The Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR System. M. Zanetti[1], B. Robinson[2], E. Anzalone[1], B. De Leon Santiago[1], E. Hayward[1], K. Miller[1], B. Steiner[1], B. Anderton[2], T. Cordova[2], J. Jetton[2], D. Langford[2], J. Reeves[2], J. Walters[2]. [1]NASA Marshall Space Flight Center, Huntsville, AL 35805, [2]Torch Technologies, Huntsville, AL, 35802. (Michael.R.Zanetti@nasa.gov).

Introduction: The return of crewed missions to the Moon and Mars is strong motivation for the development of instruments and methods that would improve terrain characterization and navigation of future lunar landing sites. One major challenge for navigation on the Moon and other planetary surfaces is the lack of Global Positioning and Navigation Systems (GPS or GNSS). Another challenge, specific to the Artemis Program and sustained exploration at the lunar South Pole, is that of extreme illumination conditions that will hamper existing photogrammetry based robotic navigation. Thus, there is a need for an alternative to image-based navigation that allows for precise and accurate mapping in GPS-denied environments on any planetary body.

The Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR instrument: We have begun work on a novel, mobile terrain-mapping and navigation system called the Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR system. The system uses *velocity-sensing* coherent light detection and ranging (LiDAR) system based on a frequency modulated continuous wave (FMCW) technique to scan a wide field of view and build a three-dimensional point cloud representation of topography. The addition of velocity information sampled at each range measurement allows us to develop advanced simultaneous localization and mapping (SLAM) algorithms and iterative feedback mechanisms for sustained inertial measurement orientation in GPS-denied environments. As part of the research and development of this instrument we are also exploring additional applications of the velocity-sensing capabilities of the instrument, such as for rocket plume exhaust surface interactions and for measuring small scale atmospheric phenomena (e.g. dust devils).

Background and Motivation: Future lunar and planetary exploration by landers, rovers, and humans will require the ability to navigate in Global Positioning System (GPS) – denied environments and to produce high-resolution topography maps for scientific investigations and virtual environment reconstruction. In robotic landing and roving missions, inertial measurement units (IMUs) can provide positioning information, but these systems suffer from accumulated errors and position "drift" when not continually updated with accurate position information from either GPS or multiple integrated onboard sensors. Essentially, this is a problem of simultaneous localization and mapping (SLAM) of an environment, and these SLAM techniques have been successfully used with camera image-based vision systems for planetary exploration on the Mars Exploration rovers (MER) and Mars Science Laboratory (MSL). However, these techniques alone will likely present engineering challenges to fully enable sustained exploration on the lunar surface where sun and shadow will need to be considered (e.g. 1, this workshop). The low-solar incidence will produce long, persistent shadows that can create large modeling errors and will hamper absolute scale measurements and traverse planning. In addition to shadows, operational challenges to avoid pointing cameras directly at the sun will need to be considered, further affecting traverse planning. Thus, there is a need for navigation and terrain mapping instruments that can operate in GPS-denied environments as well as in challenging illumination conditions. A LiDAR-based system actively measures range using a laser source to provide absolute distance measurements, and can provide critical data for navigating the South Pole illumination conditions or even into permanent shadowed regions (PSRs). The FMCW-LiDAR sensing technique described below has the added advantage of being insensitive to direct solar incidence, allowing navigation and mapping regardless of the Sun's position in the sky and thus permitting surface exploration to continue regardless of traverse azimuth and throughout the day (or night).

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 2,3,4]. This operation is in contrast to time-of-flight (ToF) LiDARs which measure the range of an object by sensing the time required to return a brief, high-power pulse of light, and are typically sent and received (~100,000 – 1 million times per second) through a fast spinning mirror, creating a line of points which is then translated across a surface creating a 3D point-cloud representation of the topography. In mobile ToF systems, such as kinematic (i.e. person-mounted) or sensors used in the self-driving automotive industry, knowledge of the scanners orientation and position is needed to compute the trajectory of the scanner and build a 3D point-cloud.

Among many other differences, ToF scanners to do not intrinsically provide velocity information in their signal, and velocity must be calculated through rapid repeat scanning. In FMCW-LiDAR sensors, scanning of a field of view is achieved with minimal moving parts using mirror - galvanometer or micro-electro-mechanical systems (MEMS) devices, which in our system is also made mobile by mounting on a backpack. Thus, ultra-high point density is accomplished for both near scanner and distant targets through repeated sampling during both static scanning and along traverses to distances of hundreds of meters.

KNaCK Technology Development: Development and testing of the KNaCK LiDAR System uses a prototype FMCW-LiDAR based sensor developed for the self-driving automotive industry. We are currently developing a terrestrial-use version of the system that incorporates the FMCW-LiDAR sensor with a tactical grade IMU and GNSS receiver that will serve as a test-article for GPS-denied use. This terrestrial system is being used to evaluate the potential of the FMCW-technique for terrain mapping from a kinematic/backpack based platform, provide information about operation methods, and for test data to evaluate GPS-denied algorithms. The choice to design a backpack system is intentional, as it can be quickly and easily deployed and tested, provides a means for rapid, large-spatial-area data collection, and can make use of subtle motions from walking to improve algorithm development. GPS-denied mapping will be achieved by integrating LiDAR velocity and range data with IMU orientation data to provide robust position solutions and minimize IMU propagation errors. This LiDAR-based position-from-velocity solution will 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.

Potential Impact: The KNaCK instrument addresses critical needs for terrain mapping and navigation in challenging GPS-denied and solar-illumination environments. The potential impact of the FMCW-LiDAR system will be an alternative to image-based navigation that allows for precise and accurate mapping in GPS-denied environments on any planetary body. This in turn enables better science by providing more access, better measurements, and better context. Perhaps of broadest interest to public is the ability to use these data to create ultra-high-resolution terrain maps for virtual reality immersion and landing site visualization. The general public will expect products that allow for an interactive experience of lunar surface exploration. Terrain maps that allow immersive virtual reality will be essential for translating exploration and science goals to the broader public.

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