An Approach for Autonomous Multi-rover Collaboration for Mars Cave Exploration: Preliminary Results

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Abstract

Mars caves are promising targets for planetary science and human shelter. Exploring these environments would pose several challenges, including limited communication, lack of sunlight, limited vehicles lifetime that would not allow humans in the loop, and a totally unknown environment. Mission to these underground environments would required levels of autonomy, coordination and collaboration never been deployed before in rovers. In this paper we propose a multi-rover coordination algorithm and experimental framework for cave exploration missions. We describe preliminary experimental results with this coordination algorithm in a realistic simulated cave. We analyze rover coordination performance in different environmental settings and provide insights on potential opportunities for enhanced autonomy with AI planning and scheduling.

1. Introduction

Exploration of planetary caves is becoming an active research topic in the planetary science community and a promising scientific target for autonomous robotic explorers. Mars in particular offers exciting opportunities for (1) human settlements, (2) understanding the planet’s evolution, and (3) the search of extraterrestrial life. Caves present the most mission effective habitat alternative for future human exploration, offering a stable, UV-shielding, meteoric-shielding environment (Boston et al. 2003), as well as access to minerals, gases and ice. Equally important, caves may preserve valuable information about the planet’s history and evolution. Specifically, they offer stable physio-chemical environments, trapped volatiles, secondary mineral precipitation and microbial growth, which are expected to preserve life signatures and provide a record of past climate (Boston et al. 2005; 2004). Moreover, caves can potentially host water deposits which, through interaction with volcanic heat and minerals, could have created a favorable environment to microbial life preservation. What makes planetary caves even more attractive is that they are quite abundant. Mars for example has more than 2000 cave-related features identified, commonly associated with lava tubes, which provides a variety of promising targets for future exploration missions.

Robotic exploration missions on Mars would provide unique science opportunities for the cognitive and robotics communities, however, they present several challenges. Communicating with a rover into any of these caves and transmitting science data out is in itself a hard technical problem. Without a link to the surface, a rover would not be able to go far into the cave without losing contact with a base station. Moreover, because sunlight is not available in the cave, a mission is likely to last only a few days since the rover 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. For example, current MSL operations requires humans in the loop to plan sequences of actions for each sol based on downlinked data (Gaines et al. 2016). Those challenges alone require rovers far more autonomous than the existing surface rovers, for their environment is quite unknown and their communication with Earth is extremely limited, if at all.

Autonomy in multi-rover coordination is a key mission enabler that would help rovers to map and explore as much of the cave as efficiently as possible. With their very limited lifetime, rovers cannot wait for large parts of each day to receive directions from ground/Earth. The need for such multi-asset coordination was identified in recent studies in Mars cave exploration (Dubowsky et al. 2005; Kesner et al. 2007; Husain et al. 2013; Thangavelautham et al. 2014) and in Mars surface exploration (Clement and Barrett 2003; Yiniezi, Agogino, and Tumer 2014). The AI community has recently started to look into coordination techniques to map and explore Mars cave environments (Husain et al. 2013). One traditional approach would be to use a centralized task allocation and communication architecture to coordinate the rovers during exploration (Chien et al. 2000; Clement, Durfee, and Barrett 2007). However, this approach becomes unfeasible in a realistic cave environment due to intermittent, unreliable communication, as well as the high cost of communication power associated with the centralized scheme. Some existing work explores distributed techniques to coordinate vehicles to maintain connectivity between a base robot and a mobile explorer at all times in more controlled environments (auf der Heide and Schneider 2008; Stump, Jadababaie, and Kumar 2008). These approaches can be leveraged to address subsurface missions, but they would need to be contiguously adapted to environments where the likelihood of connectivity loss between rovers (sometimes done proactively by rovers to increase science utility) and unknown density and geometry of obstacles. Research on multi-rover coordination under these challenging constraints is in its infancy.

In this work, we propose a multi-rover coordination strat-
tubes. Due to Mars’ lower gravity, Martian lava tubes are much larger than Earth lava tubes. Herein we target caves that are approximately 100 meters wide and potentially hundreds of meters deep, with a skylight entrance formed from a collapsed cave ceiling as illustrated in Figure 1. We assume that the terrain in the interior of the cave is unknown a priori.

Cave walls are a quite interesting science target for NASA/JPL scientists. They can provide critical constraints on lava temperature and cooling history, leading to insights into Martian magmatic processes and differentiation. Thus, in our coordination problem the rovers should try to safely remain as close to the walls as possible to characterize wall properties and facets.

2.2 Conceptual Autonomous Rovers

We consider a set of homogenous rovers that are assumed to be successfully deployed at the bottom of the cave through the skylight entrance. The problem of deploying the rovers into the cave, although interesting, is not in the scope of this work. The focus is in the exploration and coordination problem while in the cave where communication is limited.

The rovers are equipped with a battery module, mobility components, a communication component (antennas), and a science component with a set of key science instruments. Those components allow each rover to perform the following actions:

- **Ping** (communication component): a rover can send a ping to all rovers within communication range to detect the vehicles around it. Rovers (including the base rover) in the communication range respond with their position and status update. A ping process has a specific duration (e.g., 2 seconds) and also a power consumption rate known a priori. Communication range and ping duration are provided in the antenna specs.

- **Drive** (mobility components): to navigate the environment safely, each rover is able to detect obstacles within a radius (e.g. 5 meters) in 360 degrees. The cave map is stored during exploration - given that the focus of this work is not on mapping and localization per se, we assume that the knowledge about the map and coverage becomes available to all the rovers as they explore the cave. The velocity of the vehicle and power consumption during driving is known and given by the mobility specification.

- **Science** (science component): each rover has the same set of science instruments partitioned in three categories: primary instruments, secondary instruments, and periodic

Among the several mission challenges related to deploying and controlling a set of rovers in a Mars cave, in this work we focus on the hypothetical problem of 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 (base station), which will then take care of transmitting it to scientists on Earth. Figure 1 illustrates a Martian lava tube structure, with the lander positioned at the entrance and a set of science rovers exploring the cave interiors. We provide more details and constraints on the cave environment and rover platform in what follows.

2.1 Cave Environment

In this paper we focus on Martian caves associated with lava tubes. Due to Mars’ lower gravity, Martian lava tubes are much larger than Earth lava tubes. Herein we target caves that are approximately 100 meters wide and potentially hundreds of meters deep, with a skylight entrance formed from a collapsed cave ceiling as illustrated in Figure 1. We assume that the terrain in the interior of the cave is unknown a priori.

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- **Science** (science component): each rover has the same set of science instruments partitioned in three categories: primary instruments, secondary instruments, and periodic
**instruments.** Each one of these instruments has its own specs for power consumption, data volume generated by each reading and the sensing duration.

- **Transfer** (communication component): transfer is a collaboration task in which the sender first sends a transfer request to a target/receiver rover. The receiver then informs the sender when it is available to receive data. Once that confirmation is received, the sender transfers the data to the target rover. When the data is successfully transferred, the receiving rover sends a confirmation and the task is completed. The duration of the actual data transfer between two rovers (lander and/or science rover) is determined by the antenna specs, the data volume and the distance from each other (bandwidth). The bandwidth can be modeled with an arbitrary function (see Discussion).

For the simulations presented in this paper, we model bandwidth as a step-wise function of distance between communicating vehicles. For example between 0-5 meters rovers can transfer data at 11.0 Mbps, between 5-10 meters at 5.5 Mbps, between 10-15 meters at 2.0 Mbps, and between 15-25 meters at 1.0 Mbps. Power consumption rates are also known and are constant during communication, regardless of distance.

In additional to the above action specification, we list below some of the key assumptions on the exploration problem:

1. All actions consume energy from the battery component, which is a limited resource. If the battery drains out, the rover becomes non-operational.
2. We consider a constant hotel load that represents the energy consumption to keep the rover operational. We frame any cognitive process (e.g., decision making, path planning computation) as part of this constant consumption.
3. Each rover can only execute one action at a time, except sending and responding to pings. In the science case, only one instrument can be used at a time.
4. Communication model does not consider the shape, texture, material of the cave or proximity to walls. (This is actually already being incorporated in our models, but will be left for future publications.)
5. Communication is possible only up to a fixed distance between rovers, where the lander has a longer fixed range.
6. Rover can fail during exploration, which means that the coordination has to account for reconfiguration.
7. In this work we are not modeling acceleration or slippage in the motion model.
8. Finally, each rover does have a memory component for data science storage, but the memory capacity is large enough to handle days or weeks worth of data.

### 3. Approach

We propose a multi-rover coordination strategy for cave exploration that aims to send rovers as deep into the cave as possible while also maximizing data sent out to a surface base station.

The rovers explore the cave using the **Dynamic Zonal Relay with Sneakernet Relay Algorithm**, which is a two phase algorithm, starting with (1) **Dynamic Zonal Relay** and expanding with (2) **Sneakernet Relay**. One of the main aspects of this algorithm is the use of spatial zones to determine the state of the rover. Each zone is a distinct section of the cave based on distance from the lander, as shown in Figure 2.

![Figure 2: Zones based on the distance from the conceptual lander or base station (left). Nominal state transitions for the Dynamic Zonal Relay phase (right).](image)

#### 3.1 Dynamic Zonal Relay

The first phase, **Dynamic Zonal Relay**, assigns the rovers to designated, adjacent zones that keep the rovers within communication range of their immediate neighbors. The algorithm is **dynamic** in that if any rover becomes inactive (i.e., no longer communicating due to some kind of failure or running out of battery), the other rovers dynamically readjusts the zone assignments.

While **driving** to its assigned zone, the rover maintains a safe communication distance with its neighboring rovers and relays any science data that has been transferred to it to its neighbor in the direction of the lander. When in its zone, the rover moves along the length of the cave, continuing to maintain communication distance, while **characterizing** the cave. The rover sends acquired science data to the neighboring rover closest to the lander. Once at the end of its zone, the rover becomes a **relay** point. In this state, the rover transfers any remaining science data that it has collected, as well as any science data that has been transferred to it, to its neighbor closest to the lander.

A diagram of the nominal state transitions for the Dynamic Zonal Relay phase is shown in Figure 2. The diagram also shows that the rovers perform periodic pings to the other rovers to share status information, such as position, and to keep track of which rovers are still active.

In the case that a rover becomes inactive, the surrounding rovers readjust depending on their position relative to the inactive rover. Rovers closer to the lander would not need to adjust their zones; however, they need to be made aware of the new configuration. Rovers deeper into the cave need to adjust their zone closer to the other rovers to re-establish a continuous line of communication across all rovers. Since the rovers do not know how much science data the inactive rover was able to acquire and transfer out of its zone (if it was already characterizing its zone), all rovers that moves into a new zone re-characterize the entire zone.

#### 3.2 Sneakernet Relay

Once all of the data that was collected during the Dynamic Zonal phase has been passed to the lander, the rovers transition to the **Sneakernet Relay** phase. During this phase, the rover furthest into the cave is designated as the lead rover (e.g., Rover4 in a team of four rovers) and the others are designated as relayers (e.g., Rover1, Rover2 and Rover3 in the
team of four rovers). The lead rover is now tasked with characterizing the next zone, which means that one of the relays is no longer in communication range of one of its neighbors, meaning that it must sneakernet. Increased sneakernet distance is assigned in order, starting with the rover closest to the lander (e.g., Rover1 in our example), as the lead rover characterizes more zones.

The sneakernetting process is composed of cycles, where a sneakernet cycle consists of each rover incrementally increasing its sneakernetting distance. A cycle is further broken down into stages that are repeated with each assignment of increased distance: (1) extension/replacement and characterization, (2) relay, and (3) confirmation. Except at the beginning of the Sneakernet Relay phase, stage (1) and stage (3) occur simultaneously. Figure 3 helps to illustrate the evolution of the Sneakernet Relay phase, with line 1 showing the positions of the rovers for a three rover mission configuration at the end of the Dynamic Zonal Relay phase.

The beginning of a cycle is triggered by the rover closest to the lander (Rover1) beginning the extension/replacement and characterization stage, as shown in Figure 3 line 2. The initiator of this stage (in this case, the rover closest to the lander) moves forward to the relay position of its neighbor. This triggers the neighbor rover to move forward to the relay position of the rover in front of it, and so on, until the lead rover. When the lead rover is triggered, it moves forward and characterizes the next section of the cave, which is the same distance as that of the relay distance of the previous rover (the distance between the leader’s neighbor and the neighbor’s neighbor).

When the lead rover has finished collecting new data (line 3), the relay stage is initiated. The lead rover begins by moving within communication range of the rover following it and transferring all of its data. After the transfer, the transferring rover remains where it is while the receiving rover moves to communication range of its neighbor in the direction of the lander and transfers all of the data, and so on, until the rover closest to the lander transfers all of the data out of the cave. In Figure 3, line 4 shows the first rover requiring to move in order to transfer the data to the lander.

The transfer of all of the data to the lander triggers the next stage, confirmation. The rover closest to the lander now moves back to its neighbor inside the cave, confirms that the transfer was successful, and returns to its previous relay position (line 5). The next rover then moves deeper into the cave to its neighbor and reports the confirmation and returns to its relay position, and so on for all of the rovers until the confirmation reaches the lead rover. During this stage, the next rover to initiate extension moves to its next relay position during the confirmation process, triggering all rovers to move deeper into the cave as a cascading sequence of extension and confirmation, such as on line 6. In line 7, we see the lead rover moving ahead and characterizing a zone the same distance as that of the relay distance of the previous rover (distance between Rover2 and Rover1), as described previously, requiring the lead rover to sneakernet on line 8.

The remainder of Figure 3 shows the repetition of these stages, until line 13, which shows the positions of the rovers after the second cycle is initiated by the first rover (Rover1).

To remain robust to rover failures during the Sneakernet Relay phase when the rovers are no longer in communication range, the rovers rely on timeouts to estimate how long they should wait for a neighbor to initiate the next phase. If a timeout is reached, they will try to find its neighbor in the direction of the lander to re-establish the relay chain. If a relayer reaches a timeout waiting for its peer deeper in the cave, it will then act as the leader.

![Figure 3: The movement of the rovers during the Sneakernet Relay phase of the algorithm for the first cycle.](image-url)

4. Experiments in Simulation

The Dynamic Zonal Relay with Sneakernet Relay Algorithm was tested in a simulation framework using the Robot Operating System (ROS) to model the communication between the rovers as well as to model the different rover components (e.g., the science instruments, driving and navigation, etc.) and the cave. A configuration with four rovers (Rover1 through Rover4) and a base station was used, as illustrated in Figure 1, for the experiments. This configuration is based on preliminary cost and payload analysis of similar classes of missions. The cave model used is a model of the Cassone Cave (Santa-gata), scaled approximately twelve times so that the width is around 70 m, which is shown in Figure 4. The cave model is made up of approximately 350,000 triangular facets, with an average size 1.16 m².

Each rover is assumed to have an identical suite of instruments, partitioned in the three aforementioned categories: primary, consisting of a LiDAR to characterize the walls, facets and structure of the cave; secondary, including a color
camera and a spectrometer; and periodic instruments, including a thermometer, radiation detector, and hygrometer. Primary and secondary instruments are used based on movement of the rover, whereas the periodic instruments are used based on a regular, timed cadence (in this case, every 60 minutes). A summary of the assumed instrument parameters is shown in Table 1.

<table>
<thead>
<tr>
<th>Power (Watts)</th>
<th>Data Volume (Mb)</th>
<th>Sampling Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lidar</td>
<td>10.0</td>
<td>1544</td>
</tr>
<tr>
<td>Color Camera</td>
<td>5.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Spectrometer</td>
<td>10.0</td>
<td>14.4</td>
</tr>
<tr>
<td>Thermometer</td>
<td>1.0</td>
<td>0.0008</td>
</tr>
<tr>
<td>Radiation Detector</td>
<td>1.0</td>
<td>0.0008</td>
</tr>
<tr>
<td>Hygrometer</td>
<td>2.0</td>
<td>0.0008</td>
</tr>
</tbody>
</table>

The communication range was limited to 25 meters between rovers and 75 meters to the lander. Pings to communicate position and status were performed once per minute. The assumed power for communication was 4.0 Watts.

In this work we incorporate a simple approach for rover navigation and selection of the region to be explored in the cave. Each rover computes its path through the cave map using the A* algorithm, where Rover1 through Rover3 move toward the rovers ahead of them, while the leader, Rover4, uses a frontier detection algorithm (Yamauchi 1997) to move towards unexplored regions of the map into the cave. In this experiment, rovers traverse the environment at 0.005 m/s and a 5-meter range is used for obstacle detection and mapping. It is assumed that driving requires 14.0 Watts of power.

We also model a hotel load (the amount of power required for a rover to remain operational, such as basic heating and health monitoring) of 5.0 Watts.

As a comparison, an experiment was performed with a single rover using the Dynamic Zonal Relay with Sneakernet Relay algorithm, where the rover extends by a single zone (in this case 20 m) at each step. No obstacles were used for this experiment.

To evaluate the different runs, a scoring function based on the cave characterization data transferred out of the cave was used. For remote instruments (such as cameras), the score, $s_{remote}$, is the area of the triangular facets covered in the cave model based on the position of the rover, the field of view of the instrument, and any restrictions on far and near clip planes or normal angle of the facet, which is summarized in Eq. 1 for a data acquisition instance data,

$$s_{remote}(data_i) = \sum_{f \text{ visible}} \text{area}(f)$$  \hspace{1cm} (1)

For in-situ instruments (e.g. temperature sensors), the score, $s_{in-situ}$, depends on both position and time of the data. For these types of measurements, the value of the data decreases if it is taken at almost the same position and time, therefore the score is a function that decays based on the position and time of any previously taken data of that type. Given a max time of $T$ before a facet can receive a full score again, $s_{in-situ}$ is determined by Eq. 2 for a data acquisition instance data,

$$s_{in-situ}(data_i) = \sum_{f \text{ visible}} \text{area}(f) \ast d, \text{ if } f \text{ visible}$$  \hspace{1cm} (2)

where,

$$d = \begin{cases} 1 & \text{if } f \text{ last measured } > T \text{ seconds ago} \\ e^{-(T-\Delta t)/T} & \text{otherwise} \end{cases}$$

and visibility is based on a sphere with a fixed radius instead of a field of view and clip planes.

This results in a total score, $score$, defined by Eq. 3, where only data that is transferred out of the cave is scored.

$$score = \sum_{i} s_{remote}(data_i) + \sum_{f \text{ visible}} s_{in-situ}(data_j)$$  \hspace{1cm} (3)

5. Simulation Results

In what follows we present the results from the single rover and the multi-rover experiments using the simulator. A comparison of the results are shown in Table 2.

5.1 Single Rover

The single rover was able to explore up to 100 meters into the cave; however it was only able to transfer data from up to 80 meters. This can be seen from Figure 5, which shows the depth into the cave that the rover travelled with respect to time; the rover was not able to make it back close enough to the lander after characterizing up to 100 meters to transfer its most recently collected data (i.e., data collected between 80-100 meters).

The percentage of time that the rover spent performing different activities is show in Figure 6, which demonstrates that the amount of time required to drive and transfer the data is quite significant, especially with respect to the amount of...
Table 2: Comparison of simulated experiments

<table>
<thead>
<tr>
<th></th>
<th>Max Lifetime (days)</th>
<th>Max Transferred Data Distance (m)</th>
<th>Score Data Volume Transferred (GB)</th>
<th>Data Volume Un-Transferred (GB)</th>
<th>Rover Death</th>
<th>Death Time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Rover</td>
<td>1.59</td>
<td>80</td>
<td>1122.76</td>
<td>4.70</td>
<td>1.39</td>
<td>0% Obstacles</td>
</tr>
<tr>
<td>0% Obstacles</td>
<td>2.99</td>
<td>100</td>
<td>3828.27</td>
<td>6.44</td>
<td>1.02</td>
<td>2.99</td>
</tr>
<tr>
<td>10% Obstacles</td>
<td>3.00</td>
<td>100</td>
<td>4285.45</td>
<td>6.76</td>
<td>1.39</td>
<td>3.00</td>
</tr>
<tr>
<td>20% Obstacles</td>
<td>3.41</td>
<td>45</td>
<td>3347.68</td>
<td>4.34</td>
<td>0.0000077</td>
<td>3.41</td>
</tr>
<tr>
<td>Random Death</td>
<td>2.69</td>
<td>75</td>
<td>2452.43</td>
<td>5.20</td>
<td>2.41</td>
<td>Rover4, Rover1</td>
</tr>
</tbody>
</table>

time spent acquiring the data (labeled “Science”). However, when looking at the percentage of energy required, Figure 7, the transfers make less of an impact, whereas driving continues to have the greatest impact.

Figure 5: Simulated depth of the rover into the cave (y position) with respect to time.

Figure 6: Percentage of time spent on different activities.

Figure 7: Percentage of energy required to perform different activities.

5.2 Four Rovers

Figure 8 shows an example of the motion of the rovers expanding and sneakernetting in the four rover configuration with zero obstacles and no random death.

The percent breakdown of activities in terms of time is displayed in Figure 9, where it is shown that transferring data (either receiving or sending) takes a large portion of a rover’s time, increasing for the rovers closer to the lander. In fact, comparing Figure 6 and Figure 9, Rover1 spends approximately as much time transferring as the single rover. However, the largest amount of time is spent performing “other” activities, which includes pings and idle time. Unlike in the single rover scenario, with multiple rovers there are times that the state transition of a rover depends on the actions and states of the surrounding rovers, meaning that the rover must wait idly, which is why the Other time is so high in Figure 9 compared to Figure 6.

Figure 8: Simulated depth of the rovers into the cave (y position) with respect to time for a four rover sneakernet configuration with zero obstacles and no chance of random death.

Figure 9: Percentage of time spent on different activities for the four rovers and the lander in the simulation.

Figure 10 shows the energy distribution for the four rovers. Like the single rover scenario, in terms of specific activities, driving takes the most amount of energy. However, in the multi-rover scenario, each rover spends much less energy performing science activities, with Rover4 using the most energy on science, as expected since it characterized more zones. Although a small percentage of the overall energy required by the rovers, in Figure 10, it can be seen that it is not an insignificant source of energy usage.

Figure 10: Percentage of energy required to perform different activities for the four rovers and the lander in the simulation.
Figure 11: Paths of the rovers with 0% obstacle density (left), 10% obstacle density (center) and 20% obstacle density (right) with no random rover death.

Figure 12: a) Simulated depth of the rover into the cave (y position) with respect to time. The arrows point out times and locations of rover deaths. b) Paths of the rovers in the random dying rovers experiment.

With more obstacles, the paths of the rovers, shown in Figure 11 for 0%, 10%, and 20% obstacle densities and no random death, become less straight and aligned with the cave wall. In fact, with 20% obstacle density, the rovers are not able to find a path that stretches beyond 45 meters into the cave, and the rovers begin exploring farther from the cave wall. This means that Rover4 (the leader) never reaches its zone and does not take any primary or secondary data.

The experiment with random rover death shows a scenario where Rover4 dies just before Rover3, its immediate follower, finishes characterizing its zone, and Rover1 dies after the first transfer of the first sneakernet expansion data. From Figure 12 (a), we see that Rover3 seamlessly becomes the new leader and leads the way during the algorithm’s Sneakernet Relay phase. As shown in Figure 3, Rover4 expands by its neighbors relay distance.

We also see a timeout begin in Figure 12 with Rover2. When Rover2 sneakernets back toward Rover1 to relay the data, it is not able to locate Rover1, therefore Rover2 waits at the location it last saw Rover1 for a timeout duration (which in this scenario, Rover2 does not live long enough to finish). Although there are only three rovers, they are able to collect data beyond 100 meters, but are only able to live long enough to transfer out data up to 75 meters into the cave.

Figure 12 (b) shows the paths of the rovers for the experiment with random rover deaths, which looks very much like the 0% obstacle paths in Figure 11, as expected.

6. Discussion

The simulation shows that a single rover can successfully characterize up to 80 meters along a cave wall (given no obstacles) if it does not encounter any problems before running out of battery; however, this is a large assumption given the unknown environment of the cave. The sneakernet results with randomly dying rovers shows the robustness of the Dynamic Zonal Relay with Sneakernet Relay algorithm to rover loss. Furthermore, with the survival of all rovers for the duration of the battery charge, science data from deeper into the cave can be transferred out to the lander than in the single rover case.

Although the experiment with 20% obstacle density showed the rovers unable to reach as deep into the cave as other scenarios, it is interesting to note the large score. This is due to the fact that as the rovers move farther away from the cave wall, the field of view of the remote instruments is able to capture a larger section of the cave model facets. This shows an interesting trade-off that can be made between remaining close to the wall, and therefore characterizing smaller features of the cave and reaching deeper distances, versus moving away from the wall and characterizing larger sections.

In our exploration approach, the sequencing of science actions is predefined based on scientist team inputs. Nevertheless, an automated and opportunistic sequencing of science actions could provide a higher science utility. Onboard data analysis and science goals and instrument prioritization techniques are described in (Chien et al. 2016). Castano et al. (2007) describes the Onboard Autonomous Science Investigation System (OASIS), an autonomous system that is capable of analyzing imagery to generate new science tasks for execution both in simulation and on a test rover. Wettergreen et al. (2014) shows the capability of autonomous sample location selection and adaptive path planning on a rover in a deployment to the Atacama Desert. Woods et al. (2009) demonstrates the feasibility of autonomous opportunistic science with autonomous instrument placement for contact science. All of these algorithms and techniques would support desirable autonomous behavior. Moreover, our proposed approach has room for improvement with respect to the rovers responsible for relaying data. More opportunistic decision making approaches would allow relayers to potentially perform additional science tasks while also managing the task of relaying data out of the cave.

Coordination of data transfer is also an opportunity for cognitive systems. As opposed to waiting for a target rover to be available to receive data, a scheduling system could support a more efficient data transfer coordination between rovers (Clement and Barrett 2003) - assuming they can share their status and activities. The communication model and respective ranges have a great impact on this coordination. We are working on incorporating a stochastic communication model in which bandwidth degrades as a function of distance and does not have a hard constraint on the maximum distance (e.g., 25-meter max range). That provides opportunities for rovers to establish a comm link in greater distance and provides options to route data science out of the cave through different rovers. A more realistic package management during communication would make the routing problem even more interesting, in which science data could be partitioned into smaller pieces and sent to different rovers over time depending on bandwidth variations. Here we assume that data packages would be able to be prop-
erly combined at the target asset (e.g., lander or an orbiter). Such stochastic models would also create scenarios in which rovers are physically close but with a poor or unexisting communication link.

7. Conclusion

In this paper we proposed a multi-rover coordination algorithm for Mars Cave exploration. A simulation framework was created to evaluate the performance of the algorithm and to study mission configurations to explore design options for future missions to underground cavities in other planets and moons. We utilized realistic cave settings and vehicle specs to generate an initial evaluation of the feasibility of the multi-rover approach for science data collection. We also discussed opportunities for AI planning and scheduling techniques to augment rover autonomy and efficiency with respect to science utility.

This is an ongoing research project with several promising immediate next steps and future directions. In the short-term we will investigate the impact on rover performance when increasing action concurrency. More specifically, in the simulation we will allow rovers to transfer data while navigating the environment and doing science. We will also incorporate data routing techniques with the aforementioned stochastic communication model we are integrating. We are also interested in augmenting the proposed algorithm to help rovers to better coordinate data transfer and to balance data relay and science tasks.

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