Improving Navigation Accuracy in GPS-Denied Planetary Analog Environments with the Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR System.

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Introduction: Improved terrain characterization and navigation sensors and methods are needed to enhance crew safety, ISRU return, and scientific understanding of future landing sites. Specific to the Artemis Program and sustained exploration at the lunar South Pole, extreme low-angle solar illumination conditions pose significant challenges to existing photogrammetry-based robotic navigation. Additionally, a major challenge for navigation on the Moon and other planetary surfaces is the lack of Global Positioning and Navigation Systems (GPS or GNSS). Thus, there is a need for an alternative to image-based navigation that allow for precise and accurate mapping in GPS-denied environments on any planetary body [1]. Here, we describe the Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR system> we will present recent improvements to navigation and mapping accuracy using simultaneous localization and mapping (SLAM) loop-closure and terrain relative navigation techniques. Position and localization accuracies of better than 5 meters (consistent over kilometers-long traverses) have been achieved at planetary analog field campaigns with the Rover-Aerial Vehicle Exploration Network (PI: C.W. Hamilton) in the Icelandic Highlands (July 2022) and during a Joint EVA Testing Team (JETT-3) technology demonstration (Oct. 2022).

The KNaCK is a backpack-mounted, mobile navigation and terrain mapping system that uses a *velocity-sensing* coherent light detection and ranging (LiDAR) system based on a frequency modulated continuous wave (FMCW) technique [2.3], contains minimal moving parts, and employs sophisticated positioning algorithms. During a traverse, this instrument emits light pulses to continually scan a scene to build a three-dimensional point cloud representation of topography. A measure of the Doppler-velocity at each of millions of range points sampled per second allows for a 6 degree of freedom (6-DoF) estimate of the sensor's position and the development of novel position-from-velocity mapping and positioning algorithms for loop-closure in GPS-denied environments. And, being insensitive to direct solar incidence, allows navigation and mapping regardless of the Sun's position in the sky; thus permitting surface exploration to continue regardless of traverse azimuth and throughout the day (or night).

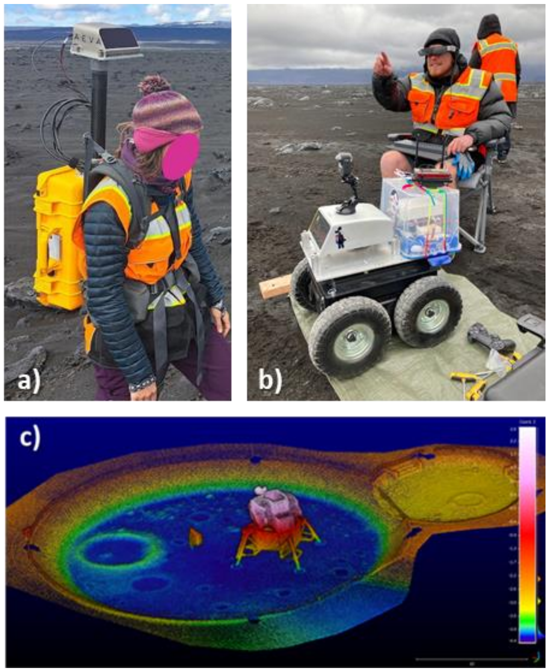

Figure 1: a) the KNaCK mobile LiDAR System with Aeva Aeries 2 velocity-sensing FMCW-LiDAR sensor. b) KNaCAR, autonomous rover, with operator using real-time data visualization in heads-up display for piloting. c) example data of full-size mockup of Apollo LEM. Post-processing of point clouds, ego-velocity, 6-DoF position from FMCW-LiDAR, and inertial navigation data using KNaCK-SLAM allows for GPS-denied topography mapping and traverse path navigation.

Motivation: The development of self-driving automobiles on Earth can be leveraged to advance exploration capabilities on planetary surfaces. LiDAR is an active source illumination method that works regardless of solar incidence (and in the dark), permitting extended activity in low-light or challenging conditions, at ranges >200m from the sensor. For humans, LiDAR can be used in real-time to aid situational awareness, and point-cloud data can be used to make ultra-high resolution (cm-scale) topography models for traverse planning as well as scientific context. Moreover, through a combination of 6-DoF state-estimation and terrain-relative navigation methods, m-scale-accuracy position tracking can be done in real-time, providing absolute knowledge of the location of assets in the environment.

The Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR instrument: Development and testing of the KNaCK LiDAR System

(Fig. 1a,b) uses prototype FMCW-LiDAR sensors developed for the self-driving automotive industry from Aeva, Inc. (Aeries 1 and Aeries 2). The KNaCK system is a backpack/person-mounted platform. Multiple COTS autonomous rover versions of the system (KNaC- Autonomous Rover (KNaCAR, fig 1b)) are also research platforms. These instruments both serve as development test-articles to evaluate the 6-DoF navigation capabilities of the FMCW-LiDAR for terrain mapping from mobile platforms, provide information about operational methods, and collect test data for GPS-denied algorithm development. Multiple rovers are used to study operations concepts for "swarms" of rovers and human-rover interactions that could enhance scientific return.

KNaCK-SLAM: The simultaneous range and velocity information sampled at each point allows us to develop advanced position-from-velocity simultaneous localization and mapping (SLAM) algorithms and iterative-feedback mechanisms to constrain IMU bias propagation errors. We have developed a novel SLAM solution that makes use of the unique capabilities of FMCW-LiDAR called KNaCK-SLAM (fig. 1c), described in detail in [4]. These solutions represent a significant advancement in spatial-state-estimation for GPS-denied environments, thus making the application of SLAM algorithms more efficient for real-time navigation and mapping. Figure 2 shows the effective accuracy of SLAM mapping in GPS denied environments using various techniques, and specifically loop-closure, which improves position accuracy along a ~500m traverse to better than 2 meters.

Additional enhancements to mapping accuracy have come from terrain relative navigation techniques, where we can demonstrate better than 5 m accuracy over a 4 km traverse when using ~2 m/pixel DEMs (similar to LROC DEM spatial resolution). This represents a significant advancement in position

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References: [1] Zanetti, M. et al., (2022), LPSC 53 Abs #2634. [2] Hexel, et al. (2022) arXiv:2201.11944v2 [cs.RO]31May2022. [3] Poulton et al. (2017) Optics Letters, Vol. 42, Issue 20, pp. 4091-4094. [4] Miller, K., et al., (2022), LPSC 53, Abs# 2808.

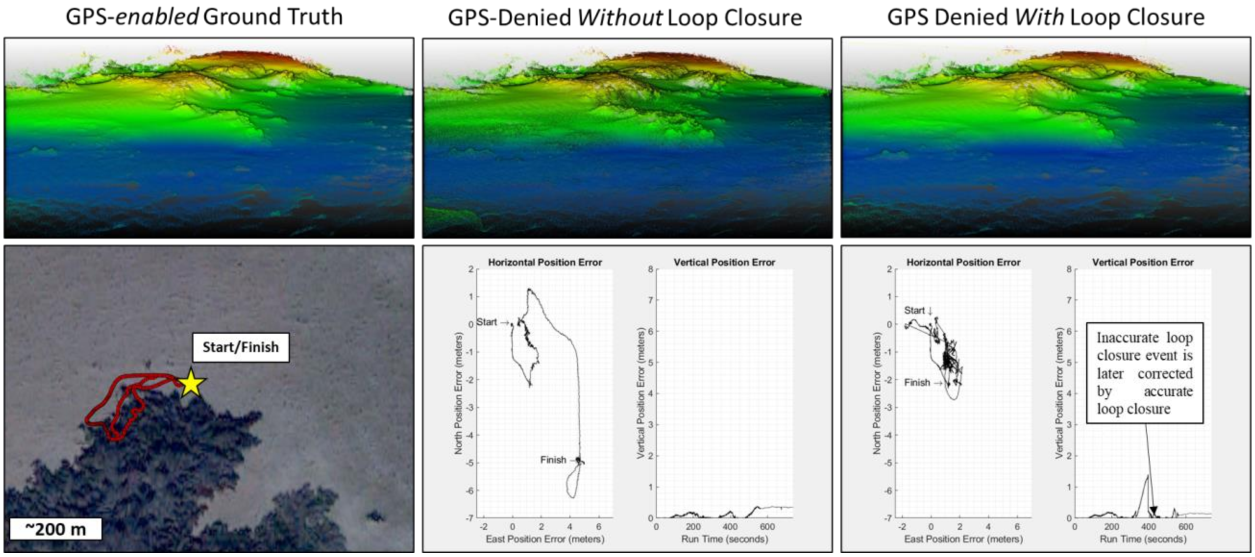

Figure 2: Example data collected by the Kinematic Navigation and Cartography Knapsack (KNaCK) which uses both FMCW-LiDAR (Aeva Aeries II) multi-beam flash LiDAR (Ouster OS-1-64, Rev 6) during the NASA PSTAR Rover and Aerial Vehicle Exploration Network (RAVEN) field campaign in July 2022). The region is located in the Icelandic Highlands where glacial sands are embaying a fresh spiky pahoehoe lava margin near the Holuhraun flow (Emplaced in 2014-2015) and represents a ~500m long traverse along the margin with a co-located start and end point. GPS-enabled post processing of LiDAR data is shown for comparison and ground truth. Using a custom simultaneous and localization algorithm (KNaCK-SLAM) data can be post-processed with no GPS position data. In this case data was process with and without loop-closure techniques, with relative accuracy of the navigation and position solution better than 6 m with no loop-closure and better than 2 m using loop closure algorithms.