Technologies Enabling Exploration of Skylights, Lava Tubes and Caves

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Abstract

Robotic exploration of skylights and caves can seek out life, investigate geology and origins, and open the subsurface of other worlds to humankind. However, exploration of these features is a daunting venture. Planetary voids present perilous terrain that requires innovative technologies for access, exploration, and modeling. This research developed technologies for venturing underground and conceived mission architectures for robotic expeditions that explore skylights, lava tubes and caves. The investigation identified effective designs for mobile robot architecture to explore sub-planetary features. Results provide insight into mission architectures, skylight reconnaissance and modeling, robot configuration and operations, and subsurface sensing and modeling. These are developed as key enablers for robotic missions to explore planetary caves. These results are compiled to generate “Spelunker”, a prototype mission concept to explore a lunar skylight and cave. The Spelunker mission specifies safe landing on the rim of a skylight, tethered descent of a power and communications hub, and autonomous cave exploration by hybrid driving/hopping robots. A technology roadmap was generated identifying the maturation path for enabling technologies for this and similar missions.

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1 Introduction

Subsurface caverns may be the best place on Mars to find life. They may be the best hope for safe havens and habitation on the Moon. They can provide a window into a planet's geology, climate, and even biology. Skylights, formed by partial cave ceiling collapse, provide access to subsurface voids. Cave entrances have been conclusively shown to exist on Mars (Cushing, Titus, & Maclennan, 2011) and the Moon (Ashley, Robinson, Hawke, Boyd, Wagner, & Speyerer, 2011). There is also evidence supporting their existence on other planetary bodies throughout the solar system (Ashley, et al., 2011) (See Figures 2 and 3).

Despite astonishing discoveries of skylights and cave entrances, and their inevitable exploration, they do not yet appear in the decadal survey. Skylights and the voids below are so unknown that it is too risky to send astronauts to explore them without prior robotic reconnaissance and modeling.

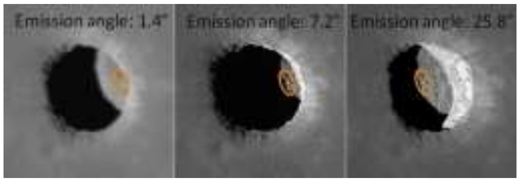

Figure 1: Three views of the Mare Tranquillitatis skylight on the Moon. In the first image the camera is close to the nadir direction; three boulders can be seen marking the position of the skylight wall. As the viewing angle increases, void space under an overhanging ceiling can be observed. (Images from a presentation by James Ashley (Ashley, Robinson, Hawke, Boyd, Wagner, & Speyerer, 2011))

While robotic exploration of skylights and caves can seek out life, investigate geology and origins, and open the subsurface of other worlds to humankind, it is a daunting venture. Planetary voids present perilous terrain that requires innovative technologies for access, exploration, and modeling. The robots that venture into caves must leap, fly, or rappel into voids, traverse rubble, navigate safely in the dark, self-power, and explore autonomously with little or no communication to Earth. Exploiting these features necessitates a leap of technology from current planetary missions, which land with large error ellipses in statistically safe terrain, rove slowly and cautiously across the surface, depend on the sun for power and light, and rely on constant human oversight and control.

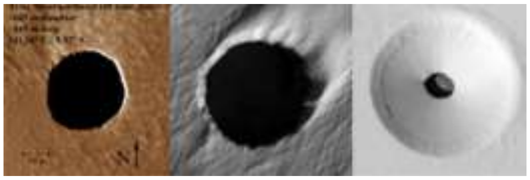

Figure 2: Possible skylights on Mars (Images from a presentation by Glen Cushing (Cushing, Titus, & Maclennan, 2011))

This research developed technologies for venturing underground and conceived mission architectures for robotic expeditions that explore skylights, lava tubes and caves. The investigation identified effective designs for mobile robot architecture to explore sub-planetary features. Results provide insight into mission architectures, skylight reconnaissance and modeling, robot configuration and operations, and subsurface sensing and modeling. These are developed as key enablers for robotic missions to explore planetary caves. These results are compiled to generate "Spelunker", a prototype mission concept to explore a lunar skylight and cave. The Spelunker mission specifies safe landing on the rim of a skylight, tethered descent of a power and communications hub, and autonomous cave exploration by multiple hybrid driving/hopping robots. A technology roadmap was generated identifying the maturation path for enabling technologies for this and similar missions.

1.1 What Is Known about Planetary Caves?

Before caves were known to exist on planetary bodies beyond Earth, scientists looked at caves on Earth and hypothesized that similar features might exist elsewhere. Even now, when caves have been proven to exist on the Moon and Mars, Earth analogs are one of the best sources of information about planetary caves as satellites provide limited and low-resolution views into subsurface features. Known mechanisms for cave formation on Earth are likely to form caves on other planets as well. These mechanisms include lava flows, volcano-tectonic fractures, and chemical dissolution.

Figure 3: Lava tube cave (Photo courtesy USGS)

Lava tube caves are formed by volcanic activity; the top layer of a channel of lava cools and forms a crust, leaving a void space when the hotter lava in the center of the channel flows out. Lava tubes tend to have smooth floors, and they may have "soda straw" stalactites formed by lava dripping from the ceiling. Sinuous rilles visible on the Lunar surface were likely formed by lava tube collapse (Oberbeck, Quaide, & Greeley, 1969), and lava tube structures have also been identified on Mars (Bleacher, Greeley, Williams, Werner, Hauber, & Neukum, Olympus Mons, Mars: Inferred changes in late Amazonian aged effusive activity from lava flow mapping of Mars Express High Resolution Stereo Camera data, 2007) (Bleacher, Greeley, Williams, Cave, & Neukum, 2007). Due to the lesser gravity, it is predicted that lava tubes on Mars or the Moon may be much larger in diameter than those found on Earth (Coombs & Hawke, 1992). Caves can form when tectonic plates shift relative to each other and leave void spaces. In contrast to lava tubes, volcano-tectonic fracture caves are less sinuous; they are likely to be straight or slightly curved (Cushing G. E., 2012). The fractures can extend kilometers beneath the surface and may be partially filled from the bottom by magma (Cushing G. E., 2012).

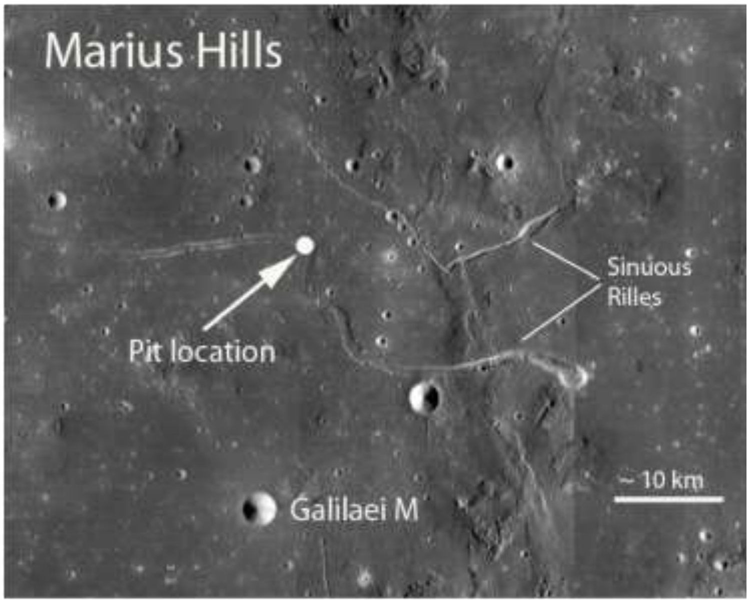

Figure 4: Sinuous rilles on the Moon. Location of the Marius Hills pit is marked (Ashley, Robinson, Hawke, Boyd, Wagner, & Speyerer, 2011).

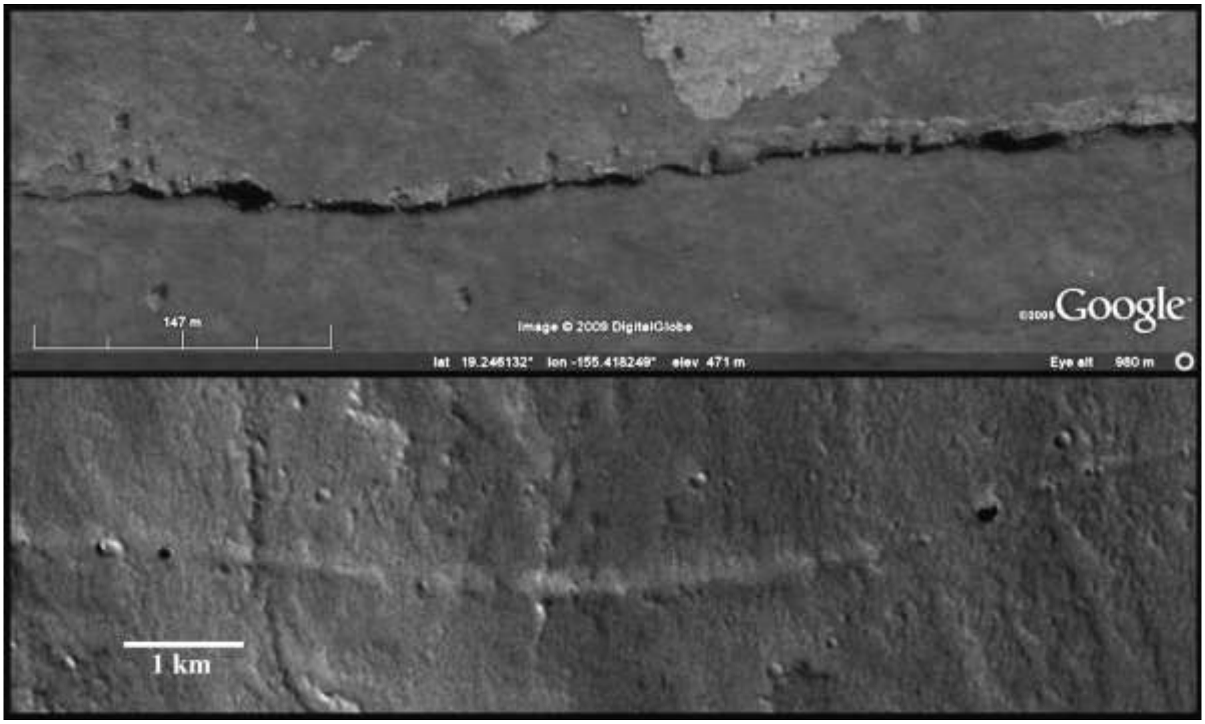

Figure 7: Volcano-tectonic fractures on the Earth (top) and Mars (bottom) with potential cave entrances (Cushing G. E., 2012)

Caves can also form when rock is dissolved by chemical means. Limestone caverns commonly found on Earth result when limestone is dissolved by water that has become slightly acidic through absorption of carbon dioxide. Karst is a name for the rock formation caused by dissolution of bedrock – the same dissolution that causes caves also results in karst formations. Karst-like features have been observed on Titan (Mitchell & Malaska, 2011). Limestone caves on Earth tend

Figure 6: Stalactites, stalagmites and columns in limestone cavern

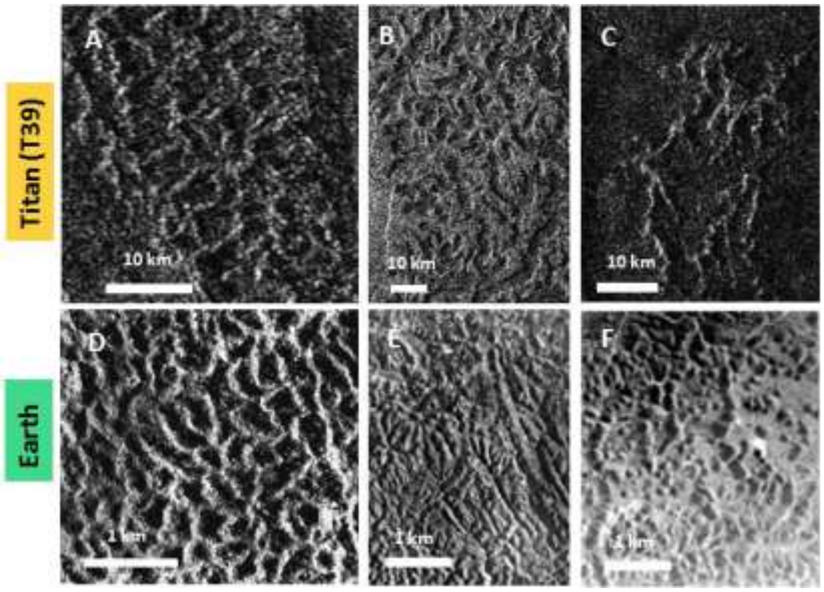

Figure 5: Karst-like features on Titan (top) compared to Karst on Earth (bottom) (Mitchell & Malaska, 2011).

to include sequences of chambers at many different levels, as opposed to the long, continuous, gently-sloping caverns in lava tubes. They often have many stalactites and stalagmites, formed when minerals are deposited by the flow of the dissolving liquid.

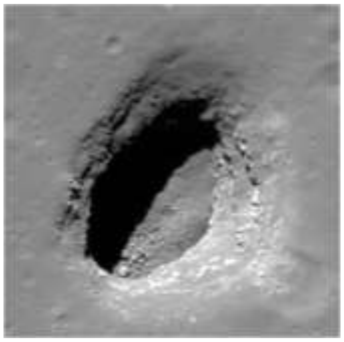

Figure 8: Mare Ingenii Skylight

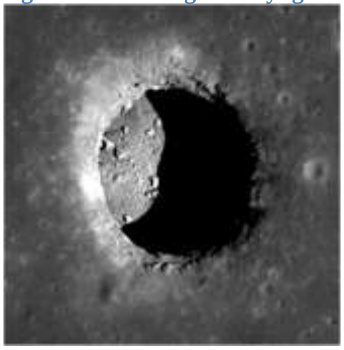

Figure 9: Mare Tranquillitatis Skylight

Figure 10: Marius Hills Skylight

Skylights[1], formed by cave ceiling collapse, can provide entrance into caves. Several skylights on the Moon and Mars have been characterized from orbital image data. Skylight diameters can be obtained by counting pixels in an image of known resolution. Shadow measurements provide rough estimates of skylight depth. More detailed information can be gained from stereography – matching features between images taken from different perspectives. A digital elevation model of the Moon's Marius Hills skylight was generated through this method. In high resolution images, the dimensions of large blocks on a skylight floor can be measured, and terrain roughness on a scale below image resolution can be estimated from the standard deviation of surface reflectance, with a higher standard deviation indicating rougher terrain (Robinson, et al., 2012).

Of the three Lunar skylights, which have been studied in detail (See Figure 8 through Figure 10), diameters range from 49m (short diameter of Marius Hills skylight) to 104m (long diameter of Ingenii skylight), and depths range from 38m (shallow end of Ingenii skylight) to 107m (Tranquillitatis skylight) (Robinson, et al., 2012). A fracture cave skylight examined on Mars (See Figure 12) has diameters from 68m to 48m; its depth was measured at 37m, but may be as shallow as 19m in the skylight center (Cushing G. E., 2012). A more circular Martian skylight (see Figure 11 a) has a diameter of approximately 65m and a depth 45m or greater (Cushing G. E., 2012). One particularly interesting Martian skylight, shown in Figure 11 b, sits at the bottom of a pit crater. This skylight is approximately 40m across, 50m below the surface and 25m deep (Cushing G. E., 2012).

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[1] For clarity in this work, a skylight is defined as an entrance to a cave from above, without regard to the formation mechanism or extent of the cave, as it is often not possible to distinguish these from existing orbital data. Tranquillitatis, Ingenii and Marius Hills pits on the Moon are assumed to be skylights, though the existence of a cave at the Ingenii pit has not been confirmed.

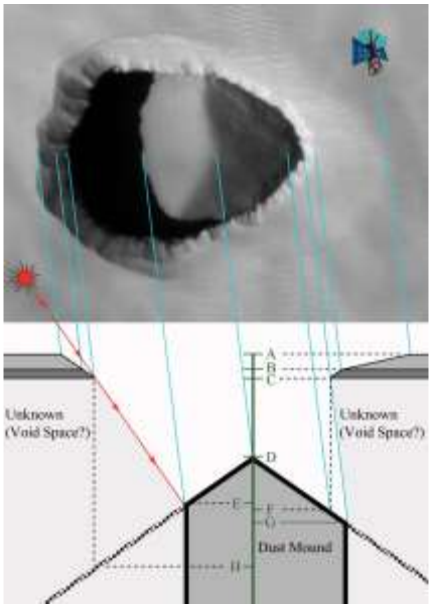

Figure 12: Fracture cave skylight on Mars

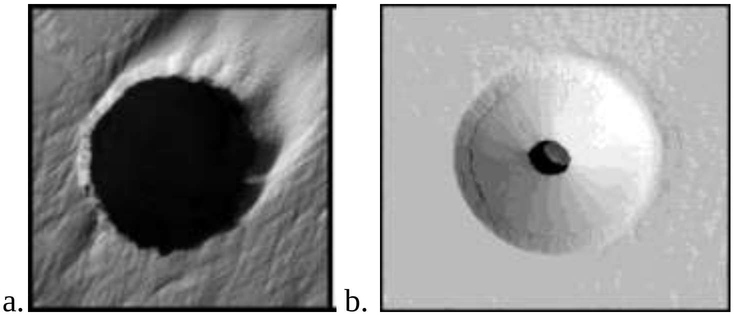

Figure 11: Martian skylights

Similar to volcanic activity, high-energy impact can also cause flows of molten rock. A number of pits have also been identified in Lunar impact melts. These pits are smaller and less well understood than the three skylights discussed above, but they may also lead into caves (Robinson, et al., 2012).

1.2 Related Work

Prior work has investigated and developed relevant technologies for some of the key challenges of robotic planetary cave exploration, including subsurface mission architectures, mobility, modeling and autonomy.

A prior NIAC Phase I study, (Werker, et al., 2003), studied the scientific value of exploring caves on other planets. This research speculated on planetary cave value by comparing to scientific knowledge gained by investigation of terrestrial caves. This study listed devices and infrastructure that are required to execute subsurface planetary exploration. Important aspects include communication networks, biological sensing, and drilling capabilities.

(Dubowsky, Iagnemma, & Boston, 2006) proposed exploration of subsurface voids with a large team of expendable robots. These robots were self-contained spherical hopping robots weighing approximately a 100 g with a 100 mm diameter. The rationale behind this development is that wheeled rovers such as Sojourner or Curiosity are not well suited to navigate through extremely rough terrain or access highly sloped surfaces anticipated to be present in subsurface environments. Additionally, Dubowsky, Iagnemma, and Boston opted for a large team of small-scale, low-cost robots, as large rovers were deemed too valuable to risk entrapment.

Prior academic research has addressed robotic model generation of terrestrial voids. Carnegie Mellon University has performed extensive research in this domain publishing algorithms to solve localization, feature extraction and scan matching problems in a cavern like environment. (Wong U. , Garney, Whittaker, & Whittaker, 2011) demonstrated significantly improved modeling in caves using range scanners and sampling the scene with a Nyquist criterion. Venturing into unknown cave environments with no access to absolute localization methods such as GPS, a robot must solve the Simultaneous Localization and Mapping (SLAM) problem. Fairfield, Kantor and Wettergreen presented approaches for SLAM applied to a robot exploring underwater caves (Fairfield, Kantor, & Wettergreen, Three Dimensional Evidence Grids for SLAM in Complex Underwater Environments, 2005) (Fairfield, Kantor, & Wettergreen, 2006) (Fairfield, Kantor, & Wettergreen, 2007; Fairfield, Kantor, & Wettergreen, Segmented SLAM in Three-Dimensional Environments, 2010).Robot motion on natural surfaces has to cope with changing yaw, pitch and roll angles, making pose estimation a problem in six mathematical dimensions. (Nuchter & Surmann, 2004) developed a fast variant of the Iterative Closest Points algorithm that registers 3D scans in a common coordinate system and re-localizes the robot. Consistent 3D maps can then be generated using a global relaxation. Zlot and Bosse coupled measurements from a spinning, scanning LIDAR with data from an inertial measurement unit to achieve SLAM from a moving platform that built a 3D model for 17km of mine tunnel (Zlot & Bosse, 2012). Prior work also encompasses planning for subterranean exploration and mapping (Morris, Ferguson, Silver, & Thayer, 2006) (Thrun, et al., 2004), and science autonomy (Wagner, Apostolopoulos, Shillcutt, Shamah, Simmons, & Whittaker, 2001) (Wettergreen, et al., 2005).

2 Mission Concepts for Exploration of Skylights, Lava Tubes and Caves

Phase I Investigation of Skylight Access
Analysis of mission requirements and configurations. Precision landing analysis. Participated in 2011 International Planetary Caves Workshop.

Phase I Insights
Ground-penetrating radar fails to detect lava tubes where lava is laid down in multiple flows, making it necessary to descend into a lava tube to measure its extent.

Safe, autonomous landings near features can be achieved without guaranteed-safe zones of landing-ellipse size, using terrain relative navigation in combination with existing hazard detection and avoidance technology.

A combination of multiple untethered cave exploration robots that can leap into the hole plus a tethered robot for a line-of-sight comm link is the current best configuration for skylight entry and exploration.

Indications for Phase II Study
Detail Spelunker mission concept.

For the purposes of this study, mission architecture includes the number of robotic entities and their roles (i.e. a single probe that descends to the planetary surface and flies into a skylight, a lander that deploys a rover to explore a cave, etc.), the approximate mass of each entity (which has implications on the traditional space mission architecture components of launch vehicle and trajectory), the methods of communication, the power strategies employed, and the concept of operations. Multi-mission architectures are also possibilities for skylight and cave exploration. One such multi-mission architecture would be broken into three phases, the first phase being the flyover and surface investigation of a skylight and deployment of a sensor package to a skylight entrance. This sensor package would be lowered into the skylight and scan the portion of the lava tube within sensor range, providing valuable insight about the environment within the tube. The second phase sends mobile robots in to explore the lava tube or cave network. The third phase includes delivery of habitats, robots, and personnel to the tube for base construction, the exploitation of resources, or the deployment of a robot with specialized scientific instruments to investigate the findings from the previous phases. Recognizing that economic and political realities sometimes make it difficult to send multiple missions to explore the same target, architectures developed in this study combined phases one and two into a single mission and further details this combined mission. In order to compare mission architectures, a reference set of mission goals are defined. For this study, those goals are to: enter a lava tube cave via a skylight, explore the cave, and send back data that includes a model of the skylight and cave.

2.1 Planetary Cave Insights That Impact Mission Architecture

Through this research, Astrobotic participated in the Planetary Cave Research Workshop, discussion with scientists at this workshop provided valuable insights for cave exploration mission architectures as detailed in this section.

Ground penetrating radar, which can be used on Earth to determine the extent of a subterranean cavern from the surface, often fails to detect lava tubes if the lava was deposited in multiple flows. This is because ground penetrating radar partially reflects at interfaces between layers of material, and repeated lava flows result in many layers of material close to the surface.

Science objectives are also important to consider when planning what parts of the cave to investigate, what sensors are required, and how far a robot must travel inside a cave to gather useful data. For caves on Earth, floors are of particular interest in lava tubes, but walls and ceilings are more interesting in other types of caves. The distance that must be traveled inside a cave to observe a regime that is significantly different from a science perspective is highly dependent on morphology, but in many cases it may be sufficient to get beyond the “twilight zone,” which is the transition between areas that are illuminated for some period during the day as the sun transits overhead, and areas of constant darkness. This region is likely to be indicative of the variation within the tube in terms of potential to support life, volatile contents, and geological features, which may be impacted by sunlight, temperature variations, or rock fall during skylight formation.

Additionally, concern was raised by some scientists about the use of propulsive vehicles in and around skylights and caves. If volatiles exist trapped at the bottom of a skylight, they could be contaminated by a vehicle’s thruster plume. Similarly, living organisms inside a cave could be killed if a vehicle’s thruster plume contained toxic chemicals. Mission architectures for exploration of skylights, caves and lava tubes must consider both the value of information gained by using a given exploration strategy and the possibility of contaminating scientifically important sites with that strategy.

2.2 Mission Architecture Issues and Options

There are five main issues that any mission for planetary cave exploration must address: access to the cave, in-cave mobility, collection and processing of data for modeling and other scientific objectives, power, and communication. Robot configuration (discussed in Section 4) has a large impact on how these issues are addressed, but mission architecture plays an important and complementary role. How many robots are there, and how do they work together? What tasks are robots commanded to perform? In this study, the space of missions architectures explored includes more than one robot (i.e. the lander that reaches the planetary surface is not the only entity) and less than many (i.e., not hundreds or thousands of entities).

Even with lower gravity on order of one sixth (Moon) or one third (Mars) of Earth's, planetary bodies are still substantial gravity wells, and precision propulsive landing requires significant fuel. Cave exploration requires power-conscious mission architecture, due to the lack of solar power underground. Energetically, it does not make sense to carry the propulsion system required for landing along for further cave exploration activities. While a braking stage might simply be discarded as a lander nears the ground, this mass could also dual-purpose as an anchor for tethered descent and/or a communications relay. Lander solar panels that provided power in cruise can also be re-purposed to perform tethered re-charging for the cave explorer.

Dubowsky and Boston proposed a many-robot architecture (Dubowsky, Iagnemma, & Boston, 2006). In this approach, many baseball-sized robots descend into a cave. Communication is achieved by relay between agents. This method is robust to the failure of one or even the majority of the robots. If a few manage to succeed, the mission succeeds. The downside of this many-robot architecture is that the robots must be very small, (in mass and volume), and very cheap in order for the mission to be feasible. Unfortunately, the extremes of small size and low cost often come with limited capability. Miniaturization has steadily decreased the size of robot components over time. Boston and Dubowsky count on this trend continuing, until 0.1kg microbots could be achieved within 10-40 years, but sometimes miniaturization runs up against physical limits. For example, chip manufacturers faced new issues when silicon gates reached a thickness of only a few atoms. Modeling in lava tubes requires active sensing, and due to the expected larger size of lava tubes on the Moon and Mars, sensors in these environments must have long range, which requires increased power. Technologies like active sensing may well provide a physical barrier to miniaturization.

Given 100kg of payload capacity, a lander could deploy 10 robots at 10kg each, versus 1000 robots at 0.1kg each. These approaches require equivalent mass. They could cover equivalent areas, with each 10kg robot traveling farther in its lifetime than each 0.1kg robot. But, if the 0.1kg robot can accommodate a sensor with 1m range and the 10kg robot can accommodate a sensor with 100m range, only one of these approaches can model a 100m-high cave ceiling. The concept of relatively small but sufficiently capable robots drives the mission architectures explored in this work.

2.2.1 Mission Concept Details

Figure 4: A conjoined multi robot system completes its tethered descent into a lunar skylight

An early mission concept involved a segmented wheeled rover that descends into a skylight via tether from a lander. A video, downloadable here, depicts this mission scenario. The rover has egressed from the lander and approaches the skylight. The tether cable enables the rover to descend slowly into the skylight. Once at the bottom, the rover is able to navigate uneven, rocky terrain. Two segments can detach, enabling the resulting two-wheeled mini-rovers to independently and autonomously explore the skylight and surrounding lava tubes. The two-wheeled rovers can return to the tethered segment to communicate exploration results and recharge.

Power and data transmission between the tether end and the cave explorer could be through a contact link, as depicted in the mission concept video above, or it could be done wirelessly. Wireless power transmission can be achieved using laser-photovoltaic power beaming[2]. Beamed power is less efficient than a physical connection, but mission concepts with exploring robot performing successive forays into the cavern and returning to range for charging, high efficiency transmission is not required. The recharge time can simply be lengthened if transmission is less efficient. Beamed power can be transmitted without contact, wherever there is line-of-sight. This means that a cave exploring robot would not have to come all the way back to the tether end to re-charge, which could be a significant risk reduction if the tether end is located in rough, rubble-pile terrain. In a beamed power scenario the tethered power beaming node could be suspended within the cavern under the skylight to extend charging range over a rough surface. Alternately, in a contact charging regime the tether end requiring a contact link could be carried by the exploration robot past the edge of the rubble pile at the skylight base, however this would increase required tether length and increase the chance of snagging the tether during deployment. Also, since the nature of the cavern interior is unknown, it is impossible to know exactly how much longer the tether would have to be. In addition to wireless power, communication can occur over a local wireless link, which is also improved in range by suspending the communication node.

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[2] Laser Motive, Inc., “LASER POWER BEAMING FACT SHEET” http://lasermotive.com/wp-content/uploads/2012/03/Laser-Power-Beaming-Fact-Sheet.pdf

A mission concept for a prototypical mission to a lunar skylight and lava tube entitled “Spelunker” is presented below and in Figure 14 through Figure 17. The mission includes a cave mobility robot entitled “Cavehopper”, a hybrid driving/hopping robot (See Figure 13). The selection Cavehopper as a promising robot configuration is detailed in Section 4.

Spelunker delivers three Cavehopper robots to the lunar surface, where they hop into a planetary lava tube via a skylight, autonomously explore using a suite of onboard sensors, and send back detailed models of the cave interior via a tethered power and comm station. This mission concept is applicable to the Moon, Mars, and any other planetary body with skylights visible from orbit. Reconfiguration of onboard sensing can adapt the mission to specialized scientific investigation.

The Spelunker mission deploys a propulsive lander that flies over the skylight during descent, scanning the terrain with LIDAR and capturing reconnaissance imagery. The lander autonomously evaluates the terrain for hazards and chooses a landing spot based on safety and on favorability of the adjacent wall for tethered descent. After landing, three Cavehopper robots egress from the lander. A fourth robot, “Livewire,” makes a tethered descent into the hole. Livewire brings a connection to the lander’s radio, the capability to beam power, and camera and LIDAR sensors to provide reconnaissance and track Cavehopper robots. After analysis of Livewire’s reconnaissance data, ground control operators select entry points around the skylight rim for the three Cavehoppers. The Cavehoppers, powered by batteries, launch themselves into the skylight. They hop to navigate rubble on the skylight floor, and use wheels to drive when they encounter smooth floor. Inside the cave, the Cavehoppers receive high-level mission direction from human operators but are capable of autonomously planning and executing exploratory traverses beyond Livewire’s communication range. While driving and hopping, the Cavehoppers model their environment using cameras with active lighting and LIDAR sensing. They also carry miniaturized science instruments to investigate cave geology. The Cavehoppers return to within line-of-sight of the Livewire to relay their data and recharge from beamed power. Livewire transmits the Cavehoppers’ data up the tether to an antenna on the lander, which transmits to a relay satellite or directly to Earth. This foray-”phone home” cycle is repeated until all lava tube regions within battery range of the skylight have been explored. Scientific investigation of targets of interest can continue until the robots exhaust their operational life.

Figure 13: “Cavehopper”, a hybrid driving/hopping robot for planetary cave exploration.

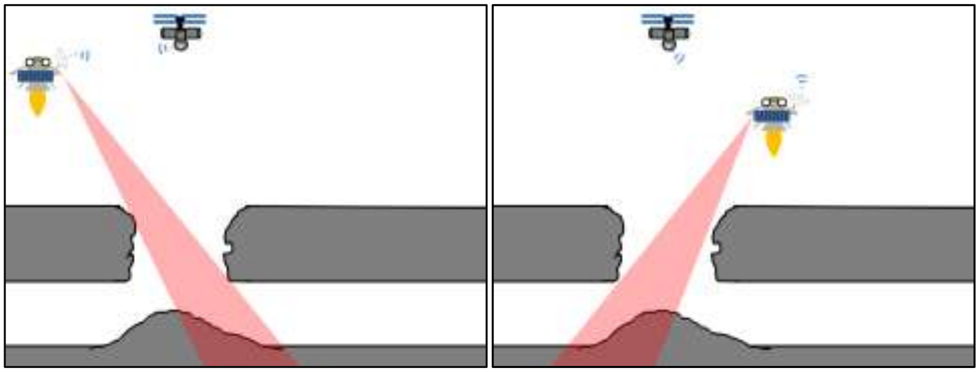

Figure 14: Lander flies over and scans skylight.

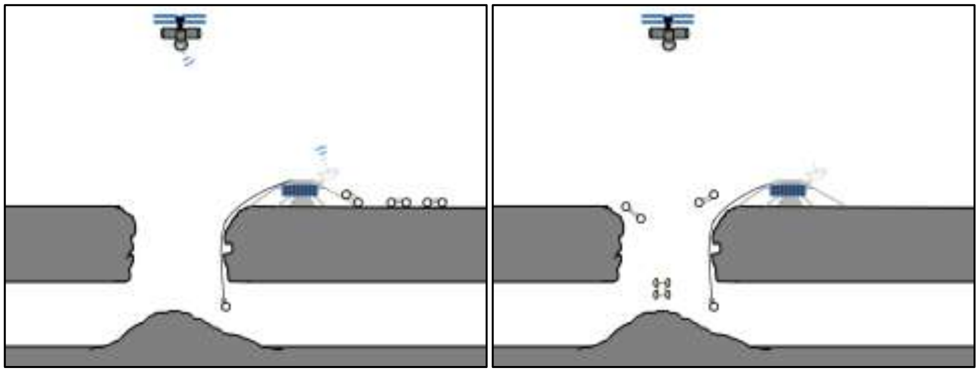

Figure 15: Livewire rappels into skylight and three Cavehopper robots leap in.

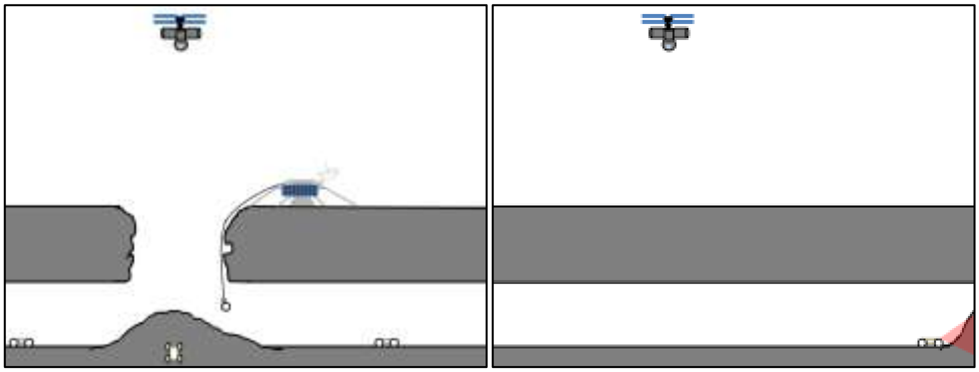

Figure 16: Cavehoppers explore lava tube.

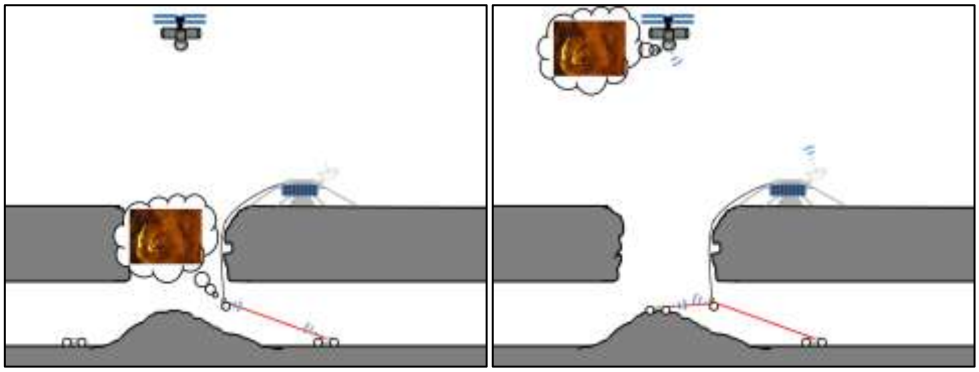

Figure 17: Cavehoppers return to recharge and communicate data to Livewire, which relays data to an orbiting satellite or directly to Earth.

3 Skylight Reconnaissance and Modeling

Phase I Investigation of Skylight Reconnaissance and Modeling

Developed complementary flyover and surface modeling for skylight reconnaissance.

Simulation of skylight and surrounding terrain developed.

Proof of concept in simulation to demonstrate technology.

Presented mission concept at International Planetary Caves Workshop.

Presented paper on complementary flyover and surface modeling at Field and Service Robotics conference.

Phase I Insights

Manual analyses of new, higher resolution satellite images are improving scientific understanding of skylight dimensions and possible formation mechanisms.

Combining Flyover and surface views achieves better coverage of skylight features than either alone.

Planning rover views from lander model results in more efficient rover paths.

Manual analyses of new, higher resolution satellite images are improving scientific understanding of skylight dimensions and possible formation mechanisms.

Indications for Phase II Study

Flyover and surface modeling should be incorporated into mission architecture.

Expanding simulation to include detailed skylight and lava tube model will be a useful tool for further technology development.

3.1 Skylight Simulation Environment

This research generated a 3D model of a skylight to enable simulation of robotic reconnaissance and exploration in and around skylights. The dimensions of this model are based on the Moon's Marius Hills Hole. Surrounding terrain in the model has the extent required to simulate landing near a skylight and the detail to simulate rover operations on the ground (See Figure 18 and Figure 19). Both camera images and LIDAR (LIght Detection And Ranging) data can be simulated through this model. Preliminary work on sensing, planning and modeling for a skylight reconnaissance mission was performed in this simulation environment.

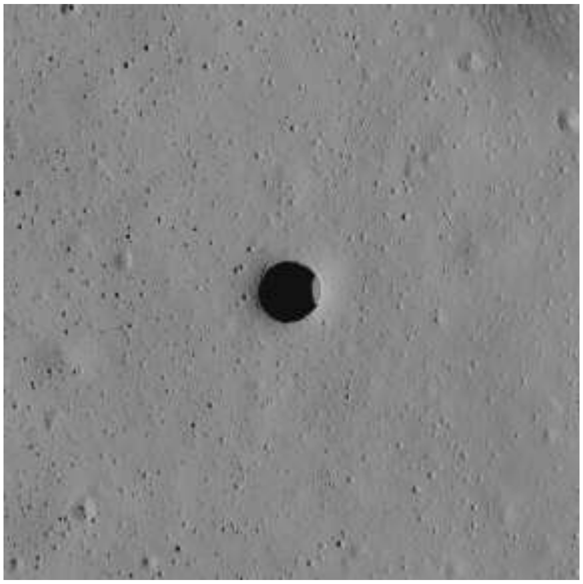

Figure 18: Overview of simulated terrain containing a skylight (section shown is 600m x 600m square, full model is larger)

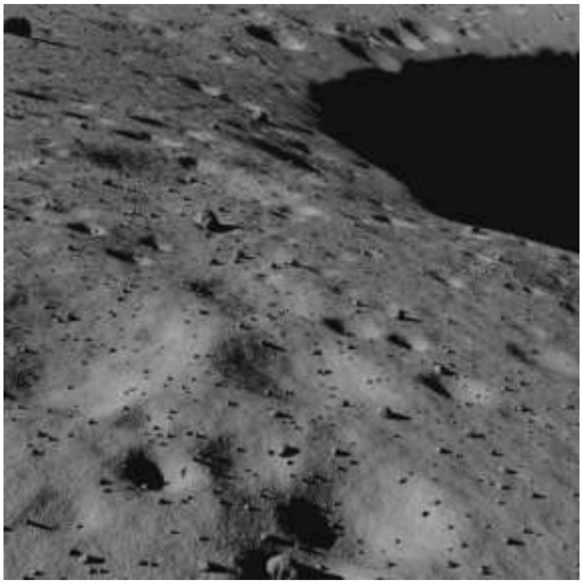

Figure 19: Simulated camera image showing a rover's-eye view of the skylight edge

Figure 20: Side view of walls and floor for manually modeled skylight

Terrain was constructed by starting from a 2 meter per post digital elevation model from LRO data. Smaller-scale craters and rocks were added according to statistical models of Surveyor data (NASA Surveyor Project Final Report, 1968) . Texture and lighting were added to the scene to create Lunar-like images from lander or rover perspectives (See Figure 21). A skylight was modeled manually using Blender[3] software and incorporated into this terrain (See Figure 20).

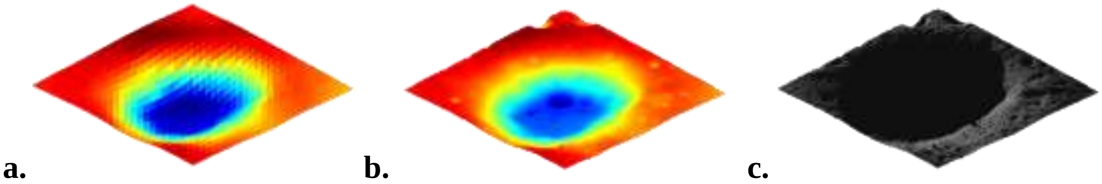

Figure 21: a. Initial 2 m/post DEM, b. DEM with detail added according to statistical models, c. Terrain with texture and lighting

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[3] Blender Foundation: Blender 2.59. www.blender.org

3.2 Complementary Flyover and Surface Modeling for Skylight Reconnaissance

Because skylights are so new and so unknown, it is much too risky to send astronauts, or even complex and expensive robotic systems, to explore these holes and the caverns below without prior reconnaissance. Surface robots can approach a skylight and scan the walls, but skylight geometry precludes viewing the floor of the hole from a surface perspective. This research innovated an autonomous mission strategy for skylight reconnaissance that integrates lander and rover exploration. Autonomy will make such missions feasible even in locations with limited communications, such as the Lunar far side or the moons of the outer planets.

Lander flyover and rover exploration data are combined to autonomously model point destinations, like skylights, where 3D detail matters. Lander and rover use both cameras and active sensors, such as LIDAR. Active sensing is needed to peer into shadowed regions, but active sensors are range-limited by available power and lack the high resolution of cameras.

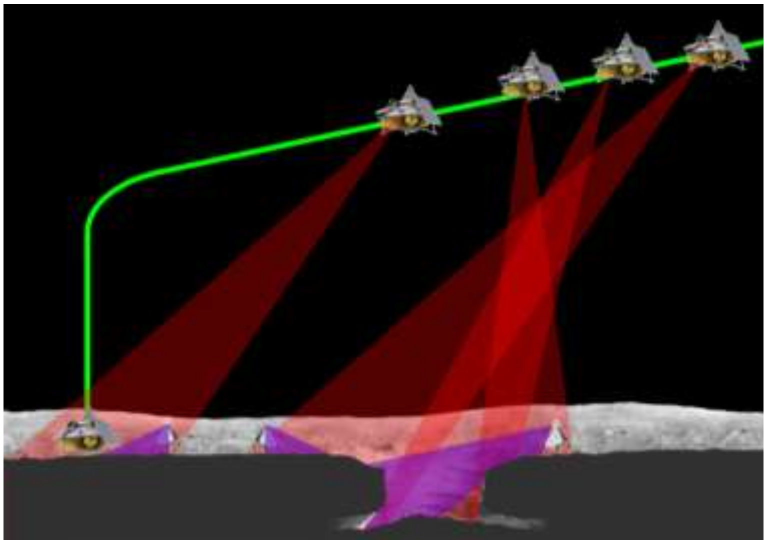

Figure 22: Complementary flyover and surface modeling. Lander captures LIDAR and camera imagery of terrain during flyover. Rover then captures data of the same region, but from a different perspective. Rover is localized within lander imagery to improve the combined model.

Advances in terrain relative navigation present the possibility of precisely flying and landing by matching lander camera images with prior satellite imagery of a planetary destination. Through this technique, landers can construct trajectories to precisely fly over features of interest, like skylights, during final descent to the surface. This technology enables landers to fly within 30m of their intended trajectory within the final 500m of descent and model regions on order of 50m across from very low altitude. Additionally, hazard detection and avoidance technology, combined with

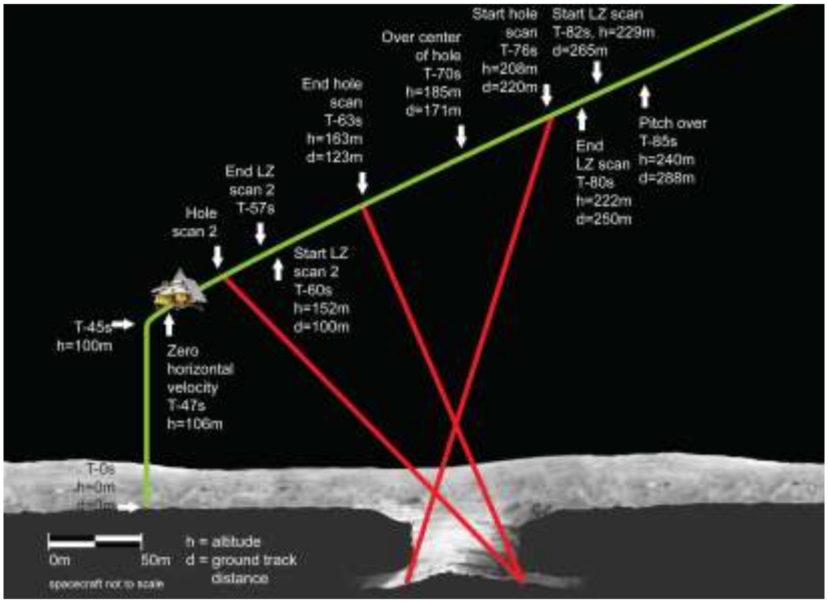

Figure 23: Gimbaled LIDAR scans landing zone 80 seconds before touchdown to detect hazards and to map terrain features of interest.

precise navigation, enables safe and autonomous landings near features even without guaranteed-safe zones of landing-ellipse size.

Rover modeling begins at the lander touchdown location, providing a common tie-point between surface and flyover models. Lander-generated surface model is used by the rover planer to enhance safety during traverse. Rover paths and sensor views can be autonomously selected, using a "next best view" approach, to fill holes in the lander-generated surface model and generate a higher fidelity and coverage combined model. Lander-generated model also improves rover localization, correcting the drift of visual odometry and other relative navigation methods.

Lander flyover captures detailed overview data, as well as perspectives that cannot be observed from a rover viewpoint. Rovers can capture close-up images of the terrain, and they can linger to capture multiple views from stationary locations, though always from low, grazing perspectives. Alternately, landers can acquire bird's-eye views but with less detail and resolution since their one-pass, always-moving trajectories are constrained by fuel limitations. Combining lander and rover data enables autonomous construction of high-quality 3D models of skylights, not possible from either platform alone.

A mission concept for flyover and surface exploration of a skylight was presented at the First International Planetary Caves Workshop (Peterson, Jones, & Whittaker, 2011). This included preliminary sensor selection and timing for scanning a skylight while flying over in the final stages of descent to a planetary body, as shown in Figure 23. Further analysis of the concept, including experiments using the simulation presented in Section 3.1, was presented in a paper at the 8th International Conference on Field and Service Robotics (Jones, Wong, Peterson, Koenig, Sheshadri, & Whittaker, 2012). This analysis is presented in later in this section

3.2.1 Complementary Flyover and Surface Modeling Experiments

To test the approach, camera and LIDAR data from both lander and rover perspectives are generated in simulation. Lander-only models, rover-only models and combined lander and rover models are constructed. Because the sensed terrain is simulated, exact ground truth for 3D structure is known, facilitating comparison between models. Coverage values for these three cases were compared.

Figure 25 shows the rover path for a naïve, rover-only approach. This path is planned to cover the region of interest as fully as possible with a rover only (for our experiments, the region of interest is a 100x100m square centered on the skylight). The length of the naïve rover path was 2152m.

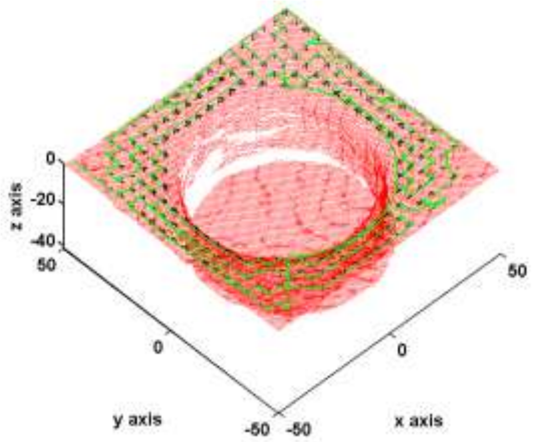

Figure 24: Planned rover path (green) and views (black), overlaid on voxel model of skylight

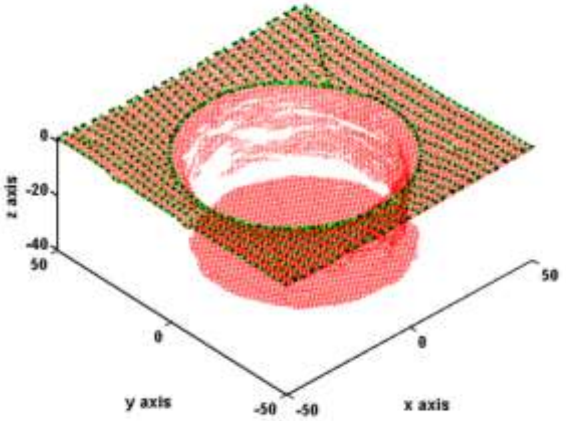

Figure 25: Naïve path for rover-only coverage (green and black) overlaid on voxel model of skylight

To autonomously plan rover views, a 3D model is generated from lander flyover data. A grid of possible positions within the region of interest is generated, excluding positions that are too close to the hole. A 3D model with occupied and unseen regions marked is used to predict the unseen areas that can be observed from each rover view. A list of previously unseen regions visible from each view is stored, as well as the total number that can be seen in all of the views from a given position. Faces that were predicted to be visible in views from the new rover position are then marked as seen, and the metric is recomputed. This is repeated until there are no rover positions for which previously unseen faces are visible. Given a set of rover positions with planned views which cover the space of visible but as-yet unseen voxels, the order in which those positions are visited can be changed without affecting the total number of as-yet unseen voxels observed, and a more efficient path is planned, taking into account the distance between rover positions. Distance is computed along a straight line rover path, unless the straight-line path would intersect the skylight or the keep-out zone, in which case the path skirts the skylight until it can continue in a straight line toward the target waypoint. Figure 24 shows the planned rover path and views overlaid on a voxel model built from lander data. The length of the planned rover path was 1281m.

Figure 26 shows a 3D model built from lander-only data. This model has 46% coverage of the terrain. From the figure, it can be seen that the skylight floor and surround terrain are well covered, but the skylight walls are not. Figure 27 shows a 3D model built from rover-only data, with a rover path as shown in Figure 25. The walls are clearly covered much more densely in this case, but there is a region in the center of the skylight floor for which the skylight geometry prevents rover viewing. The coverage of this model is 85%. Figure 28 shows a 3D model built from combined lander and rover data. This model covers the walls well, similar to the rover-only model, but it also covers the skylight floor. The coverage of this model is 92%.

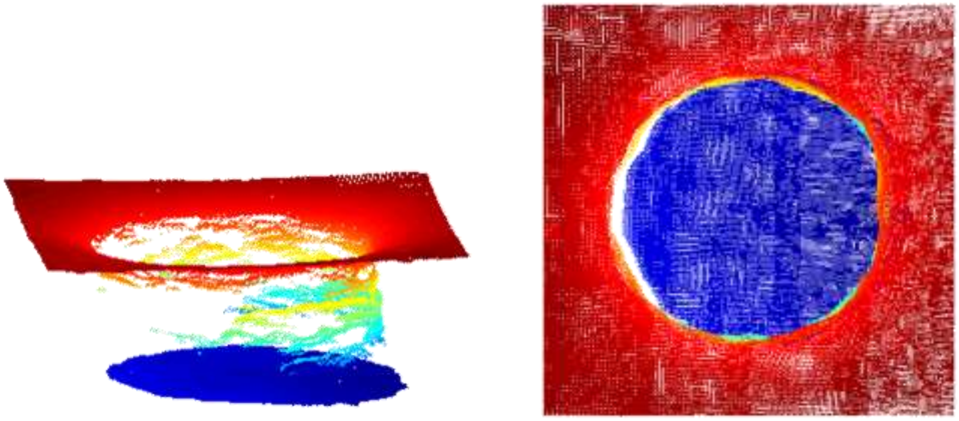

Figure 26: Lander-only 3D model. Side view (left) and top view (right)

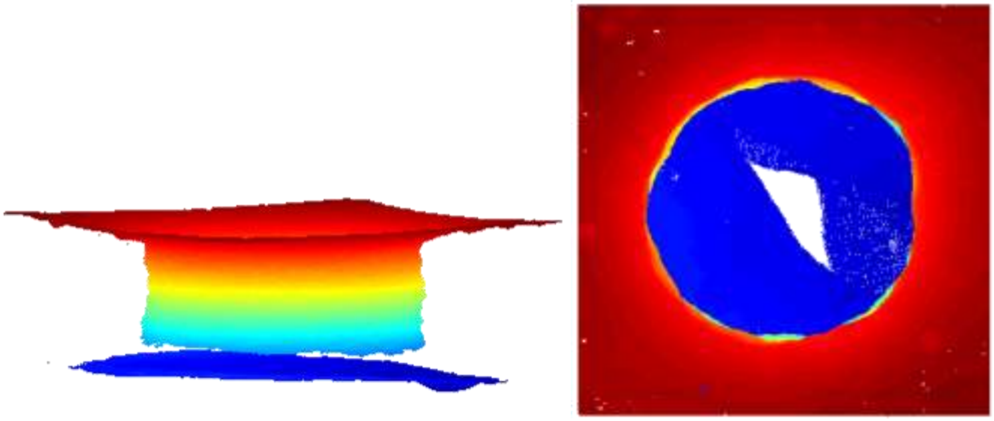

Figure 27: Rover-only 3D model. Side view (left) and top view (right)

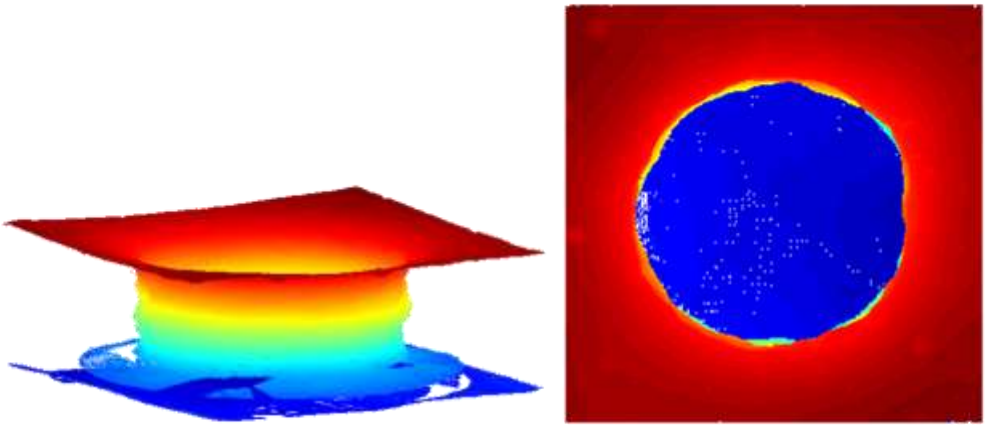

Figure 28: Combined lander and rover 3D model. Side view (left) and top view (right)

3.2.2 Methods for Stitching Lander and Rover Models

The experiments in Section 3.2.1 were conducted assuming perfect knowledge of sensor positions and orientations, but for a real mission, these will not be known perfectly. Planetary destinations lack GPS infrastructure for absolute localization, and relative localization methods, such as inertial navigation or wheel odometry, produce estimates that drift over time. A drifting position estimate can result in a severely distorted model, unless something is done to correct the model.

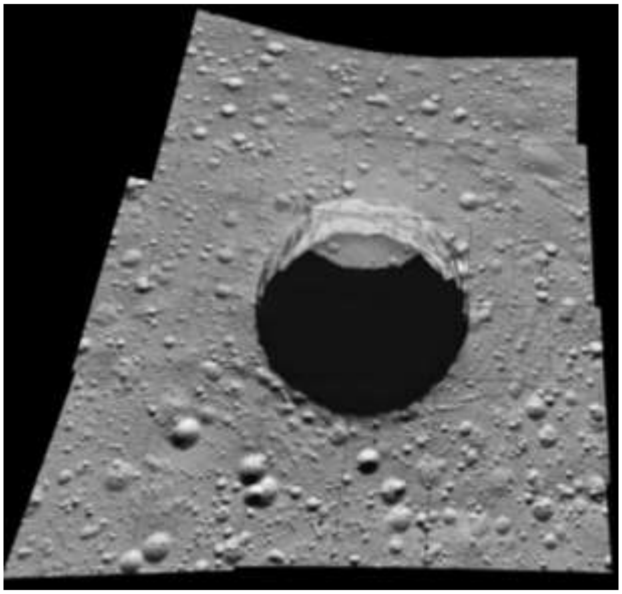

Figure 29: Simulated lander flyover imagery stitched into an overview map

One way to do this correction is using features in the data that make up the model. One common method in computer vision is to detect features in images and match features between overlapping images. Figure 29 shows an example of using this method to create a mosaic of simulated flyover images. The SIFT method was used to detect features in this example (Lowe, 2004).

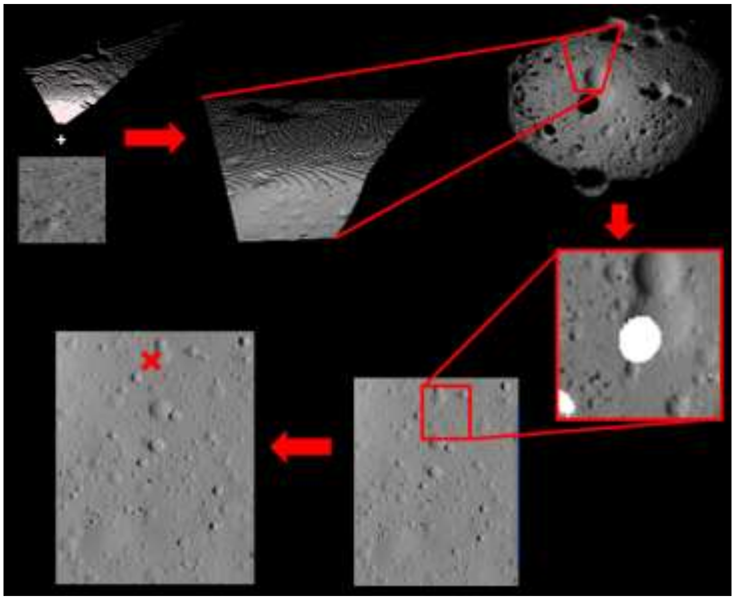

Figure 30: LIDAR and camera imagery captured by a rover is converted to a colorized point cloud. A panorama of these colorized clouds is stitched together to form a 3D model of the rover's immediate surroundings. A template is created from a top view of this model. The template is correlated with a map built from lander flyover imagery. The correlation result then determines the rover position within the lander-built map.

Matching image features between lander and rover images is complicated by the significant difference in perspective. One way to solve this problem is to build a local model, using camera and LIDAR data, that includes both 3D and color information. This local model can then be viewed from a different perspective. The method presented in Figure 30 was originally developed as a GPS-free absolute localization method for planetary rovers (Sheshadri, Peterson, Jones, & Whittaker, 2012). In that application, the overhead map comes from prior satellite imagery. The localization precision is dependent on the resolution of the overhead map, and with new high resolution imagery of the moon[4], estimates to within 2m are expected. The same method can also be used to align rover data with lander models, an essential step for complementary flyover and surface modeling, and due to the higher resolution of the lander imagery, the alignment would be more precise in this case.

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[4] The Lunar Reconnaissance Orbiter provided 0.5m/pixel imagery from its nominal mapping orbit, and it is now capturing 0.25m/pixel imagery from a lower altitude orbit (Robinson, et al., 2010) (Riris, Cavanaugh, Sun, Liivia, Rodriguez, & Neuman, 2010).

4 Robot Configuration and Operations

Phase I Investigation of Robot Configuration and Subsurface Operation
Robot trade studies. Investigation of power, communication, and autonomy technologies. Analysis of mission requirements.

Phase I Insights
Hybrid driving/hopping robot can engage likely terrain types by choosing appropriate traverse mode.

A tethered power and communications node lowered into a skylight enables robots to recharge and communicate data to ground control without requiring the mobility to return to the surface.

Wireless power and data transmission within line-of-sight of the tethered communications node eliminate the need for exploration robots to physically reach it, which is critical in unpredictable environments where the tether end may be located in a rubble pile or similarly difficult terrain.

Combination of active sensing (good for shadowed regions but lower resolution and range limited by power) and cameras (higher resolution but unable to determine 3D scale) required to build sufficiently detailed models for science and robot operations.

Commercial magneto-inductive communications system indicates an achievable data rate of 2412bps through rock.

Magneto-inductive comm requires a large and heavy antenna. While it is a great technology for later use in cave operations, it may not be feasible for the first, lightweight robotic explorers.

Skylight geometry challenges single-perspective modeling of cave entrances. Combining lander flyover and rover exploration data to autonomously model skylights exploits unique perspectives of flyover and rover, and is feasible even in communications-limited locations.

Indications for Phase II Study
Phase II will design and prototype “Cavehopper” hybrid driving/hopping robot and test in field demonstration at the culmination of the program.

Develop robust sensor packaging for the highly mobile Cavehopper platform; adapt methods and algorithms to this limited sensing capability; develop planning for model generation.

While Phase I investigation identified an available communications solution for data transmission, it requires significant mass and does not approach the data rate necessary for teleoperation, especially since operating in an unpredictable environment requires a high degree of situational awareness. Phase II study will focus on planning for autonomous hop operations (Hop Ops), including development of a Cavehopper simulation.

Adapt flyover/surface modeling to plan Cavehopper traverses using data from Livewire and from previous Cavehopper hops.

4.1 Configuration Selection

This research innovated robot configuration and operations for cave exploration addressing the following configuration challenges: access & in-cave mobility, power and communication configuration, control and autonomy, and subsurface sensing. Subsurface sensing is addressed in detail in Section 5; the other challenges are addressed in this section.

4.1.1 Access and In-Cave Mobility

While skylights provide entry into caves, they lead robots to vertical descents, traverses over significant rubble, and unpredictable obstacles (e.g., rock piles from partial ceiling collapses). A robot large enough to drive over any obstacle is unlikely to fit into narrow passages. It would also be prohibitively expensive to launch due to mass and volume requirements. This challenge necessitates innovative approaches to access and in-cave mobility.

4.1.2 Power and Communication Configuration

Specialized robotic technologies and morphologies are needed to address the unique power and communication challenges presented by subsurface environments. To explore skylights and lava tubes, these robots must overcome various difficulties, including:

- Extended periods without access to solar power
- Limited accessibility to communication
- Operating exclusively in a dark environment

4.1.3 Autonomy and Control

Limited communication, unpredictable terrain, and dark subsurface environments necessitate complex autonomy and control technologies. Tunnels, caves, and tubes block communication requiring full autonomy. Underground topology is complex and three-dimensional requiring planners that handle unseen branches and maximize information gain while considering power utilization. Planners must enable autonomous operation to gather information, perform science goals, and return to entry without getting lost or losing power.

4.2 Configuration Development and Trade Study

A trade study was conducted to explore the mobility design space for robots to enter and operate in subterranean environment accessed via a skylight. The design concepts considered in this study are illustrated in Table 1.

Table 1: Robot Configuration Trade Study Options

Spherical Hopping Microbots: Spherical, baseball-sized hopping robots for cave exploration, based on (Dubowsky, Plante, & Boston, 2006). Their mission concept launched many of these small robots into a cave, accepting that many would not survive, and used the surviving population of microbots for exploration, comm, and data return.	
Multi-segment Tethered Robot: 6-wheel locomotion with flexible suspension for tether-assisted mobility of Skylight edge, wall and touchdown in boulder field, then unassisted autonomous navigation of lava tubes. The robot is tethered from the lander until reaching the skylight floor. The tether supports vertical negotiation of the skylight wall until breakaway and horizontal departure at the lava tube floor. Once on the floor, the tether provides down-hole recharging and data link for repeated forays and prolonged exploration of the lava tube, while conveying robot exploration data to the surface for relay to Earth.	

Legged Tethered Robot: Similar tethered concept for skylight descent and down-hole power and communication. Legged locomotion improves navigability in rough terrain through carefully stepping over obstacles that stop a wheeled robot of comparable size. They are still limited by obstacles that exceed a certain fraction of their height, and by potential leg obstruction or entrapment.

Snake Tethered Robot: Similar tethered concept for skylight descent and down-hole power and communication. Snake-like locomotion improves navigability in rough terrain through slithering over boulders and through small gaps not traversible by wheeled and legged robots. Control and sensor placement are challenging and mechanisms are complex.

Cavehopper: combines hopping to overcome large obstacles with wheeled mobility for efficient flat-terrain mobility. Cavehoppers may also descend Skylight by leaping in. Power and communication would be through a separate tethered node, which could include beamed power and wireless communication to avoid return to base requirements.

Climbot: Climbing robot that climbs down side of skylight with no tether and can traverse floors and walls once in the cave. The robot would be battery-powered and return to the surface by climbing or traverse to the tunnel floor under the skylight, for power and communication. Avoids debris and obstacles by climbing wall. Re quires high mechanism and autonomy complexity, has limited range. Requires advances in robotic climbing and anchoring technology.

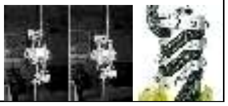
Elevator: Exploration robots lowered on a tethered platform to skylight floor. Platform would have powered wheels for horizontal movement to aid in reaching and lowering down the skylight. Wheels would be paddled in order to climb rough terrain. Elevator lowers onto rubble then robots "drive" off to stable ground. Elevator acts as a base station for communication and power. Can return to the surface enabling transport of multiple robots in and out, possibly over multiple missions

Propulsive Flying Robot: Robot accesses and traverses by small thrusters. Enables easily surpassing boulder fields like those near skylight entrance to reach stable, flat floor of lava tube. Could carry enough fuel to make multiple trips and return to surface. Could combine with a tethered node to reduce trips to surface for power and communication. On Mars it is possible to fly using atmosphere rather than limited propellant.

Telescoping Ball Robot: Robot has two mobility modes: Enclosed in sphere (for launching/rolling to access cave) and wheeled through deployment. For example, deployment could extends circular halves of the sphere as wheels in a dumbbell shape, and extend a tail. The robot can be launched or dropped from another rover or a lander to reach the skylight floor. Robot would be battery powered and could be part of a multi-robot team with each robot acting as nodes for wireless communication. Spheres could couple to create a segmented robot for rough terrain.

Prismbot: Robot shaped like a triangular prism that can travel on all three sides of the triangular faces. Each side is equipped with sensors and cameras. A tether mounted in the middle and would provide communication/power. Shape enables tipping during skylight descent and boulder field traverses.

Rope Climbing: A Tether is deployed down the skylight, robot attaches to the tether and climbs down to reach the floor. Base of tether serves as power and communication node to the surface.



Concepts were evaluated by skylight and boulder field traversibility, mass, flat ground driving efficiency, power duration, reliability, control, communication, technology readiness, and data collection. The results of the trade study are shown in Figure 31.

Figure 31: Results of trade study of robot configurations for accessing a lava tube via a skylight

Table 2: Evaluation of robot configuration; weighted design matrix

ID	Weight	Selection Criteria (Decision Drivers)	Grading Scale (Maximum)	Spherical Microbots	Tether w/ wheels	Tether w/ legs	Tether snake	Climbot	Elevator	Propulsive Flyer	Telescoping Ball Robot	Prism Robot	Rope Climbing	Cavehopper
1	3	Mass	5	5	3	2	3	4	2	3	5	3	2	5
2	5	Boulder Field Traversibility	5	4	3	4	5	3	2	5	2	3	3	4
3	5	Skylight Descent Traversibility	5	4	3	4	3	2	4	5	4	3	3	4
4	4	Flat ground Driving Efficiency	5	2	5	2	1	1	4	4	4	3	3	5
5	3	Simplicity	5	4	4	2	1	1	3	2	2	2	2	3
6	2	Power Duration	5	2	5	5	5	1	5	2	2	2	4	3
7	3	Reliability	5	4	3	3	2	1	3	2	2	3	2	4
8	2	Controllability	5	2	3	3	2	2	4	3	3	3	3	3
9	3	Communication	5	2	5	5	5	2	5	2	2	5	4	4
10	1	Technology Readiness	5	2	3	5	3	1	5	2	4	4	3	3
11	3	Data Collection	5	3	5	5	5	3	4	2	2	4	4	4
Total Weight			**170**	**112**	**129**	**120**	**109**	**69**	**120**	**111**	**99**	**107**	**101**	**135**

4.3 Selected Configuration

The configuration and exploration scenario resulting from design, analysis and trade study is the Cavehopper with a separate tethered robot (Livewire) to supply power and communication. This configuration was used as the basis to develop a detailed mission scenario and robot concepts. This concept is explained in greater detail in Section 2 of this report.

4.3.1 Access and Mobility

Legged robots have been proposed for navigating rough terrain, carefully stepping over obstacles that stop a wheeled robot of comparable size. They are still limited by obstacles that exceed a certain fraction of their height, and by potential leg obstruction or entrapment. They also cannot exploit the benefits of power-efficient wheeled motion on smooth terrain.

Hopping robots can be small and light, making them effective for tight spaces and economical to launch. By hopping, especially in the lower gravity encountered on many planetary bodies beyond Earth, they can overcome obstacles many times their own size.


Figure 32: Hopping, spherical robots proposed by (Dubowsky, Iagnemma, & Boston, 2006). Cavehopper exhibits enhanced sensing, control, and efficiency of flat ground driving.

(Dubowsky, Iagnemma, & Boston, 2006) developed spherical, baseball-sized hoppers for cave exploration. Their mission concept launched many of these small robots into a cave, accepting that many would not survive, and used the surviving population of microbots for exploration, comm, and data return. While the small sphere concept is simple, the combination of small size, round shape, and limited control profoundly limit sensing capability and suitability for a bouldered environment.

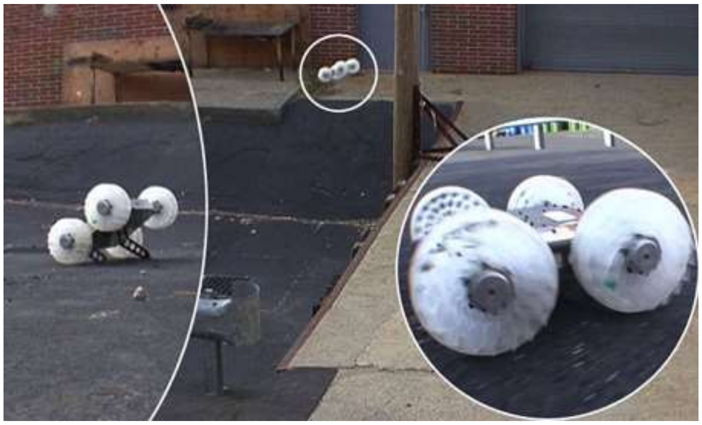


Figure 33: Combination driving and hopping robot: Boston Dynamics' Sand Flea.

A promising approach combines hopping to overcome large obstacles with wheeled mobility for efficient flat-terrain mobility. Several robotic platforms have illustrated this concept. The Sand Flea robot[5] hops to overcome large obstacles and drives in areas with more benign terrain. This approach is ideal for lava tube caves, where there

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[5] Boston Dynamics' Sand Flea is an 11 pound robot that drives like an RC car on flat terrain, but can jump 30' into the air to overcome obstacles. Watch a video of Sand Flea here.

are large expanses of relatively flat floor between piles of rubble from ceiling collapse. The Sand Flea platform has demonstrated hopping 8m in the air on Earth to leap buildings and cliffs from a start on flat ground.

Related mobility concepts relevant to combines driving and hopping have been explored at CMU, including throw tolerant driving robots and hopping robots for all terrain mobility. Dragon Runner is a rugged ultra-compact, ultra-portable mission-capable mobile robotics platform capable of being thrown off rooftops or through windows. CMU's RATS is a spherical robot with 12 piston-actuated legs for all-terrain mobility.

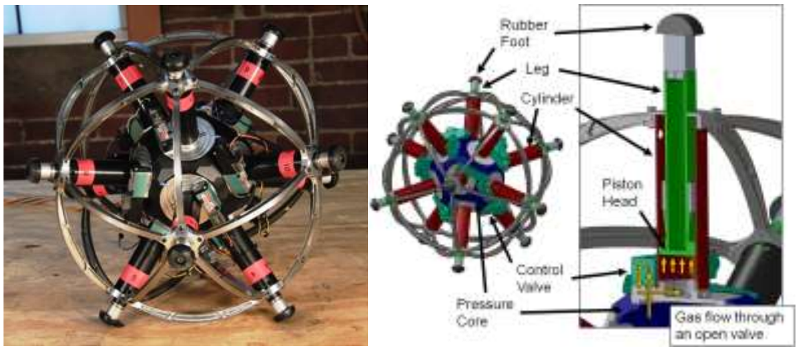


Figure 34: CMU RATS, a pneumatic hopping all-terrain robot

Figure 35: CMU Dragon Runner, a rugged compact robot capable of surviving being thrown off buildings and through windows.

Phase 1 results recommend an adaptation of these mobility concepts to conceive Cavehopper, a planetary cave explorer. Cavehopper builds on priors innovating for space-relevance, sensing and software for cave modeling, and planning techniques for mission and hopping operations.

One strategy to achieve Cavehopper jumps is a piston-powered hopping actuator, in this approach, two legs protrude to set elevation, then a piston actuator fires, impulsing upward like a grasshopper. Robot trajectory is controlled by setting the azimuth and elevation angles of the robot prior to firing and adjusting the force applied at the piston actuator. During flight, the Cavehopper robot uses an IMU to track its attitude and controls pitch by using its wheels as control moment gyros. The wheels are compliant, absorbing impact forces when the robot lands. In wheeled mode, Cavehopper is skid-steered. While the concept and underlying principles are powerful and effective on Earth, they have immense advantage in reduced gravity and 3D exploration.

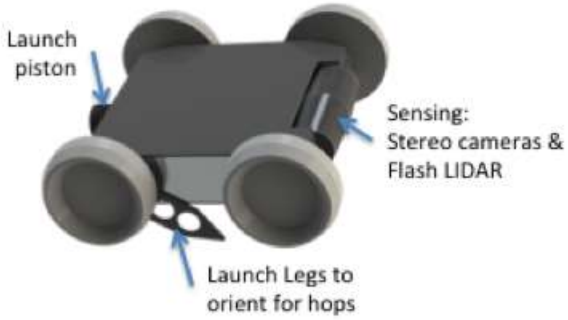


Figure 36: Cavehopper robot configuration for subsurface driving and hopping.

Piston-actuated hopping can be powered by internal combustion with a fuel and oxidizer system (like Sand Flea), pneumatics (like RATS), or mechanical energy storage such as a spring. With internal combustion, number of hops is limited, though lower force required to hop in reduced gravity on planetary bodies such as the Moon or Mars, coupled with technology development to improve the energy density of the fuel system, could significantly increase hop yield.

Alternatively, the piston could be powered by a mechanical spring compressed by an electric actuator that, while less efficient, removes the hop limit inherent in a bipropellant system. On planetary bodies with an atmosphere, pneumatic actuation or compressed air could provide rechargeable hopping.

An additional approach to achieve “hopping” is a propulsive approach to fly over hazards that cannot be surpassed by driving. This approach is limited by fuel, but has the advantage of higher controllability of flight trajectories.

4.3.2 Power and Communication Configuration

Power is addressed through the “Livewire” robot. Livewire makes a tethered descent into a Skylight. Livewire tether creates a connection to the lander’s communication and power on the surface. Livewire beams power and wirelessly communicates with Cavehoppers from a high vantage point hanging in the Skylight rather than touching down to the floor. In addition, cameras on-board Livewire could provide reconnaissance and track Cavehopper robots for improved localization. The Cavehoppers explore and return to within line-of-sight of the Livewire to relay their data and recharge from beamed power. Livewire transmits the Cavehoppers’ data up the tether to an antenna on the lander, which transmits to a relay satellite or directly to Earth. This foray-”phone home” cycle is repeated until all lava tube regions within battery range of the skylight have been explored.

Phase 1 Identified five key enabling power and communication technologies relevant to planetary subsurface exploration robots:

High energy density batteries enable longer cave excursions with low battery masses.

Power beaming enables recharging of Cavehopper robots from a solar powered lander. Power beaming is under development by several groups including LaserMotive, who won the NASA Power Beaming Challenge and are presently working for NASA to design the architecture to use lasers to launch rockets and power satellites, and, eventually, power lunar bases (LaserMotive, 2012).

Lightweight power and data cabling enables deploying tethered Livewire robots into subsurface voids to establish power and communication nodes. Low mass reliable cabling will reduce mission cost and risk. Tether development is unique and challenging due to multiple usages. The tether must function as a rappel rope. That is subject to bending and abrasion at the lip of the Skylight, since the mechanical, power and data connectivity must span back to the lander. Exposure of the surface segment leads to huge thermal swings with day/night cycle. Length approaching 300 meters requires attention to compatible mechanical stiffness and thermal expansion in the coaxial layering of data, power, insulation, strength and abrasion layers. Miniaturization and light-weighting are paramount, since the tether must be carried, then reeled out from the rover in order to avoid dragging during deployment or extensive sliding at the skylight rim.

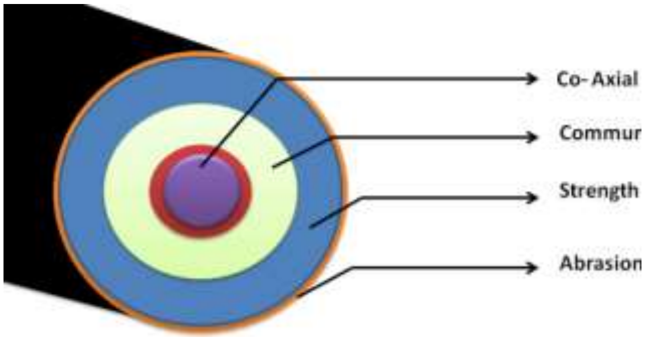


Figure 37: Cross section of possible tether design, showing key elements

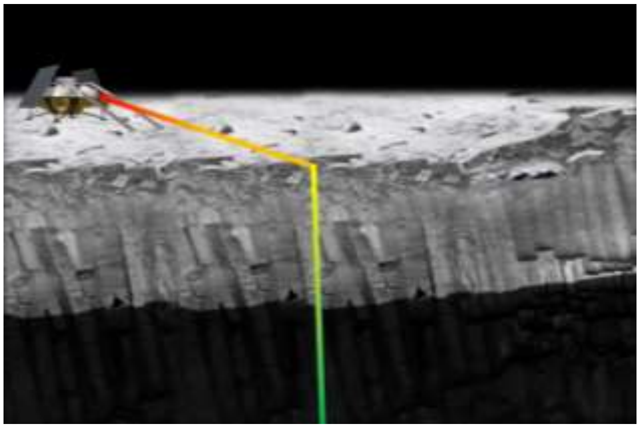


Figure 38: Thermal gradient on a tether used for skylight descent will be large

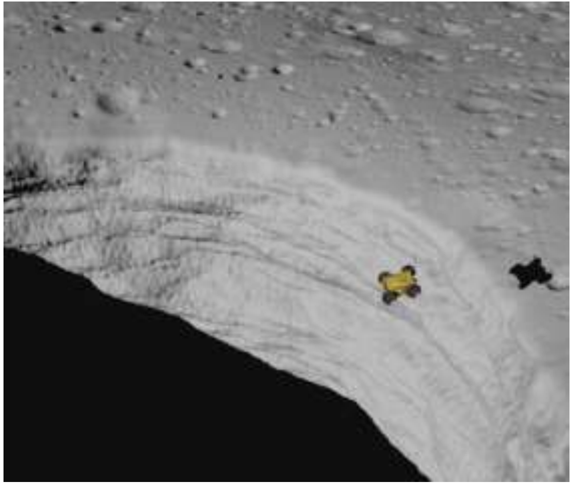
Surface to surface radio enables communication from a base inside the tube to the mobile Cavehopper.

Low Frequency "cave" radio enables communication from a base inside the tube to the mobile Cavehopper to pass through some rock obstructions. This reduces risk associated with communication loss. Limited data link through rock can be achieved with very low-frequency radio or magneto-inductive comm. These technologies are under development terrestrially for cave and mining communication and rescue and have undergone significant advances in mass and power requirements over the past few years, presenting the promise of reasonable solutions for planetary missions within 5-10 years.

Magnetic Comm Unit

4.3.3 Autonomy and Control

For a robot hopping through a rubble pile, choosing where to land next requires a high level of situational awareness. Autonomy for the Cavehopper robot presents novel challenges in planning for safe hopping and in modeling that are distinct from those faced by traditional planetary rovers and by most mobile robots on Earth.



Planetary rovers operate primarily in a 2D plane. When they encounter obstacles, they remain in contact with the ground and go around. Statically walking legged robots carefully choose foot placements to avoid slipping out of their intended footholds. Operation of dynamic walkers typically assumes that the ground is relatively flat compared to the height of a footstep and maintains a predetermined gait that avoids having to plan individual foot placement or respond mid-stride to shifts in the center of mass. Cavehopper picks a spot and plans a trajectory that will contact the ground at that location but, due to its compliant wheels, it will likely bounce away from the target spot upon landing.

Thus, the robot must account for a distribution of possible post-bounce positions around each target contact point and ensure that the vehicle remains safe throughout this distribution. Cavehopper must also plan trajectories that avoid hitting the ceiling of the lava tube, or any intervening obstacles, before reaching the target point. Prior work for planning safe, autonomous helicopter landings (Scherer, Chamberlain, & Singh, 2010) is relevant in developing similar approaches to determine safe landing locations for hops, including allowance for post-landing bounce distribution, and to plan safe trajectories to reach that location.

The needed technology development is planning for safe hopping, using a contingency planning architecture to guarantee safe operation in uncertain terrain. Contingency planning is a probabilistic approach to generating action in the presence of uncertainty. The contingency planning paradigm is to only execute actions that have guaranteed safe contingency actions. Planning software will be developed and tested first in simulation and later on robot hardware.

Sensing in planetary environments is typically done from a pan-tilt head on a mast atop a rover. The set of possible sensor views is described by the 2D rover position, the fixed rover height, and the range of motion of the pan-tilt head. Cavehopper can drive to a given position and azimuth orientation, much like a traditional rover, then use its launch legs to sweep the sensors up in elevation. It can also sense while hopping. During a hop, the robot can capture overhead views not otherwise possible. These views inform planning for the next hop. Pitch control during hopping is also critical to sensing, since it determines where the sensors will point.

Cavehopper planning can also leverage technologies for complementary flyover and surface sensing approach to hop-over and surface sensing with Cavehopper robots. This approach is described in Section 3 of this report and published as part of phase I work (Jones, Wong, Peterson, Koenig, Sheshadri, & Whittaker, 2012). A promising autonomous exploration approach identified is frontier exploration developed in (Wang, 2011) to plan robot traverses that enable sensing of unexplored areas. Control also addresses low-level planning for sensing while the robot is on the ground and during hops. Next steps include developing an approach that given a hop planned to get the robot to a target destination determines how the pitch should be controlled along the trajectory to capture the desired data.

Supervised Autonomy for Operations in Limited Communication

Robot operation in caves can vary from full autonomy, with no human input once the robot sets out on a mission, to direct teleoperation. Direct teleoperation requires that the human operator have a high degree of situational awareness, which may be difficult under limited communication. Full autonomy may be less efficient, since human operators cannot make decisions as new information arises. A compromise is supervised autonomy over low-bandwidth comm. This could enable some control when robots travel beyond line-of-sight. Limited data link through rock can be achieved with very low-frequency radio or magneto-inductive comm. A “follower” robot could trace the path of the cave explorer on the surface, providing a relay to operators on Earth (see Figure 39). Simple commands, such as “turn left” can also be sent over this link.

Table 3. Sample breakdown of data transmitted over low-data-rate comm. link

Data	Size (Bytes)
Position (3 DoF)	12
Heading (3 DoF)	12
Cave Radii (x15)	60
Temperature	4
Battery Charge	4
Power Draw	4
Robot Status	1
Robot ID	1
Timestamp	4
Science Data	140

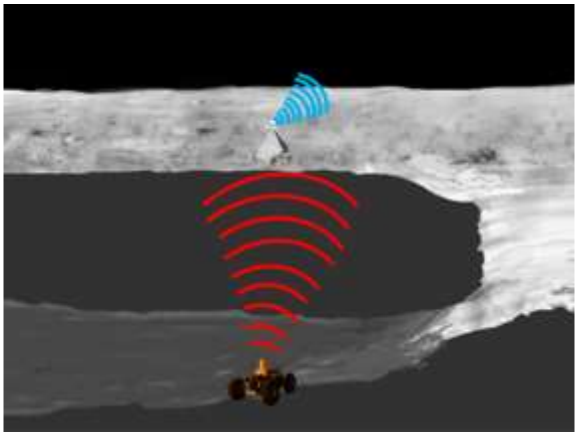


Figure 39: A limited data-rate link through cave ceilings can be achieved using very low-frequency radio or magneto-inductive comm

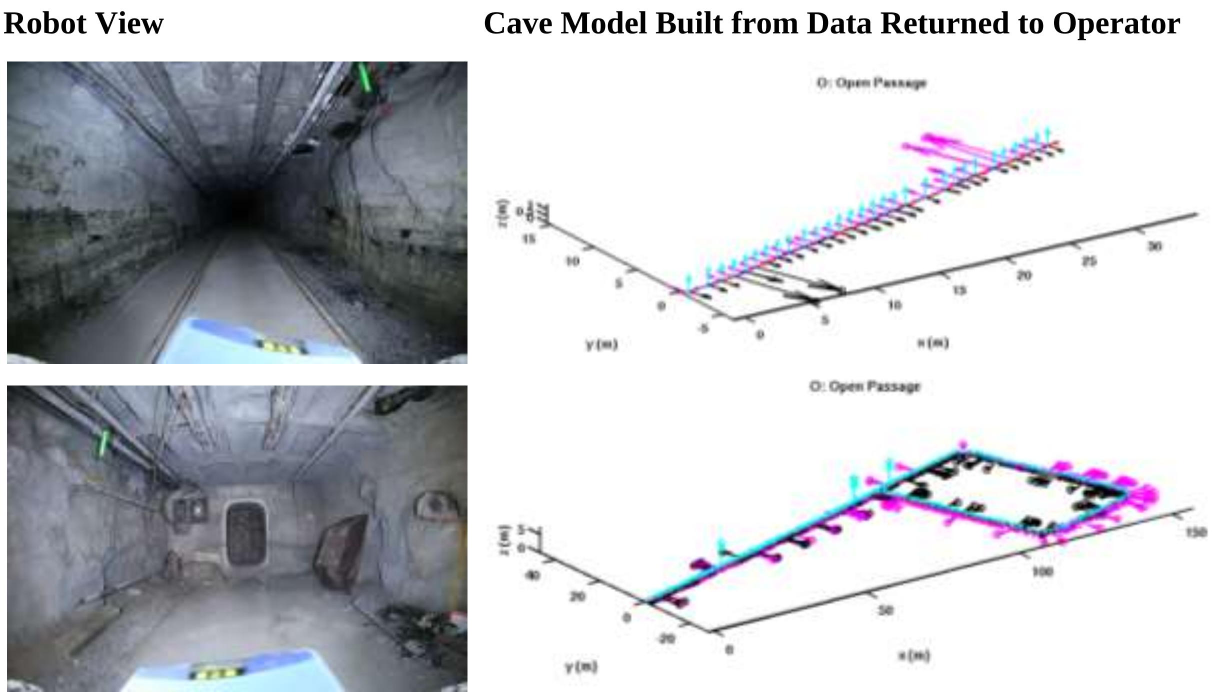


Figure 41: Concept for operation under reduced comm., showing difference between the cave exploring robot's high-definition view of the scene and the limited-data-rate model that the operator sees as the robot explores.

Specifications for an existing magneto-inductive comm. system (Ultra Electronics Maritime Systems, Inc., 2009) indicate that a data-rate of 2412 bits/second can be achieved from sub-surface to surface through lunar rock. This is far below what is needed to perceive and command teleoperated exploration, but adequate to guide autonomous operation. Once returning to a communication node after exploration, full playback of cave exploration is possible at higher bandwidth. Allowing 15% margin, and 16 bytes of overhead (assuming Reed-Solomon 255/239 byte encoding (Reed & Solomon, 1960)), 239 bytes of data can be transmitted per second. Table 3 shows a possible breakdown of data transmitted over this low-data-rate link. The bytes used for representing cave geometry could be reduced to allow more space for science data. Figure 41 shows an example with only 3 cave radii used to represent geometry – measured left, right and up from the robot's heading. Figure 40 shows a detailed 3D model of the same cave as Figure 41. This higher

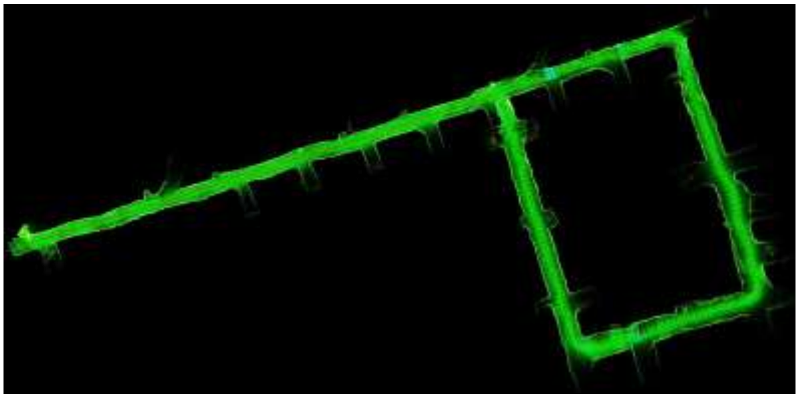


Figure 40: Detailed 3D model of cave built from LIDAR data. These detailed models and images can be sent back when a cave exploring robot returns to a region of high-band comm.

definition data could be returned after the cave explorer robot returned to an area of higher-data-rate comm.

5 Subsurface Sensing and Modeling

Phase I Investigation of Modeling
Analysis of modeling under constrained power, mass, and data.

Phase I Insights
CMU CaveCrawler demonstrates high resolution modeling of terrestrial caves with a variety of sensors.

Cavehopper mobility enables high perspective views for model enhancement, and necessitates innovative model fusion.

Lumenhancement technique developed by the proposal team shows promise for resolution enhancement of planetary subsurface models.

Indications for Phase II Study
Phase I investigation identified modeling requirements and promising solutions. Phase II study will implement modeling algorithms and demonstrate on the Cavehopper robot.

5.1 Design for Planetary Cave Sensing

Planetary caves are an untouched domain for robotic perception. Sensor design includes considerations for traditional subsurface robots – such as total darkness, low power, and limited comms - coupled with the operational difficulties in space - such as scale, distance and hardening. Quantification of these issues has thus far been considered separately. Characterization of terrestrial subsurface sensors, for example, was pioneered by this group (Wong, Morris, Lea, Whittaker, Garney, & Whittaker, 2011), and the results were heavily utilized in developing the CaveHopper concept. However, it was quickly discovered that the breadth of issues represents a significant hurdle for current optical technologies which enable everything from autonomous robot operations to 3D mapping for science.

Voids on the Moon and Mars are expected to be tens to hundreds of meters across and kilometers in length, considerably larger than most mines, tunnels and caves on Earth where state-of-the-art optical sensing for robots is deployed. Long sensing range and low power consumption, in particular, have been identified as the critical criteria for sub-surface perception in planetary environments (Coombs & Hawke, 1992). Unfortunately, satisfaction of these criteria with active sensing - both range sensors like LIDAR and intensity sensors like cameras - is limited by physical laws. The well-known inverse square relationship necessitates an exponential increase in illuminant power for increasing range.

The concept for CaveHopper enables a paradigm shift in sensor design that can tackle these issues. Prior subsurface robots with inadequate speed and limited planar movement capability are restricted to inefficient sensing. These operations have resulted in a progression of sensors that consume more power and require more mass in order to collect long range data from non-ideal locations. CaveHopper will instead utilize its superior mobility for dense coverage of the environment by repositioning to many viewpoints. This enables use of shorter range sensors reducing consumption of critical mass and power resources and produces better maps by reducing perspective occlusions. However, this approach alone is still insufficient for planetary cave exploration.

There is further capacity to enhance sensor capability with multi-modal fusion, which is the critical component of CaveHopper sensing. Prior work of this group at Carnegie Mellon University developed a class of techniques for enhancing 3D mapping by fusing camera and LIDAR data along called Lumenhancement (Wong U. Y., 2012). The key idea is an understanding of the appearance of environments – in terms of reflectivity, surface distributions and light transport- and to utilize this knowledge in constraining features in imagery. These features could be geometric, material or lighting cues which, when coupled with sparse direct range sensing from LIDAR, could enable a camera to perform the function of a number of dedicated optical sensors with similar performance. The work was shown to be particularly effective in barren, rocky and dark planetary environments.

5.2 High Quality 3D Model Building by Fusion of Range and Imaging Sensors

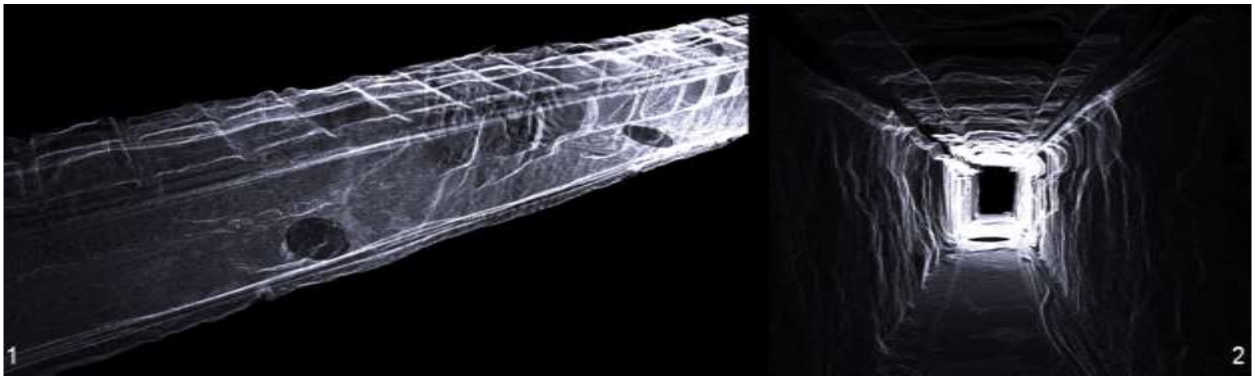


Figure 42. A 3D Point Cloud model of a mine corridor is created with a mapping robot using LIDAR. A map of the entire corridor can be inspected from a simulated isometric view in post process (1). A view of the environment from the robot perspective during data collection is shown in (2).

This section discusses one particularly relevant application of Lumenhancement, which is the creation of ultra-dense 3D models by utilizing the camera as a geometry sensor. The approach specifically enables ultra light-weight, solid state range and imaging sensors (such as low-density flash LIDAR) to produce similar or better quality maps than bulky, high-power, actuated equivalents. Solid state sensing is particularly important for the Cave Hopper concept due to resilience to decalibration from impacts and capability for hardened packaging.

The fusion of LIDAR and images for 3D modeling has been well-studied due to the complementary nature of these sensors. Sparse LIDAR data can greatly reduce the complexity and uncertainty in dense shape estimation from images. Likewise, high frequency detail from images can be used to augment interest and feature detection in 3D maps. The concept is simple: high resolution imagery contains information about scene structure between range readings. This is information that cannot be deduced from pure interpolation of sparse LIDAR, which creates no new information.

A general model for fusing raw LIDAR and image data into super-resolution range images using a Markov Random Field (MRF) was explored in (Diebel & Thrun, 2005). MRFs are undirected graphs that represent dependencies between random variables and have been used extensively in computer vision for noise removal, feature matching, segmentation and inpainting (Li, 2001). The popularity of the MRF stems from the ability to model complex processes using only a specification of local interactions, the regular grid nature of CCD images and the maximum a posteriori (MAP) solution requiring only direct convex optimization. The MAP solution determines the optimal combination of disparate data sources using a process akin to an iterative weighted average (see Figure 43).

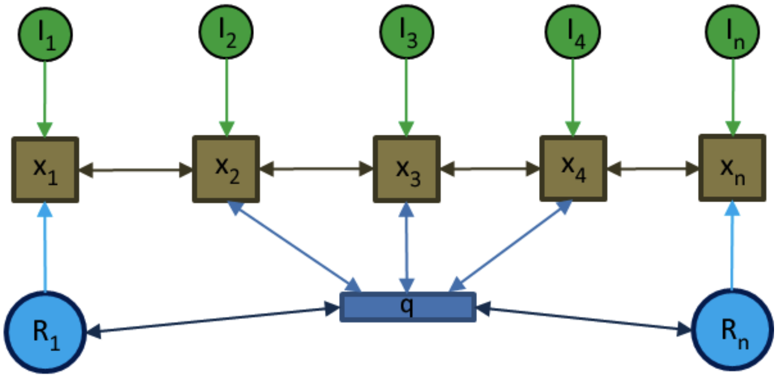


Figure 43: Markov Random Field Graphical Model. Green nodes (I) represent the image pixel data, brown nodes (x) represent the hidden true range value to be estimated, aqua nodes (R) represent the sparse range data and the blue node represents the interpolation uncertainty estimate. There is 1 pixel value for every hidden node (x), but there may be many nodes without a corresponding range value (R).

Diebel surmised that higher resolution intensity (color) data could be used to increase the range accuracy of interpolated points. The work of Diebel generated critical interest in range/image super-resolution, and notable extensions have proposed more expressive MRF models and feature detection, (Yang, Yang, Davis, & Nister, 2007) (Torres-Mendez & Dudek, 2008) (Gould, Baumstarck, Quigley, & al., 2008). Such prior work has been shown to great success in a variety of controlled indoor environments with ambient illumination and planar features. However, image information in the form of raw intensity values, cannot be converted to 3D geometry in the general case –with any expectation of accuracy - due to the underconstrained image formation problem (Wong U. , Garney, Whittaker, & Whittaker, 2009). Thus, traditional intensity MRF techniques for super-resolution cannot be used in planetary spaces.

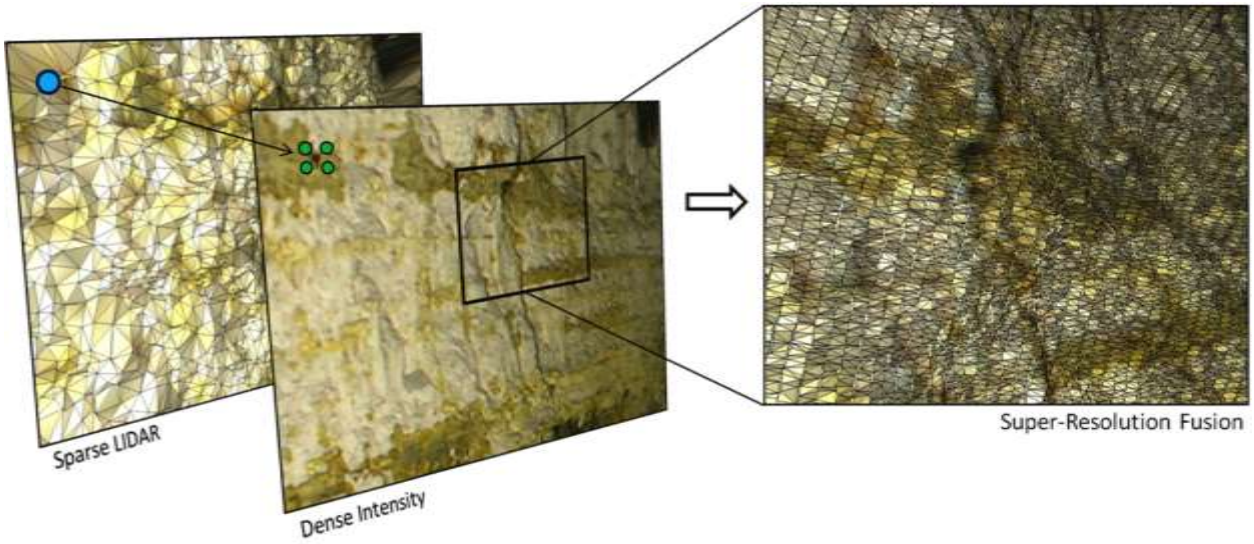


Figure 44: Super-resolution fusion of sparse LIDAR mesh data and dense actively-illuminated visual imagery creates high-throughput range sensing. This data set shows a rocky wall from robot exploration of a terrestrial coal mine interior.

Fortunately, Wong showed that these techniques can apply when certain assumptions can be made about the geometry, illumination and material distributions in the scene – collectively known as appearance (Wong U. , Garney, Whittaker, & Whittaker, 2009) (Wong U. Y., 2012). These assumptions served to simplify the image formation problem and limit the ambiguity of image values. Unique material and surface properties of planetary spaces when coupled with simple, calibrated illumination can be used to recover geometric surface features with unparalleled fidelity.

Robots must carry active illumination for imaging in these dark environments; Wong demonstrated that the form and distribution of such illumination can and should be designed for data enhancement beyond simple photography. Such methodology is directly applicable to barren environments like sub-planetary caves and lava tubes. By coupling point-source illumination with the assumption of diffuse surface reflectance in these environments, estimating geometry at every image pixel becomes a shape-from-shading (SFS) problem.

While the SFS framework can be solved with traditional statistical optimization methods, these are typically numerically unstable and inaccurate in the field. Variation of materials and albedo, complexity of intersecting geometry, and sensor noise makes estimation of shape from a single image severely ill-constrained. Sparse LIDAR data significantly simplifies the problem and bounds global errors as LIDAR provides a way to directly validate geometry. This interaction of LIDAR and camera data is the fundamental idea of super-resolution fusion. Actively illuminated imagery is used to generate locally-consistent surface detail, which is then “textured” onto blocky, but globally-consistent 3D range models.

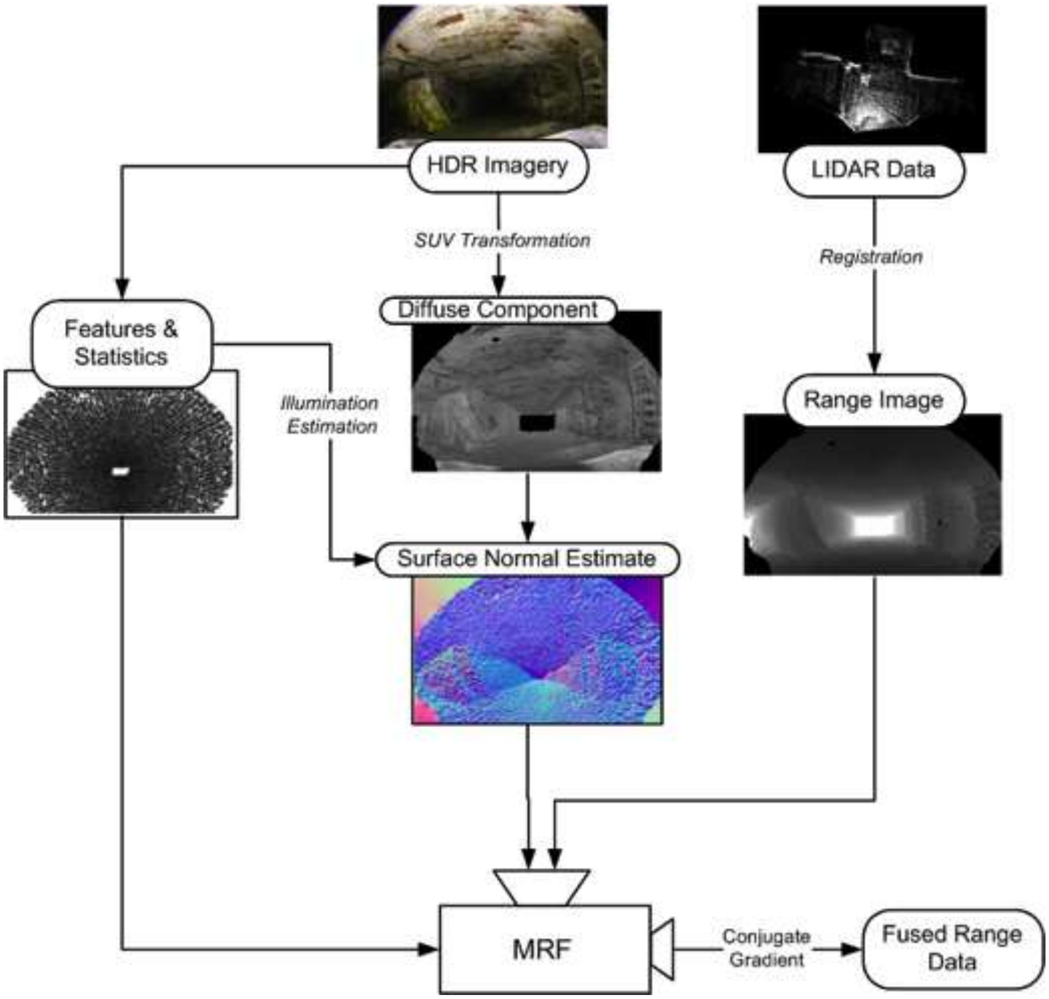


Figure 45: MRF Super Resolution Process. (1) Raw LIDAR point data is converted to a range image from the camera perspective. (2) Specularities are removed from the color HDR imagery to produce a diffuse image. (3) Surface normals are estimated from the diffuse image using shape from shading. (4) The surface normals and the range image are fused in the MRF framework.

A flow chart overview of the technique presented is shown in Figure 45. Raw LIDAR data is first projected into the space of the image, and resampled (interpolated) to form a co-registered range image at the resolution of the color image. Then, HDR color images taken under controlled illumination are transformed into a purely diffuse intensity image using the SUV transformation and knowledge of the spectrum of the light source. The diffuse image along with image features like saturation, illumination and albedo estimates are utilized in a shape-from-shading approach to generate surface normal estimates at every pixel. An MRF fuses the range image, surface normals and uncertainty map into a single high-resolution depth map.

Figure 46: A mapping robot explores a terrestrial underground space using active illumination (left). An immersive virtual model of the environment is created using camera and LIDAR fusion techniques (right).

Results from Wong have shown a 40x increase in measurement density (optics dependent) and up to 40% increase in range accuracy for some lunar analogs. While experimentation primarily utilized actuated LIDAR scanners and fisheye cameras, Wong suggests a range of solid state configurations with additional benefits that should be developed for robots like CaveHopper.

5.3 Lunar Cave Analog Modeling Experiment

This section documents field modeling experiments performed during the project. An analog planetary tunnel was prepared and mapped a mobile robot. The purpose was to evaluate a known baseline sensing and chassis configuration and investigate the modeling process in Lunar-like terrain at large scales.

The analog tunnel was staged in an abandoned steel mill at Robot City, a brownfield site for field testing robots in Pittsburgh, PA. The site was selected for freedom of access and logistic simplicity for Astrobotic and partners at Carnegie Mellon University. The analog environment is a “tunnel” inside a steel mill over 200 meters in length and 7 meters wide, with a natural rugged dirt and rock floor. The covered roof of the steel mill served as a high tunnel ceiling. The team cleared thick vegetation and layered the surface with limestone rock giving a planetary appearance and many features for evaluating sensing accuracy. This gave a lunar representation for modeling as well as mobility.

Figure 47: Team after site development (left) and outside view of modeling site (right).

Carnegie Mellon University's Cave Crawler mapping robot was sent autonomously down the interior of the analog to collect mapping data. The robot features two hemispherical rotating lasers for sensing 360 degree depth information and two fisheye lens (and high-output LED illumination) for imaging the same volume. This data was used to generate 3D models of the site as described in the next section.

Multiple test runs were performed with Cave Crawler traversing the test site along the 200 meter stretch. The objectives of these tests were to investigate the applicability of the rover configuration to a planetary environment, including navigation capability and ability to capture and process data in varied lighting conditions. The robot had no problem moving along the terrain and over obstacles.

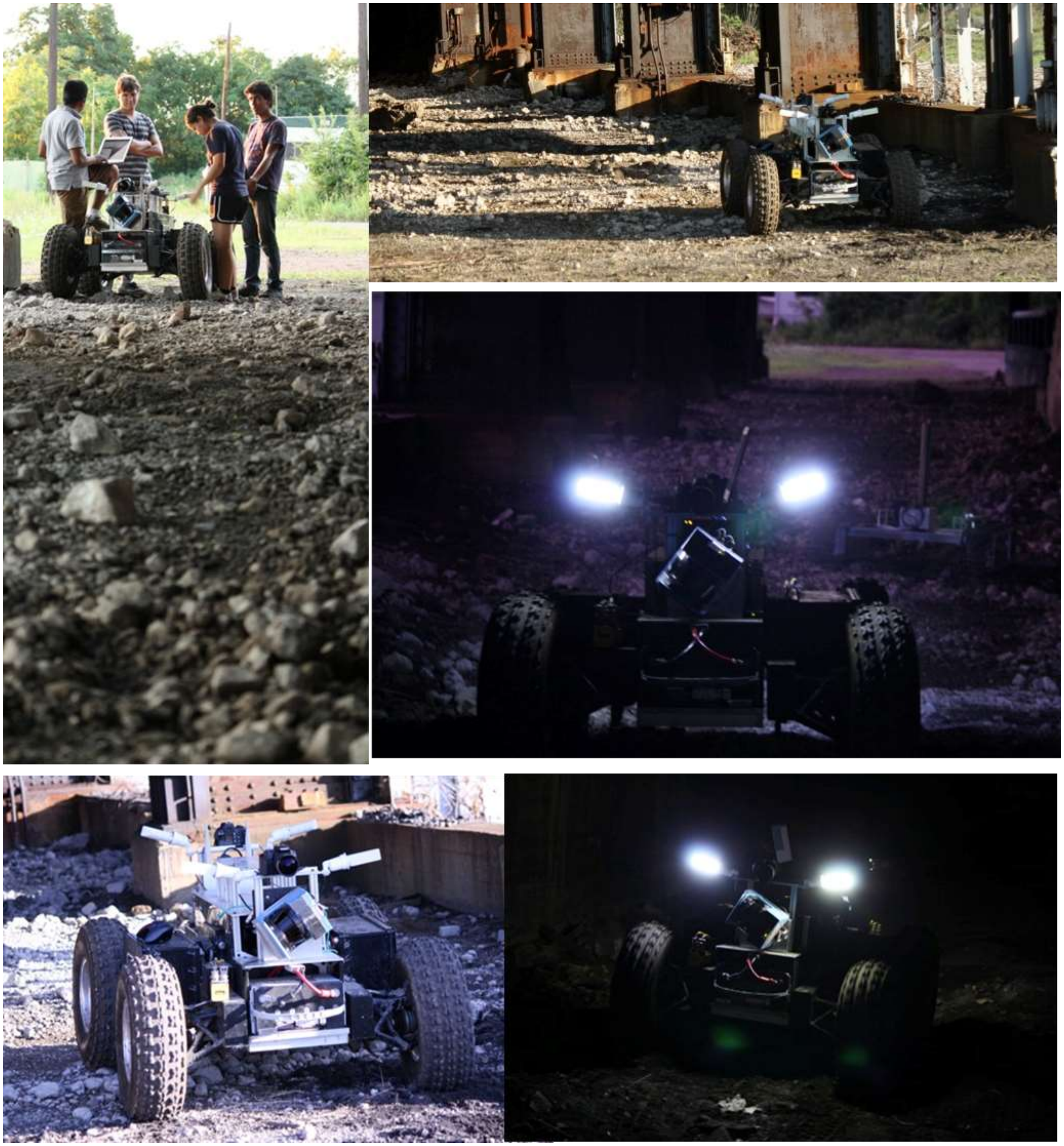


Figure 48: Various pictures of Cave Crawler exploring the test site while avoiding rocks

5.3.1 Modeling Results from Analog Experimentation

LiDAR data collected by Cave Crawler was post processed and stitched together to generate a model of the site. This model was then compared with a ground truth model of the test site. The ground truth model was created using Faro Scanners. Below are pictures of the ground truth as well as the models created using Cave Crawler.

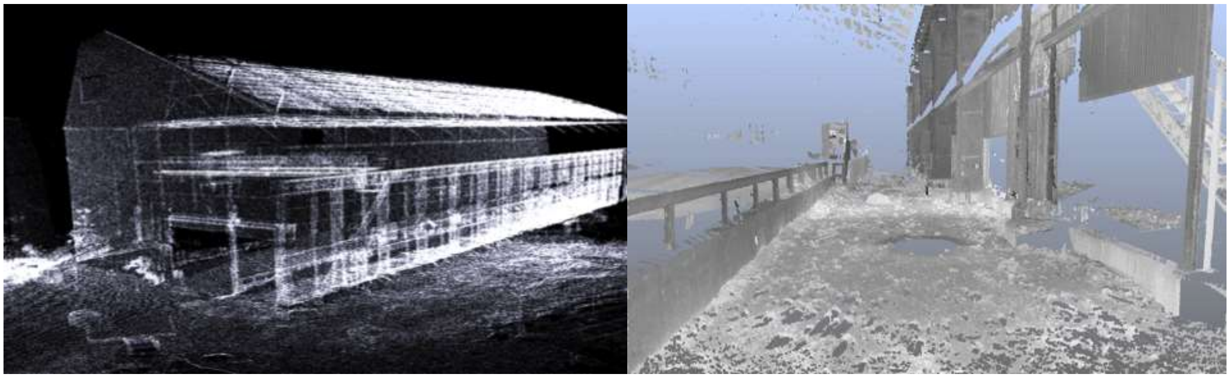


Figure 49: Ground Truth models of test site generated through Faro Scans

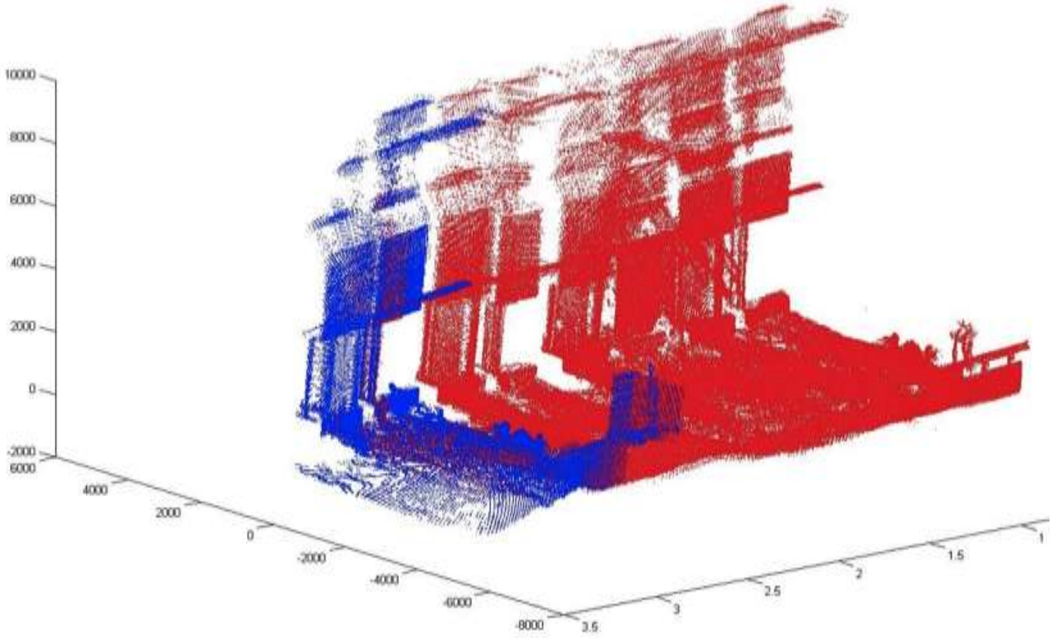


Figure 50: Two stationary scans stitched together using ICP

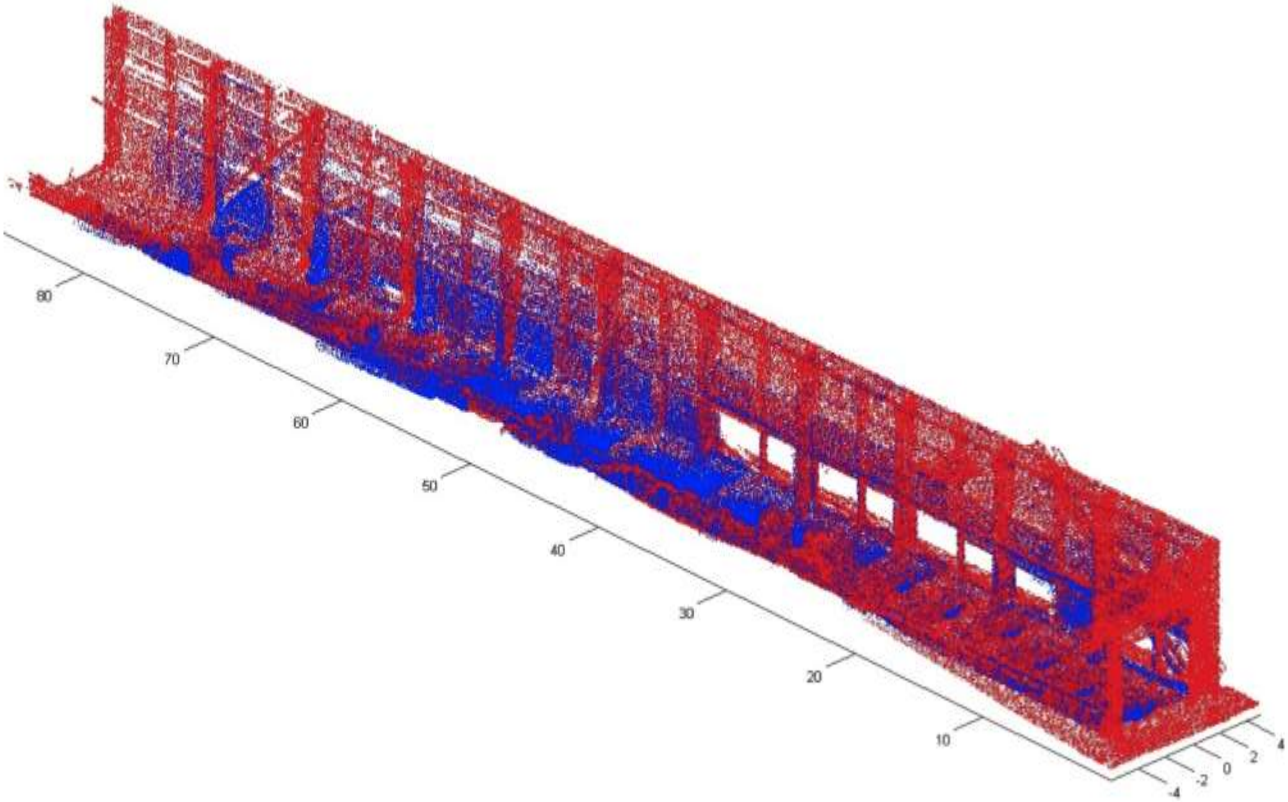


Figure 51: Blue point cloud generated by stitching various stationary scans. Red point cloud is the ground truth model.

6 Technology Roadmap

This research developed a draft technology roadmap for achieving mission readiness for the planetary cave exploration missions. The roadmap addresses proposed focused technology developments (for example in a Phase II NIAC effort) and critical supporting technology developments from other NASA programs, including precision landing, communication, and power technologies. The draft technology roadmap is shown below.

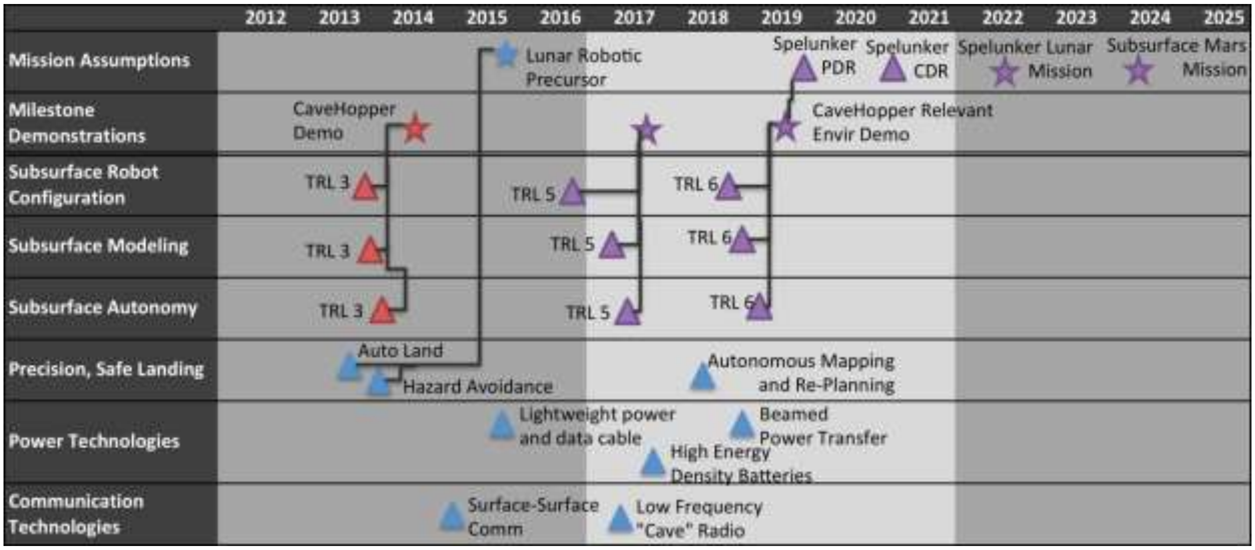


Figure 52: Draft Technology Roadmap

- **Red** items indicate technology development and demonstration in a focused technology program (such as a Phase II NIAC).
- **Blue** items are projections of key technology developments that impact mission feasibility, cost or risk, and are being developed by external programs.
- **Purple** items are proposed future technology developments, demonstrations and missions to advance and fly subsurface missions.

Explanation of Roadmap Elements and Assumptions

The list below describes key elements of the draft roadmap with corresponding assumptions and basis. Roadmap elements address key cost, feasibility, and risk elements of proposed mission architecture.

Robot Configuration

Proposed focused technology development provides a characteristic proof-of-concept for planetary cave access, mobility, and sensing to achieve early TRL 3. Follow-on subsurface mobility and sensing technology development requires designs using space-relevant sensors, computing, materials for compliant wheels, re-chargeable hopping, and lightweight chassis. The draft roadmap indicates projected TRL advancement path to achieve a 2022 initial subsurface mission.

Modeling

Proposed focused technology development provides a characteristic proof-of-concept for cave modeling with limited sensing capability and sparse data to achieve early TRL 3. Follow-on development will refine techniques and demonstrate model reconstruction on full-scale problems in analogous environments. Space-relevant sensing and computing will be used. The draft roadmap indicates projected TRL advancement path to achieve a 2022 initial subsurface mission.

Autonomy

Proposed focused technology development provides a characteristic proof-of-concept for planning to model subsurface environments from a lightweight, highly mobile platform and planning for safe hopping to achieve early TRL 3. Follow-on development refines control approaches, develops algorithms and integrates supporting software elements. Technologies are demonstrated on full-scale problems in analogous environments. The draft roadmap indicates projected TRL advancement path to achieve a 2022 initial subsurface mission.

Precision, Safe Landing

Autonomous terrain relative navigation and hazard avoidance technologies are essential for landing near a skylight rim. They are currently under development by NASA’s ALHAT group and private enterprises, including Astrobotic Technology. These technologies are estimated to reach TRL 6 by 2013-2014, prior to a robotic landed lunar mission in 2015-2016.

Autonomous mapping and re-planning technology enables rapid mapping and route planning for the surface robot prior to selecting a landing site, reducing the risk involved in reaching the skylight from the landing site. 2018 milestone assumes sufficient technology advancement for mission objectives.

Power Technologies

High energy density batteries enable longer cave excursions with low battery masses. NASA is funding multiple applicable battery development programs, in accordance with NASA roadmap element 3.2.1 Batteries.

Power beaming enables recharging of subsurface robots from a solar powered lander. Power beaming is under development by several groups including LaserMotive, who won the NASA Power Beaming Challenge and are presently working for NASA to design the architecture to use lasers to launch rockets and power satellites, and, eventually, power lunar bases (LaserMotive, 2012). This advancement dramatically increases the capability of the proposed mission by enabling recharge of subsurface robots from a solar powered surface base.

Lightweight power and data cabling enables deploying tethered Livewire robots into subsurface voids to establish power and communication nodes. Low mass reliable cabling will reduce mission cost and risk. This is a key NASA technology development associated with planetary base infrastructure and is associated with NASA roadmap element 3.3.3, Power Distribution and Transmission.

Communication Technologies
Surface to surface radio enables communication from a base inside the tube to mobile subsurface explorers. Surface radios are under development at NASA JSC.

Low Frequency "cave" radio enables communication from a base inside the tube to mobile subsurface explorers to pass through some rock obstructions. This reduces risk associated with communication loss.

Missions

Lunar Robotic Precursor | A robotic mission to the lunar surface demonstrating precision, safe landing on the Moon.

Spelunker Lunar Mission | The Spelunker mission concept at a lunar skylight.

Subsurface Mars Mission | The Spelunker mission concept, as refined by lunar experience, applied to exploration of a Mars skylight.

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