

ROBOTIC EXPLORATION AND SCIENCE IN PITS AND CAVES: RESULTS FROM THREE YEARS AND COUNTING OF ANALOG FIELD EXPERIMENTATION

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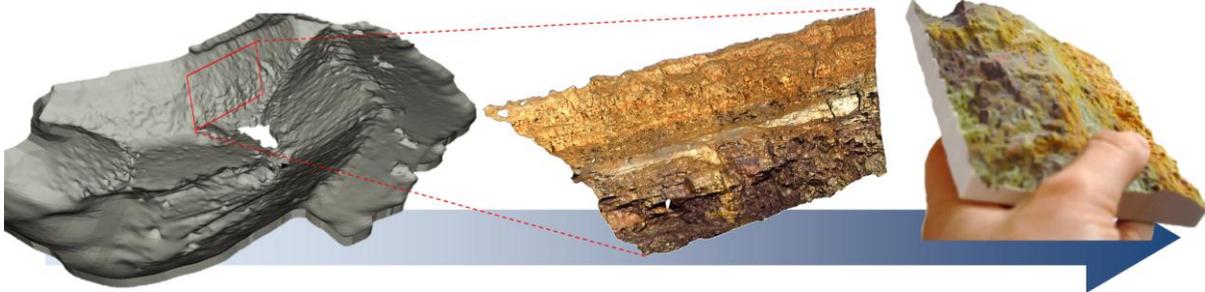


Figure 1. Maps are generated from robotic exploration of an analog pit. Enhancement with images produces models with superior definition and detail. 3D printed models convey scale, multi-perspective and tactility.

Introduction: The discovery of pits distributed across planetary bodies [1], [2], and subsequent confirmation of underlying voids [3] has opened possibilities for the study of planetary caves. Some of these pits could be the only ingress portals to intact extraterrestrial lava tubes. While orbital sensing has been invaluable in the discovery and science of pits, only subsurface exploration with up-close sensing can provide the viewpoints, observations and samples necessary for more detailed science inquiry. Robots are positioned to access, investigate, and meticulously model these environments over extended durations. We present the results of a multi-year campaign, originating at Carnegie Mellon University, to develop robotic technologies for planetary pits and caves. This work has been anchored by the most comprehensive analog field experimentations to date in this area. The continuation of this work to support lava tube astrobiology at NASA Ames Research Center (ARC) is also discussed.

Access and Mobility: Entering pits and caves from the surface poses unique mechanical challenges of slope, stability, large scale, and rough terrain. The design of robotic mobility systems for access is driven by the physical configuration of pits. Two types of pits are explored in this work – steep-walled pits with vertical ingress, and sloped pits which may exhibit gentle graded features from collapse. *Tyrobot*, a robot that traverses, raises and lowers from a tight-rope strung across pit openings, has been developed to explore and map steep-walled pits. *Pitcrawler* is an agile, low center-of-mass robot with differential suspension designed to descend slopes and navigate heavily bouldered floors. Once inside a lava tube, *Pitcrawler*'s mission is to traverse the length autonomously and map the walls with active sensing.

Science Modeling: Robots require optical sensing for safe-guarding and autonomy. Sensors commonly used include LIDAR, which provides geometric measurement, and cameras which measure appearance. Robots utilize these sensors to build 3D models – an internal map of the world - in order to reason about obstacles and plan interactions. We show that 3D models built during and for exploration can also be invaluable to scientific inquiry, effectively enabling scientists to virtually experience pits and caves first hand.

Ultra-resolution Modeling. Imaging is confounded by harsh illumination and dynamic range conditions found at the intersection of dark caves and bright surface. In contrast, LIDAR provides sparse, monochromatic data suitable only for hazard detection. These independently deficient modalities can be integrated to provide 3D models with superior data density, accuracy and completeness.

What separates this modeling approach from prior work is two-fold. Firstly, the particular appearance of regolith-covered pits under direct sunlight is exploited to enhance camera-based geometric recovery in the form of shape-from-shading. Secondly, integration of image-based shape and appearance with LIDAR measurements in a Markov Random Field (MRF) statistical framework provides global, low-frequency consistency in the model. This approach, coined *Lumenhancement*, has been demonstrated for 100-fold increases in density when mapping planetary spaces [4].

Visualization: We investigated methods for visualization of robot models to convey maximum information to human consumers. Methods for 3D printing of models ranging from life-sized rock samples to scaled versions of 100m pits in full color have been developed. Printed 3D models are excellent in conveying scale, multiple perspectives and tactility to scien-

tists. Approaches to relighting, rendering and viewing 3D models on computer displays were also developed. The key idea is to separate material (reflectance) from illumination in imagery by estimating light transport for flash-carrying robots in tunnels. By removing perspective-dependent artifacts such as specularities and shadows, the scene can be re-rendered with high-contrast photorealistic illumination.

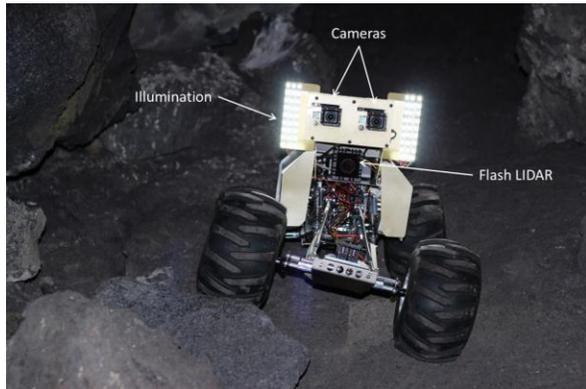


Figure 2. PitCrawler, an agile robot, maps Indian Tunnel lava tube with active illumination, stereo cameras and flash LIDAR.



Figure 3. Virtual view of King's Bowl Pit and Cave from 3D Model. This perspective is only possible through ranged robotic sensing as the steep wall precludes safe human photography from that vantage.

Analog Experimentation: Six field deployments were conducted to test technologies at three terrestrial analog sites – two surface pit mines and a natural lava tube. The surface mines, while artificial, resemble closely the shape and dimension of several known lunar pits. The lava tube features a small collapse skylight. A seventh week-long campaign comprehensively mapped geological features at Craters of the Moon National Monument, Idaho including King's Bowl rift pit and Indian Tunnel lava tube.

Pits and Caves Dataset: Robot models and ground truthing from all analog test sites have been released to

the public as open source [5]. Data is in the format of metric point clouds which were collected with high resolution (~1cm areal density) phase-shift LIDAR scanning and stitched using incremental ICP registration [6]. This is the first 3D dataset in the planetary caves domain for supporting robotics and science research. The total downloadable payload is over 5GB and includes the only metric 3D reconstructions of King's Bowl and Indian Tunnel to date.

Upcoming Investigations: Biologic and Resource Analog Investigations in Low Light Environments (BRAILLE) is a proposed upcoming project at NASA ARC led by Jen Blank (PI) to conduct science-driven exploration at Lava Beds National Monument over the course of four years. The specific emphasis is on astrobiology of lava tube microbial ecosystems and the resources (water, rock, dissolved gasses) that sustain them. Analog study at Lava Beds serves as a good proxy for extraterrestrial caves [7]. Robotics technology, such as automated sensing, mapping and sampling, will be an integral part in addressing these inquiries.

Conclusions: Robots are poised to become invaluable tools for planetary cave scientists. Robotic 3D modeling complements specialized sensing and improves scientific return in subterranean exploration. Lastly, approaches described here can be implemented using current technology for minimal cost and risk to standard mission practices.

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