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A Collaborative Robotic System for Entering and Mapping Martian Caves

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Abstract

Martian caves represent prime locations for investigating evidence of extinct or extant life. In this paper, we propose a technology demonstration mission for Martian cave exploration using a heterogeneous robotic system. Heterogeneous systems are advantageous for Martian cave exploration due to their specialisation for specific tasks, flexibility, and adaptability to diverse conditions. Our mission focuses on the exploration of type 1 atypical pit crater caves in the Elysium Mons region due to their scientific value regarding the potential existence of life and ice water deposits. These caves, situated near the equator, offer low elevation and reduced radiation effects, ensuring safer landing conditions and high scientific outputs. Our mission considers the design of a robotic system capable of entering and mapping the cave environment under five work packages (System, Mission, Payload, Electrical and Mechanical). A risk analysis, concept of operations and budget were established to make sure the requirements and objectives of the mission were fulfilled. To accomplish this mission, we have traded-off different rover locomotion concepts and selected a heterogeneous robotic system comprising a wheeled rover and a multi-rotor aerial robot in a parent-child configuration. The mission is defined in multiple phases starting with the traversal of the wheeled rover and the aerial robot from the landing site to the selected cave. Once at the cave entrance, the rover scans the circumference, and the aerial robot goes into the cave through the entrance to map it. The aerial robot will use a Simultaneous Localisation and Mapping (SLAM) algorithm along with a LIDAR to map and navigate the cave's interior. The wheeled rover (parent ship), powered by solar arrays, serves as a communication and recharging station at the cave entrance. Using a docking station, it will enable the aerial robot to recharge and communicate with Earth. The cave entry and mapping are demonstrated with a simulation to test the viability of the proposed approach. The proposed autonomy of the heterogeneous robotic system is demonstrated using simulation results in MATLAB Simulink.

Keywords: Cave, Exploration, Robotic system, Mars

ACRONYMS/ABBREVIATIONS

AOA	Angle Of Attack
CONOPS	Concept of Operations
ECSS	European Cooperation for Space Standardization
EDL	Entry, Descent and Landing
EOL	End-Of-Life
ESA	European Space Agency
LIDAR	Light Detection and Ranging
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering and Medicine
NRC	National Research Council
OBDH	On-Board Data Handling
RS	Robotic System

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SLAM	Simultaneous Localisation and mapping
SP	Special pit
TRL	Technology Readiness Level
TWR	Thrust to Weight Ratio
UAV	Unmanned Aerial Vehicle

1. INTRODUCTION

Over 3,545 subsurface access points have been found on 11 celestial bodies in our solar system. These "access points" are cave entrances. On Mars, they could give access to a warmer, more stable environments along with no ionising radiation. These underground conditions are significantly more hospitable than the surface, making these areas of high interest for the search of life on Mars, possibly allowing caves to eventually host future human habitation. Hence there is significant attention given to Martian cave exploration mission in the next decade [1].

Two key challenges of the Martian cave exploration are traversability inside caves and entrance accessibility. Based on these two challenges, the Martian caves can be typically classified in four categories: (i) low-slope low slope terrains with smooth drivable terrain (low traverse low access difficulties), (ii) narrow vertical entrances (high access difficulty) with easy-to-traverse terrain, (iii) easy horizontal access with rugged unstructured terrain to traverse, and (iv) difficult access and traversability due to vertical entrance and rugged terrain [2]. Considering this, there are various robotic systems that were proposed in the literature for cave exploration.

Robots/rovers play a vital role in planetary exploration and due to their ability to traverse rugged terrains in harsh planetary environments makes them a suitable candidate for Martian cave exploration missions. Several missions, such as NASA's Perseverance rover [3] and the Ingenuity helicopter [4], have demonstrated the potential of wheeled and aerial robots on Mars. Wheeled rovers, which currently have a high Technology Readiness Level (TRL), are reliable but face limitations when it comes to accessing and navigating challenging Martian cave terrains. As a solution, helicopter and multi-robot systems are increasingly being considered for such missions.

Various robotic systems, including wheeled, legged, and flying robots, have been proposed for traversing the complex terrains of Martian caves. Wheeled systems, while reliable, may struggle with the vertical entry points and irregular surfaces found in caves. Helicopter-based robots, such as Ingenuity [4], offer enhanced mobility and can access vertical cave entrances, though they are limited by power and endurance. Multi-robot systems, which combine different types of robots (e.g., wheeled and aerial), offer the advantage of specialization for different tasks, providing flexibility and adaptability. However, these systems come with challenges such as increased complexity and the need for robust coordination and communication between robots.

An example of a tethered multi-robot system is the Axel project [5], developed by NASA's Jet Propulsion Laboratory. It consists of the Axel rover, a two-wheeled tethered robot designed to work in conjunction with a larger mother rover. The mother rover remains on stable terrain, while Axel descends into hazardous areas, such as steep cliffs or caves, using the tether for support and retrieval. This configuration allows Axel to explore otherwise inaccessible environments while maintaining a connection for power and communication. Although the tether introduces limitations in range and complexity in system management, the Axel system shows great promise for accessing challenging Martian cave terrains [5].

The CoRob-X project [6] is another example of a multi-robot system designed for planetary exploration. It features diverse locomotion capabilities, including the SherpaTT rover, with four-wheel active suspension for rough terrain; Coyote III, with star-shaped wheels for unstructured environments; and LUVMI-X, optimized for mapping. While these robots' complementary capabilities provide flexibility in challenging terrains, managing their coordination and communication adds significant operational complexity. Nevertheless, such multi-robot systems offer promising solutions for complex Martian cave exploration [6].

To achieve the scientific objectives of a Martian cave exploration, a robotic exploration system should be able to map the cave geometry, determine the traversability challenges, document the cave environment and Map the compositional and lithological diversity of the cave materials, including looking for volatiles, and organics [7].

To develop a potential multi-robot system, key technical challenges [1] are as follows:

- Enhance robotic mobility for navigating complex planetary terrains.
- Develop autonomy for monitoring overall robot health and functionality, and traverse route planning
- Implement advanced communication networks for subsurface exploration
- Create efficient power systems for subsurface use
- Miniaturize and ruggedize robotic sensory systems suitable for low light to completely dark environments
- Miniaturize science payloads

This paper describes a baseline cave-exploration mission concept design including an autonomous heterogeneous rover system based on the results of a

four-month work of a team of students at Cranfield University. As the key contribution of this work, an autonomous heterogeneous robotic system concept is developed and investigated as a potential solution to explore a selected cave. Mapping the cave geometry and determination of traversability challenges are considered as scientific objectives of the mission. The key focus of the work is to address the following engineering challenges: selection and development of a mobility system in terms of design (mechanical, electrical, and payload) and cave exploration, efficient communication and power system definition, and autonomy for autonomous navigation including traverse route planning and decision making. These challenges and scientific objectives are posed as a stakeholder's statement of work and used to derive the requirements. The proposed mission is designed by applying a system engineering approach, assessing the overall design against requirements and stakeholder's expectations.

The remainder of the paper provides comprehensive insights into several key areas of the mission design and planning. Starting with Section 2, the mission definition outlines the aims, objectives, and top-level requirements for the mission. In Section 3, the operational site and heterogeneous robotic system selection are discussed, focusing on choosing an optimal Martian site and developing a suitable robotic system. Section 4 delves into the concept of operations, detailing the planned phases of the mission, including surface and subsurface exploration. The next section, robotic system and technologies in Section 5, elaborates on the design and technologies behind the chosen robotic system. Section 6 addresses the electrical power systems, ensuring energy efficiency, while Section 7 outlines the on-board data handling and communication systems required for autonomous operations. The budgets, discussed in Section 8, cover the mission's mass, power, and cost allocations. In Section 9, the robotic system analysis provides an evaluation of the system's performance. Finally, Section 10 presents the conclusions, summarizing the key takeaways and future considerations for Martian exploration.

2. MISSION DEFINITION

This section outlines the mission aim and objectives along with high-level requirements to achieve them.

2.1 Aim & Objectives

The aim of this mission is to demonstrate the autonomous exploration and mapping of a Martian cave using a heterogeneous robotic system. By employing a combination of robots, the mission will advance our understanding of Martian caves' geometry and environmental conditions, while validating the use of multi-robot systems in challenging subsurface environments.

To achieve the aim, two objectives are defined as follows:

- Selection of a Martian cave to be explored, based on scientific interest and accessibility.
- Design and development of a multi-robot system to demonstrate entry, traversal, and mapping of a Martian cave.

2.2 Top-level Requirements:

Based on the objectives, the top-level requirements are separated into three categories as follows:

1. Constraint requirements: These requirements address the mission's financial and technical constraints, such as adhering to the mission budget and selecting the appropriate type of caves for exploration.
2. Operational requirements: These define the operational conditions the system must meet, including the mission's lifetime, communication between the robots, and ensuring that the robots can be recharged.
3. Functional requirements: These focus on the functionality of the system, such as the traversal of the robotic system from the landing site to the cave, ensuring the landing ellipse compliments the EDL technology used, and the robotic system's ability to withstand the Martian cave environment.

The top-level requirements were developed through an iterative process over 4-6 months, allowing for adjustments based on evolving mission insights and technical considerations. This approach ensured that the final requirements were well-aligned with both the mission's objectives and its budgetary, operational, and technical constraints.

3. SELECTION OF OPERATIONAL SITE AND HETEROGENEOUS ROBOTIC SYSTEM

Based on the mission objectives, this section details the process of selecting the Martian operational site and cave, as well as the development of a heterogeneous robotic system for exploration. Through structured analysis and trade-offs, the mission aims to balance scientific value with operational feasibility, while optimizing the robotic system's performance for surface and subsurface exploration.

3.1 Selection of Operational Site

Based on the first mission objective, the process of selecting an optimal landing site and cave for the Mars mission involved a structured, multi-staged analysis

which was divided into three stages: region selection, cave type selection, and final cave selection, each supported by trade-off analysis to ensure the choices aligned with mission objectives. The requirements are that the cave should be accessible and traversable for robotic exploration along with a good potential for scientific return to ensure the selected cave map could support the future scientific missions.

3.1.1 Landing Site/Region Selection

The trade-off analysis for landing site selection compared two major regions on Mars: Tharsis Montes and Elysium Planitia. These regions were chosen for their proximity to the equator and the abundance of cave entrances, essential for scientific exploration. The analysis considered factors like diversity of volcanic history, scientific potential, ease of landing, number of caves, and climate. Elysium Planitia emerged as the preferred region due to its favourable climate, ease of landing due to lower elevation, and broader scientific return potential making it the optimal choice for the mission [8] .

3.1.2 Cave Type Selection

Within the Elysium Planitia region, three types of caves - Type 1, Type 2, and Type 3 were evaluated based on depth (scientific scope), ease of entry, traversability, and surface regularity. Type 1 caves, which are bell-shaped and very deep with flat floors, scored the highest overall. Despite challenges in ease of entry, Type 1 caves offer more depth, excellent surface regularity, and high traversability, making them ideal for significant scientific discoveries and easier navigation within the cave for robotic exploration. In contrast, Type 2 caves are bowl-shaped with uneven floors, offering better ease of entry but poor traversability and surface regularity, which reduces their suitability for exploration. Type 3 caves provide excellent ease of entry and surface regularity, but their shallow depth and moderate traversability challenges due to dust and rubble make them less favourable. Ultimately, the trade-off analysis confirmed Type 1 caves as the best candidates for robotic exploration due to their balance of scientific potential and navigability [8].

3.1.3 Final Cave Selection

A detailed evaluation of 11 Type 1 pit craters in the Elysium Mons region was conducted, focusing on their elevation, size, and potential for exploration [8]. Cave SP 5 was selected as the final target for exploration particularly due to its comparatively low elevation which facilitates easier traversal on the surface around the cave entrance and easier entry. Its vertical entrance and low elevation provide advantages for landing and operational efficiency, making it the most suitable candidate for autonomous robotic exploration and mapping [8].

3.2 Selection of the robotic system

After the landing site and cave to be explored were selected, the Robotic System (RS) was configured in an iterative process considering the following key points:

- Iterative calculations and trade-offs determining the most suitable type of architecture and the locomotion mechanism that complements it.
- Multiple parameters were considered for the RS configuration highlighting the number of robots required and the overall behaviour and interactions between them.

3.2.1 Trade-off Parameters

The Robotic System trade-off considered nine main parameters:

- Reliability and robustness of the RS to perform mission requirements.
- Whether the RS can provide one or more forms of redundancy.
- How equipped the RS is to adapt to specific or unexpected environmental conditions.
- How complex the is the RS to be integrated into the mission (software and hardware implications)
- The overall mobility potential of the RS configuration.
- The manoeuvrability potential of the RS over rugged surface/subsurface terrain.
- The stability/tendency of the RS to stay upright and not get stuck.
- The energy efficiency or how much energy each RS configuration could consume while traversing a unit distance.
- The mechanical complexity and therefore the overall financial cost required for research and development/manufacturing.

Each parameter was carefully analysed and given a weight based on its significance and impact on the mission.

3.2.2 Types of architecture

The two main types of architecture considered are the heterogeneous and homogeneous systems. Heterogeneous RS architecture was selected as it allows the configuration to consist of two distinct specialized robots where one robot is optimised for vertical cave entry and traversal of unknown terrain and the other acts as a support providing a communication link, providing an electrical power supply, performing surface exploration and providing transport to the cave site.

3.2.3 Locomotion Configuration

Six distinct types of locomotion were considered for the Robotic System which are:

- Wheeled
- Legged (walking/two legs)
- Climbing (legs with grippers for upside-down/highly angled terrain)
- Crawling (snake-like motion)
- Hopping (timed jumping)

Another trade-off analysis was then performed using the parameters discussed earlier with focus on what traversability advantages each locomotion type can provide while maintaining reasonable complexity to fit within the budget requirements.

An aerial system supported by a wheeled rover was chosen as the ideal configuration since an aerial based locomotion provides the most reliable method with minimum risk to explore the vertical cave entrance while minimising the risk of not being able to traverse terrain formations like overhanging rims or vertical terrain structures.

Since the wheeled rover has a good TRL and was tested on Mars in previous missions (like the perseverance mission). it was the obvious choice to minimise the complexity and the research and development costs of the mission [9].

3.2.4 Parent-Child Configuration

There are multiple configuration methods considered for the heterogeneous RS. The ones considered are:

- One parent – One child
- One parent – Multiple children
- Multiple independent robots

The final selection continued with the same trade-off but with emphasis on system integration complexity. One parent robot with one child robot was selected as the finial architecture since it consists of only two robots capable of supporting each other during different mission phases where the terrain is vastly different while also fitting within the budget constraints requirement.

Finally, an Unmanned Aerial Vehicle in an X8-Quadcopter configuration coupled with a wheeled rover for support was chosen as the final configuration after further analysis and simulation of the RS.

4. CONCEPT OF OPERATIONS

This section outlines the operational strategy for the mission, considering system performance constraints and power limitations and estimated timelines for various phases of the mission. The mission is divided into three key phases: Phase 1 involves the launch, cruise, and EDL operations; Phase 2 focuses on surface and subsurface exploration; and Phase 3 addresses the End-of-Life (EOL) scenarios. The primary focus of this mission is on Phase 2, which details the rover and Quadcopter's traversal and exploration of the Martian cave system after landing.

4.1 Phase 1: Launch to Landing

For phase 1, the mission's launch vehicle, trajectory, and Entry, Descent, and Landing (EDL) operations were selected based on key criteria for successful Mars deployment. The Atlas V-541 was chosen for its proven capability to carry large payloads, with the ability to transport both the rover and Quadcopter [10]. A Hohmann transfer orbit was chosen for energy efficiency, with the launch window falling between May 10, 2027 and May 30, 2027 i.e. 80-100 days after the Mars opposition on February 19, 2027, ensuring the mission takes advantage of the most favourable alignment between Earth and Mars [11] [12]. The EDL process draws on proven methods from NASA's Perseverance rover, using an aeroshell, Range Trigger technology, and a skycrane manoeuvre for precise, controlled landing [3]. The plotting of the landing ellipse on the Martian surface is shown below in Figure 1.

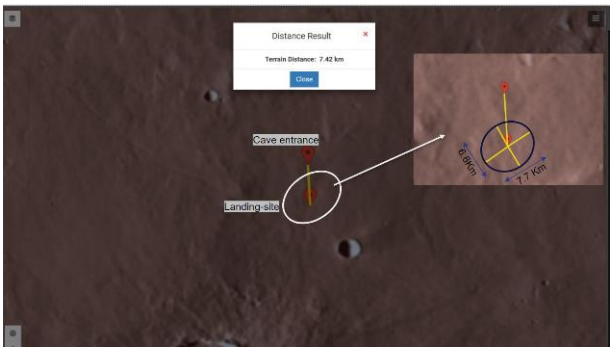

Figure 1: Landing Ellipse Location near the Cave [13].

By employing a combination of advanced technologies and strategies for EDL as Perseverance rover, the landing accuracy has improved by 50%, reducing the landing ellipse to a size of 7.7 km by 6.6 km. Using the same precision for landing, a landing ellipse was positioned as close as possible to the chosen cave, utilizing NASA's Mars Trek tool [14]. This analysis determined that the maximum distance the rover might need to travel to reach the cave would be approximately 8 km. To account for any contingencies, the maximum distance to the cave entrance was set at 11km, incorporating a safety margin for worst-case scenarios [13].

4.2 Phase 2: Surface/Sub-surface Traversal

The surface traversal phase of the mission unfolds in four operational steps. Initially, upon landing and health check, the rover transports the Quadcopter from the landing site till the cave and stops at a safe distance of 10m from the cave entrance. Subsequently, while the rover performs a safety check around the perimeter of the cave to ensure safe entry, the Quadcopter maps the cave entrance from above. Following the perimeter check, the

rover retreats to the safe distance (10m) from the cave entrance, allowing the Quadcopter to fully recharge before it enters the cave. Throughout this process, the rover serves not only as a carrier and recharging station for the Quadcopter but also as a communication link for the mission. The overall concept of operations for the surface and sub-surface mission are shown below in Figure 2.

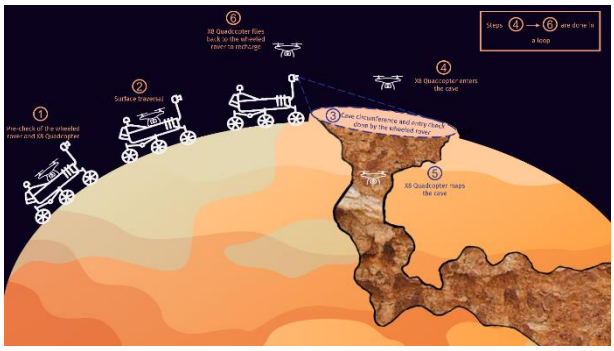

Figure 2: Mission ConOps for Surface/Sun-surface Traversal Phase.

The subsurface traversal phase involves systematic operations by the Quadcopter, which include entering the cave, mapping its interior, and recharging. Once fully charged, the Quadcopter enters the cave and begins its exploration, mapping the area until it requires recharging, while ensuring it retains enough battery power to return to the surface. It then returns to the rover to recharge fully before re-entering the cave to continue mapping from where it left off. This cycle repeats until the Quadcopter can no longer safely return to the surface on its remaining charge. During its mission, the Quadcopter operates at two speeds: a slower speed ensures stability during detailed mapping operations, and a faster speed is used for efficiently returning to the surface and re-entering the cave. This dual-speed strategy is vital for maximizing the mapping coverage, as operating at a single speed would significantly limit the area for mapping and the sub-surface mission would be finished in one flight time of the Quadcopter.

4.3 Phase 3: End-Of-Life (EOL)

There are two possible end-of-life (EOL) scenarios for this mission. In the first, the X8 Quadcopter continues its subsurface operations, repeatedly mapping the cave until its battery charge is no longer sufficient to continue exploration, but still enough to safely return to the wheeled rover for recharging. In the second scenario, the Quadcopter completes phase 2 without any interruptions, mapping as much of the cave as possible. It then returns to the rover, allowing the team to move forward and explore additional caves.

4.4 Timelines

Estimating approximate timelines for each mission phase is essential for determining a realistic mission duration, which helps in defining power and mass budgets more effectively. Using data on the rover's daily travel capacity, the timeline for the surface traversal phase was calculated, as shown below.

- The distance the rover can travel in a sol day = 0.245 km.

To travel 11 Km, which is the maximum distance it would travel from landing site to the cave entrance, the time taken is calculated as shown below.

- The time taken to reach the cave entrance = 11 / 0.245 ~ 45-sol days

The mission is divided into several key phases with defined timelines up to the cave exploration phase. The launch, cruise, and approach phases, including Entry, Descent, and Landing (EDL), are estimated to take 6 months. After landing, a 1.5-month period is allocated for the health check, surface traversal, and circumference check of the cave entrance. Due to operational variability inside the cave, precise timelines for the subsequent cave entry, mapping, and recharging cycles cannot be determined in advance.

5. ROBOTIC SYSTEM DESIGN AND TECHNOLOGIES

This section delves into the design process for the electrical power system, the communication system. Following those, the mechanical design and the thermal management system are detailed. Lastly, the section explains the autonomy of the robotic systems.

5.1 Electrical Power System

The electrical power system for the Mars mission is designed to support both the rover and the X-8 Quadcopter, essential for surface operations and subsurface cave exploration. This system relies on power generation for the rover and battery-based power for the Quadcopter, with key decisions made through trade-off analyses to optimize performance, reliability, and operational longevity in the Martian environment.

5.1.1 Power Generation and Sizing for the Rover

The rover's primary power source is triple-junction GaAs solar arrays, chosen based on a trade-off analysis comparing different power generation methods, including Radioisotope Thermoelectric Generators (RTGs) and various solar arrays. The analysis considered key parameters such as energy generation per sol, degradation over the mission's lifetime, energy density, and cost. This resulted in the following values:

- Solar Array Area: 4.68 m²
- End-of-Life Power Requirement: 253 W

- Recharge Time for Quadcopter: 20.8 hours

The solar arrays were selected for their ability to meet the mission's power requirements while minimizing degradation over 90 sols of operation. Worst-case scenarios, such as Martian dust storms, were factored into the sizing, ensuring the rover generates enough power for critical operations. The arrays power the rover's systems, including mobility, communication, and recharging the Quadcopter. The power budget also includes allowances for the rover's heating and nighttime operations.

5.1.2 Rover Power System

The rover's power system is designed to support its operational needs, including mobility, communication, thermal control, and recharging the Quadcopter. A trade-off analysis was conducted to determine the optimal balance between solar array size, battery capacity, and energy consumption to ensure continuous operation throughout the mission.

- Daytime Power Consumption: 99.1 W
- Nighttime Power Consumption: 71 W

The rover's power consumption was optimized by considering both daytime and nighttime energy requirements, including the need for constant heating and communication. The trade-off ensured the system could meet these demands with sufficient energy storage and generation, allowing for efficient recharging of the Quadcopter when it returns from its cave exploration missions.

5.1.3 Quadcopter Power System

The Quadcopter's power system is centred around its battery, which was selected through a trade-off analysis that considered battery capacity, mass, and the power required for flight on Mars. The trade-off evaluated factors such as specific energy, depth of discharge, and battery discharge efficiency to ensure the system could sustain sufficient flight time while minimizing mass.

- Flight Time: 14.2 minutes per charge
- Battery Mass: 3.96 kg
- Battery Energy Capacity: 418 Wh

The analysis included optimizing the Quadcopter's motors and Electric Speed Controllers (ESCs), balancing power efficiency, flight stability, and energy consumption. This allowed for a system that could perform cave exploration for over 14 minutes per flight, before returning to the rover for recharging. The trade-off ensured that the battery would provide the necessary energy while keeping the Quadcopter's weight within operational limits.

5.2 Communication & Onboard Data Handling

This section outlines the communication strategies and On-Board Data Handling (OBDH) systems for the mission, detailing how data is transmitted between the Quadcopter, rover, satellite, and Earth, as well as the systems enabling autonomous operations and data processing.

5.2.1 Communication

The overall communication link has been split into 3 links:

- The X8-Quadcopter to wheeled rover link
- The wheeled rover to relay satellite link
- The relay satellite to Earth link

The X8-Quadcopter aims to communicate with the wheeled rover to send the data collected throughout the trips inside the cave. This link was first investigated as a Wi-Fi link using a MATLAB simulation, but after more considerations from the Power sub-WP that requires the drone to dock on the rover to recharge, the Wi-Fi has been judged obsolete. This link has therefore been investigated using an Ethernet cable where no simulation software has been used.

The wheeled rover will process the data in its internal on-board computer and send it to Earth through ESA's Mars Express satellite that will act as a relay. This link will be a radio link, using the UHF antenna on Mars Express. The contribution of this report is on the gain required for the wheeled rover antenna to successfully achieve the link. Relevant calculations were made on Excel.

Mars Express will send the data to ESA's ESTRACK's Deep Space Network's antenna. This is the final part of the link that will allow to retrieve data on Earth. This link will be a radio link, using the X-band high gain antenna on Mars Express. Investigating this link required a study of Mars and Earth's ephemeris using a JPL tool to ensure that the existing facilities were sufficient to achieve the link at the time the mission will occur. Relevant calculations were made on Excel.

5.2.2 X8-Quadcopter to wheeled rover

The X8-Quadcopter must dock on the wheeled rover to recharge after each exploration. This opportunity will be used to transmit data at the same time. Among the main wired space-graded communication protocol, none can transmit power at the same time on the same wire. However, Ethernet has a sub protocol called Power over Ethernet (PoE) [15] that allows it in our daily life. In the space segment, Ethernet is used since very recently, allowing therefore the use of PoE in this project.

The map that we aim to retrieve on Earth is produced by the Velodyne lidar, and here is the process that led to the data rate requirements based on the drone and the lidar's specifications:

- The maximum flight time of the X8-Quadcopter is approximately 17.8 minutes back and forth, therefore, 534 secs one way.
- A 50 m diameter gives a 157 m perimeter.

- With a 3 cm accuracy, this is 5236 points to describe this perimeter, and just below 175 000 points per meter in the length of the tube.
- Flying at 0.6 m/s for 534 secs, the X8-Quadcopter can map just over 320 m with one full charge of battery.
- 320 m with 175 000 points per meter gives a total amount of about 56 million points.
- Each of these 56 million points weight 96 bits each, this gives a total of around 5.4 Gb produced by one mapping of the X8-Quadcopter. Over the span of a day, 5.4 Gb is 62.5 Kbps.

On the power side, the cable must deliver at least 33.3 W. Space graded Ethernet only exist for now on the 100BASE-TX protocol, which allows for 100 Mbps data rate and in our case 54 W, therefore, the requirements are met with this protocol.

5.2.3 Wheeled rover to relay satellite

A link budget has been calculated to know which gain of antenna allows for which distance between the satellite and the rover. It involves a lot of hypotheses that has been taken according to ESA's Mars Express's user's manual [16], regarding noise, losses, gain, etc. The link budget has shown that a 3.5 dBi UHF antenna at 400 MHz powered with 10 W by the wheeled rover allows to successfully communicate 128 Kbps with Mars Express when it is below 5,500 Km of altitude. By taking orbit considerations and communication availabilities, it would take 2 days and 7 hours to send the 5.4 Gb map.

5.2.4 Relay satellite to Earth

Here as well a link budget has been conducted with the 8.4 GHz X-band antenna and the 35 m wide DSN's antennas, but the uplink data rate was unknown. To know the data rate available throughout all the mission, the highest distance has been taken, and it shows that after 12 Kbps, the margin falls below 3 dB (when the link is unsuccessful). So, by taking 12 Kbps and the distance throughout the 90 days of the mission, the margin remains over 3 dB which allow to successfully send the 5.4 Gb map in 6 days. The link budgets from mars to earth are shown below in Figure 3.

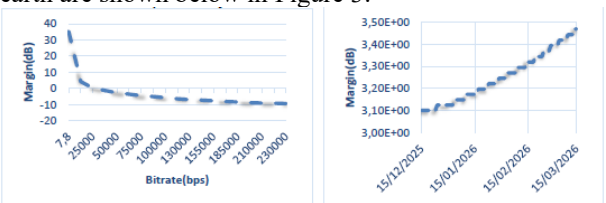

Figure 3: Link budgets from Mars to Earth using Mars Express and ESTRACK's [16].

5.2.5 OBDH

The On-Board Data Handling (OBDH) system enables autonomous operations of both the rover and X-8 Quadcopter, particularly for mapping Martian caves. The system processes data from sensors, manages navigation, and ensures real-time decision-making. The selection of key components was based on trade-off analyses to balance computational power, energy efficiency, and data handling needs.

5.2.6 On-Board Computer (OBC) Selection

The NVIDIA TX2 was chosen for its balance of high computational power and low energy consumption, making it ideal for running Simultaneous Localization and Mapping (SLAM) algorithms. The trade-off analysis compared several OBCs, with the TX2 providing the best performance for processing data from the cave exploration without draining the Quadcopter's battery quickly.

5.2.7 Mapping Sensor Selection

The Velodyne Puck Hi-Res LIDAR [17] was selected for its high-resolution 3D mapping capability and 360-degree field of view, crucial for cave mapping. It was chosen through a trade-off analysis based on resolution, range, power consumption, and weight, ensuring it met the mission's requirements while optimizing energy use.

5.2.8 Inertial Measurement Unit (IMU) Selection

The Motus MEMS IMU was selected for its stability and low drift, ensuring precise navigation inside caves. The trade-off analysis focused on stability, drift, power consumption, and mass, with the Motus IMU providing the best balance for accurate positioning over time.

5.2.9 System Integration

The OBC, LIDAR, and IMU work together to enable the Quadcopter to autonomously map and navigate inside caves. The OBDH system efficiently processes data in real-time, allowing for continuous exploration, with the rover acting as a relay and recharging station.

In conclusion, this OBDH system design ensures the Quadcopter can perform complex mapping tasks while managing energy efficiently, supporting the mission's scientific objectives.

5.3 Mechanical design

The design of robotic systems is influenced by the configuration, which plays a pivotal role in shaping the overall design of the X8 Quadcopter and the Rover. In the process of developing a comprehensive model, it is crucial to consider the specific parameters associated with the electrical and payload inputs. The mechanical configuration of the robotic systems is significantly influenced by two primary factors: the type of locomotion and the sizing of its electronic components. The rover features a substantial solar array area of 4.68 m² and the quadcopter is equipped with an electronics

volume of 6 litres, based on the electrical system input. Furthermore, the quadcopter-type robot features an advanced 8-blade coaxial rotor system as constrained by the payload work package.

5.3.1 Quadcopter design

The X8 Quadcopter is a basic model comprising of an electronics box, LiDAR box, propeller arm, propeller blades, and legs. The electronics, payload, and battery are placed inside the electronics box, and the LiDAR sensor is placed inside the LiDAR box. It consists of 8 motors, fixed at the end like co-axial rotor models. The model's design was constrained by the payload requirement, which specified the distance between the blades and the electrical volume requirement of 6 liters. The LiDAR box is isolated, and the wall thickness is reduced compared to the electronics box for better observation besides the screening barrier. Figure 4 illustrates the X8 quadcopter 3D model.

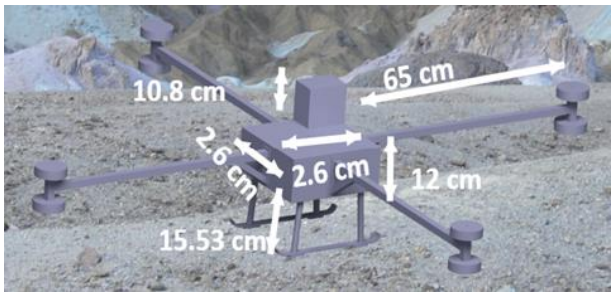

Figure 4: 3D representation of the X8-quadcopter on CATIA.

5.3.2 Rotor Configuration and Propeller Blade Sizing

A comprehensive study and analysis of various aerial vehicle systems was performed including thrust/lift and surface area calculations to determine the most feasible type of rotorcraft locomotion for this mission. The main formula used is the rotorcraft thrust formula:

$$T = C_t \rho A V^2 \quad (1)$$

Where:

- T = Thrust [N]
- C_t = Coefficient of thrust
- ρ = Mars air density [kg/m^3]
  A = Blade surface area [m^2]
- V = Blade tip velocity [m/s]

Calculations were performed to determine the total surface area covered by the rotorcraft and additional considerations for the trade-off analysis were taken. Calculating the length of the blades required for each configuration to provide sufficient lift under the Martian atmospheric conditions was performed and the results were compared in the Table 1 below.

Table 1: Comparison of different flight configurations.

Calculated for (2*MTOW)	Conventional	Tandem	Co-axial	Quadc-opter	X8 Quadc-opter
Calculated Blade Area (m^2)	7.16	3.60	3.60	1.80	0.90
Footprint of rotorcraft (m^2)	7.16	7.20	3.60	7.20	3.60
Consideration	Require tail boom rotor	No overlap	Numbers rounded (more No. of Blades: Slightly larger		

The co-axial configuration, like that of the Ingenuity Mars helicopter [4], was considered efficient, but the X8 Quadcopter was chosen for its redundancy, as its dual blade per axis design ensures the mission can continue even if some blades malfunction. A thrust-to-weight ratio of 2:1 was used to guarantee adequate thrust for this redundancy. Calculations for thrust power, angular velocity, and blade tip deflection were performed to optimize blade size and power consumption. Blade efficiency losses were accounted for using data from Ingenuity, and the final design employed a NACA 6902/4 airfoil with a maximum lift-to-drag ratio at 7° AOA, which was integrated into the final CAD model.

5.3.3 Rover design

The Perseverance rover was the most recent Martian rover from NASA. Based on the literature review [18] and requirements, the Perseverance Rover's dimensions were altered. The Rover CAD model comprises a mast pan-cam, 6 wheels, solar array, and electronics casing. The solar array (SA) sizing was calculated by the electrical work package. The CAD model of the Rover is illustrated in Figure 5.

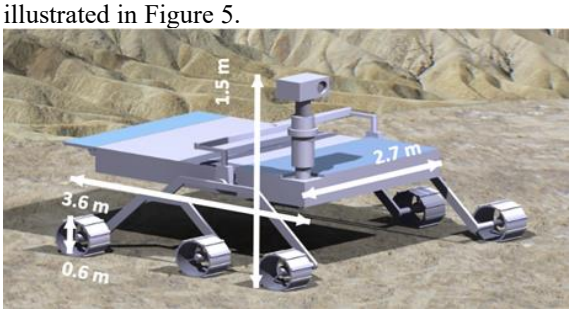

Figure 5: 3D representation of the rover on CATIA.

The rover features a 6-wheeled rocker-bogie system for improved control and stability on the Martian surface, effectively handling both hard terrain and regolith, which can cause wheel spillage and traction issues. The rover's length was increased to accommodate the quadcopter on top. A solar array, highlighted in blue in figure 4, is split into two parts: a fixed front section (3.24 m²) and a foldable rear section (1.45 m²) to allow space for the quadcopter during recharging and also because the rover will transport the quadcopter to the cave entrance during the mission's initial phase, as mentioned in the concept of operations.

5.3.4 Materials

The thermal, physical, and chemical properties of materials are compared in the selection process, and lightweight materials with good strength are preferred. Based on the literature review [19] [20] and the material properties, Carbon fibre, Aluminium alloy, and Polycarbonate were the most suitable materials for this mission. Table 2 displays the finalised materials for the X8 quadcopter.

Table 2: X8 Quadcopter's materials.

Carbon fibre	Al alloy	Polycarbonate
Legs Propeller arm and blades	Electronics box	LiDAR box

The high strength of the aluminium alloy makes the whole structure stand together sturdily under various phases of the mission. The corrosion-resistant nature helps the structure to be durable for an extended period and makes it suitable for the body of the quadcopter. Carbon fibre is also a lightweight material with good strength. It also has good impact and corrosion resistance properties, which makes it most suitable for the quadcopter's legs and arms as it is less dense when compared to aluminium. Polycarbonate has high impact resistance, corrosion resistance, and good strength. The strength may vary based on the layering and thickness of the polycarbonate. Moreover, polycarbonate acts as a LiDAR transparent material. The rover was decided to be fabricated using aluminium and titanium alloys mostly.

5.4 Thermal Management System

The quadcopter and rover are expected to function in extreme external conditions, including temperatures going from -73°C to +20°C at the surface. The Thermal Management System aims to equip the robotic system and ensure that their equipment and instruments function correctly. For this reason, an optimal thermal range is defined for each robot, based on the equipment it houses. The sensitive pieces of equipment were determined to be the quadcopter's LiDAR, and the batteries carried by the quadcopter and the rover.

The TMS is composed of different technologies. The combination of some technologies will create the right thermal environment for the sensitive pieces of equipment. A trade-off resulted in a short list of possible combination for the robotic system. The Different combinations include passive technologies such as surface coatings and multi-layer insulation, as well as active technologies such as heating units and radiators. The first combination is the simplest, with only surface coatings and insulation to manage the robot's temperature. If a source of heat is needed, a heating unit will be added and if at times the equipment's temperature is too high to be passively dispersed, a radiator can also be used.

Each of the robots are expected to exchange heat during their operations with the Martian atmosphere around them and when at the surface during the day, with the Sun. Those thermal exchanges added to the already extreme thermal range of the planet makes it complex for a robot to maintain a constant and appropriate internal thermal environment. However, equipment and instruments are characterized to function in specific conditions, which often include an optimal thermal range. For the quadcopter, the sensitive pieces of equipment are the batteries and the LiDAR. For the rover, the batteries are the only sensitive equipment. To accommodate this equipment and requirement, a Thermal Management System (TMS) is designed. After a thermal analysis is performed for both the robots, their respective TMS are confirmed. The thermal Management System's design is as follows.

The surfaces are covered with a 35 mm thick multiple layered insulation made of Kapton and carbon dioxide. This insulation is painted with a dark surface coating to reinforce the insulation. The surfaces covered in solar panel and the lidar bay are left with no insulation or coating. The surfaces needed to recharge the quadcopter or to move are covered with surface coating, but the insulation is not added to allow free movement. The heating units chosen to rely on natural decay of radioactive isotope. Units of this technology, called radioisotope heating units, are mounted in robotic systems to provide heat over time. The sizing of these units depends on the needs of the robotic system in question. The expected heat power for the quadcopter is 12 Watts. The power production aboard the rover would be 900 Watts.

5.5 Autonomy

This section outlines the methodology for the autonomy of wheeled rover and the quadcopter.

5.5.1 Wheeled Rover Autonomy

This section covers the autonomous navigation design for the wheeled rover during the surface traversal phase. The process begins with the creation of a surface map, followed by localization and path planning. Working on the top-level functional requirements derived from the mission CONOPS, the autonomy ensures the rover safely transports the X8 quadcopter from the landing site to the cave entrance and stops within 10 meters. This ensures precise and safe delivery for subsequent exploration activities.

5.5.1.1 Surface Map Creation

Initially, a comprehensive surface map of the Elysium Mons region was developed using STL and height map files, providing detailed geometric and terrain data

essential for the simulation. Data from sources like Mars Trek and NASA were integrated to improve the accuracy of the terrain [14] [21]. The surface mapping involved triangulation to extract vertices, accurately outlining the terrain geometry. MATLAB was utilized for algorithm development, ensuring proper terrain modelling for subsequent localization and path planning simulations.

5.5.1.2 Localization

Following the creation of a surface map, the rover's localization process involves initially estimating its pose using coordinates and map boundaries from STL files. This setup facilitates the simulation of lidar scans to refine the rover's position and orientation within the environment. A MATLAB-based algorithm performs these simulations, utilizing ray-casting to detect obstacles and adjust the rover's pose accordingly [22] Subsequently, Monte Carlo Localization (MCL) is applied, using a particle filter to iteratively refine the rover's pose based on lidar data and a probabilistic model, ensuring accurate localization for subsequent navigation tasks [23]. The actual and estimated rover pose is obtained as well. This comprehensive approach integrates initial data input, dynamic lidar scanning, and MCL algorithm to accurately determine the rover's location on the Martian terrain.

5.5.1.3 Path Planning

Upon establishing the rover's position within the Martian map, path planning to navigate the rover to the cave entrance while transporting the quadcopter was executed. Utilizing the A* algorithm, the simulation identified the optimal route by evaluating paths based on the distance from start node to the current location (g_cost) and estimating the remaining distance to the goal (h_cost) [24]. This allowed the rover to avoid obstacles and ensure safe passage to the cave entrance. The simulation dynamically adjusted the rover's trajectory, stopping it within 10 meters of the destination, ensuring precise alignment with mission objectives and demonstrating effective navigation in the Martian environment.

5.5.2 Quadcopter Autonomy

In the first phase of the autonomous flight, the focus is on the detection of the cave entrance. The X8 quadcopter is equipped with a LIDAR system building an occupancy map in continuous. The entrance is identified using a polynomial approximation method based on changes in elevation. This approach allows the quadcopter to scan its surroundings and determine where significant drops in elevation, indicative of a cave entrance, are located. The system is programmed to trigger a descent once the entrance is identified, with the quadcopter carefully approaching in 5-meter horizon increments. At each stop, the quadcopter scans the following 5 meters for any obstacles before advancing for 5 meters and looping back to stop and scan. This incremental descent is implemented to ensure that the quadcopter can safely navigate the entrance without colliding with the cave walls or other potential hazards. A safety margin has to be maintained by artificially expanding the 3D occupancy map to ensure the quadcopter kept a safe distance from obstacles.

The exploration phase follows a simpler, naive task-planning approach. Once inside the cave, the quadcopter will perform 360° scans to identify potential routes forward. The exploration algorithm is designed to maximize the distance covered by the quadcopter while avoiding obstacles. After each scan, it will select one of 24 directions to move, based on the clearance available in each direction. This method ensures that the quadcopter can systematically explore the cave, identifying new areas to map while continuously updating its internal 3D occupancy grid.

A key challenge in the current implementation lies in the return phase. The quadcopter's return to the surface is governed by numerous contextually driven triggers, such as battery drain or data storage capacity, allowing the quadcopter to dynamically determine the optimal moment to begin its return. In its present form, the return journey retraces the quadcopter's steps using a similar simple algorithm as the exploration phase but with the goal of minimizing the distance to the cave entry point.

As the quadcopter nears the entrance, a Rapidly exploring Random Tree (RRT*) planner is employed to improve the efficiency of navigation in the final and most critical part of the journey, where the terrain becomes more complex and narrower. The RRT* algorithm is particularly well-suited for this phase, as it facilitates real-time path planning in three-dimensional space, efficiently balancing exploration and exploitation to find the optimal route.

6. BUDGETS

This section summarizes the key resource allocations for the mission, including mass, power, and cost. Each budget was calculated to ensure the mission remains within its technical and financial constraints while meeting all operational requirements. The details on the mass, power and cost budgets are shown below in Table 3.

Table 3: Details on the mass, power and cost budgets.

Budget Category	Description	Total Estimate
Mass Budget	The mass distribution of the spacecraft was calculated based on the payload capacity, with careful allocation to components such as structure, thermal control, power, and propulsion. Adjustments were made using past mission data to optimize the mass within the limits.	Rover & Quadcopter: 6000 kg
Power Budget	The rover's solar arrays generate up to 252.8 W, with power allocated to LIDAR, onboard computers, and communication systems. The rover consumes a total of 1041.8 W, while the Quadcopter requires 1515 W for cave mapping.	Rover: 1041.8 W, Quadcopter: 1515 W
Cost Budget	Using data from missions like NASA's Perseverance, cost estimates were customized for the rover and Quadcopter. The total mission cost is £1.177 billion, with the Quadcopter costing £0.248 billion.	Mission: £1.177 billion

7. ROBOTIC SYSTEM ANALYSIS

This section provides an analysis of the structural, thermal, and autonomous capabilities of the heterogeneous robotic system designed for Martian cave exploration. It covers the thermal management systems for the quadcopter and rover, the cave design simulation used to test the system's navigation, and the autonomy simulations for both the wheeled rover and the X-8 Quadcopter. Through various simulations and testing methodologies, this analysis aims to validate the system's ability to function efficiently in the harsh Martian environment while navigating complex terrains such as caves.

7.1 Structure and Thermal Testing

This section presents the results for structural and thermal testing of the heterogeneous robotic system.

7.1.1 Thermal testing

A thermal analysis was run on the quadcopter and the rover entire configuration to design and confirm their thermal management systems. The analyses conducted on Comsol Multiphysics have validate a system for the quadcopter and another one for the rover in conditions found at Mars' surface. The analysis was conducted in the probable external conditions encountered by a robotic system.

The quadcopter's analysis alternates period in dark conditions, to reproduce Martian caves, as well as bright conditions, for the Martian surface. The duration of each condition equals the maximum duration of the operation they concern, respectively the exploratory flight and the stationary charging. The quadcopter will exchange heat with the Sun depending on the state of the solar cycle when the quadcopter is evolving at the surface and charging. At all times, exchanges with the atmosphere and the thermal environment (temperature from -73°C to +20°C).

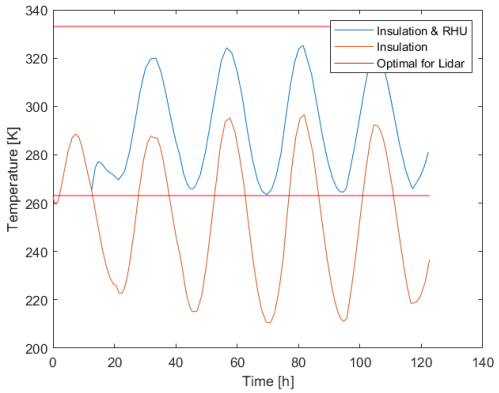

Figure 6: Comparison of the LiDAR enclosure's temperature for the simplest thermal management system and the final one.

The temperature of the sensitive equipment is measured and drawn after five Martian days. The TMS is validated if the temperature is within the limits of the equipment's optimal thermal range, represented in red in the figures. Each time, the figure includes results for the simplest TMS and for the final one, presented earlier.

The LiDAR's optimal thermal range is from -10°C to +60°C. Figure 6 exposes how the simplest TMS is not enough to create the right thermal environment. The LiDAR enclosure's temperature keeps dropping below the optimal range and the survivable one. This survivable range extends the thermal range by 10°C, in which the piece of equipment functions but may not be optimal. The final TMS respects the LiDAR requirements and create an appropriate thermal environment for its optimal use.

Similarly, the temperature inside the main part of the quadcopter is measured and illustrated in Figure 7. The battery necessitates a temperature between -10°C and +15°C to function optimally. The first TMS's performances are lacking where the final's TMS is effective, when the survivable thermal range is applied.

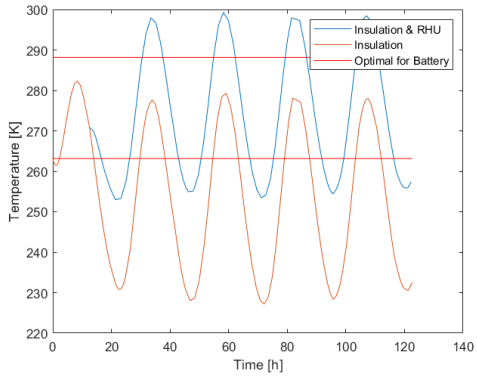

Figure 7: Comparison of the electronic bay's temperature for the simplest thermal management system and the final one.

The rover's analysis is conducted in a modelled Martian surface for five Martian day. The external conditions were made to reproduce the expected heat exchanges between the Sun, the Martian atmosphere and the rover. Once again, the simulation is conducted with a TMS of multiple layer insulation and surface coating against the same TMS plus a radioisotope heater unit. The results of those two simulations are in Figure 8. Once again, the final thermal management system is shown to be appropriate.

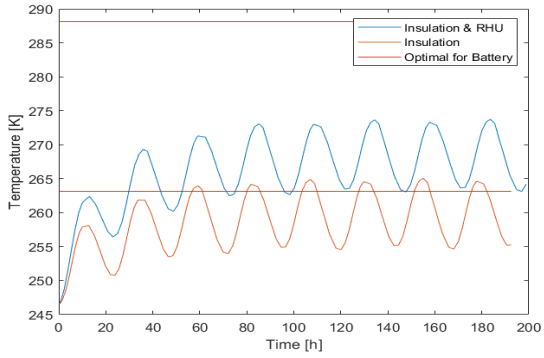

Figure 8: Comparison of the rover's electronic bay temperature for the simplest thermal management system and the final one.

7.2 Cave design

The cave was designed in a way that it met all the requirements of the Type 1 cave which we selected. 'Blender 4.0' was selected as the simulation tool to create the 3D structure of the cave with a molten lava texture. A small portion of the Martian terrain was also created to show the landing surface for robotic system [25].

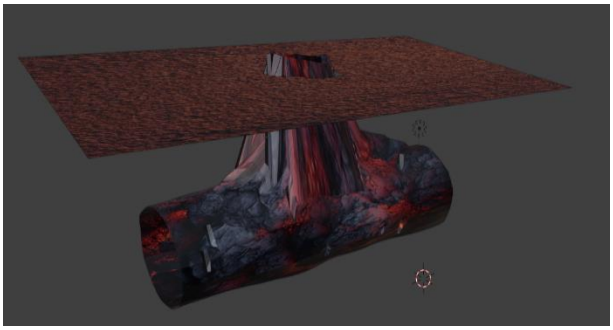

Figure 9: Cave map with texture

The cave interior was created with vertical rims and rock particles which can impact the operation. It was designed with care to show the traversability of the quadcopter inside the cave to illustrate the obstacles inside.

Comparison of the rover's electronic bay temperature for the simplest thermal management system and the final one.

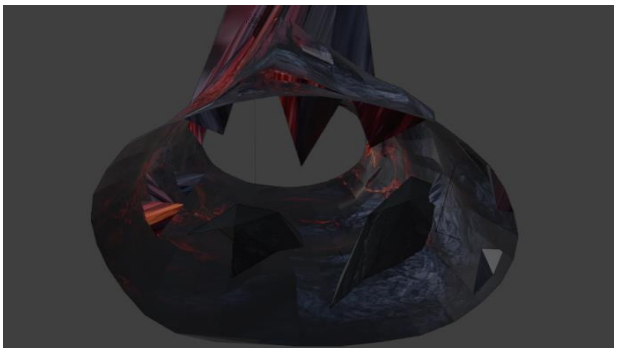

Figure 10: Cave interior with obstacles.

The design was then exported to MATLAB, where we could show the navigation of the quadcopter using LiDAR. The LiDAR scan shows the map inside cave along with the obstacles present.

7.3 Autonomy

This section outlines the results of the simulations for autonomy of wheeled rover and X-8 Quadcopter.

7.3.1 Wheeled Rover Autonomy

To simulate the wheeled rover's autonomous navigation, MATLAB Simulink was used to incorporate essential algorithms for terrain mapping, localization and path planning. The results of the simulation, as outlined below, demonstrate the rover's successful traversal of the Martian surface while fulfilling mission objectives.

The plot shown in Figure 11 depicts the surface map of the Elysium Mons region and the rover's localization on the Martian surface. The circle on the map represents the rover's position, and the arrow indicates its orientation. This visualization offers a clear

representation of the Martian surface while demonstrating how the rover's position is tracked within the terrain. It offers essential geographic context for identifying obstacles and planning optimal routes, ensuring accurate localization and path planning as the rover navigates to the cave entrance.

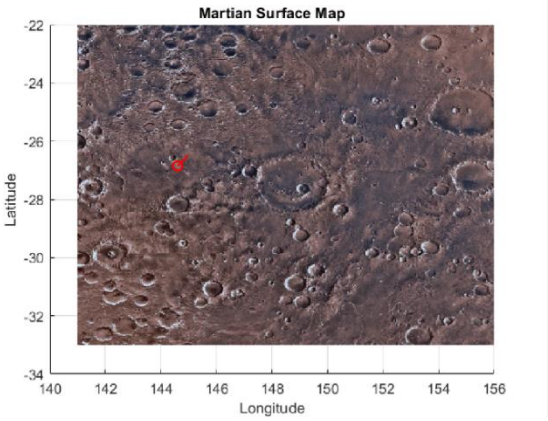

Figure 11: 2D view of the Martian Surface with Rover's Position (Elysium Mons).

The actual and estimated rover poses were also obtained during the simulation. By comparing the two, it was observed that the estimated pose closely aligned with the actual rover pose within the environment. Additionally, the analysis indicated that the rover is within the landing ellipse. Accurately determining the rover's pose on the map fulfils the criteria set for the simulation, specifically being near the landing site or within the landing ellipse.

The Figure 12 shows a low-fidelity path planning simulation, where the red circle at the top represents the start point, and the red circle at the bottom marks the goal location, near the cave entrance. The black line illustrates the rover's navigated route across the Martian surface. The simulation successfully stopped when the rover reached a point within 10 meters of the cave entrance. The orientation obtained from the final rover pose is particularly useful for determining the direction of the cave entrance, essential for the quadcopter autonomy.

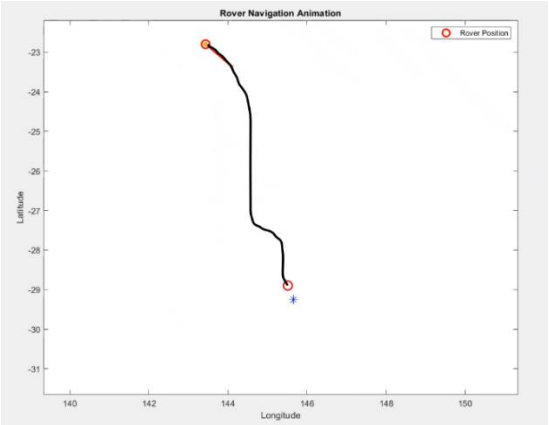

Figure 12: Plot of Rover's Path from Landing site till 10m away from cave entrance.

7.3.2 Aerial Robot Autonomy

The development of the quadcopter's autonomy system is conducted through extensive simulations in the MATLAB-Simulink environment. This environment is chosen for its flexibility in simulating robotic systems and its ability to represent complex interactions between sensors, control systems, and onboard computing. The simulation is divided into key modules: external sensors (simulated via pre-defined input data), onboard computation, and control loops. Throughout the process, the focus is on testing and validating the quadcopter's ability to navigate a simplified cave environment, with the primary constraints being the cave geometry and dimensions, rather than the actual Martian environmental conditions like gravity or atmospheric pressure. The system is not tested under Martian-specific conditions such as dust or temperature variations but focuses solely on ensuring successful navigation within the given structural constraints of the cave.

The Simulink environment offers a structured approach to implementing and testing algorithms, with the simulation running in a continuous workflow. Sensor inputs, mainly LIDAR data, are processed by the onboard computer, enabling real-time decision-making for the quadcopter's exploration and return. Simulink-based control loops ensure the quadcopter accurately follows its planned trajectory, adjusting movements based on sensor feedback. However, this is a low-fidelity model, and the quadcopter's performance has only been validated within the predefined cave dimensions and obstacles of the simulated environment.

The simulation successfully demonstrates the quadcopter's ability to autonomously detect cave entrances, explore interior geometries, and return to the surface based on time constraints. The simple exploration algorithm effectively covers significant portions of the cave, and the return mechanism functioned as expected, allowing the quadcopter to retrace its path. These initial results confirm the system's capability to navigate the

cave environment under simplified conditions. The resulting map is attached as Figure 13.

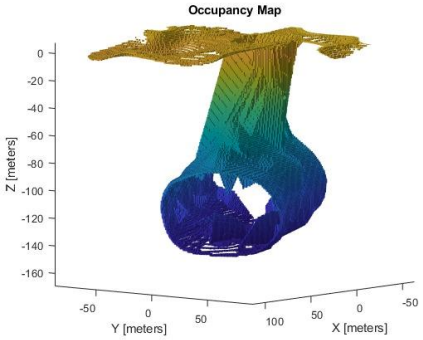

Figure 13: Plot Occupancy Map produced by the quadcopter during the exploration.

8. CONCLUSION

A conceptual Martian cave exploration mission using heterogeneous robotic system is developed from a system engineering approach. A Martian type-1 cave SP5 in the Elysium Planitia region is selected for exploration balancing the scientific objective and feasibility of robotic exploration. A wheeled rover and X8 quadcopter in parent-child configuration is proposed for cave exploration where the Wheeled rover and X8 quadcopter are used for surface and subsurface explorations, respectively. Based on the stakeholder statement, the robotic system requirements are defined and the electrical, mechanical and payload (simulation and autonomy) designs are carried out. The proposed wheeled rover concept is capable of delivering the quadcopter from the landing cite to cave with autonomous navigation, performing a cave entrance perimeter check, charging the quadcopter while sharing the data with it, and communicating data to ground station. The X8 quadcopter autonomy system demonstrates the cave entry detection, entry and cave traversal, cave mapping with SLAM, and autonomous navigation inside cave. The X8 quadcopter design focuses on overall size reduction with rotorcraft configuration and air foil selection, a thermal management system with combined MLI and surface coating, and body parts made of aluminium alloy, carbon fibre, and polycarbonate. The simulation results show the effectiveness of the thermal management system and demonstrate that the cave reached, entered and mapped autonomously with the proposed robotic system while satisfying the mission requirements. Future works will concentrate on improving the rover-quadcopter design for more constrained and rugged region traversal, enhancing autonomy in sub-surface operations, advancing thermal protection systems, and optimizing the integration of rovers and quadcopters in terms of power and communication system.

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