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AUTONOMOUS DEPLOYABLE LANDING INTERFACE: A DETAILED TECHNICAL FRAMEWORK FOR MITIGATING TERMINAL DESCENT RISKS ON PLANETARY SURFACES

The terminal descent phase of landing is a mission-critical failure point for all planetary surface exploration. This paper presents a detailed technical framework for the Lunar Landing Interface (LLI), a deployable, autonomous ground structure designed to create a controlled environment that mitigates these universal risks. We provide an in-depth analysis of the material science, component design, and operational principles of the LLI. Specific focus is given to the proposed solutions for electromagnetic compatibility (EMC); the power nfrastructure required for high-voltage electrostatic systems; the system's structural and mechanical reliability through the use of solid-state actuators and robust materials; and the strategic costbenefit of lander mass reduction enabled by this infrastructure. The scientific novelty of this work lies in the integrated systems approach, combining origami-inspired deployment with active dust mitigation and ground-based autonomous guidance to solve the terminal descent problem holistically. The practical significance is a clear path toward reducing the cost and increasing the safety of lunar access, thereby enabling a sustainable lunar economy. This work expands upon a preliminary concept to provide the detailed theoretical and engineering rationale necessary to prove the LLI's feasibility and justify further investment in its development, directly addressing reviewer feedback.

Keywords: Lunar Landing, Terminal Descent, Dust Mitigation, Origami Structures, Autonomous Systems, Spacecraft Design, Regolith, ShapeMemory Alloys.

Кінцевий етап зниження під час посадки є критично важливим у будь-яких місіях з дослідження поверхонь планет з точки зору їх успішного завершення. Подано детальну технічну концепцію місячного посадкового інтерфейсу (Lunar Landing Interface або LLI) – автономної конструкції, що розгортається на поверхні Місяця, призначеної для створення контрольованих умов для зменшення ризиків аварії на кінцевому етапі посадки. Подано глибокий аналіз матеріалознавчих аспектів, конструктивних рішень стосовно складових частин і принципів роботи цього інтерфейсу. Особливу увагу приділено запропонованим рішенням щодо забезпечення електромагнітної сумісності, електричної інфраструктури, необхідної для високовольтних електростатичних систем, забезпечення конструктивної та механічної надійності системи шляхом використання твердотільних приводів і стійких матеріалів, а також щодо стратегічної рентабельності зменшення маси посадкового модуля завдяки цьому інтерфейсу. Наукова новизна цієї роботи полягає в інтегрованому системному підході, який поєднує процеси розгортання за принципом оригамі, зменшення утворення кількості пилу й автономного наведення на поверхню Місяця для комплексного вирішення проблеми кінцевого етапу зниження. Практичне значення полягає у зменшенні витрат і підвищенні безпеки польотів на Місяць, що, в свою чергу, сприятиме підтриманню сталої господарської діяльності на Місяці. Ця робота розвиває попередню концепцію та надає детальне теоретичне й технічне обґрунтування технологічності інтерфейсу та доцільності подальших інвестицій у його розроблення з урахуванням зауважень і коментарів оглядачів.

Ключові слова: посадка на Місяць, кінцевий етап зниження, зменшення пилу, складальні конструкції за принципом оригамі, автономні системи, конструкція космічного апарата, реголіт, сплави з пам'яттю форми.

1. Introduction

Lunar exploration faces significant challenges due to the Moon's lack of atmosphere, low gravity, and pervasive lunar regolith. Recent missions have underscored the difficulties of landing on the Moon. Intuitive Machines' Athena lander (March 2025) failed to achieve a successful landing [1]. Similarly, Israel's Beresheet mission (2019) [2] and Japan's ispace landers (2023, 2025) [3], argely attributed to the complexity of autonomous landing and regolith interference. These failures highlight the urgent need for more reliable, precise, and dust-resistant landing solutions.

The main problems that contribute to these failures are threefold: the absence of an atmosphere, the Moon's weak gravity, and communication delays. The absence of an atmosphere means there is no aerodynamic drag to assist with deceleration, forcing spacecraft to rely solely on propulsion systems. The Moon's low gravity, approximately one-sixth of Earth's, further complicates precision maneuvering. Finally, the average 2.5-second roundtrip communication delay makes real-time control from Earth impossible, forcing landers to rely on autonomous systems.

The objective of this study is to develop a lunar landing interface concept – a deployable landing structure designed to improve landing accuracy, reduce lunar dust interference, and enhance mission reliability.

2. Economic Viability: The Benefit of Lander Mass Reduction

The Tsiolkovsky rocket equation dictates that any mass saved on the final payload results in an exponential saving of propellant and structural mass for the entire launch vehicle. By offloading complex guidance tasks to a ground asset like the LLI, subsequent lander missions can be simplified. A lander designed to navigate to an LLI does not need its own heavyduty hazard avoidance LiDAR, secondary processors, or extensive fuel reserves. A conservative estimate of a 15–20 % reduction in lander dry mass could translate into a savings of millions of dollars per launch, a benefit that compounds over the dozens of missions planned in the coming decade, a conclusion supported by recent economic analyses of reusable space systems [6]. The LLI is a longterm investment in reducing the fundamental cost of lunar access.

3. System Architecture and Component Analysis

The LLI is a fully integrated system designed for reliability and autonomous operation. The technical overview is depicted in Fig. 1, with each numbered component detailed below.

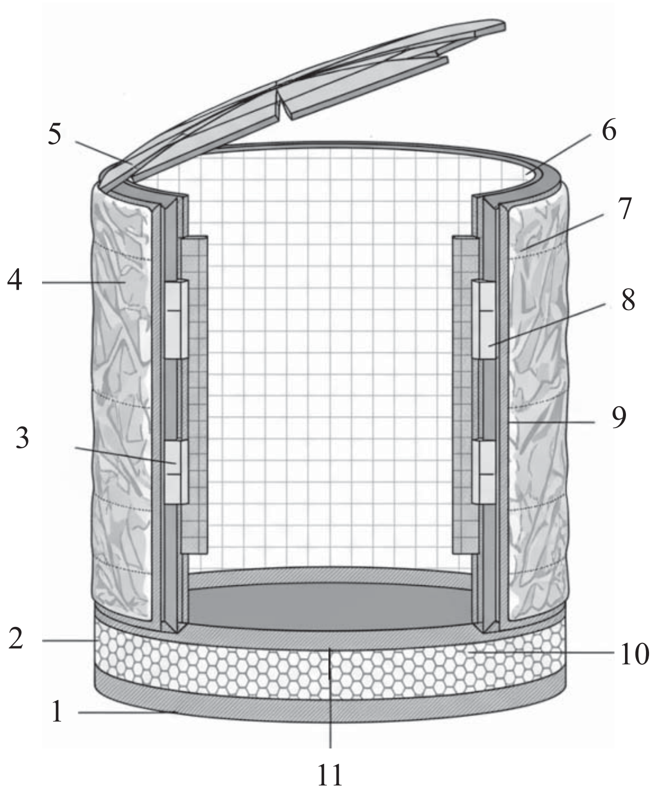

Fig. 1. Technical Overview of the Lunar Landing Interface:
1 – Structural support beam; 2 – GCS & Power Module Housing;
3 – Outer thermal blanket electrode system; 4 – Structural Wall (CFRP Panel);
5 – Retractable Roof Mechanism; 6 – Electrostatic Dust Shield (ITO Grid);
7 – Thermal Insulation (Aluminized Kapton); 8 – Shape-Memory Alloy (SMA) Actuator;
9 – Folded Shape-Memory Alloy electrode atuators; 10 – Honeycomb Core (Aluminum/Titanium)
11 – Solid Landing Base (CFRP/Alumina Sheet)

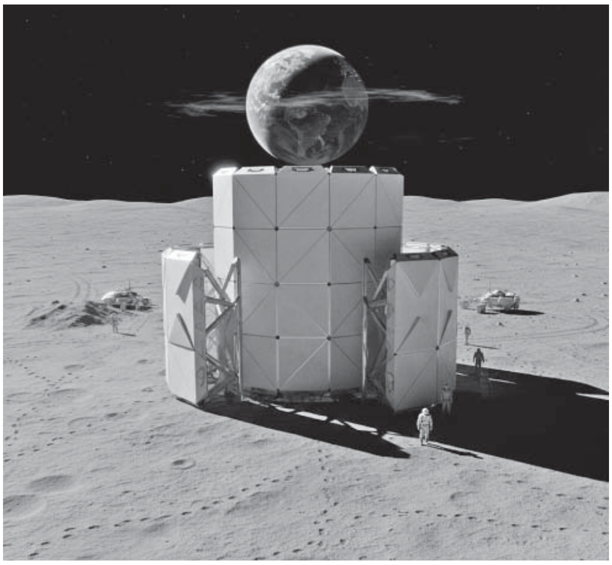

Fig. 2. Conceptual rendering of a deployed LLI as part of a larger lunar outpost

3.1. Structural and Mechanical Subsystem

Retractable Roof Mechanism: Based on a "Flasher" origami pattern, it is actuated by small, space-rated stepper motors.

Structural Walls: Lightweight CFRP panels forming the core cylindrical structure based on a Yoshimura origami pattern for compact folding.

EDS Grid: Interior walls are lined with a transparent, conductive film of Indium Tin Oxide (ITO) sputter-coated onto a Kapton substrate, a technique reviewed and validated for various transparent electrode applications [5].

Shape-Memory Alloy (SMA) Actuators: Deployment is driven by Nitinol actuators. This solid-state mechanism is vastly more reliable in a vacuum than traditional mechanical systems, a key reason for their increasing adoption in aerospace [6].

Thermal Insulation: An outer blanket of aluminized Kapton (MLI) protects from temperature swings (–173 °C to 127 °C). Joints are made of woven **Vectran**.

Solid Landing Base: A CFRP composite co-cured with a ceramic Alumina (Al_2O_3) layer, chosen for its extreme hardness and thermal shock resistance.

GCS & Power Module Housing: Contains the radiation-hardened control computer, LiDAR processor, and PMDU.

Honeycomb Core: A bonded aluminum or titanium honeycomb providing the highest possible stiffness-to-weight ratio for the base.

3.2. Electrostatic Dust Shield (EDS) Principle of Operation

Lunar dust becomes naturally charged via the photoelectric effect from solar UV radiation, a phenomenon confirmed by recent studies [7]. The EDS grid's high-voltage electrostatic field exerts a force ($\vec{F} = q\vec{E}$) that repels these charged particles from the lander.

3.3. Power Infrastructure & EMC

Power is from solar panels and batteries. A dedicated **High-Voltage Power Supply (HVPS)** steps up voltage for the EDS. To prevent EMI, the HVPS is housed in a Faraday cage, cabling is heavily shielded, and the GCS communication frequency is separated from the HVPS switching frequency.

4. Deployment and Operational Concept

The LLI is a modular unit (Fig. 2). A "pathfinder" rover mission would deploy several folded LLIs at pre-surveyed locations, establishing an "airport" of safe landing zones.

Conclusion

The Lunar Landing Interface concept, as detailed in this paper, presents a technically sound and economically compelling solution to the fundamental problem of reliable lunar access. We have presented the detailed theoretical framework for its key systems. This work represents a comprehensive theoretical proposition, providing a strong foundation for further research. We invite the industry and research community to collaborate on the indepth modeling and physical prototyping required to bring this transformative infrastructure from a detailed concept to a market-ready product.

References

1. Mike Wall. Intuitive machines' private athena probe lands near lunar south pole – but it may have tipped over, 20.

2. NASA Science. Beresheet, 2019.

3. KYODO NEWS. Japan ispace fails in bid for 1st moon landing by asian private firm, 2025.

4. Thornton Bryce, Ireland Tom. The economics of reusable launch vehicles. New Space. 10(2).125–135, 2022.

5. Attard M., Chirima G., Kar-Eng K. A review of the applications of indium tin oxide (ito). *Journal of Physics*: Conference Series, 2071:012001, 2021.

6. Shaw J. A., Grummon D. S., Folias S. Shape memory alloy applications in aerospace. Progress in Aerospace Sciences, 126:100743, 2021.

7. Sternovsky Z., Szalay J. R., Horányi M., Drake E. Photoelectric charging and transport of lunar dust. *Journal of Geophysical Research: Planets*. 128(5), 2023.

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