KNaCK-SLAM: Kinematic Navigation and Cartography Knapsack Velocity-aided LiDAR Inertial Simultaneous Localization and Mapping (SLAM). K. Miller[1], A. Draffen[2], B. Robinson[2], B. Steiner[1], J. Walters[2], P. Bremner[1], J. Jetton[2], B. De Leon Santiago[1], E. Hayward[1], M. Zanetti[1]. [1]NASA Marshall Space Flight Center, Huntsville, AL 35805, [2]Torch Technologies, Huntsville, AL 35802. (Kyle.Miller@nasa.gov, Michael.R.Zanetti@nasa.gov).

Introduction: As manned missions return to the Moon and continue on to Mars in the near future, surface navigation and mapping in extremely low solar illumination and unstructured environments without navigation aids like Global Navigation Satellite Systems (GNSS) becomes more important than ever. While several potential solutions exist for solving the planetary surface navigation problem, one that provides promise for operation in the widest variety of terrains and environmental conditions is LiDAR-based [1] Simultaneous Localization and Mapping (SLAM). Not only can such a LiDAR-based SLAM system be deployed as a self-contained instrument independent of external sensor inputs, it can also operate in unlit environments where Vision-based SLAM system are inoperable. Furthermore, the advent of chip-scale frequency modulated continuous wave (FMCW) LiDAR technology provides Doppler-velocity information for each sensed point in the scene, which can be used to further constrain localization error in the SLAM front-end. Here we discuss the development of a SLAM algorithm that makes use of the unique velocity and range sensing capabilities of FMCW-LiDAR based sensors for rover and kinematic (i.e. person-mounted) mobile navigation and terrain mapping applications for surface exploration and scientific investigations.

KNaCK-SLAM: The Kinematic Navigation and Cartography Knapsack (KNaCK) LiDAR system is a LiDAR-IMU backpack test-article developed at NASA's Marshall Space Flight Center (MSFC) [2]. It consists of one velocity-sensing FMCW LiDAR, one range only time-of-flight (ToF) LiDAR, a tactical grade inertial measurement unit (IMU), two MEMS grade IMUs, and a GNSS/INS package. These instruments are shown in Figure 1. Our primary approach is to use LiDAR maps produced in GPS-enabled mode to provide ground-truth data that can be compared to GPS-denied mapping products created via post-processing. We use both real-world and simulated environments to verify and validate algorithm performance. We developed our current SLAM algorithm for both GPS-denied and GPS-enabled SLAM and can assess various combinations of sensors as desired. Our SLAM algorithm is dubbed KNaCK-SLAM and is an enhancement of the open source Li-SLAM-ROS2 [3] algorithm created by Ryohei Sasaki. While the current iteration of KNaCK-SLAM is a post-processing solution (initial focus is accurate, large-scale map

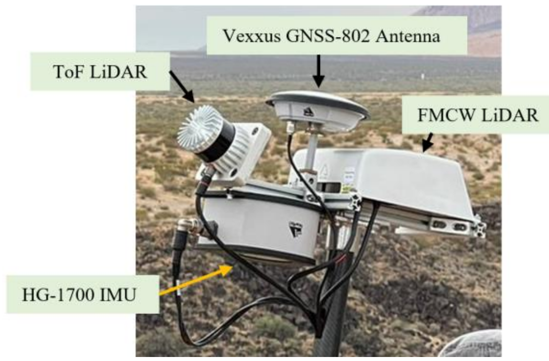

Figure 1: KNaCK backpack sensor stack.

creation), it will be adapted for real-time navigation in the future.

Background: Li-SLAM-ROS2 is an open-source SLAM implementation in Robot Operating System 2 (ROS2) that relies on a tightly coupled LiDAR-IMU front-end and a graph-based SLAM back-end. The SLAM front-end in Li-SLAM-ROS2 consists of a factor graph LiDAR-IMU sensor fusion implementation using GTSAM, a C++ sensor fusion library developed at Georgia Tech's BORG lab [4]. Using GTSAM, the front-end fuses IMU 3D accelerometer and gyroscope data with pose estimates provided by LiDAR scan-matching. For scan-matching, Li-SLAM-ROS2 uses an OpenMP-boosted version of Point Cloud Library's (PCL) generalized iterative closest point (GICP) or normal distribution transform (NDT). Both NDT and GICP are available as options for scan-matching. Considerable effort has been made in KNaCK-SLAM to improve the performance of the LiDAR scan-matching portion of the algorithm. The graph-based SLAM back-end in Li-SLAM-ROS2 is built on the g^2o general graph optimization framework [5] and includes loop closure detection.

KNaCK-SLAM-ROS2: The KNACK project's SLAM algorithm shares many common elements with Li-SLAM-ROS2, but is specialized to work efficiently and effectively with Doppler-velocity sensing FMCW-LiDAR sensors and the kinematic dynamics of the KNaCK backpack system. Four primary KNaCK system project requirements dictated necessary upgrades to Li-SLAM-ROS2. 1) A GPS-enabled SLAM mode was needed to produce accurate maps for terrestrial applications. 2) GPS-denied SLAM needed to be robust to unstructured environments. 3) GPS-denied SLAM needed to be robust to the complex translational and rotational dynamics associated with a backpack system. 4) GPS-denied SLAM needed to be able to accept 3d velocity as an aiding measurement.

The implementation of *GPS-enabled SLAM* involved passing centimeter, arc-minute accuracy post-processed kinematic (PPK) pose estimates from the GNSS/INS sensor package to the KNaCK-SLAM point cloud map publisher. Options to transform point cloud maps into multiple geodetically controlled coordinate frames and map projections were also implemented.

GPS-denied SLAM in unstructured environments such as dunes, craters, and cave systems presented a unique challenge in developing the KNaCK-SLAM algorithm. The existing scan-matching algorithms in [3], including the OpenMP-boosted versions of PCL's GICP and NDT algorithms, offered insufficient accuracy and speed when the KNaCK system was taken into unstructured terrain. In fact, it was common that the matches produced by these algorithms at 10Hz were greater than 1m in position error and 5deg in orientation error. Originally implemented to speed up KNaCK-SLAM-ROS2, the multi-threaded FastGICP algorithm created by K. Koide et al [6] was found to be robust to unstructured environments, and vastly improved performance over PCL's GICP implementation. Whereas PCL's implementation uses a Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm, FastGICP was implemented with a Gauss-Newton algorithm [6]. This might explain the performance difference.

Scan-matching with the complex and quick dynamics associated with kinematic backpack motion is challenging. Sensor mounting and limited field-of-view of the two KNaCK LiDARs results in minimal overlap between subsequent scans of either instrument. Low overlap during scan-matching is a well-known issue for algorithms like GICP and NDT, which work best when there is high overlap [7 - 9]. However, in the case of the KNaCK system, where accurate IMU measurements and velocimetry are available to predict motion in between LiDAR scans, point clouds can be "cropped" prior to scan-matching to include only those points expected to be within the field-of-views of both point clouds. This method was implemented prior to scan-matching in KNaCK-SLAM-ROS2, and had the effect of vastly improving GPS-denied scan-matching performance with the complex dynamics of kinematic motion – although it does require an accurate source of non-LiDAR odometry. A view of a point cloud map generated with the KNaCK backpack system in GPS-denied mode is shown in Figure 2.

The final notable improvement associated with KNaCK-SLAM-ROS2 is the ability to fuse velocimetry with LiDAR inertial odometry by adding a velocity factor to the GTSAM sensor fusion section of the SLAM algorithm and ensuring that coordinate frames were properly defined.

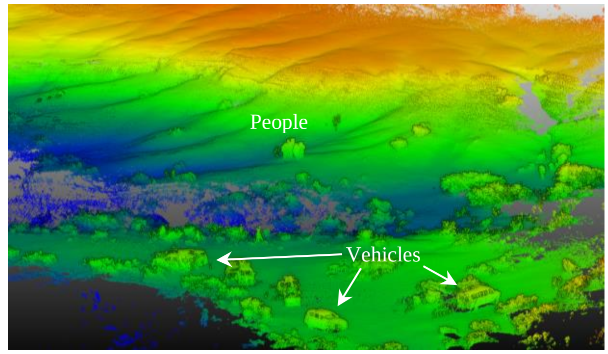

Figure 2: GPS-denied ToF LiDAR point cloud map generated at Kilbourne Hole in New Mexico with the KNaCK backpack system.

Future Work: There are four areas where future work will be focused. 1) Continued reduction of scan-matching drift, which is especially high during significant yaw maneuvers with the backpack. 2) Assessing velocity-aided performance of KNaCK-SLAM with real-world data after addressing FMCW LiDAR hardware hurdles. 3) Continued exploration of loop closure techniques with KNaCK-SLAM, as the current performance of loop closure detection and correction is insufficient. 4) Identifying the slow and inefficient parts of KNaCK-SLAM-ROS2 to make it useful for live real-time SLAM.

Conclusion: The KNaCK backpack system is novel in that it relies on a velocity sensing FMCW-LiDAR. We developed the KNaCK-SLAM algorithm, based on the open source Li-SLAM-ROS2 package, to provide system localization and mapping. Significant progress has been made in improving SLAM performance in the various unique conditions the KNaCK backpack system must operate in, such as a complex dynamic regime and unstructured environments.

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