

Robotics and Autonomous Systems for Sustainable Lunar Infrastructure: A Review

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Abstract: The ambition of spacefaring nations to establish a sustained human presence on the Moon has elevated lunar robotics to a defining engineering challenge of the 21st century. This review examines the robotics and autonomous systems technologies being designed, tested, and planned to enable sustainable lunar infrastructure. A structured literature synthesis was conducted across the domains of rover mobility, robotic manipulation, autonomous navigation, mechatronic subsystems, sensing architectures, in-situ resource utilisation (ISRU) support, additive construction, and human-robot collaboration. Key programmes, including NASA's Artemis initiative and VIPER rover, ISRO's Chandrayaan-3 Pragyan rover, ESA's Moon Village concept, and the international Lunar Gateway project, are woven throughout the analysis as concrete reference points for the current state of technology. The paper maps the principal engineering challenges facing surface robotics, lunar dust, radiation, thermal extremes, energy scarcity, and communication latency, against the mitigation strategies currently under development. Emerging directions including swarm robotics, humanoid systems, self-healing architectures, and AI-driven settlement management are assessed against realistic technology readiness timelines. This review is intended as an educational reference and synthesis resource for undergraduate aerospace students, early-career researchers, and engineers entering the field of space robotics.

Table of Contents

1. Introduction.....	1
2. Literature Review	2
3. Lunar Environment Challenges	3
4. Robotics in Lunar Exploration	5
5. Autonomous Lunar Rovers	8
6. Mechatronic Systems and Components.....	10
7. Sensors and Embedded Technologies.....	11
8. AI and Autonomous Navigation	13
9. Robotics for Sustainable Lunar Infrastructure.....	15
10. Manufacturing Technologies for Lunar Robotics	17
11. Structural Reliability and Operational Challenges.....	18
12. Future Trends and Challenges.....	19
13. Conclusion	21
14. References.....	22
15. Conflict of Interest.....	23
16. Funding	23

1. Introduction

No other destination in the solar system has been visited, studied, or argued over as persistently as the Moon. From the Surveyor and Luna robotic landers of the 1960s to the Apollo crewed missions and the more recent Chandrayaan, Chang'e, and SLIM programmes, each generation of space engineers has added a new layer of knowledge, and a new set of open questions. What has changed decisively in the 21st century is the stated ambition: rather than flags, samples, and scientific firsts, the current international consensus targets a sustained human presence. The Artemis programme of the National Aeronautics and Space Administration (NASA, 2020), ESA's Moon Village concept (European Space Agency [ESA], 2023), and the collaborative Lunar Gateway project (NASA, 2021) all aim not at a visit but at permanence.

Permanence, however, demands infrastructure that does not yet exist and cannot be assembled by human hands alone. Landing pads, roads, habitats, power networks, communication relays, and resource extraction facilities must all be built in an environment that is simultaneously too cold, too hot, too irradiated, and too dusty to permit sustained human construction work. The economic and physiological cost of extravehicular activity on the lunar surface is prohibitive for anything beyond short, targeted interventions. Autonomous robotic systems must therefore carry the primary burden of infrastructure development, operating continuously, tolerating conditions that crew members can endure only briefly, and making independent operational decisions at timescales shorter

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than the 1.2–1.4 second one-way Earth–Moon signal propagation delay permits any ground controller to act ([JPL, 2023](#); [Sheridan, 2016](#)).

The discipline of mechatronics engineering, integrating mechanical design, electrical engineering, embedded computing, and software control into coherent systems, provides the conceptual and practical foundation for these machines. Every rover wheel drive, robotic arm joint, autonomous navigation module, and sensor fusion algorithm is a mechatronic artefact. Understanding how these components interact, where they fail under lunar conditions, and how they are being improved is therefore central not only to the robotics community but to the broader aerospace engineering field.

This review is structured to give a reader who is new to the subject a clear pathway through the technology landscape while providing enough depth to be useful to someone already working in adjacent areas. Section 2 surveys the relevant literature. Section 3 characterises the lunar environment from an engineering constraints perspective. Sections 4 and 5 cover rover and mobility technologies. Sections 6 and 7 address mechatronic components and sensing. Section 8 discusses AI and autonomous navigation in depth. Sections 9 and 10 cover infrastructure robotics and manufacturing. Section 11 analyses operational reliability challenges. Section 12 surveys emerging future technologies. The paper concludes with a synthesis of open research challenges and a forward-looking perspective on the role of human–robot partnership in building the first lunar settlement.



Figure 1: NASA Artemis programme architecture showing the Lunar Gateway in near-rectilinear halo orbit, the human landing system, and surface mobility systems in the cislunar environment.

From *Artemis Plan: NASA's Lunar Exploration Program Overview* (p. 8), by National Aeronautics and Space Administration, 2020 [[Image Courtesy: NASA](#)]

2. Literature Review

The intellectual foundations of lunar robotics draw from a broad literature spanning teleoperation theory, mobile robotics, AI-based navigation, planetary geology, and aerospace systems engineering. [Sheridan's \(1992\)](#) monograph on telerobotics and supervisory control established a framework for thinking about the human–machine relationship in remote environments that continues to shape the design of lunar robotic interfaces today. On the mobility side, [Iagnemma and Dubowsky \(2004\)](#) addressed the specific problem of robot locomotion on granular terrains, an issue of direct relevance to any vehicle that must operate on a surface composed almost entirely of unconsolidated regolith.

The development of probabilistic methods for robotic navigation was consolidated by [Thrun et al. \(2005\)](#) in their landmark text on probabilistic robotics, which provided the mathematical framework for simultaneous localisation and mapping (SLAM) algorithms that now underpin every major autonomous planetary rover. Subsequent work extended this probabilistic foundation into graph-based SLAM solvers, including the g2o framework ([Kümmerle et al., 2011](#)) and the iSAM2 incremental smoother ([Kaess et al., 2012](#)), that enabled



efficient, large-scale mapping in a way that the original filter-based approaches could not. [Matthies et al. \(2007\)](#) demonstrated the operational application of vision-based navigation on the Mars Exploration Rovers, establishing a precedent for the level of autonomy achievable in planetary rover operations.

The ISRU literature has been shaped substantially by the work of [Sanders and Larson \(2015\)](#), whose comprehensive review of ISRU technologies for the Moon and Mars identified water ice extraction, oxygen production from regolith oxides, and regolith-based construction as the three highest-value resource streams for a sustainable human presence. [Schluter and Cowley \(2020\)](#) subsequently reviewed the specific chemical and electrochemical processes available for oxygen extraction from lunar minerals, providing a detailed engineering assessment that complements the system-level perspective of Sanders and Larson.

On the construction side, [Khoshnevis et al. \(2013\)](#) proposed contour crafting as a scalable extrusion-based technique for building large structures from regolith-derived materials, while Ramachandran and [Frey \(2021\)](#) reviewed the broader family of additive manufacturing approaches applicable to lunar construction. The human–robot collaboration dimension of lunar operations has been examined by [Fong and Abercromby \(2020\)](#), who conducted extensive field testing of human–robot team performance in analogue terrain, and by Sheridan (2016), who revisited his earlier supervisory control framework in the specific context of deep-space human–robot teaming. Robotic excavation prototypes for regolith handling relevant to both ISRU and habitat preparation have been systematically reviewed by [Mueller and van Susante \(2012\)](#), whose survey of prototype device designs provides a useful technology baseline for Section 9.4.

Recent reviews by [Gao and Chien \(2017\)](#) and [Ngo et al. \(2022\)](#) have synthesised the application of machine learning and deep learning methods to planetary rover autonomy, identifying perception, terrain classification, and science target identification as the domains where AI methods have yielded the most notable performance improvements. [Wolf et al. \(2018\)](#) provided a focused review of sensor fusion approaches for planetary exploration, with particular attention to the challenges of operating cameras and LiDAR in the high-contrast, dust-laden conditions of planetary surfaces.

3. Lunar Environment Challenges

Engineering for the Moon requires confronting a cluster of simultaneous environmental constraints that have no terrestrial analogue. On Earth, even the most demanding industrial environments involve some combination of atmosphere, liquid-based lubrication, electromagnetic shielding by the magnetosphere, and moderate thermal variation. The lunar surface offers none of these. Any robotic system deployed there must be designed from the outset to function across an extraordinary range of conditions, often without the possibility of maintenance intervention for months at a time.

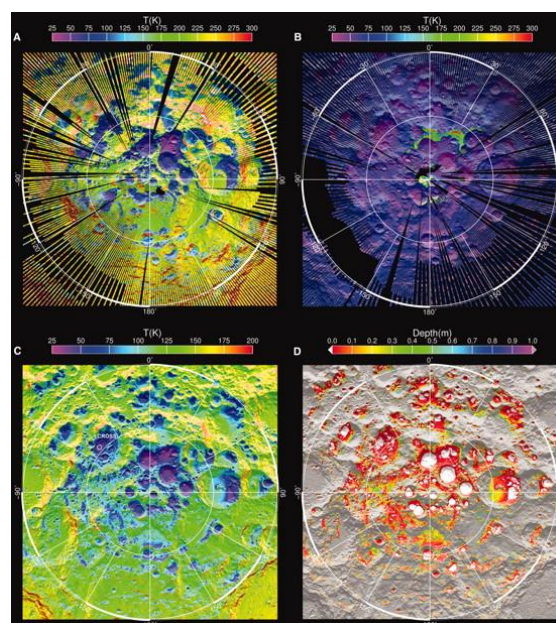


Figure 2: Diviner Lunar Radiometer false-colour thermal map of the Moon's south polar region, illustrating permanently shadowed cold traps (blues) reaching temperatures as low as -250°C and illuminated crater rims (reds/yellows) near $+20^{\circ}\text{C}$. From Diviner Lunar Radiometer Observations of

Cold Traps in the Moon's South Polar Region, by D. A. Paige et al., 2010, Science, 330(6003), p. 480 (<https://doi.org/10.1126/science.1187726>). Open access / public domain NASA instrument data.

3.1 Regolith Mechanics and Dust Adhesion

The lunar surface is blanketed by a layer of fragmented and re-welded mineral material, commonly called regolith, produced over geological timescales by the continuous meteoritic bombardment of an atmosphere-free body. Near the surface, this material is extremely loosely packed, with bearing capacities in the uppermost few centimetres that can challenge the traction systems of even purpose-designed vehicles (Iagnemma & Dubowsky, 2004). At depth, impact compaction and thermal cycling produce a more consolidated substrate, but the fine uppermost fraction is the dominant operational concern for rovers moving across it.

The engineering hazard posed by lunar dust is not primarily mechanical but chemical and electrostatic. Terrestrial mineral grains are smoothed and rounded by aqueous weathering over geological time; lunar regolith particles have never been processed by liquid water and retain sharp, irregular geometries at the microscale. Combined with persistent electrostatic surface charging driven by photoionisation and solar wind bombardment, these particles adhere to optical surfaces, solar panels, thermal radiators, and sealing interfaces with a tenacity that no simple brushing or shaking can overcome (Heiken et al., 1991). Apollo mission records document progressive degradation of visor coatings, suit fabric, and camera optics across multi-day surface operations. For a robotic system expected to operate continuously across one to two lunar years, the cumulative exposure is a correspondingly more serious design driver.

3.2 Thermal Extremes

The Moon's thermal environment challenges hardware designers at both extremes of the temperature scale. On equatorial sunlit terrain, surface temperatures approach +127 °C at local noon; overnight, the same surface cools to approximately –173 °C, a diurnal swing of roughly 300 °C imposed across a 29.5-day cycle (Paige et al., 2010). At the lunar poles, the geometry of low solar elevation produces radically different conditions: selected topographic high points on polar crater rims may receive nearly continuous illumination, while crater floors in permanent shadow reach temperatures as low as –250 °C (Paige et al., 2010).

The engineering consequences of these extremes are pervasive. Conventional hydrocarbon lubricants freeze or outgas; polymeric seals lose compliance; electronic components operating beyond their rated temperature ranges experience accelerated ageing or immediate failure; and thermal fatigue at joints between materials with mismatched coefficients of expansion accumulates with every day-night cycle. The entire thermal management architecture of a lunar rover, multilayer insulation blankets, variable-conductance heat pipes (VCHPs), heater circuits, and thermally optimised radiator placement, is driven by the need to maintain all hardware within operational limits across this extraordinary range (Tabata & Takahashi, 2022).

3.3 Radiation Environment

The Moon's negligible atmosphere and absence of a global magnetic field leave its surface entirely exposed to the deep-space radiation environment. Two qualitatively different sources dominate. Galactic cosmic rays (GCRs) are a relatively steady, isotropic flux of highly energetic protons and heavier ions delivering a continuous radiation dose to surface hardware, accumulating as total ionising dose (TID) over the mission lifetime. Solar energetic particle (SEP) events, associated with solar flares and coronal mass ejections, are episodic and can deliver dose rates orders of magnitude above the GCR background for periods of hours to days.

Both mechanisms degrade electronics through distinct but complementary pathways. Cumulative TID shifts transistor threshold voltages, increases leakage currents, and ultimately causes logic circuits to malfunction. Individual energetic particles can induce single-event upsets (SEUs), transient bit flips that silently corrupt data, or single-event latchup (SEL), a potentially destructive high-current state. Robotic avionics for the lunar surface must therefore rely on radiation-hardened logic, triple-modular redundancy (TMR) where critical, error detection and correction (EDAC) memory, and watchdog systems capable of autonomous recovery (Biesbroek & Hufenbach, 2022).

3.4 Vacuum and Lubrication

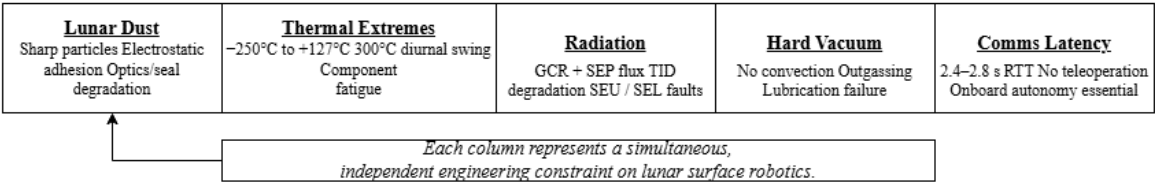
With a surface pressure of approximately 3×10^{-15} atm, the Moon sustains a hard vacuum that precludes all convective thermal exchange and rapidly removes any volatile compound from exposed surfaces. The practical implication for mechanical design is the elimination of almost all conventional lubrication options: oil films evaporate, greases outgas, and even some solid polymers experience significant mass loss under sustained vacuum



exposure. Space-qualified dry lubricants, principally sputtered molybdenum disulfide (MoS₂) and ion-beam-deposited polytetrafluoroethylene (PTFE) coatings, are the standard mitigation, but their finite wear life under cycling loads makes them a reliability driver for any mechanism with high operational duty cycles (Landis, 2021).

3.5 Communication Constraints

The finite speed of light establishes an irreducible communication latency between Earth and the Moon of approximately 1.2 to 1.4 seconds one-way, yielding a round-trip delay of 2.4–2.8 seconds (JPL, 2023; Sheridan, 2016). While modest in comparison to the approximately 20-minute delays of Mars operations, this latency is still sufficient to make direct teleoperation of fast-moving or dynamically unstable systems genuinely hazardous. The consequence for system design is a requirement for genuine onboard autonomy at the operational timescale: the robot must be able to detect and respond to hazards before a human operator could act on the corresponding telemetry.



Block Diagram 1: Summary of the five principal simultaneous engineering constraints imposed by the lunar surface environment on robotic systems. Adapted from the environmental parameter data in Heiken et al. (1991), Lunar Sourcebook: A User's Guide to the Moon, Cambridge University Press; and thermal data from Paige et al. (2010), Science, 330(6003), 479–482, <https://doi.org/10.1126/science.1187726>. Original diagram by the author; environmental parameters are in the public domain.

4. Robotics in Lunar Exploration

4.1 Lunar Rover Technologies

The constraints described in Section 3 define the design space within which lunar rovers must operate, and the history of rover development reflects a progressive expansion of capability within that space. The Soviet Lunokhod vehicles of the early 1970s demonstrated that a remotely operated wheeled platform could survive the lunar day-night cycle and traverse meaningful distances, Lunokhod 2 covered approximately 39 km over its five-month operational period, but they relied on a continuous teleoperation link that reflected the communication architecture of the era. The crewed Apollo Lunar Roving Vehicle (LRV) operated in a fundamentally different mode, with human astronauts providing real-time situational judgment, but its range was constrained by the need to remain within walking distance of the lander as a safety margin.

Contemporary rover designs depart from their predecessors in every subsystem. Closed-loop autonomous navigation, multi-spectral science instrument suites, and structural materials, carbon fibre composites, titanium alloys, aerogel insulation, are combined with radiation-tolerant avionics that were simply unavailable to engineers of the 1970s. NASA's VIPER rover, prior to its cancellation in July 2024 (see Table 1 note), exemplified this generation: a 430 kg vehicle carrying a near-infrared spectrometer, mass spectrometer, and neutron spectrometer, designed to navigate autonomously through the complex topography and extreme illumination gradients of the lunar south pole (Colaprete et al., 2019). ISRO's Pragyan rover, which operated successfully during the Chandrayaan-3 mission in August 2023, demonstrated a complete end-to-end national capability for lunar surface science; alpha particle X-ray spectrometer (APXS) elemental analyses of the south polar regolith confirmed the dominance of ferroan anorthosite, providing the first high-latitude ground truth for remote-sensing models of lunar crustal composition (Vadawale et al., 2024).

The design of any lunar rover requires resolving a set of competing constraints simultaneously: the mass that the launch vehicle can deliver, the power that the solar array can generate, the thermal envelope within which all electronics must remain, the communication bandwidth available for science data return, and the terrain trafficability required to reach the scientifically interesting or operationally necessary locations. Modern systems engineering practice treats these not as sequential trade-offs but as a coupled optimisation problem in which decisions at any subsystem level propagate through the entire system (NASA, 2020).

Table 1: Comparison of Major Lunar Rover Missions by Agency, Mass, Power Source, Autonomy Level, and Mission Designation

Rover	Agency	Year	Mass (kg)	Power Source	Autonomy Level	Mission
Lunokhod 1	Soviet Union	1970	756 ^a	Solar + nuclear	Remote	Luna 17
Apollo LRV	NASA	1971–1972	210 ^b	Battery	Human-driven	Apollo 15/16/17
Lunokhod 2	Soviet Union	1973	836 ^a	Solar + nuclear	Remote	Luna 21
Yutu	CNSA	2013	140	Solar + nuclear	Semi-autonomous	Chang’e 3
Yutu-2	CNSA	2019	140	Solar + nuclear	Semi-autonomous	Chang’e 4
Pragyan	ISRO	2023	26	Solar	Semi-autonomous	Chandrayaan-3
VIPER	NASA	Cancelled (2024) ^c	430	Solar	High autonomy	CLPS mission

Note. ^a Mass values for Lunokhod vehicles are rover-only (lander masses excluded). ^b Apollo LRV mass is vehicle dry mass without crew or payload. ^c VIPER was cancelled following a NASA programme review in July 2024 due to cost growth; the entry is retained for historical completeness (NASA, 2023a). CNSA = China National Space Administration; CLPS = Commercial Lunar Payload Services; ISRO = Indian Space Research Organisation; LRV = Lunar Roving Vehicle; NASA = National Aeronautics and Space Administration.

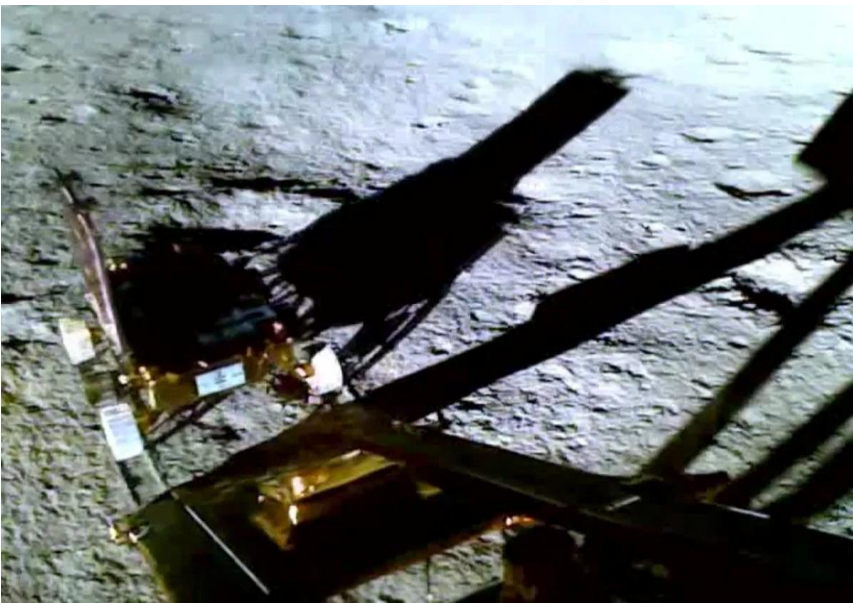


Figure 3: ISRO Pragyan rover deployed on the lunar surface during the Chandrayaan-3 mission, August 2023, illustrating the representative architecture of a small solar-powered semi-autonomous planetary rover, including rocker-bogie suspension, solar panel array, and instrument mast. From Chandrayaan-3 Mission Imagery [Photograph], by Indian Space Research Organisation, 2023 (<https://www.isro.gov.in/Chandrayaan3.html>). Published by a government agency; freely available for non-commercial academic use. Scientific results reported in Vadawale et al. (2024), *Nature*, 633(8029), 327–331, <https://doi.org/10.1038/s41586-024-07870-7>.



4.2 Robotic Arms for Lunar Operations

A rover's ability to reach a location is only part of its operational utility; what it can do when it gets there depends critically on its manipulation capability. Robotic arms enable sample collection, instrument deployment, surface interaction, and increasingly the execution of construction and maintenance tasks. The pedigree of space manipulators is well established: the Canadian Space Agency's Canadarm on the Space Shuttle and Canadarm2 on the International Space Station (ISS) demonstrated that robotic arms can perform precision operations in the space environment over multi-decade operational lives (Canadian Space Agency, 2023). The DEXTRE system on the ISS further demonstrated that fine-manipulation tasks, replacing orbital replacement units (ORUs), handling cables, operating mechanisms, can be performed robotically without direct human presence at the worksite.

Lunar surface manipulators face additional stresses do not present in the orbital context. Direct contact with the regolith during sampling or excavation imposes high reaction loads on the arm structure and its mounting interface. The wide temperature range of the surface environment creates differential thermal expansion challenges within the arm joints. Future designs address these challenges through sealed harmonic drive joints, force-torque sensors at each wrist joint to enable impedance-controlled contact operations, and interchangeable end-effectors that allow a single arm to perform diverse tasks by drawing from a mounted tool rack (Woolfrey et al., 2021). Experimental demonstrations of visual servoing on planetary rover analogue hardware have reported positioning repeatability of better than ± 5 mm under laboratory illumination conditions (Woolfrey et al., 2021).



Figure 4: The Canadian Space Agency DEXTRE Special Purpose Dexterous Manipulator (SPDM) mounted on the International Space Station, demonstrating the concept of robot-executed orbital replacement unit (ORU) servicing that informs the design of autonomous maintenance systems for lunar surface infrastructure. From About the Special Purpose Dexterous Manipulator (DEXTRE)

[Photograph], by Canadian Space Agency, 2023 (<https://www.asc-csa.gc.ca/eng/iss/canadarm2/about-canadarm2-dextre.asp>). © Canadian Space Agency / NASA; freely available for educational use with attribution.

4.3 Autonomous Maintenance Systems

The sustainability of any long-duration lunar installation depends on its ability to maintain itself between crewed visits. Autonomous maintenance robots are therefore a fundamental requirement for the vision of a permanently inhabited lunar base. The problem is conceptually straightforward: a mobile robot must be able to find a fault, characterise it, select and apply the appropriate remedy, and verify the repair, all without human guidance at the task level. In practice, this requires a sophisticated hierarchy of capabilities: inspection platforms equipped with visual, thermal, and acoustic sensors; fault diagnosis algorithms; and task planning modules that compute

sequences of manipulation steps to address identified faults (Fong & Abercromby, 2020). DEXTRE's routine ORU swaps on the ISS demonstrate the feasibility of modular, robot-accessible hardware design, a principle that must be carried directly into the design of lunar surface infrastructure.

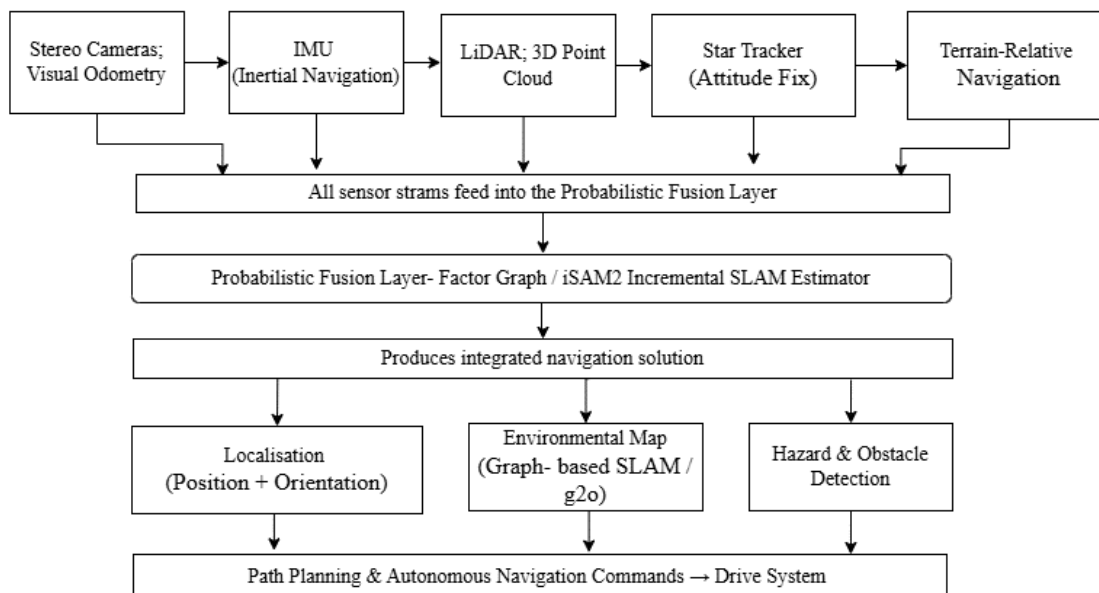
The autonomous maintenance capabilities described above presuppose a mobile platform capable of reaching any point in the installation, a requirement that connects directly to the navigation and mobility architectures examined in Section 5.

5. Autonomous Lunar Rovers

5.1 Navigation Systems

Navigation on the lunar surface strips away every infrastructure element that terrestrial robotic systems take for granted. There is no satellite navigation constellation, no structured environment offering reliable landmarks, and no atmosphere to soften the photometric extremes imposed by direct solar illumination at near-zero elevation angles. A rover must build its situational awareness entirely from the sensors it carries, with no external reference except orbital imagery captured weeks or months before the mission began. The consequence is a navigation architecture built around self-consistent estimation: the vehicle must know where it is well enough to navigate safely and navigate safely enough to acquire the observations that keep it knowing where it is.

The standard architecture fuses multiple complementary sources of position information. Visual odometry estimates incremental position changes by tracking features across successive camera frames. Inertial navigation integrates inertial measurement unit (IMU) measurements to propagate the position and attitude estimate between camera frames. Star tracker measurements provide absolute attitude references. Terrain-relative navigation matches observed terrain features or crater patterns against a reference map derived from orbital imagery to obtain absolute position fixes (Purves & Striepe, 2020). The fusion of these sources in a probabilistic estimator, typically an extended Kalman filter or a factor graph, yields a navigation solution more robust than any single source alone. Published results from the Mars Exploration Rovers have demonstrated that visual odometry fused with IMU data can maintain position errors below 1% of total distance travelled over traverses of several kilometres (Matthies et al., 2007).



Block Diagram 2: Conceptual workflow of a probabilistic SLAM-based autonomous navigation system for a lunar surface rover, integrating visual odometry, LiDAR point clouds, IMU data, star tracker attitude fixes, and terrain-relative navigation into a unified factor-graph estimator. Based on the mathematical framework in Thrun et al. (2005), Probabilistic Robotics, MIT Press; graph-based SLAM components from Kümmerle et al. (2011), IEEE ICRA Proceedings, pp. 3607–3613, <https://doi.org/10.1109/ICRA.2011.5979949>; and iSAM2 from Kaess et al. (2012), The International Journal of Robotics Research, 31(2), 216–235, <https://doi.org/10.1177/0278364911430419>. Original diagram by the author.



5.2 Mobility Mechanisms

The rocker-bogie suspension system, first flown on the Mars Pathfinder Sojourner rover in 1997 and subsequently adopted for every NASA Mars rover through Perseverance, has become something close to the standard architecture for six-wheeled planetary rovers. Its appeal lies in its passive compliance: the rocker-bogie linkage allows each of the six wheels to maintain ground contact independently, allowing the vehicle to climb obstacles up to wheel height without active suspension control (Iagnemma & Dubowsky, 2004).

Legged mobility offers a qualitatively different set of capabilities, the ability to step over large obstacles, climb steep inclines, and negotiate confined spaces, at the cost of substantially greater mechanical complexity and higher energy consumption per unit distance on flat terrain (Lichtenheldt et al., 2020). Track-based systems offer a middle ground, providing improved flotation over soft terrain and superior tractive effort on steep slopes. The selection of a mobility architecture for any specific lunar mission ultimately depends on the terrain characterisation at the landing site, the required traversal range and rate, the available mass and power budget, and the acceptable level of mechanical complexity.



Figure 5: NASA Mars 2020 Perseverance rover illustrating the rocker-bogie suspension system, the reference mobility architecture adapted for contemporary planetary rovers including those planned for the lunar south pole. The passive-compliance linkage allows all six wheels to maintain ground contact independently on irregular terrain. From Mars 2020 Perseverance Rover: Rover Components [Photograph], by National Aeronautics and Space Administration / Jet Propulsion Laboratory – California Institute of Technology, 2021(<https://mars.nasa.gov/mars2020/spacecraft/rover/>). In the public domain.

5.3 Energy Systems

Power availability is perhaps the single most constraining design parameter for a lunar surface robot. Every capability of the system, mobility, computing, sensing, communication, thermal management, and payload operation, draws from a finite power budget. Near the lunar poles, selected topographic high points on polar crater rims can receive illumination for 70–90% of the lunar year, while crater floors in permanent shadow must be serviced by power cables, wireless power transfer, or radioisotope or fission power sources (Landis, 2021). NASA's Fission Surface Power project has validated a compact nuclear power architecture capable of providing 1–10 kW of continuous electrical power from a reactor assembly below 1,500 kg (Landis, 2021).

During the 14-Earth-day lunar night, rovers must survive on stored battery energy in minimum-power survival mode or rely on radioisotope or fission power. Lithium–carbon fluoride (Li-CF_x) primary batteries have demonstrated the highest specific energy densities at low temperatures, approximately 700 Wh/kg at -40°C (Landis, 2021), but their non-rechargeable nature limits their applicability to one-time deployments or emergency reserves.

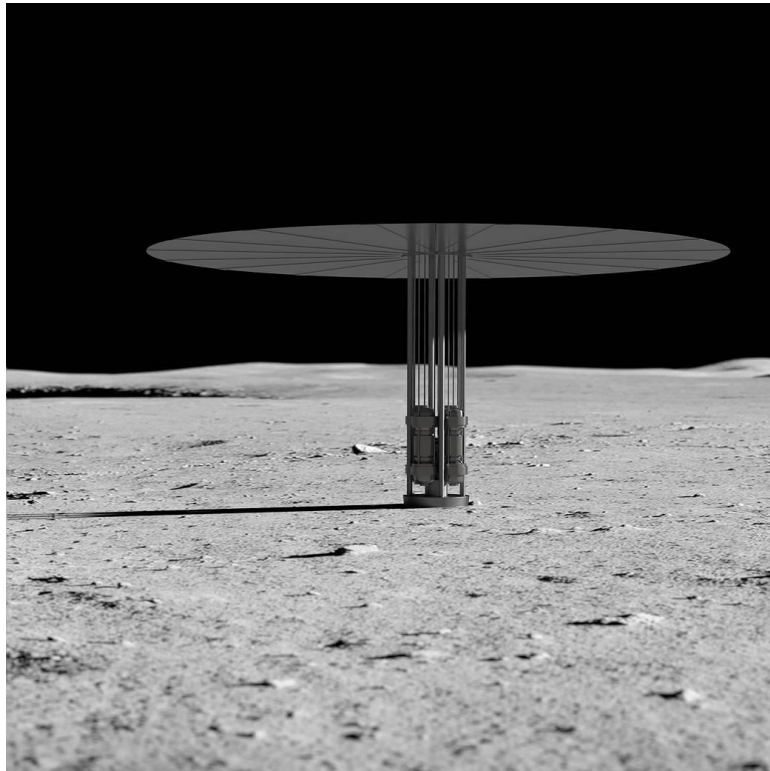


Figure 6: Artist's concept of a NASA Fission Surface Power (FSP) system deployed on the lunar surface, providing 10 kW of continuous electrical power independent of solar illumination. The system is designed to support both robotic systems and crewed habitats during the 14-day lunar night. From Fission Surface Power [Image], by National Aeronautics and Space Administration / Glenn Research Center, 2022 (<https://www.nasa.gov/directorates/stmd/tech-transfer/fission-surface-power/>). In the public domain.

6. Mechatronic Systems and Components

6.1 Sensors

The operational effectiveness of a lunar robot is bounded directly by its sensor suite. A typical science rover carries forward-looking stereo cameras for navigation and hazard detection, a panoramic camera for situational awareness, wheel encoders and IMUs for odometric and inertial navigation, thermal sensors for thermal management monitoring, and science instruments, spectrometers, magnetometers, seismometers, tailored to the mission's objectives (Wolf et al., 2018). Sensor fusion, the statistical combination of measurements from multiple sensor modalities, is as important an engineering discipline as the sensor hardware itself. On a lunar rover, the outputs of the stereo camera, LiDAR, IMU, and wheel encoders are combined in a probabilistic navigation filter to produce the vehicle's best estimate of its position, orientation, and velocity.

6.2 Actuators

Every degree of freedom of a lunar robot is actuated by a device that converts electrical energy into controlled mechanical motion. Brushless DC (BLDC) motors are the dominant choice for planetary rover applications because they offer high power density, long operational life, and precise controllability when paired with high-resolution position encoders. Their motor-plus-drive system efficiency in the 85–95% range also minimises thermal dissipation in the motor and drive electronics, all of which must be managed radiatively in the lunar vacuum (see Table 2). Harmonic drive gearboxes are the standard transmission for robotic arm joints because they provide very high gear ratios, 50:1 to 160:1, in a compact, zero-backlash package. Pyrotechnic actuators, one-shot devices, play a specific but critical role in rover deployment sequences.



Table 2: Comparison of Motor Types Used in Lunar Robotic Systems by Efficiency, Reliability, Dust Tolerance, and Typical Application

Motor Type	Efficiency (motor+drive)	Reliability	Dust Tolerance	Temp. Range	Typical Application
Brushless DC	85–95%	Very high	Good	–180 to +120 °C	Drive wheels, arm joints
Brushed DC	70–85%	Medium	Poor	–120 to +85 °C	Older spacecraft mechanisms
Stepper motor	50–70%	High	Medium	–150 to +100 °C	Precision instrument positioning
Linear actuator	~75%	High	Good	–170 to +120 °C	Solar panel deployment
Piezoelectric	High	Very high	Excellent	–200 to +150 °C	Fine-positioning microdrives

Note. BLDC = brushless direct current. Temperature ranges reflect qualified operational limits reported in peer-reviewed actuator characterisation studies.

6.3 Embedded Systems and Computing

The computing architecture of a lunar rover must satisfy requirements that are genuinely difficult to reconcile: radiation tolerance, real-time performance, low power consumption, and sufficient computational capacity to run AI-based navigation and science autonomy algorithms. Heritage planetary rover designs have relied on radiation-hardened processor devices that provide the SEU immunity and TID tolerance required for multi-year operation (Biesbroek & Hufenbach, 2022). Modern lunar rover computing architectures employ a hierarchical organisation: a mission computer managing high-level navigation and science planning; a vehicle management computer coordinating subsystem activities; and dedicated microcontrollers handling fast control loops. Radiation-tolerant FPGA platforms have opened new options, with TMR implemented in FPGA fabric demonstrating acceptable reliability for critical avionics functions at the TID levels expected on the lunar surface (Biesbroek & Hufenbach, 2022).

6.4 Motor Control Systems

Field-oriented control (FOC), also called vector control, is the standard algorithm for brushless DC motor control in high-performance robotic drive systems. FOC transforms the three-phase stator currents into a rotating reference frame aligned with the rotor magnetic flux, allowing independent control of the flux-producing and torque-producing current components, yielding smooth, precise torque regulation over the full speed range of the motor, including zero speed.

7. Sensors and Embedded Technologies

7.1 LiDAR Systems

Three-dimensional LiDAR has become an indispensable complement to camera-based perception for planetary rover navigation. By measuring the round-trip time of individual laser pulses reflected from the terrain, a LiDAR unit generates a dense point cloud representation of the rover's surroundings with typical depth accuracies in the centimetre range at ranges of up to 100 m, depending on system specification and target reflectivity. Solid-state LiDAR systems, which use electronically steered laser beams and arrays of single-photon avalanche diode (SPAD) detectors rather than mechanically rotating mirrors, are particularly attractive for space applications. Fusing solid-state LiDAR point clouds with stereo camera depth maps in a Kalman filter framework has been reported to substantially reduce obstacle detection false-negative rates on high-contrast terrain analogous to the lunar poles (Wolf et al., 2018).

7.2 Machine Vision

Camera-based machine vision remains the primary perception modality for all current planetary rovers, and the application of deep learning to this problem has matured substantially over the past decade. Semantic segmentation networks trained on Mars surface imagery have demonstrated pixel-classification accuracies above 90% for the major terrain categories represented in their training sets, with transfer-learning approaches enabling adaptation to lunar surface imagery where labelled ground-truth datasets are far more sparse (Kim et al., 2021; Ngo et al., 2022). These accuracy figures should be read with the caveat that they reflect performance on validation sets drawn from the same distribution as the training data; generalisation to terrain types not represented in training, including the permanent-shadow terrain most relevant to polar operations, remains an active research challenge. The extreme photometric conditions of the lunar poles, where solar elevation angles below 3° cast shadows many times longer than the objects producing them, present a domain mismatch that no terrestrial or Mars-derived dataset can bridge without deliberate augmentation using physically accurate synthetic renders (Ngo et al., 2022).

7.3 Thermal Sensors

Thermal sensing on lunar robots serves two distinct purposes. As a science instrument, a thermal infrared camera measures surface emission to characterise regolith thermal inertia and identify thermally anomalous regions that may indicate subsurface volatile concentrations (Paige et al., 2010). As a housekeeping sensor, distributed thermistors enable the vehicle health management system to detect overheating or over-cooling anomalies before they become failures. Uncooled microbolometer focal plane arrays have emerged as the standard technology for rover-mounted thermal imaging, achieving noise-equivalent temperature differences of 50–100 mK at frame rates of 30–60 Hz.

Table 3: Comparison of Sensor Technologies Used in Lunar Robotic Systems

Sensor Type	Parameter Measured	Range	Accuracy	Power (W)	Key Application
Stereo camera	Depth, texture, colour	0.5–50 m	±2 cm	3–8	Navigation, science imaging
LiDAR (solid-state)	3-D point cloud	0.1–100 m	±1 cm (typical)	5–15	Terrain mapping, hazard detection
IMU	Accel., angular rate	±16 g; ±2000°/s	±0.1°	0.5–2	Inertial navigation, pose estimation
Thermal camera	Surface temperature	0.1–50 m	±1 °C	2–5	Thermal anomaly detection
Neutron spectrometer	Hydrogen (water ice)	Surface layer	Qualitative	5–10	Subsurface ice detection
NIR spectrometer	Mineralogy	1–10 m	High	8–15	Regolith composition analysis
Wheel encoder	Shaft rotation	Local	±0.1°	<0.1	Odometric dead-reckoning

Note. IMU = inertial measurement unit; NIR = near-infrared. Power values reflect steady-state operational consumption, not peak startup draws. LiDAR accuracy values are typical for space-qualified implementations and depend on system specification and target reflectance.

7.4 Communication Systems

The primary Earth link, carrying science data downlink, telemetry, and command uplink, typically operates on the Deep Space Network (DSN) in X-band (8–12 GHz) or Ka-band (26–40 GHz), with a typical small rover achieving downlink rates of a few Mbit/s in Ka-band (JPL, 2023). Local inter-system communication uses shorter-range radio links in S-band or UHF. The relay architecture through the Lunar Gateway is particularly important for operations



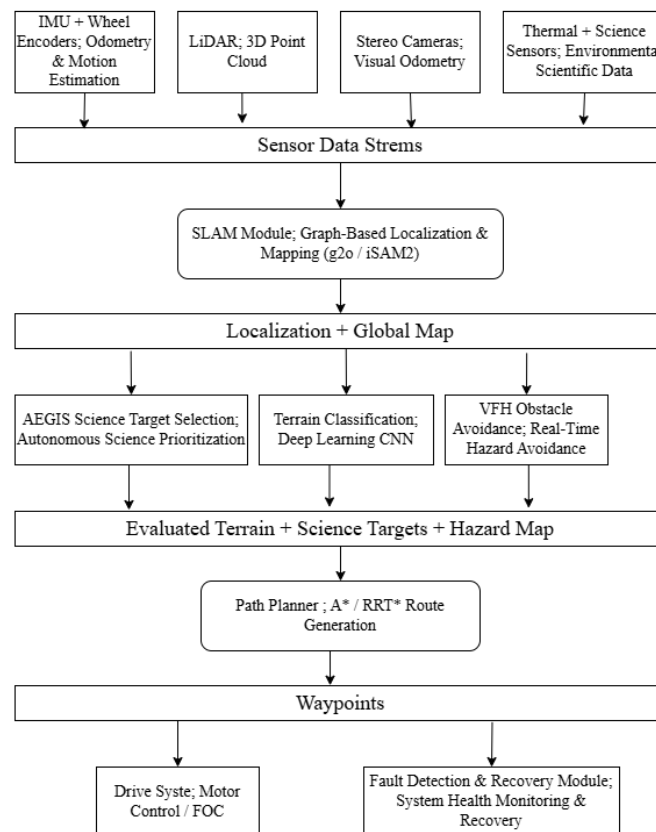
on the lunar farside and in deep crater interiors, and the development of relay communication protocols compatible with the Gateway's planned communication infrastructure is an active element of the Artemis programme's human-robot integration work (NASA, 2021).

8. AI and Autonomous Navigation

The sensor data streams described in Section 7 are the raw material from which autonomous navigation systems must construct actionable situational awareness in real time, under computational and power constraints, without any guarantee of communication with Earth.

8.1 SLAM Algorithms

Simultaneous localisation and mapping (SLAM) is the enabling capability that allows an autonomous robot to navigate in an environment it has never visited before. Early SLAM algorithms based on the extended Kalman filter (EKF) managed this challenge by maintaining a joint covariance matrix over all landmark positions and the robot pose, but the quadratic scaling of computation with the number of landmarks limited their applicability (Thrun et al., 2005). Graph-based SLAM formulations, including the g2o framework of Kümmerle et al. (2011) and the iSAM2 incremental solver of Kaess et al. (2012), represent the current standard for planetary rover SLAM implementations, achieving computation times that scale nearly linearly with graph size. Visual SLAM approaches have been demonstrated to maintain position errors below 0.5% of path length over kilometre-scale traverses on Mars analogue terrain (Matthies et al., 2007).



Block Diagram 3: Architecture of an AI-based autonomous navigation and decision system for a lunar surface rover, showing the integration of perception (stereo cameras, LiDAR, IMU), SLAM localisation, terrain classification, obstacle avoidance, science autonomy (AEGIS), path planning, and fault detection modules. Based on the system architecture described in Gao and Chien (2017), Science Robotics, 2(7), eaan5074, <https://doi.org/10.1126/scirobotics.aan5074>; AEGIS module described in Estlin et al. (2012), ACM Transactions on Intelligent Systems and Technology, 3(3), Article 50, <https://doi.org/10.1145/2168752.2168764>; and SLAM framework from Thrun et al. (2005), Probabilistic Robotics, Probabilistic Robotics, MIT Press. Original diagram by the author.

8.2 Obstacle Avoidance

The Vector Field Histogram (VFH) algorithm, originally developed by [Borenstein and Koren \(1991\)](#), represents the local obstacle density as a polar histogram and computes a steering direction that maximises clearance while remaining consistent with the global path direction. For lunar rovers operating near the poles, slope avoidance is at least as important as rock avoidance. Integrating slope data from the rover's terrain model into the obstacle representation is standard practice in modern implementations. Learned obstacle avoidance policies, trained using reinforcement learning in simulated lunar environments, have demonstrated higher average traversal speeds than classical reactive algorithms on complex rocky terrain, though the sim-to-real gap remains an active research challenge.

8.3 Path Planning

Long-range path planning requires reasoning about terrain properties over a spatial scale that exceeds the rover's local sensor range. The A* search algorithm on a grid-based terrain representation is the workhorse of planetary rover path planning. Sampling-based methods such as RRT and RRT* offer advantages in environments with narrow passable corridors. Machine learning approaches to path planning are under investigation as approaches that can adapt to terrain conditions not represented in the training distribution, though interpretability limitations remain open concerns ([Ngo et al., 2022](#)).

8.4 AI-Based Decision Systems

The AEGIS system, Autonomous Exploration for Gathering Increased Science, deployed on both the Mars Science Laboratory (Curiosity) and Mars 2020 (Perseverance) rovers, illustrates what practical autonomous decision-making looks like at operational maturity. AEGIS analyses navigation camera images in real time, identifies rock targets meeting predefined science criteria, and autonomously commands the rover's laser-induced breakdown spectrometer to analyse those targets before ground controllers have even received the previous sol's telemetry ([Estlin et al., 2012](#)). This capability has demonstrably increased science data return per unit of rover operational time compared to fully ground-commanded targeting. Machine learning classifiers applied to nominal and fault-condition telemetry across reviewed planetary rover studies have shown fault detection accuracy above 85% at severity levels below the threshold detectable by conventional threshold-based monitoring, though these figures reflect results aggregated across varied architectures and should be interpreted as indicative rather than universally guaranteed ([Gao & Chien, 2017](#)).

Table 4: Comparison of Autonomous Navigation Algorithms for Lunar Rovers

Algorithm	Type	Comp. Load	Accuracy	Adaptability	Application
EKF-SLAM	Filter-based	Medium	High	Low	Real-time localisation
Graph SLAM (g2o)	Optimisation	High	Very high	Medium	Batch map optimisation
A* path planning	Search-based	Medium	Optimal (discrete)	Low	Long-range route planning
RRT / RRT*	Sampling-based	Medium	Near-optimal	High	Complex, cluttered terrain
Deep RL navigation	Learning-based	High (train); Moderate (infer)	Adaptive	Very high	Autonomous driving policy
VFH avoidance	Reactive	Low	Moderate	Medium	Real-time hazard avoidance
AEGIS autonomy	Rule-based + ML	High	Mission-specific	High	Onboard science targeting



Note. EKF = extended Kalman filter; SLAM = simultaneous localisation and mapping; RRT = rapidly exploring random tree; RL = reinforcement learning; VFH = vector field histogram; AEGIS = Autonomous Exploration for Gathering Increased Science; ML = machine learning. Computational load ratings reflect qualitative assessments for current radiation-tolerant processor implementations.

9. Robotics for Sustainable Lunar Infrastructure

9.1 Robotic Habitat Construction

Every kilogram of construction material launched from Earth carries a cost that scales directly with delivered mass, historically in the range of \$10,000 to \$100,000 per kilogram to the lunar surface (Crawford, 2015), though emerging commercial launch systems are beginning to compress this figure. Even at the lower end of that range, a structurally meaningful habitat built from imported materials represents an implausibly expensive proposition. Regolith, by contrast, is present in essentially unlimited quantity. The central challenge of lunar construction robotics is therefore not finding a building material but developing robotic systems capable of processing and depositing it reliably, at scale, without continuous human supervision.

The contour crafting method developed by [Khoshnevis et al. \(2013\)](#) uses a large gantry-mounted extrusion head to deposit layers of regolith-based slurry in patterns defined by a digital building model. Sulphur concrete, produced by mixing molten elemental sulphur with regolith aggregate, has emerged as the most promising near-term binder candidate because sulphur is present in lunar mare regolith at concentrations of 0.04–0.12% by mass and the process requires no added water ([Ramachandran & Frey, 2021](#)). Specimens of sulphur concrete produced from lunar regolith simulants have demonstrated compressive strengths of 40–60 MPa after thermal cycling. Microwave sintering of regolith simulants has also been demonstrated at laboratory scale, as reviewed in [Ramachandran and Frey \(2021\)](#).



Figure 7: Artist's concept of the ESA Moon Village, showing autonomous robots constructing dome-shaped habitats from 3D-printed lunar regolith using the D-Shape large-format binder jetting process. The concept illustrates regolith excavation, transport, and layer-by-layer deposition sequences managed by robotic systems without direct human supervision. From Moon Village: ESA's Vision for Sustainable Lunar Development [Image], by European Space Agency, 2023(https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Moon_Village). © ESA/Foster + Partners; freely available for educational use with attribution

9.2 Autonomous Repair Systems

Infrastructure that cannot be maintained will eventually fail. The orbital replacement unit (ORU) philosophy demonstrated by the DEXTRE manipulator on the ISS provides the most important design precedent for

autonomous maintenance on the lunar surface. DEXTRE's ISS operations have demonstrated this capability in orbit; applying it to the lunar surface requires adapting the interface standards and the repair robot's end-effector design to the dust, thermal, and gravity conditions of the surface environment (Canadian Space Agency, 2023). Beyond module replacement, autonomous repair systems will need to perform more open-ended maintenance tasks requiring AI-based task planning systems that can decompose a high-level maintenance goal into a sequence of robot-executable manipulation steps (Gao & Chien, 2017).

9.3 Human-Robot Collaboration

Autonomous robots and human astronauts are complements on the lunar surface. Effective human-robot collaboration (HRC) leverages their complementary strengths. Supervisory control, in which the human specifies task goals and constraints while the robot determines execution details, is generally considered the most productive mode for complex construction and maintenance operations (Sheridan, 2016). Interface design for lunar HRC must account for the physiological constraints of EVA operations: reduced manual dexterity and tactile sensitivity, a restricted visual field, and distorted voice communication. The Artemis programme has invested in HRC interface research specifically for the lunar surface environment (NASA, 2020).

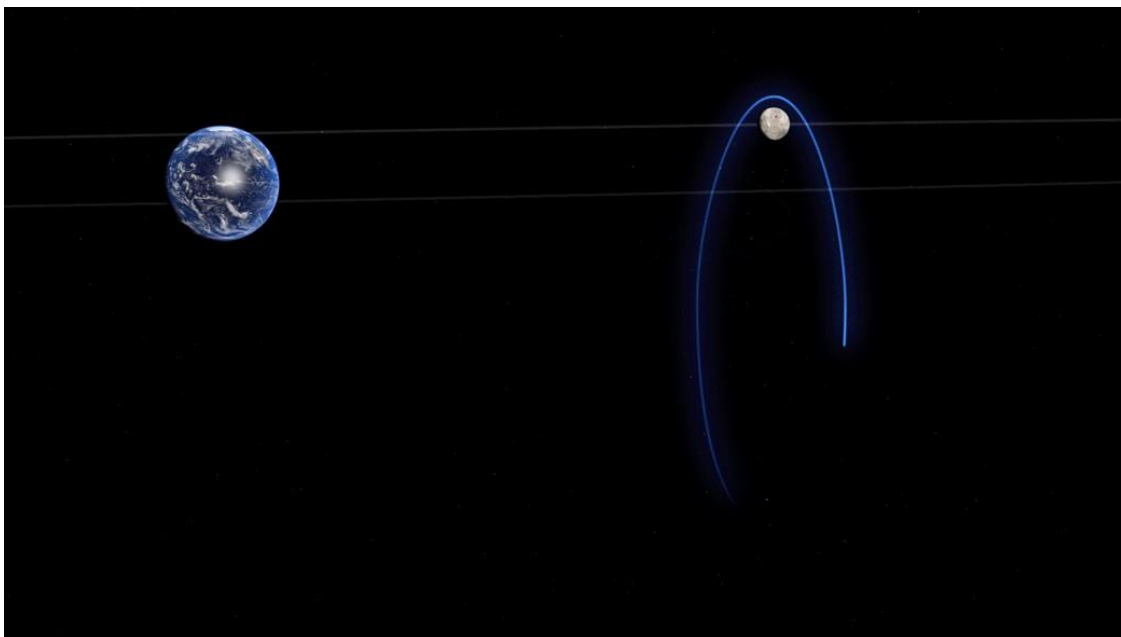


Figure 8: Artist's concept of the NASA–international Lunar Gateway in near-rectilinear halo orbit (NRHO) around the Moon. The Gateway serves as a communication relay node for surface robots, a staging point for human crews, and a platform for orbital science. Astronauts aboard the Gateway can supervise surface robot operations with lower latency than Earth-based controllers. From Lunar Gateway Overview [Image], by National Aeronautics and Space Administration, 2021(<https://www.nasa.gov/gateway>). In the public domain.

9.4 Lunar Resource Utilisation Support

In-situ resource utilisation (ISRU) refers to the practice of extracting and processing materials available at the exploration site. On the Moon, the resource streams of highest near-term value are water ice, present in permanently shadowed craters near the poles, and the oxygen and metallic elements bound in regolith oxide minerals (Carpenter & Fisackerly, 2020; Sanders & Larson, 2015). Schluter and Cowley (2020) identified molten oxide electrolysis and hydrogen reduction as the two approaches with the highest demonstrated oxygen yield per unit of reactor mass.

The prospecting phase of the ISRU development sequence was to be addressed by the VIPER rover (Colaprete et al., 2019), which was cancelled in 2024 (NASA, 2023a); prospecting capability will therefore need to be addressed through alternative mission architectures. The design of lunar excavation hardware for ISRU applications has been surveyed by Mueller and van Susante (2012), whose review of robotic device prototypes identifies engineering trade-offs between auger drills, bucket-wheel excavators, and bulldozer-blade approaches for regolith handling at scale.



10. Manufacturing Technologies for Lunar Robotics

10.1 Additive Manufacturing

Selective laser sintering (SLS) of regolith simulant powders has been demonstrated at laboratory scale to produce specimens with mechanical properties adequate for non-structural applications. A persistent challenge is the wide particle size distribution of lunar regolith, which differs significantly from the carefully engineered powder distributions used in terrestrial SLS processes (Ramachandran & Frey, 2021). Fused deposition modelling (FDM) with thermoplastic feedstock is the most mature additive manufacturing technology at technology readiness level (TRL) 7 (see Table 5). Recycling of damaged or obsolete plastic parts back into printable filament using an onboard extruder is a well-demonstrated capability that could significantly extend the effective feedstock inventory of a lunar FDM system.

10.2 3D Printing for Lunar Habitats

ESA's Moon Village initiative has driven substantial investment in the conceptual design and ground testing of regolith-based large-scale 3D printing (ESA, 2023). The D-Shape large-format binder jetting process uses a magnesium-based binder sprayed onto layers of regolith-like powder to produce a stone-like composite material. Laboratory specimens have demonstrated compressive strengths adequate for self-supporting structural elements. Scaling laboratory demonstrators to the tens of square metres per day deposition rate required to construct a meaningful habitat structure remains the primary challenge (Ramachandran & Frey, 2021). Structural health monitoring must be integrated into the construction process from the outset, using embedded sensors, acoustic emission transducers, strain gauges, or distributed fibre-optic sensing, that can detect voids, cracks, and delamination's non-destructively.

10.3 Robotic Assembly Systems

Many critical components will continue to be manufactured on Earth and delivered to the Moon. Assembly robotics for lunar surface applications must address the challenge of working with large, heavy, or flexible components in 1/6 g. Standardised robotic interfaces, both mechanical docking ports and electrical connectors, are essential for enabling the modular assembly approach described in Section 9.2. NASA's ongoing work on the Exploration Extravehicular Mobility Unit (xEMU) spacesuit design has explicitly incorporated the requirement for suit-compatible robotic interfaces (NASA, 2020).

Table 5: Additive Manufacturing Technologies Evaluated for Lunar Construction and Spare-Parts Production

Technology	Feedstock	Resolution	Build Rate	TRL (2025) ^a	Application
Contour crafting	Regolith–binder slurry	~10 mm	Fast	4	Large structural walls
Selective laser sintering	Regolith powder	~0.1 mm	Slow	5	Precision structural parts
Binder jetting	Regolith powder	~0.3 mm	Medium	4	Modular structural blocks
D-Shape binder jetting	Regolith–salt mix	~5 mm	Medium	3	Full-scale habitat shells
Sulphur concrete extrusion	Sulphur concrete	~5 mm	Fast	5	Roads, landing-pad surfaces
FDM (thermoplastic)	HDPE / PLA filament	~0.2 mm	Medium	7	Spare parts, hand tools
<i>Note.</i> ^a TRL values are approximate estimates appropriate to lunar vacuum qualification. Corresponding terrestrial TRL ratings may be 1–2 levels higher. TRL = technology readiness level; FDM = fused deposition modelling; HDPE = high-density polyethylene; PLA = polylactic acid.					

11. Structural Reliability and Operational Challenges

11.1 Radiation Effects on Electronics

The cumulative TID experienced by electronics on the lunar surface at mid-latitudes is approximately 5–15 krad(Si) per year from GCRs alone, rising to potentially hundreds of krad(Si) during major SEP events ([Biesbroek & Hufenbach, 2022](#)). EDAC based on Hamming codes or Reed–Solomon codes can correct single-bit errors and detect double-bit errors in each memory word. For critical control functions, TMR, in which three independent computing units simultaneously execute the same computation, and a majority voter selects the output, provides protection against any single unit's output being corrupted by an SEU. The power penalty of TMR (approximately 3× the power of a single unit) makes it selective to the most critical functions ([Biesbroek & Hufenbach, 2022](#)).

11.2 Lunar Dust: Operational Impact and Mitigation

Apollo mission experience, documented comprehensively in Heiken et al. (1991), established that dust penetrated every seal, abraded every surface, clogged every mechanism, and degraded every optical element it contacted. Observational data suggest optical attenuation of the order of 0.1–0.3% per day is credible for surfaces near the equator ([Gaier, 2005](#)). Electrostatic dust removal (EDR) systems have demonstrated removal efficiencies of 90–95% per actuation cycle in laboratory vacuum tests ([Calle et al., 2009](#)). The service life of MoS₂ dry film lubricants in simulated lunar dust environments has been characterised to approximately 10⁶ wear cycles under moderate contact pressures ([Landis, 2021](#)).

11.3 Thermal Management in Operations

Variable-conductance heat pipes (VCHPs) are the primary passive thermal management tool for routing waste heat from electronics boxes to external radiators. A VCHP uses a non-condensable gas reservoir to control the active length of the heat pipe, allowing it to maintain a relatively constant electronics temperature across the wide variation in internal heat generation and external thermal environment characteristic of lunar surface operations ([Tabata & Takahashi, 2022](#)). During the lunar night, heater circuits powered by the battery keep critical electronics and battery cells above their minimum operating temperatures, typically –30 to –40 °C for lithium-ion cells.

11.4 Energy Management and the Lunar Night

Lithium–carbon fluoride (Li–CF_x) primary batteries offer the highest specific energy density available, approximately 700 Wh/kg at –40 °C, approximately twice that of lithium-ion rechargeable cells at the same temperature but are non-rechargeable and must be sized to last the entire mission's night periods from the outset ([Landis, 2021](#)). Solid-state lithium batteries, currently at TRL 3–4 for space applications, offer the prospect of higher specific energy with better cold-temperature performance and are a research priority for future lunar surface power systems.

11.5 Communication Architecture and Latency

A rover navigating across a boulder field at 10 cm/s travels approximately 25 cm between the time a hazard is observed in telemetry and the time a stop command could reach the rover. Any robotic task with dynamic hazards that develop on a timescale shorter than 2–3 seconds must therefore be handled by the rover's autonomous systems rather than by ground control. The Lunar Gateway will provide a communication relay capability, though intermittently, the Gateway is in line-of-sight of the south polar region for approximately 6 days per orbit ([NASA, 2021](#)). Astronauts aboard the Gateway can supervise surface robot operations with lower latency than Earth-based controllers.

The reliability strategies examined in this section, radiation hardening, dust mitigation, thermal management, energy storage, and communication relay architecture, define the envelope within which current lunar robotic systems must operate. Extending that envelope, whether through greater autonomy, larger robot fleets, or self-sustaining operational architectures, is the domain of the emerging technologies surveyed in Section 12.



Table 6: Lunar Environmental Challenges, Operational Effects on Robotic Systems, and Mitigation Strategies

Challenge	Severity	Effect on Robots	Mitigation Strategy	Dev. Status	Source
Radiation	High	TID degradation, SEU/SEL	Rad-hard ICs, EDAC, TMR	Operational	Biesbroek & Hufenbach (2022)
Lunar dust	Very high	Power/sensor degradation	Electrostatic cleaning, sealed joints	In development	Heiken et al. (1991)
Thermal extremes	Very high	Component/lubricant failure	MLI, VCHPs, dry lubricants	Operational	Tabata & Takahashi (2022)
Vacuum	High	Outgassing, cold welding	Space-grade dry lubrication	Operational	NASA (2020)
Comms delay	Medium	Manual control latency	Onboard AI, supervisory control	In development	Sheridan (2016)
Low gravity (1/6 g)	Medium	Reduced traction, dynamics	Compliant wheel design	Operational	Iagnemma & Dubowsky (2004)
Micrometeorites	Low–medium	Surface pitting, damage	Redundant structure, shielding	In development	Heiken et al. (1991)
<i>Note.</i> TID = total ionising dose; SEU = single-event upset; SEL = single-event latchup; MLI = multilayer insulation; VCHP = variable-conductance heat pipe; EDAC = error detection and correction; TMR = triple-modular redundancy; AI = artificial intelligence.					

12. Future Trends and Challenges

12.1 Swarm Robotics

Swarm robotics draws on the observation that collective behaviour in natural systems, ant colonies, bird murmurations, arises from simple local interaction rules rather than centralised coordination. Translated to a lunar construction context, this implies that a large fleet of relatively simple robots, each following locally specified rules, could perform excavation, transport, and deposition tasks at rates impossible for any single complex machine. The architecture is also inherently fault-tolerant: the failure of individual units degrades performance gracefully rather than catastrophically. Studies reviewed by [Dorigo et al. \(2021\)](#) indicate, however, that coordination performance degrades materially when inter-robot radio links experience packet loss above roughly 20%, a plausible condition in the complex multipath propagation environment of an active construction site surrounded by berms, machinery, and partially erected structures. Resolving this communications fragility is among the principal open engineering problems for swarm deployment on the lunar surface.

12.2 Humanoid Robots

The case for humanoid robots on the lunar surface rests on a straightforward observation: human habitations are designed for humans. Every tool, every workbench, every valve, and every electrical connector in a lunar base will be designed with human hands in mind. NASA's Robonaut programme demonstrated the concept of a torso-and-arms humanoid for ISS operations, successfully performing a range of bench-top manipulation tasks in the microgravity environment of the station; NASA's Robonaut 2 documentation confirms that dexterous manipulation approaching suited-astronaut capability has been demonstrated in orbital operations ([NASA, 2023b](#)). More recent commercial and research humanoid platforms have demonstrated improvements in whole-body coordination, dynamic balance, and manipulation dexterity, with broader reviews of space robotics identifying loco-manipulation as the principal remaining gap for surface deployment ([Gao & Chien, 2017](#)). Adapting such systems to the radiation, vacuum, and thermal constraints of the lunar surface remains an open engineering challenge.



Figure 9: NASA Robonaut 2 (R2) humanoid robot on board the International Space Station, demonstrating dexterous two-armed manipulation tasks in the microgravity environment. R2 establishes the design precedent for humanoid robots capable of operating in human-designed workspaces, a capability directly applicable to future lunar surface maintenance operations. From About Robonaut 2 [Photograph], by National Aeronautics and Space Administration, Johnson Space Center, 2023 (<https://www.nasa.gov/robonaut2/>). In the public domain.

12.3 Self-Healing Robotic Systems

Self-healing capabilities for robotic systems span a wide spectrum: at the materials level, self-healing polymers that autonomously seal cracks; at the mechanism level, shape memory alloy actuators that return to their designed geometry when heated; at the system level, modular reconfigurable architectures in which failed modules are automatically identified and swapped. AI-based health monitoring is the enabling technology: machine learning classifiers trained on telemetry data from healthy and degraded rover subsystems can detect the early signatures of actuator wear, bearing contamination, and electronic component ageing before the affected component reaches failure. Studies on terrestrial industrial robots have demonstrated that vibration-based fault detection algorithms can predict bearing failure with greater than 80% accuracy at lead times well ahead of failure (Gao & Chien, 2017).

Self-healing capabilities at the materials, mechanism, and system levels reduce the rate at which a lunar installation accumulates unresolved faults, but they do not eliminate the need for a higher-level system capable of coordinating maintenance across dozens of simultaneously operating platforms and subsystems. That coordination function is the domain of AI-driven settlement management.

12.4 AI-Driven Autonomous Settlement Management

A permanently inhabited lunar settlement presents a management problem that has no direct analogue in current industrial practice. Dozens of heterogeneous robotic systems, a dynamic power grid supplied by a mix of solar and fission sources, life support systems with tight safety margins, an ISRU processing chain with variable feed rates, and a continuous maintenance backlog must all be coordinated simultaneously, with human supervisors available only intermittently and at communication latencies that preclude direct intervention in fast-developing situations. The enabling technology for such coordination is a digital twin, a continuously updated computational model of the entire settlement, ingesting sensor telemetry from embedded infrastructure nodes, robots, and life support monitors alike. Recent developments in multimodal AI architectures suggest that natural-language supervisory interfaces, through which crew members could query and direct the settlement management system conversationally, are a technically grounded near-term prospect. The harder open problem is integrating such interfaces with formal safety verification systems capable of preventing the management AI from accepting high-level instructions that would create dangerous states at the subsystem level.



12.5 Smart Autonomous Infrastructure

Smart infrastructure embeds sensors and communication nodes directly into structural elements at the time of construction, enabling the management AI to monitor structural health, detect environmental anomalies, and track resource flows. Radiation-hardened sensor nodes based on silicon carbide (SiC) or gallium nitride (GaN) electronics, which maintain acceptable performance at temperatures up to +400 °C, are candidates for embedding in high-temperature construction processes. Incrementally deploying smart infrastructure capabilities, beginning with the monitoring functions most critical to crew safety, is the risk-managed path to the long-term vision of a fully instrumented and autonomously managed lunar settlement.

Table 7: Emerging Technologies for Future Lunar Robotic Systems

Technology	Key Capability	Current TRL	Est. Deployment	Primary Benefit	Main Challenge
Swarm robotics	Parallelised construction	3–4	2030–2035	Robustness and scalability	Coordination under comms loss
Humanoid robots	Human-compatible tool use	4–5	2032–2040	Versatility in human workspaces	Dexterity, mass, power budget
Self-healing systems	Autonomous structural repair	2–3	2035–2045	Extended mission life	Material and actuator limits
AI settlement mgmt	Integrated autonomous ops	2–3	2040+	Optimised resource use	System integration complexity
Smart infrastructure	Embedded sensing and control	4–5	2028–2035	Adaptive operational resilience	Dust ingress into sensor nodes
Wireless power transfer	In-field robot recharging	4	2030–2035	Operational continuity	Beam alignment, efficiency
<i>Note.</i> TRL = technology readiness level. Deployment estimates reflect first operational demonstration in a lunar surface mission context; full maturation to reliable operational use may require an additional 5–10 years. All estimates are subject to the funding and programme decisions of the relevant space agencies.					

13. Conclusion

This review has traced the development of robotics and autonomous systems for sustainable lunar infrastructure from its theoretical foundations to its current operational frontier and toward its likely future trajectory. The scope has deliberately been broad, encompassing rover mobility, manipulation, autonomous navigation, mechatronic systems, sensing, AI, habitat construction, additive manufacturing, and human–robot collaboration, because the challenge of a permanent lunar presence is a genuinely systems-level problem that cannot be understood by examining any single technology in isolation.

Several findings emerge clearly from this synthesis. First, the lunar environment is more demanding than any single environmental parameter suggests in isolation. Radiation, dust, thermal extremes, vacuum, and communication delay are individually manageable challenges; their simultaneous occurrence across a multi-year operational timeline is a qualitatively harder problem that drives the need for system-level reliability engineering of a sophistication that current terrestrial industrial practice rarely requires. Second, the perception that autonomous AI-based navigation belongs to some future generation of spacecraft is simply not supported by the evidence. The Chandrayaan-3 Pragyan rover, whose APXS results confirmed ferroan anorthosite composition at south polar high latitudes (Vadawale et al., 2024), the Mars Curiosity and Perseverance rovers, and the AEGIS science autonomy system have all demonstrated that meaningful autonomous operation in planetary surface environments is achievable with technology available today. The gap between current capability and what a permanent lunar base requires is real but is a gap of integration and system maturity, not of fundamental scientific possibility.

Third, two challenges stand out as underserved relative to their importance. The integration of individually validated subsystem technologies into complete robotic systems tested under realistic combined environmental conditions remains rare. The development of practical human–robot collaboration protocols specifically adapted to the physiological and cognitive constraints of suited EVA operations on the lunar surface has received comparatively little attention relative to the underlying robotics research. Both of these gaps need to close before the Artemis programme’s vision of a sustained human presence can be safely and productively realised.

Several limitations of this review should be acknowledged. The literature synthesis prioritises English-language sources and may therefore underrepresent contributions from the Chinese and Russian space engineering communities, whose national lunar programmes are active and technically sophisticated. The TRL assessments in Tables 5 and 7 represent a synthesis of available public documentation and should be treated as order-of-magnitude guidance rather than authoritative programme status. Programme timelines cited throughout are subject to the funding decisions and political priorities of the relevant agencies and have historically been revised substantially. This review does not evaluate commercial lunar robotics programmes specifically, an area of rapidly growing activity whose public technical documentation remains limited.

The discipline of mechatronics engineering sits at the intersection of every technology discussed in this review. Training the next generation of engineers with the breadth of skill and depth of understanding to design, verify, and operate these systems is as important an investment in the future of lunar exploration as any specific technology development programme. The Moon’s engineering frontier is not defined by what any single discipline knows but by what all of them, working together, can achieve.

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The author declares no competing conflict of interest.

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