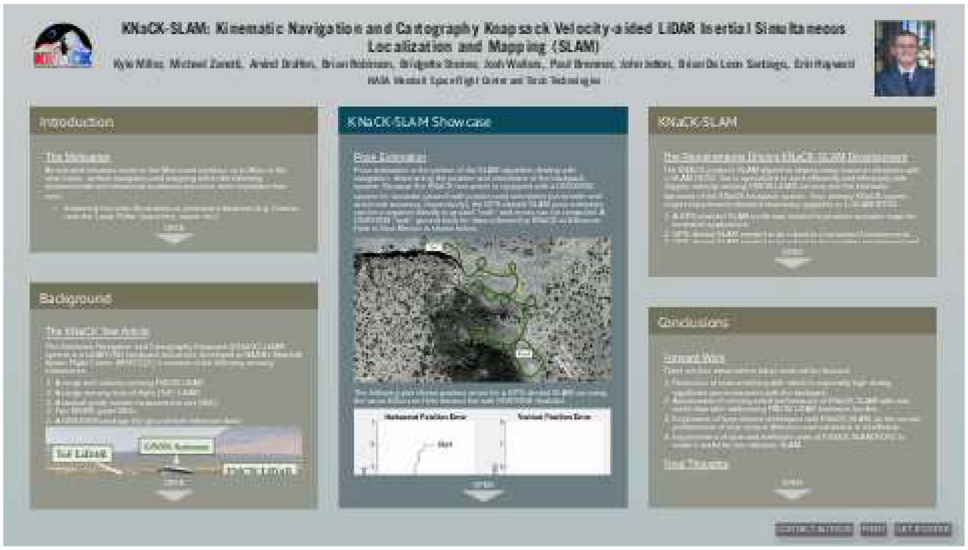
KNaCK-SLAM: Kinematic Navigation and Cartography Knapsack Velocity-aided LiDAR Inertial Simultaneous Localization and Mapping (SLAM)



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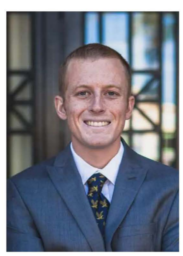

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INTRODUCTION

The Motivation

As manned missions return to the Moon and continue on to Mars in the near future, surface navigation and mapping within the following environmental and situational conditions becomes more important than ever:

- Extremely low solar illumination or permanent darkness (e.g. Craters near the Lunar Poles, lava tubes, caves, etc.)
- Unstructured environments
- Without external navigation aids like Global Navigation Satellite Systems (GNSS)

The LiDAR Solution to Surface Navigation and Mapping

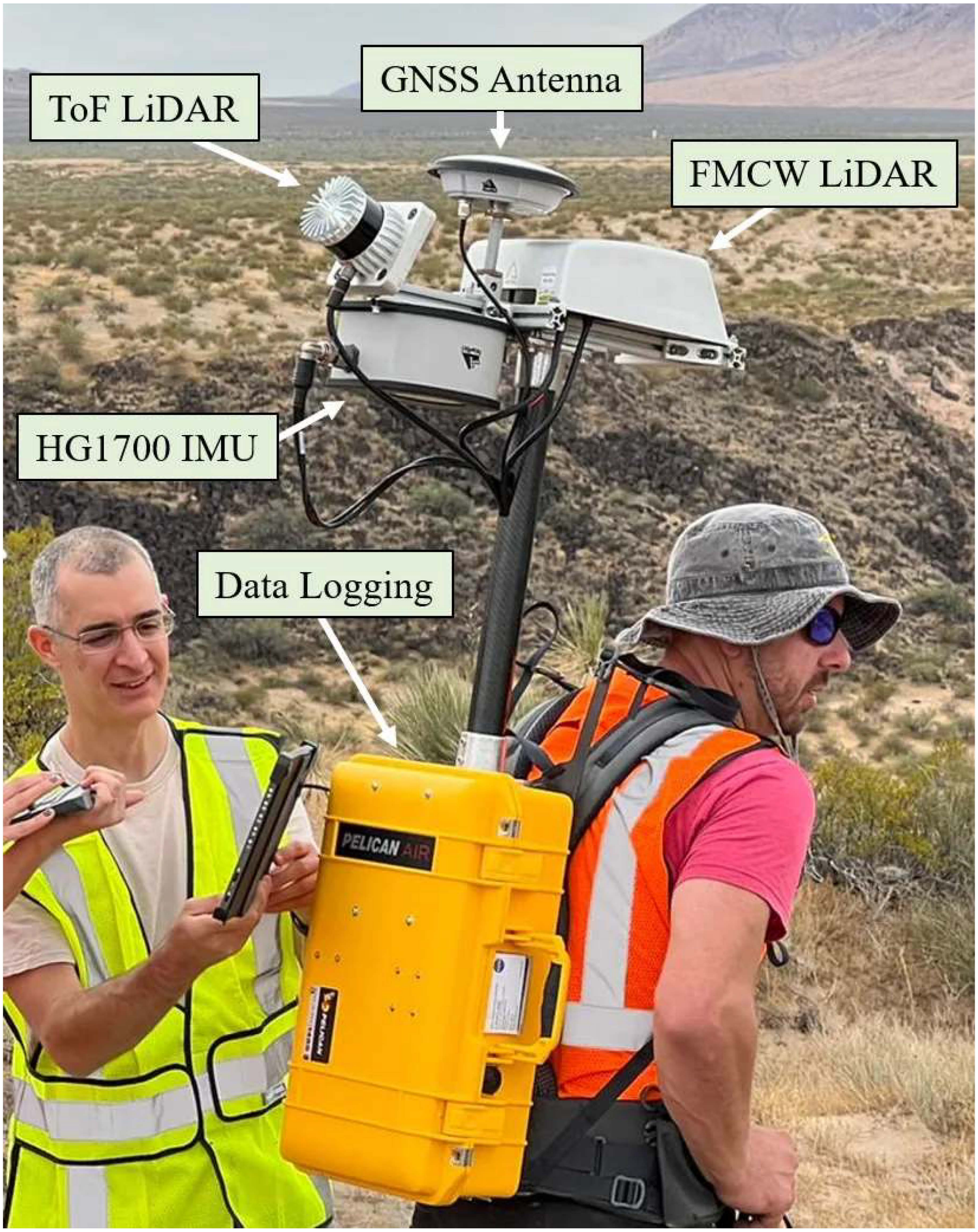
While several potential solutions exist for solving the planetary surface navigation problem, one that provides promise for operation in the widest variety of terrains and environmental conditions is LiDAR-based [1] Simultaneous Localization and Mapping (SLAM). Not only can such a LiDAR-based SLAM system 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.

BACKGROUND

The KNaCK Test Article

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 the following sensing instruments:

1. A range and velocity-sensing FMCW LiDAR
2. A range-sensing time-of-flight (ToF) LiDAR
3. A tactical grade inertial measurement unit (IMU)
4. Two MEMS grade IMUs
5. A GNSS/INS package (for ground truth reference data)



The SLAM Development Approach

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.

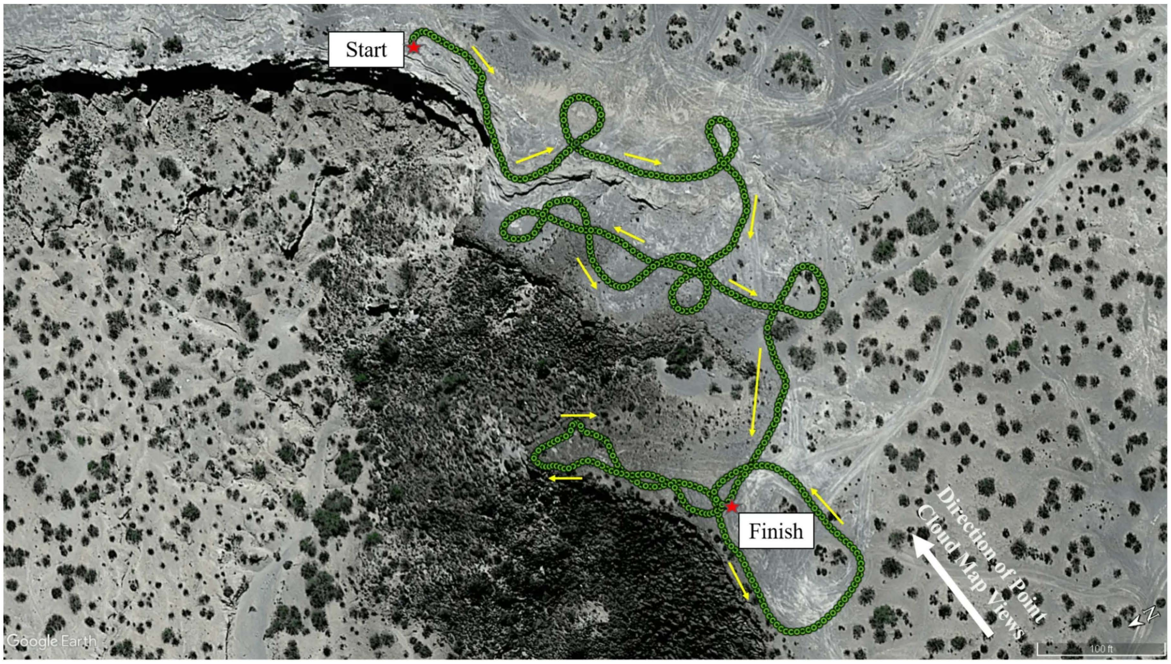
The KNaCK-SLAM Ancestor

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 g2o general graph optimization framework [5] and includes loop closure detection.

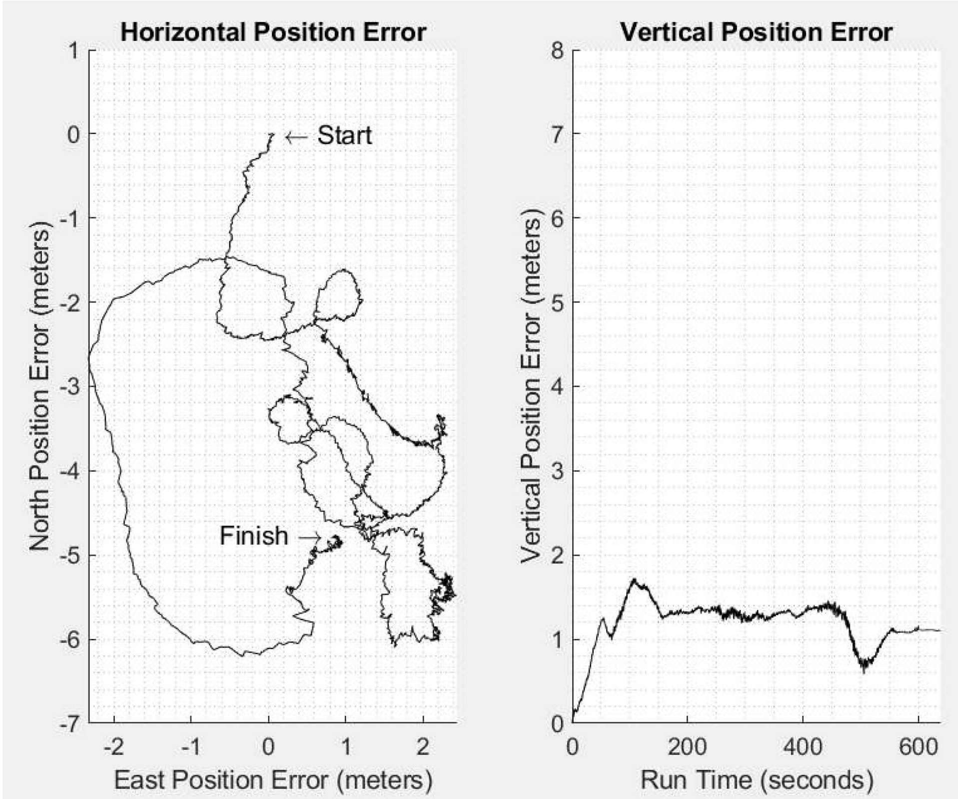
KNACK-SLAM SHOWCASE

Pose Estimation

Pose estimation is the portion of the SLAM algorithm dealing with navigation, determining the position and orientation of the backpack system. Because the KNaCK test-article is equipped with a GNSS/INS system for accurate ground truth position and orientation (centimeter and arcminute accuracy, respectively), the GPS-denied SLAM pose estimates can be compared directly to ground "truth" and errors can be computed. A GNSS/INS "truth" ground track for data collected by KNaCK at Kilbourne Hole in New Mexico is shown below.



The following plot shows position errors for a GPS-denied SLAM run using the same Kilbourne Hole dataset but with GNSS/INS disabled.

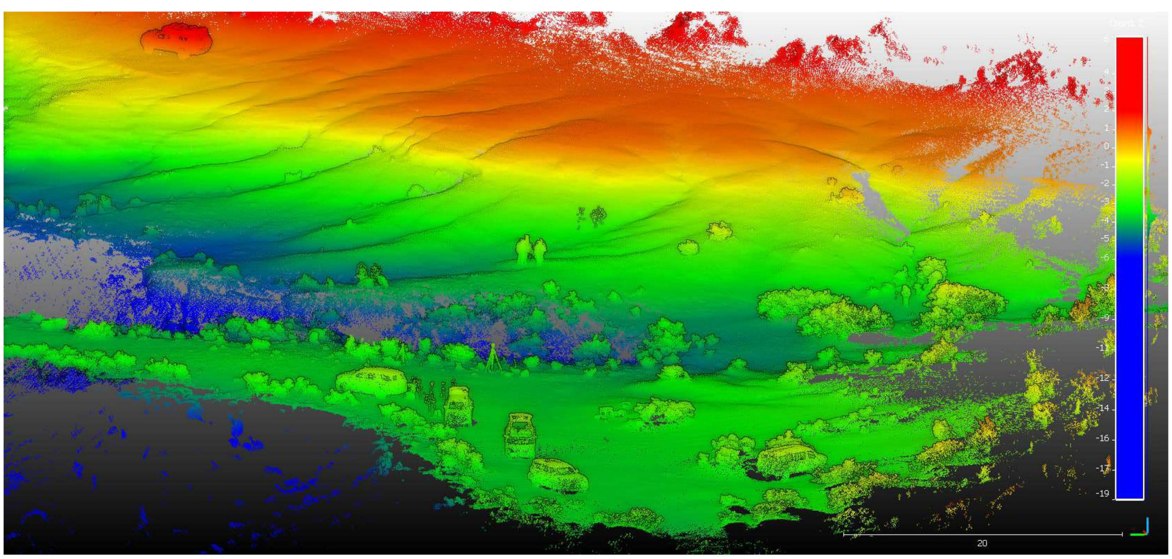


The GPS-denied position accuracy for this dataset is very good. Less than 6 meters of total RSS error is accumulated over the 600+ seconds of SLAM operations. While this SLAM performance is good, it will be improved in the future with continued exploration of loop closure, Doppler-velocity aiding, and alternative scan-matching schemes.

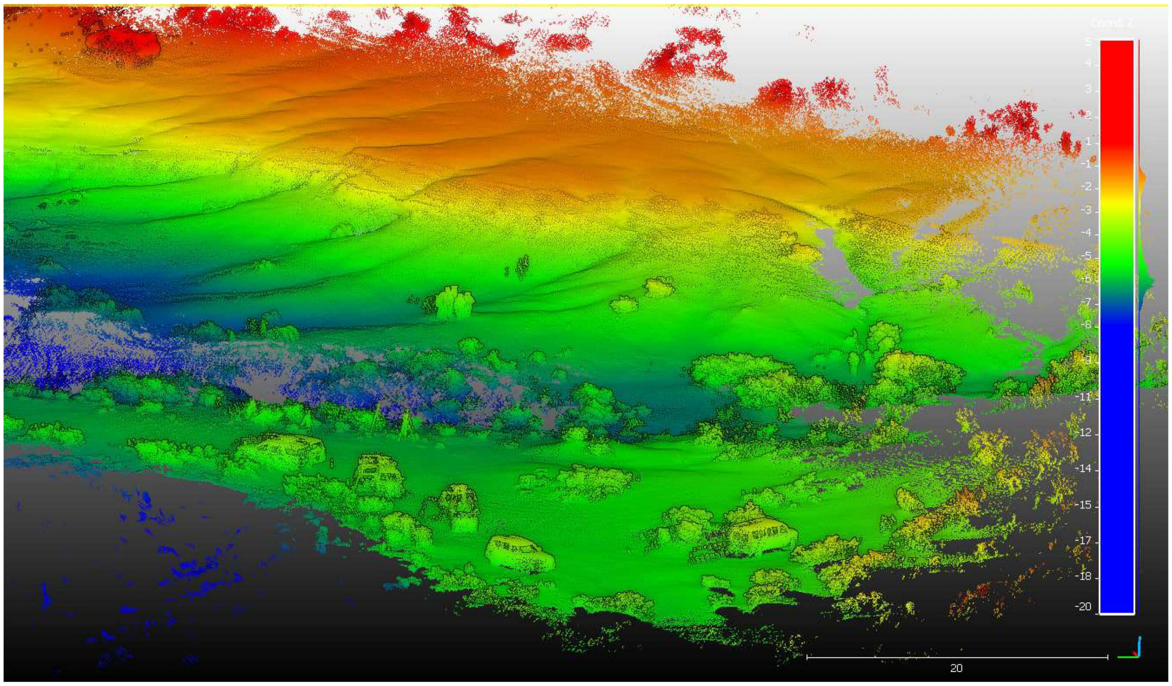
Mapping

Mapping is the portion of the SLAM algorithm concerned with generating a 3D point cloud map of the environment. For the same Kilbourne Hole dataset mentioned in the previous section, GPS-enabled and GPS-denied maps are displayed below.

GPS-Enabled:



GPS-Denied:



As becomes evident from closely comparing the two maps visually, the GPS-denied map of this mostly unstructured environment is less accurate in certain areas than the GPS-enabled map. However, the GPS-denied mapping performance is considered good and useful for certain geological scientific investigations. While GPS-enabled LiDAR mapping solutions are generally a better representation of the landscape, the main thrust of this project is to enable LiDAR mapping in locations where GPS is unavailable.

KNACK-SLAM

The Requirements Driving KNaCK-SLAM Development

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 use 3d velocity as an aiding measurement.

KNaCK-SLAM Implementation

1. 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.
2. *GPS-denied SLAM* in unstructured environments such as dunes, craters, and cave systems presented a unique challenge in the development of the KNaCK-SLAM algorithm. The existing scan-matching algorithms in Li-SLAM-ROS2 offered insufficient accuracy and speed when the KNaCK system was taken into unstructured terrain. In fact, it was common that the individual scan-to-scan 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.
3. *GPS-denied scan-matching* within the complex and quick dynamical regime 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.
4. The final notable improvement associated with KNaCK-SLAM-ROS2's *GPS-denied* functionality is the ability to fuse velocimetry with LiDAR inertial odometry. This was acheived by adding a velocity factor to the GTSAM sensor fusion section of the SLAM algorithm.

CONCLUSIONS

Forward Work

There are four areas where future work will be focused.

1. Reduction of scan-matching drift, which is especially high during significant yaw maneuvers with the backpack.
2. Assessment of velocity-aided performance of KNaCK-SLAM with real-world data after addressing FMCW LiDAR hardware hurdles.
3. Exploration of loop closure techniques with KNaCK-SLAM, as the current performance of loop closure detection and correction is insufficient.
4. Improvement of slow and inefficient parts of KNaCK-SLAM-ROS2 to make it useful for live real-time SLAM.

Final Thoughts

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 dynamical regime and unstructured environments.

AUTHOR INFORMATION

Kyle Miller (Kyle.Miller@nasa.gov) received his B.S. in Aerospace Engineering from Embry-Riddle Aeronautical Univ. (2017). He joined NASA's Marshall Space Flight Center in 2018. While at NASA, he has worked on several projects in the areas of Mission Design and Guidance, Navigation, and Control. Recently, his work has focused on Lunar descent and surface navigation, as well as solar sail mission design, navigation, and momentum management.

ABSTRACT

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. This work explores the use of LiDAR-based Simultaneous Localization and Mapping (SLAM) to solve those problems.A LiDAR-based SLAM system be deployed as a self-contained instrument independent of external sensor inputs, and can 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.

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