Autonomous Quadrotor for the 2012 International Aerial Robotics Competition

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ABSTRACT

The Michigan Autonomous Aerial Vehicles team (MAAV) will compete in the 2012 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 2012 International Aerial Robotics Competition will be held in Grand Forks, North Dakota from July 31 to August 3. 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 two cameras, a 30 meter laser range finder, a 4m 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 recognize 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 finders will feed distance and angle measurements of objects around the quadrotor to a SLAM algorithm to build a map of the environment. Path planning software will command the vehicle to explore 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 an electromagnet will deploy the decoy. All of these objectives will be completed within the allotted ten minute time limit.

1.3 Yearly Milestones

MAAV is entering its third year as a competitor in the IARC. Several improvements have been made from last year's system. Most notably, we have greatly improved our communication latency. This has been achieved through three improvements: upgrade to a wireless-N router, improved packet management and timing from vehicle to ground station, and lastly increased processing power onboard via an Intel Atom Pico ITX board.

MAAV has also devised a novel approach for 3D mapping in a static environment. Most quadrotors require vertical sweeps or a servo-mounted laser scanner to collect sufficient information for three-dimensional rendering of the world. The MAAV quadrotor has been equipped with a second laser scanner, mounted in a vertical orientation (see Figure 2). This allows 3D data to be collected while the vehicle rotates through the course while traversing. *Figure 1* below shows the MAAV system architecture

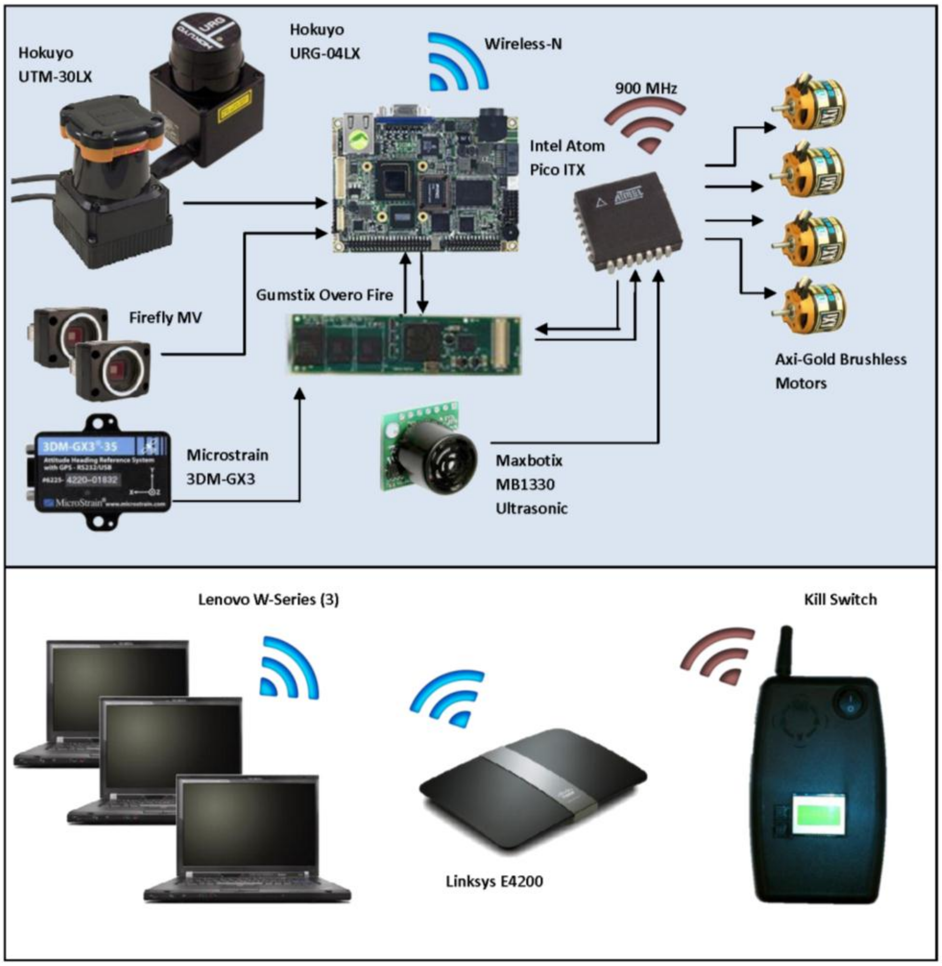

Figure 1: MAAV System Architecture

2. AIR VEHICLE

The MAAV quadrotor weighs approximately 1.47 kg, spans 19 inches from blade tip to blade tip, has a height of eleven inches from base to the top of the Hokuyo, and has a vertical thrust of ~35N. *Figure **2*** below shows a fully assembled vehicle.

Figure 2: A front 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 using a nonlinear controller for roll, pitch, yaw, height, x, and y. This controller was derived from the system dynamics and functions similarly to a PID controller with added nonlinear terms and conversion factors based on the vehicle's physical properties. The roll, pitch, and yaw are monitored through a Microstrain inertial measurement unit. A Maxbotix ultrasonic sensor monitors the height of the vehicle. Once the vehicle is stable, it is able to traverse to waypoints by altering the roll and pitch setpoints until a position is reached. Two Hokuyo laser range finders allow the vehicle to build a three dimensional map of the surrounding environment.

2.2.1 Stability Augmentation System

The quadrotor stability control loops are referred to as the inner loops and receive setpoints from the navigation software. 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 gains for the control 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 four components: global (or high-level) planning, on-board planning, on-board laser/IMU odometry, and Simultaneous Localization and Mapping (SLAM). Due to on-board computational constraints of the quadrotor, the SLAM and global planning algorithms run on a standard laptop at the ground-control station (GCS). Additionally, the GCS offers feedback and an accurate situational awareness to the human operators, even though no interaction is allowed during the mission.

Global Planning: The high-level planner attempts to meet all mission objectives by tasking the quadrotor(s) to complete intermediate objectives which are within the computational limits of the on-board processor. This break-up allows the robots to safely *forget* aspects of the environment and mission that are no longer relevant and thus focus solely on the immediate task at hand. The global planner takes the following information into account when tasking the individual quadrotors through the environment: 1) mission objectives, 2) explored space (overall map, or blueprint, of the mission area), 3) detected windows, Arabic signs, and USB-sticks, 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 robot has limited processing capabilities and thus *forgets* past experiences to allow it to fully utilize its available CPU for the current task at hand. The types of tasks that the on-board planner can complete include 1) waypoint following (most common task), 2) take picture of target object, 3) pick up object, 4) fly through window, and 5) safely land. The primary task of the on-board planner is to follow 3D waypoints via on-board path-planning and obstacle detection algorithms. Due to real-world communications constraints, and tactical advantage, the on-board planner must run with high-confidence and thus have been strongly tuned to avoid any hazardous obstacles.

Laser/IMU Odometry: Predicting how an aerial robot has translated based on integrated data from an IMU is highly unreliable (especially yaw estimation). Therefore, the data from the IMU is augmented with additional information provided by laser odometry. A horizontally mounted laser range-finder offers accurate *x, y, and yaw* feedback (at 40 Hz) by comparing consecutive laser returns. The height (*z*) of the robot is estimated via both the downward facing ultrasonic sensor and the vertically mounted laser range finder. Together with the roll/pitch data directly from the IMU, a decent estimate of the instantaneous quadrotor pose can be generated; this estimate is periodically generated as an odometry edge encoding in 6DOF the quadrotor's estimated movement between time *t* and *(t+1)*. The more accurate this estimate the better the overall system error, however, the SLAM algorithm uses global information (rather than simply consecutive scans and the most recent IMU return) to get a more accurate *global* position of the robot.

Simultaneous Localization and Mapping (SLAM): The odometry edges created on-board the quadrotor suffer from a severe case of temporal nearsightedness. These edges are accurate up close but the errors build up over time, thus, SLAM uses global information to *close loops* over large time horizons to reduce the overall error in the robot's position and map. The algorithm runs on the GCS and is a variant of pose-graph SLAM where the edges in the graph represent the 6DOF 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.

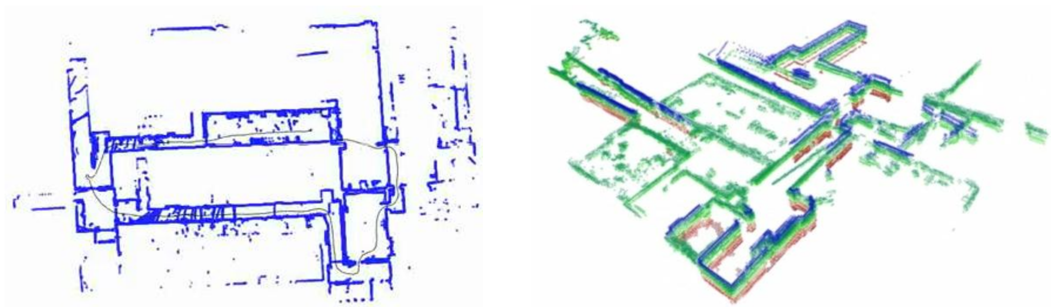

Figure 3: (left) 2D map generated with only a horizontal laser, (right) 3D map generated with both lasers

2.2.3 Control Architecture

As an inherently unstable and under-actuated system, a quadrotor requires a well-tuned, robust controller to stay aloft. MAAV has tested both a proportional-integral-derivative (PID) controller and an integral backstepping nonlinear controller and found that the nonlinear controller both maintains stability of the quadrotor in a larger range of states and rejects disturbances across the operating envelope better than the PID controller. The nonlinear controller is derived from the dynamics, which are widely known and available and are therefore not reiterated in this paper. After deriving the controller, MAAV converted it to use the same tuning parameters as a standard PID controller along with the added nonlinear terms from the dynamics. The controller uses an outer loop to control position and height, which sends setpoints to an inner loop that controls roll, pitch, and yaw.

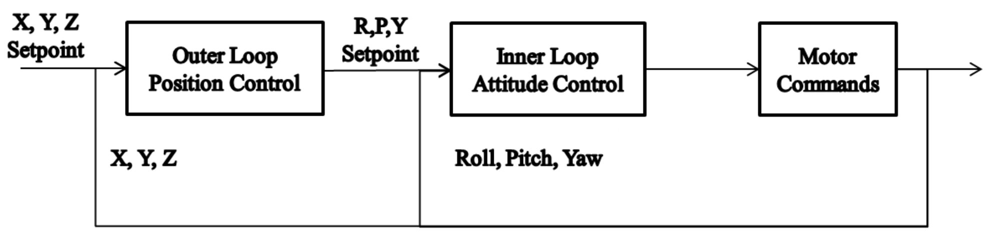

Figure 4: Control scheme diagram

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. There are two buttons on the killswitch; one button commands a safe landing, while the other severs power and halts the motors immediately. *Figure* 5 below shows the custom built kill switch.

Figure 5: Custom quadrotor killswitch

3. PAYLOAD

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 angular 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) Maxbotix ultrasonic range finder (right).

Maxbotix ultrasonic height sensors: One Maxbotix ultrasonic height sensor is mounted below the quadrotor. The ultrasonic sensor is pictured on the right in *Figure 6*.

Hokuyo UTM-30LX Laser Range-Finder: A top-mounted 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*.

Hokuyo URG-04LG-UG01 Laser Range-Finder: A vertically mounted laser-range finder returns a point cloud of 540 points in a 270 degree, 4 meter range surrounding the vehicle 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.

Figure 7: Hokuyo UTM-30LX Laser Range Finder (left) and Hokuyo URG-04LG-UG01 Laser Range-Finde (right).

Cameras: Two Firefly MV cameras operating at 640x480 resolution at 60 frames per sec (fps) mounted one pointing forwards and one pointing down. These images are streamed down to the ground station for processing at a rate that is much slower than 60 fps due to the restrictions on the communication system.

3.1.2 Mission Sensors

Target Detection:

Image processing is done on the ground station due the intensity of the computer vision algorithms. Blue LED detection is done with a blob detector by filtering the image for the appropriate color. 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. 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 the blobs are then filtered by area so small insignificant blobs are not considered.

Arabic sign recognition is done using the Speeded Up Robust Features (SURF) algorithm, which is a feature matching algorithm. We opted to use SURF instead of a faster FERNS due to the fact that FERNS gives many false positives. While SURF is a couple times slower it is extremely robust. Off-bard image processing means the stability of SURF outweighs the speed benefits of FERNS.

USB thumb drive detection is done by SURF modified so that we take color into account as well as the outline of the thumb drive. The thumb drive itself doesn’t have many identifiers therefore it is hard to just rely on the SURF algorithm. The use of the color as well as extracting the outline of the thumb drive is required so there are less false positives when the quadrotor is flying through the environment.

Figure 8: 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 Hokuyo laser range finders onboard. 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 is broken into two parts; 900MHz radio and 5GHz WiFi. The 900MHz signal carries commands from the kill switch and the WiFi carries signals relating to the mission. 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 through a voltage splitter.

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. 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 USB RC controller to give x, y, yaw, and height set points to the vehicle, allowing the pilot to intuitively control the vehicle.

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

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 also have mounted the motors on rubber washers to separate their high frequency oscillations from the rest of the structure. We have also taken certain precautions to protect the payload. Intentional breakpoints are located at each leg-joint so that should the quadrotor crash, the legs will break, thus absorbing the shock and not harming the expensive GNC sensors onboard.

5.1.2 EMI/RFI Solutions

If not properly handled, electro-magnetic interference can be problematic for an intertial measurement unit. MAAV has found that the IMU's yaw data is too largely affected by EMI for the data in this direction to be useful. We have eliminated this issue by extracting yaw data from scan-matching with the laser-range finder, a device that is unaffected by EMI. As was previously mentioned, we have eliminated a large number of our RFI issues from previous years by moving processing that was located on the ground station onto an Intel Atom Pico ITX board.

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 tested in 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 9*.

Figure 9: 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.

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 PWM to RPM and RPM to force are calculated using the MAAV "Test Cell" shown in *Figure 10*. 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 information is output to a text file that is used directly by the onboard controller.

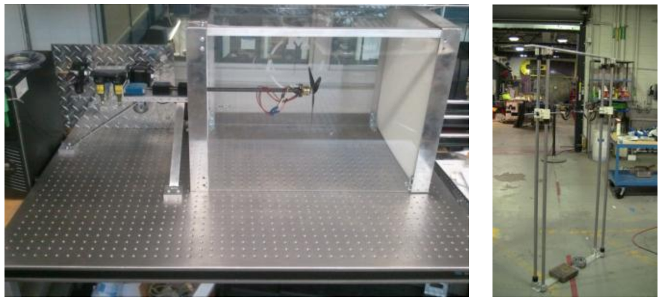

Figure 10: Motor test cell (left) and the vehicle test stand (right)

5.4.2 Restrained Testing

Once the individual components were done testing, the vehicle was fully assembled and placed on our test stand shown in *Figure 10*. 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, free flight testing is performed. Initially, the height control is removed from the system and the height setting is manually controlled from the joystick. 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 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 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 1.47kg 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.

MAAV would like to thank Northrop Grumman Corporation, our title sponsor, as well as all of our other sponsors for their generous contributions to our project…

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