A Journey Through an Autonomous Multi-rover Coordination Scenario in Mars Cave Exploration

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Introduction

Exploration of planetary caves offers exciting opportunities for 1) human settlements, 2) understanding the planets evolution, and 3) the search of extraterrestrial life (Boston et al. 2004). Earth's moon and Mars have abundant cave targets for future robotic exploration missions, however several technological challenges need to be addressed. Communicating with a rover into any of these caves and transmitting science data out is in itself a hard problem. Without a link to the surface, a rover would not be able to go far into the cave without losing contact with the base station. Moreover, because sunlight is not available in the cave, a mission is likely to last only a few days since the rovers will rely exclusively on battery power. Given limited communication, power and mission duration (just days), it is impractical to wait for humans' commands and feedback like in current Mars operations (Gaines et al. 2016). Cave rovers would have to be far more autonomous than the existing surface rovers, for their environment is unknown and their communication with Earth is extremely limited, if at all.

Autonomy in multi-rover coordination is a key mission enabler to help rovers to map and characterize as much of the cave as efficiently as possible. The AI community has recently started to look into techniques for rover coordination to map and explore these cave environments (Husain et al. 2013; Dubowsky et al. 2005; Thangavelautham et al. 2014) A traditional approach would be to use a centralized system to coordinate task allocation and communication among the rovers. However, this approach becomes unfeasible in a realistic cave environment due to intermittent, unreliable communication, as well as the high cost of commutation power associated with the centralized scheme. Research on multi-rover coordination under these constraints is in its infancy.

Our group at JPL has been developing multi-rover coordination algorithms to study the conceptual mission design and requirements for Mars Cave exploration; one of these algorithms is briefly described in this abstract. One important requirement of this study is the the ability to visualize and simulate the rover coordination mission concept in realistic settings and cave environments. That ability is key to evaluate algorithm performance, understand the impact of autonomy, explore different coordination approaches, design options, mission settings, and environment configurations.

In this demonstration, we present a Mars cave exploration scenario with a set of autonomous simulated rovers. It walks the viewers through the mission concept in an immersive setting in which they can explore the cave, follow the rovers and observe their operations. We also present simulation framework that (1) allows different multi-rover mission configurations (e.g., rover's battery capacity, power usage, number of rovers, exploration algorithms), as well as (2) supports the measurement, visualization and analysis of the mission.

Cave Exploration Problem

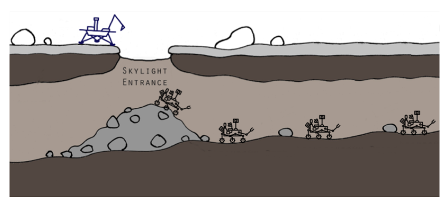

Figure 1: Illustration of hypothetical multi-rover coordination problem in Mars cave exploration. Rovers not to scale. Credit: Figure adapted from the Wikimedia Commons, Longitudinal cross-section of a martian lava tube with skylight.

In this work we focus on autonomously coordinating multiple rovers to (1) map and characterize a Martian cave as far into the cave as possible from the entrance, and (2) to transmit as much science data collected by the rovers' instruments as possible out of the cave to a lander, which will then take care of transmitting it to scientists on Earth. Figure 1 illustrates the target exploration scenario, which shows a Martian lava tube structure, with the lander positioned at the entrance and four science rovers exploring the cave interior.

Coordination Approach

The proposed *Dynamic Zonal Relay with Sneakernet Relay Algorithm* is a two step algorithm. The first phase (Dynamic Zonal) drives each rover to a designated zone along the length of the cave, while maintaining communication distance between neighboring rovers. Each rover only takes science data in its designated zone and transmits it to the neighboring rover in the direction of the lander. If a rover is no longer operable, the other rovers would re-distribute the zones to maintain communication and characterization of the environment. The next step (Sneakernet Relay) would allow the rovers to acquire science data further in the cave by driving beyond the communication distance and driving between neighboring rovers to relay the data out of the cave. More details on the algorithm will be available in (Vaquero, Troesch, and Chien 2018).

Simulation Framework

The simulation framework is implemented using the Robot Operating System (ROS). Herein, each rover is modeled as a set of four main components: a navigation component, responsible for navigating and planning the path of the rover through the environment; a communication component, that manages the data transfers and pings between rovers (which incorporates bandwidth and ranges specs); a science component, which can perform science tasks with different instruments; and a controller, which reasons and dispatches actions to the other components. The simulator also models the cave environment as a 3D model, combined with heightmaps and costmaps as input to navigation. In our work the cave map is initially unknown and revealed as the rovers explore it through sensors.

In order to set a particular cave exploration scenario, we have to provide the simulator a set of inputs and parameters. The main inputs are the mission specs, the rover specs and the cave specs. The mission is defined by parameters such as the number of rovers and exploration algorithm (e.g. the one described above), while the cave is defined by its 3D model, dimensions and obstacle densities. The rovers have a large set of parameters, which makes the framework quite flexible and useful for large scenario configurations. Some of the parameters that can be set are: driving parameters (power, velocity); instruments on board (power, data volume, sensing duration); communication parameters (power, bandwidth, range, frequency); hotel load; and failure rate to test robustness. Simulations can be run in real time or sped up. The clock adjusts during computationally heavy procedures in order not to bias the timing of activities.

Visualization and Post-Process Analysis Tools

The framework includes a set of tools to visualize the cave environment (terrain, obstacles, walls and facets), rovers' activity timeline, resource usage, and data transfer out of the cave with some post-processing tools after a simulation has completed. In addition to timelines, charts and 3D models, we use virtual reality (using Unity) to provide a more immersive experience (Figure 2, left). The framework helps designers to observe closely the rovers behaviors and cave properties. During the simulation, the exploration scenario can also be visualized in RVIZ (Figure 2, center and right).

The set of tools allows users to analyze the spectrum of the aforementioned configurations and score each approach based on data volume transmitted out of the cave, mission life span, and distribution of energy and time spent in different activities to help inform future mission design.

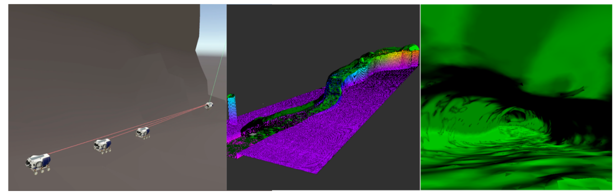

Figure 2: Virtual reality environment (left) and RVIZ visualization with the surface height (middle) and cave model (right). Credit: Cave model courtesy (Santagata); Rover 3D model from NASA LaRC Advanced Concepts Lab, AMA Studios.

During the demonstration we will show viewers a start to end mission in which they will be allowed to explore the cave and observe the rovers through a software application. We will also walk through the details of how the simulation is set-up.

Acknowledgments

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References

Boston, P.; Frederick, G.; Welch, S.; Werker, J.; Meyer, T.; Sprungman, B.; Hildreth-Werker, V.; Murphy, D.; and Thompson, S. 2004. System Feasibility Demonstrations of Caves and Subsurface Constructed for Mars Habitation and Scientific Exploration. Technical report, USRA Reports, NASA Institute for Advanced Concepts.

Dubowsky, S.; Iagnemma, K.; Liberatore, S.; Lambeth, D. M.; Plante, J. S.; and Boston, P. J. 2005. A concept mission: Microbots for largescale planetary surface and subsurface exploration. *AIP Conference Proceedings* 746(1):1449–1458.

Gaines, D.; Anderson, R.; Doran, G.; Huffman, W.; Justice, H.; Mackey, R.; Rabideau, G.; Vasavada, A.; Verma, V.; Estlin, T.; et al. 2016. Productivity challenges for mars rover operations. In *Proceedings of 4th Workshop on Planning and Robotics (PlanRob)*, 115–125. London, UK.

Husain, A.; Jones, H.; Kannan, B.; Wong, U.; Pimentel, T.; Tang, S.; Daftry, S.; Huber, S.; and Whittaker, W. L. 2013. Mapping planetary caves with an autonomous, heterogeneous robot team. In *IEEE Aerospace Conference*, 1–13.

Santagata, T. Università degli Studi di Modena e Reggio Emilia. Inside the Glacier Project.

Thangavelautham, J.; Robinson, M. S.; Taits, A.; McKinney, T.; Amidan, S.; and Polak, A. 2014. Flying, hopping pit-bots for cave and lava tube exploration on the moon and mars. In *2nd Int. Workshop on IPM*.

Vaquero, T.; Troesch, M.; and Chien, S. 2018. An approach for autonomous multi-rover collaboration for mars cave exploration: Preliminary results. In *paper submitted to ICAPS'18 Workshop on Planning and Robotics (PlanRob)*.