Autonomous Quadrotor for the 2011 International Aerial Robotics Competition

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ABSTRACT

The Michigan Autonomous Aerial Vehicles team (MAAV) will compete in the 2011 International Aerial Robotics Competition (IARC) with a custom quadrotor Unmanned Aerial Vehicle (UAV). This vehicle is capable of autonomous, covert entry into, and navigation throughout, an unknown building using Simultaneous Localization and Mapping (SLAM) algorithms. Using image recognition, the vehicle is able to recognize posted Arabic signs and a flash drive. A magnetic retrieval mechanism collects the flash drive while simultaneously dropping off a decoy. The entire mission will be completed in the allotted ten minute time frame.

1. INTRODUCTION

The 2011 International Aerial Robotics Competition will be held in Grand Forks, North Dakota from August 8-12. The University of Michigan has assembled a team, MAAV, to compete in this annual competition. This document presents the system MAAV has designed and fabricated and will be bringing to competition.

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 is required to enter a Nari military compound to retrieve and replace a small USB thumb drive. The only existing intelligence of the compound layout is the images of three Arabic signs that may be used to identify the Security Compound, Ministry of Torture, and Chief of Security's office. The Chief of Security is on a ten minute patrol route, thereby setting the time limit for the vehicle to get into and out of the compound to only 10 minutes. Should the vehicle be detected by either the chief of security or by the compound's security cameras, the mission is "dirty" and the vehicle must exit the building within 5 minutes. The vehicle must be small enough to fit through a one meter by one meter window and also must remain under 1.5 kg.

1.2 Conceptual Solution

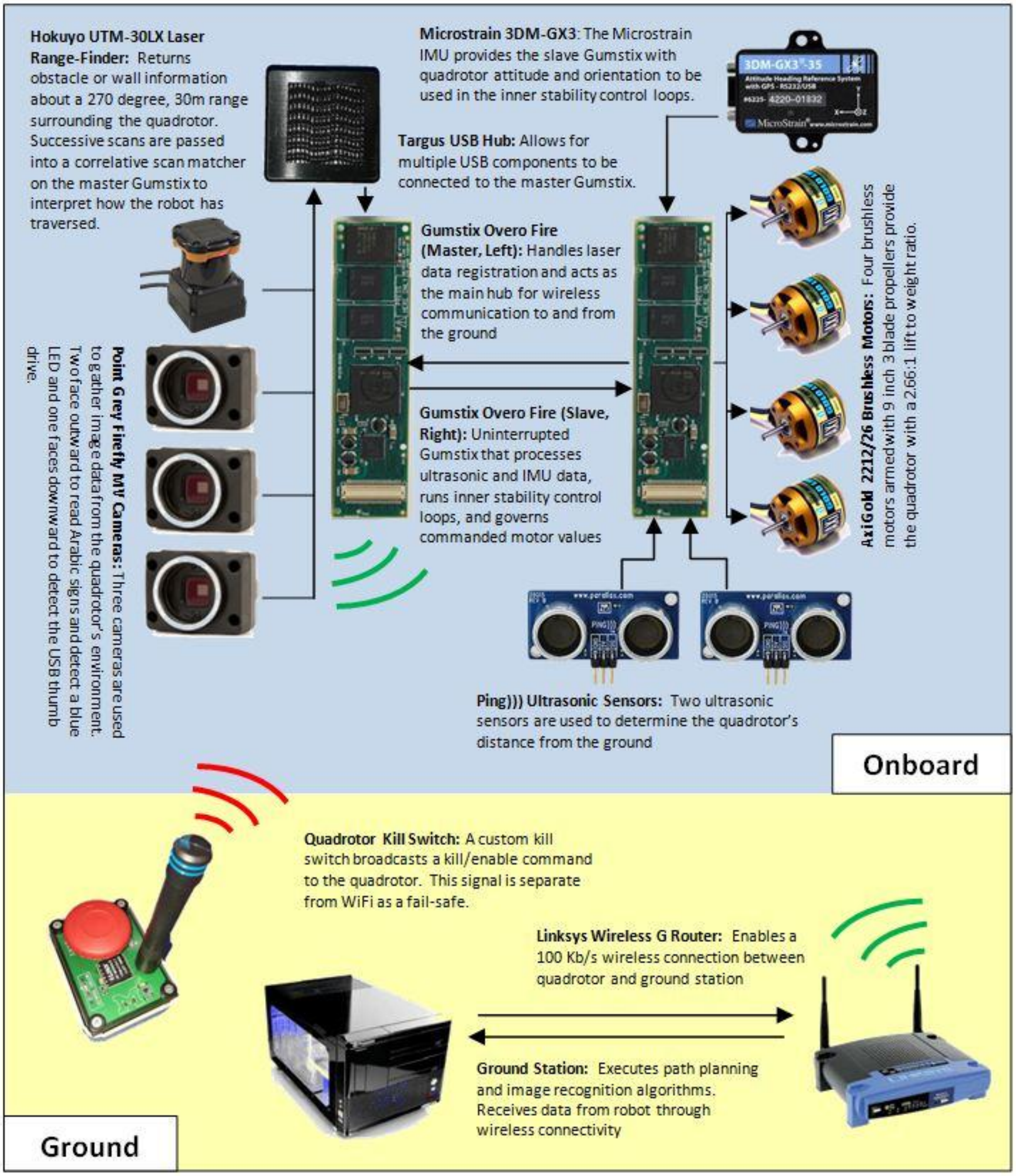
MAAV has designed, fabricated, and tested a quadrotor UAV to complete the mission into the Nari compound. The quadrotor incorporates three cameras, a 30 meter laser range finder, and a retrieval mechanism that will allow the vehicle to enter undetected, retrieve the flash drive, deploy the decoy, and exit the building. Image detecting software will recognized the blue LED to determine if covert entry is possible, interpret the Arabic signs for navigation assistance, and locate the lasers crossing the hallways. The laser range finder will feed distance and angle measurements of objects around the quadrotor to a mapping algorithm to build a map of the environment. Path planning software will command the vehicle to navigate the environment in the most efficient path possible. Image detection will recognize the flash drive, commanding the vehicle to deploy its retrieval mechanism. The retrieval mechanism will collect the flash drive with magnets and a servo will rotate the tray to deploy the decoy. All of these objectives will be completed within the allotted ten minute time limit.

1.3 Yearly Milestones

MAAV entered this competition year with knowledge of several problems that needed to be addressed, as well as many further goals. Among the important changes to this year's vehicle are the isolation of the ultrasonic sensors and the inertial measurement unit (IMU) from the vibration of the vehicle. Great strides have been made towards completing the autonomous portion of the mission. Simultaneous localization and mapping (SLAM), as well as registration and recognition of laser and camera data, is complete. Finally, several retrieval mechanisms have been designed and fabricated.

The quadrotor's airframe and circuitry has been redesigned to reduce the mass of the system by nearly 200 grams. With this mass overhead, the old 4m Hokuyo laser range-finder has been replaced with its 30m counterpart, greatly improving mapping robustness and granularity. A killswitch has also been implemented to guarantee shutting down vehicle power when WiFi connectivity is interrupted or shut down. The quadrotor processing power has also been improved to execute control loops at four times the rate of last year's quadrotor (now 100Hz). Control algorithms can also now be tested on the custom test stand that restrains the quadrotor to pitching or rolling motion and also allows for vertical translation.

*Figure **1*** below shows a full system architecture with all of the data flow.



Hokuyo UTM-30LX Laser Range-Finder: Returns obstacle or wall information about a 270 degree, 30m range surrounding the quadrotor. Successive scans are passed into a correlative scan matcher on the master Gumstix to interpret how the robot has traversed.

Microstrain 3DM-GX3: The Microstrain IMU provides the slave Gumstix with quadrotor attitude and orientation to be used in the inner stability control loops.

Targus USB Hub: Allows for multiple USB components to be connected to the master Gumstix.

Gumstix Overo Fire (Master, Left): Handles laser data registration and acts as the main hub for wireless communication to and from the ground

Gumstix Overo Fire (Slave, Right): Uninterrupted Gumstix that processes ultrasonic and IMU data, runs inner stability control loops, and governs commanded motor values

Point Grey Firefly MV Cameras: Three cameras are used to gather image data from the quadrotor's environment. Two face outward to read Arabic signs and detect a blue LED and one faces downward to detect the USB thumb drive.

AxiGold 2212/26 Brushless Motors: Four brushless motors armed with 9 inch 3 blade propellers provide the quadrotor with a 2.66:1 lift to weight ratio.

Ping))) Ultrasonic Sensors: Two ultrasonic sensors are used to determine the quadrotor's distance from the ground

Quadrotor Kill Switch: A custom kill switch broadcasts a kill/enable command to the quadrotor. This signal is separate from WiFi as a fail-safe.

Linksys Wireless G Router: Enables a 100 Kb/s wireless connection between quadrotor and ground station

Ground Station: Executes path planning and image recognition algorithms. Receives data from robot through wireless connectivity

Figure 1: Full system architecture displaying data communication paths

2. AIR VEHICLE

The MAAV quadrotor weighs approximately 1.2 kg, spans 23 inches from blade tip to blade tip, has a height of six inches from base to the top of the Hokuyo, and has a vertical thrust of 3.6 kg. *Figure* ***2*** below shows a fully assembled vehicle.

Figure 2: An overhead shot of the MAAV quadrotor fully assembled

2.1 Propulsion and Lift System

The quadrotor is lifted by four, 9 inch, three blade propellers mounted on Axi Gold 2212/26 motors. These produce approximately eight pounds of lift for a lift-to-weight ratio of 2.6. MAAV chose three bladed propellers instead of two bladed propellers in order to reduce the overall diameter to nine inches. The efficiency of these propellers is less than two bladed propellers, but the battery power is sufficient enough to achieve a full flight.

2.2 Guidance Navigation and Control

The quadrotor maintains a stable hover position by altering the motor power to each motor through separate PID controls for roll, pitch, yaw, and height. The roll, pitch, and yaw are monitored through a Microstrain inertial measurement unit. Two Ping ultrasonic sensors monitor the height of the vehicle. Once the vehicle is stable, it is able to traverse to waypoints by altering the roll and pitch set points until a position is reached. A Hokuyo laser range finder allows the vehicle to build a map of the surrounding environment.

2.2.1 Stability Augmentation System

The quadrotor maintains stability in the roll, pitch, and yaw axes as well as height through four PID loops. These are referred to as the inner control loops. The Microstrain sensor sends the vehicle the current roll, pitch, and yaw angles in radians as well as the roll, pitch, and yaw rates in radians per second. These values are sent directly to the inner control loop. The inner control loop attempts to maintain a desired set point, typically set at zero for steady hover, but can be set up to 10° for lateral movement. The initial gains for the PID loops are determined by using the simulation developed in Simulink with the physical properties of the quadrotor. The final gains are determined through testing on the custom quadrotor test stand and testing in free flight. The gains are also determined for various situations such as draining battery power or aggressive maneuvers.

2.2.2 Navigation

MAAV’s navigation solution consists of two parts: the registration of raw laser data or laser odometry and Simultaneous Localization and Mapping (SLAM).

Laser Odometry: Predicting how an aerial robot has translated based on integrated data from an IMU is highly unreliable. Therefore, the more robust method of laser odometry is used. A Hokuyo laser scanner returns a point cloud of 1080 points surrounding the robot at a rate of 40 Hz. By comparing consecutive laser returns, it can be inferred how the robot has translated and build a map of its surroundings. Closing a loop in the map when the robot returns to a place it has already been requires a search through scans that are not consecutive.

MAAV uses a method of laser data registration known as "correlative scan matching". Correlative scan matching is a probabilistically motivated algorithm developed by Professor Edwin Olson at the University of Michigan. It is now part of an open source set of robotics algorithms called the APRIL Robotics Toolkit.

Simultaneous Localization and Mapping (SLAM): MAAV's SLAM solution also comes from the APRIL Robotics Toolkit. This algorithm is a variant of square root smoothing and mapping (SAM). *Figure **3*** shows a demonstration of the robot's SLAM performance in the student shop at the University of Michigan.

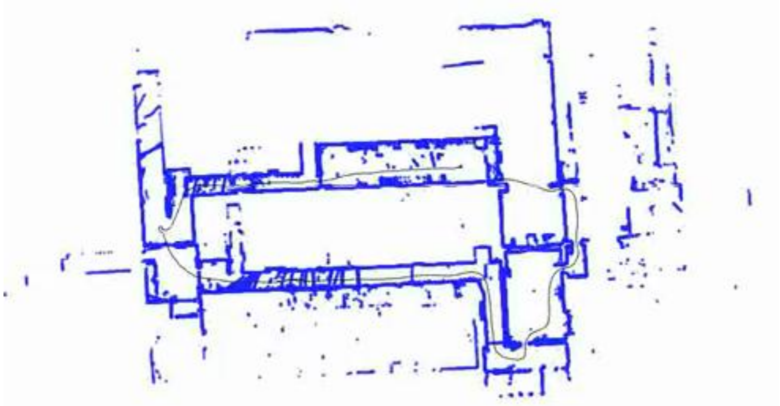


Figure 3: The map of the MAAV workspace generated from correlative scan matching

2.2.3 Control Architecture

The four motors receive commands between 0 and 100 that correspond to 0% and 100% motor power. The percent power is determined from the PID control loop shown in *Figure **4***. Each motor receives a command based upon the error from the set point and the dynamics of a quadrotor. The dynamics are widely known and available and are therefore not reiterated in this paper. Each axis has a trim setting that is applied after the PID gains. The trim allows for the motor power to have a starting point that will allow the vehicle to hover level without the center of gravity being perfectly in the center of the vehicle. The loop is written as a nested for loop with the outer loop changing the motor number and the inner loop cycling through the axes.

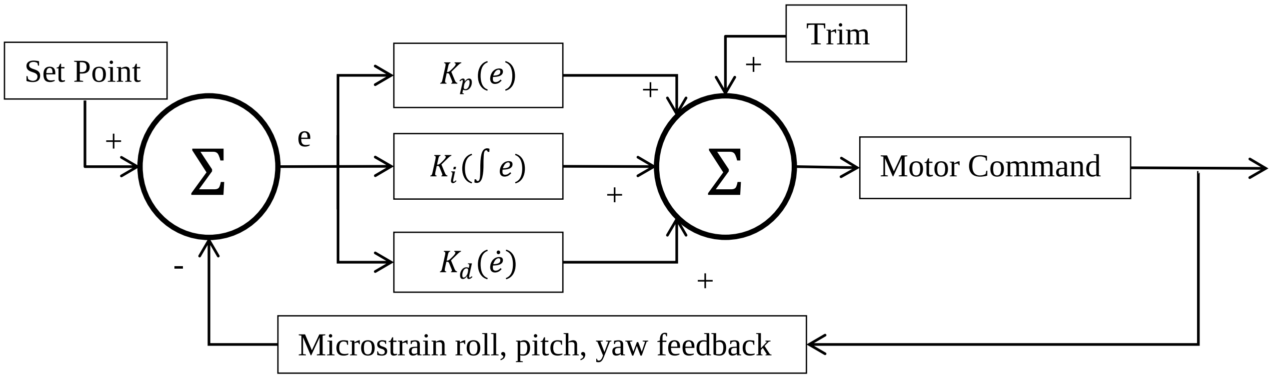


Figure 4: Control scheme diagram showing how motor commands are calculated from state feedback.

2.3 Flight Termination System

In the event that the quadrotor is unresponsive to commands from the ground station, a backup kill switch has been developed. The kill switch operates on a separate frequency than the WiFi and will turn off power to all of the motors when pressed. When the kill switch is released, the 'motors enabled' light turns on warning the users that the motors are receiving power and are operable. Depressing the switch cuts power to the motors. In current test flights, the kill switch has worked 100% of the time. *Figure **5*** below shows the custom built kill switch.

Figure 5: The custom designed and fabricated kill switch that broadcasts over its own frequency

3. PAYLOAD

The quadrotor is capable of carrying a 750 gram payload while remaining underneath the competition mass limit of 1.5 kg. This large payload mass allows the vehicle to carry more advanced sensors without having to sacrifice performance.

3.1 Sensor Suite

3.1.1 GNC Sensors

Microstrain 3DM-GX3-25 AHRS: The Microstrain sensor returns the roll, pitch, and yaw angles as well as the roll, pitch, and yaw anglular rates in the form of radians and radians per second respectively. These values are already filtered and are handled directly in the control loops. The Microstrain is pictured on the left in *Figure **6***.

Figure 6: The Microstrain 3DM-GX3-25 (left) Ping ultrasonic range finder (right). These two sensors are mounted on the vehicle to monitor roll, pitch, yaw, and height.

Ping ultrasonic height sensors: Two Ping ultrasonic height sensors are bracket-mounted at a 15° angle off-axis from the quadrotor. This configuration allows the sensor readings to be averaged when the vehicle is in a relatively horizontal position but also allows for greater vehicle tip before the ultrasonic ping does not return. The Ping is pictured on the right in *Figure* ***6***.

Hokuyo UTM-30LX Laser Range-Finder: A laser range-finder returns a point cloud of 1080 points in a 270 degree, 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 is pictured in *Figure* ***7***.

Figure 7: Hokuyo UTM-30LX Laser Range Finder. This laser range finder can see up to 30 meters in a 270° span which allows the vehicle to build a map of its surroundings

3.1.2 Mission Sensors

Target Detection: Three Firefly MV cameras are mounted to the vehicle, two allowing a ninety degree frontal view and one pointed directly downward. Data from the frontward-facing cameras is merged to form a single image, and then processed in search of both the blue LED that indicates when it is safe to enter the building and any of the three Arabic signs labeling rooms of the compound. Images taken by the downward-facing camera are examined and combed for the flash drive.

Detection of the blue LED and flash drive is accomplished by a combination of simple color processing and a size-based classification algorithm. First, 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. Once the original images have been converted to binary and cleaned up, the problem becomes slightly less trivial. In order to distinguish the blue LED and flash drive from other objects of similar color, the size and shape of each blob is approximated by a series of projections onto random lines that splits the image into several smaller ones. These pieces are finally evaluated and compared separately to the known proportions of the target objects.

Recognition of the three Arabic signs calls for more elaborate and robust methods. Weighing the options of several key point detectors, the newly proposed FERNs algorithm comes out on top for its speed and invariance under different lighting and viewpoint conditions. In order to better suit the computational constraints of real-time processing, the original local extrema of Laplacian method is replaced by a FAST corner detector and a dynamic threshold is used to limit the number of key points in each frame. The result is a speedy and accurate image recognition algorithm, nicknamed PhonyFERNs. *Figure 8* below shows a demonstration of the algorithm.

Figure 8: A demonstration of the PhonyFERNs algorithm on an Arabic sign

Threat Avoidance: Immediate environmental threats are monitored from the Hokuyo laser range finder. The object avoidance procedure does not reference the output of the SLAM algorithms, but looks directly at the raw data output from the Hokuyo. In order to filter out noise from the Hokuyo, objects are only deemed threats if a large enough number of returns from the laser agree. The number of positive threats returned from the laser is a tunable parameter to control how frequently the quadrotor responds to environmental threats.

3.2 Communications

Communication to the vehicle is achieved through a WiFi connection between the router on the ground station and the master Gumstix. The master Gumstix talks to the slave Gumstix and relays information back to the ground. Low level control of the vehicle remains on the slave Gumstix, but the orientation of the vehicle is relayed back to the ground for monitoring purposes. The high level control is commanded from the ground station to the master Gumstix, which then changes the orientation set points to achieve lateral movement. The kill switch communication is on a separate frequency than the WiFi in the event that WiFi communication is broken.

3.3 Power Management System

As the quadrotor loses battery power, the vehicle responds differently and requires varying gains throughout the duration of the flight. Initially, the voltage of the battery is near 12.5V. Its nominal voltage is 11.1V. Once the battery drains a majority of its power, its voltage is reduced to approximately 9.8V. The voltage is monitored on the vehicle to alter the gains mid-flight and to safely shut down the vehicle before damaging the battery.

4. OPERATIONS

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

4.1 Flight Preparations

Prior to the first flight, sensors are calibrated to ensure optimal performance during the mission. The IMU is hard iron calibrated to the magnetic field within the mission environment. This ensures that the yaw value remains steady during the flight. Additionally, the cameras are calibrated to the lighting to ensure proper color recognition. Then, before each individual flight, the vehicle undergoes more safety and performance checks. Battery voltage is checked to be at operating level and the propellers are securely tightened to the motors. Next, the vehicle is connected to the WiFi network and communications are initialized. Then the enable signal is sent and the vehicle is ready for flight.

4.2 Man/Machine Interface

There are two configurations of the man/machine interface for the vehicle, one for autonomous flight and the other for human controlled flight. During both autonomous and non-autonomous flight, the vehicle feeds IMU data, height sensor data, motor commands, laser scans, and camera shots to the ground station. This data is used in real time to determine if the kill command must be sent. The data will also be reviewed after the mission as feedback on the performance of the vehicle. This function will also be operational during non-autonomous flight, but will be accompanied by an input interface that uses a 3DConnexion SpaceExplorer to give roll, pitch, yaw, and height set points to the vehicle, allowing the pilot to intuitively control the vehicle.

Figure 9: 3DConnexion SpaceExplorer used for manual flight during the testing phase.

5. RISK REDUCTION

Many levels of risk reduction have been put in place in order 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 the flight, these properties are recorded for further analysis in the future. All of the data is transferred over the LCM protocol.

5.1.1 Shock/Vibration Isolation

Vibrations are mitigated at every mechanical connection with the use of rubber washers and Sorbothane. “Sorbothane is a patented viscoelastic material that has good vibration and shock absorption characteristics” (Sorbothane). On the 2010 MAAV quadrotor, vibrations were a major concern and caused the ultrasonic height sensors to return false data a majority of the time. It was not understood that vibrations were the issue until the 2011 quadrotor was created. The addition of the Sorbothane and rubber washers has completely removed faulty data from the height sensors. It has also dramatically helped the data from the Microstrain and the Hokuyo.

5.1.2 EMI/RFI Solutions

In previous iterations of the MAAV quadrotor, electromagnetic interference played a large role in unstable flight. The Microstrain sensor was mounted directly to the circuit boards, which had large power plane layers running through them. These power plan layers created Eddy currents, which caused the magnetometers to malfunction. Since the Microstrain uses the magnetometers for its initial calibration and yaw filtering, it was nearly impossible to maintain a solid heading. The current quadrotor has mitigated this issue by mounting the Microstrain further away from the circuit boards and lowering the overall area of the power planes to reduce the magnitude of the Eddy currents. No additional shielding was necessary and the electromagnetic interference does not appear to be present in other sensors or equipment.

5.2 Safety

In order to ensure safe flight and testing of the vehicle, a number of precautions are taken. Testing of the vehicle is done initially on a steel test stand that allows isolation of a single axis for tuning the controller and keeps the vehicle from breaking loose and injuring someone. After the control loops are tuned on the test stand, the vehicle is taken outdoors to test free flight. While the vehicle is in free flight, it has a fishing line tether to the ground to prevent the vehicle from flying away if control is lost. Finally, in all cases when the vehicle is flying, it is subject to two separate kill switches: one in the normal flight software and one external, dedicated kill switch that operates on a completely 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. The custom fabricated parts were machined using CATIA as well. 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 specific vehicle. An image of the CAD model is shown on the left in *Figure 10*.

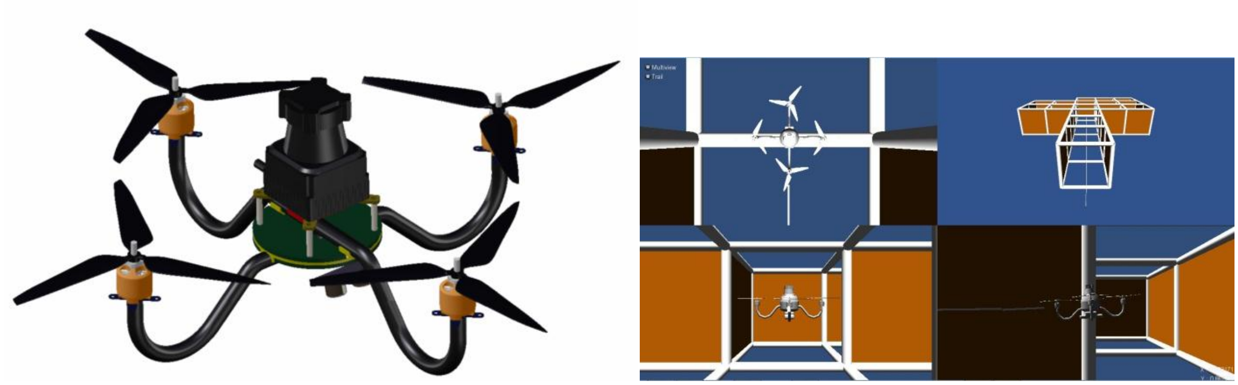


Figure 10: A model in CATIA V5. This was used for full vehicle fabrication and assembly (left) Simulation for path planning algorithms and vehicle stability testing (right)

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 long before the vehicle could fly. Next, the simulation was augmented to control the xy position of the vehicle and take set points for navigation. Finally, the path planning algorithm was implemented and a 3D visualization was created. Thus, the final simulation is able to test both the low level control and high level path planning. A screenshot of the simulation is shown on the right of *Figure 10*.

5.4 Testing

Testing was broken into three stages: calibration, restrained testing, and free flight testing. In the calibration stage, each of the sensors and components was tested off the vehicle to verify their functionality.

The Microstrain AHRS was tested against a Vicon system to verify its output was correct and then it was placed on the vehicle to perform a hard iron calibration to remove any electromagnetic noise in the system. The Hokuyo laser range finder was tested on a rolling cart to calibrate and verify the scan matching and SLAM algorithms that were developed for the mission. Multiple environments were tested under different sensor settings until the results were highly repeatable. The motors and propellers were tested on a force balance in a wind tunnel to record the thrust curve for each of the motors with different propeller configurations. The Ping ultrasonic height sensors were tested under various vibrational loads to determine how much vibration damping would be necessary to preserve the correct sensor output.

Once the individual components were done testing, the vehicle was fully assembled and placed on our custom test stand. 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.

After each of the axes has been tuned on the test stand, free flight testing is performed. Initially, the height control is removed from the system and the height setting is manually controlled from the 3DConnexion Space Explorer. The vehicle is raised roughly one foot off the ground to verify roll and pitch stability and tune yaw stability. Once stability is achieved at one foot off the ground, the vehicle is slowly raised to an operating altitude of four feet. 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 Space Explorer. Movement in each direction is tested before autonomous movement is attempted. Once the outer control loops are stable, preprogrammed, autonomous movement is tested. After movement has been properly achieved, then the Hokuyo laser range finder is used to locate and map the surrounding environment and give the vehicle a world reference coordinate system. At this point the vehicle is tested to maintain a set coordinate with respect to the environment and traverse a predetermined path.

6. CONCLUSION

MAAV has designed and constructed a small quadrotor UAV, weighing only 1.2kg that is capable of autonomous entry into and navigation throughout an unknown building. The vehicle is currently undergoing testing under both manual and autonomous control. We expect our robot to be able to navigate the competition arena and recover the flash drive.

7. REFERENCES

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