consolidated layers. Research on lunar regolith simulant powders shows that chemistry, mineralogy, particle size distribution, reflectance, and powder flow behavior all affect laser-based additive manufacturing performance[13]. This is why the excavation subsystem should be viewed as part of a larger end-to-end material preparation process. The team is not only collecting regolith; it is also conditioning the raw material for downstream use. That framing strengthens the engineering justification for adding a sieve below the hopper, because the sieve is not an accessory. It is the feature that transforms raw excavation output into more consistent manufacturing feedstock.

VII. Modeling and Analysis

A three-dimensional CAD model of the chassis was developed to define structural geometry, subsystem placement, and integration interfaces. The model incorporates a six-wheel rocker-bogie configuration and includes mounting features for motors, suspension components, and payload subsystems. The CAD assembly was used to establish load paths, verify subsystem packaging, and support structural evaluation. The complete chassis assembly is shown in Fig. 4.

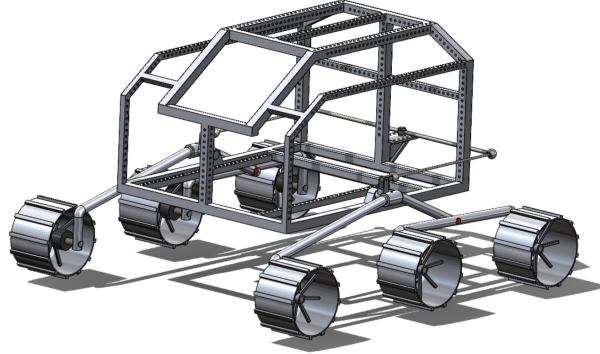


Fig. 4 Full CAD assembly of the chassis subsystem.

A static finite element analysis (FEA) was conducted using SolidWorks Simulation to evaluate stress distribution, displacement, and factor of safety under representative loading conditions. A worst-case loading scenario corresponding to the combined subsystem mass (~ 200 kg) was applied as a distributed load at subsystem mounting interfaces. Boundary conditions were applied at the wheel interfaces to represent ground contact, and gravitational loading was included.

The chassis was modeled as Aluminum 6061 with standard material properties and discretized using a standard mesh. Loads were applied at mounting interfaces to reflect expected structural load paths.

The Von Mises stress distribution indicates that most of the chassis experiences low stress levels, with localized peaks near suspension mounting regions and geometric transitions. These peaks are confined to small regions and are attributed to stress concentrations rather than global structural limitations.

The maximum displacement is

$$\delta_{\max} \approx 0.73 \text{ mm}$$

indicating sufficient global stiffness relative to chassis dimensions.

The factor of safety is defined as

$$\text{FOS} = \frac{\sigma_{\text{yield}}}{\sigma_{\max}} \quad (1)$$

The minimum observed value is

$$\text{FOS}_{\min} \approx 1.06$$

which occurs in a localized region associated with geometric discontinuities. The majority of the structure maintains a

higher factor of safety, indicating acceptable overall performance with localized areas requiring refinement.

Localized reductions in factor of safety are driven by sharp geometric transitions and can be mitigated through minor refinements such as adding fillets, smoothing transitions, and reinforcing high-stress regions. These changes are expected to improve structural reliability without significantly increasing mass or complexity.

VIII. Prototyping and Validation

Prototype systems were developed for excavation, chassis, and additive manufacturing subsystems.

A. Chassis Prototype and Validation

1. *Prototype Description*

A physical prototype of the chassis subsystem was developed to validate mobility performance, structural behavior, and system integration. The prototype incorporates a half-scaled six-wheel rocker-bogie suspension, motorized wheel assemblies, and a structural frame representative of the final design geometry.

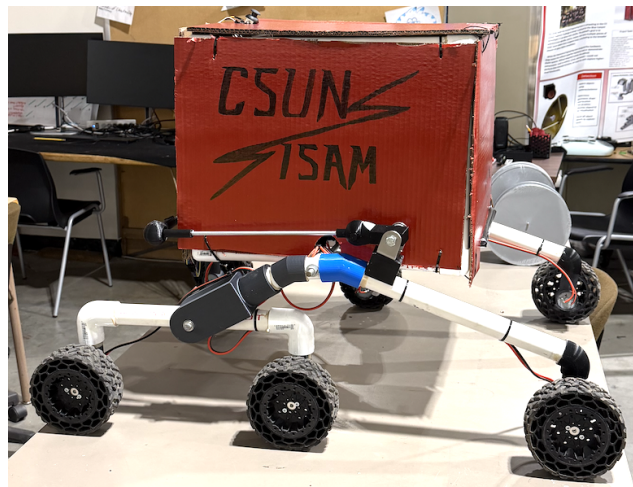


Fig. 5 Physical prototype of the chassis subsystem used for mobility and validation testing.

The system was designed to replicate key functional behaviors of the full-scale rover, including suspension articulation, load distribution, and skid-steering capability. This enables evaluation of real-world performance under representative operating conditions, as shown in Fig. 5.

2. *Testing Procedures*

A series of tests were conducted to evaluate chassis performance relative to mission requirements, focusing on mobility, stability, and maneuverability.

Slope traversal testing was used to determine the maximum incline angle the rover could ascend and descend without loss of traction or stability, as well as its performance on cross-slopes. The prototype achieved slopes up to

approximately 30° and maintained stability on cross-slopes up to 15°.

Traversal over uneven terrain was used to evaluate suspension articulation, obstacle negotiation capability, and continuous wheel-ground contact. The system demonstrated the ability to navigate around obstacles up to approximately 0.15 m in height.

Turning performance was evaluated through skid-steering maneuvers, confirming capability of zero-radius turning. Speed testing under nominal operating conditions yielded a maximum velocity of approximately 0.161 m/s.

B. Excavation Prototype and Validation

The Excavation team created a prototype for the harvesting system that was used to demonstrate our prototype being capable of harvesting lunar simulant. The scaled down prototype showed the harvesting arm had an average collection rate of 160 grams per minute. It also demonstrated its ability to store and dump the harvested regolith at a later date. This allows us to reliably use the harvesting drum as a storage system.



Fig. 6 Excavation Bucket Drum

C. Additive Manufacturing Prototype and Validation

A prototype of the additive manufacturing subsystem was developed to validate the feasibility of regolith-based layer-by-layer fabrication. The prototype integrates a gantry system and recoater mechanism into a single mechanical assembly capable of executing a simplified printing process.

The gantry and recoater systems were constructed and programmed to operate in a coordinated motion pattern, demonstrating the ability to maintain consistent positioning and repeatable motion during operation. This validated the capability of the system to perform controlled layer deposition.

Laser testing was conducted using a 150 W diode laser system to determine suitable power and speed parameters for regolith sintering. Multiple test samples were produced using varying laser settings, and a range of parameters was identified that resulted in consistent material consolidation.

Material testing was performed using small-scale samples consisting of three-layer, 1×1 inch geometries. These samples were evaluated through visual inspection and manual handling to assess structural integrity and consistency. Based on these results, a set of near-optimal laser parameters was selected for continued testing.

A physical sample was produced using the selected parameters as a demonstration of the additive manufacturing process, confirming the feasibility of layer-by-layer regolith sintering under controlled conditions.

Further validation, including compression testing of printed samples, is planned to quantitatively evaluate material strength once appropriate laboratory facilities become available.

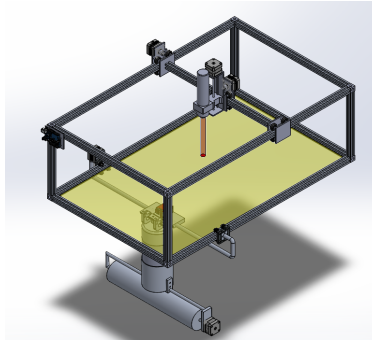


Fig. 7 Gantry and Recoater

D. Controls

Using a simulation first prototyping approach to enable rapid iteration, risk reduction, and repeatable testing. A hybrid architecture was implemented in which the autonomy stack was executed on an NVIDIA Jetson platform, while a Gazebo environment simulated rover mobility and environmental interaction. This approach allowed early validation of perception, decision-making, and safety behaviors without exposing hardware to potential failure conditions. To support quantitative evaluation, the system recorded synchronized telemetry using ROS2 logging and per-frame CSV traces. Key performance indicators included mission success rate, cycle time, number of safety interventions, and recovery time following off nominal events. These metrics provided both high level system performance insight and low-level traceability of decision-making processes.

Hardware in the loop elements were incorporated using an embedded safety controller, which provided independent watchdog and emergency-stop functionality. This ensured that safety critical behaviors could be validated independently of the primary autonomy stack.

IX. Results and Discussion

A. Chassis Results and Discussion

Results from both finite element analysis and physical prototyping demonstrate that the chassis design meets primary structural and mobility requirements.

From the FEA, the chassis maintains structural integrity under worst-case loading conditions representing the combined subsystem mass of approximately 200 kg. The majority of the structure exhibits a factor of safety greater than 1.5, with a minimum localized value of approximately $FOS_{\min} \approx 1.06$ occurring at geometric stress concentrations. These regions are highly localized and do not indicate global structural failure. The maximum displacement observed was approximately $\delta_{\max} \approx 0.73$ mm, confirming that the chassis maintains sufficient global stiffness under load.

Prototype testing supports these findings. The rover demonstrated stable mobility across uneven terrain while maintaining continuous wheel-ground contact through the rocker-bogie suspension. Slope traversal testing confirmed the ability to ascend and descend slopes up to 30° and operate on cross-slopes up to 15° without loss of stability or traction. The system achieved a maximum velocity of approximately 0.161 m/s, exceeding the minimum requirement of 0.1 m/s.

Skid-steering performance testing confirmed a zero-radius turning capability, and obstacle traversal testing demonstrated the ability to navigate uneven terrain and climb small obstructions. No structural failure or excessive deformation was observed during testing, indicating that the chassis maintains rigidity under operational conditions.

The agreement between simulation and experimental results validates the overall chassis design. The rocker-bogie configuration improves terrain adaptability by maintaining continuous contact and distributing loads effectively, while the low center-of-gravity design enhances stability on inclined surfaces.

The primary limitation identified is the localized reduction in factor of safety due to geometric stress concentrations. This is not indicative of a fundamental design issue and can be mitigated through minor refinements such as adding fillets and smoothing geometric transitions. These improvements are expected to increase structural reliability without significantly increasing system mass or complexity.

Overall, the chassis provides a robust and reliable platform for integrated lunar surface operations.

X. Conclusion

This work presents the design and validation of an autonomous ISRU-based rover capable of performing excavation, material conditioning, and additive manufacturing on the lunar surface. The integration of these subsystems enables a complete construction workflow and addresses a key limitation in current lunar infrastructure development approaches.

Structural analysis and prototype testing confirm that the system meets performance requirements, including stability, load distribution, and manufacturing feasibility. The inclusion of material conditioning improves compatibility with

additive manufacturing processes and enhances system reliability.

The results demonstrate the feasibility of autonomous lunar construction using regolith as feedstock. Future work will focus on refining subsystem integration, improving structural performance, and validating operation under representative lunar environmental conditions.

Acknowledgments

The authors acknowledge the support of our faculty advisor Dr. Christoph Schaal and our mentors Jerry Fuller and Micheal Hernandez, California State University, Northridge and the ISAM senior design program.

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