Planetary Locomotion Systems for Enhanced Mobility Through Hybrid and Adaptive Methods

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Exploring distant planetary surfaces presents significant challenges, with extreme and unpredictable terrains requiring highly specialized locomotion systems. To navigate these extreme environments, planetary vehicles rely on different types of movement, each with their own distinct capabilities and limitations. This research focuses on categorizing existing locomotion methods, analyzing their advantages and disadvantages, and identifying the most promising hybrid systems for future planetary exploration. Wheeled designs are widely employed for efficiency and stability on firm ground, but they often struggle in soft sand and rocky terrain. Legged systems provide greater adaptability by stepping over obstacles, making them suitable for rough or uneven surfaces, though they are more mechanically complex and demand more power. Tethered systems enable access to steep slopes and deep craters, expanding exploration possibilities beyond what traditional systems can achieve. However, they are limited by tether length, complexity in deployment, and potential entanglement issues. Undulating robots, such as eel-like designs, introduce new movement strategies that enhance versatility and allow access to reach tight places but face challenges such as limited payload capacity, difficulties in terrain adaptability beyond narrow pathways, and potential issues with sensor integration for navigation. Hybrid locomotion, such as combining wheels with legs or rolling with flying, offers potential for navigating and maneuvering on a wide range of terrains. While no single locomotion method is applicable for all terrains, the findings from this research will help identify which combination of movement technologies could be more effective across different planetary environments. Future studies can build on this foundation to develop hybrid systems that improve adaptability, efficiency, and success rate in planetary exploration.

I. Introduction

Humanity has long searched for ways to explore further into space, conduct missions to see the world beyond the Earth, and that's where the role of Robotics becomes increasingly vital. Here, we will discuss the applications of robotics particularly for planetary exploration. A major challenge for these robots is navigating diverse terrains and encountering obstacles on other planets [1,7]. The capacity for locomotion through diverse and typically unpredictable environments is a fundamental property of most animal species, and replicating this capacity in robotic platforms has demanded advanced physical and computational architectures [1]. A central insight is that all robotic machines can be considered as adaptive experimental platforms allowing the exploration of fundamental principles of motion and environmental interaction [1].

Physics-based methods offer robots not just as tools but as platforms for experimentation to more profoundly grasp the mechanics of locomotion. The complex interactions between a robot's internal degrees of freedom and the external environment yield significant insight into the speeds, stabilities, and efficiencies of energy consumption [1]. By systematically exploring heterogeneous environments, researchers have been capable of extracting useful insights into robust motion planning and control, thus the enhanced reliability and performance of robot motion [1]. By

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systematically analyzing interactions in heterogenous environments, researchers have gleaned valuable lessons on robust motion planning and control, thus making robotic movement more reliable and efficient [1].

Another important direction of locomotion research includes adaptive systems capable of surviving severe conditions on other planets. These robots, for instance, must traverse poorly consolidated soil, loose sand, and rough rocky terrain. Single-mode locomotion strategies (e.g., legs only or wheels only) fail in the presence of the diversity of Martian or lunar terrains [7]. Dual-mobility systems have been implemented in recent studies with reconfigurable, shape-shifting wheels that expand into a wider ground-contact patch to increase traction on soft soils [7].

In terms of theoretical foundations and algorithmic developments, both bipedal and quadrupedal robot modeling and control have greatly advanced through the research of zero-moment point (ZMP) tracking, capture-point control, central pattern generators (CPGs), and hybrid zero dynamics, among others [10]. Though ZMP-based approaches have been successful at producing stable walking gaits on flat ground, researchers still pursue control architectures that more closely replicate the adaptive and reflexive responses of biological movement [1][10].

Despite major progress, many unanswered questions still drive ongoing research. Most prominent among these are the search for exceedingly robust behaviors that adapt with ease across varied environments. Thus, in the future, hybrid robotic systems integrating various locomotion systems need more sophisticated tools and a greater understanding of the systems. Lastly, the fusion of physics-based experimentation, compliant mechanisms, and bioinspired control systems heralds the dawn of a new era in which robots not only navigate earthly terrain with greater efficiency but are also poised to travel to remote planetary bodies.

II. Literature Review

A comprehensive review of existing locomotion methods is essential to understanding the current state of technology and identifying potential improvements. Locomotion techniques for planetary exploration can be broadly categorized into conventional and adaptive methods.

A. Conventional Locomotion Methods

Planetary exploration first focused on wheeled vehicles because of their relative mechanical simplicity, reliability, and prior heritage on Earth-based missions. For instance, NASA's Mars rovers are predominantly wheeled [15]. As rovers can employ rigid wheels for minimal friction and maximum traction, they provide an efficient trade-off between energy consumption and distance covered, especially over relatively even or gently undulating terrains [7]. However, soils on planetary bodies, particularly Mars, often have flow-like properties, which can lead to wheel slip and sinkage in loose regolith or fine sands [7]. This potentially causes damage to the wheeled locomotion system and might even interrupt its mechanical components.

Legged robots, particularly quadrupeds, have been developed to cope with severe terrain complexity thanks to independent and dynamic foot placements [2]. For instance, the TITAN and TEKKEN series demonstrate the feasibility of four-legged machines to tackle steep slopes, steps, and rocky fields [2]. Although quadrupeds can be more complex to control (compared to wheeled systems), they remain appealing for planetary missions involving rough or unpredictable surfaces [10].

Overall, each classical approach, wheeled, or legged, carries trade-offs in efficiency, stability, and environment suitability. Continuous improvement in mechanical design, sensor integration, and computational control methods help them become more robust for planetary exploration tasks, leading to expansion into new frontiers.

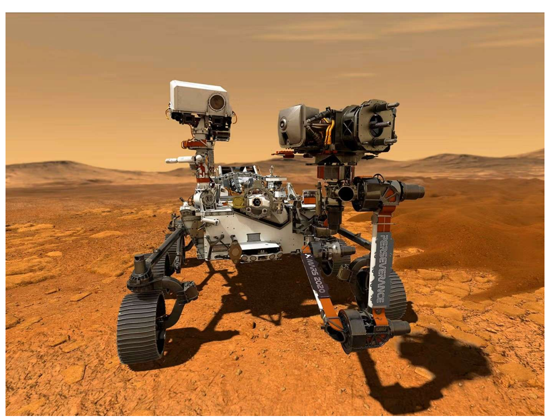

Figure 1. Wheeled Locomotion – The Perseverance Rover [12]

B. Adaptive and Machine Learning-Based Locomotion

Recent developments in adaptive and learning-based locomotion address the variety and unpredictability of planetary surfaces [1]. Traditional model-based control systems often assume simplified ground contact scenarios (e.g., uniform friction or known slope angles). Yet, real planetary environments feature fluid-like sandy regolith, thick dust, or even granular ice with drastically changing friction and mechanical properties. Resistive Force Theory (RFT) has thus emerged as a powerful physics-based approximate model for describing legged or limbless locomotion in granular media, enabling better predictions of how limbs or bodies push and displace loose substrate [1]. By incorporating frictional anisotropy, robots can more accurately gauge how best to angle or time their steps to maintain forward progress.

Aside from soft-soil contexts, ice worlds (e.g., Enceladus or Europa) also challenge locomotion due to slippery surfaces and uncertain geometry. Automatic learning-based strategies can help snake-like or quadruped robots plan footholds and prevent large slip events [16]. By fusing inertial data, local 3D mapping, and onboard sensor feedback, these controllers can pivot or re-plan footprints adaptively, yielding reliable performance across complex terrains.

Thus, this synergy of physics-based modeling (e.g., RFT, anisotropic friction modeling) with data-driven learning methods (reinforcement or supervised approaches) is key to handling the broad environmental uncertainties typical of planetary exploration, enabling more truly autonomous, robust locomotion.

Figure 2. TITAN-XIII: sprawling-type quadruped robot [2]

III. Analysis of Locomotion Methods & Their Placement

Various locomotion strategies have been developed to optimize mobility across different landscapes. These include wheeled locomotion, legged mobility, tethered systems, undulating locomotion, and airborne locomotion. Each of these approaches is suited to specific environmental conditions, offering distinct advantages and limitations.

A. Wheeled Locomotion

Wheeled locomotion is fundamentally built on a design that minimizes mechanical complexity while maximizing efficiency and speed [6]. This approach leverages the continuous rolling motion of wheels to translate rotational energy into forward movement with low energy dissipation [6]. Modern wheeled platforms often incorporate advanced drive mechanisms such as omnidirectional and mecanum wheels to facilitate lateral movements and rotations without changing the robot's heading, thereby enhancing maneuverability in confined spaces, however, the mecanum wheels are not suitable for planetary settings [15]. These design features make wheeled robots particularly popular in industrial settings, autonomous guided vehicles (AGVs), and self-driving cars, where efficiency and predictable motion profiles are critical [6]. Control strategies for wheeled systems typically involve feedback loops that regulate wheel speeds and directions based on sensor inputs from gyroscopes, encoders, and laser range finders [6]. However, there is a drawback to having rovers on different planetary surfaces especially on the moon where there is electrostatically charged regolith which sticks to the mechanisms of the rovers and their wheels which then causes damage to the robots [22].

Environments: Well-suited for relatively even, hard-surfaced terrains such as the basaltic plains on the Moon or the smooth regolith regions on Mars where low-friction and predictable contact conditions exists [19]. However, on surfaces with loose soils, steep slopes, or significant irregularities, and electrostatically charged regolith, wheeled systems may experience slippage, reduced traction, or damage which can impair navigation and overall mission efficiency [6]. In such cases, wheeled platforms are sometimes augmented with suspension systems or adaptive wheel designs to dynamically adjust the wheel–ground interaction and extend their operational envelope [15].

Figure 3. Curiosity Rover Rendering Showcasing the Martian Surface Conditions [15]

B. Legged Locomotion

Legged locomotion draws inspiration from biological systems and is designed to handle a broader range of terrain irregularities [1]. Legged robots, including bipeds, quadrupeds, and hexapods, can dynamically adjust their gait and maintain balance over uneven surfaces by lifting and repositioning their limbs [1]. Sophisticated control algorithms often employ central pattern generators (CPGs), adaptive impedance control, and real-time sensory feedback enable legged robots to negotiate obstacles and recover from perturbations effectively [10]. Despite the increased complexity in controlling multiple degrees of freedom which reduces energy efficiency, and managing hybrid dynamics, legged systems offer superior adaptability and versatility in challenging environments [10].

Environments: On planetary surfaces, such as the rocky and cratered regions of Mars or the regolith-rich lunar terrain, legged robots excel by stepping over obstacles and adjusting their stride to accommodate highly irregular topography [2]. Their ability to "feel" and respond to the ground makes them ideal for missions involving detailed scientific exploration, sample collection, and operation in terrains that are unpredictable or too rough for wheeled platforms [2]. Recent advances in sensor fusion techniques now allow legged systems to integrate data from multiple sources such as cameras, LiDAR, and inertial sensors to build a comprehensive picture of their environment. Combined with machine learning algorithms, these systems can analyze sensor data in real time to predict obstacles, optimize gait selection, and adjust movement patterns dynamically. For example, by learning from past interactions with complex terrains, robots can fine-tune their responses to unpredictable challenges like loose gravel or uneven surfaces, resulting in significantly improved mobility and stability [10].

C. Tethered Systems

Tethered robotics address one of the most extreme challenges in planetary exploration: steep crater walls, deep pits, and otherwise inaccessible ravines. With a tether, a robot can safely rappel into or ascend from these dangerous locations while remaining powered and communicating through the tether link. One leading example is the Axel rover concept developed by NASA's Jet Propulsion Laboratory (JPL) [5]. Axel is a minimalist rolling platform on a tether, specifically engineered to descend deep craters or venture into lava tubes. Its design includes a compact body and independently actuated wheels. When attached via tether to a lander or another host rover, Axel can lower itself hundreds of meters down, analyzing crater interiors or investigating permanently shadowed regions.

Another example of a tethered system is the Exobiology Extant Life Surveyor (EELS) Robot [6]. While EELS is fundamentally a serpentine, undulating robot, its early prototypes incorporate tethered deployment for steep ice or vent descents. EELS's multi-segment design allows it to flex and conform to uneven or sloped walls, aided by a tether that stabilizes it during extreme climbs or descents [6]. This tether ensures the robot does not lose traction in hazardous, icy passages, and enables partial or total offboard power supply.

Environments: These systems are ideal for exploring steep, rugged terrains such as lunar or Martian craters, deep pits, and icy, shadowed regions. The tether ensures continuous power and communication while safely navigating areas where conventional mobility might fail.

Figure 4. Axel Rover [5]

D. Undulating Locomotion

Undulating or snake-like robots have recently emerged as a promising alternative for maneuvering in cramped, highly irregular, or cluttered environments. Such robots typically consist of a series of modules connected by joints that produce wave-like motions along the robot's body. By coordinating these bends, the robot can move forward, sideways, or even climb if friction or protrusions allow anchoring [14]. In partial or microgravity environments, undulating locomotion can also be adapted for swimming-like motions.

Environments: On planetary surfaces, one application for serpentine machines is accessing narrow lava tubes or passages filled with rock debris. The segmented body can curve around obstructions, enabling deeper penetration than a similarly sized wheeled or legged system. Another active research area is amphibious or sub-ice designs suitable for ocean worlds such as Europa or Enceladus. Here, an undulating robot may swim through subglacial water or brine channels, using wave-based propulsion that might be more efficient than propellers under certain conditions [16]. Controllers for undulating robots must manage the many joint degrees of freedom, balancing wave amplitude, frequency, and friction properties in synergy with environmental demands [13]. Though complex, these designs yield extraordinary maneuverability where other forms of locomotion fail.

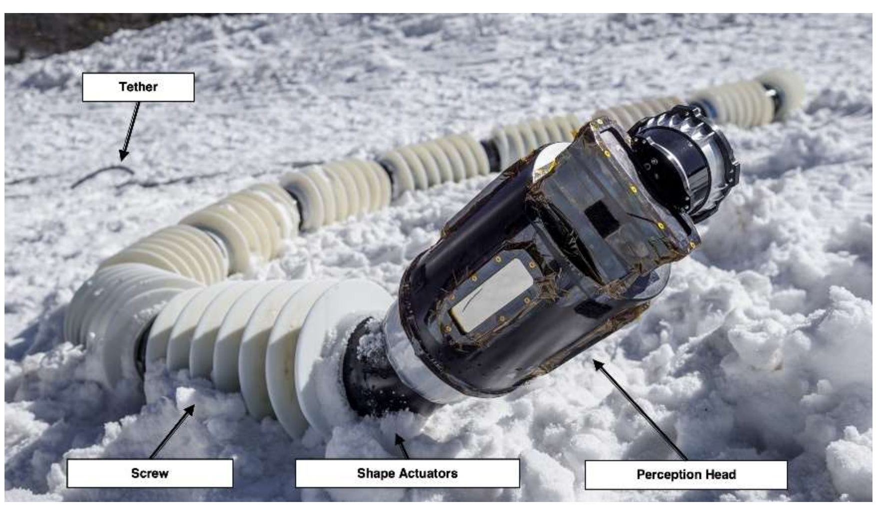

Figure 5. Early Prototype of EELS Robot [16]

E. Airborne Locomotion

The Ingenuity Mars Helicopter employs rotary-wing flight, a unique locomotion method that leverages powered flights in Mars' extremely thin atmosphere to explore terrains that traditional wheeled rovers cannot access. This capability not only allows Ingenuity to scout and assess geological features from the air, thereby providing valuable reconnaissance data to assist the Perseverance rover, but it also validates advanced technologies critical for future Mars missions. By successfully achieving controlled, powered flight under conditions with less than 1% of Earth's atmospheric density, Ingenuity demonstrates that aerial vehicles can expand the scope of planetary exploration and scientific discovery, paving the way for more versatile exploration strategies on Mars [11].

Environments: This type of locomotion is particularly well-suited for environments characterized by extreme conditions, rugged terrain, and vast, open areas where traditional mobility is constrained. In extraterrestrial settings like Mars, where the landscape includes rocky outcrops, steep slopes, and expansive dunes, the ability to fly over obstacles and rapidly change positions is invaluable.

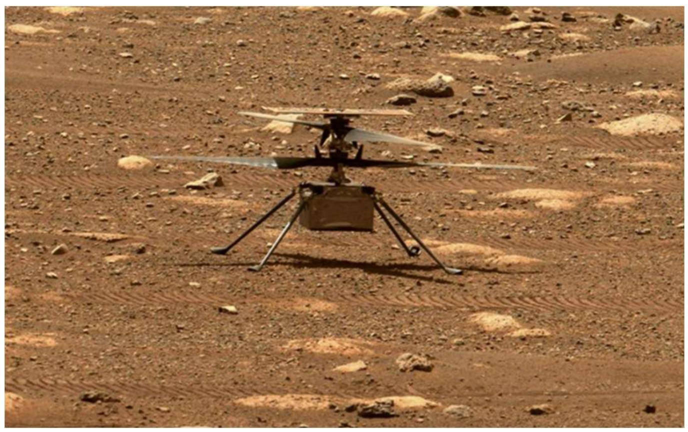

Figure 6. New Successful Locomotion System - Ingenuity Helicopter [11]

IV. Hybrid Locomotion Systems

A major recent trend is the integration of multi-modal locomotion, specifically, bridging aerial and ground capabilities to maximize exploration efficiency [4]. There is a variety of combinations of locomotion that can be chosen to optimize and make the mission more efficient.

One approach is to make a bipedal robot that combines walking and flying which makes it capable of doing more complex maneuvers [21]. The LEONARDO robot, developed by researchers at Caltech, is a hybrid locomotion system that combines bipedal walking with aerial flight capabilities [21]. This innovative design leverages multi-joint legs for precise ground movement while employing propeller thrusters to maintain balance and provide lift when needed. The synchronized control between leg actuators and thrusters enables the robot to walk by shifting its center of mass and remain upright, as well as to transition into a flying mode where it behaves like a drone. This dual-mode approach allows LEONARDO not only to navigate uneven and challenging terrains more efficiently but also to perform dynamic maneuvers such as slacklining, hopping, and even skateboarding that require a high degree of balance and agility. By intelligently blending walking and flying, the system reduces the energy demands typically associated with continuous aerial flight while enhancing its adaptability to real-world obstacles. Moreover, the integration of a deep neural network-based landing control algorithm in future iterations promises to further optimize the robot's autonomous decision-making, ensuring it selects the safest and most energy-efficient mode of locomotion for any given environment [21].

Figure 7. LEONARDO, the Bipedal Robot [21]

Another approach is to physically mount a small aerial drone onto a terrestrial rover, whether wheeled or legged, so the combined system can address widely varying mission demands. This is not necessarily a hybrid model but more of a synergistic combination, it combines two modes of locomotion in which one can function independently of the other. The ground unit provides large-scale robust mobility and consistent energy resources, while the drone can detach for close-range inspection of steep cliffs, vents, or crater walls. For example, a quadruped robot such as Boston Dynamics' Spot can traverse kilometers over relatively unpredictable terrain, carrying instrumentation and serving as a stable platform [3]. A drone can be docked on top, employing a specialized landing platform that locks and recharges the UAV. If the environment becomes too perilous or inaccessible, for instance, a deep crevasse or a vertical shaft the drone can undock, fly closer or descend partially for scanning, then return to the quadruped for re-docking. Researchers have demonstrated early prototypes of this synergy, showing robust passively or actively secured landing systems that do not impede leg movement [4].

Figure 8. Dual System Concept of a quadruped and Drone [4]

Summarizing the Locomotion types below in Table 1.

Locomotion type	Example	Applications	Environments
Wheeled	Mars Rovers (JPL): Curiosity, Perseverance.	• Efficient long-distance travel for broad surveys • Ideal for routine scientific data collection.	• Smooth, hard surfaces such as basaltic plains. • Areas with stable, predictable regolith.
Legged	Titan series quadruped and Spot from Boston Dynamics.	• Adaptive gaits to step over obstacles • Enables precise maneuvering in variable terrains.	• Rocky and cratered regions with uneven topography. • Terrains where wheels may slip due to irregular surfaces.
Tethered Systems	Axel Rover (JPL).	• Maintains power and communications through a tether during high-risk maneuvers.	• Deep pits, steep crater walls. • Icy or shadowed regions with unstable surfaces.
Undulating	EELS (JPL).	• Designed for navigating narrow lava tubes or constricted passages. • Can be adapted for amphibious or sub-ice missions where flexibility is key.	• Narrow channels within lava tubes. • Granular or sub-ice regions where a flexible body can conform to tight spaces.
Airborne	Ingenuity (JPL).	• Get a wider view of Terrain for visuals. • Supports ground missions by identifying potential Hazards.	• Rugged terrains with obstacles (e.g., rock outcrops, dunes) • Vast open areas where ground navigation is limited
Hybrid	Leonardo (CalTech).	• Offers ground stability with the added benefit of aerial flexibility for diverse tasks.	• Mixed environments with both rugged ground and open spaces • Areas where transitioning between ground and air is beneficial

Table 1. Locomotion Categories and Applications in Different Environments

V. Future Studies

Emerging research is set to redefine planetary exploration by boosting robotic efficiency and eliminating current limitations, unlocking a universe of possibilities for our machines.

A lab at Embry-Riddle is working on research and investigating the integration of quadrupedal walking and flight movement systems, with the core design of a hybrid drone-quadruped system known as HyDroQuad. The research improves control algorithms, such as model predictive control and adaptive PID controllers, to enable smooth mode transitions between walking and flying. At the same time, the design employs lightweight materials like carbon fiber composites, advanced polymers, and titanium alloys to minimize weight while maintaining structural integrity, a key feature for both terrestrial and space applications.

HyDroQuad utilizes a novel approach that integrates adaptive gait methods by augmenting leg trajectories and stepping patterns based on machine learning. It utilizes real-time sensor data to enable dynamic leg motion adaptation by modifying stride frequency, step amplitude, and trajectory, thus optimizing travel on varied terrain with reduced energy expenditure. This methodology ensures that the robot maintains stability and prolongs its operating time in challenging environments, whether climbing the steep slopes of Mars or walking on the uneven surfaces on Earth.

In addition to the improvements developed in HyDroQuad, the complementary research by Fiorini et al. [20] presents a new approach to exploring planetary surfaces. Their research explains a robot with a novel combination of hopping and rolling modes of locomotion. The robot design is quite small and egg-like, with a self-righting capability powered primarily by a spring-powered hopping motion. A single actuator is used to produce the hops and to control the robot by modifying a non-central mass, thus enabling intentional directional motion through rolling. The integration of a critical sensor array, comprised of a video camera and key electronic components, with an onboard microcontroller allows for autonomous travel and real-time terrain inspection [20]. Although initial laboratory tests showed the robot could execute short, controlled hops, there remain challenges regarding mechanical losses and the inefficiencies of energy transfer. A thorough analysis of the static and dynamic models of the robot points to the need for mass distribution optimization and actuator performance improvement to ensure both distance and accuracy of hopping motion. This initial work provides the basis for future potential improvements in control algorithms, energy efficiency, and sensor fusion techniques, marking an important step toward the development of agile robotic systems capable of performing well in extraterrestrial as well as challenging terrestrial environments.

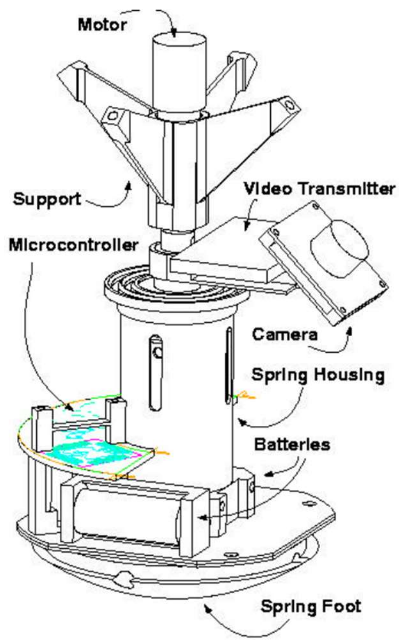

Figure 9. Hopping mechanism Illustration [20]

VI. Conclusion

In conclusion, the current research has made a thorough analysis of various locomotion methods relevant to planetary exploration, outlining the strengths and weaknesses inherent in each method. Wheeled systems offer an effective and simple way of moving on flat ground, while legged robots improve mobility in difficult and varied terrain. Tethered and undulating robot systems allow for operational capabilities in areas with steep inclines of craters and narrow paths, while aerial platforms complement these capabilities by allowing for monitoring and navigation above obstacles from a raised position.

The integration of these diverse methodologies into hybrid systems represents a significant breakthrough, allowing robots to be seamlessly switched between different mobility modes and thus improving their ability to traverse complex and heterogeneous terrains. Through the integration of physics-based modeling with adaptive control methods enhanced by machine learning methods, future robotic space explorers will achieve increased levels of robustness, efficiency, and autonomy. Not only does this integration address current technological limitations but also opens the door to more ambitious missions on planetary bodies, where the ability to travel safely and efficiently across planetary and terrestrial terrain is imperative.

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