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The Flying Machine Arena as of 2010

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Abstract— **The Flying Machine Arena (FMA) is an indoor research space built specifically for the study of autonomous systems and aerial robotics. In this video, we give an overview of this testbed and some of its capabilities. We show the FMA infrastructure and hardware, which includes a fleet of quadrocopters and a motion capture system for vehicle localization. The physical components of the FMA are complemented by specialized software tools and components that facilitate the use of the space and provide a unified framework for communication and control. The flexibility and modularity of the experimental platform is highlighted by various research projects and demonstrations.**

I. INTRODUCTION

Indoor research testbeds provide a protected environment for testing of new technologies and algorithms. They allow for repeatable results shielded from the hazards of testing outside. A recent trend is to equip such platforms with motion capture systems that track marked objects in real-time with millimeter accuracy, cf. [1]–[3]. This allows researchers to bypass the localization problem in order to concentrate on other topics such as on controls or on more sophisticated learning schemes.

We equipped a 1000 cubic meter indoor space with a commercial motion capture system. This is the Flying Machine Arena (FMA), a state-of-the-art experimental platform for research in aerial robotics and control. Most experiments in the FMA rely on small quadrocopters and aim to explore the physical and dynamical limits of both the vehicles and the overall control architecture. To support such research we are working to make the FMA platform as intelligent and convenient as practically possible, minimizing the overhead of managing the system and the vehicles.

The subsequent video summary[1] describes the platform's architecture including hardware, software, and networking components, cf. Section II. The development of the infrastructure was started in 2007 and, by now, has yielded various research results and demonstrations as shown in Section III.

Similar indoor testbeds for aerial robotics are currently found at the University of Pennsylvania [1] and at MIT [2].

II. SYSTEM OVERVIEW

The FMA testbed is the result of the integration of several modular hardware and software components.

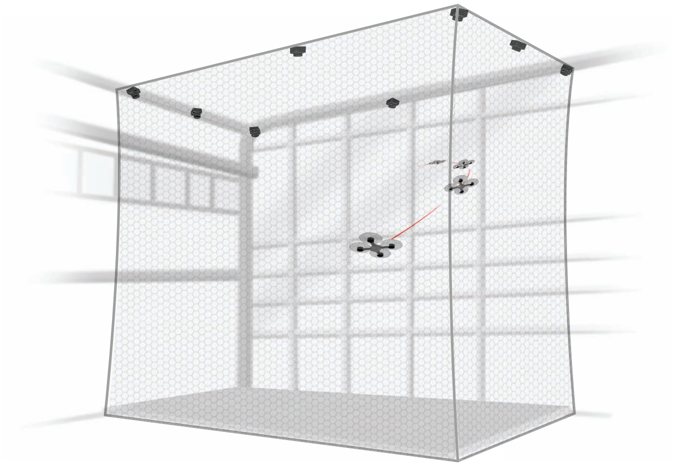

Fig. 1. Conceptual drawing of the Flying Machine Arena.

A. Airspace and Motion Capture Volume

The FMA airspace is a $10 \times 10 \times 10\,\mathrm{m}$ cube, see Fig. 1. Reinforced glass and net walls, along with padded flooring provide an enclosed and safe environment. The walls and the floor covering can be removed, allowing us to reconfigure the entire space for different purposes. An 8-camera Vicon motion capture system [4] provides position and attitude data for all appropriately marked vehicles at 200 Hz, with a latency of about 10 ms. Due to the size of our space, we developed a new camera calibration routine, where a quadrocopter flies around the space autonomously, using an existing but suboptimal calibration to collect data for a new one.

B. Quadrocopter Vehicles

The quadrocopter (Fig. 2) is characterized by its small size, light weight, and structural and electronic robustness, making it versatile and easy to operate. The base platform is a X3D 'Hummingbird' quadrocopter [5]. Measuring 53 cm in diameter, the vehicle's total weight is 460 g. The operational flying time varies between 10 (aggressive flight) and 25 (hover) minutes. Four brushless DC motors produce an upward acceleration of up to $12.5\,\mathrm{m/s^2}$.

Though the original propulsion system, the motor controllers and the frame of the standard X3D quadrocopter were preserved, the central electronics and onboard sensors were replaced to obtain better control over the onboard algorithms and to have access to better-quality and higher-range sensor data. These changes allow for more aggressive maneuvers, faster turn rates, and generally better flight performance.

The quadrocopter accepts collective thrust and angle or angle rate commands at 70 Hz. An onboard 800 Hz feedback

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[1] The video is available at `http://tiny.cc/fma2010`.

Fig. 2. Quadrocopter with retro-reflective markers.

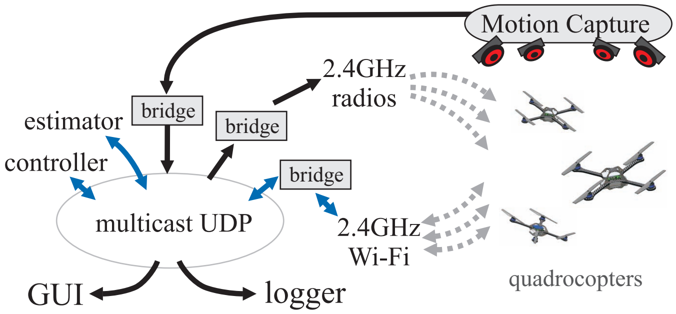

Fig. 3. Overview of the Flying Machine Arena testbed.

controller uses rate gyros to track the given commands. The vehicles learn propeller efficiency factors in flight to compensate for wear and changing flexible propeller properties. Each quadrocopter is equipped with two radio systems: a one-way 2.4 GHz module used exclusively for controlling the vehicle, and a bidirectional 2.4 GHz transceiver with a different modulation for non-time-critical communication such as data feedback or onboard parameter reads/writes.

C. Control and Communication

The overall organization of the system is illustrated in Fig. 3. The localization data provided by the motion capture system is sent to a network of off-the-shelf PCs, which then execute estimation and control components. These in turn send commands to the quadrocopters. The overall system time delay, from sending a vehicle command to detecting the corresponding effects in the vehicle's pose data, varies between 20 ms and 40 ms with a mean value of 30 ms.

Data is sent via a multicast UDP scheme, allowing for convenient online visualization of all data sent over the network, and also for recording, playback, and export of arbitrary customized data series. A convenient side-effect of this setup is that components are binary-identical when running in the real system or in simulation.

The vehicle's translational degrees of freedom are typically controlled by cascaded controllers designed for both near-hover and dynamic operation. To achieve trajectory tracking, a sequence of reference points is fed to the controller together with the appropriate feedforward commands. A utility called the 'Copilot' relays commands from controllers to the vehicles. It serves a dual purpose of protecting the vehicles from deadly controllers and of managing takeoffs, landings and charging.

More details may be found in [3].

III. RESEARCH AND DEMONSTRATIONS

First research dealt with basic control techniques for autonomous quadrocopter flight. Adaptive aggressive maneuvers were developed next [3], requiring several learning iterations in order to achieve reasonable performance. An ongoing project is to create rhythmic flight choreographies with multiple quadrocopters set to music [6], [7]. And, recently, a quadrocopter was able to balance an inverted pendulum [8].

In parallel, several interactive demonstrations with quadrocopters were developed as educational tools for explaining the fundamental concepts of feedback control to visitors.

IV. CONCLUSIONS AND FUTURE WORK

The FMA is a flexible research platform reconfigurable for different purposes. It features built-in and ready-to-use components such as a vehicle estimator, simulator, a hierarchical controller, the 'Copilot' for vehicle management and protection, and various communication interfaces. The testbed has been used to support various internal and external projects.

The Flying Machine Arena is under continued development with the ultimate goal of a fully automated platform that can be operated continuously and/or remotely. Recent research in the FMA includes ball-playing quadrocopters and the development of a ground vehicle.

V. ACKNOWLEDGEMENTS

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