Multirotor Aircraft Developed By Kennesaw State University to Compete in the 2016 International Aerial Robotics Competition

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Abstract

For Mission 7 of the International Aerial Robotics Competition, the Kennesaw State University Aerial Robotics Team has developed a multirotor aerial vehicle capable of stable interest-based autonomous flight. Using its on-board sensor array, the multirotor can locate and interact with other robotic vehicles in order to accomplish the objectives. Additionally, the robust 3D-printed design allows the multirotor to safely withstand collisions with obstacles and other aerial vehicles encountered during the mission.

1 Introduction

1.1 Problem Statement

Mission 7 of the IARC requires teams to have an autonomous aerial vehicle that can demonstrate the ability to interact with moving targets, navigate within a dynamic environment with no external aids, and interact with other autonomous aerial vehicles. These factors are assessed by the team's ability to successfully guide ten randomly moving ground robots through one side of an arena while simultaneously avoiding obstacles in its path.

1.2 Conceptual Solution

To successfully complete the mission, we will use a multirotor designed for autonomous flight in a GPS-restricted environment. The strategy will be to focus the effort on one single ground robot until it reaches the goal. The multirotor will first detect any ground robots within its visual reach. Once a target has been chosen, the multirotor will attempt to traverse the arena to hover above the target. The multirotor will then be able to guide the target by interacting with the ground robot's sensors if their orientation is in need of adjustment. The multirotor will continue to target new ground robots while avoiding pylons until time runs out.

If the multirotor cannot detect a new target, it will go into a patrolling state. The multirotor will navigate around the perimeter within the arena until it can detect a new target. The object avoidance system will also be running in parallel throughout the procedure. If the multirotor has currently locked onto a target, it will avoid any pylons by hovering above the height of the pylons while still in pursuit of the current target. In other cases, the multirotor will attempt to move right or left around the pylon in order to avoid it.

The vehicle will decide how to interact with the ground robots based on the following goals:

1. Takeoff and localize the multirotor to the arena.
2. Identify a targeted color (green or red).
3. Traverse the arena to hover over the targeted ground robot.
4. Detect the orientation of the targeted ground robot.
5. Modify the targeted ground robot's trajectory to guide it toward the goal line of the arena.
6. Continue to guide the current targeted ground robot until it has reached the goal.

If at any point the multirotor cannot locate a ground robot, it will default to patrolling the perimeter of the arena while attempting to detect a new target. This process will repeat until the timer runs out. Figure 1 shows a visual representation of our strategy for Mission 7.

1.3 Yearly Milestones

Receiving the *Most Innovative Design* award two years in a row for Mission 7 is a proud achievement; however, the implemented hardware and software was not fit for accurate localization and targeting. In order to improve the capabilities of our system, we have added several cameras and a DJI Guidance system. To make full use of this new hardware, many parts of our software have been modified or completely redesigned. Using these new sensors and software techniques, we have dramatically increased the stability and tracking of our system. The milestones for the years following the 2016 competition are itemized below:

- Retaining accurate flight plans while maneuvering on the field.
- Accurately estimate the vehicle's position.
- Continuously integrate electronic components and sensors more seamlessly.
- Improve obstacle detection, classification, and avoidance.
- Continuously evolve the multirotor's structural elements to increase performance and crash worthiness, as well as modularity so that parts that do break may be easily swapped out for replacements.

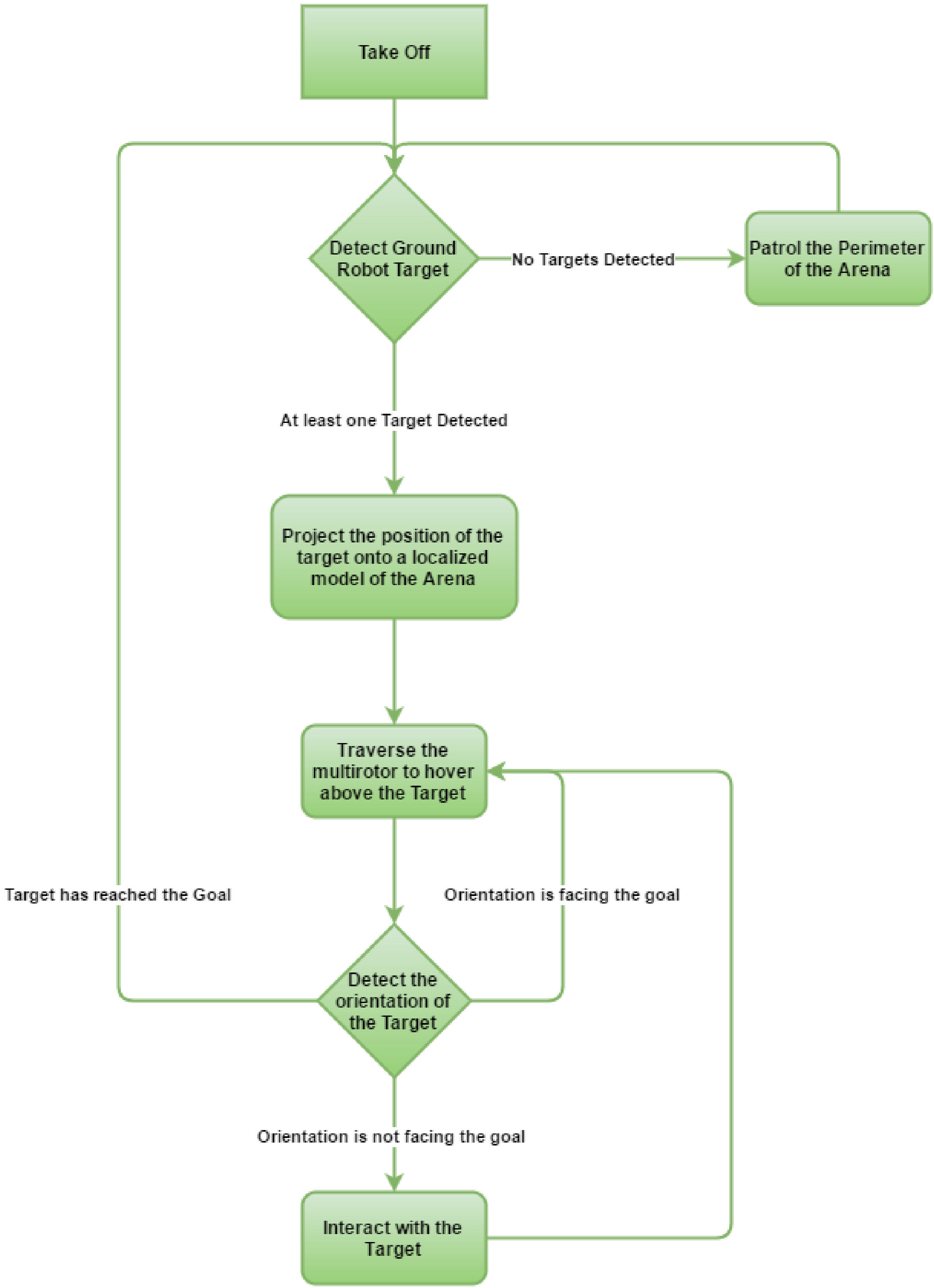

Figure 1: A visualization of our Mission 7 strategy.

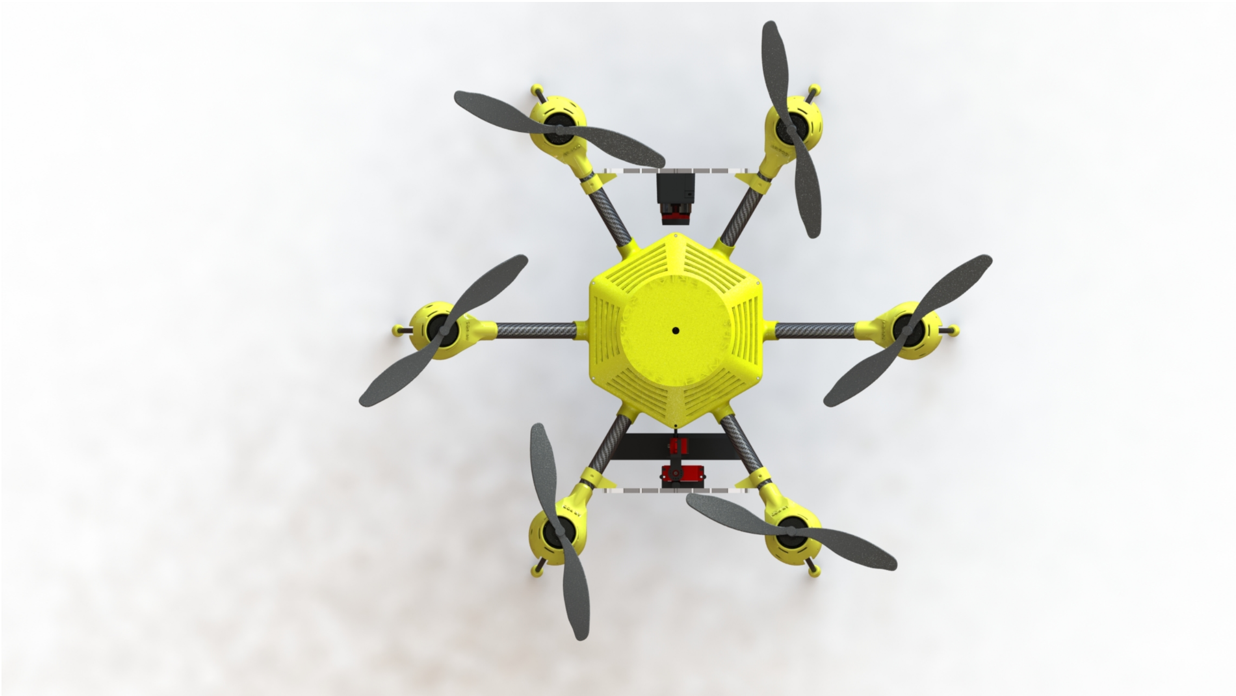

Figure 2: A render of the top view of the multirotor airframe.

These improvements will build upon the next generation which will tackle different issues. These future issues may include the following:

- Tracking and localizing the position of multiple ground robots in real time.
- Better interaction systems from multirotor to ground robot.
- Optimized flight patterns for object avoidance and targeting.

2 Air Vehicle

The multirotor utilizes a modular composite airframe as shown in Figure 2. The 3D printing method of fabricating the "pods" of the airframe allows for rapid design changes and more design freedom with the contours of the arms. A ten degree tilt was implemented to direct propeller wash outward, increasing the stability of the airframe. The "arms" consists of magnetic circuit connectors inserted into the carbon-fiber tube structure. The carbon fiber tubes have an airfoil shape to reduce drag from direct propeller wash. The core of the structure is made up of a series of 3D-printed plates which interlock with each other as well as levels for mounting sensor packages. Through careful design tests, these plates are capable of structurally holding the craft together and provide many platforms to hold our sensors and flight computer.

2.1 Propulsion and Lift System

Six Tiger U3 700 kV motors and 12" × 4.5" propellers provide lift for the multirotor. The total thrust generated is 9600 g, with an efficiency of 6.44 g/W of thrust at maximum throttle output. At hover throttle, the craft has an efficiency of 10.31 g/W. The propulsion system is powered with a 4 cell lithium-ion polymer battery.

2.2 Guidance, Navigation, and Control

The movement of the vehicle is dictated by three systems interacting with each other. The first system is the high-level planning control system. This system is responsible for determining tasks for the multirotor based on accumulated sensor data and the current progress towards mission objectives. The second system is the low-level path planning control system, which generates short-term waypoints for the multirotor. This incorporates the desired goals from the first system, as well as obstacle avoidance subsystems. The third system is the stability augmentation system, which is responsible for sending the control signals to the motors and executing the low-level plans. These three systems work together to help complete the objectives of Mission 7.

2.2.1 Stability Augmentation System

For flight stabilization, a Pixhawk autopilot designed by the PX4 open-hardware project is used. The on-board inertial measurement unit (IMU) handles flight stabilization and disturbance rejection, such as wind blowing from air conditioning units at the venue.

2.2.2 Navigation

One of the biggest challenges of Mission 7 is being able to accurately navigate within an environment without external navigation aids. By establishing a point of reference (e.g. the top left corner of the arena) and accurately measuring displacement from that reference, the multirotor will always know its position within the arena. We utilize sensor fusion of a number of different sources to be able to measure the displacement and reduce drift. The multirotor is equipped with DJI's Guidance system consisting of five stereo visual and depth sensors. In addition, a downward-facing HD webcam is used to detect the 1 meter white squares and interpolate the multirotor's position within each square. This combination of sensors, as well as the use of Kalman filtering, will give us a reasonably accurate estimate of the multirotor's displacement. In the event the multirotor detects a large variance between estimates from each sensor, it will return to its point of reference to zero out the displacement.

The Pixhawk, running the ArduCopter-3.3 beta firmware, is a nearly feature-complete open-source UAV solution. For this reason, the high level navigation and planning is centered around utilizing the ArduCopter firmware to its fullest. However, since most of ArduCopter's autonomous features are based on GPS, tweaks were needed to be able to utilize ArduCopter's navigation and mission planning in a GPS-denied environment. This problem was overcome by sending Pulse Width Modulation (PWM) signals that the Pixhawk thinks are manual pilot inputs, but is really a set of the multirotor's static reference point. The set is generated and updated by the displacement estimator described earlier. This navigation method allows us to focus on the main competition goals and spend less time implementing a low-level flight system.

2.3 Flight Termination System

In the event that the multirotor suddenly experiences undesired behavior that poses an immediate threat to people or the environment, pressing a switch located at the ground station will kill all power to the motors. Alternatively, a signal can be sent to safely land the multirotor or allow manual override of the controls in the presence of a less serious event.

3 Payload

3.1 Sensor Suite

All sensors on the multirotor can be classified as one of two types: GNC (Guidance, Navigation, and Control) sensors or mission-specific sensors.

3.1.1 GNC Sensors

The GNC sensors on the multirotor include the Pixhawk's IMU, the DJI Guidance system, and a Hokuyo LiDAR. The Pixhawk's IMU has 9 degrees of freedom and is used for data collection

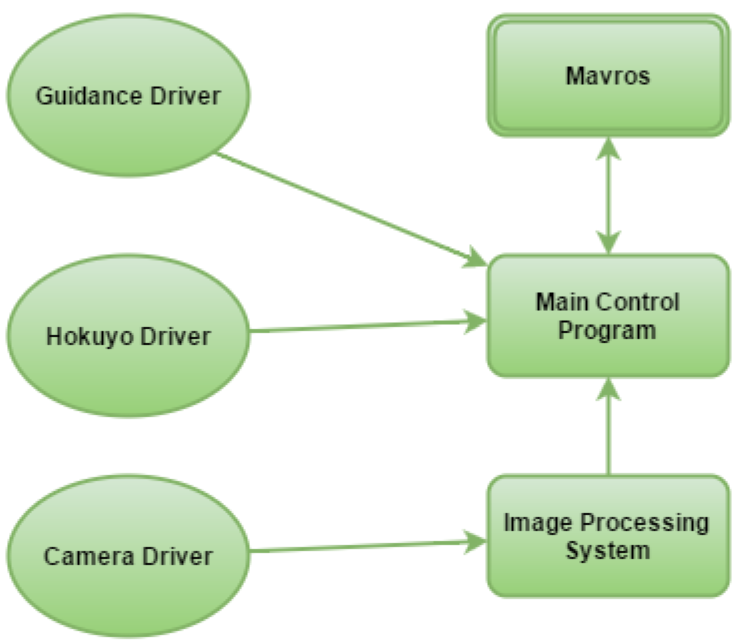

Figure 3: Sensor network diagram.

and fed into the position and velocity estimator. The Guidance system is used as our primary localization sensor. It utilizes optical flow to track the vehicle's velocity and position reasonably accurately. The Hokuyo is used for object detection and altimetry.

3.1.2 Mission Sensors

The mission specific sensors used on the multirotor include a Fisheye HD Camera and DJI Guidance system. Both visual sensors will be tracking and confirming detection of the colored plates on the ground robots. The Hokuyo will also be used for detecting the proximity of the four large pylons.

3.2 Communications

The multirotor relays vital data to a ground station using the IEEE 802.11n and IEEE 802.15.4 wireless standards. Additionally, the manual override employs the use of a radio frequency transmitter operating in the 2.4 GHz range.

3.3 Power Management System

A single four-cell 14.8 V Lithium-ion Polymer (LiPo) battery is used to power both the brushless motors and the on-board electronics. A power distribution board with built-in circuit protection and voltage regulation is used to ensure the electrical system is safely powered. Batteries are charged safely and expeditiously using a Thunder AC6 Smart LiPo balance charger.

4 Operations

4.1 Flight Preparations

Before each flight, steps are taken to ensure the flight is both safe and successful. First, the batteries are checked to see if they are fully charged. Partially charged batteries can cause undesired flight behavior that may result in damage to the multirotor. Next, at least two team members must inspect the multirotor and confirm that all hardware is properly connected and secured to the frame. When everything is cleared of any problems, the ground station and manual override transmitter are powered up and checked. Afterwards, the aerial vehicle is powered on and a launch script activates all necessary software and peripherals. After a connection to the ground station has been established, a table-top test is performed to confirm that data is being correctly relayed, and that the manual override and kill switch inputs are being acknowledged by the multirotor. Once all the preceding steps have been performed, the multirotor may be safely flown.

- ☐ Batteries are fully charged.
- ☐ FIRST INSPECTION: All connectors and hardware secured in the right place.

- ☐ SECOND INSPECTION: All connectors and hardware secured in the right place.
- ☐ Ground station and manual override transmitter powered on.
- ☐ TABLE-TOP TEST 1: Acknowledgement of manual override.
- ☐ TABLE-TOP TEST 2: Acknowledgement of kill switch.
- ☐ Manual override pilot on standby.
- ☐ Takeoff!

4.2 Human-Machine Interface

A ground station located outside the arena displays vitals such as the multirotor's current position and behavior. Images from the multirotor's onboard cameras may also be viewed. The vehicle is equipped with a radio controlled kill switch. This kill switch remotely disconnects the power to the vehicle in the event of an emergency. The ground station also has a software manual override that can be triggered simply by pressing the designated key on the keyboard. When the software manual override is engaged, the vehicle stops all actions and lands at a preset decent rate.

5 Risk Reduction

5.1 Vehicle Status

5.1.1 Shock/Vibration Isolation

The multirotor is designed using materials that exhibit an acceptable amount of elasticity to prevent unnecessary vibration from the high RPM motors. Vibration originating from the motors is absorbed and dampened by the structure of the multirotor. Metal structural components have the characteristic trait of transferring vibrations to all attached components. Therefore, this problem has been prevented by manufacturing the vehicle using ABS plastics, nylon hardware and G10 fiberglass. The elastic nature of the multirotor's structure and assembly hardware reduces the need for additional shock/vibration protection. These features enable the multirotor to obtain stable images from the onboard cameras without the added weight of additional shock protection.

5.1.2 Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) Solutions

To prevent back EMF or power spikes caused by the switching motor coils, protection circuitry is used on all computer hardware. Low-pass filters and shielded cables are used whenever possible to counteract high-frequency noise caused by EMI. Communications antennas are placed as far away from motors and other antennas as possible. Additionally, multiple radio frequency bands are used to minimize RFI between them, as well as RFI from outside sources at the venue.

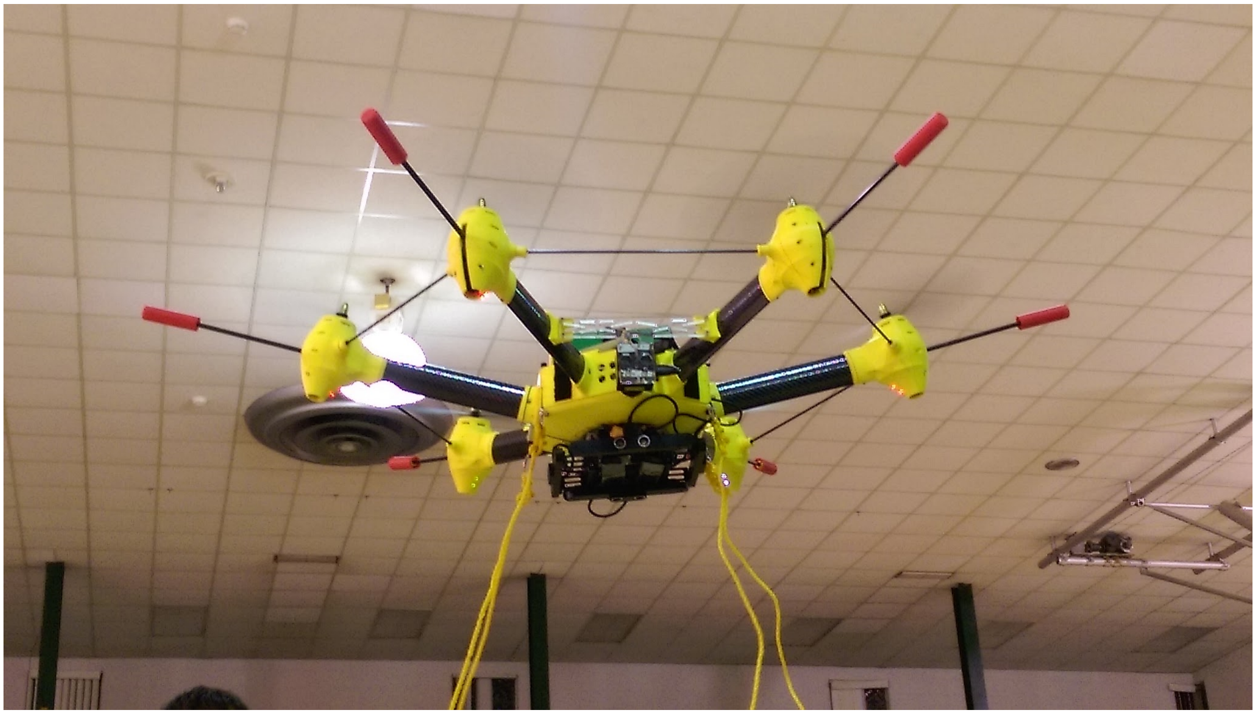

Figure 4: An autonomous flight test conducted with safety tethers attached.

5.2 Safety

In the event that the multi-rotor suddenly experiences undesired behavior that poses an immediate threat to people or the environment, pressing a switch located at the ground station will kill all power to the motors. Alternatively, a signal can be sent to safely land the multirotor or allow manual override of the controls in the presence of a less serious event. The landing gear also retracts in-flight and doubles as the multirotor's propeller guards.

5.3 Modeling and Simulation

In order to test the behaviors of the multirotor in the Mission 7 environment, the 3D visualization tool *rviz*, as well as custom Unity simulations were used. With the use of these programs, the multirotor's behaviors can be tested effectively. This not only saves time, but it is also cost-effective. Instead of purchasing several iRobot Create ground robots, the multirotor's behaviors can simply be tested in this virtual environment. The interactions due to the pseudo-random behavior of the ground robots can be observed, and strategies to complete the mission can be developed and tested based on these observations.

5.4 Testing

Initial testing of the multirotor involved placing it on a test stand and ensuring the flight control systems worked as expected. Tests of autonomous takeoff and landing functionality were performed.

Once the multirotor was able to autonomously ascend and descend safely, the ability to travel along a given flight trajectory was tested. Tests of the multirotor's ability to detect and track the ground robots were also performed. The final tests involved successfully landing in front of a ground robot while avoiding static obstacles placed in its flight path. An on-campus gym was used to closely recreate the Mission 7 environment.

6 Conclusion

The Kennesaw State University Aerial Robotics Team has developed a multirotor aerial vehicle capable of solving several problems posed by Mission 7 of the International Aerial Robotics Competition. Using its on-board sensor array, the multirotor can locate and interact with other robotic vehicles in order to accomplish objectives. The structure of the multirotor is able to safely withstand collisions with obstacles and other aerial vehicles encountered during the mission. With the completion of Mission 7 likely to happen some time in the next few years, the IARC will have once again pushed the envelope in the state of the art of aerial robotic flight behavior.