MONOCULAR VISUAL-INERTIAL ODOMETRY WITH DYNAMIC LIDAR SCALING FOR SAFE AND PRECISE LANDING ON UNMAPPED PLANETARY BODIES

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Abstract. Safe and precise deorbit, descent, and landing operations require robust navigation capabilities that are reliable across extremes of sensor measurements. This work introduces a monocular visual-inertial odometry solution aided by range measurements from altimetry for high altitude localization and nadir-pointed imaging LiDAR during the landing phase. This system has been developed to investigate advanced landing capabilities that would enable future landed missions to icy moons without the need for precursor orbital missions to map these distant bodies, which would reduce time, cost, and complexity of potential future missions.

Introduction. Prior work at Astrobotic has developed AstroNav, a real-time, high-rate, multi-sensor simultaneous localization and mapping (SLAM) suite designed for navigation in GPS-denied environments. The system was initially designed to provide robust visual- and LiDAR-inertial relative navigation and mapping of complex domains such as subterranean caves and other planetary voids, including skylights, that present dramatic variations in scene lighting and structural complexity. We have achieved promising results with this configuration and have demonstrated its performance in several GPS-denied flights on uncrewed aerial vehicles (UAVs) in terrestrial applications for commercial clients and research partners. Astrobotic’s LiDAR mapping technologies have recently been used for planetary geology studies in icy lava tubes near the Apollo training grounds in Lofthellir, Iceland (Fig. 1).

Astrobotic is presently developing additional navigation capabilities for high-altitude and deorbit, descent, and landing (DDL) operations. Current mission architectures involving safe and precise landing rely on precursorman missions (e.g., terrain relative navigation techniques for Mars 2020) or significant data gathering phases (e.g., OSIRIS-REx asteroid mission) to generate maps used to refine navigation performance. Either option results in increased time, cost, and complexity. Astrobotic is targeting capabilities that would reduce the need for extensive prior mapping for navigation and safe landings. Landing systems capable of navigating without using a priori maps are particularly important for future missions to icy moons, like Saturn’s Enceladus, where the surface and sites of interest, such as geysers, could change between the time data is collected and when the spacecraft initiates landing. An overview of the concept of operations is shown in Fig. 2.

Precision DDL operations typically integrate an inertial measurement unit (IMU), a low-noise visual sensor, and a complementary sensor, such as a range altimeter, doppler velocimeter, or imaging LiDAR to generate usable scale estimates. In this paper, we present a high level overview of Astrobotic’s monocular high-altitude vision processing, imaging LiDAR data incorporation, and the simulation environment developed to evaluate performance. Tentative directions for future iterations are also discussed.

Related Work. A recent review of current monocular visual-inertial odometry (VIO) techniques benchmarked performance of several current algorithms, including OKVIS, MSKCF, SVO, and VINS-Mono, paired with backend optimizers employing filtering, smoothing, and full bundle adjustment solutions. Results were gathered using compute platforms ranging from ARM Cortex A8 to desktop processors. In their findings, SVO combined with an incremental smoothing backend based on iSAM2 had the lowest total processing time across platforms as well as the lowest variance in memory and CPU usage. These results corroborate the performance of our developed system, also based on an iSAM2 incremental smoothing backend. This level of performance is especially important for free-flying vehicles in terrestrial applications, which have limited battery power and processing, or planetary applications with constrained computing. Other approaches with similar performance required greater computation, incorporated active initialization not feasible in DDL scenarios, or provided odometry estimates that were not reliably smooth.

Monocular Visual-Inertial Odometry. Our monocular vision pipeline employs keyframe-based localization with sparse features and Lucas-Kanade optical flow tracking is used to record the motion of these features through subsequent frames. New keyframes are generated when the number of tracked features from the previous feature set can be found within a set of features tracked through a window of recent frames. An estimation of 3D camera motion is made by minimizing the error between the 3D location estimate of tracked features in pixel space. Recovery of camera ego-motion for state estimation remains challenging for monocular camera methods, but current approaches to this problem have expanded to include factor graph methods. In a factor graph odometry framework, nodes represent poses and/or landmarks and graph edges that connect nodes represent sensor measurements and other information that constrains the connected poses. Due to inconsistency of measurements from sensor noise and unmodeled factors, finding a graph configuration that is most consistent with measurements
is approached by finding the solution of a large error minimization problem. In our solution, this factor graph implementation is incrementally smoothed using iSAM2. This makes real-time operation possible through the optimization of only the most recently updated portions of the navigation solution rather than reconciling the full solution upon the addition of each keyframe.

**Nadir-pointed Imaging LiDAR.** Many imaging LiDAR sensors provide an adjustable tradeoff between operational range and data resolution or field of view. At the highest operational altitudes, imaging LiDARs may provide single range measurements or otherwise reduced resolution data as compared to lower altitudes.

In our system, a single range measurement enables the introduction of a coarse scale correction to the inherently up-to-scale visual odometry estimates. Small frame-to-frame displacements in feature locations correspond to relatively large vehicle motion at high altitudes, while the same measurements are associated with less motion at low altitudes. This range measurement provides a metric scale for the relative odometry estimates, and the quality of this scale factor can be improved at lower altitudes using increased imaging LiDAR resolution.

At lower altitudes, the tradeoff between power draw and imaging LiDAR resolution allows for higher resolution data at each measurement. Incorporating the LiDAR data into the monocular odometry solution requires registering the imaging LiDAR to the camera frame, and assigning a depth estimate to each discovered visual feature based on nearby range estimates projected into the camera frame (Fig. 3). This depth is then used to scale the estimated feature locations in the global coordinate frame.

Astrobotic has previously been deployed on custom sensor packages outfitted with stereo cameras and a horizontally-oriented multi-channel 360° scanning LiDAR in low-altitude and subterranean terrestrial environments. For high-altitude applications, a nadir-pointed system is more appropriate as it provides dense information in the landing-relevant area below the vehicle. Our Astrobotic navigation and mapping solution uses a scanning LiDAR that leverages the LOAM algorithm. LOAM performs LiDAR-based odometry by determining edges, surfaces, and features within a reconstructed point cloud of data and tracks them over time to produce a motion estimate and environment map. At altitudes where sufficient imaging LiDAR resolution is available, these same methods of point cloud feature extraction and tracking can be extended for use on planar data, thus enhancing navigation, mapping, and precision landing capabilities.

**Simulation Environment.** A simulation environment for testing algorithm performance was developed based on the open source software Unreal Engine 4 and Microsoft AirSim. A high fidelity visual simulation environment has been created that realistically represents the expected landscape of an icy moon such as Enceladus. Clouds and Earth-specific atmospheric effects have been removed, leaving terrain characterized by rocky mountainous regions, snow, and ice (Fig. 4). The simulation enables high altitude flight, up to several kilometers above the surface depending on the dynamics expected. Actual lunar landing trajectories have been leveraged to provide realistic paths for the simulated spacecraft. A simulated sensor suite, including nadir-pointed imaging LiDAR, nadir-pointed camera, and IMU is used for algorithm development and testing for high altitude descent phases and lower altitude divert maneuvers that might be employed during hazard avoidance.

**Discussion.** Precision landing and hazard avoidance capabilities enable successful landing in uncertain environments, including unmapped planetary bodies. Ongoing work entails building a precision map onboard during descent and navigating with respect to that map using environmentally appropriate sensors. This extends navigation capability by identifying hazardous areas, selecting safe landing sites, and guiding the spacecraft to a suitable target.

Astrobotic is actively developing hazard detection and avoidance modules to construct and refine a 3D representation of the ground and potential landing sites (Fig. 5), taking into account aspects such navigational error. Astrobotic has previously demonstrated hazard avoidance software on helicopter and Masten Zombie VTOL test flights along with terrain relative navigation (TRN). Portions of the hazard detection software stack have been rewritten and others have been modified to incorporate hazard detection as an optional capability within the AstroNav framework. This module depends only on incoming LiDAR data and spacecraft pose to produce local hazard maps and can work with scanning as well as imaging LiDAR models. Other components for this work include a precision SE(3) tracking controller and a successive convexification guidance manager, that could offer accurate estimates of the position, attitude, and velocity during complex maneuvers and generate trajectories minimizing flight time and fuel usage. With the AstroNav framework and improved guidance and control modules, Astrobotic continues to develop the foundations of a robust and efficient guidance, navigation, and control stack, and remains focused on realizing new capabilities for space-relevant hardware.

**References.**


Figure 1. LiDAR point cloud collected during GPS-denied flight testing in the Lofthellir lava tube overlaid on an aerial image of the skylight entrance to the lava tube.

Figure 2. Concept of operations overview for precision landing on a previously unmapped body.

Figure 3. Imaging LiDAR method of applying an accurate scale to each detected visual feature. Blue points represent LiDAR depth measurements. Red and green points represent features that have been detected once and multiple times, respectively. Pink lines connect each visual feature with the nearest LiDAR depth measurement.

Figure 4. Simulation environment used for simulating DDL on a rugged snow-covered surface.

Figure 5. Examples of two LiDAR-derived hazard metrics, which are computed in an integrated hazard module in the AstroNav framework. The left image depicts a terrain induced slope metric, which approximates the angle of a lander vehicle at each point. The right image is computed from the same imaging LiDAR sensor model sample and shows pointwise scores for where a vehicle may land based on ground clearance.