

CONSIDERATIONS IN POWER ELECTRONICS AND ELECTRIC MACHINE DESIGN FOR LUNAR EXPLORATION ROVER DRIVETRAINS

Lukas Radomsky*, Thanh Tuan Nguyen^{‡§}, Robert Keilmann*[†], Regine Mallwitz*[†], Ji-Young Lee^{‡§}

* Institute for Electrical Machines, Traction and Drives, Technische Universität Braunschweig, Germany

[†] Cluster of Excellence SE²A - Sustainable and Energy-Efficient Aviation, Technische Universität Braunschweig, Germany

[‡] University of Science and Technology, Daejeon, South Korea

[§] Korea Electrotechnology Research Institute, Changwon, South Korea

Abstract

An increasing number of governmental and private entities are conducting or planning missions to the lunar surface. These missions are increasingly incorporating mobile platforms, such as lunar rovers of various sizes, which can be deployed from the lunar lander, and expand (surface) exploration capabilities. At the core of these mobile research platforms lies the electric drive system. In addition to energy storage, key components include power conversion and the electrical machine, which are essential for reliable and efficient operation. This growing interest necessitates an overview of the associated challenges and potential solution approaches to aid the growing number of power electronics and electrical machine engineers in developing such systems.

Keywords

Lunar Exploration Rover; Electrical Power System; Drivetrain Design; Power Electronics; Electric Machine

1. INTRODUCTION

The new space age has begun, with the Moon as one of its primary destinations. An increasing number of governmental and private entities are conducting or planning missions to the lunar surface. These missions are increasingly incorporating mobile platforms, such as lunar rovers of various sizes, which can be deployed from a lunar lander, and expand (surface) exploration capabilities. An example is shown in Fig. 1. At the core of these mobile research platforms lies the electric drive system. In addition to energy storage, key components include power conversion and the electrical machine, which are essential for reliable and efficient operation. This growing interest necessitates an overview of the associated challenges and potential solution approaches to aid the growing number of power electronics and electrical machine engineers in developing such systems. In order to do so, Section 2 outlines the unique environmental constraints and design requirements imposed by lunar surface conditions. Section 3 highlights the diversity of lunar rover missions, emphasizing the dependence of system design on mission objectives, landing site selection, and mission sequence. Section 4 details the architecture and components of the electrical power and thermal control system, discussing both power generation/distribution and thermal management strategies. Section 5 focuses on power electronics for lunar rovers, covering the influence of environmental stressors on semiconductor behavior, device selection, integration approaches, and considerations for converter topology selection. Finally, Section 6 addresses the specific demands for electric machine design for lunar surface mobility.

2. CHALLENGING ENVIRONMENTAL CONDITIONS AND DESIGN OBJECTIVES

The environmental conditions under which electric drive train components in lunar applications (in this work, specifically power electronics and electrical machines) must operate are harsh and pose a significant challenge to the setup of a reliable, power-dense, and efficient overall system.

To characterize the challenging lunar environment several different categories have to be considered. First, the properties of the lunar regolith and the vacuum conditions are of significance (Subsection 2.1). Second, thermal environment and location- and terrain-related illumination aspects must be taken into account (Subsection 2.2). Additionally, "space weathering" effects associated with radiation are critical (Subsection 2.3). Moreover, the influence of the Sun-Earth-Moon geometry and micrometeoroid environment must also be considered.

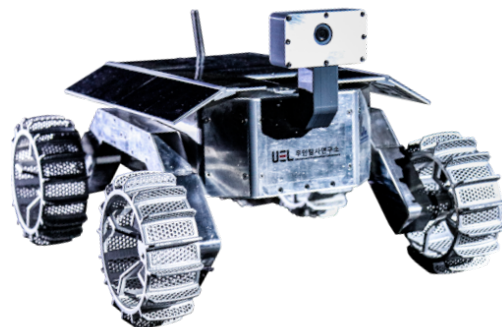


FIG 1. Unmanned Exploration Laboratory (UEL) Haetae 4-wheel medium-sized rover concept. Image taken from [1].

Additionally, further challenges arise from mission execution, which subjects components to mechanical shock and vibration.

2.1. Dust, Mechanical Vibration, and Shock

The lunar surface is coated with lunar regolith, a material characterized by its fine grain size, angular morphology, and high abrasiveness. These properties present substantial challenges for mechanical systems, particularly those with exposed or imperfectly sealed moving components, such as bearings and gear assemblies, which are susceptible to wear-induced degradation. Additionally, the electrostatic charging of regolith particles facilitates adhesion to non-grounded conductive materials [2]. For example, during both the Apollo 16 and 17 missions, thermal management challenges arose due to the accumulation of lunar dust on the radiator of the Lunar Rover Vehicle (LRV), which caused battery overheating [2]. Lunar regolith is furthermore characterized by poor thermal conductivity. This influences the accurate thermal modeling of the lunar surface environment (c.f. Subsection 2.2). An overview of properties and composition of lunar regolith or soil, as well as its interaction with "space weathering" (c.f. Subsection 2.3) is provided, e.g., in [3]. Furthermore, power systems must be designed to endure significant mechanical loads resulting from high acceleration and deceleration forces experienced during launch and landing.

2.2. Temperature and Illumination

The lunar thermal environment and day/night cycle differs substantially from terrestrial conditions. A lunar day spans approximately 27.3 Earth days. As a result, the lunar surface is subject to extreme thermal cycles, with surface temperatures varying significantly at lunar night and day. The lunar surface temperature profiles shown in Fig. 2 can be used as a first indication of the temperature conditions. Lunar surface temperature changes multiple Kelvins per hour, with day and night surface temperatures ranging from 150...400 K during the day to 50...100 K during the night, depending on the latitude. At the lunar poles, even more extreme illumination and temperature conditions exist. Crater floors may remain in permanent shadow, while, depending on elevation, some crater rims may be continuously illuminated. Permanently shadowed regions (PSRs) near the poles are of particular interest due to their potential for harboring frozen water. Regions with quasi-continuous solar illumination are especially desirable, as they facilitate uninterrupted photovoltaic energy harvesting possibilities and reduce the need for night survival strategies.

Given the absence of an atmosphere, the Moon presents a high-vacuum environment, rendering convective heat transfer negligible. Consequently, thermal energy exchange is governed by conduction through the Lunar regolith and radiative transfer. The lunar regolith acts as a thermal insulator, and local shading by rocks, terrain features, or the lander/rover

itself can significantly influence the surface temperature distribution. Since thermal behavior is strongly coupled to solar illumination, precise modeling of site-specific illumination conditions is required. Thermal design methodologies for hardware operating on lunar surface or in lunar orbit are detailed in [5]. For an analysis of the irradiation and temperatures at the lunar poles, it is referred to [6].

A robust thermal management architecture is critical for sustaining rover functionality under such conditions. Mission duration and landing site selection significantly influence the thermal design requirements. Equatorial regions are often selected by emerging space programs due to simplified landing and improved Earth communication, whereas polar sites are of interest because of the availability of frozen water and energy, supporting longer-lasting missions. Short-duration missions that are confined to a fraction of a lunar day may largely mitigate the challenge of cold night temperatures, allowing a design focus on managing irradiation-induced heating. Conversely, extended-duration missions necessitate means for surviving prolonged periods without solar irradiation. To ensure thermal survivability, strategies such as system hibernation, where power is disengaged during the night to allow components to cool down with the environment, may be employed. Upon sunrise, the system is then reactivated. The implementation of such systems must also consider long-term effects, including material degradation due to thermal cycling and the impact of repeated freeze-thaw transitions on component reliability. Alternative techniques focus on "staying warm", and include the use of thermal energy storage, radiators with variable emissivity, chemical-based heating elements, and passive solutions such as insulation.

Based on these thermal constraints and mission-specific parameters, a detailed thermal model of the rover can be developed to evaluate expected internal temperature distributions and assess component-level thermal stress. Such models are indispensable for ensuring operational reliability and the structural integrity of all subsystems throughout the mission.

2.3. Radiation Environment

The lunar radiation environment poses multiple risks to electronic systems and materials, with Solar Particle Events (SPEs) and Galactic Cosmic Rays (GCRs) representing the primary ones. SPEs, associated with solar flares, may occur several times annually and release substantial fluxes of predominantly low-to medium-energy protons (typically 1...100 MeV). These events can persist from several hours to multiple days, during which the high-energy particles can impair materials and induce damage in electronic systems. GCRs, originate from beyond the solar system and comprise fully ionized nuclei of nearly all elements, with protons (hydrogen) constituting the majority ($\approx 89\%$) of the spectrum. Despite their relatively low flux, their extremely high energies pose a significant threat to semiconductor devices, as individual particles are capable of inducing destructive

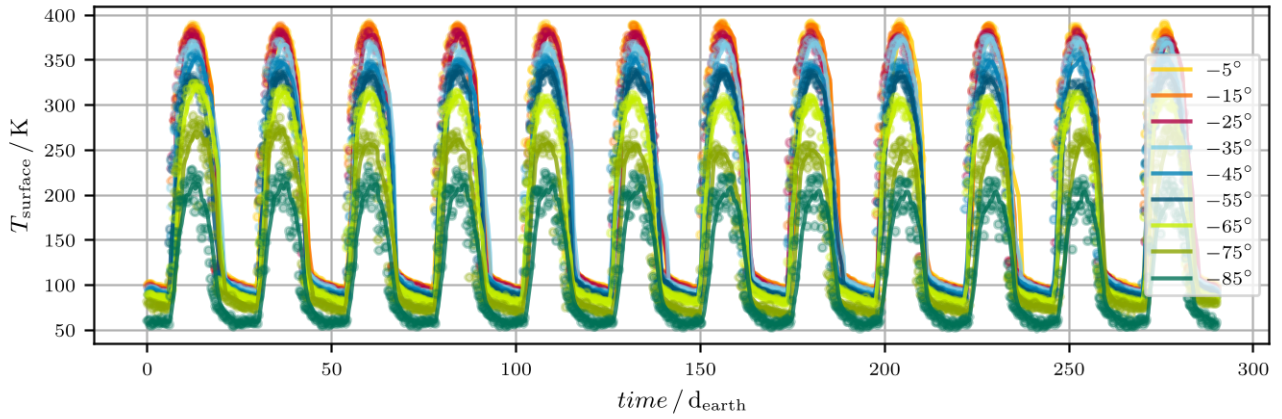


FIG 2. Exemplary lunar surface bolometric temperature for different latitudes from the equator towards the lunar south pole. Time span of 12, approx. one (Earth) month-long lunar day/night cycles. Data taken from Diviner Lunar Radar Experiment [4].

single-event effects (SSEs) or permanent damage in sensitive electronics. In addition to SPEs and GCRs, solar wind, consisting mainly of low-energy protons and electrons, impacts the rover continuously. Although its particle density is high, its comparatively low energy makes it less critical in terms of component degradation. Furthermore, interactions of high-energy particles with the lunar regolith generate secondary particles, including albedo neutrons, photons, and other particles, which must be accounted for in comprehensive radiation modeling. Cosmic rays and solar energetic particles (SEP) can induce a range of undesired effects [7] in electronic components, as will be further examined in Section 5.1. While the long-term accumulated radiation dose is primarily attributed to the continuous exposure to GCRs, transient but intense SEP events can lead to critical short-duration exposure scenarios with the potential to compromise system integrity [7].

2.4. Design Objectives

In light of the previously described challenging environmental conditions on the lunar surface, several key objectives must be addressed in the design of the drivetrain for lunar exploration rovers.

Maximizing both volumetric and gravimetric power density is a key design objective for power systems, particularly in the context of spacecraft with strict weight and size restrictions. Mass and volume must be limited due to constraints imposed by the available payload capacity and internal volume of the lander. These restrictions are primarily cost-driven. [8], e.g., indicates that delivering of 1 kg of payload to the lunar surface incurs a cost in the order of \$1.2 million.

Given the inherently constrained energy availability on the lunar surface, due to limited PV array capacity even during periods of solar illumination, system-level efficiency is another design parameter. This requirement extends across both the electric drive train architecture and the scientific payload subsystems.

Overarching the objectives power density and efficiency, system reliability must be considered throughout all design and optimization efforts, as it represents the most critical aspect in space environ-

ments. This is primarily due to an otherwise early mission end and, in the context of future manned missions, the potentially life-threatening consequences of failure [9, 10].

3. LUNAR ROVERS

As emphasized in Section 1, the advancement of lunar exploration critically depends on capabilities that enable to traverse over the lunar surface, and, thus, enabled access to scientifically valuable locations. This mobility has to be executed with high reliability and operational efficiency. The functional requirements of such mobility systems, which may range from small robotic rovers to large-scale human and cargo transport units, necessitate the integration of various technological subsystems (c.f. Subsection 4). The setup of such platforms exhibits an intrinsic complexity, which arises from the interdependence of the subsystems and their direct interaction with the specific lunar environment and mission profile, which will be discussed in the following Subsections.

3.1. The Importance of Location and Mission

In contrast to orbiting spacecraft, lunar surface mobility platforms exhibit a more variable and less predictable power demand and a more complex energy availability profile [11]. This variability primarily arises from the nature of surface interactions and non-uniform terrain and environmental conditions. Mission planning and mission-level constraints significantly influence rover design [12]. As visualized in Fig. 3, this especially concerns environmental conditions (illumination and temperature) at the designated landing site (equator vs. poles), operational lifetime/mission span (multiple lunar days vs. half a lunar day), and power requirements arising from both the carried payload, as well as the driving profile. These constraints significantly influence the design, e.g., in terms of energy source/ storage concept (solar vs. RTG), appropriate thermal management (heating vs. cooling), and redundancy [13].

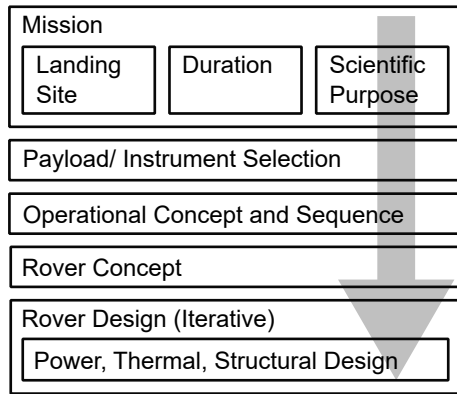


FIG 3. Considerations in lunar rover design and mission planning (c.f. [12]).

3.1.1. Mission Purpose and Payloads

The primary objective of lunar exploration missions is the execution of scientific investigations, which are facilitated by mission-specific payloads. Mobile platforms, such as rovers, serve a critical function by enabling access to the sites of interest where these investigations shall then be conducted [14].

The lunar surface presents a wide array of scientifically relevant features, necessitating the deployment of various instrumentation equipment [15]. Among the potential payloads are systems for chemical element detection, particularly those aimed at detecting volatiles such as water ice [12, 14]. In this context, spectrometers are commonly employed to assess chemical surface composition [16–18], and locations hypothesized to harbor cold-trapped volatiles, such as the poles, are aimed at by rover missions [14]. In addition, radiometric instruments are utilized to characterize the lunar radiation environment, and imaging systems contribute to the examination of surface morphology and geological structures [15–17] along the rover's traversal path. Furthermore, investigations into mineralogical content may involve the use of multispectral sensors [12, 16, 17] or radar systems [17]. An overview of scientific goals may be found in [19–21].

3.1.2. Landing Site(s) Definition

The scientific objectives of a lunar mission and the selection of the landing site are inherently interdependent, with the latter representing a critical parameter influencing system design considerations. A comprehensive assessment of prioritized lunar landing zones and their associated scientific goals can be found, e.g., in [20, 22, 23]. Among the scientifically significant regions are equatorial areas, which provide access to studies related to lunar bombardment history, interior structure, volcanic activity, impact processes, and the exosphere [15]. These targets are spatially dispersed, thereby requiring surface mobility (see Fig. 4). Environmental factors, particularly illumination profiles and resulting thermal conditions, may necessitate the consideration of night-time survival capabilities. Sites near potential lunar skylights, surface openings possibly leading to

subsurface cavities, are of particular interest [24, 25]. In these scenarios, a lunar surface rover is required to approach the skylight from the landing site. It serves multiple roles, including mechanical anchoring, data relay, and energy provision. Additional specialized mobile platforms are required for the in-depth investigation of subsurface cavities associated with these skylights. In contrast, lunar polar regions impose differing, unique constraints on rover design. As previously discussed in Section 2, these regions present extreme environmental conditions. Unlike at latitudes closer to the equator, the conventional lunar day-night cycle does not apply uniformly at the poles. Instead, PSRs and areas of continuous illumination exist, each associated with distinct thermal challenges that directly impact power management and thermal control architectures.

3.1.3. Mission Duration and Mission Sequence

As previously noted, the lunar surface is characterized by a day-night sequence that spans approximately one Earth month. Consequently, the lunar day, defined as the period of continuous solar exposure, lasts around 14 Earth days, during which incident solar radiation can be harvested, subject to local topographical and surface illumination conditions. This period is followed by an equally long lunar night, during which solar input ceases and the temperature drops drastically (c.f. Fig. 2). Many rover systems are constrained to operate exclusively during the lunar day due to limitations in thermal and energy storage capabilities, inherently restricting mission duration [11]. The development of systems capable of enduring the long lunar night would enable a substantial extension of mission duration, and therefore traverse distance, and geographical coverage. This capability would significantly enhance mission efficiency by achieving broader scientific objectives per deployment and reducing the cost per traveled distance [15, 26]. With continued technological progress and experience, extended-duration surface missions are becoming increasingly viable. Challenging for such missions is ensuring the survivability and functionality of all critical (sub-)systems

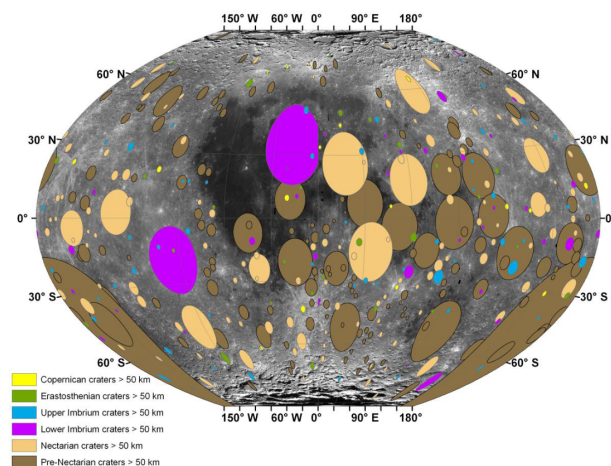


FIG 4. Map of dated lunar craters. Figure taken from [22].

during the two Earth weeks-long absence of solar energy and extreme thermal conditions associated with this lunar night [27]. Depending on the mission duration, it may be possible to neglect the influence of certain long-term degradation mechanisms, such as the aging of PV modules or electrochemical storage systems [24].

From these considerations, certain requirements for the lunar rover system can be derived. Foremost, the rover must maintain full operability under the environmental constraints, which are further defined by the specific conditions of the selected landing site. Regarding energy provision, one key factor is the availability of solar illumination, which varies spatially and temporally across the lunar terrain. Building upon this, the power system must ensure a reliable and continuous supply to all onboard subsystems and payloads throughout the predefined mission duration. This operational requirement leads to initial design assumptions concerning the electrical architecture. These include, but are not limited to, the type and quantity of power electronic converters, their electrical and thermal specifications, as well as the sizing and type of the energy storage [28]. The present work specifically addresses these required power conversion and drive train technologies that enable efficient and reliable mobility on the lunar surface.

4. ELECTRICAL POWER AND THERMAL CONTROL SYSTEM

The rover architecture is composed of several key subsystems, including the Electrical Power System (EPS), Thermal Control System (TCS), mobility and locomotion units, avionics and data handling, as well as perception, control, navigation, and teleoperation functionalities. All subsystems are mechanically integrated within a structural framework providing mechanical support and environmental protection [26, 29].

Power electronics and electric machines represent a core element of the electric drive train and, therefore, of the EPS, as can be seen in Fig. 5. Electrical components are directly influenced by the thermal environment, which is regulated by the TCS. The TCS ensures thermal stability, safeguarding temperature-sensitive electronics against extreme lunar conditions.

4.1. Electrical Power System

The core of mobile lunar rover platforms is the EPS, which encompasses onboard power generation, storage, conversion, and distribution functionalities. The EPS supplies critical onboard loads, such as the traction drives, scientific instruments, and elements of the thermal management system [11]. The design and operation of the EPS is governed by the mission requirements and environmental conditions specific to the lunar surface [11, 29, 30]. The EPS exhibits a strong interdependence with the TCS (c.f. Section 4.2), as thermal management may

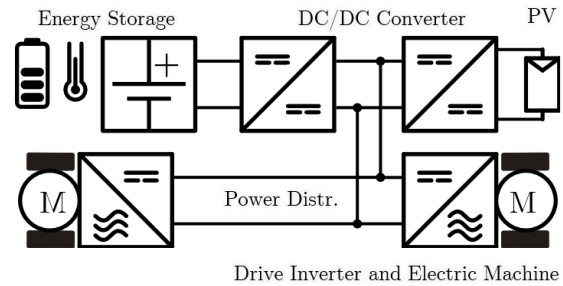


FIG 5. Simplified electric drivetrain schematic of a lunar rover.

be partially realized via the EPS. Both subsystems exert a substantial influence on the overall system architecture [26]. A detailed discussion of the EPS and TCS is presented in the subsequent subsections.

4.1.1. Electrical Sources

To support continuous operation throughout the planned mission duration, the lunar rover requires a reliable energy supply. Depending on the specific mission profile, power provision must be ensured for multiple lunar days or even years. A reliable power supply is critical for mission success. Typically, a distinction is made between primary energy sources (e.g., photovoltaic arrays) and secondary sources (e.g., rechargeable batteries). While rover-integrated solutions combining both are common, alternative concepts exist in which rovers periodically recharge via a stationary lunar lander serving as an energy hub.

PV Arrays

The most widely adopted option for power generation employs photovoltaic (PV) arrays in conjunction with rechargeable batteries [13, 31, 32]. Due to the irregular nature of solar irradiance along the rover's traversal path, continuous energy supply cannot be guaranteed solely through PV modules, and battery storage is required to bridge periods of insufficient illumination. For such applications, power-dense solar arrays are essential [30]. Furthermore, the physical placement and orientation of solar cells are critical and must be adapted to the location and path of the vehicle. In polar regions with shallow solar inclination, solar panels may be positioned on the rover's sides or front and back. Conversely, in equatorial regions, horizontal mounting on the top surface might be considered [14, 26, 29]. The mounting of solar cells on the surface of the rover is especially common for micro rover platforms (c.f. Fig. 1). Deployable panels, optionally equipped with sun-tracking mechanisms, can enhance energy yield and be retracted during traversal phases [28, 33], necessitating, however, thorough reliability assessments. The positioning of PV modules must also be coordinated with the thermal management system, particularly the integration of radiative surfaces. While solar-facing areas are optimized for energy harvesting, shaded sides can be utilized for thermal dissipation. Further information on this thermal-electrical co-integration is provided in

Subsection 4.2 [34].

Batteries

Due to fluctuations in the power output of photovoltaic arrays, caused by rover movement and transient load conditions such as terrain inclines or rocks, energy storage systems must frequently supplement the primary energy source [31]. Batteries are also essential during short-term passages through shaded areas. For extended missions, in most lunar surface regions, energy storage is further required to ensure operability during the prolonged lunar night. Lunar thermal conditions impose significant constraints on battery performance. During daylight, thermal management is required to prevent exceeding the maximum allowable battery temperature. Conversely, during nighttime, the battery must be maintained above its minimum operational temperature. This is typically achieved using resistive heaters powered by the battery itself, or by utilizing internal discharge-related thermal losses [30]. As a result, sufficient energy must be stored in advance to offset heat leakage throughout the night [26]. An alternative research direction focuses on developing battery chemistries capable of tolerating extreme cold with minimal or no active heating [35, 36]. In this context, the reliability of the battery under such conditions and cold-start capabilities at lunar dawn are of importance. Besides batteries with a long cycle life, to minimize overall system mass, batteries with high specific energy are critically needed [24, 30, 35]. An indication of future trends in specific energy density of battery technologies can be found in [37]. Due to their high energy density, lithium-based batteries, e.g., Li-Ion [28, 33, 38, 39] and Li-Po [11, 26, 29] are considered for lunar rover designs. The choice of energy storage technologies is crucial, and a combination of electrochemical energy storage in the form of batteries with other types of energy storage should be considered.

Radioisotope Power System

Systems utilizing the decay of a radioisotope, commonly referred to as radioisotope power systems (RPS), are widely employed for both electrical power supply and thermal management [28]. RPS can generally be categorized into Radioisotope Thermoelectric Generators (RTGs) and Radioisotope Heater Units (RHUs) [40]. Details on the latter are provided in Subsubsection 4.2.1.

RTGs generate electrical power by thermoelectric conversion, utilizing the Seebeck effect to transform the thermal output of radioisotope decay into usable electrical power. Compared to photovoltaic systems, RTGs provide stable, continuous power output independent of available illumination, and can support extended mission durations, determined primarily by the decay characteristics of the selected isotope [13, 41]. The key advantage of RTG-based systems lies in their ability to ensure uninterrupted operation during both lunar daylight and darkness, thereby eliminating or reducing reliance on energy storage for night-time operation [2]. For certain

mission scenarios, such as extended activities within permanently shadowed regions, RTGs may be the only technically viable solution [18]. Nevertheless, such systems face limitations related to mass and conversion efficiency. The inherently low efficiency of thermoelectric energy conversion and the significant system mass render RTGs unsuitable for small-scale mobility platforms such as microrovers [15, 41]. Furthermore, for prospective human missions, the associated radiation exposure and the associated need for shielding introduce additional design constraints [28].

4.1.2. Electrical Distribution System

To this point, energy generation and storage have been discussed. Electrical loads of the lunar rover vary. The electrical distribution architecture is responsible for facilitating power flow between energy sources (e.g., photovoltaic arrays, batteries) and the respective loads efficiently and reliably. The system must be resilient to faults originating from connected units, particularly short circuits, which can impair or disable system functionality. Environmental factors such as radiation exposure can degrade insulation materials, leading to failure. To alleviate this, embedded conductors or backbone-based designs [11, 42] are viable approaches. A typical architectural approach involves the implementation of a central DC bus that interconnects power sources and loads [43]. The voltage level of this bus significantly impacts the overall design and performance of power electronic converters, influencing aspects such as converter topology, semiconductor type, and voltage ratings, and, ultimately, overall efficiency [44]. For small-scale unmanned platforms, DC bus voltages in the 12 V to 48 V range are frequently cited in the literature, with 24 V and 28 V being particularly common [14, 18, 24, 29, 31, 33, 44, 45]. In contrast, for larger systems with higher power demands, including potentially crewed vehicles, voltage levels exceeding 100 V are under consideration [28, 39].

4.2. Thermal Control System

Although payloads constitute the primary scientific justification for lunar exploration missions, they do not necessarily represent the dominant electrical loads within the rover system. In particular, electric traction and thermal management systems impose substantial demands on the electrical power architecture. The TCS, together with the overarching thermal design, must compensate for the extreme environmental temperature variations, determined by the mission scenario, by minimizing the power required to maintain operational temperatures for onboard electronics and dissipating internally generated heat during periods of illumination. The rover's external surface acts as a major interface concerning both the source and loss of heat. The TCS may employ a combination of passive and active thermal control techniques [13, 26, 41]. Alternatively, some concepts propose a hibernation-based approach, where the system is allowed to freeze during extended periods

of darkness and is subsequently reactivated at lunar dawn. This strategy relies on cryogenic-tolerant electronics capable of cold-start operation, enabling sequential recovery of subsystems as thermal energy becomes available. However, such an approach introduces additional design complexity and necessitates a dedicated investigation into component reliability and operational lifetimes under extreme thermal cycling. These aspects fall outside the scope of this work [35, 46]. Approaches on "How to survive a Lunar night" may, for example, be found in [27].

4.2.1. Heating

During the lunar night, thermal protection of the rover and its subsystems is of paramount importance. Heat losses must be compensated for to prevent freezing.

Electric Heaters

Freezing prevention is typically achieved through a combination of waste heat recovery from electrical components and supplemental electrical heating. Electrically powered PTC heaters are commonly employed due to their compact form factor, robustness, and controllability [28, 33].

Radioisotope Heater Unit

Heat cannot only be generated electrically, but also through a Radioisotope Heater Unit (RHU). RHUs provide direct thermal output from isotope decay without electrical conversion, rendering them more compact and structurally simpler than RTGs (c.f. Subsubsection 4.1.1). RHUs have been widely used in lunar rover designs to ensure thermal survivability during extended periods of darkness [33]. The integration of RHUs into actively controlled thermal architectures, such as those employing radiators with multi-layer insulation (MLI) shutters, has been shown to offer promising performance under the extreme lunar environment [41]. However, the continuous thermal output of RHUs presents an integration challenge, particularly in avoiding daytime overheating of temperature-sensitive components.

4.2.2. Insulation, Thermal Distribution, Radiator

Waste heat rejection during the lunar day is addressed through radiative cooling elements, supported by a dedicated thermal distribution system [25, 28, 41, 47]. Similar to photovoltaic surfaces, proper orientation of radiators with respect to solar exposure is critical. Radiator performance may degrade over time due to lunar dust accumulation [2, 38, 39]. Moreover, radiators represent a heat leak during the night, necessitating the use of covers or variable-conductance thermal connections to interrupt the heat path when cooling is not desired [26, 41]. For long-duration missions, active radiative cooling systems are typically required, whereas for single-day missions, passive approaches may be sufficient to minimize mass and complexity [48]. Internally, waste heat transfer from electronic components and external surfaces is facilitated by dedicated thermal conduction paths, such as heat pipes [28]. In certain

cases, active fluid transport mechanisms may be necessary [13]. The rover's hull should generally be thermally insulated using MLI and special surface coatings to minimize both external heat ingress during daylight and heat egress during the night. The optimization of insulation performance constitutes a distinct area of research [15, 26, 34, 41, 48].

5. POWER ELECTRONICS FOR LUNAR ROVER APPLICATIONS

Previously, considerations concerning the EPS were detailed. Different sources and sinks were discussed, and the interconnection of EPS and TCS was expanded on. Power converters for lunar applications must meet strict requirements imposed by the environment discussed in Section 2. Power electronics interface the different subsystems of the EPS and are therefore key to it. This drives research into high-performance power semiconductor technologies. Effects and complications related to the influence of radiation must be considered, and operability across the entire temperature range must be ensured. This holds true not only for the power devices themselves but also for auxiliary components. Furthermore, the choice of power converter topology and aspects such as functional integration are crucial.

5.1. Semiconductor Technology

Power semiconductor devices constitute the fundamental building blocks of modern power electronic converters. Their characteristics directly influence the overall conversion efficiency and are essential for ensuring reliable system operation. In this context, both temperature- and radiation-induced effects have to be considered.

5.1.1. Temperature and Radiation Influences, Effects and Complications

Semiconductor behavior is strongly temperature-dependent, making thermal effects a critical aspect of device design and operation. A major challenge lies in managing mismatches in the coefficients of thermal expansion (CTE) between materials within the semiconductor package. For reliable operation, components must be characterized across a wide temperature range, including cryogenic conditions. In addition, dedicated thermal control strategies are essential to ensure the components' performance. In the lunar environment, radiation and temperature jointly affect the reliability of electronic components, including both logic ICs and power semiconductors. Among these, power semiconductor devices are particularly vulnerable to catastrophic failures caused by high-energy particle interactions, most notably single-event burnouts (SEB) and single-event gate ruptures (SEGR). These effects can lead to irreversible destruction and represent one of the most critical challenges for high-voltage power electronics in space applications. Radiation impacts on power devices are dominated by single-event effects (SEEs), with SEB and SEGR being the most critical

for power MOSFETs and IGBTs (c.f. Fig. 8. These hard errors occur when a high-energy ion penetrates the device and induces a localized high-current path, resulting in thermal runaway or structural destruction. Figure 6 shows a typical destruction trace caused by SEB.

Device vulnerability to heavy-ion interactions is commonly characterized by the linear energy transfer (LET), measured in $\text{MeV} \cdot \text{cm}^2 / \text{mg}$. This parameter quantifies the energy deposited per unit path length and is crucial in assessing SEE susceptibility [50]. Test protocols often use ions like krypton, xenon, and gold, with LET values of 37, 60, and $90 \text{ MeV} \cdot \text{cm}^2 / \text{mg}$, respectively [51]. Unlike other radiation-induced mechanisms, shielding is largely ineffective against SEEs in power semiconductors. As a result, de-rating the components, operating them significantly below their nominal voltage, is the primary mitigation strategy. However, this approach severely limits the usable voltage range. According to [52], reliable operation is currently limited to below 200 V, necessitating series and parallel configurations that increase the system's size and weight. Hence, the development of high-voltage, radiation-hardened power devices is a key enabler for compact and efficient spaceborne power systems. Radiation-hardened (rad-hard) devices implement internal design measures to suppress SEB and SEGR, which are validated through extensive SEE testing campaigns [51–53].

While SEB and SEGR dominate the failure landscape of power semiconductors, other effects like total ionizing dose (TID) and displacement damage (DD) affect both logic and power devices to varying degrees. Displacement damage (DD) is caused by high-energy particles (e.g. protons) displacing atoms in the semiconductor lattice. This alters device characteristics such as leakage current and breakdown voltage. Although shielding can reduce DD, it comes with penalties in terms of mass and volume [50, 52]. Total ionizing dose (TID) refers to the accumulation of trapped charges in insulating layers, leading to shifts in threshold voltage and degradation of device behavior. Power MOSFETs, for example, show a reduction in V_{th} over time, as illustrated in Fig. 7.

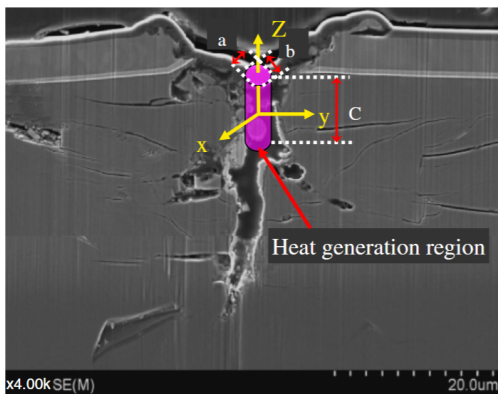


FIG 6. Cross-sectional SEM view of SEB destruction trace. Figure taken from [49].

Mitigation strategies include shielding and device de-rating.

In contrast to the hard errors relevant for power devices, soft errors like single-event upsets (SEUs), multiple-bit upsets (MBUs), and single-event functional interrupts (SEFIs) primarily affect digital and analog integrated circuits. These errors are transient and typically do not cause permanent damage, but can disrupt computation or sensor data acquisition. Their relevance is higher for logic-heavy systems such as processors or imaging sensors [32].

5.1.2. Semiconductor Materials

Different semiconductor materials exhibit different susceptibility to failures/effects. Under discussion is the use of silicon (Si), and wide bandgap (WBG) materials, especially silicon carbide (SiC) and gallium nitride (GaN) devices.

Si power devices, featuring decades of successful space operations, are supported by well-established qualification protocols and therefore remain the benchmark for high-reliability aerospace electronics [10]. Manufacturer Infineon, for instance, offers radiation-hardened n-channel MOSFETs with voltage ratings from 60 V to 650 V [10].

WBG SiC devices may be a compelling alternative. The increased switching speed of SiC MOSFETs allows for a reduction in converter mass and volume. Thanks to the intrinsic material advantage of having a WBG, these devices show excellent resilience to TID and DD. However, both SiC MOSFETs and diodes are very susceptible to heavy-ion-induced SEEs [50, 52, 54–56].

GaN high-electron-mobility transistors (HEMTs) are emerging as suitable candidates for space-qualified power stages. The supplier base, however, remains small. Infineon, for example, markets radiation-tolerant GaN FETs verified against SEEs up to a LET (GaN) of $70 \text{ MeV} \cdot \text{cm}^2 / \text{mg}$ (Au ions) [10, 57]. In this context, also, the materials' flat response of electrical characteristics over a broad temperature span aligns well with the thermal extremes of lunar environments. Like SiC, GaN enables faster switching, which enables reductions in system mass and volume, which is key to size, weight, and power (SWaP)-constrained missions. Understanding the

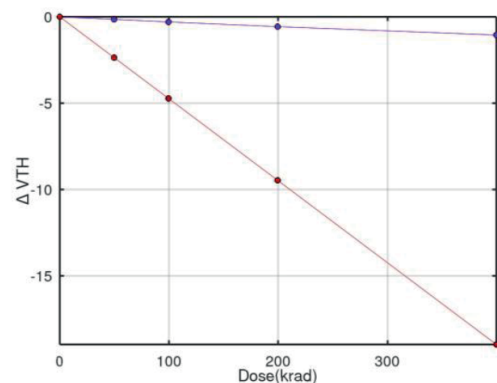


FIG 7. Shift in V_{th} over TID for SiC (blue) and Si (red) MOSFET. Figure taken from [50].

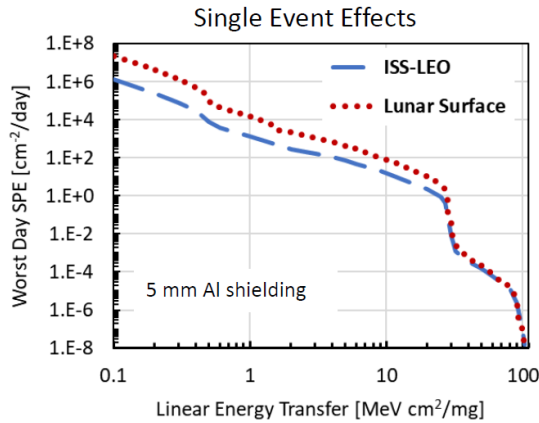


FIG 8. SEE: SPE over LET. Figure taken from [54].

device's failure modes under space conditions and the device structure poses challenges for widespread deployment. Further design and test efforts are required.

To ensure reliable operation under extreme environmental conditions, power semiconductor devices must undergo rigorous quality conformance testing. Established qualification protocols exist in both the European and U.S. sectors. Examples would be, the European Space Components Coordination (ESCC) standard ESCC-5000 and the U.S. military specification MIL-PRF-19500, Test Method 1080 [51, 53].

5.2. Functional Integration, Central Housing and Modularity

Advanced integration and packaging are crucial for power management and distribution subsystems of lunar rovers. Centralizing the electric power system in a single, shielded enclosure simplifies thermal control while also offering joint electromagnetic shielding. The approach outlined by the authors of [11, 34, 42], for example, implements each subsystem as a plug-in card that docks to a common backplane within a single enclosure (c.f. Fig. 9). CubeSat-derived form factors have emerged as a standard [11, 29]. This approach extends beyond the design of the EPS and increasingly shapes the overall rover architecture. In the light of growing commercialization, standardized and reconfigurable system design is gaining importance.

5.3. Space/ Lunar-rated Components

Besides power semiconductors, all other converter components must be screened in terms of radiation tolerance, wide-temperature range operability, and mechanical robustness. Printed circuit boards (PCBs), which interconnect the subcomponents, have to be designed for space. In this context, especially the behavior of solder joints, for example, between the PCB and electronic package, under thermal stress caused by CTE mismatches, is challenging [32, 41]. Similar considerations apply to resistors, capacitors, inductors, and integrated circuits (ICs). Comprehensive investigations are provided in [40]. Although companies such as Infi-

neon supply radiation-hardened products, the limited product range continues to motivate the re-rating and screening of commercial-off-the-shelf (COTS) components to alleviate this issue [11, 25, 40, 45].

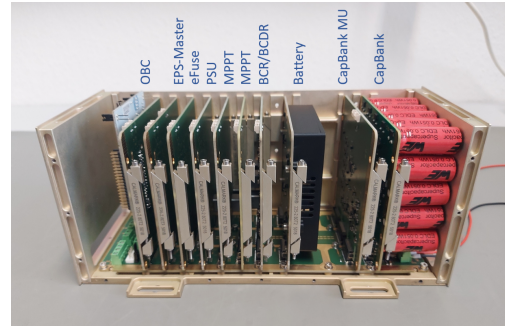


FIG 9. Example for an integrated electric power system within a central housing. Figure taken from [11].

5.4. Power Electronics Solutions and Converter Topologies

Converter performance is dependent not only on the individual components but also on the circuit topology. Within the EPS, DC/DC converters connect batteries and PV generators to the electric bus while also interfacing between different DC voltage levels. Connection of solar arrays is accomplished either by direct-energy-transfer (DET) shunt regulators or by maximum-power-point-tracking (MPPT) converters, the latter employing switched stages controlled by an MPPT algorithm that can shift the power point, for example, under light load conditions. Solar controllers are commonly realized with bidirectional boost converters [58], synchronous step-down converters [11, 34], or SEPIC converters [31]. As battery charge controllers, also buck-boost converters [44] or SEPIC converters [11, 34] may be used. When galvanic isolation or extreme conversion ratios are required, dual-active-bridge (DAB) or resonant LLC converters may be considered [30, 54, 59, 60]. Finally, redundancy constraints also influence converter type and circuit topology selection.

Similar to the DC/DC converter, the DC/AC converter or motor controller must be configured with radiation-tolerant or radiation-tested components. The design of motor controllers has to be closely coordinated with the requirements of the associated electric machine. While DC motors are still commonly used in space applications, three- or more-phase motors are the state of the art for automotive or aircraft applications. [42], for example, details the design of a BLDC power stage using three GaN-FET half-bridges. [61] presents results of radiation testing of a motor driver.

6. ELECTRIC MACHINE DESIGN

Electric machines, including motors and actuators, play a critical role in space exploration systems. They are widely applied in space rovers and related mechanisms, supporting diverse functions such as locomotion, powertrain operation, robotic arm ac-

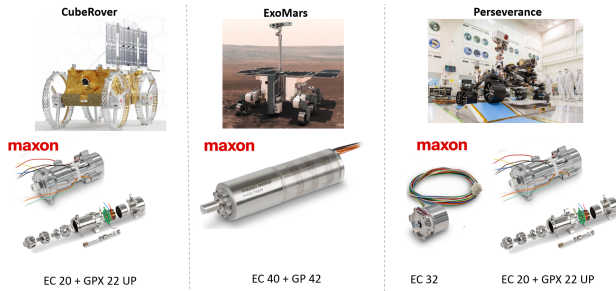


FIG 10. Recent space rovers and electric actuators in each rover (c.f. [64]).

tuation, sampling, and drilling. For instance, early developments on robotic arm and rover actuator systems highlighted the importance of reliable motor technologies under extreme Martian conditions [62]. Similarly, advanced mechanisms like the STIG two-speed transmission demonstrate how actuator–motor combinations enable efficient coring and drilling operations in the Mars 2020 mission [63]. In addition, catalogued missions and commercial motor developments illustrate that both brushed and brushless DC motors are indispensable in numerous rover applications, ranging from CubeRover locomotion to the ExoMars drill, as shown in Fig. 10 [64].

These examples emphasize that electric machines are not only essential for basic mobility but also for enabling complex scientific tasks in extraterrestrial environments. Motor design for space applications, which generates the torque required for rover mobility, is also significantly impacted by environmental conditions such as extreme temperatures, radiation, vacuum, and high vibration. Therefore, the review of referenced motors and actuator designs for space applications with specific approaches will be considered.

6.1. Machine Topology and Performance

In space robotics, motor topology plays a decisive role in achieving both reliability and efficiency under extreme environments. Brushless DC motors have been widely adopted due to their superior efficiency, thermal performance, and reduced maintenance requirements, as highlighted in the development and testing of Mars rover actuators [65, 66]. Conversely, brushed DC motors have also been applied in missions such as the ExoMars drilling and sampling mechanisms, where robustness and simplicity remain critical factors [62, 67].

To meet the stringent mass and torque requirements of lunar and Martian rovers, motors are often integrated with high-ratio gearboxes. The use of compact drives such as the EC20 flat motor combined with the GPX 22UP gearbox enables a significant increase in torque output while maintaining a lightweight structure, as documented in the CubeRover development [64]. This trade-off between motor topology and transmission design is further illustrated in Fig. 11, which presents the 2D dimensions and weight of the motor–gear assembly, and in Fig. 12, which compares the torque–speed characteristics of the

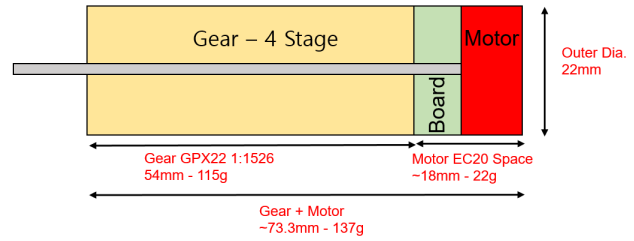


FIG 11. 2D dimensions and weight of gear and motor in the CubeRover mission.

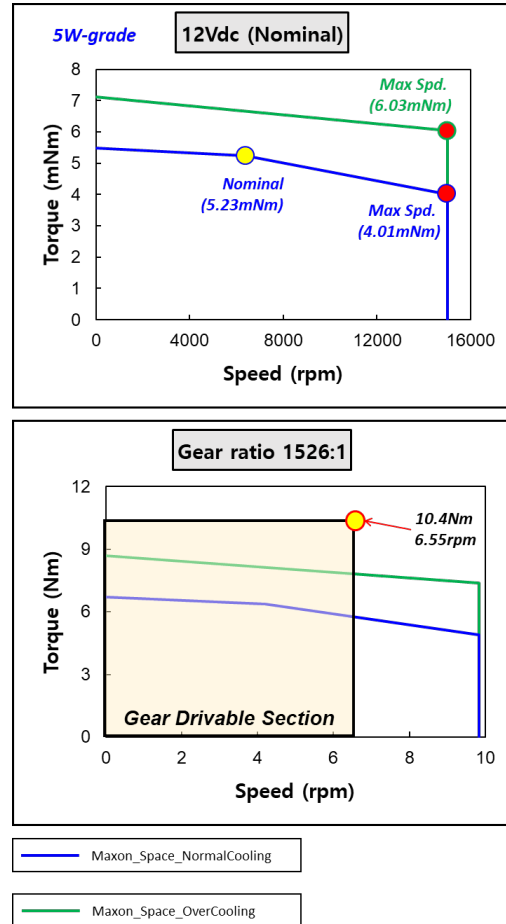


FIG 12. Torque–Speed curve for motor only and motor with gear in the CubeRover mission.

standalone motor against the motor–gear combination. These results clearly demonstrate that the integration of high-ratio gears is essential for enabling lightweight actuators to deliver the high torque required for rover locomotion and payload operations.

6.2. Commercial Off The Shelf Approach

Fig. 13 illustrates the idealized development process for space-grade actuators or motors, progressing from standard catalog components to the final flight-ready model. The process begins with a Breadboard (BB) unit, which is primarily used for testing electrical performance and may involve simple interface customization but no environmental considerations. Next is the Engineering Model (EM), which closely resembles the final configuration but allows for further design modifications based on test results.

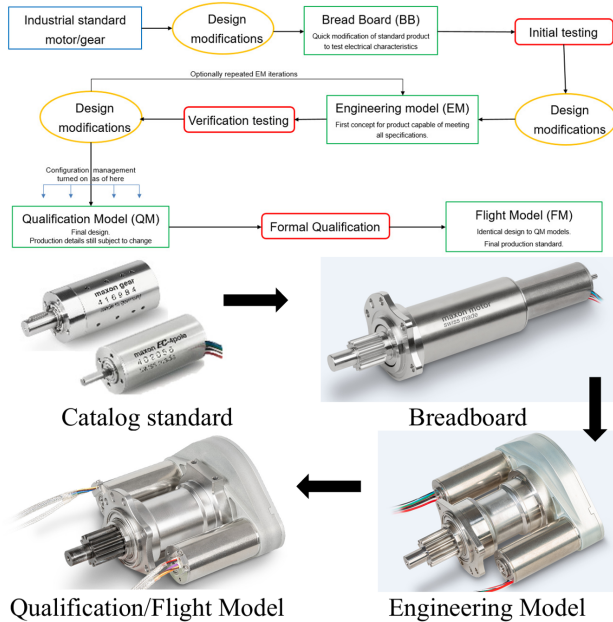


FIG 13. Example development process following the COTS approach. Figure taken from [64].

Following successful verification [68], the Qualification Model (QM) is produced, mirroring the Flight Model (FM) in both design and materials. It includes material certifications and documentation for any deviations from industrial standards. The Flight Model (FM) is the final, fully qualified unit manufactured according to EN9100-certified "space" standards, suitable for mission deployment [64].

The visual also shows the transition from catalog products through BB and EM phases, culminating in the QM/FM, with corresponding tests and design adjustments at each stage. This structured development ensures that the final product meets stringent reliability and performance requirements for space applications.

6.3. Machine Material for Harsh Environment

The rover motor design for lunar applications emphasizes the careful selection of materials to ensure optimal performance in the harsh environment of the Moon. The housing and flange materials are upgraded from aluminum (Al-7075) to titanium alloy (Ti-6Al-4V) to minimize differential thermal expansion and reduce overall system mass, as shown in Fig. 14 [69]. Structural components utilize stainless steel for strength and integrity, while copper is used for windings due to its high electrical conductivity. The design also incorporates permanent magnets, with materials selected based on thermal and radiation stability requirements as illustrated in Fig. 15 [69]. Bearing systems are either greaseless or lubricated with vacuum-compatible grease such as Braycote 601EF [70]. For rotor position sensing, the system can employ either bipolar Hall sensors or resolvers, with the latter being more robust for extreme temperature and radiation conditions.

In space-grade electric machines, copper windings are typically made from high-purity copper with polyimide (e.g., Kapton) insulation to withstand vacuum

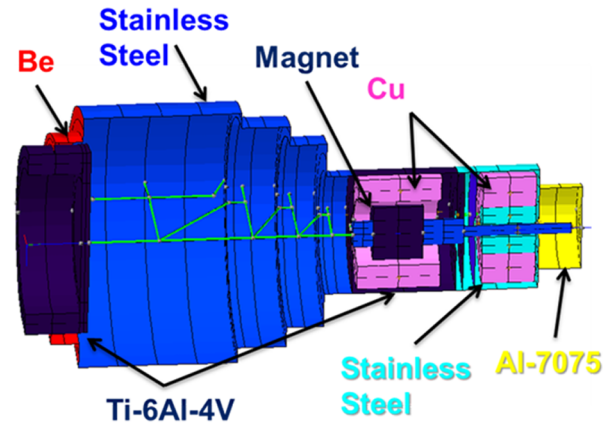


FIG 14. Cross section of the thermal model showing materials used in the Wheel Steering Actuator. Figure taken from [69].

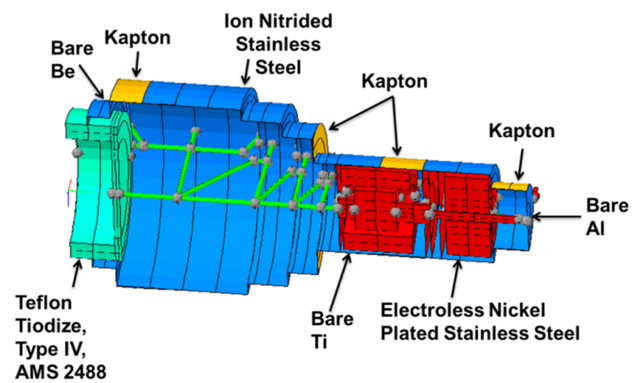


FIG 15. Cross section of the thermal model showing external surface properties of the Wheel Steering Actuator. Figure taken from [69].

and high temperatures. Magnetic cores often use cobalt-iron alloys like Hiperco 50 due to their high saturation flux density and thermal stability, though silicon steel may be used in less demanding applications. For permanent magnets, samarium-cobalt (SmCo) is preferred for lunar and deep space missions because of its excellent thermal and radiation resistance, while neodymium-iron-boron (NdFeB) may be used in lower-risk environments with adequate protective coatings [71]. These material choices ensure reliable operation under extreme thermal cycling, vacuum exposure, and mechanical stress encountered in space missions.

6.4. Experimental Setup

To ensure the performance and reliability of electric machines for space applications, multiple critical experimental verifications must be carried out [69, 72–75]. The first stage typically involves the evaluation of electromagnetic performance, including motor efficiency, torque–speed characteristics, and back-EMF validation. Such tests have been extensively conducted in both subsystem-level and system-level actuator development for rovers [72, 73], with a representative setup illustrated in Fig. 16.

In addition, thermal testing plays an important role in validating the correlation between analytical models

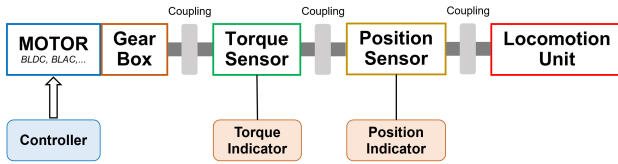


FIG 16. Motor performance test set up.

and hardware behavior under extreme space environments. Previous studies on Mars mobility actuators and MMX rover locomotion subsystems demonstrated the necessity of verifying temperature rise, cooling strategies, and long-term thermal stability under mission-relevant operating cycles [69, 73]. Another indispensable aspect is the radiation test, which ensures that the motor and its drive electronics remain operational under the harsh radiation conditions of lunar and Martian missions. Experiments on both brushed and brushless DC motors have confirmed that radiation tolerance directly impacts long-term reliability [67, 69, 73]. Beyond the motors themselves, radiation resistance is also a decisive factor for selecting sensors, particularly Hall sensors used for rotor position detection. The selection of robust radiation-hardened Hall sensors has been emphasized in previous actuator developments [67, 76], underlining their importance for the overall dependability of space-grade actuators.

7. CONCLUSION

This work has highlighted the crucial role of power conversion and drive train technologies in enabling mobility on the lunar surface. The extreme thermal environment and discontinuous energy availability impose stringent requirements on the design of the electrical architecture, converter topologies, and electric machines. Through the discussion of these constraints and the identification of possible solution approaches, this work provides a foundation for developing robust power electronics and electric machine systems suitable for the unique demands of lunar rovers. Future research should further refine these technologies through mission-specific optimization and experimental validation, thereby advancing the reliability and performance of such systems.

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