THE KINEMATIC NAVIGATION AND CARTOGRAPHY KNAPSACK (KNACK): DEMONSTRATING SLAM (SIMULTANEOUS LOCALIZATION AND MAPPING) LIDAR AS A TOOL FOR EXPLORATION AND MAPPING OF LUNAR PITS AND CAVES.

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Introduction: Renewed interest in deep space exploration has made establishing a persistent human presence on the Moon, and eventually Mars, a priority. Sustained habitation of the Moon will require in-situ resource utilization (ISRU) and protection from radiation at the surface. Lunar caves interest the space community because they could provide shelter from radiation [1], access to water deposits, and a space for habitation, as well as hold information about the geology, volcanology, and evolution of the Moon [2]. Developing the tools to explore, map, and characterize these voids is key to understanding the Moon as a planetary body and to establishing a permanent human presence there.

Our team is developing tools that enable ultra-high resolution terrain mapping and navigation using mobile light detection and ranging (LiDAR) and simultaneous localization and mapping (SLAM) algorithms in fully GPS-denied and no-light environments. 3D mapping with LiDAR and SLAM is relatively under-used, particularly in the context of planetary exploration and planetary analog environments. The backpack mounted LiDAR instrument under development by the Kinematic Navigation and Cartography Knapsack (KNaCK) team demonstrates the potential of mobile SLAM LiDAR for lunar, planetary, and terrestrial cave exploration, study, and utilization. Descriptions of the instrument and associated SLAM algorithms used for GPS-denied mapping are referenced here [3, 4].

Advancing State of the Art for Cave Mapping: The KNaCK team is using terrestrial caves and lava tubes to develop and refine mapping techniques for use on other worlds while simultaneously advancing the state of the art for terrestrial cave exploration and study. Mobile LiDAR systems hold promise as a tool for investigating caves on Earth and throughout the solar system due to their ease of use, ability to see beyond the cast of visible light, ability to operate without GPS, and their rapid survey potential. These systems capture 3D point clouds by fusing range data from a sensor with estimates of the instrument's position as it moves through the environment. A multitude of point clouds are matched together with a SLAM algorithm to produce a complete picture of the environment's topography.

In traditional cave surveys, compass and inclinometer techniques are still the most common method for terrestrial cave exploration and documentation. Though digital devices that quickly measure azimuth and inclination with magnetometers and accelerometers such as the Disto-X2 and the BRIC4 have streamlined the process immensely in the last decade, cave surveying is still tedious and time consuming. Further, this traditional technique does not capture detail sufficient for most geoscientific or architectural applications and is incompatible with the EVA suits and robotic systems required for planetary applications. Creating a survey of a moderately sized terrestrial cave can take many days with traditional techniques. Mobile LiDAR offers the prospect of producing a survey fit for scientific and architectural use in only the time it takes to navigate through the cave passage. In a terrestrial context, mobile LiDAR drastically reduces time and effort spent. In a planetary context, mobile LiDAR could enable exploration that simply would not be possible with current state-of-the-art techniques.

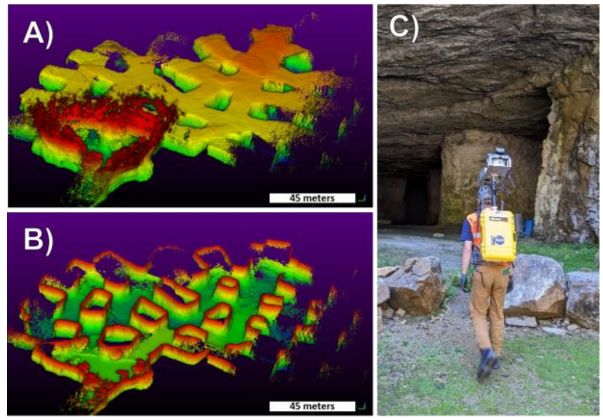

Fig. 1. *Three Caves Quarry, Huntsville, AL: (a) Full point cloud. (b) Cross-section exposing the interior volume. (c) Entering quarry with the instrument.*

Analog Testing: The KNaCK instrument was used to map two terrestrial caves: Three Caves, a quarry in Huntsville, Alabama, and Lava River Cave, a lava tube in the San Francisco Volcanic Field of northern Arizona. Data used to generate the map of Three Caves (Fig. 1) was collected in just 6.5min, capturing a substantial portion of the maze-like complex with only a short, 370m traverse. The data used to produce the map of Lava River Cave (Fig. 2) was collected in roughly 30min over 1100m and records the morphology of the cave at cm-scale. These maps contain 18.4M and 44.8M points, respectively, after post-processing.

Planetary Applications: Subsurface voids on the Moon and other planetary bodies are primarily in the form of lava tubes, also called pyroducts [5]. These subterranean spaces may be entered through skylights, places where the ceiling of the pyroduct has collapsed. Mobile LiDAR can probe the darkness and gather topographical and reflectivity data about these features from skylight rims. This information can be used to assess the scientific significance of the feature, its potential for ISRU or habitation, and establish the concepts of operation necessary to enter the pyroduct on future robotic or manned missions. LiDAR instruments can also enhance missions to probe the depths of these features, rapidly gathering data to illuminate the geologic history of passages and their potential usefulness.

KNaCK is also an invaluable tool for terrestrial science. Detailed models of karst and volcanic features enable enhanced studies of geomorphology, speleogenesis, hydrology, air circulation, habitat inventory, and other environmental and geologic studies.

Summary: Soon, humanity will return to the Moon for the first time since a lunar skylight was confirmed in 2009 [6]. Interest in lunar pits and lava tubes is growing as they represent access to resources, safe spaces for habitation, and a unique opportunity for science. SLAM LiDAR has the potential to penetrate the darkness and rapidly characterize the topography of these features. The KNaCK team has demonstrated this utility in terrestrial caves and is working to produce space-hardened equipment to extend this capability to lunar subterranean environments and accelerate the space community towards the exploration and utilization of lunar lava tubes.

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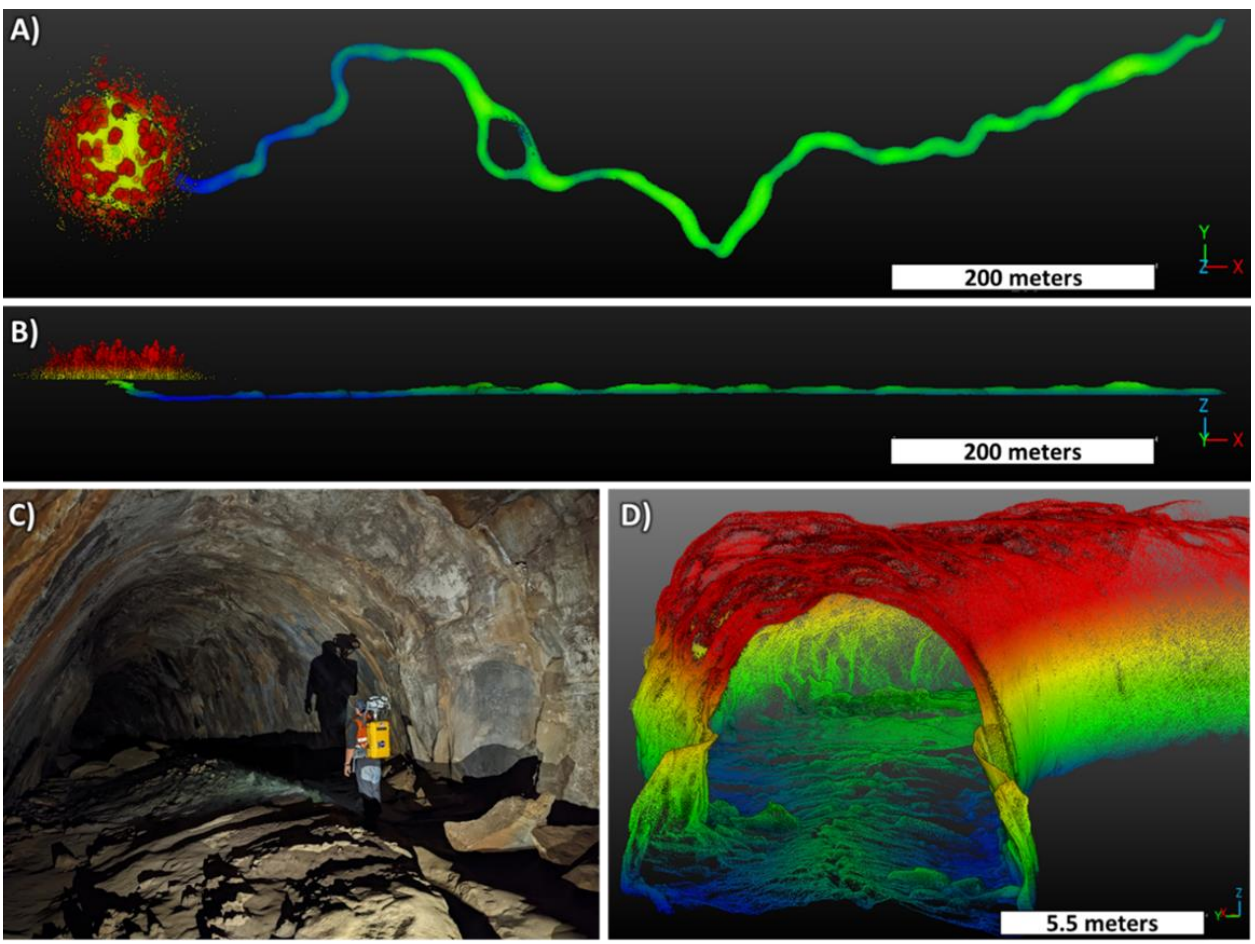

Fig 2. *Lava River Cave, Arizona: (a) Plan view. (b) Profile view. (c) Instrument in use. (d). Fissure in passage floor indicates extensional fracturing from inflation of lava moving below the surface. LiDAR allows analysis of sections and profiles from any direction and precise measurement of passage topography and high-lava marks along walls.*