VIO-Swarm: An Autonomous Swarm of Vision Based Quadrotors

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Abstract—**In this paper, we present the system infrastructure for a swarm of quadrotors, which perform all estimation onboard using monocular Visual Inertial Odometry. This is a novel system since it does not require an external motion capture system or GPS and is able to execute formation tasks without inter-robot collisions. The swarm can be deployed in nearly any indoor or outdoor scenario and is scalable to higher numbers of robots. We discuss the system architecture, estimation, planning, and control for the multi-robot system. The robustness and scalability of the approach is validated in both indoor and outdoor environments with up to 12 quadrotors.**

Index Terms—**Aerial Systems: Applications; Swarms; Visual-Based Navigation**

I. Introduction

QUADROTORS equipped with on-board sensors are popular Micro Aerial Vehicles (MAV) due to their size, ability to hover, and navigate complex 3D environments. They can be used for a variety of applications ranging from inspection to search and rescue. Collaborative teams of quadrotors, or Swarms, are able to cover larger areas, gather more information, and are resilient to agent failure.

Previous Swarm implementations have relied heavily on external position feedback such as Motion Capture or Global Positioning Systems (GPS). While motion capture systems are able to provide high precision robot tracking [1]–[3], they confine operations to a tracked control volume and require a centralized computer to communicate to all robots. GPS information avoids the requirement of a central computer [4], yet suffers from a lack of precision ($\sim$2 m) and is prone to interference in indoor settings, limiting swarms using GPS to remain spaced far apart and only operate outdoors.

Visual Odometry offers an alternate solution in which robots localize by perceiving their environment with cameras. By performing localization onboard, robots do not rely on a central source of information to operate. Visual Odometry can provide precise estimation ($\sim$10 cm) without boundaries in both indoor and outdoor environments.

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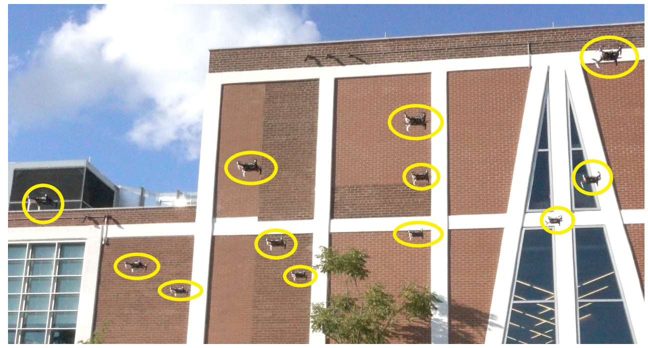

Fig. 1: The VIO Swarm during outdoor flight without the use of GPS or External Motion Capture system.

Previous vision-based multi robot systems have created operating zones with fiducial markers placed in the environment to guide robot localization and obstacle avoidance [5]. Others perform relative localization with markers placed on vehicles [6]. Cooperative mapping using loop closure and heavy inter-robot communication were performed in [7].

This work builds from the previous work [8] which was a first attempt at a vision based autonomous swarm. Yet we utilize a commercially available vehicle platform which can execute agile motions as presented in [9] by performing Visual Inertial Odometry (VIO) with the Multi-State Constraint Kalman Filter (MSCKF) algorithm.

The VIO-Swarm leverages advancements in vision based MAVs and extends them to multi robot formation flight. The architecture used for controlling multiple vision based quadrotors can be scaled to larger swarm sizes and extended for future capabilities. This is the first time that perception, planning and control are combined for autonomous navigation of up to 12 quadrotors without relying on GPS or motion capture. Commercially available components were used and the source code is available online[1]. At the time of publishing, this is the largest swarm of autonomous quadrotors that does not rely on motion capture or GPS.

II. Vehicle Architecture

Shown in Fig. 2, the VIO-Swarm utilized a quadrotor platform used in past works on lightweight agile autonomous applications such as [9]. The platform was built around the Qualcomm® Snapdragon™ Flight computation board, and used commercially available components[2]. Each robot measured 32 cm tip-to-tip, weighed 250g, and had a flight time of 8 minutes.

[1] https://github.com/orgs/MultiRobotUPenn/dashboard
[2] https://worldsway.com/product/dragon-drone-development-kit/

Fig. 2: Qualcomm® Snapdragon™ Flight Platform shown on takeoff plate used to set starting location. Note that reflective markers are used only for post analysis.

A nonlinear controller based on [10] was used to model and control for large excursions from hover during rapid formation changes and high wind gusts.

Each robot estimated its 6DOF pose using monocular Visual Inertial Odometry (VIO) from the downward facing camera and IMU. This estimation only tracked relative displacement, so the robots started at known locations. As described in our recent work [9], two nested filters were used to achieve high quality tracking, as shown in Fig. 3. An EKF combining visual and IMU data provided initial pose estimates at 30Hz. Then, a UKF estimated the full state of each vehicle at 500Hz. This estimation method produced fast and computationally tractable pose estimates. However, it was prone to drift and errors in linear scale.

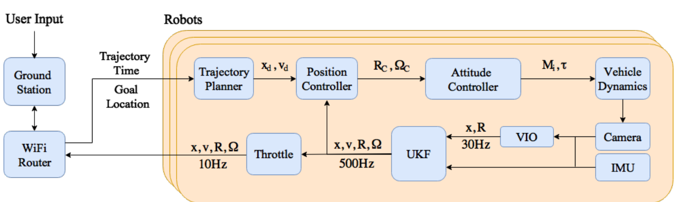

Fig. 3: Diagram of major system components.

III. System Architecture

Each robot ran a ROS[3] network to tie together a high level interface with low level estimation and control. The robots responded to ROS services to perform basic actions and to plan and execute trajectories. Odometry updates were published at a throttled 10 Hz on the network.

A Ground Station computer was used for user interface and centralized multi-robot coordination. The ground station distributed ROS services and published trajectory information via a 5 GHz WiFi network. Also, the Chrony NTP Suite[4] was used to synchronize system clocks.

The Centralized Concurrent Assignment and Planning of Trajectories Algorithm (C-CAPT) [3] was performed on the ground station to generate dynamically feasible, collision-free goal assignments for the robots. This planning ensured that robots maintained a minimum separation distance, which experimentally accounted for vehicle radius and odometry errors. After the ground station published individual goals and timing information, robots generated minimum jerk trajectories onboard to reduce bandwidth usage.

[3] http://www.ros.org

[4] https://chrony.tuxfamily.org/index.html

IV. Experimental Results

Indoor trials were performed using six robots flying in formation shapes such as rectangles, circles, and lines without colliding. A nominal inter-robot spacing of 0.6 m was utilized to account for tracking errors. For these experiments, chalk and colored tape were applied to the floor to provide ample features for tracking. Additionally, takeoff plates, shown in Figure 2 were used to initialize starting offsets.

In order to accommodate the full 12 robots of our swarm, the next set of trials were performed outdoors. The swarm performed similar formation changes as in the indoor trials, albeit with larger numbers, greater distances covered, higher speeds, uncontrolled lighting, and gusting wind. Performance of the swarm was slightly worse than during indoor trials due to the imprecision of takeoff locations on non-level ground. Footage from experimental trial is included in the accompanying video.

V. Future Work

The primary focus for future work is to increase the size of the swarm. This will involve decreasing vehicle size and improving relative odometry by incorporating multi-robot loop closure algorithms. These algorithms will require greater communication between the vehicles, presenting further research opportunities related to decentralized approaches with limited bandwidth. Next, a more robust method of initializing robot locations, such as a fiducial origin marker, should be added. Finally, behaviors allowing the swarm to respond to unknown environments should be built into the VIO-Swarm architecture.

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