i-SAIRAS 2024

Exploration of Martian Caves with the Scout Rover: Robust Design and Advanced Navigation

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Abstract

The Scout Rover, designed for Martian cave exploration, marks a breakthrough in planetary robotics with its robust build and advanced navigation. It’s engineered to endure the harsh Martian cave conditions. A key feature is its lighting system, enhancing the stereo camera's ability to perform SLAM in dark, complex environments. The integration of a LIDAR sensor allows the rover to utilize CSIRO’s Wildcat SLAM and Navstack systems, proven in the DARPA Subterranean Challenge. The rover’s newly designed spokes improve maneuverability in tight spaces. Extensive testing, including a 2022 drop test into a volcanic crater, has validated its resilience. An upcoming test in October 2024 will further assess its robustness and communication systems in a simulated Martian cave environment.

Introduction

The DLR Scout Rover's mission concept focuses on exploring Martian and lunar lava tubes, providing critical insights into potential habitats and geological structures. The rover is designed for robust, autonomous operations in challenging environments, including the ability to survive drops into caves without complex tethering systems. This concept was detailed by [1], emphasizing the importance of modular design and battery efficiency for extended missions. These fundamental developments set the stage for further tests, aimed at refining the rover's capabilities for extraterrestrial cave exploration. Thus, in preparation for advancing the capabilities of robotic exploration in extraterrestrial caves, the DLR Scout Rover underwent its first in-cave tests, as detailed by [2]. The Rover demonstrated its ability to navigate through challenging obstacles and narrow passages during these tests. These tests in a terrestrial limestone cave provided critical insights into operational challenges, including signal reception and equipment resilience. These findings form the foundation for further testing, including the upcoming evaluation of the Scout Rover's autonomy and communication.

Figure 1: The Scout Rover during the preparation of the campaing in cueva de la naturalistas on Lanzarote; photo: Dr. Roy Lichtenheldt.

State of the art

Robotic exploration of extraterrestrial caves is a growing field due to its potential to provide insights into planetary geology and habitability. The following articles highlight significant developments in this area:

[3] focuses on the exploration of extraterrestrial lava tubes using tethered robotic systems. It highlights the significance of these caves for astrobiology and planetary science, proposing robots as essential tools for investigating areas inaccessible to humans. Key considerations include mobility to enter the caves using a tethered axle of the Axel rover. Thereby the tether also allows to supply power and means of communication. However, the system is constrained to its tether length.

[4] gives an overview on a previous cave field test using a variety of rovers as a team. The main focus was on deployment of the tethered system, while all mission phases including exploration of the skylight area are shown.

Several teams have developed multi-layered autonomy architectures to handle the complexities of cave exploration. For instance, the approach used by Otsu et al. in the DARPA Subterranean Challenge employs a supervised autonomy framework [5]. This system combines high-level human supervision with low-level robot autonomy, allowing for effective operation in communication-constrained environments. The architecture includes modules for mapping, localization, path planning, and multi-robot coordination.

In contrast, Bayer et al. present a fully autonomous exploration framework for ground vehicles [6]. Their system uses a dense local mapping for precise traversability estimation combined with a sparse topometrical map for multi-robot coordination. This approach allows for decentralized decision-making, crucial in environments where constant communication cannot be guaranteed.

The MARBLE team's planning solution, as described by Ahmad and Humbert, takes a different approach [4]. They formulate the path planning as a constraint-satisfaction problem, significantly improving computational efficiency. Their system also accounts for environmental changes, such as blocked passages.

LIDAR-based systems have become predominant for creating accurate 3D maps of cave environments. The Wildcat system by Ramezani et al. combines real-time LIDAR-inertial odometry with pose-graph optimization, allowing for online continuous-time 3D mapping [7]. This approach has proven robust in perceptually challenging cave settings.

For navigation, learned robot-terrain interaction models have shown promise. Agishev et al. propose a method that optimizes trajectories while maximizing environment coverage [8]. This allows robots to navigate efficiently through rough terrain while respecting operational constraints like limited mission time.

We will present the integration of the Wildcat system [7] with the Scout Rover and discuss an upcoming test campaign in lava tubes of the Canary Islands.

The Wildcat system on the Scout together with the autonomy brings two essential components together: a robust and versatile robotic platform specially developed for cave exploration and Wildcat plus CSIRO’s autonomy, a sub ground navigation solution that has very well proven its suitability for the application.

The Scout Rover Concept

The rover developed for cave exploration integrates a robust and straightforward design tailored to meet the dual demands of cave and planetary exploration. Its simple, yet effective concept minimizes complexity, thereby reducing the risk of single points of failure of the mechatronic system and enhancing overall reliability. The rover features compliant spokes and a backbone structure that allows for effective terrain adaptation and shock load mitigation during falls. It is able to drive upside down and to upright from sideways landing after falls.

Designed with modularity in mind, the rover includes a dedicated payload area and allocates a specific mass budget (> 6kg) to it, facilitating versatile scientific applications. The system aims for a battery life of approximately 20 hours, although the current available battery life is around 10 hours. Deployment strategies include either dropping the rover into caves or using a rappelling system for high cave entrances.

Perception, SLAM and Autonomy

In order to achieve autonomous navigation, perception of the environment as well as SLAM are key features. In the next paragraphs we will outline the rover’s autonomy setup.

The autonomy system developed by CSIRO for the DARPA Subterranean Challenge provides a strong foundation for enabling autonomous navigation capabilities on the Scout Rover. At the core of the autonomy stack is the Wildcat SLAM system, which provides real-time localization and mapping using LIDAR and inertial data.

Requirements for Martian cave exploration

Robotic exploration of planetary caves on Mars and the Moon imposes stringent requirements for autonomy and decision-making to ensure mission success and safety.

Autonomy and Mission Efficiency: Given the vast distances and communication delays inherent in planetary exploration, rovers must operate with high levels of autonomy. This autonomy is crucial to eliminate roundtrip times for commands, which is particularly important for short-duration missions where every minute counts. The rover must be capable of performing complex tasks independently to maximize scientific output within the limited timeframe.

Navigating Uncertain Terrain: The exploration rovers need to make decisions in environments where paths are not clearly defined. They must be equipped to evaluate and select the best option from several potentially hazardous routes. This capability requires advanced algorithms to assess and prioritize paths based on their relative risks and traversability.

Obstacle Classification and Traversability: Effective navigation depends on a nuanced classification of obstacles. This includes determining the level of difficulty and risk associated with each obstacle to identify the safest and most feasible path forward.

Decision-Making on Communication: The rover must autonomously decide when to pause and request guidance from mission operations. This decision-making process involves evaluating the potential risks and benefits of continuing versus stopping for additional input.

Strategic Placement of Repeaters: To maintain robust communication throughout the mission, repeaters should be strategically placed. They should be positioned just before navigating risky obstacles that could jeopardize a rover's ability to return.

Scientific Target Identification: Autonomy also extends to scientific exploration. The rover needs to identify potential science targets and evaluate their significance. If a closer investigation is warranted, the rover must be able to request further instructions from scientists.

Overall, these requirements emphasize the need for advanced autonomous systems that can make real-time decisions, manage communication effectively, and adapt to the dynamic and unpredictable nature of planetary cave environments.

Perception Hardware Setup

The Scout Rover’s hardware setup is designed to ensure robust performance and advanced navigation capabilities in Martian and Lunar cave environments. At the core of its computational architecture is a x86-64 main OBC. This onboard computer is responsible for real-time gait and motor control, enabling the rover to navigate complex terrains with precision and stability.

For processing environmental information for the SLAM system, the rover utilizes an additional ARM computer. This module handles localization and mapping of the rover’s surroundings. For this purpose, Scout is equipped with multiple environmental sensors, such as a LIDAR and two RGBD cameras, which are mounted at the opposing ends of the rover.

The 3D LIDAR sensor is accompanied by an Inertial Measurement Unit (IMU). To complement this data with color information, the mounted cameras have to be used in addition.

Wildcat SLAM

The Scout Rover utilizes Wildcat, a state-of-the-art online 3D LIDAR-inertial SLAM system, for localization and mapping in the challenging lava tube environment. Wildcat combines a robust real-time LIDAR-inertial odometry module with an efficient pose-graph optimization module, enabling accurate mapping of large-scale environments.

At its core, Wildcat uses a continuous-time trajectory representation based on cubic B-splines to fuse asynchronous LIDAR and IMU measurements and mitigate motion distortion effects. The odometry module processes data in a sliding window fashion, generating surfels (surface elements) from LIDAR points and optimizing the robot trajectory using IMU measurements and surfel correspondences. This allows Wildcat to produce locally consistent trajectory estimates and surfel maps in real-time.

The pose-graph optimization module then leverages these local estimates to build a globally consistent map. It periodically generates submaps - six-second bundles of odometry estimates and accumulated surfel maps. By treating submaps as rigid blocks and optimizing their relative poses, Wildcat can efficiently map large environments while correcting for odometry drift. The pose graph is further constrained using loop closures detected between non-consecutive submaps.

Several key features make Wildcat particularly well-suited for lava tube exploration:

1. Proven performance in perceptually challenging subterranean environments, as demonstrated in the DARPA Subterranean Challenge where it outperformed other SLAM systems.

2. Robustness to sensing degradation from dust and low-light conditions common in lava tubes.
3. Ability to generate globally consistent maps online by fusing data from multiple robots.
4. Efficient submap-based representation enabling low-bandwidth sharing of map data between robots and with the base station.
5. Versatility across various platforms (e.g. wheeled, legged, aerial) and sensing configurations.
6. Commercial deployment in underground mining operations, validating its reliability in GPS-denied subterranean environments.

Wildcat's exceptional performance in the diverse and challenging environments of the DARPA SubT Challenge, including natural caves, urban underground, and tunnel systems, demonstrates its suitability for lava tube exploration. Its ability to produce accurate, globally consistent 3D maps in real-time will be crucial for scientific survey, hazard avoidance, and enabling potential future human exploration of lava tube systems on the Moon and Mars. Current research to bring the system towards space grade hardware is ongoing.

Visual SLAM for Scout

Besides the LIDAR-internal Wildcat SLAM, an experimental visual RGB-D SLAM system was designed with the particularities of the Scout Rover and especially the compliant connection between the two depth cameras in mind. This system builds upon the open source Real-Time Appearance-Based Mapping (RTAB-Map) graph-based SLAM and is tightly integrated into the ROS2 middleware. An overview of the concept and performance testing is presented in [10].

Autonomy and Navigation

Scout's special design and exclusive capabilities require a custom autonomy development based on specific requirements. The CSIRO Navstack gaps planner autonomously plans and executes motions through narrow gaps commonly found in confined spaces like tunnels and caves, maximizing scientific outcomes while minimizing risks.

The system detects both negative and positive obstacles (e.g., pits and boulders) and plans paths around them. While the lower LIDAR perspective on Scout may improve ground plane estimation, it could also complicate negative obstacle detection. In cases where no alternative path exists, a human may command the robot to attempt a risky maneuver, though fully manual teleoperation is unlikely due to communication delays with Earth.

Given a higher risk acceptance rate compared to other missions, increasingly risky activities may be undertaken over time to enhance scientific data return after achieving the highest priority objectives during the test campaign.

LIDAR data is fed into the perception pipeline, providing crucial information for local path planning and navigation. The skid-steer planning module developed for wheeled SubT robots will be adapted for Scout's rimless wheels. This unique wheel design introduces uncertainty in odometry estimates but also allows for easier navigation over obstacles.

NavStack's hierarchical path planning, particularly its advanced Planner Gaps, is well-suited for lava tube exploration, integrating continuous optimization into the search process for reliable pathfinding through narrow gaps. Its costmap generation classifies terrain based on robot constraints to avoid hazards in lava tubes. Additionally, NavStack handles "virtual surfaces" to represent obscured terrain in partially observable environments and employs market-based task allocation for efficient exploration of complex cave systems. The robust Mule communication system supports disruption-tolerant messaging in unpredictable terrains.

The local planner will be updated to reflect Scout's motion constraints and self-righting capability. Higher-level exploration and global planning algorithms will align with specific cave mission goals, such as covering maximum ground and maintaining reliable communication.

The autonomy system will integrate with Scout's subsystems, like the matrix lighting system [9], for optimal environmental perception in dark cave environments. A comprehensive testing campaign in the lava tubes of Lanzarote will validate and refine the autonomy system, identifying technical gaps specific to Scout's configuration and mission profile. Results from these experiments will guide further development and optimization.

Analog Site Campaign

An analog site campaign is designed to thoroughly test the rover with all its components. Thereby we do not only intend to test the locomotion in harsh terrain, but also the autonomy, perception, lighting and other relevant subsystems in terrestrial conditions that are as close to the space application as possible.

Cueva de los Naturalistas Lanzarote

The selection of the test cave for evaluating the rover described in this paper was guided by several critical factors to ensure a comprehensive and practical assessment of its capabilities.
Ease of Approach and Access: The cave was chosen primarily for its convenient accessibility. Located near a road with a walk-in or easy climb-in entrance, the cave facilitates straightforward deployment and retrieval of test equipment. This ease of access is crucial for efficient testing and minimizes logistical challenges.
The cave's proximity to transportation routes allows for quick and efficient setup of test equipment. This efficiency is essential for conducting a range of tests without significant delays, thus optimizing the overall testing process.
Safe Environment for Non-Caving Personnel: Safety was a key consideration in the cave selection process. The chosen cave provides a relatively safe environment for personnel who may not have extensive caving experience. This safety factor ensures that the test activities can proceed with minimal risk to the team involved.
Multiple Entrances for GPS/GIS Data: The cave features several entrances, enabling loop closures with readily available GPS and GIS data. These multiple access points are advantageous for testing navigation and mapping technologies, as they allow for comprehensive data capture and analysis of the rover's performance in various sections of the cave.
Varied Locomotion Difficulties: Inside the cave, there are different levels of locomotion difficulty, which provides an opportunity to evaluate the rover's adaptability and performance across diverse terrain types. This variation is essential for testing the rover's ability to handle both simple and challenging environments.
Branches for Autonomy and Operations Training: The cave includes several branches, offering a valuable opportunity for training both autonomous systems and operational control. This aspect of the cave enables the assessment of the rover's decision-making capabilities in complex environments, including its ability to navigate and make real-time operational decisions. The cave contains both smaller and larger galleries, which are ideal for testing simultaneous localization and mapping (SLAM), lighting conditions, and overall mapping

accuracy. These varied environments allow for a thorough evaluation of the rover’s technological capabilities.

Overall, the selected cave offers a well-rounded testing environment that meets the essential criteria for evaluating the rover’s performance in terms of accessibility, safety, operational efficiency, and technical capabilities.

Experiments & Setup

The upcoming tests for the Scout Rover in the Lanzarote cave are designed to evaluate its performance across a range of scenarios and capabilities critical to its mission objectives. These tests will provide valuable insights into the rover’s survivability, operational efficiency, and technical functionalities.

Cave Entry Tests: We will conduct a series of tests to evaluate different methods of cave entry without a tether. Starting with the simplest and safest approaches, we will progressively test more challenging scenarios involving higher vertical drops with increased risk. The primary goal is to assess the rover’s survivability and resilience when exposed to varying levels of difficulty during entry.

Long-Range Operational Test: A five-hour long-range test will be carried out to simulate and assess the rover’s performance towards its planned mission duration of 10-20 hours. This test aims to determine the rover’s operational capabilities within a limited timeframe and identify any issues that need to be addressed to extend its operational endurance.

Matrix Lighting System Tests: The effectiveness of the matrix lighting system will be evaluated by testing different illumination strategies. This includes optimizing the use of various lighting areas to adequately illuminate specific cave sections and enhance the identification of obstacles. The results will guide adjustments to improve visibility and obstacle detection in varying lighting conditions.

Autonomy Tests: We will test the rover’s ability to navigate the confined spaces of the cave autonomously. This includes obstacle recognition and the selection of the most feasible path among potentially hazardous options. A comparison will be made between the rover’s autonomous navigation decisions and those an operator might choose, providing insights into the effectiveness of the rover’s autonomous systems.

Mapping and SLAM Tests: The accuracy of the rover’s SLAM (Simultaneous Localization and Mapping) capabilities will be tested using loop closures and ground truth measurements within the cave. Additionally, we plan to evaluate the rover’s ability to generate a 3D model of the cave, which will be used to create a detailed speleological map. These tests will assess the precision of the mapping system and its ability to produce useful geological data.

Entrance-to-Entrance Loop Closure with Obstacles: A comprehensive test will be conducted to navigate from one entrance of the cave to another while traversing various obstacles. This test will simulate a realistic exploration scenario with predefined goals, allowing us to evaluate the rover’s performance and adaptability in overcoming challenges throughout the cave.

Deployment and Ad-Hoc Connection of Repeaters: We will test the deployment of repeaters and their ad-hoc connections within different cave galleries and geometries. Initial tests will involve manual placement of repeaters to simplify the process. The objective is to assess coverage distances and determine optimal repeater positions. Insights gained will inform the development of an automated deployment mechanism for future missions.

Ground Structure and Tactile Sensing Tests: To understand the ground structure and its parameters, we will measure motor currents and use them as tactile sensors in conjunction with visual information. This approach will help in identifying the ground conditions and adapting the rover’s behavior accordingly. These tests aim to enhance future versions of the rover’s autonomy by providing better situational awareness and adaptability.

These tests are designed to thoroughly evaluate the Scout Rover’s performance in a controlled yet challenging environment, ensuring that it is well-equipped to handle the complexities of cave exploration on planetary surfaces.

Summary & Outlook

In this article, we‘ve introduced the Scout Rover and shown its readiness for the tests, outlined the preparation and execution plan for a lava tube test campaign of the Scout Rover on Lanzarote, focusing on critical areas such as locomotion, communication, and navigation & autonomy. The tests are designed to simulate realistic exploration scenarios, including a long-range test that begins at the cave entrance and progresses toward a defined exploration goal. This campaign will rigorously assess the rover's capabilities in a challenging environment similar to extraterrestrial caves. The findings and results of these extensive tests will be presented in our upcoming talk at i-SAIRAS 2024, where we will share insights into the Scout Rover's performance and potential for future missions. In this talk we will give details on the results and findings towards robotic exploration of caves in general. This will also include the possibility of obstacles that we did not expect in the first place. Furthermore, we will discuss the possible obstacle size for the rovers size in-situ for both modes: teleoperation and autonomous operations. We will also show the manually planned paths to avoid or travers obstacles and the respective outcome and findings. This work aims to further refine the rover's design and functionality, ensuring its readiness for future planetary exploration missions in similar environments.

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