Autonomous Quadrotor for the 2014 International Aerial Robotics Competition

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ABSTRACT

While flight vehicles have become pervasive in today's society, they remain technologically restricted to using GPS for navigating open areas. Vehicles capable of flying in open environments without relying on GPS will pave the way toward redefining currently outdated and expensive methods of structural inspection, search and rescue, and law enforcement operations that often take place in areas with limited GPS availibility. Michigan Autonomous Aerial Vehicles (MAAV) designs and builds lightweight quadrotor unmanned aerial vehicles (UAV) capable of stable, autonomous flight without GPS. MAAV's vehicle will compete in the 2014 International Aerial Robotics Competition (IARC) where it will demonstrate its ability to autonomously manage a herd of ground vehicles in an open environment. Using a combination of control, computer vision, and path planning algorithms, it will herd ground robots over the goal line in the required time.

1. INTRODUCTION

The 2014 International Aerial Robotics Competition will be held in Eufaula, Alabama, from August 3 to August 6. 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

To further advance unmanned aerial vehicular technology, the International Aerial Robotics Competition has put forth a mission that involves open-area navigation and inter-robot coordination. Competing teams must present a vehicle that can navigate indoors without the use of external localization devices, using only visual cues to navigate. The vehicle must be unmanned and operate autonomously. The arena itself is 20m x 20m, and will be populated by autonomous ground vehicles traversing semi-random paths. The UAV must be able to herd these vehicles across the one designated goal line without letting more than 3 of the ground vehicles to escape via the 3 designated out-of-bounds lines. It is also necessary that the presented vehicle be able to avoid dynamic obstacles.

1.2 Conceptual Solution

MAAV has designed, fabricated, and tested a quadrotor UAV to complete the IARC mission. The quadrotor utilizes four cameras, a 4m laser rangefinder, a depth camera, and an optical flow camera. These payloads will allow the vehicle to observe the arena, detect ground robots and

obstacles, and navigate in an open environment. Image processing software will recognize ground robots and the lines in the arena. The laser rangefinder will generate a 2D point cloud around the quadrotor to be used for detecting the obstacles in the arena. Path planning software will command the vehicle to assign priorities to ground robots and plot the most efficient path to control the ground robot with the highest priority. All of these objectives will be completed within the allotted 10 minute time limit.

1.3 Yearly Milestones

MAAV is entering its fifth year as a competitor in the IARC. Due to the new mission and the relaxing of the mass restriction, we have completely redesigned the physical structure of the vehicle. The new vehicle body is much stronger and built with thicker carbon fiber. We are incorporating more safety into the design as well by adding propeller guards and dedicated casing for the battery. The navigational software has been completely overhauled as well. The new software is written in C++ instead of Java and doesn't incorporate SLAM. Instead, algorithms have been developed to navigate based on the location of the ground robots and the goal line in relation to the vehicle. Computer vision algorithms have been developed to recognize ground robots and the lines in the arena and extrapolate those lines to build a full arena model for the quadrotor to use.

2. AIR VEHICLE

The MAAV quadrotor weighs approximately 2 kg, spans 50 cm from blade tip to blade tip, has a height of 30 cm, and has a vertical thrust of ~35N. *Figure 1* shows the MAAV system architecture.
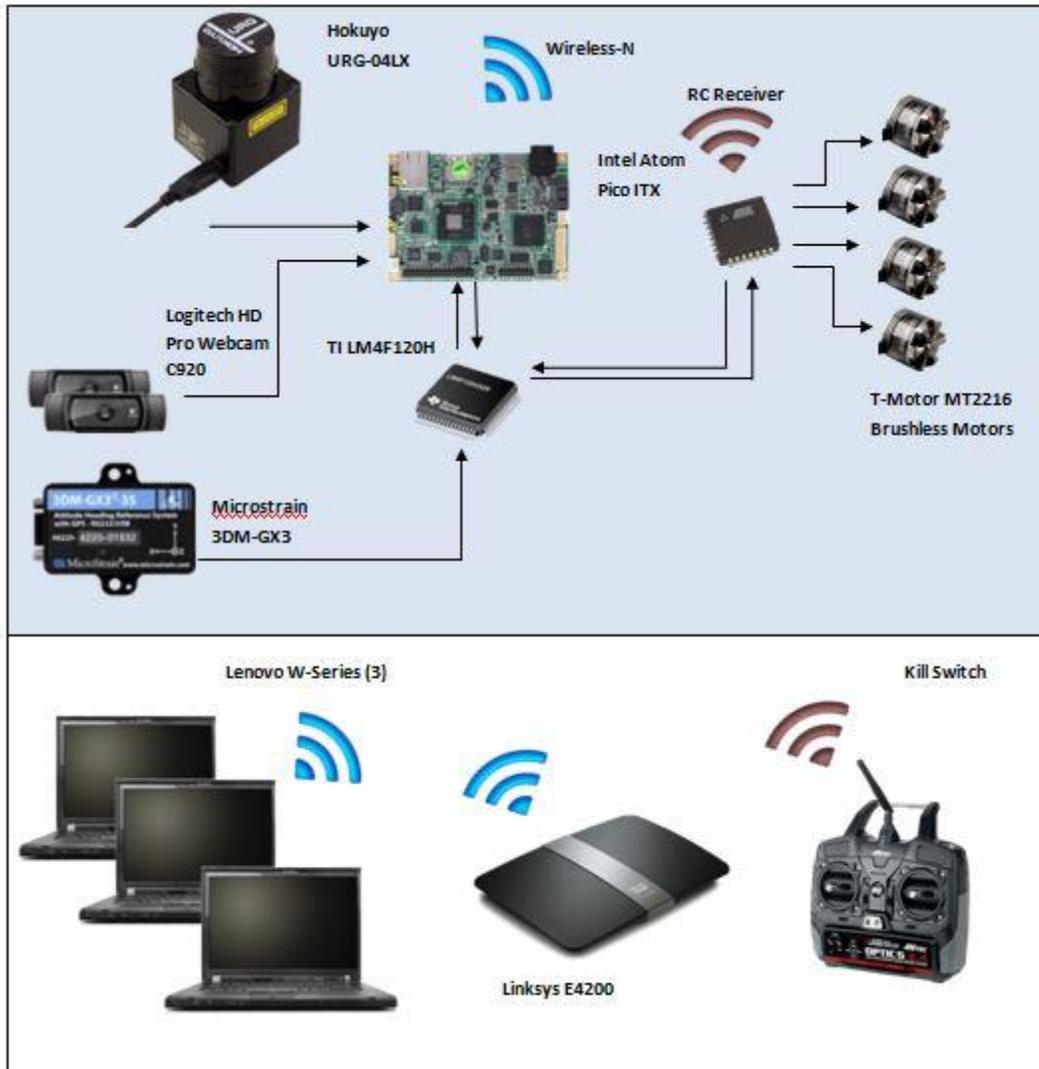
Figure 1: MAAV System Architecture

2.1 Propulsion and Lift System

The quadrotor is lifted by four 25 cm, two-blade propellers mounted on T-Motor MT2216 motors. These produce approximately 35 N of lift for a lift-to-weight ratio of 1.8. MAAV chose two-bladed propellers to achieve higher efficiency.

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. Velocity is measured using optical flow, and height is tracked by using a depth camera. Four cameras allow the vehicle to build a 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 the highest priority ground robot to control, moves to control the selected ground robot, and then repeats. The laser rangefinder is used to add obstacles to the map. Once the map is built, a simple cost map is generated and an A* search is used to plot a path from the UAV to the selected ground robot.

On-board Planning: The on-board planner can take off, build a map of the arena, generate and follow waypoints while avoiding obstacles, and safely land. The primary task of the on-board planner is to build the map, select a target ground robot, and generate waypoints to travel to. For safety and reliability reasons, this planner has been programmed to avoid all obstacles at any cost.

Camera/IMU Odometry: An inertial measurement unit (IMU) is typically used to guess at how much a robotic platform has moved. Safely flying in a large, open space, however, means that a rough estimation on the location of the vehicle is not accurate at distances longer than a few meters and suffers significant error as time progresses. Therefore, the data from the IMU is augmented with additional information provided by camera odometry. The height of the robot is estimated via the depth camera. 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.

2.2.3 Control Architecture

The general control architecture of the system is shown in *Figure 2*. 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.
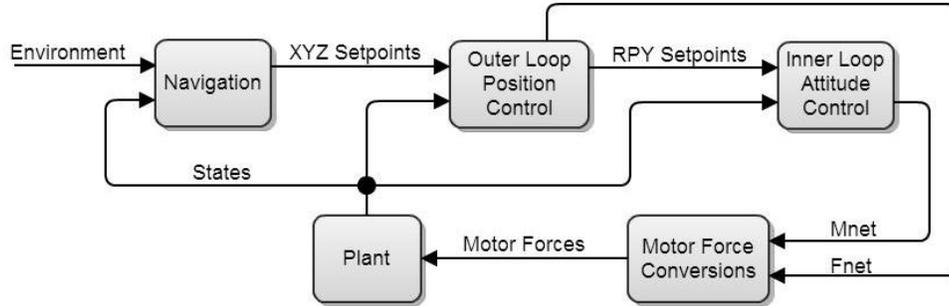
Figure 2: Control scheme diagram

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 3*.

Figure 3: From left to right, The Microstrain 3DM-GX3-25, Logitech C920 Webcam, Hokuyo URG-04LG-UG01 Laser Rangefinder, and PX4 Optical Flow Sensor

Hokuyo URG-04LG-UG01 Laser Rangefinder: A horizontally 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 laser has been mounted horizontally to provide feedback for obstacle avoidance algorithms.

Cameras: Four Logitech web cameras operating at high definition (HD) provide visual feedback of the arena. These sensors send back images which are then analyzed to identify ground robots in the environment, and determine their location with respect to arena boundaries.

PX4 Optical Flow Sensor: Two PX4 optical flow sensors will be mounted on the vehicle to provide velocity and height feedback.

3.1.2 Mission Sensors
Target Detection: To detect ground robots, a blob detector filters the image for red and green 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 to ensure their size is within the acceptable range that defines a ground robot.

Threat Avoidance: The quadrotor detects and avoids threats by analyzing feedback from the Hokuyo laser range finder. MAAV has chosen to employ a cost-map approach to obstacle avoidance. The laser provides information on where any obstacles may be within a 2 m bubble around the vehicle. Paths that require the vehicle to go near any obstacles will have a higher cost than paths that do not, and paths that intersect with any obstacles will have an "infinite" cost.

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 6600mA-hr lithium polymer (LiPo) battery. This allows for a flight time of roughly 12 minutes under flight 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 graphical 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. As a final level of vibration isolation, we have also mounted the IMU on Sorbothane.

Additionally, we have taken precautions to protect the payload. Intentional breakpoints are located in the prop-guards and carbon fiber arms of the vehicle; should the quadrotor crash, the legs or prop guards will break, thus absorbing the shock and protecting more 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

Some safety features are present in the design of the vehicle itself. The most recent MAAV quadrotor features prop-guards that prevent catastrophic failure during minor collisions, provide a level of safety for humans present during flights, and also absorb shock in the event of a crash. MAAV's latest quadrotor design also has a battery cage that protects the batteries from major damage in the event of a crash.

The team has also incorporated a number of precautions into our flight procedures. These precautions ensure safe flights and testing of the vehicle. 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, delrin 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 4*.
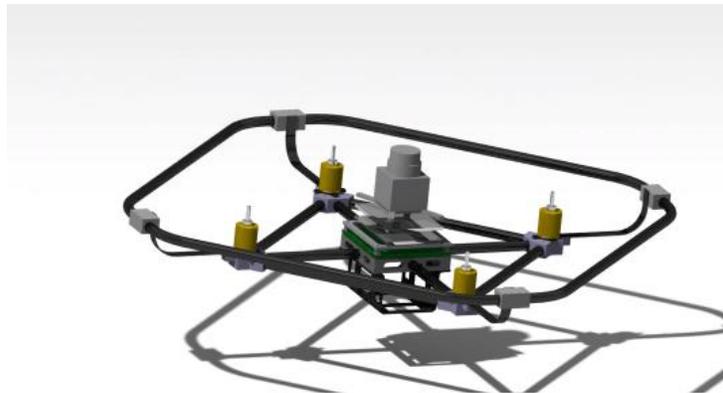
*Figure 4: A model in CATIA V5. This was used for full vehicle fabrication and assembly*

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.
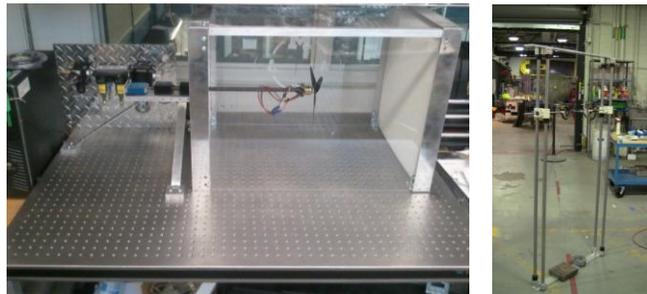
Figure 5: Motor test cell (left) and the vehicle test stand (right)

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 onboard sensors are used to locate and map the surrounding environment. Next, the GUI is used to examine the actions the quadrotor would take if set in autonomous mode. 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 around 2 kg that is capable of autonomous interaction with and control of autonomous ground robots. The vehicle is currently in the manual and autonomous testing phases. We expect the quadrotor to navigate the competition arena and complete the mission objectives in the alloted time. MAAV would like to thank Northrop Gruman Corporation, our title sponsor, as well as all of our sponsors for