Autonomous Mapping and Characterization of Terrestrial Lava Caves Using Quadruped Robots: Preparing for a Mission to a Planetary Cave, J.G. Blank[1,2], B. Morrell[3], A. Bouman[3], T. Touma[3], M.F. Ginting[3], Chris Patterson[4], A. Aghamohammadi[3], and the BRAILLE-CoSTAR Teams, [1]NASA Ames Research Center (Moffett Field, CA USA), [2]Blue Marble Space Institute of Science (Livermore CA USA; jen@bmsis.org), [3]NASA/Caltech Jet Propulsion Laboratory (La Cañada Flintridge CA USA), [4]McGill University (Montréal, Canada).

Introduction: Subsurface voids on the Moon and Mars are attractive targets for exploration, for potential human use, and, in the case of Mars, for the search for evidence of extant or past life. Orbiting satellite data have been used to identify more than a thousand candidate cave entrances on each of these planetary bodies. While planetary cave access has many challenges, rapidly evolving technologies will soon make the concept of a mission to one of these caves feasible rather than an imagining of science fiction. Here, we present results of robotic exercises from ongoing field deployments to a volcanic cave, a terrestrial analog for planetary lava tubes. The motivation for this work derives from the NASA BRAILLE PSTAR project. The capabilities tested and described have been developed over the past three years by JPL's CoSTAR Team, winners of the second phase of the current DARPA SubT Challenge [1].

Mars-Analog Field Site: Our field tests were conducted in Valentine Cave, a lava tube open to public visitation and located within Lava Beds National Monument (N. California, USA). The cave is 651m long and reaches a maximum depth of 20m below the surface. Basaltic block steps, commencing ~10m from a designated parking area, lead into the cave; intrepid human visitors can traverse the entire length of the cave, albeit on hands, knees, and bellies near the toe.

Technologies: We used two Auto-Spot quadrupeds, a synthesis of the Boston Dynamics "Spot" robot and the NeBula Autonomy payload developed by the CoSTAR Team [1]. This payload included LiDAR, imaging cameras, and environmental and gas sensors, along with processors running our high-level AI framework, *NeBula*, to enable autonomous navigation, traversability, and skill development in dark settings [2]. Au-Spot has dimensions of 1.1x0.5m and a mass, with our payload, of ~37 kg. Default walking height is 0.6m, though the robot can ambulate in extended or crouch mode at ±0.1m.

Mobility. Auto-Spot successfully traversed the floor of Valentine Cave, maneuvering over ropey pahoehoe flow with undulatory ridges and fractures, across cave roof breakdown debris, and down a 1.2m quenched lavafall. The robot adjusted its walking height in response to changing cave tube dimensions and navigated the steps in and out of Valentine. The robot walked in loose, tephra-rich regolith on the surface at a pace faster than that of a wheeled robot.

3D Simultaneous Localization and Mapping (SLAM). Auto-Spot generated a 3D map of the local cave environment in real time, fusing LiDAR, vision, and other sensing modalities. The robot dropped communication nodes autonomously to maintain a link to the scientists outside the cave, who monitored the map evolution in real-time.

Autonomous Navigation and Sensing. Using deep learning techniques, *NeBula* mitigates risk and allows the robot to explore autonomously and search autonomously for scientific targets. It relies on neural networks, trained in this application on imagery data collected and annotated over several years by BRAILLE scientists to highlight features of general scientific interest. These include fractures in the cave walls, aqueous pools and drips, speleothems and mineral crusts, and biofilms. We evaluated the ability of Auto-Spot to identify and locate these features in Valentine.

Conclusions. The Auto-Spot quadruped robots exhibit promise for successful and nimble navigation of terrestrial lava caves. Planetary Mission concepts in the early stages of development involve multiple Auto-Spot-like quadrupeds cooperating to enable successful cave ingress and exploration [e.g., 3,4]; we envision testing some of these scenarios in future field deployments. Our work makes the rationale for future missions to planetary caves using autonomous robots.

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References: [1] Agha, A., et al. (2021) arXiv:2103.11470v2; [2] Bouman, A. et al. (2020) arXiv:2010.09259v3; [3] Phillips-Lander, C.M., et al. (2020) AGU Fall Mtg. P057-04; [4] Touma, T. et al. (2020) AGU Fall Mtg. P057-07.

The Auto-Spot quadruped in Valentine Cave (Sept 2020).