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Autonomous Multi-Floor Indoor Navigation with a Computationally Constrained Micro Aerial Vehicle

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I. INTRODUCTION

We are interested in the problem of surveilling and exploring environments that include both indoor and outdoor settings. Aerial vehicles offer mobility and perspective advantages over ground platforms and micro aerial vehicles (MAVs) are particularly applicable to buildings with multiple floors where stairwells can be an obstacle to ground vehicles. A challenge when operating in indoor environments is the lack of an external source of localization such as GPS. For these reasons, in this work we focus on autonomous navigation in buildings with multiple floors without requiring an external source of localization or prior knowledge of the environment. To ensure that the robot is fully autonomous, we require all computation to occur on the robot without need for external infrastructure, communication, or human interaction beyond high-level commands. Therefore, we pursue a system design and methodology capable of autonomous navigation with real-time performance on a mobile processor using only onboard sensors (Fig. 1); where in this work autonomous navigation considers multi-floor mapping with loop closure, localization, planning, and control.

We note that the topic of autonomous navigation with a MAV is addressed by others in the community with some similarities in approach and methodology. Relevant to this paper is the work of Bachrach et al. [1, 2], Grzonka et al. [3], and Blösch et al. [4] with results toward online autonomous navigation and exploration with an aerial vehicle. The major points of differentiation between existing results and our work are threefold. First, all the processing is done onboard requiring algorithms that lend themselves to real-time computation on a small processor. Second, we consider multi-floor operation with loop closure. Third, we design adaptive controllers to compensate for external aerodynamic effects which would otherwise prohibit operation in constrained environments.

II. METHODOLOGY AND RELATED LITERATURE

The discussion follows the logical flow of the system design (Fig. 2). The six degree-of-freedom (DOF) pose of the robot is defined by its 3D position, roll, pitch, and yaw Euler angles, $\{x, y, z, \phi, \theta, \psi\}$.

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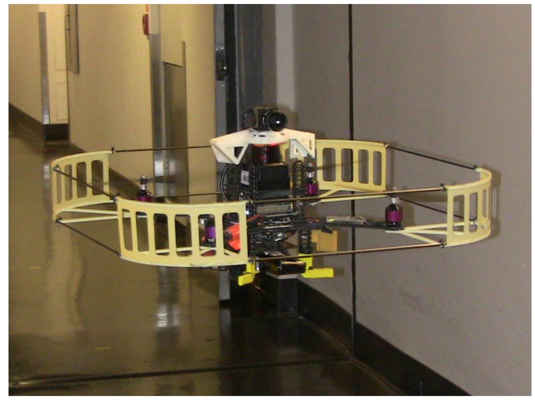

Fig. 1. The experimental platform with onboard computation (1.6 GHz Atom processor) and sensing (laser, camera, and IMU).

A. Pose Estimation

A scanning laser range sensor retrofitted with mirrors for beam redirection to the floor and ceiling serves as a primary source of information for position and yaw estimation. We evaluated several laser-based methods for pose estimation such as exhaustive search [5] and feature-based approaches [6, 7]. However, because our limited onboard computational resources, we chose the Iterative Closest Point (ICP) algorithm [8], which yields a robust and inexpensive continuous pose estimate. We make use of a grid based search [9] to speed up the computationally expensive closest point search in ICP. The result of the ICP algorithm is an estimate of $\{x, y, \psi\}$. The algorithm implementation is able to run at 20 Hz and requires approximately 20% of the total CPU time of the onboard processor.

We extend the method of [3] to fuse IMU data with redirected laser scans to provide altitude estimation and detect multi-floor structures. The remaining state variables, $\{\phi, \theta\}$, are estimated using the onboard IMU.

B. Simultaneous Localization and Mapping

We address the problems of mapping and drift compensation via an incremental simultaneous localization and mapping (SLAM) algorithm. Given the incremental motion of the robot provided by ICP-based scan matching and the IMU, we correct the error in $\{x, y, \psi\}$ by aligning incoming laser scans against the existing map using a windowed exhaustive grid search. If a stable floor transition is detected by the pose estimator, we create a new layer in a multi-layered occupancy grid. The incremental SLAM algorithm runs at 10 Hz and consumes less than 30% of the total CPU time.

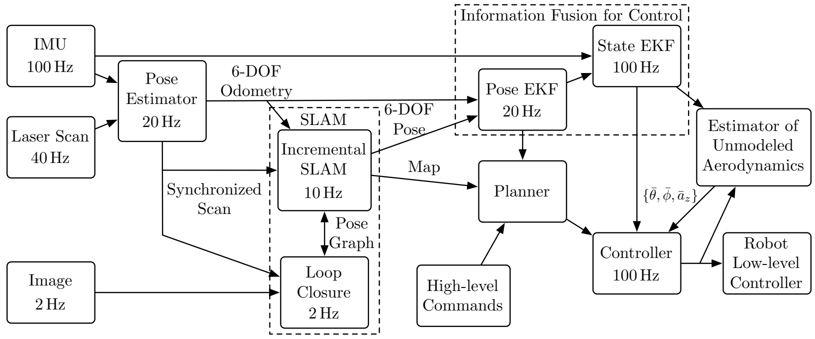

Fig. 2. Architecture diagram showing the important software modules with update rates.

To correct the global inconsistency caused by incremental SLAM, we employ vision-based techniques to enable robust loop closure detection that does not depend on the actual pose estimation error [10]. Loop closures add constraints to a pose graph, where each node in the graph is a sparse sample of the robot poses and their associated sensor data. Akin to the methods of [11], we apply an optimization based on an Iterative Extended Kalman Filter (IEKF) to create a globally consistent pose graph configuration. The optimization occurs in the full 6-DOF pose space with the assumption that closure only happens at the same floor level. We also use approximations that further speed up the optimization.

C. Information Fusion for Control

To ensure high-rate, accurate, and drift-free pose estimates for feedback control, we use two separate Extended Kalman Filters (EKF) to fuse and boost the pose estimate to 100 Hz. The first EKF combines the 20 Hz pose estimate and the 10 Hz SLAM pose correction. The second EKF combines the 20 Hz pose estimate from the first EKF and the 100 Hz IMU data to provide 100 Hz pose and linear velocity estimates in world frame.

III. Experimental Results

A. Experiment Design and Implementation Details

Three experiments are presented: (1) navigation across two floors in an indoor environment; (2) navigation starting in the same environment and transitioning to the outdoor periphery; and (3) a large two-floor loop.

The robot platform is sold by Ascending Technologies, GmbH [12] and is equipped with an IMU (accelerometer, gyroscope, magnetometer), pressure sensor, camera, and laser. The experiment environment includes three buildings and a courtyard in the School of Engineering and Applied Science at the University of Pennsylvania. See the attached video for more details.

B. Indoor Navigation across Multiple Floors and Outdoors

We consider autonomous navigation between multiple floors in an indoor environment. Additionally, we consider the case when a robot exits the indoor environment into the surrounding area.

C. Closing Large Multi-floor Loops

The final experiment seeks to push the limits of the onboard processing and demands non-trivial loop closure across multiple floors. To pursue a large scale experiment with a length that exceeds feasible flight time, we carry the vehicle such that it emulates flight.

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