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RANGE - Robust Autonomous Navigation in GPS-denied Environments

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Abstract— **This video highlights our system that enables a Micro Aerial Vehicle (MAV) to autonomously explore and map unstructured and unknown GPS-denied environments. While mapping and exploration solutions are now well-established for ground vehicles, air vehicles face unique challenges which have hindered the development of similar capabilities. Although there has been recent progress toward sensing, control, and navigation techniques for GPS-denied flight, there have been few demonstrations of stable, goal-directed flight in real-world environments. Our system leverages a multi-level sensing and control hierarchy that matches the computational complexity of the component algorithms with the real-time needs of a MAV to achieve autonomy in unconstrained environments.**

I. INTRODUCTION

Micro Aerial Vehicles (MAVs) present an appealing platform for applications such as search and rescue, civil engineering inspection, and a host of military tasks where it is dangerous or difficult to send people. Enabled by GPS and MEMS inertial sensors, MAVs in outdoor environments have achieved advanced levels of autonomy. Unfortunately, most indoor environments and many parts of the urban canyon remain without access to external positioning systems such as GPS. Autonomous MAVs today are thus limited in their ability to fly through these areas. Simultaneous localization and mapping (SLAM) algorithms build a map of the environment around the vehicle while using it to estimate the vehicle's position. Although there have been significant advances in developing accurate, drift-free SLAM algorithms in large-scale environments, these algorithms have focused almost exclusively on ground or underwater vehicles. In contrast, attempts to achieve the same results with MAVs have not been as successful due to a combination of limited payloads for sensing and computation, coupled with the fast and unstable dynamics of the air vehicles.

To stabilize the fast dynamics of the MAV, both the state estimation and planning algorithms must ensure that accurate estimates of the vehicle's velocity are available at all times. This is in contrast to their ground robot counterparts, where simply estimating position tends to be sufficient. In addition, the velocity estimates must be computed with low delay, limiting the amount of temporal smoothing that can be performed on noisy measurements. After analyzing the design constraints, we developed a vehicle, shown in Figure 1, that is able to autonomously explore GPS-denied indoor environments using only onboard sensing.

Note that this video describes the capabilities of our platform at a high level; for a more detailed system description, we refer the reader to [1].

Fig. 1. Our quadrotor helicopter. Sensing and computation components include a Hokuyo Laser Rangefinder with laser-deflecting mirrors for altitude, a pair of stereo cameras, a monocular color camera, an IMU, and an Intel Atom based flight computer.

II. RELATED WORK

Autonomous flying robots capable of GPS-denied flight have become an area of increasing research interest. There have been numerous efforts to fly helicopters autonomously indoors using monocular camera sensors. [2] detects lines and [3] tracks corners on the floor of a hallway to localize the vehicle in office environments with known structure. These authors have demonstrated autonomous flight in indoor environments; however, they are constrained to limited environments with specific features, and thus may not extend to general GPS-denied environments. [4] extracted corner features that are fed into an EKF-based Vision-SLAM framework, building a low-resolution $3D$ map sufficient for localization and planning. However, an external motion capture system was used to simulate inertial sensor readings.

The system shown in our video builds on previous work in [5], where we present a planning algorithm for a laser-equipped quadrotor helicopter that is able to navigate autonomously indoors with a given map. We have extended the work by developing a system that is able to perform navigation, localization, mapping, and autonomous exploration *without* a prior map.

Recently, [6] designed a quadrotor configuration that was similar to the one presented in [5]. [6] used particle filter methods to globally localize their helicopter with a precomputed map that was generated by a ground-based robot. Unfortunately, they did not present experimental results demonstrating the ability to stabilize all 6 *dof* of the helicopter autonomously using onboard sensing.

III. SYSTEM OVERVIEW

Our quadrotor helicopter, shown in Figure 1, is the AscTec Pelican manufactured by Ascending Technologies GmBH. We outfitted the barebones vehicle with both laser and camera sensors, which allows us to obtain accurate information about the $3D$ environment around the vehicle.

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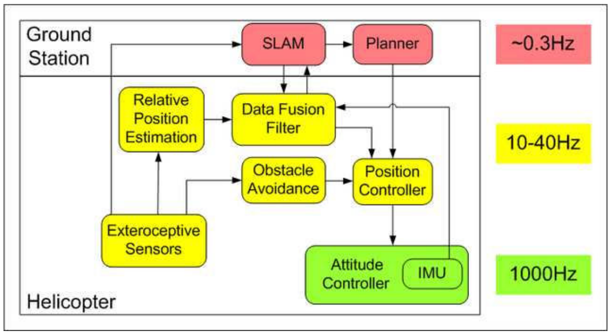

Fig. 2. Schematic of our hierarchical sensing, control and planning system. At the base level, the onboard IMU and controller (green) create a tight feedback loop to stabilize the vehicle's pitch and roll. The yellow modules make up the real-time sensing and control loop, which stabilizes the vehicle's pose at the local level and avoids obstacles. Finally, the red modules provide high-level mapping and planning functionality.

The AscTec Pelican is equipped with attitude stabilization, using an onboard IMU and processor to stabilize the helicopter's pitch and roll [7]. This tames the nastiest portions of the quadrotor's extremely fast, nonlinear, and unstable dynamics, allowing us to focus on stabilizing the remaining degrees of freedom in position and heading. The onboard controller allows the helicopter's dynamics to be approximated as a simple 2^{nd}-order dynamical system. We learn the parameters of the model by flying the helicopter inside a motion capture system while recording the pilot's control inputs and fitting the model parameters to the data using a least-squares optimization method. Using the Matlab® linear quadratic regulator (LQR) toolbox, we then find feedback controller gains for the dynamics model. Despite the model's simplicity, our controller achieves a stable hover with $6cm$ RMS error.

To compute the high-precision, low-delay state estimates needed for such hover performance, we designed the 3-level sensing and control hierarchy, shown in Figure 2, distinguishing processes based on the real-time requirements of their respective outputs. We use a very fast, accurate, and robust scan matching algorithm along with visual odometry [8] to generate estimates of the relative position of the vehicle. While scan matching algorithms have been used extensively on ground robots, MAVs require a much higher matching resolution to accurately estimate the vehicle velocities. This high resolution must be achieved while remaining computationally efficient to minimize delay. Our scan matching algorithm is able to achieve both of these performance goals to provide accurate, low delay relative position estimates. An extended Kalman filter (EKF) is used to fuse these relative position estimates with inertial measurements, estimating the full MAV state (including velocity). The accuracy of the resulting state estimates is evident in the stable flight demonstrated in the video, and the crisp shapes visible in the $3D$ point cloud shown in Figure 3.

With the MAV's fast dynamics stabilized in all 6 degrees of freedom on-board, we can leverage off-board SLAM algorithms originally developed for other platforms to close loops and create globally consistent maps. The SLAM process usually takes 1 to 2 seconds to process incoming measurements which means that it can run online, but cannot be directly incorporated into the real-time control loop. Instead the SLAM process periodically sends position corrections to the data fusion EKF to correct any drift in the relative position estimates.

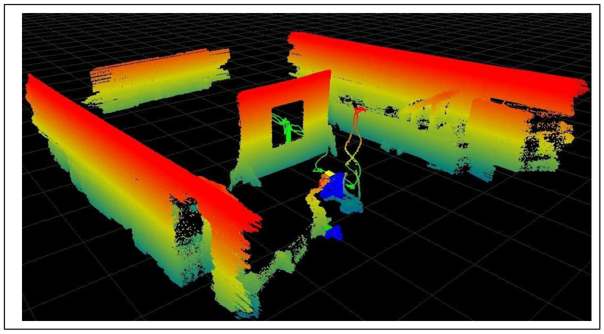

Fig. 3. A $3D$ point cloud generated by projecting the laser scans using the pose estimates computed by our system. The crisp outlines of the environment enable high level autonomous capabilities such as extracting and flying through the window in the middle of the point cloud.

We have tested the system in a number of large scale GPS-denied environments both indoors and outdoors in the urban canyon. The system has worked quite well in these test environments, as well as in our team's winning entry in the 19^{th} AUVSI International Aerial Robotics Competition. However, in all cases it is important to ensure that the paths taken by the vehicle are through areas with sufficient environmental structure for the relative position estimation algorithms, precluding it from extended flight in large open spaces or featureless hallways.

IV. CONCLUSION

In this video we demonstrate the advanced capabilities of our quadrotor platform. By reasoning about the key differences between autonomous ground and air vehicles, we have created a suite of estimation, control, and planning algorithms that accounts for the unique characteristics of air vehicles. The resulting system is capable of fully autonomous exploration in unstructured and unknown GPS-denied environments, relying solely on sensors onboard the vehicle. We have now achieved a stable platform that opens many potential avenues for future research in rich, $3D$ environments.

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