Better than 10m GPS-Denied Navigation Accuracy with the Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR System. M. Zanetti1, K. Miller1, C. Whetsel1, W. King1, E. Hayward1, P. M. Bremner1. 1NASA Marshall Space Flight Center, Huntsville, AL 35805, (Michael.R.Zanetti@nasa.gov).

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. Here we present recent improvements to navigation and mapping accuracy using simultaneous localization and mapping (SLAM) 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 and in local testing at NASA MSFC’s Lunar Regolith Terrain facility (Fig 1).

The Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR instrument: The KNaCK is a backpack-mounted, mobile navigation and terrain mapping system that a development test article for commercial off-the-shelf LiDAR sensors (e.g. Ouster OS-1 64 rev7 time-of-flight (ToF) multi-beam flash and Aeva Aeries 2 velocity-sensing frequency modulated continuous wave (FMCW) techniques, and include tactical grade inertial measurement units (IMU) and GPS position for ground truth. Results reported here are with the Ouster OS-1 sensor. During a traverse, this instrument emits light pulses to continually scan a scene to build a three-dimensional point cloud representation of topography. Using these sensors we are developing novel Simultaneous Localization and Mapping (SLAM) and navigational positioning algorithms using Terrain Relative Navigation and loop-closure closure techniques for navigating and mapping in GPS-denied environments. And, being insensitive to direct solar incidence, this system 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). The KNaCK backpack and multiple small rovers equipped with the same sensors provide information about operational methods and collect test data for GPS-

Figure 1: (top) 1 cm/pixel context topography map created by the KNaCK instrument of the Lunar Regolith Terrain (LRT) facility at NASA MSFC. Red line corresponds to the traverse path shown in blue in error panels. (middle) horizontal position of the traverse path of the KNaCK-SLAM w/ TRN (black) compared to pure SLAM dead-reckoning (pink) and GPS ground-truth (blue). (bottom) Horizontal position error of TRN and SLAM-dead reckoning. Note: horizontal errors with TRN enabled are better than ~1m once a fix to the base map is achieved.
denied algorithm development. Multiple rovers are used to study operations concepts for “swarms” of rovers and human-rover interactions that could enhance scientific return and provide initial infrastructure building (in development now at MSFC with the Collaborative Autonomous Surface Mobility (CASM) project).

**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 >100 m 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.

**KNaCK-SLAM with TRN:** 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]. Improvements to KNaCK-SLAM include a Terrain Relative Navigation function, wherein the local SLAM map created by the sensor is compared to a pre-existing low resolution base map to enhance positional accuracy. In the case shown we compare a local ~1 cm spatial resolution SLAM map to a low resolution 3 m/pixel base map (similar to resolutions available from LROC remote sensing of lunar landing sites).

Figure 1 shows GPS ground truth (from the d-GPS accurate (cm-scale) sensor on the KNaCK backpack; blue line), versus KNaCK-SLAM w/ TRN (black line) and a SLAM-only (no TRN) dead-reckoning solution (using LiDAR cloud matching and inertial measurement unit odometry). When the TRN algorithm matches the local point cloud scene to the base map, the navigation solution position errors improve dramatically from the dead-reckoning solution, and essentially match the GPS ground truth data with a minor 1-2 m positional offset. Overall, in testing, position errors are much less than 10 m, and <2 m error are most common. Vertical errors relative to the GPS base map are negligible. 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 1 shows the effective accuracy of SLAM mapping with TRN in GPS denied environments improves position accuracy along a ~500 m traverse to better than 2 meters.

**Other Applications and Ongoing Projects:**

The KNaCK-SLAM algorithm is also proving very useful in mapping pure-GPS-denied environments, including subterranean planetary cave environments. An associated abstract from King et al. (2023, 2024) is also presented at this conference (Fig. 2 is a small subset of data from Lava River Cave, Flagstaff, AZ that is being used in SSERVI GEODES research (see Wilke et al., 2024; McCall et al., 2024, this conference).

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**Figure 1:** Images from subset of KNaCK LiDAR System Data from Lava River Cave, a 1.2 km (0.75 mi) long lava tube in Flagstaff, AZ USA, and a useful completely GPS-denied and planetary analog cave environment. (left) Oblique view of the Lava River Cave entrance and surrounding forest with the lava tube trace extending beneath the sub-surface. (right) a subset of the KNaCK LiDAR data from within the cave, with ~3 cm spatial resolution, showing the cave shape, rocks, and lava flow features. For more information see King et al., 2024, this conference. Additional studies using these data for GPR and seismic studies with the SSERVI GEODES team are in Wilke et al., 2024, and McCall et al., 2024; this conference.