Autonomous Quadrotor for the 2013 International Aerial Robotics Competition

Isaac Olson
B.S.E. Aerospace Engineering 2014
Jonathan Bendes
B.S.E. Computer Science, 2013

ABSTRACT

While flight vehicles have become pervasive in today's society, they remain technologically restricted to unpopulated, open-air settings. Vehicles that specialize in safe flight through confined, obstacle-ridden environments will pave the way toward redefining currently outdated and expensive methods of structural inspection, search and rescue, and law enforcement operations. Michigan Autonomous Aerial Vehicles (MAAV) designs and builds lightweight quadrotor unmanned aerial vehicles (UAV) capable of stable, confined-space flight. MAAV's vehicle will compete in the 2013 International Aerial Robotics Competition (IARC) where it will demonstrate its ability to autonomously enter into, and navigate throughout an unknown building. Using a combination of control, computer vision, Simultaneous Localization and Mapping (SLAM), and path planning algorithms, it will locate and retrieve a target flash drive, deploy a decoy flash drive and exit the compound within the allotted 10 minute time frame.

1. INTRODUCTION

The 2013 International Aerial Robotics Competition will be held in Grand Forks, North Dakota from August 5 to August 8. The University of Michigan has assembled a team, MAAV, to compete in this annual competition. This document presents the MAAV system designed and fabricated and for the IARC.

1.1 Problem Statement

Highly sensitive information has surfaced in the Hesamic Republic of Nari's Intelligence Organization. A request for a small autonomous aerial vehicle has been issued. This vehicle must enter a Nari military compound to retrieve and replace a small USB flash drive. The only existing intelligence of the compound layout is the images of three Arabic signs used to identify the Security Compound, Ministry of Torture, and Chief of Security's office. The Chief of Security is on a 10 minute patrol route, thereby requiring the vehicle get into and out of the compound in less than 10 minutes. Should the vehicle be detected by either the chief of security or by the compound's security cameras, the mission time limit is reduced to 5 minutes. The vehicle must be small enough to fit through a 1 m by 1 m window and must remain under 1.5 kg.

1.2 Conceptual Solution

MAAV has designed, fabricated, and tested a quadrotor UAV to complete the IARC mission. The quadrotor utilizes two cameras, a 30 m laser rangefinder, a 4 m laser rangefinder, and a retrieval mechanism. These payloads will allow the vehicle to enter the compound undetected, retrieve the flash drive, deploy the decoy, and exit the building in less than 10 minutes. Image processing software will recognize a blue LED to determine when covert entry is possible, interpret the Arabic signs for navigation assistance, and locate the lasers crossing the hallways. The laser rangefinders will generate a 3D point cloud around the quadrotor and use a SLAM algorithm to build a map of the environment. Path planning software will command the vehicle to explore the environment planning the most efficient path possible. Image processing will recognize the flash drive and command the vehicle to deploy its retrieval mechanism. The retrieval mechanism will pick up the flash drive with magnets and a release mechanism will deploy the decoy flash drive. All of these objectives will be completed within the allotted 10 minute time limit.

1.3 Yearly Milestones

MAAV is entering its fourth year as a competitor in the IARC. We made several improvements to this year's system. Most notably, we expanded the mapping technique from a 2D blueprint style map to a dynamic, dense 3D map of the environment. This map allows the quadrotor to navigate the compound while avoiding any and all obstacles in its way. The map also allows for object recognition. The vehicle can recognize and identify objects such as tables and boxes, allowing the vehicle to find the flash drive sooner.

Another notable improvement is the implementation of a real-time, parallel, motor control algorithm. This new algorithm increases flight stability, allowing the vehicle to more accurately navigate in confined spaces. Custom electronic speed controllers and multi-dimensional Kalman filters improve the quality of both sensor data and motor control greatly increasing the vehicle's flight stability.

MAAV has also developed computer vision algorithms to recognize Arabic signs, security cameras (blue LEDs), and most importantly the target flash drive. We modified conventional computer vision algorithms, which are usually very computationally intense, to run in real-time on a GPU in the ground station computer. The benefits of a GPU allow us to do more robust image processing while maintaining the necessary speed and reliability.

2. AIR VEHICLE

The MAAV quadrotor weighs approximately 1.47 kg, spans 48 cm from blade tip to blade tip, has a height of 24 cm, and has a vertical thrust of ~35N. *Figure 1* shows a fully assembled vehicle. *Figure 2* shows the MAAV system architecture.

Figure 1: A front shot of the MAAV quadrotor fully assembled

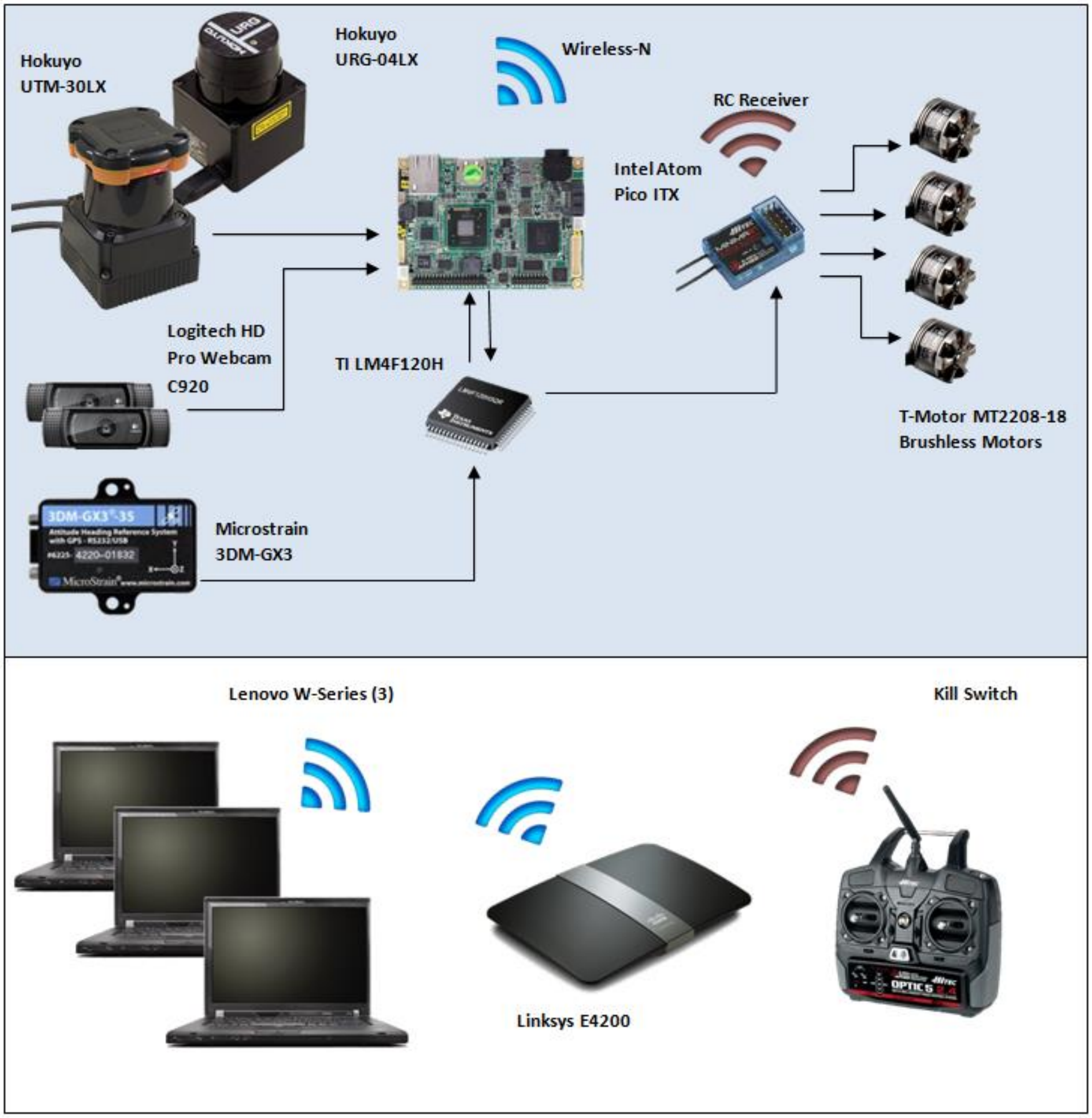

Figure 2: MAAV System Architecture

2.1 Propulsion and Lift System

The quadrotor is lifted by four 23 cm, three-blade propellers mounted on T-Motor MT2208-18 motors. These produce approximately 35 N of lift for a lift-to-weight ratio of 2.4. MAAV chose three bladed propellers instead of two bladed propellers to achieve the same lift for a smaller overall system diameter. Although the efficiency of these propellers is less than two bladed propellers, this disadvantage is outweighed by the reduction of the overall system diameter.

2.2 Guidance Navigation and Control

The quadrotor maintains a stable hover position by altering the power to each motor using a nonlinear controller for roll, pitch, yaw, height, x, and y. This controller was derived from the vehicle's system dynamics, functioning similarly to a PID controller with additional nonlinear terms. The roll, pitch, and yaw are monitored through a Microstrain inertial measurement unit. Two Hokuyo laser rangefinders allow the vehicle to build a three dimensional map of the surrounding environment. Once the vehicle is stable, it is able to traverse waypoints by altering the roll, pitch, and yaw setpoints, as well as the net force applied by the motors.

2.2.1 Stability Augmentation System

As an inherently unstable and under-actuated system, a quadrotor requires a well-tuned, robust controller to stay aloft. MAAV uses a nested proportional-integral-derivative (PID) controller with nonlinear terms that are derived from vehicle dynamics. For each degree of freedom, the controller has a PID loop that converts from value error to desired rate. A second PID loop then converts from rate error to force input. This architecture allows for incremental tuning thus expediting the testing process. The controller maintains stability of the quadrotor in a large range of states while rejecting external disturbances.

2.2.2 Navigation

In order to effectively and efficiently explore the compound, MAAV's UAV implements a simple navigation scheme; it observes the environment, builds a map, selects new frontiers to explore, and then repeats. When it observes interesting features in its environment – such as tables, Arabic signs, blue LEDs, etcetera – it changes its behavior to prioritize further exploration of these features. In the event of a flash drive detection, the vehicle changes its behavior to immediately deploy the retrieval mechanism to pick up the flash drive. After retrieval, the vehicle drops the decoy flash drive and navigates out of the building.

Global Planning: A high-level, off-board, global planner attempts to meet all mission objectives by tasking the quadrotor to complete intermediate objectives within the computational limits of the on-board processor. This division allows the robot to safely forget aspects of the environment and mission that are no longer relevant and focus solely on the immediate task at hand. The global planner takes the following information into account when tasking the quadrotor through the environment: 1) mission objectives, 2) explored space (overall map of the mission area), 3) detected windows, tables, blue LEDs, Arabic signs, and flash drives, and 4) the capabilities of the quadrotor.

On-board Planning: The quadrotor receives and completes tasks given to it from the high-level planner. The on-board planner can take off, follow waypoints while avoiding obstacles, retrieve a flash drive, and safely land. The primary task of the on-board planner is to follow the waypoints sent from the global planner via path-planning and obstacle detection algorithms. For safety and reliability reasons, this planner has been programmed to avoid all obstacles at any cost. If the vehicle determines that a certain waypoint is too dangerous, it will disregard that waypoint and wait for the next command.

Laser/IMU Odometry: An inertial measurement unit (IMU) is typically used to guess at how much a robotic platform has moved. Safely flying in a confined space, however, means that a rough estimation on the location of the vehicle is no longer adequate. Therefore, the data from the IMU is augmented with additional information provided by laser odometry. A horizontally mounted laser rangefinder offers accurate location and horizontal orientation feedback by comparing consecutive laser returns. The height of the robot is estimated via the vertically mounted laser rangefinder. Together with the roll/pitch data measured by the IMU, we generate a decent estimate of the state of the quadrotor. The more accurate this estimate, the better the overall system can predict vehicle position. However, the estimate of the vehicle's position and orientation (pose) has inherent error. A SLAM algorithm uses global information (rather than consecutive scans and the most recent IMU data) to get a more accurate global position of the robot.

Simultaneous Localization and Mapping (SLAM): The purpose of SLAM is to generate an accurate and consistent map of the world. Lasers and IMU odometry can give very accurate estimates of robot pose, but over time even the smallest errors compound and distort the map from its true shape. SLAM uses re-observation of unique environmental features to fix and adjust the estimated map thereby generating a highly accurate and consistent map of the world. The algorithm runs on the ground station and is a variant of pose-graph SLAM where the nodes in the graph represent the pose of the robot and the edges represent constraints between these poses (e.g., odometry edges). The algorithm is based on Edwin Olson's open source SLAM implementation available in the APRIL Robotics Toolkit.

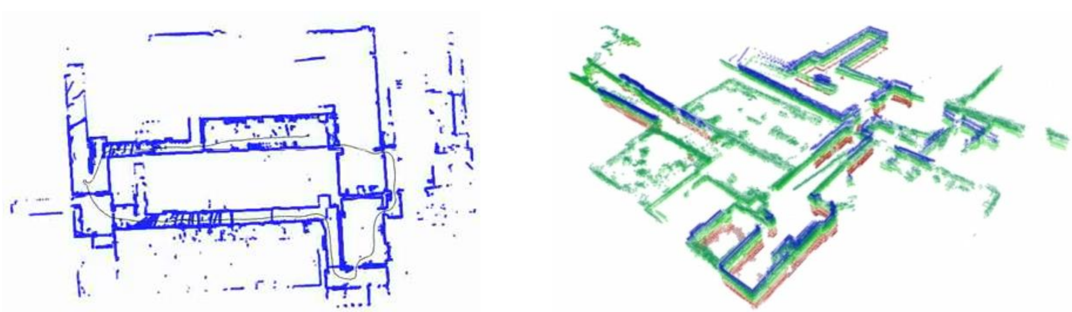

Figure 3: (left) 2D map generated with only a horizontal laser, (right) 3D map generated with both vertical and horizontal lasers

2.2.3 Control Architecture

The general control architecture of the system is shown in *Figure 4*. The navigation software outputs position waypoints to the outer PID loop. The outer-loop position controller outputs net motor force as well as roll, pitch, and yaw setpoints. These setpoints are the inputs to the inner PID loop. The inner-loop attitude controller outputs the necessary torque resultants. The net force and torque values are input through a function that calculates individual motor commands.

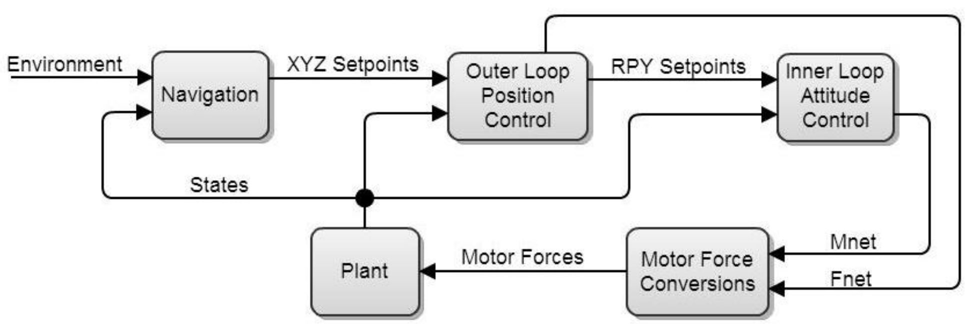

Figure 4: Control scheme diagram

2.3 Flight Termination System

As a last resort, our system implements a backup kill switch. In the event of a complete computer meltdown that causes the quadrotor to enter into an unresponsive and dangerous state, a human-operated backup kill switch disables all power to the motors. The source of the kill switch signal originates from a common RC controller supplied, and operated by IARC judges. This standardization guarantees that the kill switch operates on a reliable frequency, separate from the communication frequencies used by the vehicle for data and video transmission. The signal from the kill switch receiver is a PWM signal that is processed by a microcontroller independent of the main system. We chose to use a microcontroller instead of the suggested design to give added flexibility to how the vehicle responds to the receiver’s signal. The added complexity is justified because it allows us to add important features like noise immunity, and fail safe functionality without sacrificing response time.

3. PAYLOAD

3.1 Sensor Suite

3.1.1 GNC Sensors

Microstrain 3DM-GX3-25 AHRS: The Microstrain attitude and heading reference system (AHRS) returns the roll, pitch, and yaw angles as well as the roll, pitch, and yaw angular rates in the form of radians and radians per second. These values are already filtered and are handled directly in the control loops. The Microstrain is pictured on the left in *Figure 5*.

Figure 5: The Microstrain 3DM-GX3-25 (left), Hokuyo UTM-30LX Laser Rangefinder (Center) and Hokuyo URG-04LG-UG01 Laser Rangefinder (right).

Hokuyo UTM-30LX Laser Rangefinder: A top-mounted laser rangefinder returns a point cloud of 1080 points over a 270 degree sweep, 30 meter range surrounding the vehicle at a rate of 40 scans per second. These point clouds are analyzed to extract rigid body transformations between prior robot poses. The Hokuyo UTM-30LXLIDAR is pictured in the center of *Figure 5*.

Hokuyo URG-04LG-UG01 Laser Rangefinder: A vertically mounted laser rangefinder returns a point cloud of 540 points over a 270 degree sweep. The sensor has a 4 meter range surrounding the vehicle and operates at a rate of 10 scans per second. This point cloud, coupled with that of the top laser, allows for 3D scanning without a servo-mounted laser. The Hokuyo URG-04LG-UG01 is pictured on the right of *Figure 5*.

Cameras: Two Logitech web cameras operating at high definition (HD) resolution transmit video to a ground station at 20 frames per sec (fps). One camera is mounted pointing forward and one is mounted pointing down. On-board hardware video encoding reduces the streams' data size and allows the vehicle to stream HD video in real-time.

3.1.2 Mission Sensors

Target Detection: While image processing is crucial to the success of the mission, it is not a flight-critical process and has therefore been tasked to the ground station computer. Offloading the image processing computation to the ground station allows more robust and computationally intensive image processing algorithms to inspect the video footage to find Arabic signs, blue LEDs, and the target flash drive. Although utilizing a GPU would hugely speed up image processing to the point where the algorithms could run on-board the vehicle, GPUs have prohibitively high power draw and would drastically lower the vehicle's flight time. Accelerating these algorithms with the use of a GPU becomes possible, however, when completed by a ground station.

To detect blue LEDs, a blob detector filters the image for the blue pixels. Each pixel's hue, saturation, and intensity are checked for satisfaction of predetermined range conditions to form a new binary image. If all a pixel's attributes fall within the ranges, the pixel is set to white, representing 'on', in the new image. Otherwise, it is set to black, or 'off'. The binary image then goes through a series of dilations and erosions. Dilation increases the size of blobs around the edge, thus filling in any holes and gaps. Erosion does the opposite, eliminating any small noise. The image is segmented to isolate individual blobs in the image frame, and its moments are calculated to finds its position and area in the image frame. All candidate blobs are further filtered for candidates that are small enough to be LEDs and large enough to not be mistaken for noise.

Speeded Up Robust Features (SURF) algorithm is responsible for Arabic sign recognition. We use SURF instead of faster feature recognition algorithms because SURF combines the reliability of returning very few false positive image matches, with the ability to be run on a GPU. SURF is also used to detect the USB flash drive. We modified the SURF algorithm for flash drive detection to take into account both color and the outline of the flash drive. The flash drive itself has few unique identifiers and is therefore hard to identify using conventional SURF. The addition of the color of the flash drive as well as its outline reduces the number of false positives identified when the quadrotor is flying through the environment.

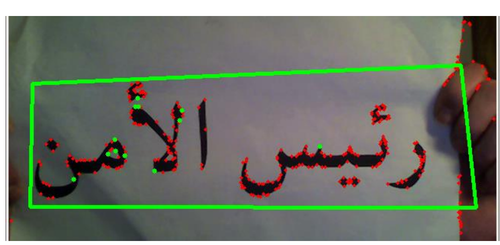

Figure 6: A demonstration of the image recognition algorithm on an Arabic sign

Threat Avoidance: The quadrotor detects and avoids threats through the 3D mapping produced from the two on-board Hokuyo laser rangefinders. The ability to carry two laser scanners allows the vehicle to see threats in all directions instead of simply in a plane around the vehicle.

3.2 Communications

The communications system consists of a 5GHz WiFi channel for data and video transmission. All WiFi communications are through a wireless protocol known as Lightweight Communications and Marshalling (LCM). LCM allows for low-latency multi-process communication.

3.3 Power Management System

The quadrotor is equipped with a 4000mA-hr lithium polymer (LiPo) battery. This allows for a flight time of roughly 12 minutes at hover conditions. LiPo batteries maintain a constant voltage for most of their charge and thus it is important to have a method for monitoring battery charge. MAAV monitors battery status on our custom circuit board to maintain safe flight conditions.

4. OPERATIONS

A majority of the vehicle is autonomous, but manual communication and control is still incorporated for testing phases, safety, and vehicle status monitoring.

4.1 Flight Preparations

Battery voltage is checked to be at operating level and the propellers are securely tightened to the motors. The vehicle is then connected to the WiFi network and communications are initialized. The enable signal is sent and the vehicle is ready for flight.

4.2 Man/Machine Interface

Our man/machine interface is comprised of a single process with a complex guided user interface, or GUI. GUIs are pivotal to successfully debugging complex systems. Our custom flight GUI takes all of the information on the current state of the vehicle, including IMU data, height sensor data, motor commands, laser scans, camera feeds, etcetera, and displays it in an intuitive, cockpit style display. This allows for remote operation of the quadrotor. A user friendly and intuitive GUI allows the operator to determine if the vehicle has experienced a system meltdown and needs to be killed. All data is logged for future review and debugging.

5. RISK REDUCTION

Many levels of risk reduction are in place to prevent personal injury and damage to hardware. The preliminary models are fully tested in a simulated environment followed by a strictly controlled environment. All systems are continuously monitored and recorded to compare to simulations. Safety is the most important concern of the project.

5.1 Vehicle Status

The ground station monitors many properties of the quadrotor including roll, pitch, yaw, height, motor commands, laser scan data, and camera images. During flight, these properties are recorded for future analysis.

5.1.1 Shock/Vibration Isolation

Vibrational effects have not proven to be a concern for the newest MAAV quadrotor. Structural reinforcement and secure fastening has greatly mitigated previous effects of vibration. We have also mounted the motors on rubber washers to separate their high frequency oscillations from the rest of the structure. Additionally, we have taken precautions to protect the payload. Intentional breakpoints are located at each leg-joint; should the quadrotor crash, the legs will break, thus absorbing the shock and protecting the fragile, on-board sensors.

5.1.2 EMI/RFI Solutions

Circuitry is prone to electromagnetic and radio frequency interference. Fortunately, our data and video streams are transmitted over UDP where the communication protocol checks to make sure all data is successfully sent. In the case of interference, checksums and other error checking procedures invalidates the flawed message.

Electromagnetic interference can also be problematic for an inertial measurement unit. Magnetometers inside the IMU measure the magnetic field of the earth to determine the IMU's orientation. However, the magnetic field becomes too corrupted by the EMI from the motors for this data to be useful. We eliminated this issue by combining integrated gyroscope data with the output of scan-matching from the laser rangefinder. Both the gyro and the laser devices are unaffected by EMI.

5.2 Safety

In order to ensure safe flight and testing of the vehicle, a number of precautions are taken. The vehicle is initially tested on a steel test stand that isolates a single axis for tuning controller gains while keeping the vehicle restrained. After tuning the control loops on the test stand, the vehicle is tested with safety ropes and finally in free flight. In all cases the vehicle is subject to two separate kill switches: one in the normal flight software and one external, dedicated kill switch that operates on a separate frequency to circumvent the dangers of a loss of WiFi connection.

5.3 Modeling and Simulation

The entire quadrotor design was conceived using CATIA V5. The model was designed and assembled to ensure proper placement of all components, which allowed the team to predict the physical properties (i.e. moment of inertia, center of gravity) of the vehicle to import to the simulation. CATIA was also used to generate the tool paths for machining custom parts. All of the parts, including the carbon fiber airframe, aluminum center piece, PCBs, sensor mounts, and motor mounts, were custom designed and fabricated for this vehicle. An image of the CAD model is shown in *Figure 7*.

Figure 7: A model in CATIA V5. This was used for full vehicle fabrication and assembly

Simulations created in Simulink were used in order to test the feasibility of the controller and path planning algorithms before the vehicle could fly. The first simulation used a PID controller to stabilize the roll, pitch, yaw, and height of the vehicle. This allowed the control loops to be tuned before the vehicle could fly. Next, the simulation was augmented to control the x-y position of the vehicle and take set points for navigation. Finally, the path planning algorithm was implemented and a 3D visualization was created.

5.4 Testing

Testing is broken into three stages: calibration, restrained testing, and free flight testing.

5.4.1 Calibration

Calibration is required for each motor/speed-controller/propeller triad. Motor/speed-controller/propeller calibration curves mapping RPM to force are calculated using the MAAV "Test Cell" shown in *Figure 8*. The test cell is equipped with an air bearing, force and torque transducers, and a data acquisition system (DAQ). The test cell automatically collects relevant data for each motor/speed-controller/propeller combination. The calibration equations are calculated and used directly by the on-board controller.

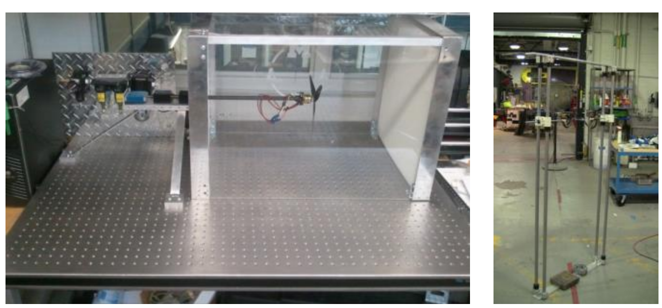

Figure 8: Motor test cell (left) and the vehicle test stand (right)

5.4.2 Restrained Testing

Once the individual components are tested, the vehicle is fully assembled and placed on our test stand shown in *Figure 8*. The test stand restrains vehicle motion to either the roll or the pitch axis along with the yaw and height axes. This allows the PID gains to be tuned for one axis at a time. The stand also allows for the roll, pitch, and yaw axes to be restrained while the vehicle moves up and down on linear bearings. Once the roll, pitch, and height are tuned, the test stand allows the vehicle to adjust height while controlling either roll or pitch. This allows the vehicle to be tuned while observing the coupling behavior between two axes.

5.4.3 Free Flight Testing

After each of the axes has been tuned on the test stand, the vehicle is tested off of the test stand. We attach ropes for further tuning. Initially, the height control is removed from the system and the height setting is manually controlled from the joystick. The vehicle is raised roughly 30 cm off the ground to verify roll and pitch stability and tune yaw stability. Once stability is achieved at 30 cm off the ground, the vehicle is slowly raised to an operating altitude of 1.5 m. Slight adjustments are made to account for leaving the ground effect zone. At this point in the testing, the vehicle has no knowledge of its surroundings or its relative location to the environment.

Once inner loop stability is achieved, manual roll, pitch, yaw, and height set points are sent to the vehicle from the ground station. The set points are altered by moving the joystick. Movement in each direction is tested before autonomous movement is attempted. Once the outer control loops are stable, preprogrammed, autonomous movement is tested. After verifying proper vehicle response, the Hokuyo laser rangefinder is used to locate and map the surrounding environment and give the vehicle a world reference coordinate system. At this point the vehicle is placed into semi-autonomous mode where it attempts to localize itself with respect to the environment eventually traversing a predetermined path. Finally, the exploration functions are enabled and the vehicle is ready to fly the mission.

6. CONCLUSION

MAAV has designed and constructed a small quadrotor UAV weighing only 1.47 kg that is capable of autonomous entry into and navigation throughout an unknown building. The vehicle is currently in the manual and autonomous testing phases. We expect the quadrotor to navigate the competition arena and recover the flash drive in the allotted time.

MAAV would like to thank Northrop Grumman Corporation, our title sponsor, as well as all of our sponsors for their generous contributions to both MAAV and the advancement of UAV technology…