# Lunar Caves Exploration with the DAEDALUS Spherical Robot

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**Introduction:** During the past few years crewed and robotic exploration of the Moon has regained focus in the activities of the scientific community and space agencies. Following this trend, ESA placed a call for ideas on its Open Space Innovation Platform for a SysNova LunarCaves system study to explore lava tubes through skylights. Part of this effort is the DAEDALUS (Descent and Exploration in Deep Autonomy of Lava Underground Structures) mission design concept that aims at exploring and characterising the entrance of Lunar lava tubes within a compact, tightly integrated spherical robotic device, with a complementary payload set and autonomous capabilities. The mission concept specifically addresses the identification and characterisation of potential resources for future ESA exploration, the local environment of the subsurface and its geologic and compositional structure using laser scanners, cameras and ancillary payloads. A sphere is ideally suited to protect sensors and scientific equipment in rough, uneven environments. When lowering the sphere into the skylight via a crane, it explores the entrance shaft, associated caverns and conduits. A moving mass enables motion on the bottom of the pit. To improve the locomotion capabilities, to increase stability for data collection and to prevent failures extendable pods complete the actuator scheme.

**Mission Summary:** The DAEDALUS mission is planned within the Marius Hills region where a lunar skylight with underlying void has been discovered in the past decade [1] and consists of four mission phases to improve the science return. Approaching the pit is not part of this mission. Nevertheless, a characterisation of the landing site was carried out as part of the DAEDALUS study to ensure feasibility of landing, approach to the pit and deployment of the sphere [2]. During the first three phases the sphere is lowered into the pit by a crane allowing for both tethered communication and power supply. Only in the last phase the sphere is detached and operates autonomously.

*I) Skylight approach and descender deployment:* The DAEDALUS sphere is deployed and lowered into the pit using a crane system mounted on a dedicated rover. Since the Marius Hill skylight has a sloping area before the void, the spherical shape of the robot and the extendable pod subsystem help to overcome issues arising when the sphere cannot be suspended directly into the pit due to a shortness of the crane.

*II) Skylight descent and mapping:* While descending the laser scanner and the panoramic cameras are used to create a 3D point cloud of the shaft. An encoder measuring the tether length gives an inital depth estimate. Redundancy is achieved by performing robotic SLAM (Simultaneous Localization and Mapping) on the laser data and stereo vision as well as SfM (Structure from Motion) on the camera data. Besides context 360 imagery, VIS dual hemispheric cameras provide also stereo imaging of illuminated overlapping areas as well as close-range imaging, useful for textural characterization of the lava layers of the shaft walls. In the meantime, thermal, radiation and dust sensors will provide information about the thermal gradient as well as the environment condition within the pit enabling the generation of vertical radiation and temperature profiles during descent.

*III) enter the main void and mapping from the descender tether the main cave environment:* When passing the cave ceiling, the lidar system acquires the first 3D point cloud from within the cave taking advantage of the larger range from an elevated view point and allowing for a structural analysis of the cave. The cameras capture a full view of the main void using natural or artificial illuminations, if required. Thermal/radiation/dust sensors acquire define horizontal radiation and temperature profiles. Before touchdown, the objective of close characterization of the ground with multi-band LIDAR and cameras will be achieved.

*IV) Initial navigation and tunnel mapping:* Once touching the ground the sphere detaches from the tether and navigates through the cave autonomously using the 3D data from phase III for initial navigation planning. Depending highly on the morphology and geometry of the lava tube, exploration up to several hundred meters is possible with the tether acting as a wifi hotspot and charging station. Obstacle evaluation and terrain strength data are to be acquired by passive seismometry with the embedded accelerometers and extendable pods acting as Schmidt hammer at touchdown. While terrain roughness, obstacles, radiation and rock magnetism limit the deployment and distance of travel, this mission phase is highly dependent on the unpredictable cave configuration.

**Science Return Levels:** The DAEDALUS mission is designed to yield progressive scientific return in each of the phases. The overall scientific objectives are:

1. Exploration of the evolution of volcanism through windows within the lava flow successions on lunar maria;
2. Identification and characterization of potential paleo-regolith layers and pyroclastic deposits;
3. Detection of fresher rocks and outcrops from deeper locations less affected by space weathering;
4. Generatation of a 3D map based on LiDAR and SfM data of pit walls and lunar caves;
5. Verification of the volatiles' presence within the cave;
6. Research of locally sourced resources that can be integrated in crewed missions architecture;
7. Definition of subsurface environmental conditions;
8. Generation of temperature and radiation profiles.

While the minimum viable scientific return is achieved in phase I and the early stages of phase II by analysing the lunar skylight entrance, the nominal mission science return is achieved during phase II and phase III by analysing the entire pit and the cave floor at the main void. The extended mission science return will be achieved during the tunnel mapping in phase IV. Here more information about the stability of the cave ceiling as well as the trafficability of the cave is collected.

**Robotic Sphere:** The DAEDALUS sphere design consists of two main structures (Figs. 1, 2). The inner structure comprises the imaging and controlling components, namely two laser scanners, four multispectral cameras with hemispheric lenses, two micro controllers, two switches, one heater, and one rotatable battery. To characterize the surface material the lidars operate in two different wavelengths and the cameras are coupled with narrowband filters for further analysis of the surface composition using four identified spectral bands. In idle position off-centered battery shifts the center of mass towards the ground. The outer structure holds mainly the pole mechanism, a light source, and the shell itself. One of the outer poles is used as a physical connection , electrical and data transfer when connected to the cable. Two electrical motors connect the inner and the outer structures allowing them to rotate relatively to each other.

Figure 2 depicts the four different operation modes. In descending mode, while being lowered into the cave, the sphere is coupled to the tether via one of the side pods. The inner structure rotates to enable full coverage of the surroundings by the optical sensors and LIDAR. When on the ground, due to the low center of mass of the inner structure caused by the battery, using the motors triggers rotation of the outer structure leading to a rotation of the entire sphere and therefore locomotion. Steering can be achieved by rotating the battery and therefore center of mass to one side. The camera system has full

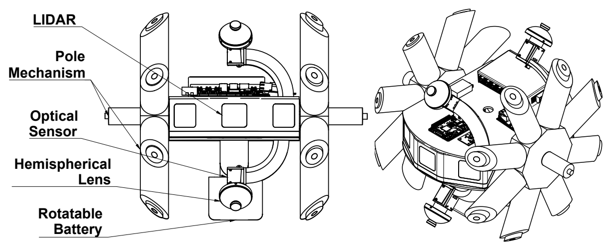


Figure 1: Overall CAD sphere design without outer shell.

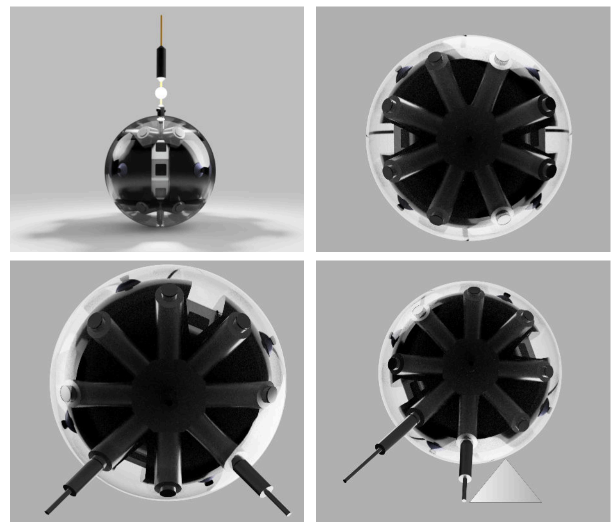

Figure 2: The different modes of the Sphere. Top-Left: Desending Mode. Top-Right: Rolling Mode. Bottom-Left: Scanning Mode. Bottom-Right: Obstacle Mode.

mono and partial stereo coverage. The lidar scans forward and backward. To overcome this two limitations in lidar, optical stereo coverage and to increase the data resolution a special scanning mode is introduced, where the poles lift up the sphere acting as a tripod. Activating the motors will now lead to a rotation of the inner structure of the sphere and with it the optical payloads. In the obstacle mode the poles are used to push the sphere over obstacles, resolving the limitations of locomotion by rotation .

## References

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