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# Multicopter Aircraft Developed By Kennesaw State University to Compete in the 2015 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 multicopter aerial vehicle capable of stable interest-based autonomous flight. Using its on-board sensor array, the multicopter can locate and interact with other robotic vehicles in order to accomplish the objectives. Additionally, the robust 3D-printed design allows the multicopter 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 sterile 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 multicopter designed for autonomous flight in a GPS-restricted environment. Our strategy consists of patrolling the arena perimeter to guide the ground robots toward the goal line. This flight pattern will allow the vehicle to constantly monitor the arena's perimeter and potentially catch any runaway ground robots before they cross the arena boundary. The aircraft will detect, identify, and estimate the trajectories of ground robots using an RGBD camera, a secondary downward-facing camera, and computer vision algorithms.

Due to the pseudo-random behavior of the ground robots and the limited observability of the arena, we have determined the most effective way to complete the mission is by restricting flight

to the "defensive" pattern of patrolling the arena perimeter. This allows the ground robots to casually interact with each other, while the aerial robot will only interact with ground robots that have been identified as having a high probability of exiting through an incorrect side of the arena.

The vehicle will decide how to interact with the ground robots based on prioritized goals. A basic list of goals from high to low priority are as follows:

1. Takeoff and localize the multirotor to the arena.
2. Maintain a "defensive" flight pattern by following the arena perimeter dynamically while avoiding other obstacles.
3. Detect and localize the ground robots in the arena.
4. Target a ground robot for "herding" (i.e. modifying the robot's trajectory to guide it toward the green line of the arena) if it is detected within a specific distance from the multirotor.
5. Calculate the trajectory of the currently targeted ground robot.
6. Herd the ground robot by landing in front of the robot to engage the bumper sensor, or by interacting with the Hall-effect sensor using a magnet.

### 1.3 Yearly Milestones

Despite receiving the *Most Innovative Design* award during the first year of Mission 7, the multirotor did not meet its expected goals due to drive crashes of the on-board computer, communications issues, and a catastrophic failure of the power system mid-flight. Many improvements have been made over the past year to solve these issues and to work towards the milestones set in 2014. For the 2015 competition year, these milestones remain largely the same:

1. 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.
2. Continuously integrate electronic components and sensors more seamlessly.
3. Improve optical flow technology and localization techniques to be able to move freely around the arena with minimal drift.
4. Improve obstacle detection, classification, and avoidance.
5. Improve detection of ground robots by being able to detect robot orientation.



Figure 1: Improved airframe design.

## 2 Air Vehicle

The multirotor utilizes a fully 3D-printed airframe. The 3D printing method of fabricating the "arms" 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 core of the structure is made up of a series of G10 plates manufactured using a CNC mill. This material is rigid, lightweight, and can handle large impacts. These internal plates place the flight controller board directly over the center of gravity within the airframe.

### 2.1 Propulsion and Lift System

Six Scorpion 1280 kV motors and 8 in by 4 in propellers provide lift for the multirotor. The total thrust generated is over 3600 g, with an efficiency of 6.22 g/W of thrust.

### 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 goals for the multirotor to achieve 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 and final 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 the rejection of disturbances, 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 in a sterile 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 a PX4Flow embedded optical flow camera that is capable of calculating flow vectors at 120 Hz in low light conditions. 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. A high-resolution 3-axis Phidgets IMU is used to provide position and velocity estimates as well. This combination of sensors, as well as the use of Kalman filtering, will give us a reasonable 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 signals that the Pixhawk thinks is GPS data, but is really an offset of the multirotor's static reference point. The offset 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 path planning 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.

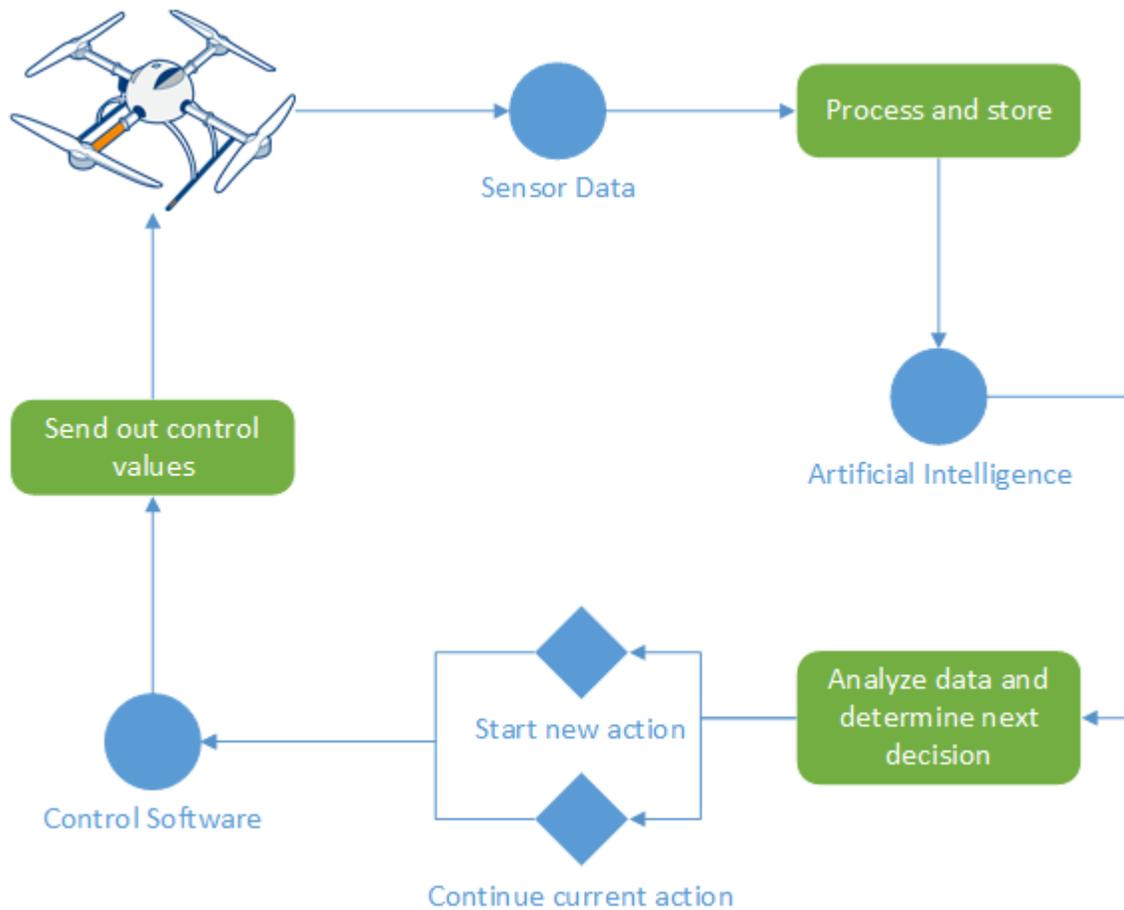


Figure 2: Control system architecture.

### 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 PX4Flow optical flow system, and a LiDAR Lite. The Pixhawk's IMU has 9 degrees of freedom and is used primarily for stability augmentation, but the data is also collected and fed into the position and velocity estimator. The PX4Flow is also used for position and velocity estimation, while the LiDAR Lite is used for altimetry.

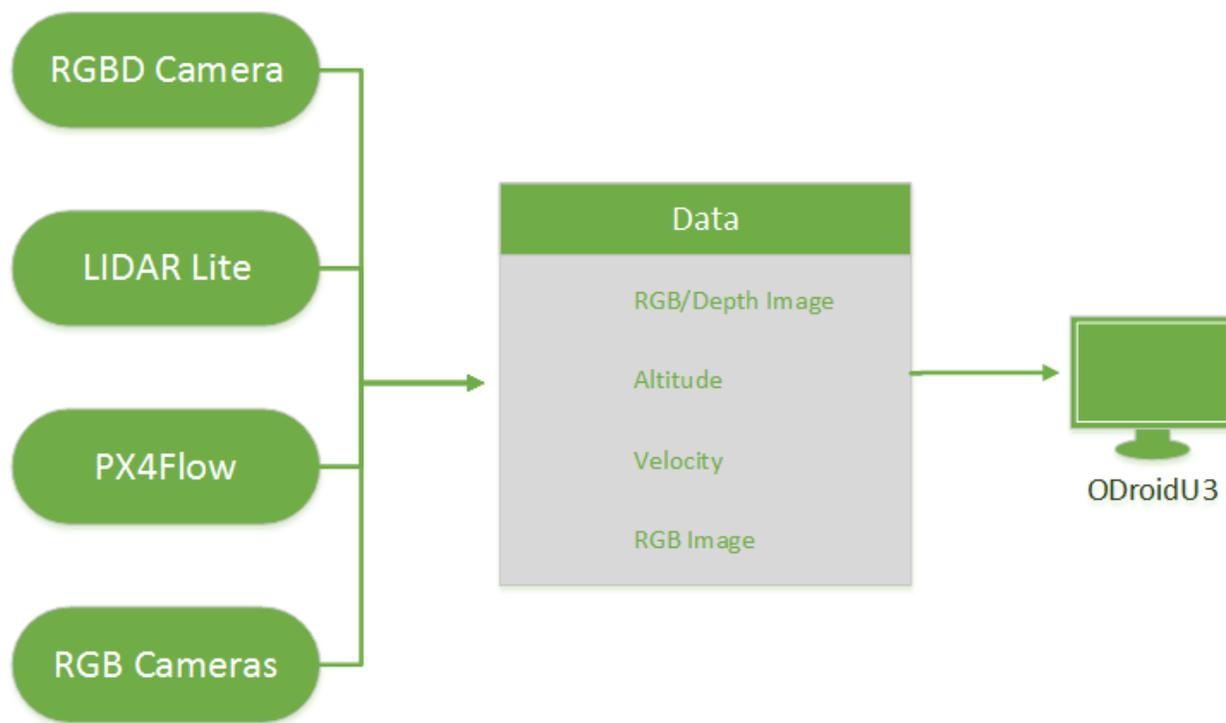


Figure 3: Multicopter sensor suite.

### 3.1.2 Mission Sensors

The mission-specific sensors used on the multicopter include an Xtion Pro Live RGBD camera, as well as an HD webcam. The Xtion Pro Live is used to detect the iRobot Create ground robots and avoid the four large pylons in the arena. The HD webcam is used to detect the grid lines in the arena for more accurate localization.

### 3.2 Communications

The multicopter relays vitals and other 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 vitals are 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 pose and behavior. Images from the multirotor's onboard cameras may also be viewed. The kill switch and manual override transmitter are both located at the ground station as well.

## 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.

## 5.2 Safety

To prevent injury, numerous protections have been put in place. 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. 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 PlayStationMobile simulation were used. With the use of these programs, the multirotor's behaviors can be effectively tested. 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 good 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 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.

## 6 Conclusion

The Kennesaw State University Aerial Robotics Team has developed a multirotor aerial vehicle capable of solving some of the problems proposed in 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 sometime 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.