LunarLeaper – Unlocking A Subsurface World. A. Mittelholz[1], S. C. Stähler[1], H. Kolvenbach[1], V. Bickel[2], J. Church[1], S. E. Hamran[3], O. Karatekin[4], B. Ritter[4], J. Aaron[1], B. Anhorn[1], S. Coloma[5], L. de Palézieux dit Falconnet[1], M. Grott[6], C. Ogier[1], J. Robertsson[1], K. Walas[7], [1]ETH Zurich, Zurich, Switzerland (anna.mittelholz@erdw.ethz.ch). [2]University of Bern, Switzerland, [3]University of Oslo, Norway, [4]Royal Observatory of Belgium, Belgium, [5]University of Luxembourg, Luxembourg, [6]DLR, Berlin, Germany, [7]Poznan University of Technology, Poland.

Fig. 1: LunarLeaper exploring a lunar pit.

Introduction: LunarLeaper is a mission to explore the lunar subsurface, proposed in response to the 2023 ESA call for small lunar missions (Fig. 1). Lunar pits, also known as skylights, are collapse features on the lunar surface and they might provide access to subsurface lava tube systems that could harbor future human explorers for extended periods of time [1,2]. They further provide a window into the Moon's ancient past because they uniquely expose a record of the magnitude, timing, and composition of volcanic flows along their edges. As such, we propose a mission to explore the Moon's subsurface: LunarLeaper is a 10kg-class legged robot that is set to approach the Marius Hills pit (MHP), one of the skylights thought to tap into a large cave system [2,3,4], located in one of the Moon's youngest and mysterious volcanic provinces. LunarLeaper's innovative design enables it to autonomously navigate challenging terrain around the pit and characterize the traversed terrain using a combination of well-proven geophysical and imaging methods. LunarLeaper will shed light on fundamental questions about the Moon's geologic history: Are volcanic rilles the surface expression of large caves? What is the timing of lunar lava flow events? How did the composition of lunar volcanism change over time? LunarLeaper will confirm whether the pit indeed taps into the hypothesized cave system and further assess its suitability for human exploration and habitation.

Mission concept: Multiple pits (200+) have been mapped on the lunar surface [2]. We focus on the MHP on the lunar nearside, because imaging under different illumination angles supports the hypothesis that it offers an entryway to an ancient lava tube. The pit is located in Oceanus Procellarum, a region where extensive lava tube systems are expected. With a diameter of ~50m, the pit is small which makes the surroundings easily traversable with a robot [3,4]. Notably, the Marius Hill skylight has been subject of mission concepts [5,6] and such mission ideas are often extensive (and expensive), and aim to access the lava tube, relying on the hypothesis that the lava tube is indeed underlying the observed pit. Typically, large rover and crane systems are utilized, while terrain characteristics are challenging and stability close to the pit is a major unknown. Here, we propose to approach the pit with a small legged robot (<10 kg), the LunarLeaper, which can access complex terrain and steep slopes that are expected at the pit edge. LunarLeaper will land on the lunar surface and traverse across the lateral extent of the hypothesized subsurface lava tube (Fig. 2 and 3). 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 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 structure stability and its use as a possible lunar base. The mission is expected to last 1 lunar day (14 Earth days).

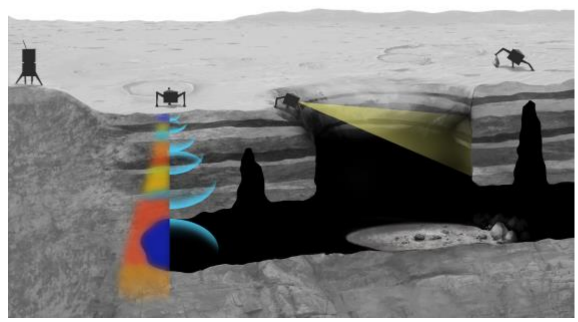
Fig. 2: Lunar Leaper taking measurements while approaching and crossing the pit connected to a lava tube.

Mission Objectives: We expect 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 investigate 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. 3), 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. First, suspected lava tubes span hundreds of kilometers on the lunar surface, 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 and traversability with large robotic (crane-) systems or other equipment to be lowered into the pit.

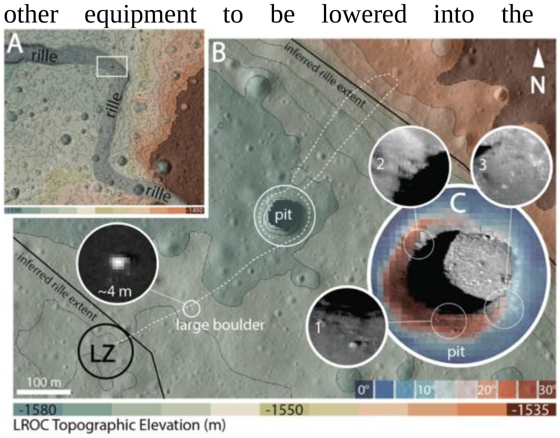

Figure 3 - Overview: (A) Topography surrounding the MHP highlighting the volcanic rille. (B) zoom in of white box in (A) with outline of a notional landing zone (LZ) and traverse path (white dashed). Note the adapted color scale. A ~4m-large boulder is highlighted to represent possible features of interest along the way. The white circle outlines (C) the pit. Color represents the slope angle along the pit edge. Several boulders and challenging terrain along the edge are visible.

O3: Assess geological processes, with a focus on volcanic evolution of the Moon. Exposed stratigraphy is uniquely accessible along a pit wall [3] and allows to address questions about mare emplacement, including the number of flows, their volume, and timescales, central to understanding lunar volcanism and thus interior evolution. 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 [7]; thus, they provide a view of the compositional lunar interior and provide a unique location to gain understanding of ancient melt sources and magma compositional evolution over time. Further, the exposure of said layers represents mare layering in the overall region and connecting these observations with studies of the geophysically inferred shallow subsurface allow to extend the extremely localized view at the pit to a more regional one.

O4: Investigate the local and regional extent of the regolith. 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 thus still an open question, one that can ideally be addressed using a mobile robot with a ground-coupled GPR for subsurface investigation; similarly uncertain are physical properties. Both aspects are highly relevant for future ISR utilization and exploration activities [8], as discussed in the context of O2. Pits exposing several layers protected from more recent geological activity and that might ultimately be accessible underground, i.e., from lava tubes, are unique sample sites.

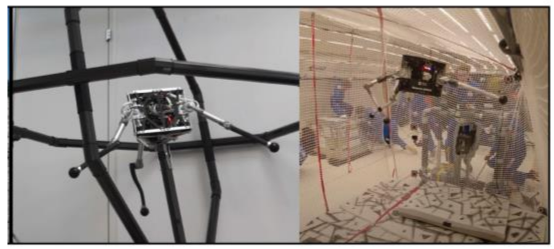

Fig 4: Several legged robot validation campaigns have been performed by the consortium, such as a locomotion test at 83rd ESA Parabolic Flight Campaign.

Beyond LunarLeaper: As several recent Moon landings have occurred, and new missions are preparing the way 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.

- The potential for future exploration: Investigated caves could offer ideal targets for a lunar base.
- Robotic advances (Fig. 4): The legged robot system 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.
- A landed mission: It is of great importance to demonstrate a leap in progress in lunar surface science, exploration and technology [9]. This can only be achieved by soft-landing on the surface. The robot can be delivered to the surface by a small lander, currently developed and planned by various national and commercial agencies.

References: [1] Sauro et al., 2020, *Earth Sci. Rev.*, 209. [2] Wagner and Robinson, 2014, *Icarus*, 237, 52-60. [3] Robinson et al., 2012, *Planet. Space Sci.*, 69, 18-27. [4] Haruyama er al., *GRL*, 36, 2009. [5] Hooper et al., 2023, *PSJ*, 4, 2. [6] Miaja et al., 2022, *Acta Astronaut.*, 192, 30-46 [7] Shearer et al., 2006, *Rev. Mineral. Geochem*., 60, 365-518. [8] Rasera et al., 2020, *Planet. Space Sci.*, 186. [9] Crawford et al., 2012, *Planet. Space Sci.*, 74, 3-14.