
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; 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, 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 the development of novel position-from-velocity mapping and positioning algorithms for loop-closure in GPS-denied environments.

Background and Motivation: Photogrammetry-based navigation and mapping techniques present engineering and operational challenges that might impede sustained exploration of the lunar surface at the South Pole; where the low-solar incidence will produce long, persistent shadows. These conditions will create large modeling errors that affect absolute scale measurements and traverse planning. Operational challenges to avoid pointing cameras directly at the sun will need to be considered, further affecting traverse planning. LiDAR-based systems actively measure range using a laser source to provide absolute distance measurements and can provide critical navigation data in poorly illuminated or even permanently shadowed regions (PSRs) but need to be robust to these effects.

Frequency Modulated Continuous Wave (FMCW) LiDAR: The FMCW-LiDAR technology is a chip-scale LiDAR that uses coherent laser detection and measures the Doppler shift of a chirped continuous wave to provide velocity, range, and intensity for each XYZ-point in a 3D cloud of points [for detail see 1,2,3]. Ultra-high point density is accomplished for targets both near the scanner and far away through repeated sampling during both static scanning and along traverses, out to distances of hundreds of meters. The FMCW-LiDAR sensing technique’s use of coherent detection has the added advantage of being insensitive to direct solar incidence, allowing 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 Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR instrument: Development and testing of the KNaCK LiDAR System (Fig. 1a,b) uses a prototype FMCW-LiDAR based sensor developed for the self-driving automotive industry from Aeva, Inc. The KNaCK system is a backpack/person-mounted platform. An autonomous rover version of the system (Kinematic Navigation and Cartography Knapsack Autonomous Rover, KNaCAR) uses the same laser technology to provide navigation and mapping data that allows for autonomous traverse planning and execution.

Figure 1: a) the KNaCK backpack-mounted mobile LiDAR System. b) KNaCAR, autonomous rover using velocity-sensing FMCW-LiDAR sensor. c) example data collected. Post-processing of point clouds, ego-velocity, and inertial navigation data using KNaCK-SLAM allows for GPS-denied mapping and navigation.
Cartography Autonomous Rover (KNaCAR, fig 1b)) is a fully autonomous self-driving rover that is also under development. These instruments both serve as development test-articles to evaluate the capabilities of the FMCW-LiDAR for terrain mapping from mobile platforms, provide information about operational methods, and for test data to evaluate GPS-denied algorithms.

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, this conference]. 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.

Terrestrial Applications: The KNaCK system is field-ready, and in the last year has been deployed for a diverse range of applications. The 3D mapping capability has been used to map the United States Space and Rocket Center in Huntsville, AL as part of NASA’s Human Exploration Rover Challenge (HERC) STEM activity, and for terrain characterization at the Potrillo Volcanic Maar with NASA’s SSERVI RISE2 and GEODES teams [6]. A major future initiative of this project is large-area shoreline mapping project for strategic infrastructure monitoring.

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Figure 2: Example data collected by the FMCW-LiDAR sensor on KNaCK (Aeva Aeries, B1). This is a still image snippet of a real-time video and data capture of a landing UAV drone at the Kilbourne Hole Volcanic Maar during a RISE2 field campaign in Nov, 2021. HD Video image (upper left) shows a cloud of dust and sand kicked up by a landing UAV drone. Range image (upper right) shows depth and distance from the scanner. Velocity image (bottom) shows the Doppler velocity of the rotating vortex of dust during the landing. Blue regions are moving toward, red regions are moving away from the sensor (white is no relative motion). Note that the sensor can measure the speed and direction of the vortex. These proof-of-concept results indicate that larger-scale atmospheric phenomena (e.g. Dust-Devils) can be studied in unprecedented detail.