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Conceptual System Design of a Mother–Daughter Lunar Rover for South-Polar Exploration: Dust-Resilient Mobility, Uneven Terrain Navigation, and Multi-Stage Sample Collection

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Abstract

The lunar south pole presents extreme terrain and environmental challenges, including low illumination, abrasive dust, steep slopes, and deep shadowed regions. These conditions limit the ability of conventional rovers to reach scientifically important sites. This paper presents the research based conceptual and unique design of a mother–daughter rover system developed for reliable mobility, autonomous navigation and multi-stage sample collection in this environment. The mother rover provides the primary mobility platform, power system, and subsurface drilling capability, while the daughter rover accesses hazardous or confined areas for surface sampling. Dust-resistant wheels, a hybrid solar–battery power architecture, and thermal protection systems support continued operation under south-pole conditions. The perception suite integrates cameras, environmental sensors, and motion estimation to support terrain mapping and hazard avoidance. A complete workflow for subsurface drilling, surface sample retrieval, transfer, and insulated storage is also demonstrated. System limitations and opportunities for future improvement are highlighted based on component level and energy budget analysis.

Keywords
Lunar rover, south pole, mobility, navigation, sampling, daughter rover and power system.

1. Introduction

Lunar south polar regions are key scientific targets because of their complex terrain, volatile rich soil, and permanently shadowed areas. These conditions create major challenges for rover operations, including steep surfaces, loose abrasive regolith, low sunlight, and extreme temperature changes. As missions increasingly focus on sites near Shiv Shakti Point, there is a growing need for rover systems that can navigate hazardous terrain while collecting reliable scientific samples.

This work presents a conceptual lunar rover design that uses a mother and daughter rover system to address these challenges. The mother rover provides mobility, sensing, communication, and power. The daughter rover reaches narrow or unstable areas that the larger rover cannot enter. The system includes dust tolerant wheels, a hybrid power strategy, a sensor based navigation suite, and an integrated sampling system with drilling, robotic handling, and daughter rover collection. The paper describes the methodology, architecture, component design, sampling workflow, and energy considerations that form the basis of this concept for future south polar missions.

1.1 Objectives

- To propose a conceptual mother–daughter rover architecture suited for mobility, navigation, and sampling in the challenging environment of the lunar south pole.
- To outline the functional design of key subsystems including mobility, sensing, power, and sampling required to support coordinated surface and subsurface sample collection.
- To establish a complete operational workflow for drilling, surface retrieval, sample transfer, and storage based on system-level reasoning rather than simulation or experimental validation.

2. Literature Review

Recent advancements in lunar rover research demonstrate rapid progress in mobility, sensing and environmental resilience. But several gaps remain that directly inform the development of the proposed rover system. Previous mobility focused designs, such as the wheel–leg hybrid locomotion concept show improved obstacle negotiation on rough terrain but at the expense of higher mechanical complexity, increased actuator load and reduced long-term reliability in dusty environments (Yakubu, 2025). In contrast, studies on optimized wheel geometries particularly the wheel–soil interaction analysis highlights how tread design, soil flow behavior and slip characteristics can be refined to enhance traction without added mechanical burden (Zhang, 2025). These findings align more closely with the simpler, non-pneumatic, dust-resistant wheel approach adopted in our system, which prioritizes robustness over mechanical sophistication. Navigation and terrain assessment research have also contributed significantly to rover autonomy. The multi-level map based routing method by (JIA, 2025) provides improved path planning across highly uneven surfaces. This approach enhances global navigation, but it remains limited to software optimization and does not fully address the mechanical and environmental durability needed for operations in regions such as the lunar south pole. Our system builds on these insights by integrating dust-resilient sensors, a stable mobility platform and a dual-rover framework which will allow safer traversal as well as reliable sampling in shadowed or hazardous terrain where conventional rovers may be unable to operate.

Environmental dust is one of the most critical challenges for lunar missions. (Manenti, 2024) demonstrated that the photoelectric charging of materials under intense UV radiation significantly increases dust adhesion, influencing both thermal performance and actuator reliability. Their work guides material selection and surface treatment but does not propose hardware-level mitigation strategies. Similarly, slip estimation methods using chassis strain (Iizuka & Inaba, 2023) and high-resolution subsurface radar techniques (Shen, 2025) provide valuable insight into navigation safety and geological exploration but primarily focus on sensing rather than sample-handling or dust-resistant mechanisms. Our design addresses this by incorporating sealed actuator interfaces, simplified kinematic structures and a modular sampling assembly that minimizes dust ingress. Sample collection technologies have also advanced in recent missions. The CAM-M microscope camera enables high-resolution regolith imaging for detailed surface analysis (Els, 2024), while passive regolith samplers provide a lightweight and simple method for collecting undisturbed soil. Calibration targets used in SHERLOC help maintain long-term spectroscopic accuracy in harsh environments which supports reliable in-situ analysis(Fries, 2022). These developments emphasize the importance of durable and contamination-resistant sampling systems. Additional progress has been made in rover mobility and mission operations. A dual-mode rocker–bogie system proposed by (Pandey, 2022) enhances traction and stability on uneven terrain, demonstrating improved control through optimized link design. Operational studies from the Rashid rover highlight the benefits of structured rehearsal procedures and contingency planning to ensure navigation safety during surface activities (Alzaabi, 2024). Subsurface exploration technologies, such as the dual-channel radar system on Chang'E-7, further support the detection of buried structures and potential water-ice deposits in polar regions (Shen, 2025). Overall, the literature shows notable advancements across mobility, sensing, sampling and mission planning as well as many efforts address these challenges individually. The proposed mother–daughter rover system combines dust-resilient mobility, robust sensing, and a flexible sampling workflow within a single architecture tailored for hazardous south-polar terrain. This integrated approach offers a more comprehensive foundation for future exploration of volatile-rich and shadowed lunar environments.

3. Methodology

The methodology adopted in this research follows a structured systems-engineering approach to develop a complete lunar rover mission architecture optimized for the extreme environmental and operational constraints of the lunar south pole. The overall workflow is illustrated and is divided into five major stages: (1) mission requirements definition, (2) conceptual system design, (3) subsystem-level design, (4) environmental survivability planning, and (5) navigation and sampling operations engineering (fig. 1). Each stage builds upon the previous one to ensure that the proposed rover configuration is feasible, internally consistent and capable of meeting mission objectives.

3.1 Mission Requirements and Constraint Definition

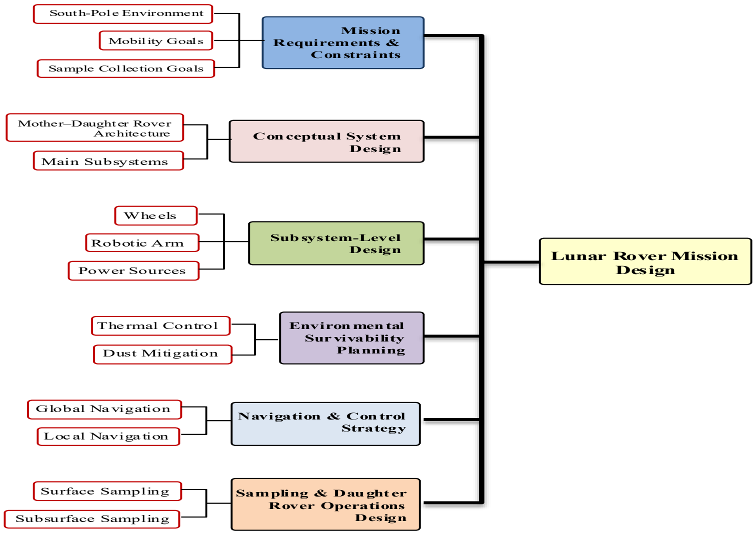

Figure 1. Lunar Rover Mission Design Overview

The methodology begins with an assessment of key challenges at the lunar south pole, including low sunlight, steep and uneven terrain, abrasive regolith (Figure 1), and extreme temperature changes. Mobility needs such as crossing boulder fields, moving on soft soil, and reaching scientific targets are defined along with sampling needs for drilling and surface retrieval. These requirements set the foundation for both the mother and daughter rover designs.

3.2 Conceptual System Design

Based on these requirements, a conceptual design is formed using a mother rover and a daughter rover. The mother rover serves as the main platform for mobility, power, and scientific instruments, while the daughter rover operates in narrow or hazardous areas. Major subsystems such as mobility, sensing, sampling, communication, power, and structure are selected and arranged into a coherent system framework.

3.3 Subsystem-Level Design and Functional Detailing

After defining the system layout, detailed subsystem engineering is carried out. The mobility system uses honeycomb wheels, cycloidal gearboxes, and articulated mounts for traction and load management. The sensing suite, including MastCAM, NavCAM, dust sensors, REM units, and microphones, supports navigation and environmental monitoring. The robotic arm is designed for sample handling and the power system uses solar arrays with $LiSOCl_2$ and rechargeable batteries. Each subsystem is defined by its components and operational role.

3.4 Environmental Survivability Planning

Survivability planning ensures the rover can operate near Shiv Shakti Point. Thermal protection is provided through multilayer insulation, heat paths, heaters, and a warm electronics box. Dust protection includes sealed joints and dust-resistant sensors with continuous monitoring. These measures allow mobility, sensing, and electronics to function despite regolith abrasion, temperature extremes, vacuum, and limited sunlight.

3.5 Navigation and Control Strategy Development

Navigation is developed through global and local strategies. Global navigation uses elevation maps, illumination data, and terrain models to plan safe long-range paths. Local navigation uses stereo imaging, depth estimation, slip detection, IMU data, and dust-adjusted perception for real-time movement. This feedback process maintains reliable mobility in irregular terrain.

3.6 Sampling and Daughter Rover Operations Design

Sampling operations combine the strengths of both rovers. The mother rover extracts subsurface material with a vertical drill and the daughter rover collects surface samples from risky or narrow areas using its parallel gripper. Its deployment, movement, return, and sample transfer are planned as a single operational cycle. Samples are stored in an insulated chamber for preservation.

4. System Architecture

The rover uses a layered architecture that combines sensing, mobility, decision making, sampling, and communication into a single operational cycle (see fig. 2). As shown in fig. 3, the system integrates a mast with navigation and science cameras, a robotic arm for surface manipulation and sample handling, a deck-mounted drill for subsurface extraction, and a multi-compartment container for storing collected material. The mobility system is supported by large mesh wheels designed for uneven terrain. High and low gain antennas enable communication during surface operations. The overall structure is designed to operate reliably in the challenging environment of the lunar south pole, where low illumination, temperature extremes, abrasive dust, and irregular terrain influence every aspect of rover performance.

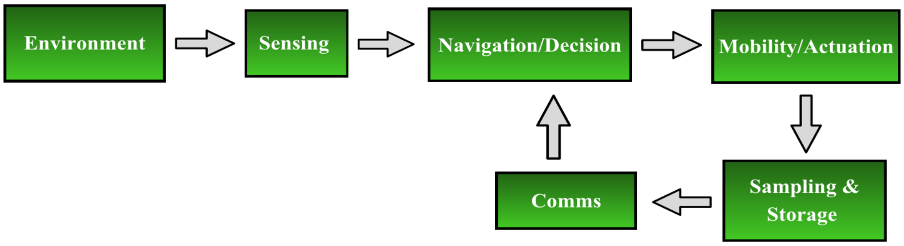

Figure 2. System Architecture and Operational Feedback Loop

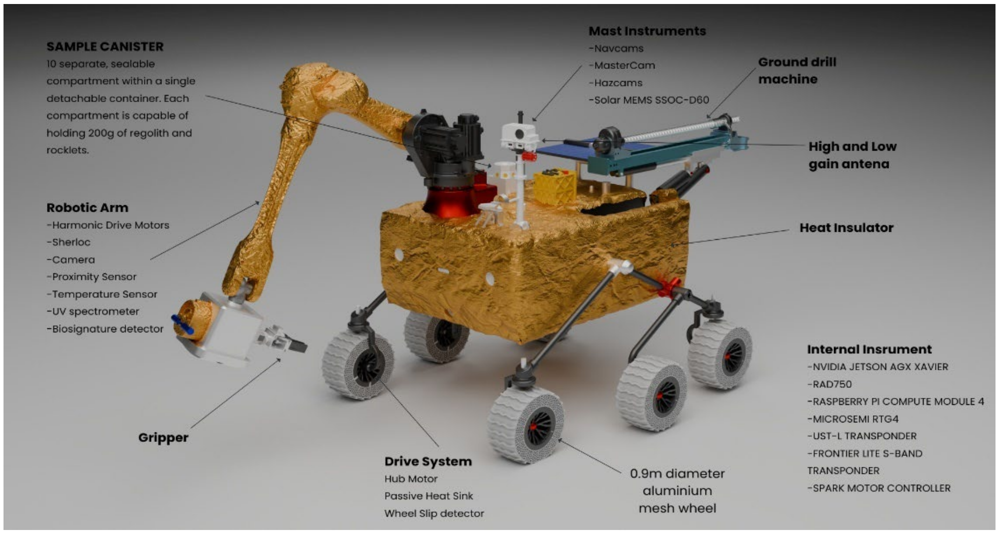

Figure 3. Mother Rover Cad Model

4.1 Architectural Layers and Functional Allocation

The system is organized into six functional layers to separate perception, planning, actuation, and mission tasks. This structure reduces integration risk and allows each layer to operate reliably even when others are degraded. Table 1 summarizes the layers, their roles, major inputs, and outputs.

Table 1. System Architecture Layers and Core Functions

<table>
<tr><th>Layer</th><th>Primary Role</th><th>Major Inputs</th><th colspan="2">Major Outputs</th></tr>
<tr><td>Environmental Interaction</td><td>Defines external conditions</td><td>Terrain slope, regolith, temperature, illumination, dust</td><td colspan="2">Constraints for navigation and thermal demand</td></tr>
<tr><td>Perception and Sensing</td><td>Measures environment and rover state</td><td>Camera images, dust readings, IMU, encoders, radiation</td><td colspan="2">Terrain map, hazard markers, state estimates</td></tr>
<tr><td>Navigation and Decision</td><td>Plans safe motion and mission actions</td><td>Terrain map, slip risk, thermal and power state</td><td colspan="2">Route, speed profile, task schedule</td></tr>
<tr><td>Mobility and Actuation</td><td>Executes motion and tool operations</td><td>Motor and joint commands</td><td colspan="2">Rover motion, arm and drill actions</td></tr>
<tr><td>Sampling and Storage</td><td colspan="2">Collects and preserves samples</td><td>Drill output, daughter rover payload</td><td>Secured samples and storage status</td></tr>
<tr><td>Communication and Data</td><td colspan="2">Transmits and receives mission data</td><td>Telemetry, payload data, link status</td><td>Downlinked data, updated task commands</td></tr>
</table>

4.2 Environment Interaction Layer

This layer represents the external factors that influence rover performance. At the south pole, illumination varies rapidly due to cratered terrain, regolith is abrasive and electrically charged, and slopes create risks of slip and sinkage. These conditions guide navigation limits, thermal needs, and traction margins used by upper layers.

4.3 Perception and Sensing Layer

The perception layer gathers sensing data needed for terrain mapping, localization, hazard detection, and environmental monitoring. The sensing suite includes stereo navigation cameras, dust and radiation monitors, and motion sensors such as the IMU and wheel encoders. Together, these instruments enable robust navigation and environmental awareness under south-pole conditions.

4.4 Navigation, Decision, and Control Layer

Navigation uses a two-part strategy. Global planning relies on elevation and illumination maps to choose safe routes. Local planning uses real-time stereo vision, IMU data, and slip estimation to avoid hazards and adjust movement. This combination ensures safe mobility despite uneven terrain and dust.

4.5 Mobility and Actuation Layer

This layer converts navigation commands into movement through the drivetrain and robotic tools. Honeycomb wheels and cycloidal gearboxes provide traction and shock tolerance on soft and rocky regolith. Actuation also includes the robotic arm, drill, and the docking system for the daughter rover.

4.6 Sampling, Handling, and Storage Layer

Sampling is shared between the mother and daughter rovers. The mother rover performs subsurface drilling, while the daughter rover collects surface material in narrow or hazardous regions. After collection, samples are transferred back to the mother rover and stored in an insulated chamber.

4.7 Communication and Data Management Layer

Communication uses two links: a long-range link for sending science and health data, and a short-range link for mother–daughter rover coordination. Data is prioritized to ensure essential telemetry and navigation summaries are always transmitted.

4.8 Closed-Loop Feedback and Autonomy Robustness

The architecture is feedback-driven. After each movement or sampling step, new sensor data updates localization, terrain conditions, dust, and power state. This allows adaptive actions such as rerouting during hazards, reducing speed during slip, delaying drilling, or postponing daughter rover deployment until energy is sufficient.

5. Subsystem and Component Design

5.1 Component Overview

This section presents the detailed design of the hardware subsystems that realize the architectural layers described in Section 4. The rover is intentionally built around a limited but carefully selected set of components so that each element contributes directly to mobility, energy robustness, autonomous navigation, or sample acquisition. Table 2 provides an overview of the fourteen key components considered in this work, followed by detailed descriptions of their geometry, operating principle, and functional integration.

Table 2. Major Components and Primary Functions

ID	Component	Subsystem Role	Primary Function in Mission
1	Wheel	Mobility	Provide traction, shock absorption, and low sinkage on regolith
2	Wheel Mount	Mobility	Support wheels and distribute loads on uneven terrain
3	Cycloidal Gearbox	Mobility / Actuation	Deliver high torque at low speed with minimal backlash
4	Solar System	Power	Generate electrical power from low-angle solar illumination
5	$LiSOCl_2$ Battery	Power	Long-duration, low-temperature-tolerant primary energy storage
6	Rechargeable Battery	Power	Support peak loads from actuators and instruments
7	Mast, SHERLOC and Parallel Gripper Assembly	Sampling / Science	Enable close-up inspection and fine manipulation at the mast end
8	MasterCAM, NavCAM, Microphone, REM Package	Sensing / Environment	Provide imaging, acoustic, and radiation/environment data for navigation and science
9	Dust Sensor	Environment Monitoring	Detect and quantify airborne regolith and deposition
10	High-Gain Antenna	Communication	Provide long-range, high-bandwidth link to Earth/orbiter
11	Robotic Arm	Manipulation	Handle tools, assist sampling, and support daughter-rover interaction
12	Drill System	Sampling	Extract subsurface regolith cores at controlled depth
13	Daughter Rover	Sampling / Hazard Access	Retrieve samples from hazardous or confined terrain and deliver to mother rover
14	MOXIE-Inspired Module	ISRU Payload	Demonstrate concept for in-situ oxygen extraction feasibility

5.2 Mobility Components

5.2.1 Wheel

The honeycomb wheel (see Figure 4) is designed as a nonpneumatic structure that balances stiffness and flexibility, allowing it to deform over rocks while maintaining low sinkage on loose regolith. The directional tread improves shear resistance and forward traction (Figure 5). The open cell interior reduces mass and prevents dust entrapment that would otherwise increase rolling resistance.

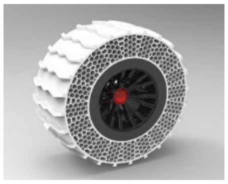

Figure 4. Honeycomb

Figure 5. Wheel Mount

5.2.2 Wheel Mount

The wheel mount connects each wheel and gearbox to the chassis and provides articulation required for uneven terrain (fig. 5). Its geometry maintains a low center of gravity and supports stable obstacle negotiation without disturbing wheel alignment. Cabling channels inside the mount protect wiring from dust and thermal extremes.

5.2.3 Cycloidal Gearbox

The cycloidal gearbox (fig. 6) provides high torque at low speed with minimal backlash and excellent shock tolerance, which is essential for slow maneuvering on steep slopes or soft terrain. Its sealed housing preserves lubricant performance across extreme temperature variations.

5.3 Power Generation and Storage Components

5.3.1 Solar System

The solar panel is optimized for low angle sunlight typical of the south pole. The supporting frame prevents flexural oscillation during rover motion and includes a reflective backing to reduce thermal losses during shadowed periods (Figures 6,7,8).

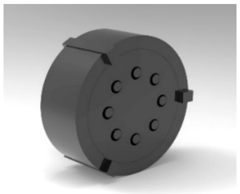

Figure 6. Cycloidal Gearbox

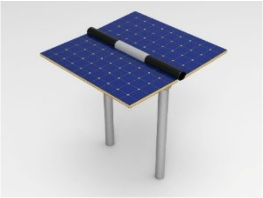

Figure 7. Solar panel

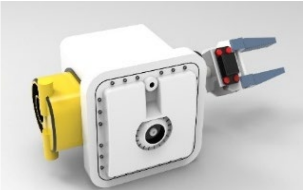

Figure 8. Mast, sherloc and Parallel Gripper Assembly

5.4 Sensing, Mast, and Environmental Monitoring Components

5.4.1 Mast, SHERLOC, and Parallel Gripper Assembly

This assembly (see fig. 8) provides elevated imaging and fine scale manipulation. The mast ensures stable observation while the parallel gripper allows small object handling near the mast tip.

5.4.2 MastCAM, NavCAM, Microphone, and REM Package

This multi sensor package supports terrain mapping, hazard detection, acoustic diagnostics, and environmental monitoring. MastCAM provides high resolution imaging while NavCAM enables stereo depth mapping. The microphone identifies mechanical cues related to regolith conditions, and the radiation and environment monitor tracks local radiation and thermal conditions (Figures 9, 10, 11).

Figure 9. MastCAM, NavCAM, Microphone, and REM Package

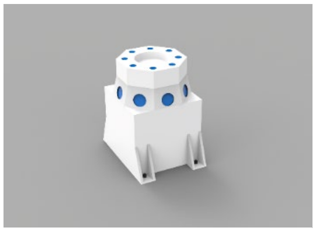

Figure 10. Dust Sensor

Figure 11. High Gain Antenna

5.4.3 Dust Sensor

The dust sensor in fig. 10 measures concentration and surface deposition of fine regolith particles. The instrument helps adjust navigation confidence, identify dust storms, and evaluate solar panel cleanliness.

5.5 Communication and Manipulation Components

5.5.1 High Gain Antenna

The model shown in fig. 11 is high gain antenna. It provides the primary communication link between the rover and Earth or an orbital relay. Its structure tolerates dust impacts and large temperature cycles without pointing errors.

5.5.2 Robotic Arm

The robotic arm (see fig. 14) is a multi joint manipulator used for sample handling and daughter rover interaction. It provides sufficient reach to access the drill area, storage compartment, and near surface materials. Joint insulation and localized heaters maintain performance during cold periods.

5.6 Sampling and Daughter Rover Components

5.6.1 Drill System

The vertical drill (fig. 12) extracts subsurface regolith cores at controlled depth. Current sensing and penetration rate monitoring detect binding or excessive resistance. Flutes on the drill bit manage debris transport away from the hole.

5.6.2 Daughter Rover

The daughter rover in Figures 12 and 13 is a compact tracked vehicle designed to reach hazardous or confined areas that the mother rover cannot enter.

Figure 12. Vertical Drill System

Figure 13. Daughter Rover

5.6.3 MOXIE Inspired Module

The MOXIE inspired module demonstrates the concept of extracting oxygen from lunar regolith. Although not the main mission focus, it shows feasibility for future resource utilization (Figure 14 and Figure15).

Figure 14. Robotic Arm

Figure 15. MOXIE

6. Energy Production and Power Architecture

The rover employs a hybrid power architecture that combines solar power generation with dual battery storage. This approach enables continuous operation in both illuminated and low-illumination conditions near the lunar south pole. The mother rover carries the primary solar array and both battery types, while the daughter rover uses a smaller rechargeable pack that is replenished when docked.

6.1 Solar Power System

The primary energy source during the lunar day is a high-efficiency solar panel mounted on the upper deck of the mother rover (Figure 6: Solar Panel Assembly). The panel area and cell efficiency are selected so that typical south-pole illumination can simultaneously operate nominal loads and recharge both battery systems (see Table 3). The array orientation maximizes incident flux when parked, and the positions of the mast and antenna are arranged to minimize shading.

The electrical power generated by the solar array is expressed as

$$P_{\text{solar}} = \eta A I \cos\theta \qquad (1)$$

where η is efficiency, A is panel area, I is solar irradiance, and θ is the incidence angle. This relation is used for sizing in Section 10 (Table 3).

Table 3. Solar Panel Design Parameters

Parameter	Value (Conceptual)	Rationale
Panel area	0.20–0.25 m^2	Fits rover envelope; yields 120–150 Wh per day
Cell efficiency	26–28 percent	High-efficiency space-grade technology
Operating temperature range	–150°C to +120°C	Matches lunar extremes with margin
Mounting angle	Fixed toward local sun vector	Simplifies mechanical design and control

6.2 $LiSOCl_2$ Primary Battery

The $LiSOCl_2$ primary battery (Figures 16, 17) serves as the rover's long-duration reserve and supports survival loads, thermal control, and essential computing when solar energy is absent. The chemistry provides high energy density and extremely low self-discharge, which is important for extended shadowed phases.

Figure 16. $LiSOCl_2$ Primary battery

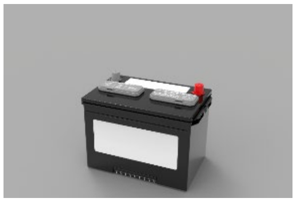

Figure 17. Rechargeable battery pack

6.3 Rechargeable Battery Pack

The rechargeable battery (fig. 17) supports routine operations and high-power tasks. It is charged whenever solar power is available and supplies energy for:

- Wheel drives and cycloidal gearboxes
- Robotic arm and drill operation
- Daughter rover deployment and recovery
- Brief periods of high-rate communication

6.4 Power Distribution and Operating Modes

All power sources interface with a central conditioning and distribution unit. Two modes define overall behavior:

- ✓ **Solar-rich mode:** Solar power feeds the system and recharges the rechargeable battery; $LiSOCl_2$ output is minimal.
- ✓ **Low-sun or survival mode:** Most loads run from the rechargeable battery; $LiSOCl_2$ supports essential functions such as thermal regulation and core computing.

This architecture enables scientific operations during illuminated periods while ensuring survival during long shadow intervals.

7. Navigation on the Lunar Surface

Navigation uses a two-layer strategy combining global path planning with local hazard avoidance. At the global level, the rover uses preloaded topographic data, illumination maps, and known hazard locations around Shiv Shakti Point to define safe waypoints between sampling sites. These paths avoid steep slopes and maintain communication visibility where possible.

At the local level, the NavCAM stereo pair produces a three-dimensional map of nearby terrain. IMU and wheel odometry refine pose estimates and support slip detection. Honeycomb wheels and cycloidal gearboxes provide smooth low-speed control for adjusting heading and speed as terrain conditions change. Slip estimation, based on mismatches between commanded and sensed motion, guides selection of alternative micro-paths in soft or steep regolith. The daughter rover follows similar logic but within short ranges and under mother-rover supervision, relying on its onboard camera and proximity sensors for return-to-dock guidance.

8. Operations at Shiv Shakti Point (Extreme Environment)

Operations at Shiv Shakti Point must accommodate variable illumination, cold traps, and cratered terrain. The operational strategy emphasizes thermal survival, dust-tolerant mobility, and energy-aware scheduling. During favorable illumination, the mother rover advances toward target craters using global and local navigation to balance scientific access with safety. The honeycomb wheels, wheel mounts, and cycloidal gearboxes maintain traction across uneven surfaces, while the high-gain antenna is periodically reoriented to sustain communication.

Thermal survival is maintained by minimizing exposure to prolonged shadowed periods. When entering darker terrain, the time spent is limited by available rechargeable-battery capacity and thermal control capability. Insulation around the warm electronics bay reduces heater power requirements.

Dust monitoring uses the dust sensor and imaging data. If concentrations rise, wheel speeds are reduced to limit lofting, and the rover may pause to allow particles to settle. The daughter rover is deployed only when the mother rover has a safe vantage point near, but not inside, steep or heavily shadowed regions. Through these measures, the rover can repeatedly explore areas around Shiv Shakti Point without compromising system health.

9. Sample Collection Workflow

The sample collection strategy uses both the drill system on the mother rover and the parallel-gripper-equipped daughter rover, allowing access to both subsurface and surface materials in varied terrain. The nominal workflow proceeds as follows. After the mother rover navigates to a candidate site and establishes a stable pose, the drill assembly is deployed. The drill penetrates the regolith to the desired depth, forming a core or collecting cuttings depending on bit design. The material is brought to the surface and deposited in a small accessible zone that is visible to both the mast cameras and the daughter rover.

If the terrain around the drill site is benign, the robotic arm on the mother rover can directly transfer the sample into the internal storage chamber. For more complex terrain such as steep crater rims or locations with rock obstacles, the daughter rover is deployed. It leaves its docking bay, navigates a short distance to the sample location and uses its parallel gripper to grasp the core or regolith packet. After securing the sample, the daughter rover returns along a pre-validated path to the mother rover and aligns with the docking interface. The sample is then handed off either into a transfer tray accessible by the mother rover's arm or directly into a chute leading to the storage compartment. Inside the mother rover, samples are placed in a thermally controlled storage module where they are mechanically secured and isolated from external dust and temperature swings. This process can be repeated at multiple sites, allowing a curated collection of samples representing both illuminated and shadow-affected regions around Shiv Shakti Point.

The sample-collection sequence is illustrated in Figures (18-21). These images show the coordinated interaction between the mother rover, its drilling assembly, and the daughter rover during surface–subsurface sampling operations. The procedure highlights how the daughter rover accesses confined or hazardous locations beneath the mother rover frame and retrieves drill-generated material for transfer to the storage module.

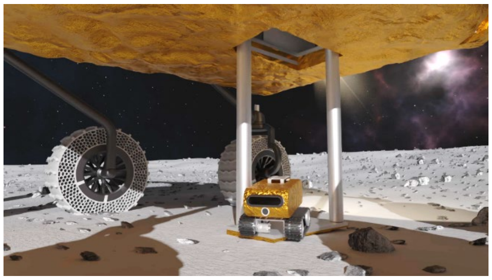

Figure 11. Daughter rover positioned beneath the mother rover for sample retrieval.

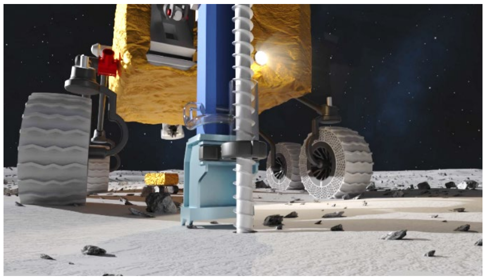

Figure 19. Drilling assembly operating while the daughter rover stages for material collection.

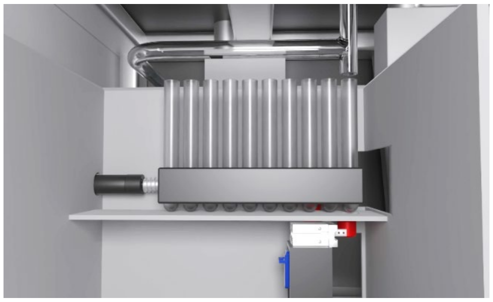

Figure 20. Internal sample-transfer mechanism inside the mother rover.

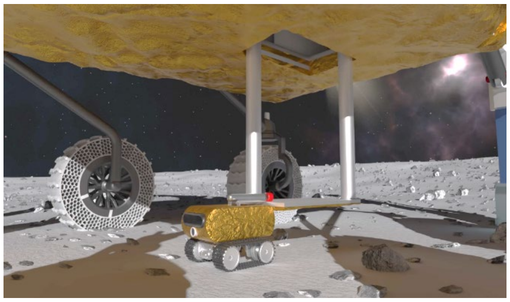

Figure 21. Daughter rover transporting a collected sample toward the docking interface.

10. Engineering Calculations and Energy Consumption Analysis

A set of analytical evaluations verifies the feasibility of the rover's energy system over a representative day.

10.1 Power Budget Formulation

The total instantaneous power demand is

$$P_{\text{total}} = \sum_{i=1}^{n} P_i, \quad (2)$$

where P_i includes mobility, computing, communication, sensing, thermal control, and sampling actuators.Two regimes are defined:

Cruise regime: dominated by wheel drives, navigation sensors, and computing.

Sampling regime: dominated by the drill, robotic arm, and daughter rover (Table 4).

Table 4. Representative Subsystem Power Levels

Subsystem	Typical Power (W)
Drive motors and gearboxes	30–40
Navigation sensors and compute	8–12
Communication (nominal link)	10–20
Drill system (active)	60–80
Robotic arm (active)	20–30
Daughter rover (active)	15–25
Thermal control (heaters, avg)	10–15

10.2 Mobility and Drilling Energy

Mobility energy for a traverse length L is

$$E_{\text{mob}} = P_{\text{mob}} \frac{L}{v}, \tag{3}$$

and drilling energy for depth d is

$$E_{\text{drill}} = P_{\text{drill}} \frac{d}{v_{\text{pen}}}. \tag{4}$$

These relations are used to verify whether sampling sequences fit within the available daily energy.

10.3 Solar Input and Battery Sizing

Daily solar energy harvest is

$$E_{\text{solar,day}} = \int_0^{T_{\text{illum}}} P_{\text{solar}}(t)\, dt. \tag{5}$$

Battery capacity is sized according to

$$C_{\text{req}} = (E_{\text{day}} - E_{\text{solar,day}}) \frac{1}{\text{DoD}} (1 + m_{\text{margin}}), \tag{6}$$

where DoD is the allowed depth of discharge and m_{margin} is a safety factor.

10.4 Example Daily Energy Balance

Table 5. Example Daily Energy Consumption

Activity	Power (W)	Duration (min)	Energy (Wh)
Mobility (driving)	35	30	17.5
Navigation and sensing	10	60	10.0
Drill operation	70	10	11.7
Robotic arm and handling	25	10	4.2
Daughter rover sortie	20	15	5.0
Communication (high-gain)	25	10	4.2
Thermal control (average)	12	180	36.0
Total	—	—	**88.6**

If the solar array produces 120–150 Wh per day under the local illumination pattern, the rover can satisfy its daily energy needs with margin while preserving $LiSOCl_2$ reserve capacity for extended shadow periods (Table 5).

11. Conclusion

The conceptual development of the mother and daughter rover system demonstrates that the primary objectives of this study have been effectively addressed. The proposed architecture illustrates how coordinated mobility, sampling, and material storage can operate together in the difficult conditions of the lunar south pole. It provides a complete

operational framework that includes subsurface drilling performed by the mother rover, surface material collection by the daughter rover, and secure preservation of samples within an insulated storage chamber.
Because this work focuses on conceptual design rather than simulation or hardware validation, the outcomes emphasize feasibility, subsystem functions, and system level integration. The layered structure for perception, navigation, power management, sampling, and communication shows how each component contributes to the overall mission. Although the system has not yet undergone experimental testing or analytical evaluation, the design offers a strong foundation for future engineering advancement.

Several aspects still require further development, including verified mobility on uneven terrain, detailed thermal modelling for extended dark periods, and mechanical testing of sampling hardware. Even with these limitations, the proposed approach highlights the benefits of employing a two rover arrangement to increase sampling reach, improve mission safety, and support scientific exploration in the south pole region. With additional refinement, prototyping, and simulation, this concept can progress toward a fully developed engineering solution for future lunar missions.

12. Future Work

Several improvements and extensions can be made as the conceptual design progresses toward a detailed engineering model:

I) **Detailed Mobility and Navigation Simulation:** Terrain-aware simulations will be required to evaluate wheel performance, slip behavior, and autonomous path planning on realistic south-pole topography.
II) **Refinement of Sampling Mechanisms:** The drill, gripper, and sample-transfer interfaces can be optimized through mechanical modeling and prototyping to ensure reliable operation under dust, vibration, and low-temperature conditions.
III) **Power and Thermal Analysis:** Comprehensive energy modeling and thermal simulations will help validate the hybrid solar–battery architecture and ensure survival during extended low-illumination periods.
IV) **Prototype Development:** Building physical prototypes of the mother and daughter rovers will enable early testing of mobility, docking mechanisms, and sampling workflows using lunar regolith analogs.
V) **Autonomy and System Integration:** Future work should incorporate autonomous decision-making, communication protocols, and fault-handling logic to support long-duration, semi-independent operation on the lunar surface.

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