LunarLeaper – Unlocking A Subsurface World. A. Mittelholz[1], S. C. Stähler[1], H. Kolvenbach[1], P. Arm[1], V. Bickel[2], J. Church[1], J. Gomez[1], M. Gschweitl[1], R. Margarit[3], J. Aaron[1], S. Coloma[4], M. Grott[4], S. E. Hamran[6], M. Hutter[1], O. Karatekin[7], E. Krasnova[1], M.A. Olivares-Mendez[3], B. Ritter[7], J. Robertsson[1], K. Walas[8], [1]ETH Zurich, Zurich, Switzerland (anna.mittelholz@eaps.ethz.ch). [2]University of Bern, Switzerland, [3]Utrecht University, Netherlands, [4]University of Luxembourg, Luxembourg, [5]DLR, Berlin, Germany, [6]University of Oslo, Norway, [7]Royal Observatory of Belgium, Belgium, [8]Poznan University of Technology, Poland.

Fig. 1: LunarLeaper exploring a lunar pit.

LunarLeaper is a mission concept designed to revolutionize our understanding of the Moon's subsurface and geologic evolution by exploring volcanic pits, steep-walled collapse features on the lunar surface (Fig. 1). To date, approximately 300 such pits have been identified through remote sensing [1]. Lunar pits reveal detailed records of the Moon's geologic history due to their exposed stratigraphy along the pit walls, including information on scale, timing, and nature of mare-forming lava flows. Predominantly found in impact melt and mare regions, pits are of high exploration interest as they might provide access to lava tubes and could thus serve as natural shelters for future astronauts, protecting them from radiation and extreme surface conditions. Orbital imaging suggests that some pits may connect to extensive lava tube systems. However, these observations are constrained by low spatial resolution, and only a surface mission can confirm and characterize the relation between pits and caves. Ground-truth exploration is critical not only to validate orbital findings but also to refine strategies for future lunar exploration and habitation.

As such, LunarLeaper proposes an innovative solution to these challenges [2]: a lightweight (<15-kg) legged robot capable of traversing challenging terrain as expected around pits. Unlike traditional wheeled rovers, which struggle with slopes and boulder fields, and the high cost of large, more complex systems, LunarLeaper's versatile design enables it to explore pit edges and navigate in challenging terrain autonomously. This capability positions LunarLeaper as an effective tool for investigating key scientific questions about the Moon's volcanic history and evolution.

Mission Objectives: LunarLeaper aims to address the following mission objectives O1 – O4:

O1: Investigate subsurface lava tubes: The primary objective of the mission is to confirm the existence and assess the extent of subsurface voids, probing whether lava tubes could be available as a potential site for future investigations. By combining high resolution local ground surveys with available orbital observations (Fig. 2), we can gain further insight on regional geology, thus going beyond a local study of the selected landing site / pit. In addition, the results can be used in the analysis of orbital predictions of similar structures elsewhere on the lunar surface.

O2: Assess the suitability of lava tubes for human exploration and habitation. Lava tubes are hypothesized to span hundreds of kilometers [3], yet only 10 pits have been located in the Mare region. This raises the question of why the collapse occurred and whether further collapse is likely. A further critical aspect in the assessment of suitability for a lunar base is the availability of in-situ resources (ISRs). Lastly, the capabilities of the legged robot allow us to approach the pit and determine the accessibility of the pit edge with potential future large robotic systems or other equipment to be lowered into the pit.

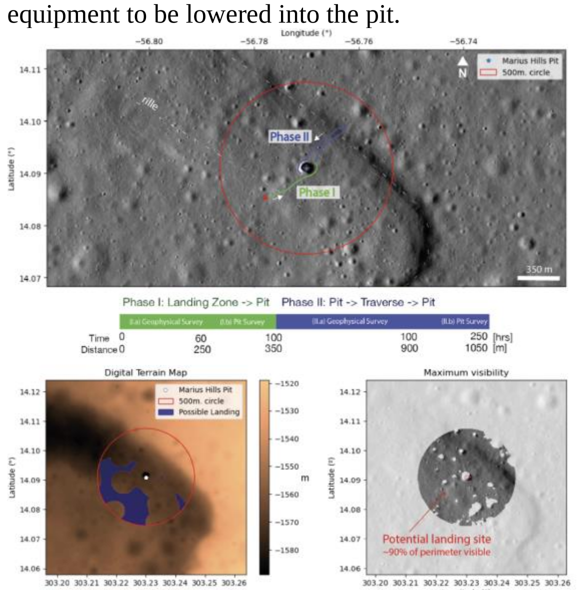

Fig. 2: Traverse example for Marius Hills Pit: Mission scenario with a 2-phase mission. The lower panels show (left) possible landing sites (blue) with minimum distances of 100 m from slopes steeper than 8° in a radius of 500 m around the pit and (right) an exemplary line-of-sight map between a 4-m lander antenna (red dot) and a 0.3 m robot antenna, enabling direct

communication for about 90 % of the perimeter.

O3: Assess geological processes, with a focus on the volcanic evolution of the Moon. The exposed stratigraphy along a pit wall provides a unique opportunity to study key aspects of lunar volcanism and interior evolution. By examining the mare emplacement processes, LunarLeaper aims to determine the number of flows, their volume, and their timescales, which are central to understanding the Moon's volcanic history. Lunar mare basalts are enriched in FeO and TiO_2, depleted in Al_2O_3 and are thought to be a product of remelting of mantle cumulates from early differentiation [4]; These basalts offer critical insights into the compositional evolution of the lunar interior and ancient melt sources. Further, the exposed stratigraphy represents mare layering in the overall region and connecting these observations with studies of the geophysically inferred shallow subsurface allow to extend findings from specific sites to more regional context.

O4: Investigate the local and regional extent of the regolith. Regolith, including paleo-regolith is directly linked to the geological and impact history of the Moon, and its composition and structure holds crucial information. The lateral and vertical extent of regolith is still an open question, one that can ideally be addressed using a mobile robot with a ground-coupled GPR for subsurface investigation. The properties of lunar regolith, including its composition, structure, and mechanical behavior, directly impact mission design, landing safety, mobility, and the feasibility of in-situ resource utilization (ISRU) for future lunar exploration [5] as discussed in the context of O2.

Mission concept: After landing and taking advantage of the currently offered lunar landing infrastructure, we propose to approach a chosen pit with a legged robot, which can access complex terrain and steep slopes that are observed at the pit edge. LunarLeaper will land on the lunar surface and traverse across the rille, i.e., the extent of the hypothesized subsurface lava tube (Fig. 2 for the Marius Hills Pit). On its traverse it will take measurements with a ground penetrating radar (GPR) and a gravimeter, measurements that will allow us to survey the subsurface structure and detect and map lava tube geometry if present. The robot will approach the pit edges and acquire high resolution images and compositional information of the pit walls containing uniquely exposed layers of the geophysically mapped lava flows and regolith layers. These images will allow not only scientific advances of lunar volcanism and regolith formation but also enable assessment of the pit structural stability and its use as a possible lunar base. The mission is expected to last 1 lunar day (14 Earth days with margin).

Beyond LunarLeaper: As several recent Moon landings have occurred, and new missions are preparing for eventual human habitation, LunarLeaper can play a role as an important reconnaissance mission, paving the way for missions to come and exploiting novel robotics systems. Notably, the robot will be the first technology demonstration of legged locomotion in space and not only demonstrate current capabilities, but also create future opportunities for applications on the Moon and beyond. The mission will validate several technologies related to robot design, actuation and AI-based control. While several validation campaigns including locomotion tests in parabolic flight campaigns (Fig. 3) have been successful, the design of a space-qualified system is currently ongoing. This mobility solution offers access to the previously inaccessible, and complements ongoing efforts to explore the lunar surface and develop a lunar infrastructure for science and exploration [6]. Lastly, the compact robot design allows for delivery to the surface by small landers as currently developed and planned by various national and commercial agencies.

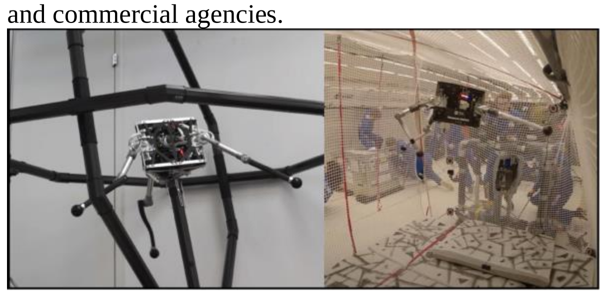

Fig. 3: Several legged robot validation campaigns have been performed by the consortium, such as a locomotion test at 83rd ESA Parabolic Flight Campaign.

Conclusion. LunarLeaper stands out in its ability to substantively advance the fields of science, exploration and technology. By exploring lunar pits, it advances exploration by enabling access to previously unreachable terrains and investigating potential future habitats for astronauts. Scientifically, it addresses fundamental questions about the Moon's volcanic history, including the presence of subsurface caves, the timing of lava flows, and changes in volcanic composition. Technologically, it pioneers the use of a lightweight (<15-kg) legged robot, where versatility and autonomous capabilities offer an effective solution to traversing challenging lunar terrain with broad applications for planetary exploration.

References: [1] Wagner & Robinson, 2014, *Icarus*, 237, 52-60. [2] Kolvenbach et al., 2024, *IAC* [3] Sauro et al., 2020, *Earth Sci. Rev*., 209. [4] Shearer et al., 2006, *Rev. Mineral. Geochem*., 60, 365-518. 46 [5] Rasera et al., 2020, *Planet. Space Sci.*, 186. [6] Crawford et al., 2012, *Planet. Space Sci.*, 74, 3-14.