Motion Capture Control of a Nano Quadrotor

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Abstract–Motion capture control of quadrotors is a relatively well known and established method of researching quadrotor flight dynamics. However, these capture systems are usually very expensive because they require many cameras, a large space, and relatively large quadrotors. In this project, we explore the viability of using a minimally sized motion capture camera setup to serve as a framework for autonomous flight of a quadrotor. The system that we utilize consists of four Optitrack Motion capture cameras, a Crazyflie 2.0 Nano-quadrotor, and a Pixhawk flight controller. The Optitrack cameras capture the precise position of the quadrotor within a predefined capture volume. The positional information is sent to a ground station computer via Ethernet. The positional data is then processed and sent wirelessly to the quadrotor. This system will serve as a proof of concept that smaller camera setups are viable, and provides basic guidelines for other research groups. In addition, the system will be used as the foundation for researching various control algorithms for quadrotors.

Keywords—engineering, quadrotors, motion capture, control

I. INTRODUCTION

There are four main methods for controlling a multirotor aerial vehicle or MAV: manual control, GPS based, on-board vision, and off board vision. The traditional method of flying a MAV is via manual control using a radio transmitter, shown in Figure 1. While this method gives the user absolute control of the MAV, it generally requires many hours of practice to reach high proficiency and even still it otherwise lacks the fine control and finesse needed in fast paced situations. Additionally, as the MAV moves farther away from the user, it becomes exponentially more difficult for the user to perceive changes in position without moving or using added visual aids. Another popular method of controlling MAVs is by using GPS programmed waypoints [1]. This method utilizes GPS sensors alongside a software interface which allows the user to select waypoints on a map and have the MAV fly through all of them without user input. While this is generally useful for large activities like surveying, it is not suitable for fine control tasks in small areas due to the large GPS margin of error.

On board vision systems can be used with or without GPS sensors [2] [3] [4] [5]. These systems utilize on-board cameras and sensors to gather as much environmental data as possible to help supplement the poor positional accuracy of GPS and to navigate smaller areas with potential obstacles. However, this method is very processing intensive and often requires a second on-board computer just to handle the visual and sensor data processing. This can be very taxing with respect to the weight and energy limitations of a MAV. The last method, as well as the focus of this paper, is off-board based vision control. This method provides similar functionality to all the methods mentioned above albeit to a much higher degree of precision and accuracy. In this case, all of the processing is performed by a computer separate from the MAV. Off board vision control is generally achieved using motion capture systems [6] [7] [8].

Figure 1: A Taranis X9D Plus radio transmitter [9].

A. *Previous Effort on Quadcopter Control*

Motion capture systems have been used for years to explore the capabilities of multirotor aerial vehicles, specifically quadrotors. The GRASP lab at the University of Pennsylvania is one of the groups at the forefront of this research. In 2011, the GRASP lab researchers were using VICON motion capture systems to research various methods to implement perching in a quadrotor [10] [11]. Seoul National University researchers used a single down facing optical sensor to implement position locking hover control of a micro-sized quadrotor without the aid of external positional aids (i.e., motion capture) [12]. In 2016, the Robotics and Perception group at the University of Zurich developed a quadrotor system to autonomously generate a live 3D map of an unknown area using low-cost off-the-shelf components [13]. The Coordination and Interaction System group in Switzerland has been working on collision avoidance algorithms using on-board vision systems on quadrotors [14].

B. *Motion Capture Systems*

Motion capture systems generally utilize large arrays of high framerate infrared cameras positioned all around a predefined capture volume (see Figure 2 andFigure 3) in combination with spherical reflective markers. Placing several reflective markers on a rigid body allows the system to triangulate and calculate the position and orientation of any object within the capture volume to submillimeter tracking accuracy. As such, a motion capture system allows for extremely precise path planning within the capture volume. Additionally, obstacles in the capture volume can be specified allowing for any autonomous system within the volume to be aware of the potential path obstructions. Most, if not all of the processing for a motion capture system is performed separately from the actual robot/vehicle in the capture volume. This relieves the burden of processing from the robot and allows for a stronger focus on the movement dynamics and path planning in the robot/vehicle.

Figure 2: Example motion capture camera arrangement [15].

While there are many advantages for using a motion capture system, there are also some significant drawbacks. There are a several companies that produce motion capture systems; however, the systems are generally very expensive and a large system can easily cost significantly upwards of $100,000 USD [15]. Therefore, the barrier to entry for using this type of system is very high. Second, motion capture systems require a significant amount of space depending on the type of work being done. In the case of MAV research, the requirement is that a large capture volume is needed, and preferably with high ceilings. Lastly, a byproduct of the precise positional tracking is that the system calibration can be easily disturbed. Therefore, the motion capture cameras must be securely mounted in locations where they cannot be easily moved.

Figure 3: Optitrack motion capture cameras [16].

C. Multirotor Aerial vehicles

Multirotor aerial vehicles, or MAV(s), refers to any vehicle with more than one rotor. There are manned vehicles with multiple rotors; however, MAVs generally refer to smaller unmanned aerials vehicles such as quadrotors (see Figure 4). These MAVs can range in size: from smaller than a human hand, to the size of a small car. MAVs are also generally powered by electricity and can carry small payloads relative to the size of the vehicle. Due to the state of battery technology, flight time is usually limited to 20-30 minutes on average [17].

Figure 4: A DIY quadrotor [18].

The past 5-10 years have yield significant advances in the research and development in the field of MAV research. There have been many prominent advances in the development of open sourced flight controllers, such as PixHawk [19]. Additionally, there has been significant progress with respect to the creation and optimization of control algorithms. This research has led to many potential applications for MAVs, such as using MAVs for package delivery and adding robotic manipulators to MAVs. Much of this research has been conducted using the aforementioned motion capture systems.

II. OBJECTIVE

The goal of this project was to create a low-cost, minimally viable system that utilizes motion capture cameras to control a small MAV in a small capture volume. Upon successful completion, this system will serve as a foundational experimental setup that allows for more advanced exploration into the flight dynamics of MAVs; as well as dynamics of robotic systems in general. Additionally, this project will serve as an example that this type of advanced control research setup can be achieved in smaller spaces with a relatively low budget (shown in Table 1).

TABLE I
PROJECT BUDGET

Description	**Cost**
4 Optitrack Prime 13W Cameras	$10,000
Misc. Optitrack Hardware	$850
Tracking software	$1,000
Camera mounting hardware	$150
2 Crazyflie 2.0 quadrotors	$400
Total	$12,400

Figure 5 shows a simplified process diagram of the experimental system. The quadrotor has an onboard processor that handles the basic flight controller. The ground system consists of a desktop computer connected with the motion capture system.

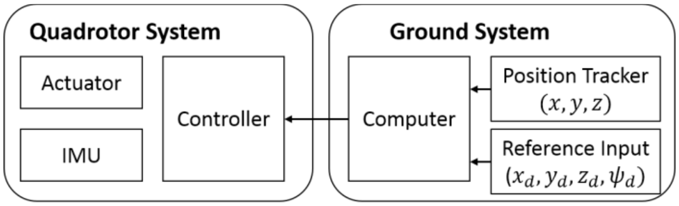


Figure 5: Motion capture process diagram.

III. EXPERIMENTAL SETUP

A. *Motion Capture Space*

There are many companies that provide motion capture solutions; however most of them are extremely expensive. Fortunately, Optitrack has several motion capture product lines that are relatively affordable and support much of the same functionality as the more expensive systems. Four of Optitrack's Prime 13W cameras were chosen for this project. The Prime 13W has a resolution of 1.3 megapixels and can achieve framerates up to 240 frames per second [16]. Additionally, the Prime 13W has a wide angle lens which is helps to ensure maximum coverage of the capture volume.

The motion capture cameras were mounted on top of 10 foot telescoping poles in a square 10'x10' arrangement. The cameras were angled downwards to ensure maximum overlapping camera view space. The cameras were powered and connected to an Ethernet switch using power over Ethernet (POE) cables creating a local Ethernet network between cameras. The switch was then connected to the PC using a single Ethernet cable.

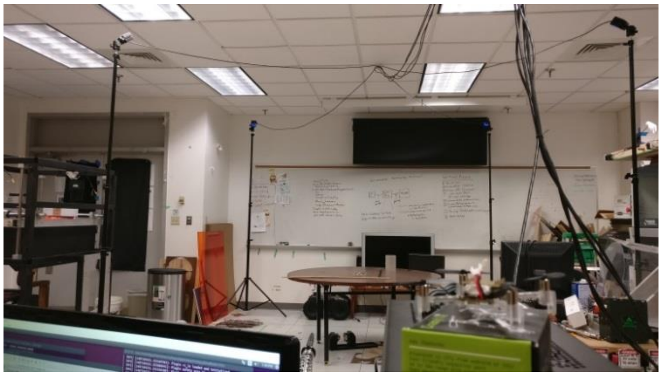


Figure 6: Motion capture space in the ASRL.

B. *Quadrotor*

Due to the limited size of the capture volume, it would not make sense to purchase a large DIY quadrotor platform as other researchers have done in the past. As such, the Crazyflie 2.0 (CF2) was chosen for this project. The CF2 was mainly chosen for its small size, which measures 92 x 92 mm, but also because the CF2 is very resistant to crash damage due to its low mass (27g) and inertia. Furthermore, the CF2 is designed as a research platform and sports a 32-bit, 168-MHz ARM microcontroller with floating-point unit that is capable of significant onboard computation [20]. The software and hardware are both open-source. The CF2 communicates with a PC over the Crazyradio PA, a 2.4 GHz USB radio can transmit up to two megabits per second in 32-byte packets.

The CF2 has a max payload of 15 grams. Four tracking 'dots' were needed in order to achieve consistent tracking of the CF2. In total, the tracking dots had a combined weight of 4 grams. A simple and lightweight, 2 grams, mount was custom designed and 3d printed to attach the tracking dots. As a result, the total weight of the added hardware was 6 grams.

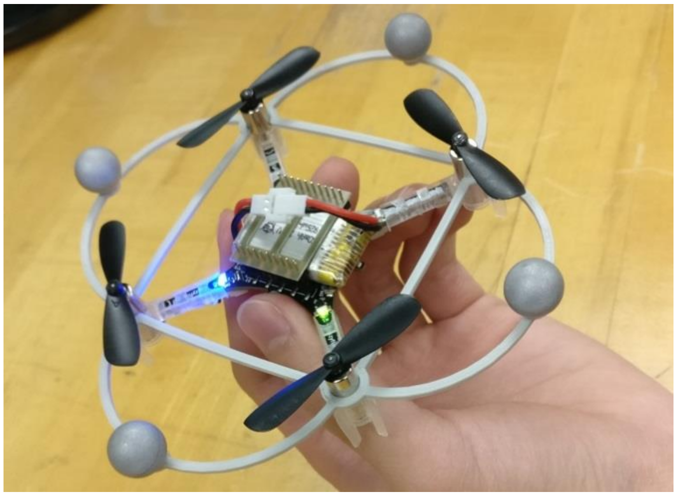


Figure 7: Crazyflie 2.0 nano-quadrotor with custom-mounted tracking dots.

C. *Software*

The core of the project lies in the software. A windows PC was used alongside a virtual machine (VM) running Ubuntu (Figure 8). The tracking software provided by Optitrack requires either a windows or Mac OS to operate.

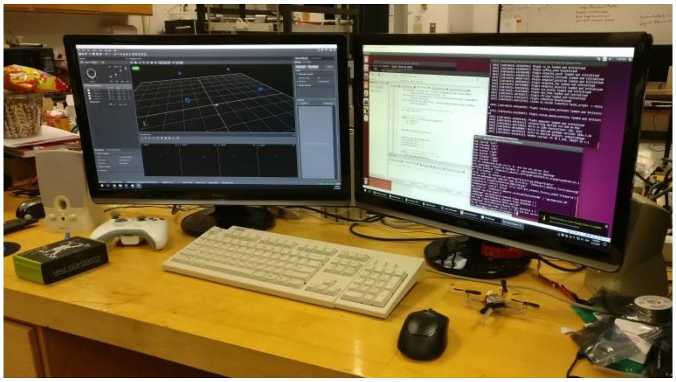


Figure 8: Software setup in the ASRL.

The tracking software captures and processes different objects denoted by different sets of spherical markers to create a list of rigid body data. This data is then streamed from the windows partition into the Ubuntu VM. At this point, the data is received and processed by the robot operating system or ROS. A custom in-house script was written to depacketize and convert the rigid body data into a usable coordinate system for ROS. Then the data was sent to a ROS sub-package, MAVROS, a software package specifically written to handle communication for MAVs. Once the MAVROS receives the data, it is then wireless sent to the quadrotor over a local wifi network.

IV. QUADROTOR DYNAMICS

Quadrotors have four fixed pitch-angle blades, whereas class helicopters have variable-pitch-angle blades. The control of a quadrotor is performed by varying the speed of each rotor. A concept of the quadrotor is shown in Figure 9 [21].

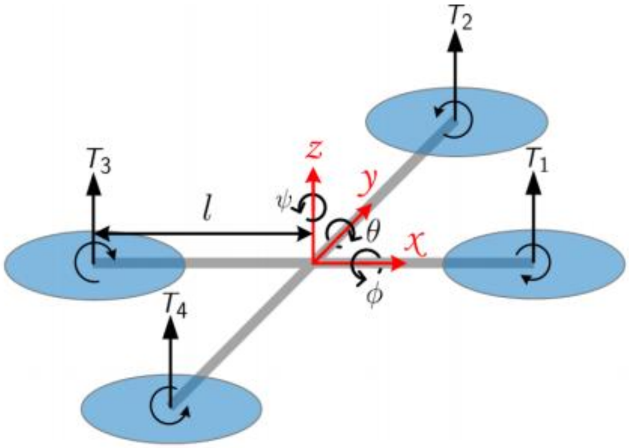


Figure 9: Quadrotor Model

The dynamic equations of the quadrotor model may be derived from a Lagrange approach, and is simplified as follows (Eqns. 1-6):

$$\ddot{x} = u_1(\cos\phi sin\theta \cos\psi + sin\phi sin\psi) \qquad (1)$$

$$\ddot{y} = u_1(\cos\phi sin\theta \cos\psi - sin\phi sin\psi) \qquad (2)$$

$$\ddot{z} = u_1(\cos\phi cos\theta) - g \qquad (3)$$

$$\ddot{\phi} = u_2 l \qquad (4)$$

$$\ddot{\theta} = u_{3l} \qquad (5)$$

$$\ddot{\psi} = u_4 \qquad (6)$$

where [x, y, z] are positions of the quadrotor in the inertial frame; [φ, θ, ψ] Euler angles represent roll, pitch, and yaw angles, respectively; and g the acceleration of gravity: and l is the length between the center of the quadrotor and the rotor.

The control inputs u1, u2, u3, u4 are defined as follows (Eqns. 7-10):

$$u_1 = \frac{1}{m}(T_1 + T_2 + T_3 + T_4) \quad (7)$$

$$u_2 = \frac{1}{J_1}(T_2 - T_4) \qquad (8)$$

$$u_3 = \frac{1}{J_2}(-T_1 + T_3) \qquad (9)$$

$$u_4 = \frac{C}{J_3}(T_1 - T_2 + T_3 - T_4) \quad (10)$$

where u_1 is the normalized total lift force, and u_2, u_3, and u_4 correspond to the control inputs of roll, pitch, and yaw moments, respectively; J_i $(i = 1,2,3)$ is the moments of inertia with respect to the axes; and C is the force-to-moment scaling factor

V. PD CONTROLLER

Since the quadrotor is as under-actuated system which has six state variables and four control inputs, two states, x and y, are not controlled directly. Hence, the desired pitch and roll angles to control x and y using desired x and y as follows (Eqns. 11 and 12) [22]:

$$\phi_d = sin\psi(\alpha\dot{e}_x - \beta\dot{e}_x) - cos\psi\left(\alpha\dot{e}_y + \beta\dot{e}_y\right) \quad (11)$$

$$\theta_d = cos\psi(\alpha\dot{e}_x + \beta\dot{e}_x) + sin\psi\left(\alpha\dot{e}_y + \beta\dot{e}_y\right) \quad (12)$$

where α and β are constant values, $\dot{e_x} = \dot{x}_d - \dot{x}$, $e_x = x_d - x$, $\dot{e_y} = y_d - \dot{y}$, $e_y = y_d - y$. Through these equations, x-y plane motion can be controlled using u_2 and u_3 with ϕ_d and θ_d. In addition, u_1 and u_4 can be defined to control the z and ψ states directly. As a result, the PD controller of the quadrotor can be written as follows (Eqns. 13-16):

$$u_1 = k_{p,z}(z_d - z) + k_{d,z}(\dot{z}_d - \dot{z}) + g \qquad (13)$$

$$u_2 = k_{p,\phi}(\phi_d - \phi) + k_{d,\phi}\left(\dot{\phi}_d - \dot{\phi}\right) \qquad (14)$$

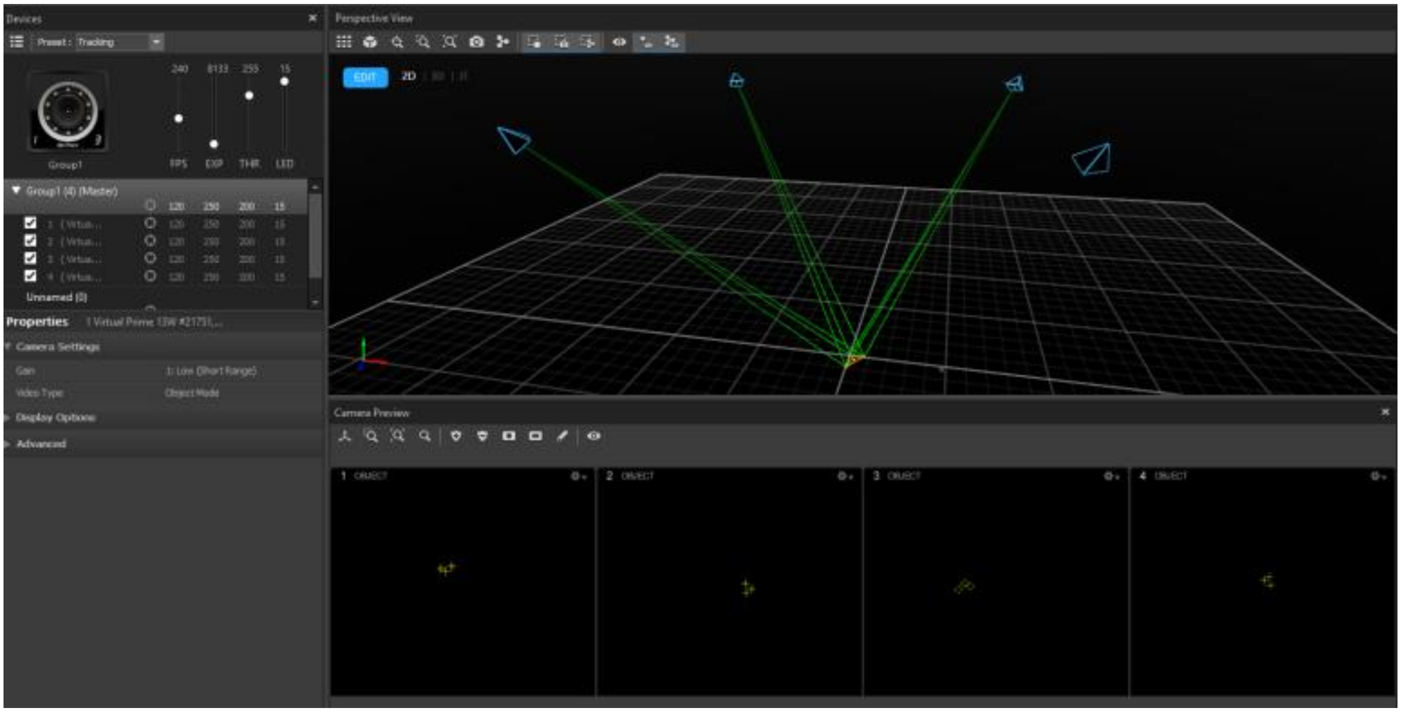
$$u_3 = k_{p,\theta}(\theta_d - \theta) + k_{d,\theta}\left(\dot{\theta}_d - \dot{\theta}\right) \qquad (15)$$

$$u_4 = k_{p,\psi}(\psi_d - \psi) + k_{d,\psi}\left(\dot{\psi}_d - \dot{\psi}\right) \qquad (16)$$

where k_p and k_d are proportional and derivative gains, respectively.

VI. PRELIMINARY DATA

As of now, the project is nearing 90 percent completion. At this point, the motion capture system has been setup and calibrated. Figure 10 shows the motion capture tracking interface using multiple cameras to triangulate the position of a tracked object. The motion capture cameras are represented as floating blue triangular prisms.



Preset : Tracking

▼ Group1 (4) (Master)

		○	120	250	200	15
☑	1 (Virtua...	○	120	250	200	15
☑	2 (Virtua...	○	120	250	200	15
☑	3 (Virtua...	○	120	250	200	15
☑	4 (Virtua...	○	120	250	200	15

Unnamed (0)

Properties 1 Virtual Prime 13W #21731...

▼ Camera Settings

Gain	1: Low (Short Range)
Video Type	Object Mode

▶ Display Options

▶ Advanced

Figure 10: Motion capture tracking interface.

The motion capture software is capable of recording the position of tracked objects. Figure 11 shows a sample recording of a quadcopter flying in a circle and then subsequently landing.

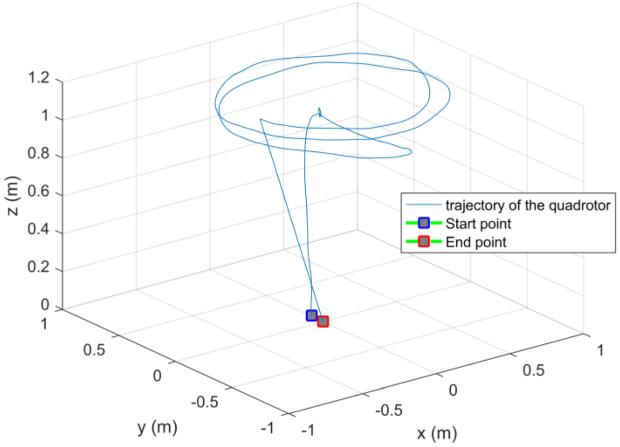


Figure 11: Sample positional tracking data obtained from preliminary test flights.

Motion capture system aside, the quadcopter has been flashed with the appropriate firmware. The tracking software streams the tracking data from Windows into Linux and ROS. A custom program was written to send target set points for the quadcopter to fly to and hold at using local position estimators. Furthermore, a script was created to handle the remote arming/disarming of the quadrotor (in case of emergency). Unfortunately, there have been issues with the wireless communication with the quadrotor. However, we believe that this can be resolved by switching from the radio transmitter over to a local wireless network instead.

VII. FUTURE WORK

We intend to resolve the communication issues we are having at present and then begin testing basic positional control programs. Upon successful completion of the basic tests, we will begin exploring different quadrotor control algorithms, path planning, and world exploration techniques. Furthermore, we will begin development on a more customizable DIY quadrotor frame, as opposed to using an off the shelf solution, in order to explore possibilities such as attaching companion robots and sensors to a quadrotor. This paper serves as a basic introductory guide for researchers interested in developing a low-cost, low-space tracking system for MAVs.

VIII. ACKNOWLEDGEMENTS

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