Space Exploration Challenges
A Novel Investigation and Study of Unmanned Space Vehicles

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Space exploration has become one of the most significant endeavors today, driven by global innovation and technological efforts that focus on space observation and the study of extraterrestrial life through interplanetary travel. This work aims to systematically review and analyze the challenges countered by current and past generations of rovers, such as Spirit, Curiosity, Perseverance, and Pragyan, with the focus on power systems and autonomous navigation capabilities during unexpected events on extraterrestrial bodies which lead to catastrophic failure. These problems can be addressed in several ways. (1) Current power system often relies on solar panels for power generation. The lifecycle of this system can be significantly extended by developing a model-based design. By installing miniature shakers working along with the use surface mechanics generate specific frequencies of vibrations causing dust and foreign particles to dislodge from the solar panel surface that might get deposited during dust/sandstorms or other impact events. Since solar panels are a renewable energy source, they could have remarkable advantages for power, moreover solar panels are the best overall about power generation for space operations. (2) Autonomous navigation presents additional challenges, as rovers must process real-time environmental data to avoid hazards. Machine learning techniques, such as deep neural networks and attention-based models, can improve obstacle detection and path planning. Hardware accelerators like neural processing units could enhance real-time decision-making, reducing the risk of damage to critical components such as wheels. However, computational constraints and the need for space-ready AI models remain key challenges. This study examines these issues and proposes targeted engineering solutions to improve the efficiency, autonomy, and durability of future interplanetary rovers.

I. Introduction

Exploring extraterrestrial bodies presents numerous challenges that can lead to mission failures. Harsh environments, including extreme temperatures, abrasive dust, and high radiation, degrade

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spacecraft components. Earth-based telescopes play a crucial role in monitoring planetary conditions, providing essential data for space agencies before launching missions.

Leading space agencies such as NASA, ISRO, and ESA allocate approximately 0.36% ($25B), 0.26% ($1.5B), and 3.85% ($7.9B) of their respective budgets. Recent reports estimate the space market to be worth $418B, with forecasts predicting growth to $788.8B by 2034—a rise of over 54% based on CAGR and more than 6% year-over-year, according to the latest space economy market analysis and estimation of the United Nations, 66 % of world GDP is concentrated in Europe and North America, with Asia at 24%. Africa scores badly with 1% of world GDP [1].

Space exploration investments are crucial for long-term objectives such as planetary colonization [2]. However, colonization efforts require a deep understanding of extraterrestrial environments, particularly those of Mars and Venus. But not to leave behind the base which we are planning to do colonization is through moon familiar for midway to interplanetary exploration [3]. Successful exploration depends on efficient data collection from multiple locations in a short timeframe. By comparing mission data with previous findings or leveraging collaborative efforts between space agencies, researchers can improve decision-making while optimizing costs. Reducing mission expenses while maximizing data acquisition remains a key challenge in space exploration.

Dust accumulation is a major factor affecting the efficiency of solar arrays [4], mobility systems, and mechanical joints. Several active dust removal techniques have been implemented, including self-cleaning surfaces, electrostatic curtains, flexible electrodynamic screens, and electrodynamic dust shields [5-6]. While self-cleaning mechanisms provide temporary relief, they have limitations, such as incomplete dust removal and potential long-term degradation of panel surfaces. To enhance dust mitigation, this study proposes integrating multiple techniques. One approach involves installing miniature shakers beneath the solar panels to generate vibrations that dislodge dust particles. Additionally, optimizing surface mechanics, such as adjusting surface roughness and incorporating a curved surface profile, could reduce dust accumulation and improve self-cleaning efficiency [7-8]. By combining these strategies with existing methods, the effectiveness of dust removal can be significantly improved, increasing the operational lifespan of power systems on extraterrestrial missions.

Another critical aspect of planetary exploration is developing energy and computation efficient methods for rover operations. Among these, autonomous navigation is particularly power-intensive. It requires strategies that are needed to optimize energy consumption while maintaining reliable mobility and decision-making capabilities. There are few methods adopted on present and past generation rovers like real time data analysis and decision making but still lapses communication and problem persists can be addressed in specific Machine learning technique which brings the fusion of high-speed on-board processing units, machine learning algorithm to improve the performance of rovers operation in real time. This ML methods combination make the decision in unfavorable conditions and situations in real on time with reduced delays present in current generation rovers by finding potential threats from harsh environment and unexpected events. Wheel mechanism is also important to address causing overall health degradation of rover and can be more effective using above two methodologies combined here. By modifying the surface of wheels with some roughness and curved surface profile to decrease the loss of energy while navigating and identifying the unnecessary paths and terrains well before and make plan for safer place to hide out during severe conditions [14].

II. Methodology

A. Miniature Shakers with Surface Mechanics

Dust accumulation is one of the main reasons for solar panels not utilizing their full power to achieve potentially designed operational timing. Dust cleaning on solar panels of rovers uses active and passive methods depending on the respective generation technology employed in its systems. Numerous concepts have been recommended for implementation in real time till now. The power conversion efficiency may be affected by 20 percent due to dust, grime, pollen, and other particulates that scrape together on the solar panels. For high dust/debris or duned areas like Mars, a dusty solar panel can lose its power use by up to 30 percent. Different mechanisms for monitoring and self-cleaning of solar panels exist, including wipers and sprayers, motorized brushes, piezo-ceramic actuations, and electrostatic and robotic cleaning. Of them all most solar panel monitoring and cleaning systems are completely manual [15] [17]. In many cases they rarely rely on natural things like wind and rain to wash off the solar panels. Self-cleaning mechanisms like Sprayer, Sprinklers and Wipers need human monitoring time to time on the surface of panels which is always not possible to analyze and make decision of its own. While rovers operate in space or other planets frequently have unexpected events that might result in failure of power systems. We want to bring in the concept of vibration technology in line with surface mechanics as an important concept on which power systems can rely on. The Electrodynamic Dust Shield (EDS) [16] system is a promising technology that uses the electrodynamic force to mitigate dust adhesion and accumulation on optical elements such as PV panels, thermal radiators, mirrors, and lenses. The challenges involved in adopting these current methods have a lot of constraints like scaling and environmental effects which cannot be exactly simulated on earth. We focus here on using miniature shakers [30] kind of electrostatic methods that use power source from the system depending upon the size and quantity of dust particles deposited on the solar panels as one of the active methods. A tiny instrument with millimeters in size and vibrates to dislodge the particles accumulated on surface. These kinds of miniature shakers are commonly used in electric circuits. In addition to that we plan to use the surface mechanics as a combination of surface roughness and curved profile of surface as shown in figure 1 and positioning the miniature shakers or piezo shakers. Surface roughness plays significant role in washing out dust particles specially in the case where undesirable events are common in mars with harsh environments. Particles of dust sitting on surface have the combination of many forces and are related directly to smoothness or roughness. These forces are also related to contact angle, increasing the contact angle decreases adhesion thereby allowing the dust to flow off from surface with ease [20]. Similarly, by making the surface profile curved with a certain angle, particles will roll out further smoothly by themselves. The traces of remaining dust on surface need some external sources of energy to throw them off, by installing the miniature shakers (Nano Shakers/Micro Shakers/Piezo Shakers) below the surface of solar panels in effective pattern based on available surface area to consume less energy and generate more vibration to break bond from surface as well as particles to each other to flow them off. These concepts can be the solution individually and more effective when brought in together depending on design and advancement in technology used in rovers.

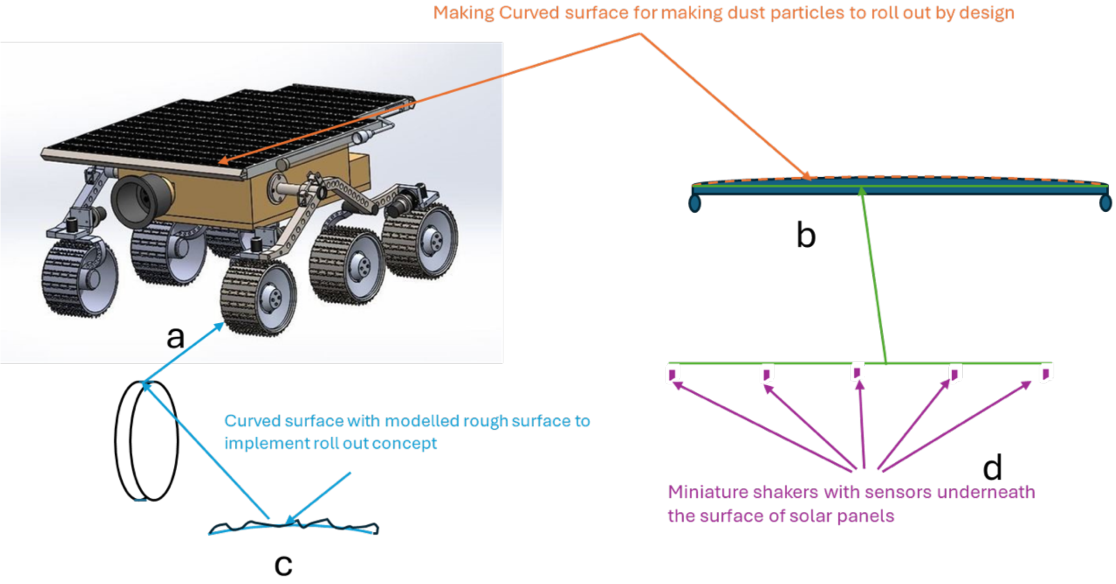

Figure 1: Depiction of the proposed idea of implementing to utilize the rover's capability to its maximum extent, a) & b) as Curving the surface will roll out the dust particles as a natural tendency compared to flat surfaces, c) making the surface rough to level which can avoid surface adhesion by increasing contact angle and d) installing the miniature shakers beneath the surface on designed locations based on surface area calculations for producing maximum vibrations with minimum power respectively.

B. Autonomous Navigation

Exploring extraterrestrial bodies presents many challenges that generally lead to catastrophic mission failures due to communication delays of 5–20 minutes between Mars and Earth prevent real-time intervention, contributing to an even higher failure rate. Failed missions like *Mars Polar Lander* (1999) [9] is one of the well-known examples. Landing risks, as seen with the Philae lander and *Spirit* rover, highlight mobility challenges on rough terrain should not be overlooked as well [10] On Mars, rovers have a speed cap because of the complex and ever-changing martian terrain, reducing the rover's ability to cover a larger area in its designed mission timeline. Current rovers navigation is often reliant on Earth-based decision making because AutoNav systems struggle with complex terrains requiring earth-based intervention. Additionally, hazard identification is limited, and communication delays further constrain efficiency, as it must evaluate hazards meticulously before proceeding ahead. AutoNav on perseverance rover detects rocks and slopes but cannot distinguish between safe terrain, sharp or curved rocks, and scientifically valuable targets [11]. Energy consumption is another challenge, as real-time navigation demands significant power sources from the Radioisotope Thermoelectric Generator (RTG), affecting mission longevity. Moreover, AutoNav follows pre-set waypoints and lacks the ability to autonomously redefine its mission aims based on unexpected discoveries. Algorithms for autonomous navigation systems in the extraterritorial environment can be significantly improved using the modern hardware that relies more on the Realtime data processing navigation systems. AutoNav on perseverance decides the best route using satellite data followed by using Visual Odometry to Track movement by analyzing changes in camera images over time. The rover creates a 3D map of the terrain from stereo images then proceed safely after reroute around an obstacle or stop and request human intervention if unable to solve the problem[12], but the rovers capability of Realtime decision making is significantly limited, relying on a RAD750 processor, restricts advanced AI decision-making, operating at speeds up to 200 MHz and delivering approximately 400 MIPS (Million Instructions Per Second), the RAD750 lags behind modern processors that operate in the GHz range and handle billions of instructions per second[13]. This low processing speed hampers the processor's ability to execute complex AI algorithms, which typically require substantial computational power. Moreover, the RAD750's architecture lacks dedicated hardware accelerators such as GPUs (Graphics Processing Units) or NPUs (Neural Processing Units), which are essential for efficiently performing parallel computations in AI algorithms. slowing real-time terrain analysis [18] resulting in the rover's low speed (~120m/hr.).

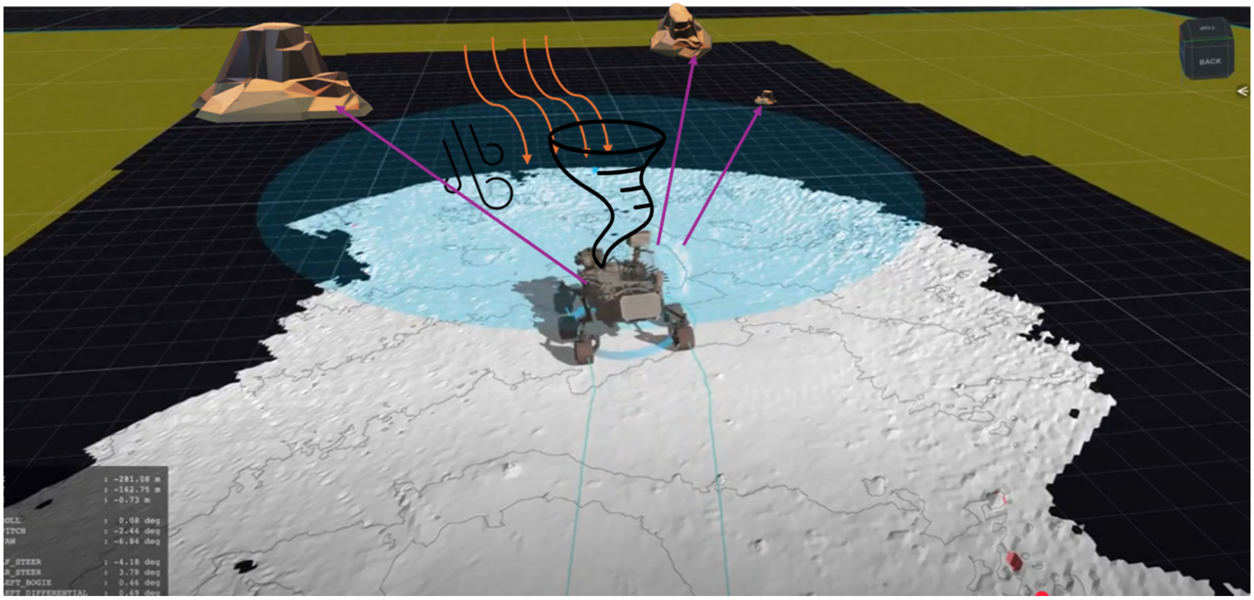

Figure 2: The image illustrates how rover can identify and monitor distant potential hazards and safe locations. The safe locations might be utilized by the rover for self-preservation if a hazardous object approaches or is in its path.

The Seeker project, developed under ESA's Star Tiger program, demonstrates long-range autonomous navigation for planetary rovers using vision-based navigation. Conducted in the Atacama Desert, it tested visual odometry, digital elevation mapping, and AI-driven path planning to enable kilometer-scale navigation per day, surpassing current rover limits (~200m (about 656.17 ft)/sol). The system, integrated on the Robovolc rover, successfully traversed 5.05 km in one day, proving the feasibility of AI-driven autonomy for future Mars and lunar exploration, informing ESA's ExoMars and Sample Fetch Rover missions [19].

With our adaptation of advanced technology, autonomous navigation algorithms can be significantly improved. Modern GPUs offer substantially enhanced parallel processing capabilities, suggesting that a rover designed with the latest hardware-based AI processing cores [21] would be faster, more intelligent, and more autonomous. High-resolution surface data, including depth information, could be captured by the rover's depth NAVCAM and processed in real time using hardware-accelerated processing on NPUs, creating a virtual 3D map of the rover's surroundings which will be used by Deep Neural Network. Deep Neural Network could optimize pathfinding and real-time tracking of distant moving objects, using forward propagation, adjusting weights and biases via backpropagation and gradient descent to minimize errors and improve accuracy through iterative training [22]. This would result in a significantly more intelligent rover capable of navigating its environment while carefully avoiding dynamically changing obstacles altogether, reducing potential impact on the rover's physical systems. Therefore, this upgrade will protect the rover from dynamically changing challenges, such as unpredictable dust storms. DNNs are already widely used in autonomous vehicles and robotics. On-device Large Language Models (LLMs) for DNNs can also run offline [23]; thus on-rover AI will improve the decision-making speed for autonomous navigation enhancing the rover's capabilities while simultaneously gathering more training data to further refine the algorithm. For hazards, that are close to the rover e.g., Sharp rocks or quicksand, a completely different model will be used. Rover hazard cams will be used to generate added data, when combined with 3D model and analyzed by the multi head latent attention model [24]. Multi-Head Latent Attention (MLA) model is a significantly efficient model that improves performance by efficiently managing memory usage and focusing on key features. Traditional multi-head attention mechanisms can be memory-intensive, particularly with high-dimensional data such as images and videos. MLA addresses this by compressing the keys and values into a shared latent space, substantially reducing memory consumption without sacrificing attention quality. This compression allows the model to process multiple parts of an image or video frame concurrently, capturing intricate details and temporal dynamics crucial for accurate recognition and analysis. For example, in the Deep Seek v3 architecture, MLA is used to focus on multiple image regions simultaneously, enhancing the model's ability to capture fine-grained details and leading to a more thorough understanding of visual data [25]. This model's understanding of the intricate details will enable the rover to understand its surroundings better and have a lot more headroom to process details about scientifically interesting rocks and automatically gather data without human intervention. Hence, significantly improve the rover's safety, preventing it from accidentally traversing sharp rocks or quicksand, as seen with the Curiosity rover. This will be extending the rover's lifespan and enabling it to collect more valuable scientific data by covering a larger area within its planned timeline and potentially beyond. But the use of advanced GPUs and NPUs in space missions requires significant power requirements, high-power AI accelerators require substantial energy input and advanced thermal management systems to prevent overheating in vacuum conditions [26].

C. Wheel Mechanism

The mobility of a rover on extraterrestrial terrain, whether smooth or rough, is largely dependent on its wheel mechanism. Past and present rovers, including Spirit/Opportunity, Curiosity, Perseverance, and Pragyan, have faced significant challenges related to wheel durability, traction, and energy efficiency. Design modifications in terms of size, tread patterns, and material composition have been continuously explored, yet rovers still experience issues such as excessive wear, slippage on loose surfaces, and energy loss during traversal [27].

One of the important aspects of wheel design is the interaction between the wheel surface and the terrain, particularly in environments where the ground varies between sand, regolith, and rock. Many mobility failures stem from insufficient traction on soft or granular surfaces and this leads to situations where rovers getting stuck in Martian sand (e.g., Spirit rover).

To address these challenges, we propose an approach to wheel design that incorporates curved surface geometry combined with engineering surface roughness. This technique, partially inspired by the dust mitigation techniques used on solar panels. The main aim of this approach is to enhance traction, reduce slippage and related sinkage, as well as minimize energy losses during traversal. A slightly curved wheel profile dynamically adjusts its contact points based on the terrain. On soft surfaces, this prevents excessive sinking, distributing the rover's weight more effectively. On rough or uneven landscapes, the curvature provides a better grip. An additional advantage lies in self-righting motions. A well-designed curve can help a rover recover from minor entrapments without requiring excessive energy consumption and can improve long-term mobility.

Beyond structural modifications, engineered surface roughness further enhances performance. By incorporating strategic texturing on the wheel surface, friction increases in low-grip conditions, preventing uncontrolled sliding. This roughness also plays a secondary role which is reducing dust adhesion. Fine dust particles, which often adhere to rover components and degrade mechanical efficiency, are less likely to accumulate on a strategically textured surface [28]. This concept is supported by biomimetic principles seen in tree frogs and mountain goats, whose specialized surface structures allow them to traverse soft, unstable terrain with ease [32,33]. A similar approach has been observed in Perseverance's wheels, which feature curved treads that improve resistance to terrain penetration [34]. Preliminary simulations suggest this design could reduce energy loss by 15%, improving both mobility and mission longevity [35]. However, further validation is required, particularly through laboratory tests using simulated Martian regolith.

III. Conclusion

In this review paper, by addressing these challenges through enhanced power systems, we can unlock the full potential of high-performance AI-driven processors in space, paving the way for autonomous deep-space exploration and real-time decision-making capabilities. One of the primary constraints is power generation, as space missions typically rely on radioisotope thermoelectric generators (RTGs) with limited solar power. However, with high-efficiency renewable power source solar panels combined with our dust removal technology, we can significantly increase power production capabilities, allowing the integration of more power-hungry processors without compromising overall system stability. This increased power availability enables real-time AI parallel processing for autonomous navigation and onboard data analysis, reducing dependence on Earth-based command systems. Thereby, the mission's success not only guided on performance upgradation but also by minimizing the number of interplanetary travels with cost reductions. [29] [30] [31] in each mission by using the full functionality of rover and brings down the gap between decades to years on exploration.

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