ESA OSIP Lunar Caves System Study

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| Project: | Bio-inspired robotic hopper locomotion for navigation through hazardous terrain in extreme space environments |
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# 1. Introduction

Traditional planetary exploration missions utilise a single rover platform with wheeled locomotion that can traverse moderately uneven terrain. More extreme rocky surfaces are challenging, and the risk to mission success of the lone rover becoming lodged or toppling is prohibitively high. Exploration of lunar pits incorporates locomotion on mixed media, featuring smooth and rocky features, making wheeled rovers inviable.

To address this, we propose a network of low cost, low mass agile hoppers that have the locomotive capability to negotiate complex terrain. Hopping locomotion also offers a low cost of transport across smooth terrain when operating in a low gravity environment. Each hopper would have the capacity to operate independently while also communicating with nearby rovers to share navigation and mapping data, utilising a range of complementary sensing packages, which could be deployed across the hopper network. The use of a multi-hopper network will support a wider exploration range. It also provides an opportunity for some rovers to descend into the pit, while others remain around the pit rim. The design will also consider integration of technologies, which will support descent into lunar pits and cave systems and the powering and operation of the rovers within these systems; a core ambition here is for the descended hopper to support future missions by establishing a mechanical and communications link between pit and lunar surface. Additionally the design will consider integration of suitable sensor packages to address key lunar science and exploration scientific objectives.

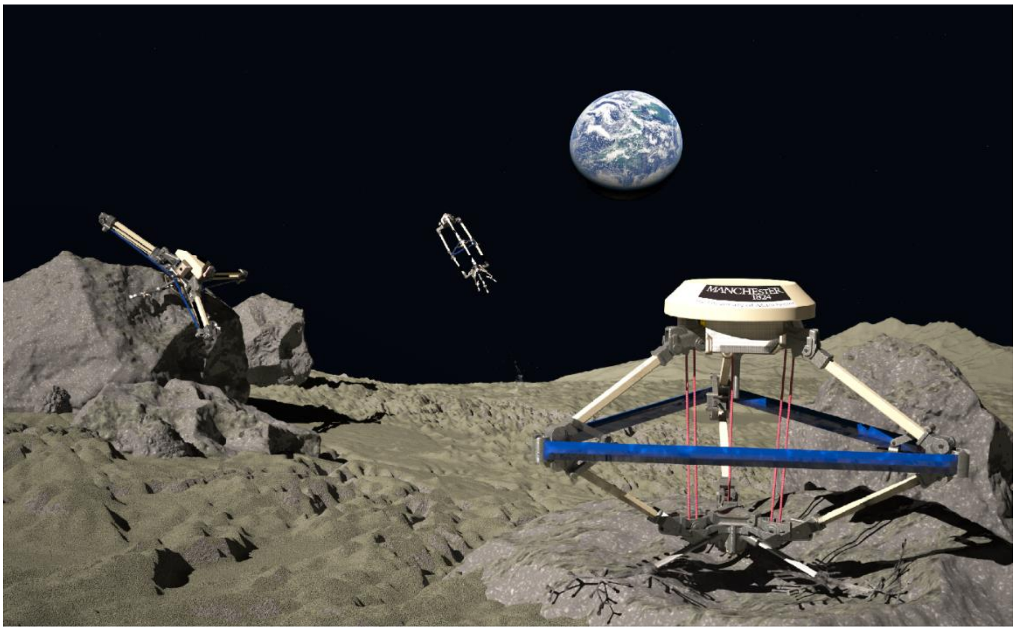


Figure 1.1 Artistic render of preliminary hopper mechanism design , excluding protective envelope and cage.

## 2. Example Mission description

To support the design of a suitable hopper platform an example mission to the Marius Hills region and the Marius Hills lava tube skylight, which is situated at coordinates 14.091 °N, 3030.2232 °E (Figure 2.1), has been proposed by the ESA Lunar Caves team. The principal aims of the mission would be to demonstrate hopping locomotion for lunar exploration, undertake exploration of the pit rim and provide a locator beacon for future missions to the MHH skylight.

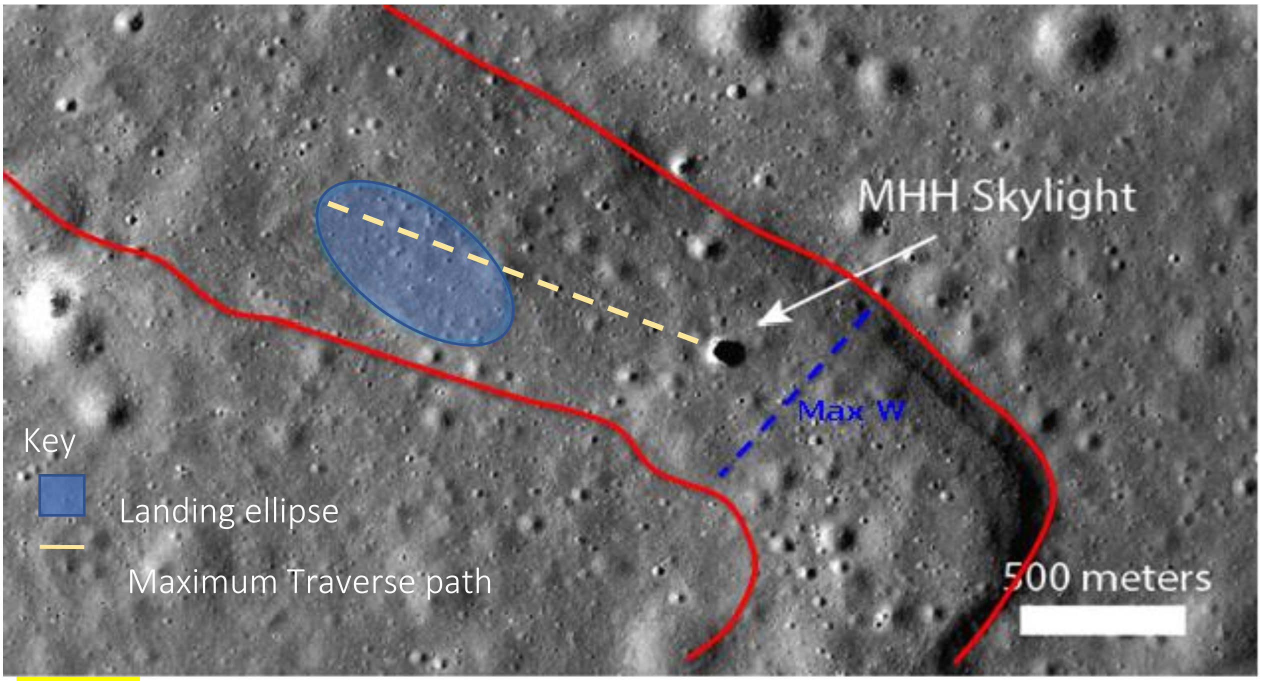


**Figure 2.1.** ESA Lunar Caves Proposed exploration site in the Marius Hills Skylight (image credit LROC: NASA/GSFC/ASU adapted by ESA Lunar Caves team and UoM).

The top level mission requirements are identified in table 2.1

Table 2.1 Mission requirements.

| ID | Description |
|---|---|
| MR1000 | The mission should have a maximum duration of 1 lunar day |
| MR2000 | The system shall be capable of traversing between the landing site and the MHH skylight |
| MR3000 | The mission should include exploration of the pit floor |
| MR4000 | The mission shall include integration with EL3 lander or similar lander mission |

# 3. System design development

The system design development process involved a review of potential science questions and complementary payloads

A parametric system model has been developed to support the analysis of the design options under consideration. The overall system model design structure matrix (DSM) identifying the key components for the mission is given in figure 3.4. A more detailed view of the DSM for the hopper system alone is given in figure 3.5. The model includes outputs from simulation tools (Matlab , Unity and COMSOL) , the key aspect of the modelling for each subsystem is covered in the subsequent subsections of this report.

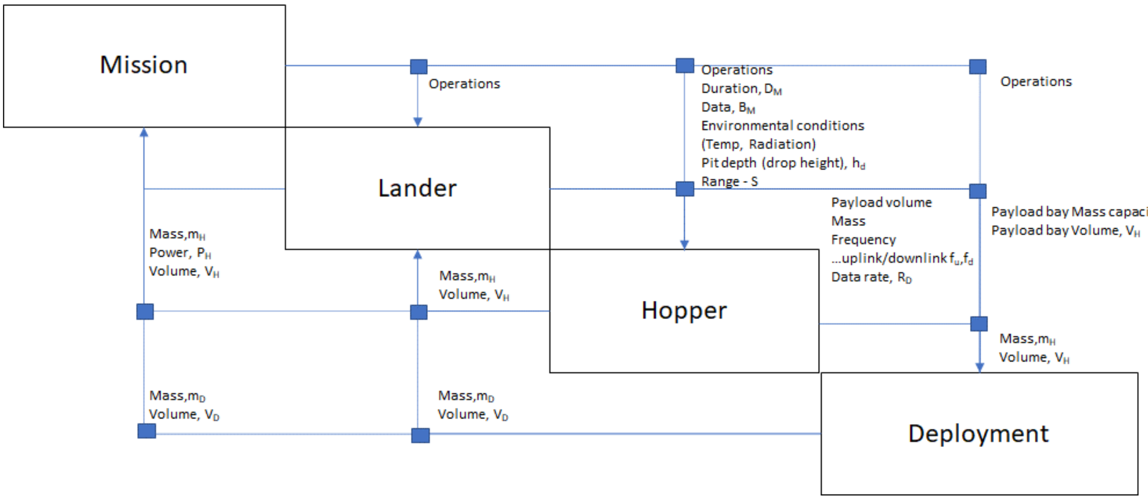


Figure 3.4 Mission system model Design structure matrix (DSM)

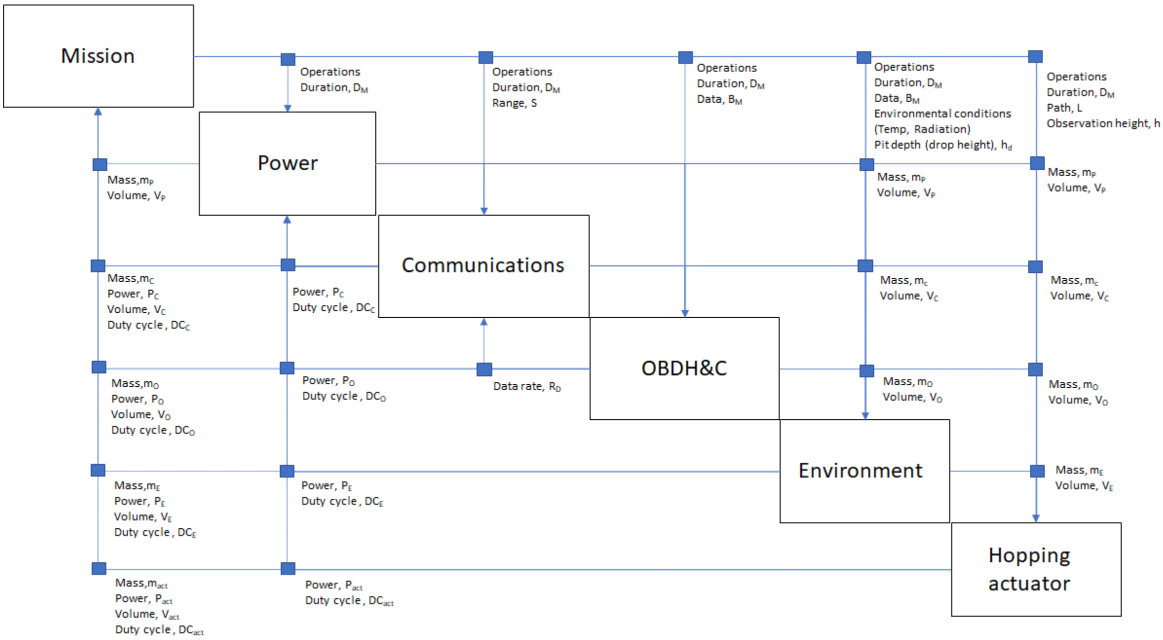


Figure 3.5 Hopper system model DSM

## 3.1 Science payloads

The first consideration for selecting hopper payload instruments was mission operations and constraints from an engineering, electrical, or safety perspective. A key science question we aim to address with lava tube exploration is whether lunar caves would be useful for future human habitation of the Moon, from a physical habitat and resources perspective. When designing the payload package, we wanted to ensure that instruments were capable of assessing cave accessibility, cave size, hazards within the cave, the presence of volatile elements, and the composition of potential volatile reserves. The proposed payload package is given in Table 3.1

Table 3.1 proposed payload package

| | | | | |
|---|---|---|---|---|
| | Temperature probe x2 , Magnetometer, Camera (EECam), LIDAR (OSI-128), | Human, Regolith properties (thermal conductivity), Hazard mapping, magnetic field strength,, public engagement | 38 W | 1 kg |

## 3.2 Hopping actuator

The design of the hopping actuator is one of the critical aspects of the overall hopper system design. There are two principal designs for the hopping actuator: direct driven (DD) where a motor directly drives a lever arm to produce the hopping moment for the rover, or compression spring driven (CS) where the motor is used to energise a compression spring which upon release provides the energy for the hop. The direct-driven system is conceptually and mechanically simpler, but is limited by the maximum mechanical output power of the motor. The compression spring system used the mechanical spring to amplify the motor output power and achieve greater larger take-off velocity and jump height that the direct driven system for a given motor.

A trade off analysis of these actuator options identified that the CS driven system provided more favourable performance.

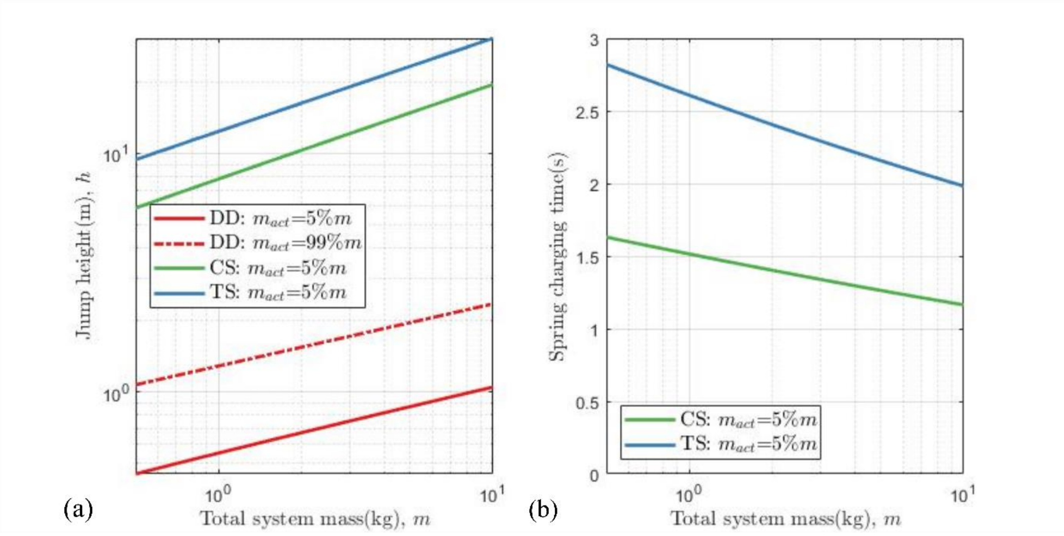

Figure 3.19 The trade-off between systems: (a) jump height difference, (b) spring-charging time difference

# 4. System design

This section provides an overview of the proposed system design and road map for technology development.

## *4.1 Proposed system description*

The proposed design is a torsion spring-driven rhomboidal hopping actuator, has an overall mass of approximately 3.8kg and has a maximum height of 50cm. In each fully-charged jump, the system stores 132J of elastic potential energy in the torsion springs. If all the stored elastic energy is converted to the gravitational potential energy, it would jump over 20m under lunar gravity; or travel a distance of 33m with the take-off angle at 63 degrees. The spring charging time is around 2.2s if using a 62W brushless DC motor. The payload consists of a LIDAR (OSI-128) , camera unit (EECam) and two thermocouples the location and relative sizes of each of these elements are illustrated in Figure 4.1.

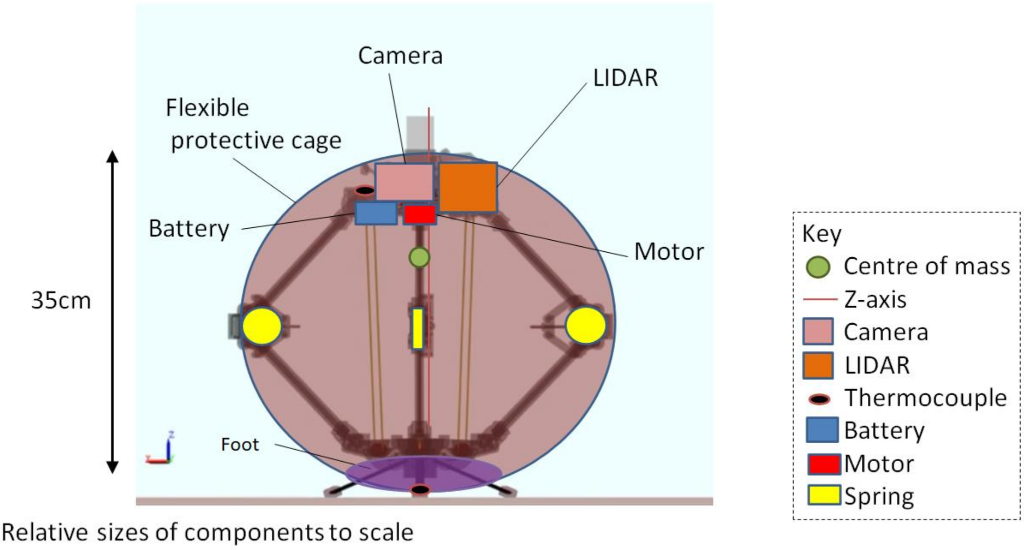


Figure 4.1 Proposed 3.8kg hopper system.

The mass breakdown of the proposed design is shown in figure 4.2. The 1.5kg scientific payload and descent mechanism occupies nearly 40% of the system mass and follows by the battery (26%). The capacity of the battery is sufficient to cover five times the required distance (1600m) and powers the onboard scientific instruments for 2 hours at 100% duty cycle. The pair of torsion spring have a mass of approximately 650g (17%) with a spring stiffness of 13.4Nmrad$^{-1}$. The structure is 10% of the system mass approximated further more detailed analysis of the structure is required. As the lightest component in the design, the actuator mass is approximately 190g. The remaining 2% of unassigned space is left as the tolerance (or spare mass) of the model.

Table 4.1 provides an estimate of the TRL of the key components of the hopper defined by the ISO Technology Readiness level (TRL). Where TBD the final equipment has not yet been identified however an anticipated TRL is identified from existing commercially available technologies that have been developed for CubeSat platforms and could be easily adapted to fit within the hopper design.

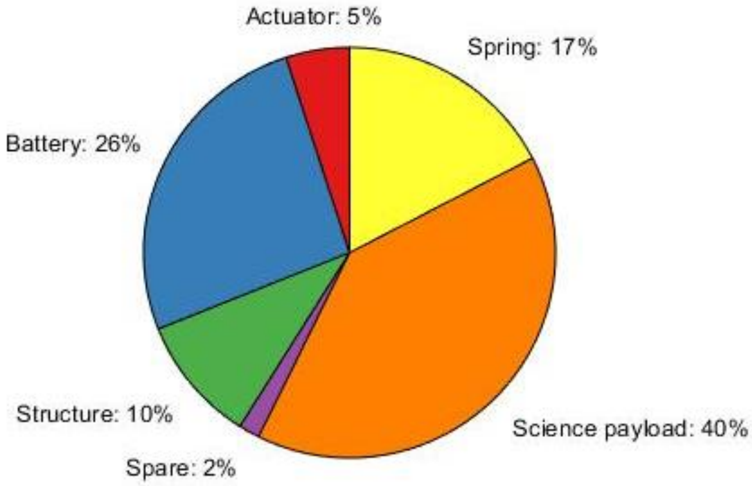


Figure 4.1 Mass breakdown of the purposed design with a torsion spring-drive rhomboidal hopping actuator. Max jump height : 20m , Max leap 33.6m. Total mass 3.8kg, Motor power 65,9W, spring charing time 2.2s. Misison ideallised travelling time 48min (253 jumps)

Table 4.1Component Technology Readiness level (TRL) for the hopper.

| Sub-system | Equipment | TRL |
|---|---|---|
| A. Power | Battery (Saft VES16) | 8 |
| | Power conditioning unit | TBD (expected 8) |
| | Charging interface | 3 |
| B. Communications | Antenna | TBD (expected 8) |
| | Transceiver | TBD (expected 8) |
| C. OBDH&C | Processor | TBD (expected 8) |
| | Data storage | TBD (expected 8) |
| | Sensors: Accelerometer | TBD (expected 8) |
| | Sensors: Camera | 8 |
| | Sensors: Science payload (LIDAR) | 8 |
| | Sensors: Science payload (Camera - EECam) | 8 |
| | Sensors: Science payload ( Thermocouple x2 Magnetometer) | 8 |
| D. Environmental | Dust screen | 2/3 |
| | Crane interface | 3/4 |
| | Impact protection : Airbag | 3 |
| | Thermal control: Radiator | 3 |
| | Thermal control: Heater | 3 |
| E. Hopping Actuator | Actuator: Motor- 62W brushless DC Maxxon motor | 8 |
| | Actuator: Spring | 4 |
| | Actuator: Structure | 4 |
| | Actuator: Thrust vector | 3/4 |

## *4.2 Road map technology development*

TBC