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Soft Deployable Airless Wheel for Lunar Lava Tube Exploration

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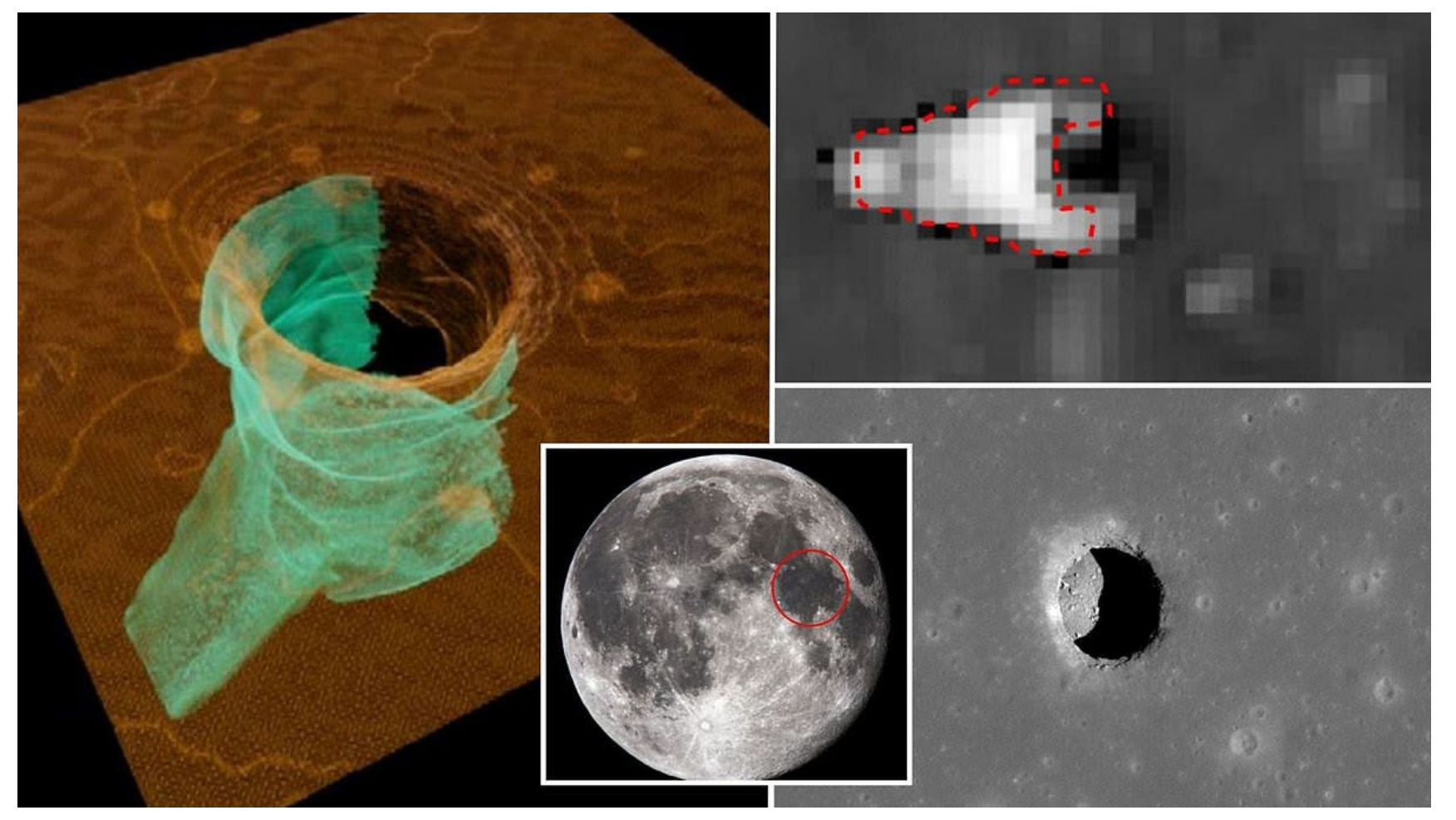
Unmanned Exploration Laboratory

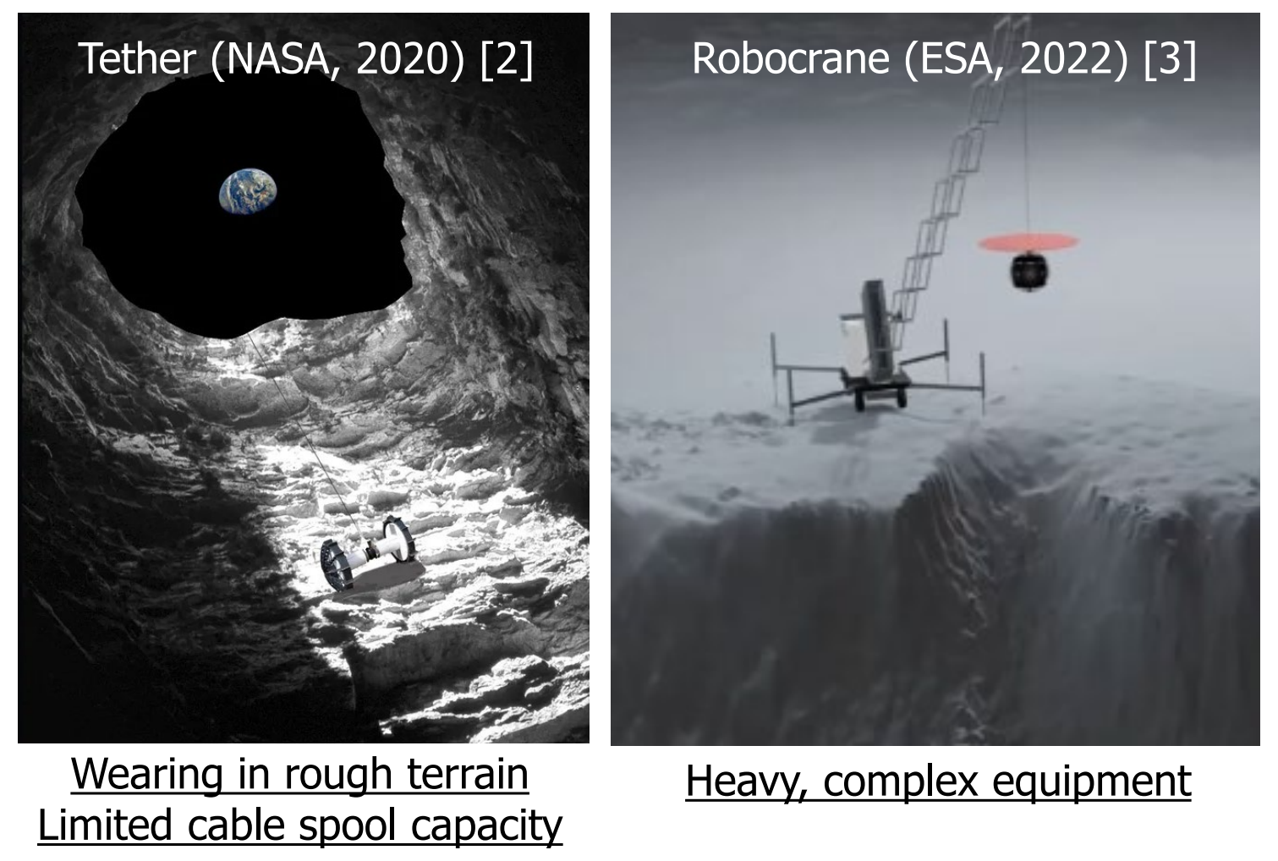
➢ Motivation - Entry Methods for Lunar Cave Exploration

► Background

Lunar caves are not only considered key locations for lunar exploration base camps but also hold significant potential as future human habitats. However, due to their tough terrain and challenging accessibility, comprehensive exploration has yet to be conducted.



Skylight of Mare Tranquillitatis Pit on the Moon [1]

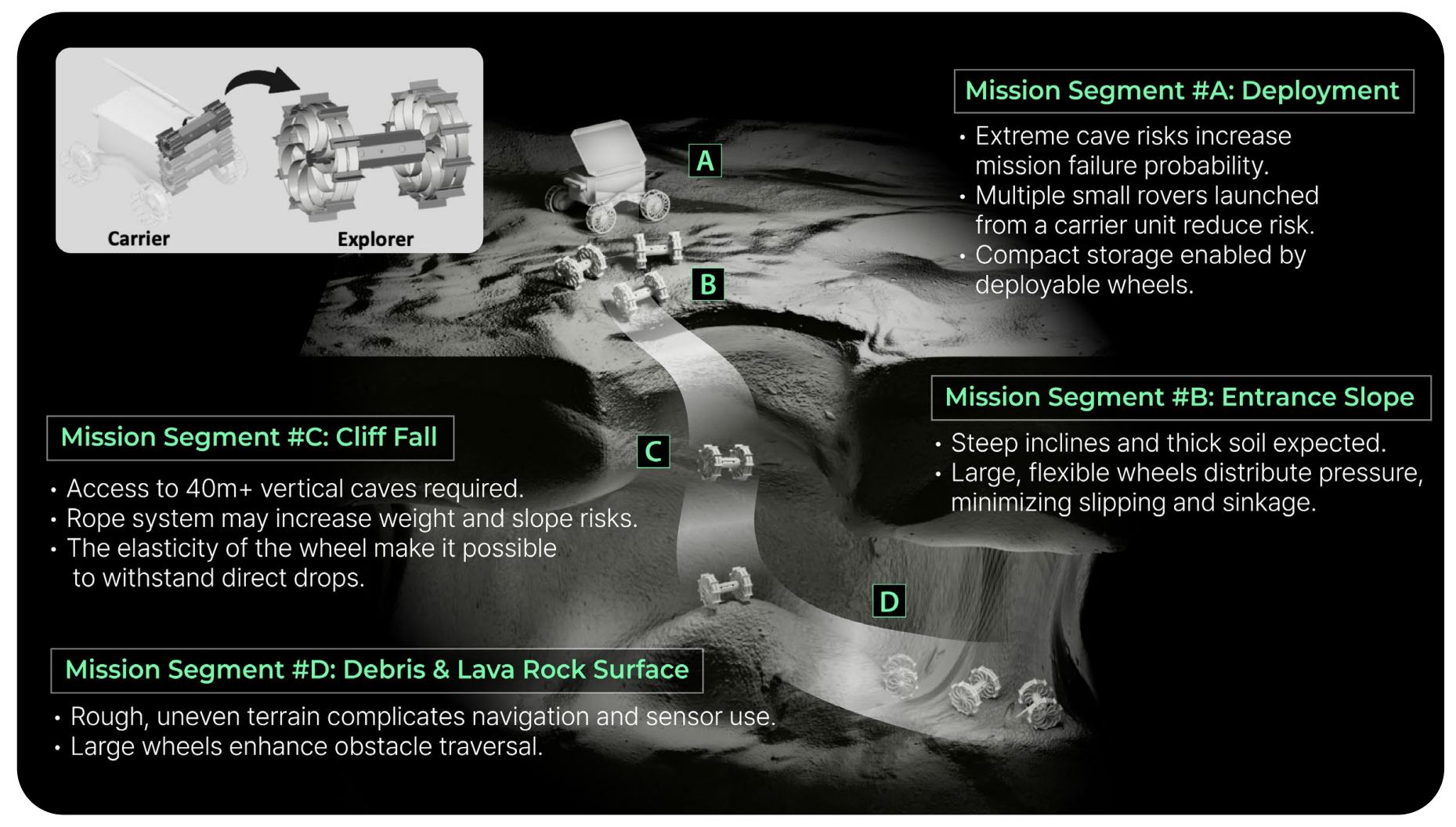


Previously Proposed Entry Method for Lunar Cave

[1] Carrer, Leonardo, et al. "Radar evidence of an accessible cave conduit on the Moon below the Mare Tranquillitatis pit." *Nature Astronomy* 8.9 (2024): 1119-1126.
[2] Fong, Terrence. "NASA Autonomous Systems & Robotics: Roadmap and Investments." Lunar Surface Innovation Consortium Fall 2021 Meeting. 2021.
[3] Lunar scientists and engineers design Moon cave explorer,
https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Lunar_scientists_and_engineers_design_Moon_cave_explorer

► Objectives

We propose a drop-based entry method for accessing lunar caves by descending over 100-meter-high cliffs without additional equipment. The figure below highlights the challenging aspects of this approach for cave exploration.



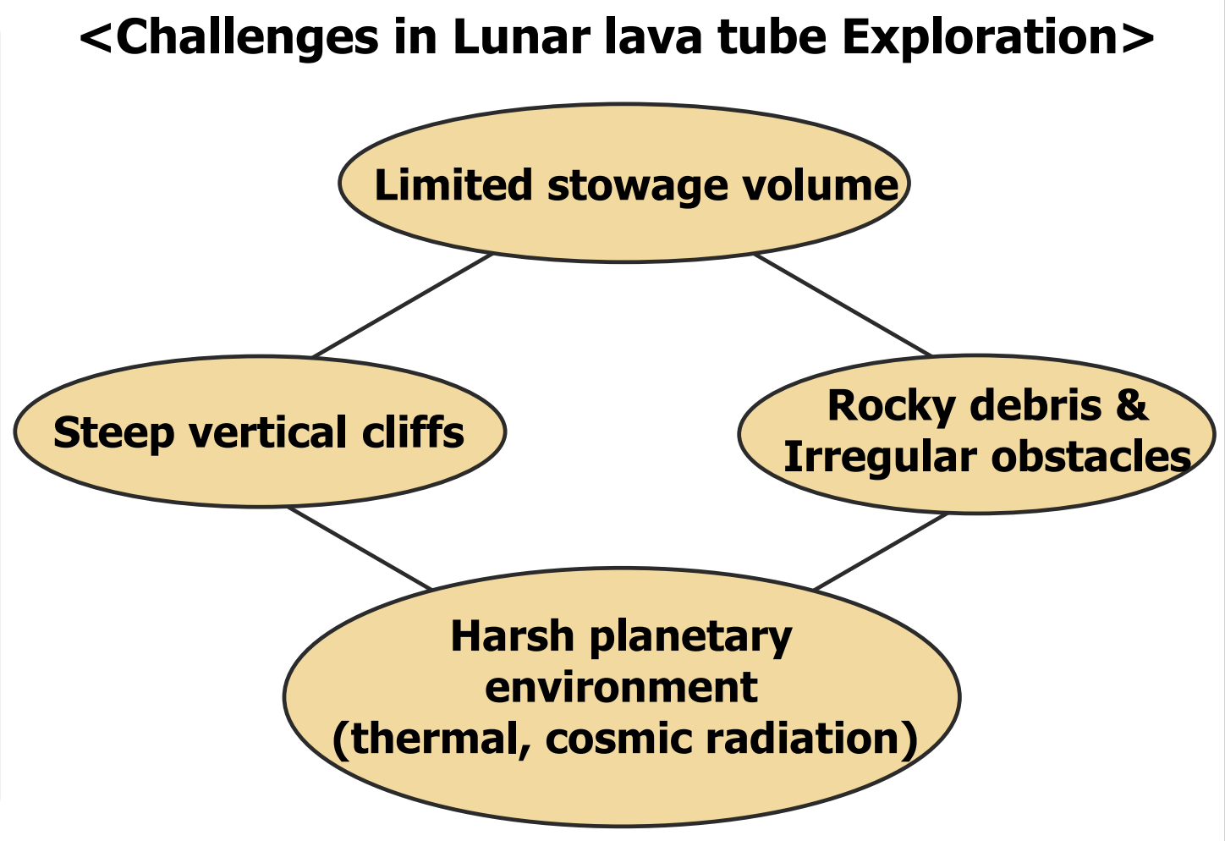
Mission Segment #A: Deployment
- Extreme cave risks increase mission failure probability.
- Multiple small rovers launched from a carrier unit reduce risk.
- Compact storage enabled by deployable wheels.

Mission Segment #B: Entrance Slope
- Steep inclines and thick soil expected.
- Large, flexible wheels distribute pressure, minimizing slipping and sinkage.

Mission Segment #C: Cliff Fall
- Access to 40m+ vertical caves required.
- Rope system may increase weight and slope risks.
- The elasticity of the wheel make it possible to withstand direct drops.

Mission Segment #D: Debris & Lava Rock Surface
- Rough, uneven terrain complicates navigation and sensor use.
- Large wheels enhance obstacle traversal.

Lunar Pit Exploration Mission Scenario



<Challenges in Lunar lava tube Exploration>

Limited stowage volume
Steep vertical cliffs
Rocky debris & Irregular obstacles
Harsh planetary environment (thermal, cosmic radiation)

► Requirements

1. Deformability

Enhancing mission reliability through multi-robot deployment, requiring compactly storable rovers, while also incorporating large-diameter wheels for traversal in rough terrain.

2. Soft wheel structure

A soft wheel structure designed to withstand impact and deformation upon ground collision during a drop-landing approach.

3. Space-compatible material adaptability

The space mobility should be fabricated from space-compatible materials, including steel, enabling durability under impact, thermal-vacuum, and high-temperature extreme lunar environments.

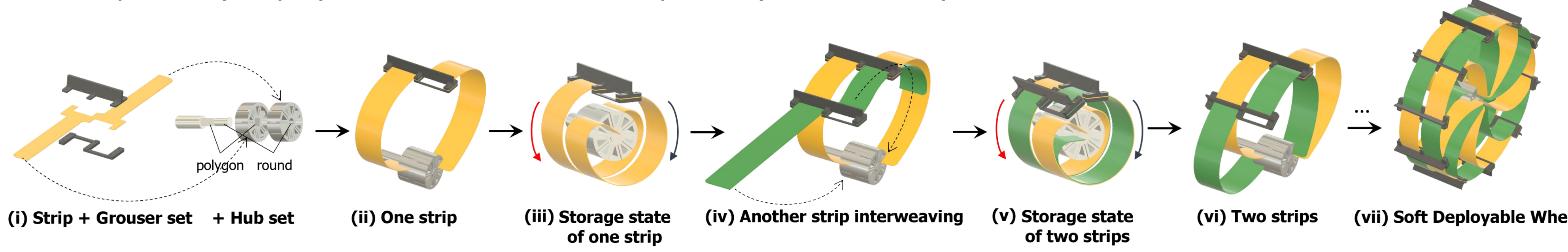
4. Non-hinge component

Rotational joints for shape deformability struggle to operate in dusty environments and are prone to failure under high-impact forces.

➢ Research Results

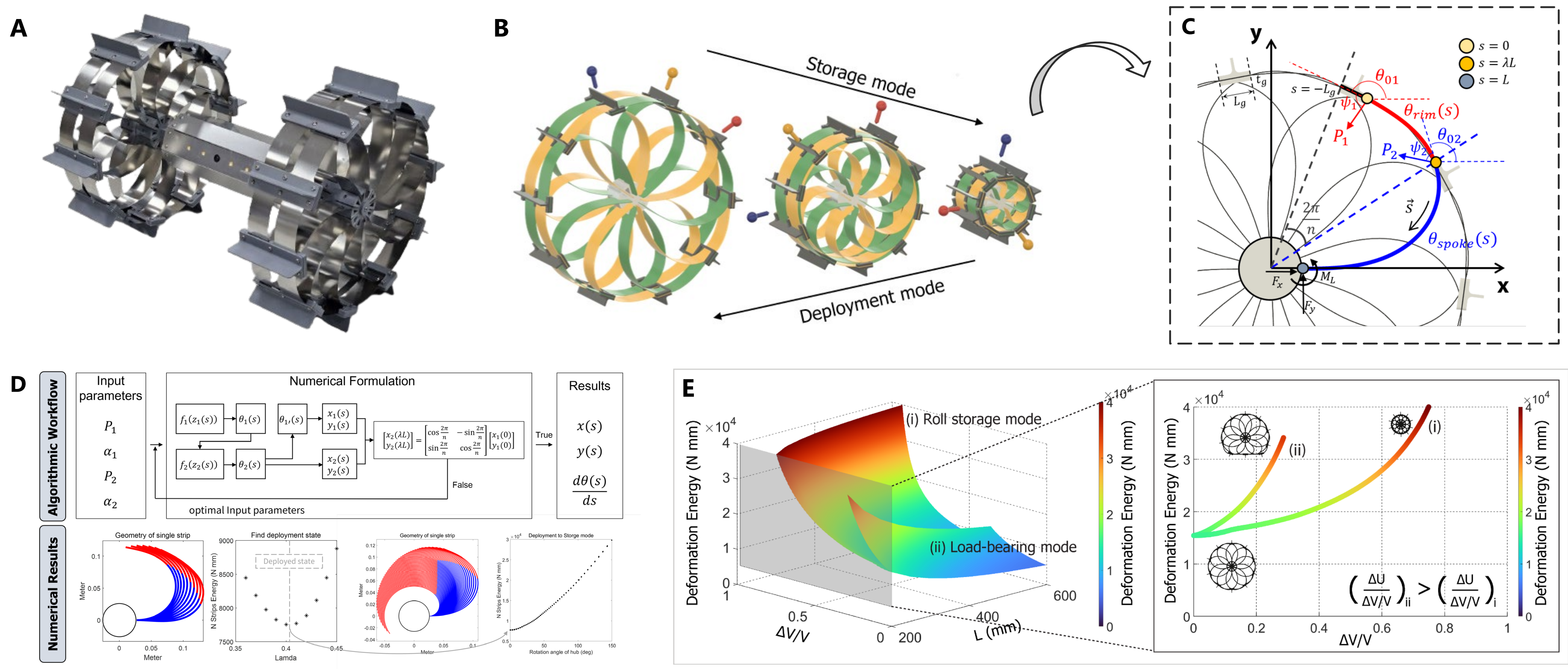
► Soft Deployable wheel fabrication process

The wheel is fabricated by assembling flexible metallic strips into a hinge-free woven structure that can be compactly stowed, passively deployed, and withstand harsh pit-entry and cave-exploration conditions.

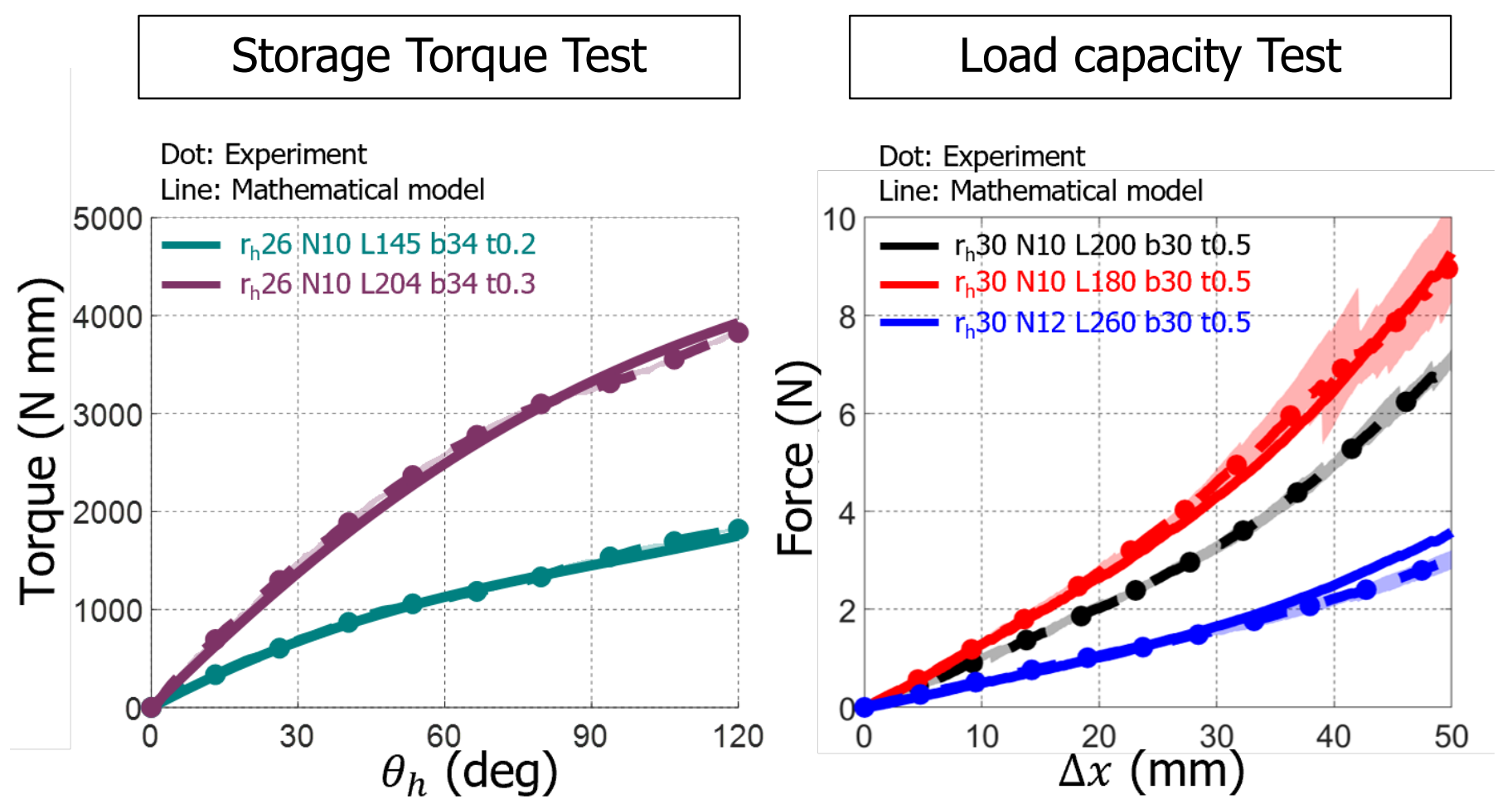


► Analysis of wheel's deployment mechanism and its configuration

A cantilever-beam-based strip model was used to compare the storage–deployment motion and vertical load-bearing deformation, showing that the reciprocal structure enables low-energy storage and high vertical load capacity as an anisotropic, rotational hinge-free wheel structure.

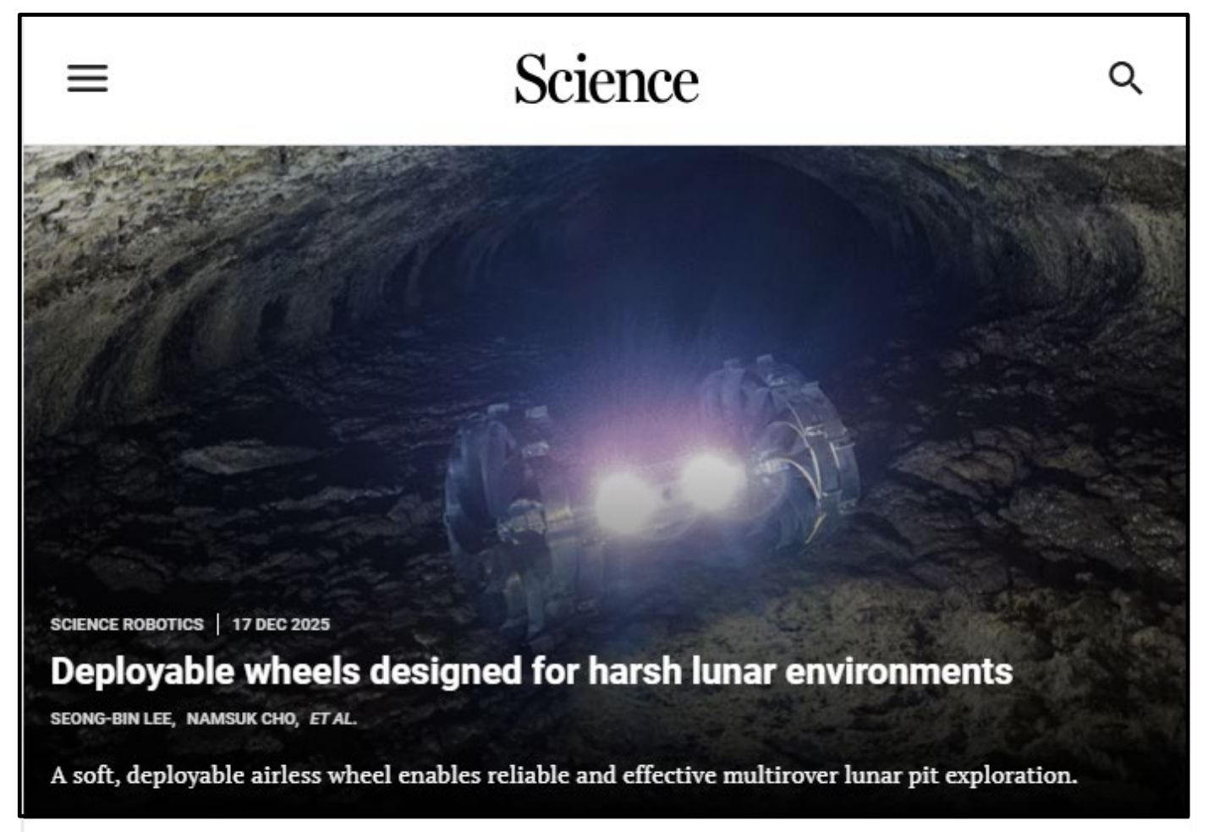


Geometrical description of the wheel structure and coiling mechanism. (A) Soft deployable wheeled rover and **(B)** its structure configuration with roll storage shape mode. **(C)** Shape analysis of a single strip shown in (B). **(D)** Wheel Modeling Algorithm and Shape Analysis Results **(E)** Energy comparison in two different deformation modes, (i) storage and (ii) load-bearing capacity: The reciprocal structure enabled dual stiffness levels and anisotropic properties without the need for additional joints to adjust stiffness



Validation of analysis model. The storage–deployment motion and vertical load-bearing deformation were modeled and experimentally validated, confirming anisotropic behavior with low storage energy and high load capacity.

► Research Output



Science

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Deployable wheels designed for harsh lunar environments

SEONG-BIN LEE, NAMSUK CHO, *ET AL.*

A soft, deployable airless wheel enables reliable and effective multirover lunar pit exploration.

Seong-Bin Lee et al. ,"Soft deployable airless wheel for lunar lava tube intact exploration." ***Sci.Robot.*** **10, eadx2549(2025). DOI:10.1126/scirobotics.adx2549**

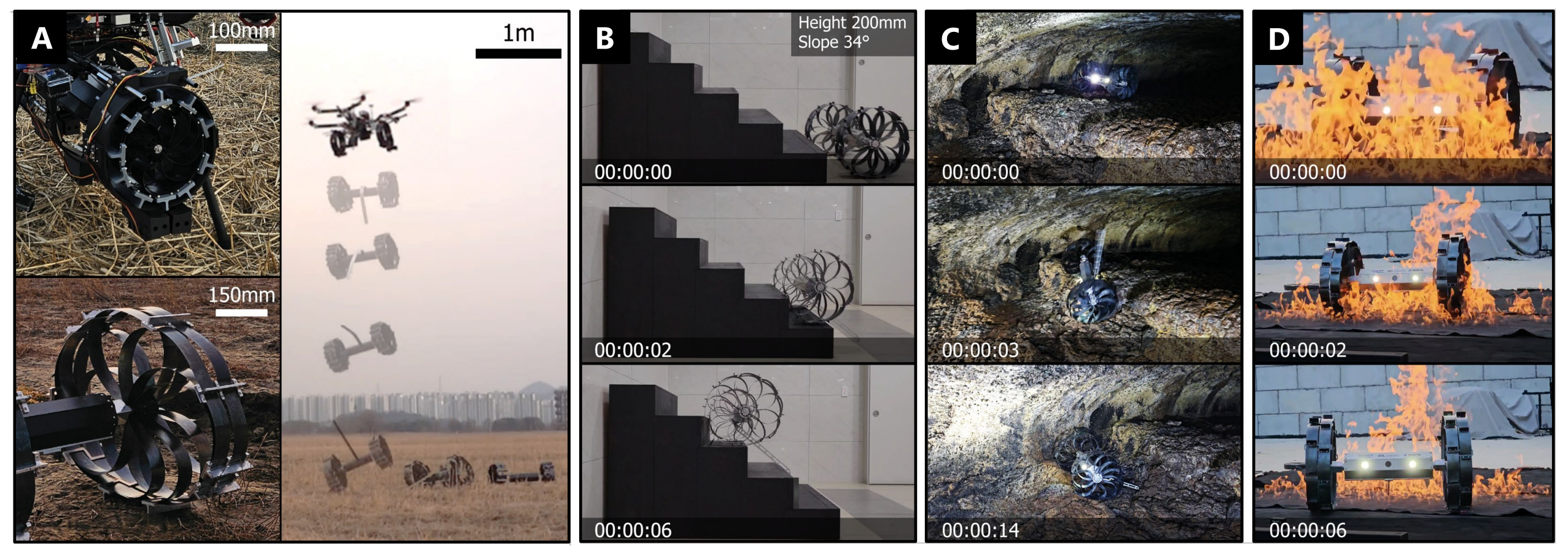
(Link) Research paper

(Link) Youtube video

➢ Mobility Evaluations

► Field Tests

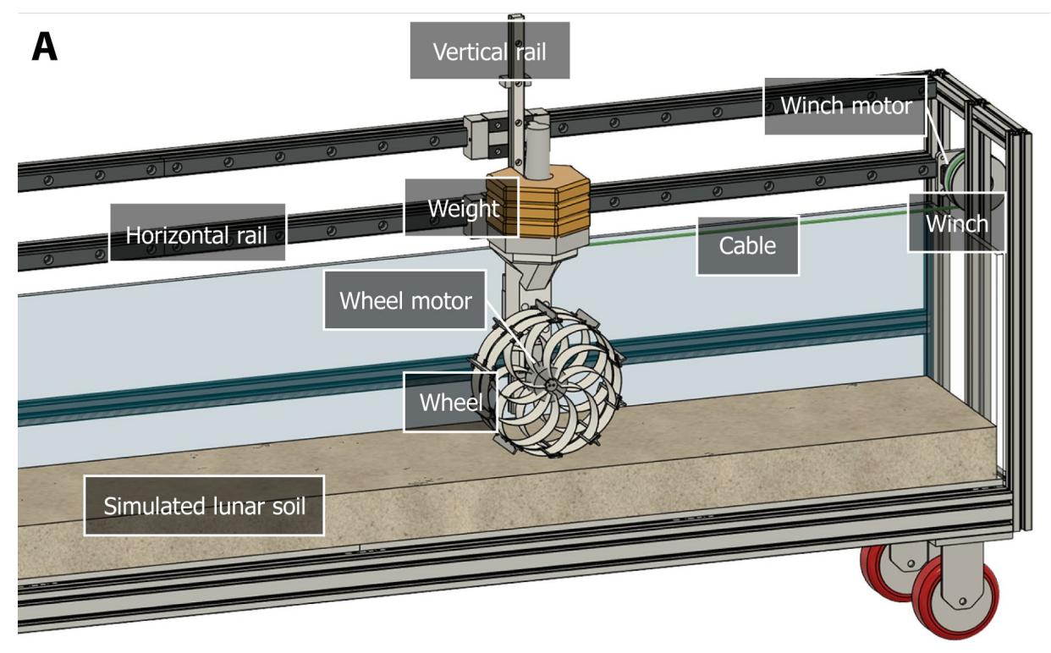
Field tests evaluated rover mobility under key lunar lava tube mission scenarios. These results show that the deployable wheel can connect pit entry and cave exploration within a single compact rover platform.



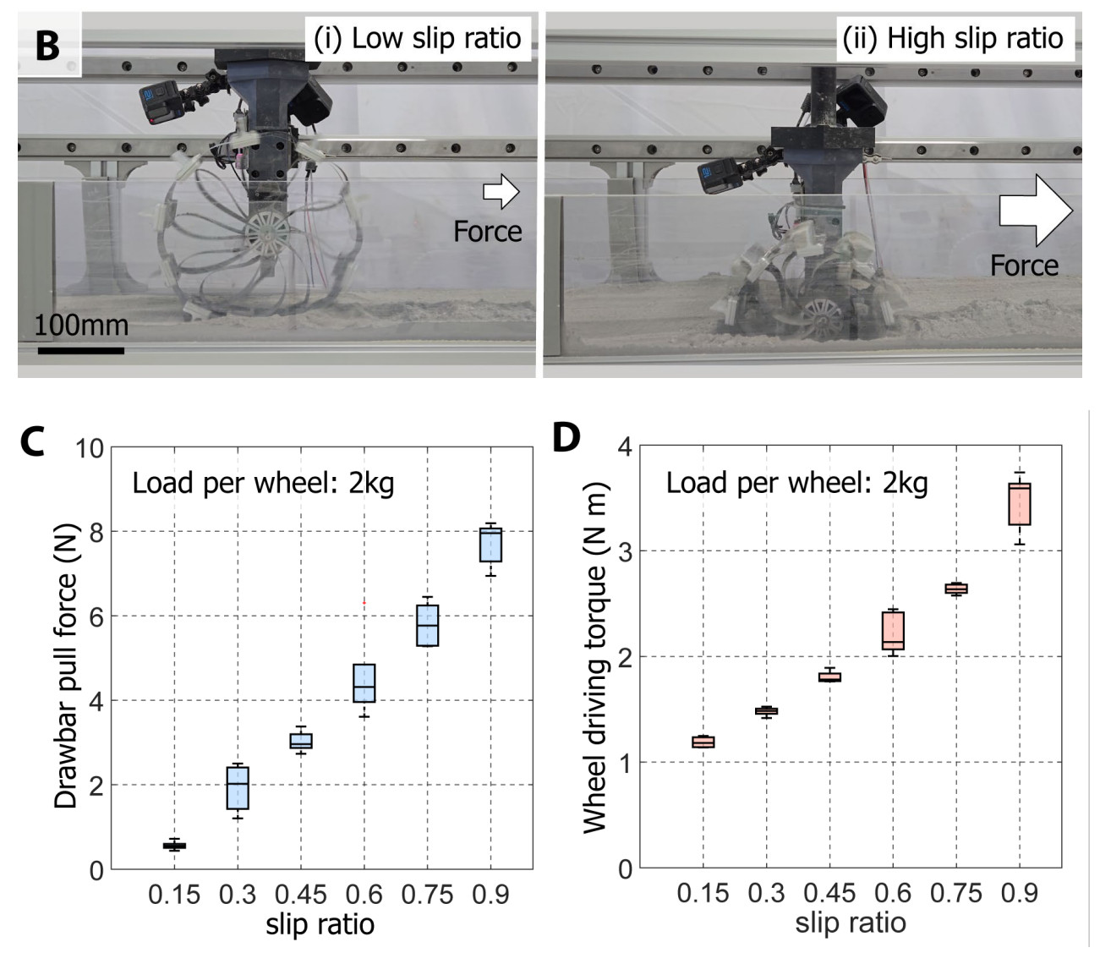
Field tests of the two-wheeled dummy rover equipped with soft deployable wheels under extreme mission conditions. (A) Impact resilience after a 4-m drop, verifying structural integrity. **(B)** Climbing over a 200-mm stair-like obstacle with a 34° incline, demonstrating obstacle-traversal capability. **(C)** Rocky terrain traversal inside a terrestrial cave to validate mobility over irregular cave terrain. **(D)** Driving test at fire environments, confirming thermal durability of the wheel.

► Drawbar Pull Test and Regolith Traversability

The wheel's traction performance was evaluated in simulated lunar regolith by measuring drawbar pull force and driving torque across slip ratios, confirming stable mobility on loose granular terrain.

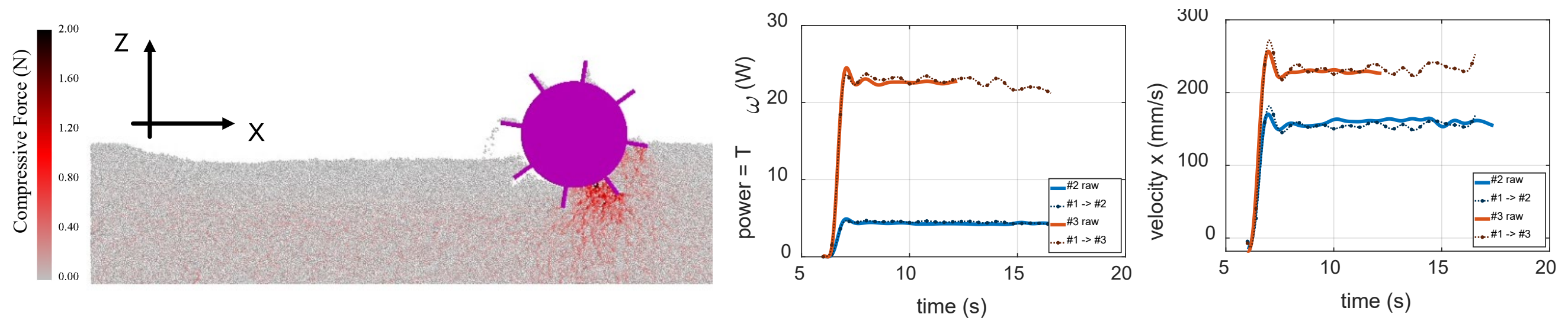


(A) Drawbar pull force testing platform to evaluate performance in simulated lunar regolith **(B)** Performance comparison across slip ratios in simulated lunar regolith **(C)** Drawbar pull versus slip ratio and **(D)** driving torque versus slip ratio were measured



► Ongoing | EDEM-based Mobility Evaluation

Wheel–particle interaction is simulated to predict slip, torque, power and traversability under different wheel configurations and environments.



Particle-based simulation using SIEMENS EDEM is conducted to analyze the mobility of grousered wheel designs and predict dynamic driving performance, including power and velocity, based on terramechanics theory.

	g	M	D	h_g	B	ω
# 1	1635	6	100	20	30	90
# 2	6540	6	100	20	30	180
# 3	9810	13.5	150	30	30	180

g: gravity acceleration (mm/s^2), M: mass (kg), D: Diameter (mm), h_g: length of grouser (mm), B: Width of wheel (mm), ω: angular velocity of wheel (deg/s)

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