ROBUST NAVIGATION FOR AUTONOUMOUS EXPLORATION OF EXTREME ENVIRONMENTS FROM A FREE-FLYING PLATFORM.

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Introduction: Permanently shadowed regions and lava tubes on the Moon are sites of considerable geological interest, and hold the potential for in-situ resource utilization and future human habitation. However, these domains present daunting challenges to exploration and sampling. Free flying vehicles have the mobility to explore such environments but require robust and precise navigation for advanced autonomy. Astrobotic is developing these capabilities under a Phase II NASA STTR contract to enable high impact science and exploration on the Moon (Fig. 1).

Figure 1: Free-flyer exploration concept for extreme environments.

Sensing: Robust, high-rate GPS-denied navigation is required for autonomous exploration of lava tubes and caves and presents unique challenges. On the surface, detailed maps are unavailable, but the surrounding terrain is illuminated and allows for visual navigation. Conversely, underground there is little-to-no light, but the craft will be surrounded by rich geometric surfaces. Astrobotic is developing a solution that fuses LiDAR and visual sensing such that precision navigation is maintained during the transition from light to dark and back. A sensor package combining stereo global shutter image sensors and a Velodyne VLP-16 LiDAR is used to develop and test these capabilities, and sensor measurements are precisely synchronized and collected with a custom sensor interface controller.

Navigation: With a factor graph-based simultaneous localization and mapping (SLAM) formulation, these different navigation modalities are robustly fused. A requirement for drift of < 5% of distance traveled ensures that the free-flyer can safely exit after exploring the cave. Image feature observations are triangulated with stereo cameras and tracked between images with optical flow. LiDAR scan features are registered using LOAM [1] and then processed to generate relative pose measurements. An iSAM2 [2] incremental smoothing backend efficiently fuses these measurements into a coherent, low-drift pose estimate.

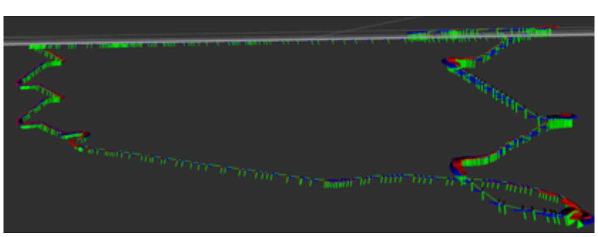

Figure 2: Example indoor navigation capability: side view of a 130-m path that travels down and back up one story.

Field Testing: Robust navigation is being tested with indoor, urban, and cave datasets (Fig. 2). Continuous testing ensures robustness while accuracy and performance are improved. A navigation drift rate of less than 1% has been achieved in a variety of scenarios with LiDAR, visual, and combined LiDAR-visual navigation [3]. For field validation, these algorithms are being deployed on a terrestrial hexcopter (Fig. 3). With integrated high performance computing, all navigation, exploration, and mapping is performed onboard.

Future Work: By Fall 2018, navigation algorithms will be field tested in a realistic skylight entry scenario. The terrestrial hexcopter, with an onboard sensing and computing payload, will autonomously take off from a base station, navigate to a cave entrance, and enter, map and explore the cave, before returning to the base station. Future tests may also incorporate lightweight sampling equipment and validate the full free-flyer mapping and sample collection concept of operations.

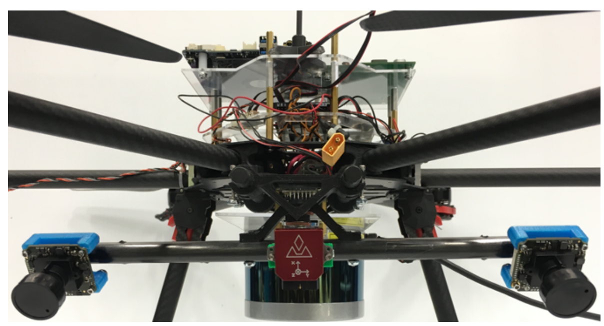

Figure 3: Hexcopter sensing and computing platform.

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References: [1] Zhang J. and Singh S. (2014) *RSS X*. [2] Kaess M. et al. (2012) *IJRR*. [3] Snyder K. et al. (2017) *IEEE IPSN*. [4] Tabib W. et al. (2016) *IEEE IROS*. [5] Tabib W. et al. (2016) *IEEE SSRR*.