Autonomous Quadrotor for the 2015 International Aerial Robotics Competition

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ABSTRACT

Unmanned Aerial Vehicles (UAV) are becoming more popular for both professional and casual uses, but are restricted to open areas and require GPS for navigation. Vehicles capable of flying in environments without relying on GPS will pave the way toward redefining currently outdated and expensive methods of structural inspection, search and rescue, and law enforcement operations that often take place in areas with limited GPS availability. Michigan Autonomous Aerial Vehicles (MAAV) designs and builds lightweight quadrotor UAVs capable of stable, autonomous flight without GPS. MAAV's vehicle will compete in the 2015 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 2015 International Aerial Robotics Competition will be held in Atlanta, Georgia, from August 12 to August 14. 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, two 4m laser rangefinders, an inertial measurement unit, 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 sixth year as a competitor in the IARC. The center of the vehicle body has been simplified structurally to reduce weight and increase strength. Stronger propeller guards add more safety into the design. In addition, the battery case has been redesigned to prevent any chance of direct impact to the battery. The navigational software has been expanded with new algorithms for path planning and localization. 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.
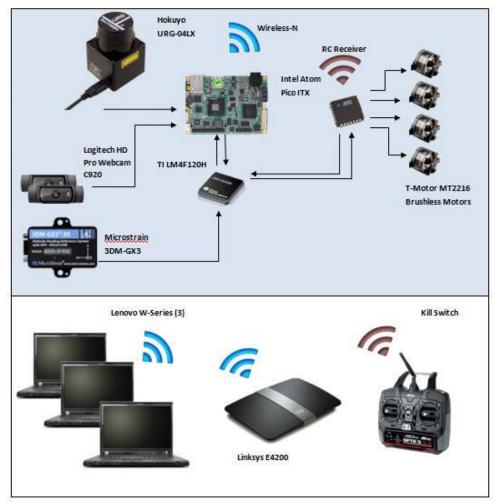

Figure 1: MAAV System Architecture

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 tested 6 different propellers, and chose the set that provided the highest efficiency while providing adequate thrust.

2.2 Guidance Navigation and Control
The quadrotor maintains stable flight by using a two-loop controller architecture that alternates power to each motor controller for roll, pitch, yaw, height, x, and y. The inner control loop is implemented by a DJI Naza-M Lite quadcopter controller (which will herein be referred to as the DJI) and directly controls each motor to change the quadrotor's roll, pitch, yaw rate, and overall body-frame thrust. The outer control loop uses the vehicle's system dynamics to control its x, y, yaw, and height through a PID control algorithm and directly feeds the DJI its desired inputs of pitch, roll, yaw rate, and thrust. The outer loop is implemented an ARM Cortex M4 microcontroller, which also handles communication with the vehicle's navigation processor and various onboard sensors. The vehicle's roll, pitch, and yaw are monitored through a Microstrain inertial measurement unit (IMU). X-Y velocity is measured using the PX4 optical flow camera, and height is tracked by using a laser rangefinder. Four cameras allow the vehicle to build a map of the surrounding environment and track ground robots. Once the vehicle is stable, it is able to traverse waypoints in 3D space determined by the navigation algorithm running on an Intel Atom processor.

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 cascaded proportional-integral-derivative (PID) controller with nonlinear terms that are derived from vehicle dynamics. For each degree of freedom in the inertial or global state of the quadrotor (x, y, z), the controller has a PID loop that converts from value error to desired rate. A second PID algorithm then converts from rate error to force, and inner-loop controller inputs for roll, pitch, and thrust. This architecture allows for incremental tuning thus expediting the testing process. For controlling the yaw of the vehicle, only a value error to rate error PID is used as the inner-loop DJI implements yaw rate error to yaw moment control. The controller maintains stability of the quadrotor in a large range of states while rejecting external disturbances.

2.2.2 Navigation
The navigation software is optimized for the known IARC arena as well as a sparse environment. Straight-line path planning augmented with a simple height-based avoidance algorithm for obstacle avoidance provides a path in $O(n)$ with n obstacles in the path. The ground robot to target is chosen by a combination of vehicle location, ground robot location, and probabilistic estimates of future ground robot positions. The laser range finder provides a point cloud, which is used to update the locations of the dynamic obstacles in the arena. The cameras feeds provide information on the location of the ground robots. Since the ground robot movement and obstacle movement both contain randomness and the usual mechanical noise, their respective locations are updated using state estimation based on physical models.

On-board Planning: The on-board planner can take off, populate its map of the arena, generate and follow waypoints while avoiding obstacles, and safely land. The primary task of the on-board planner is to continuously populate 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 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 with a laser sensor. The navigation software predicts the state of the arena that should be seen by the cameras and corrects its position estimates based on the differences between prediction and reality.

2.2.3 Control Architecture

The general control architecture of the system involves a multi-processor and multi-step feedback control loop. The navigation software (implemented on the navigation processor) outputs inertial position waypoints of x, y, and z and a desired heading or yaw to the outer-loop controller. The outer-loop position controller (implemented on the flight controls microcontroller) outputs net forces on the vehicle that are used to calculate the roll, pitch, yaw rate, and thrust setpoints. These setpoints are the inputs to the DJI inner-loop controller. The inner-loop attitude controller calculates the final force and torque resultants, balances them across the vehicle's four motors, and ultimately controls each motor. All sensor feedback for measuring the vehicle's state are sent back to the flight controls microcontroller which filters the measurements using an Extended Kalman Filter. The filtered state feedback is sent to the navigation processor and outer-loop controller.

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.

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

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: One PX4 optical flow sensor will be mounted on the vehicle to provide inertial velocity feedback.

Pulsed Light Lidar-Lite Laser Module: One Lidar-Lite laser rangefinder will be mounted on the vehicle to provide 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 competition 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
MAAV tested the sensors under flight conditions and found that the cameras and IMU were sensitive to vibrations while the motors were running at high power settings. To counter this, the cameras have been mounted with fittings that incorporate vibration dampening material. The IMU is mounted to the vehicle on a bed of sorbothane to isolate it.

Additionally, our vehicle has shock absorbing landing gear to protect against hard landings and crashes. The landing gear is designed to absorb shock from both direct drops to the ground, and angled impacts. The vehicle is also fitted with rigid propguards. These not only protect the vehicle from harming objects in its environment, but protect the propellers from impact damage as well.

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 battery 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 a prototype CAD model is shown in *Figure 4*.
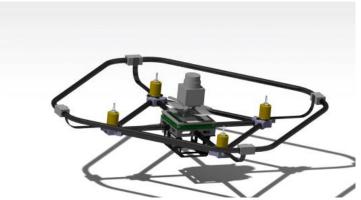

Figure 4: A prototype model in CATIA V5

Simulation of the navigation and control algorithms was done with the Gazebo Robotics simulator. Gazebo is a full physical simulator, which allows for the testing of the controls algorithms. In addition, Gazebo includes models and tutorials for IMU, laser, and camera noise to put strain on the Kalman filter and the computer vision algorithms. Lastly, the navigation algorithms and all the diagnostic information that is generated can be viewed in real-time and stored for later analysis.

5.4 Testing

Testing is broken into two stages: calibration, 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.

Figure 8: Motor test cell

5.4.2 Free Flight Testing
After performing calibrations, the vehicle is tested in free flight. This is because the inner-loop DJI controller is a tested, off-the-shelf module that requires no tuning. However, the outer-loop controller still needs to be tested and its PID gains need to be tuned. For safety purposes, ropes are attached to the vehicle. Initially, the height control is removed from the system and the height setting is manually controlled from a joystick. The vehicle is raised roughly 30 cm off the ground to verify DJI functionality and tune x, y, and yaw stability in the outer loop. 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. Once this stability is achieved the PID gains for height control are tuned until they are stable. Following this, manual x, y, 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 allotted time. MAAV would like to thank Northrop Grumman Corporation, our title sponsor, as well as all of our sponsors for their generous contributions.

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