# Soft Deployable Airless Wheel for Lunar Lava Tube Exploration

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*Abstract*— **Lunar pits and lava tubes have attracted significant attention as important targets for future exploration and habitation because they may provide access to subsurface geological records and naturally shielded environments. However, exploration of these sites requires a mission sequence including pit approach, subsurface entry through steep or vertical sections, and cave traversal, which is difficult to support with a conventional single-rover platform alone. This paper discusses the applicability of a soft deployable airless wheel and carrier–explorer architecture for lunar lava tube exploration. In the proposed concept, multiple compact rovers are transported onboard a carrier in a stowed configuration and, after deployment, use the deployable wheel for pit approach and subsurface entry. Results showed that the proposed wheel expands from approximately 230 mm to 500 mm in diameter, traverses 200 mm stair-like obstacles, achieves stable locomotion on simulated lunar soil, and maintains structural integrity under an impact condition corresponding to an approximately 100 m free fall under lunar gravity. Applicability to thermal-vacuum and high-temperature environments was also supported. These characteristics suggest that the proposed wheel can serve as a promising enabling hardware element for compact multi-explorer lunar subsurface missions.**

## I. INTRODUCTION

Lunar pits and lava tubes are widely regarded as high-value targets for exploration because these expose geological records along their interior walls without requiring drilling, while providing a naturally shielded environment as prime candidates for future lunar habitats against extreme thermal fluctuations and cosmic radiation [1-5]. Orbital investigations have further suggested that many pits are not merely surface depressions but potential entrances to subsurface voids or caves, implying that access to these environments requires traversing steep slopes and near-vertical cliffs [3-5]. Under such extreme conditions, lunar lava tube exploration should not be framed simply as a problem of rough-terrain mobility. Rather, it should be addressed as a continuous mission sequence that includes approach to the pit entrance, vertical entry into the subsurface, and subsequent traversal within the cave.

Existing concepts for lunar pit exploration have largely relied on heavy access systems, such as cranes or tethered descent mechanisms [6-9]. While these approaches provide a plausible means of delivering a robotic platform into a pit, they also introduce substantial penalties in mass and system complexity. They may further increase operational risk at the pit rim, where local terrain instability and collapse hazards are already significant, and can transfer mission risk to the primary rover responsible for surface operation. Multi-robot exploration strategies offer a potential way to reduce overall mission risk and improve robustness through redundancy, but these are difficult to implement within currently proposed entry architectures.

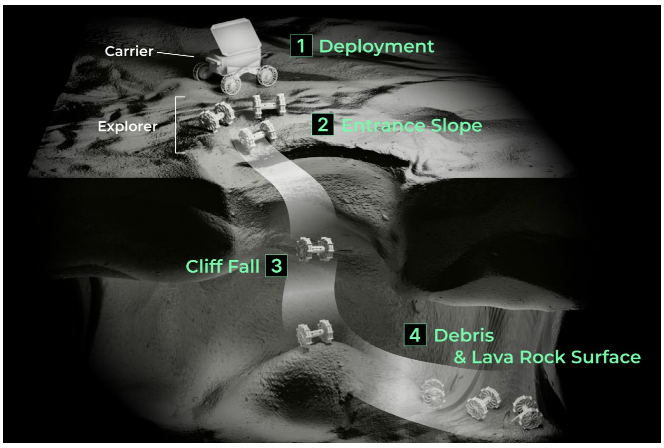


Figure 1. Concept of operations for exploration of lunar lava tube.

To address this gap, our group proposed a soft deployable airless wheel with a reconfigurable reciprocal structure for multi-robot lunar exploration (Fig.1) [10]. The wheel was designed to improve the mobility of compact robotic platforms while increasing stowage efficiency, and its reciprocal structure provides enhanced impact tolerance for direct-entry scenarios involving drops or hard landings. Building on that hardware development, this paper discusses how the proposed wheel enables alternative mission architectures for lunar lava tube exploration, why such architectures are meaningful from a systems perspective, and how they may be extended toward future multi-robot subsurface missions.

## II. MISSION ARCHITECTURE AND MOBILITY CONCEPT

The proposed mission architecture consists of a main rover, referred to as the carrier, and multiple compact rovers, referred to as explorers (Fig.2A). Each explorer is configured as a two-wheeled rover consisting of a central body, deployable wheels, and a rear tail structure. The central body houses the onboard equipment, and the tail provides a passive stabilizing function by constraining body rotation induced by wheel torque during driving. The carrier approaches the vicinity of a lunar pit and remains at a safe distance from the entrance, while the explorers are transported in a stowed configuration onboard the carrier (Fig.2B). Each explorer is protected and

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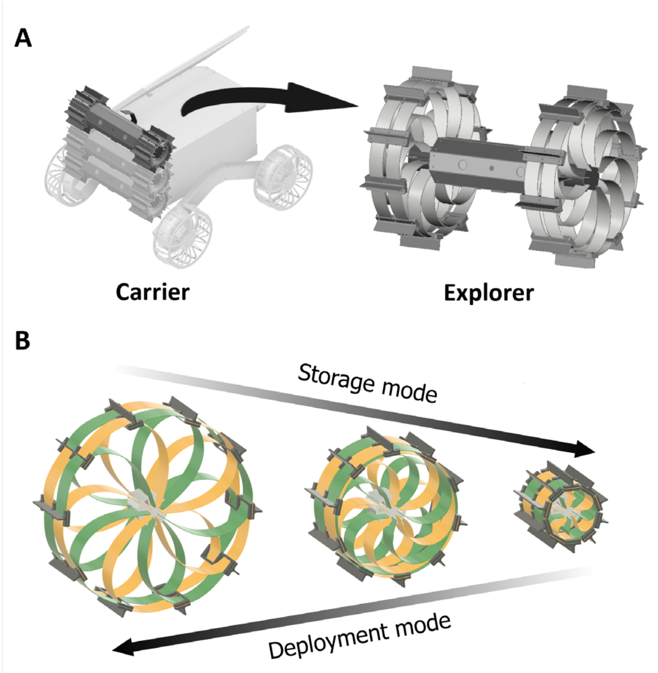


Figure 2. Rover architecture and deployable wheel concept. (A) Configuration of the Carrier and Explorer (B) Deployed and Stowed configuration of the soft deployable wheel

retained in its stowed configuration during transport by releasable shielding integrated into the carrier. Once released from the carrier, the explorer wheels passively deploy through their inherent elasticity, without requiring an additional active deployment actuator.

After release, each explorer deploys its wheel structure, approaches the entrance region, and proceeds toward subsurface entry (Fig.1). Depending on terrain hazard, communication availability, and operational objectives, pit entry may be performed sequentially or in parallel. The principal advantage of this architecture lies in achieving mission redundancy within a limited volume budget. In contrast to a single large rover assigned to all exploration tasks, multiple compact explorers allow partial mission failure to be tolerated while improving robustness in hazardous terrain.

Compact packaging is required during transport, whereas a large effective wheel diameter, obstacle traversal capability, and impact tolerance are required during exploration and pit entry. Explorers equipped with deployable soft wheels are intended to satisfy the conflicting requirements of transport efficiency and field mobility. A continuum-deforming wheel based on a reciprocal structure accommodates these competing demands within a single mechanical architecture, enabling both compact stowage and load-bearing capacity without dependence on mechanically complex articulated deployment systems, such as rotational hinge [10]. This allows many explorers to be carried by the carrier within the same stowage volume, while preserving the mobility needed to traverse loose regolith near the pit entrance and irregular obstacles inside the subsurface environment, while also providing structural durability against impact loading and rapid thermal variations.

These structure mechanisms support simplified entry strategies for multi-platform missions. Direct free-fall entry is not assumed to be universally applicable. However, structural impact tolerance at the wheel level can reduce dependence on dedicated descent hardware and broaden the range of feasible access strategies. This is especially relevant when multiple explorers are deployed, because individual platforms need not rely on a shared, high complexity access mechanism. Instead, entry attempts can be distributed across multiple units, and observations from earlier deployments can inform later ones, yielding a more fault-tolerant operational framework for lunar subsurface exploration.

## III. Wheel Validation For Pit Exploration

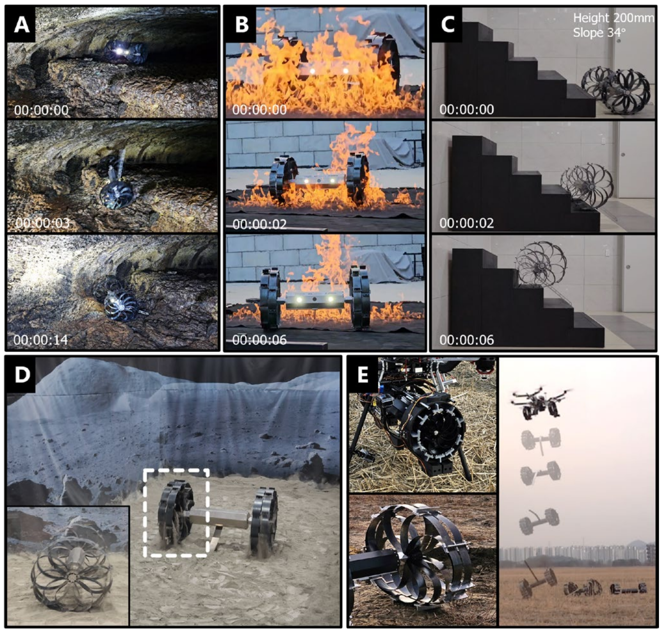


Figure 3. Field tests for evaluating operational feasibility in the proposed mission scenario. (A) Driving ability on inside of lava tubes, (B) high-temperature test in a fire environment, (C) Traversal of stair-like obstacles, (D) on simulated lunar soil (E) An impact resilience test

The proposed wheel was developed as a woven helical structure composed of elastic metallic strips. The system could be stowed at a diameter of approximately 230 mm and expanded to approximately 500 mm in the deployed state. Because the compliant wheel structure can be fabricated from flexible metallic materials such as steel sheets, it can maintain functionality under high-temperature conditions, as demonstrated by the fire-environment test. Experimental validation further demonstrated traversal over a 200 mm stair-like obstacle, stable driving performance on simulated lunar soil, and preservation of structural integrity under an impact condition corresponding to an approximately 100 m vertical drop under lunar gravity (Fig.3). Additional verification under thermal-vacuum and high-temperature conditions further supported applicability in extreme environments [10].

These results indicate that the value of the proposed soft deployable wheel is not captured by any single performance metric, but rather by its relevance to a mission scenario that has remained difficult to realize despite its scientific and engineering importance. A high deployment ratio improves packaging efficiency, allowing a carrier with limited stowage volume to transport a larger number of compact explorers.

Once deployed, the large effective wheel diameter and compliant reciprocal structure improve mobility on loose regolith near pit entrances as well as over uncertain obstacles within the subsurface environment. Impact tolerance and survivability under thermal-vacuum conditions additionally increase the likelihood of preserving rover functionality under abnormal loading events, including abrupt terrain transitions or hard-contact entry conditions. Taking together, these characteristics do not necessarily replace all existing access systems, but instead suggest an alternative mission configuration in which the complexity of dedicated support hardware can be reduced relative to the operational risk of the mission.

One of the important points is that the utility of this wheel cannot be reduced to a single measure such as deployment ratio, obstacle height, or impact resistance alone. Compact stowage enlarged ground-contact geometry, structural compliance, and impact survivability become meaningful in combination when considered in the context of pit exploration. For this reason, the proposed wheel serves not only as an extension of conventional wheel-soil interaction research, but as an enabling hardware element for multi-rover mission architectures. From this perspective, a central question is not merely whether the wheel performs well in isolation, but under what combinations of pit geometry, access constraints, and operational objectives this concept becomes most effective.

## IV. Discussion

Figure 4. Cooperative exploration scenario inside a lava tube environment using multiple explorers.

The present study is intended to motivate discussion on which combinations of pit geometry, access constraints, and operational conditions are most compatible with alternative entry strategies for lunar subsurface exploration. A central direction for follow-up work is to examine how the mechanical survivability provided by the deployable soft wheel can be translated into mission-level success under realistic cave conditions, including low illumination, restricted visibility, and limited communication. Another important direction is the integration of cooperative multi-explorer operation, with the goal of improving robustness against unknown challenges encountered after subsurface entry.

For example, within cave interiors, limited illumination and restricted field of view may make complete terrain understanding less practical than local hazard avoidance and conservative path selection. In such settings, an impact-tolerant mobility platform can absorb part of the uncertainty associated with imperfect perception through structural margin, which may be particularly advantageous for compact autonomous explorers. Sequential deployment of multiple explorers also enables collaborative exploration strategies in which terrain observations from earlier units inform the entry decisions and traversal behavior of subsequent units (Fig.4) [11, 12].

From this perspective, the proposed soft deployable wheel is better interpreted not merely as an improved mobility component, but as a key enabling element for multi-explorer mission architectures targeting lunar lava tube exploration. Its significance becomes more substantial when considered together with future developments in autonomous navigation, communication strategy, and science payload integration.


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