Development of 'Eagle Quad' quad-rotor for the International Aerial Robotics Competition 2011

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1 ABSTRACT

For the International Aerial Robotics Competition's (IARC) 6th Mission in August 2011, Embry-Riddle Aeronautical University (ERAU) is sending a newly designed quad-rotor called Eagle Quad to compete. The quad-rotor is made with the latest 3D-printing technology with a material that is robust and light. The quad-rotor vehicle is both simple and very portable as it can be assembled and disassembled without difficulty. It will have a small laser range finder that can scan up to five meters, camera and a magnetic dredging tool to complete the flash-drive pick-up.

2 INTRODUCTION

2.a Problem Statement

ERAU created a team of aerospace, mechanical and computer engineers to build an aerial vehicle to compete in IARC's sixth mission which will be held in August 2011. The IARC team at ERAU has chosen a quadrotor design for this year's mission. According to the sixth mission, the vehicle must fly autonomously inside a secured building without the use of Global Positioning System (GPS), to explore and search for a flash-drive that will be placed on a table inside the building. Once it is located, the vehicle will pick it up and fly it back to the team. Throughout the mission, the quad-rotor must also be capable of avoiding traps and warning sensors. Heading and status information must also be transmitted back to the Ground Control Station via WI-FI, to be monitored by judges and the team.

2.b Conceptual Approach

For the sixth mission, an aircraft that can hover is necessary to pick up the flash-drive and be cautious of the security system. This ruled out fixed wing aircrafts. In past missions, ERAU has experimented with numerous types of rotorcrafts such as a co-axial helicopter, a helicopter and even entered a mono-copter however; a quad-rotor had never been used. The airframes are 3D printed at Boeing Company, using Poly-carbonated Acrylonitrile Butadiene Styrene (PC/ABS). This material is chosen because it has the best ratio of strength and flexibility to density. The sensor suite has the Gumstix Overo Fire which runs Ubuntu Linux, a Hokuyo Laser Range Finder, a SpacePoint Fusion Inertial Measurement Unit, a Pololu serial to PWM and a Hoverfly autopilot. The Gumstix has code powered by C++ for obstacle avoidance and altitude correction. The ground-control station will receive, interpret and relay data to the vehicle via WI-FI.

2.c Yearly Milestones

ERAU participated in the 4th IARC Mission for the first time in 2007 to understand the scope of the competition. In 2008, the team has completed the autonomous three kilometer flight portion of the competition, and was placed third overall out of twenty seven. A sub-vehicle was also developed to capture images inside the building as one of the parts of the 4th mission.

The team developed a performance specification to evaluate prospective configurations for the 5th Mission. The specification ruled out most off-the-shelf small UAV platforms. After a month of testing and evaluation, the monocopter became the primary focus of the IARC team's attention. Despite not being able to complete the competition at the time, the monocopter has earned the most innovative design recognition.

For the 6th mission, the team decided to create a new platform due to the difficulty of the monocopter to complete the mission. After a month of evaluation, a quadrotor became the new focus of the IARC's team. Instead of using an Arduino, we are using a Gumstix as our onboard controller and a Hoverfly autopilot.

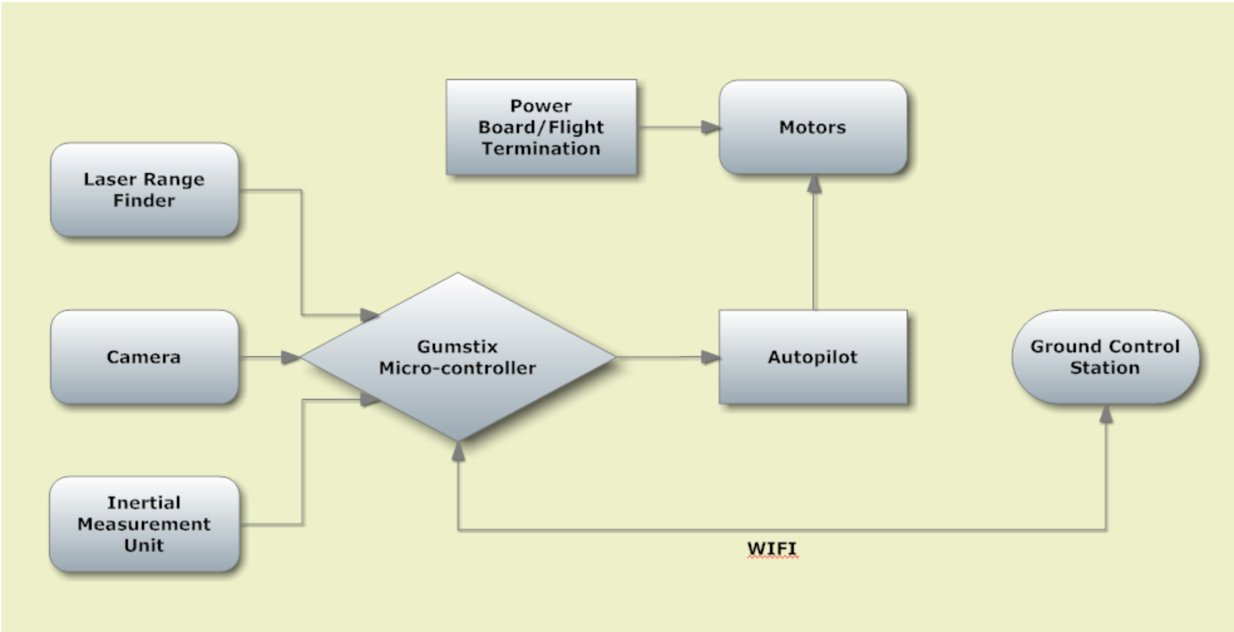

Figure 1. The Quad-rotor System Architecture.

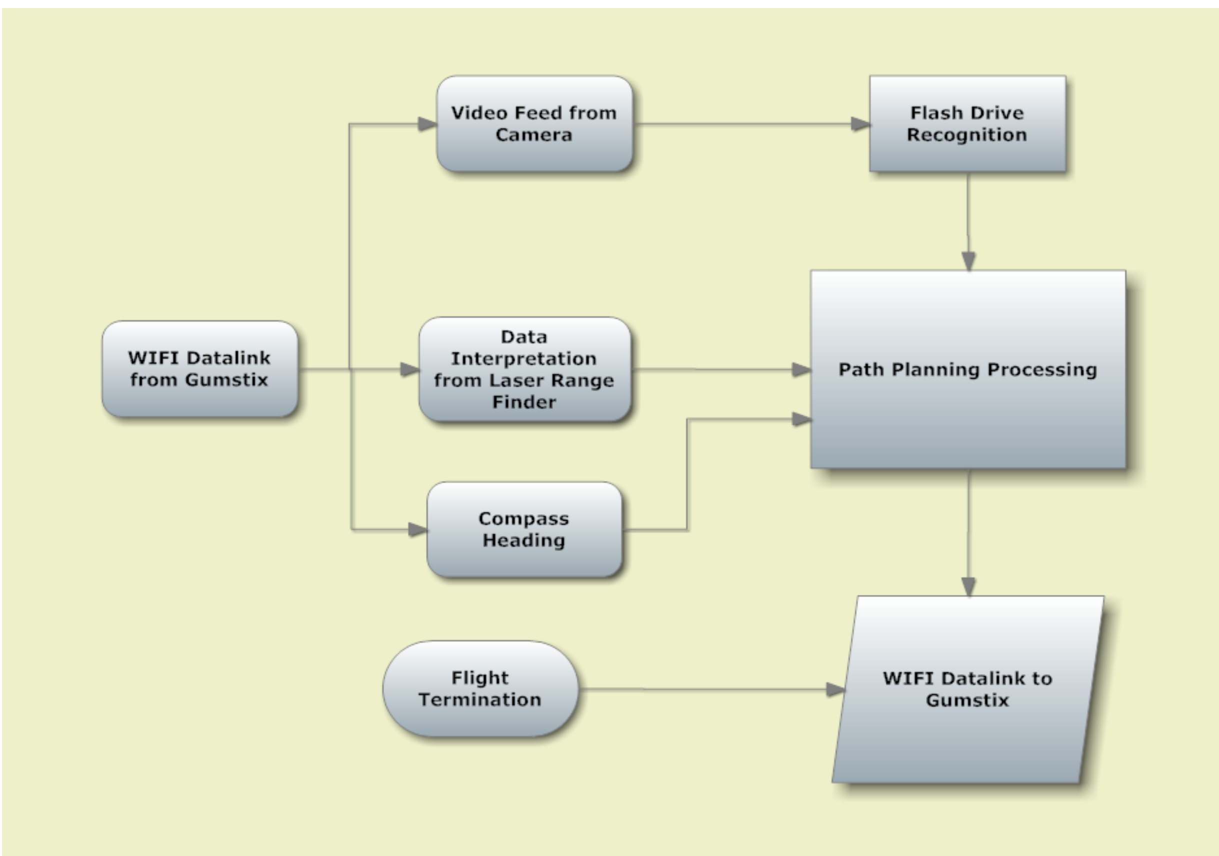

Figure 2. The GCS System Architecture.

3 AIR VEHICLE

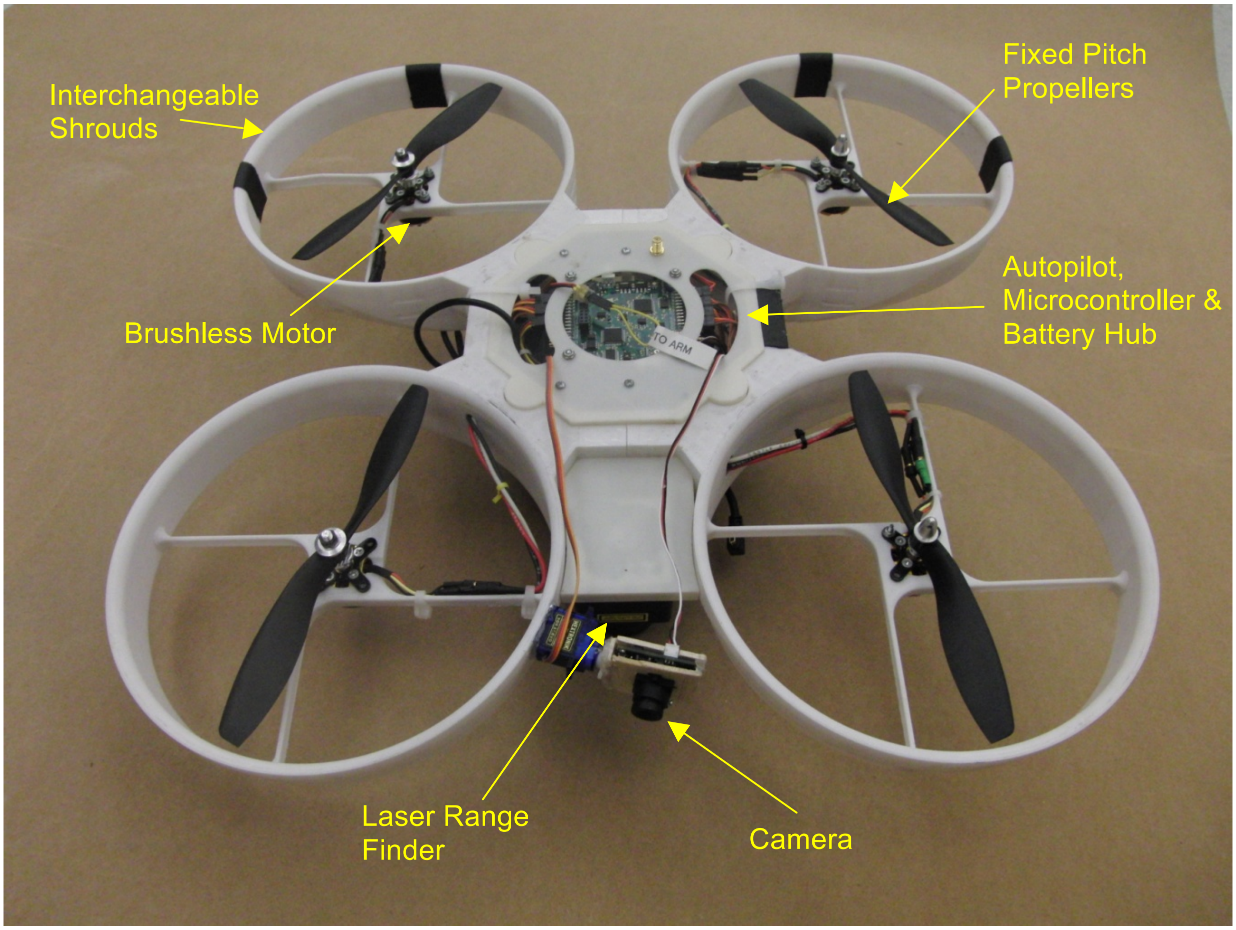

Figure 3. Eagle Quad General Configuration.

The Eagle Quad has four interchangeable motor mount arms that interlock into the sensor compartment in the middle of the platform. The four interchangeable arms are the main selling point for this concept. These arms allowed the vehicle to be disassembled and reassembled with minimal parts. Also by having them be interchangeable less spare parts are needed to maintain the vehicle. Figure 3 shows the general configuration of the Eagle Quad prototype. This quadrotor has shrouds to protect foreign objects from the props. The ducts also supply a small increase in thrust. Eagle Quad flies in an "X" configuration with the camera and laser range finder protected between two ducts.

In the middle of the Eagle Quad is a sensor hub where all the required electronics like the onboard computer and autopilot are housed. For autonomous mode, the laser range finder will be placed at the front for scanning and the camera will be placed above it at an angle to look below for a flash-drive. The quad-rotor system employs a unique USB flash drive retrieval mechanism. A magnetic dredge like device will be employed on the back of the vehicle to allow for the flash drive to be retrieved with minimal data processing and environment sensing.

3.a Propulsion and Lift System

To begin the selection process of a motor and propeller, the desired thrust had to be calculated. This was done by taking the maximum takeoff weight of 1.5 kg, and adding a factor of safety of 1.5 to that. This meant that in total, the four motors must be able to provide 2.25 kg of thrust, or 562.5 g per motor. The factor of safety was included so that there would be an excess of thrust available to be able to maneuver the quadrotor. If there was only enough thrust to maintain a hover, when a maneuver would be attempted there would not be enough lift to sustain flight, so additional lift capacity was needed. It was researched that an out runner brushless motor would provide high RPM ranges, while being small and light weight. The propellers that were to be compared were between 8-10 inches in diameter and had varying pitch lengths and airfoil designs. It was also decided that the maximum diameter for the propeller was to be eight inches due to sizing constraints. The three propellers chosen for lab testing were the APC 8X6 TE, Draganfly 8X4.5, and a three bladed GWS 8X4. These were chosen because all of the propellers have tractor and pusher versions available which are needed for the counter rotating motors.

To size the battery needed, the power consumed by the motor had to be determined. Instead of using the power rating of the motor, an equation was used to determine the power consumed by the propeller to provide a 1.2 G maneuver for seven minutes. A seven minute flight time was selected based on the two allotted times given to complete the IARC challenge. However, a dirty, detected, mission was only allotted five minutes. This time was increased to seven minutes for a factor of safety. The motors required a 3-cell LiPo battery which meant that the nominal voltage (V) would be 11.1 volts. From this equation, it was found that the least efficient propeller would require approximately 2450 mAh for a seven minute flight. Once the testing was done, the power needed could be more accurately calculated, which meant the energy capacity needed may have had to be changed. Based on this initial calculation, the battery chosen for test flights was the Thunderpower 5000 mAh battery. Though it was much larger than the battery that was needed for competition it allowed for longer flights during testing, which meant less down time for charging. The only requirement for the ESCs was to be able to handle the max current burst for the motor selected. The Castle Creations Thunderpower 36 ESCs was capable of handling 36 amps, which is enough to handle any of the motors being looked at, and it was also very lightweight (20 g).

The motor selected to be thrust tested was the Scorpion 2208-28. This motor was selected due to its low weight, small size, and high power rating. Despite the existing magnets on the lid, the motors are far enough away that it would not be hindered. While ducting the shrouds to maximize thrust was considered, it was determined that the additional weight needed to gain efficiency would be greater than the additional thrust gained. Because of this, the shroud size was decreased, so as to just cover the propeller, to keep the weight low while still providing safety. The stators, which act as the motor mounts, were originally angled help reduce turbulence off of the propeller. It was determined that not adding this angle would be more beneficial since all of the shrouds could then be interchangeable.

3.b Guidance, Navigation, and Control

Upper level control comes from a ground control station programmed in LabVIEW. Data from the Laser Range Finder and Inertial Measurement Unit (IMU) is sent via WIFI from the vehicle to the ground control station. This data is used to determine where the vehicle should search. A velocity vector is sent back to the vehicle, which takes the vector and augments it depending on current obstacles around the vehicle. The new direction is then sent to the Hoverfly Pro board along with necessary altitude corrections, which adjusts the pitch, roll, yaw and throttle of the vehicle to match the desired orientation.

On board the vehicle, three programs are running. One sends and receives data from the sensors and relays between the ground control station and the vehicle. The onboard computer also runs a PID controller to maintain a pre-defined altitude, and obstacle avoidance. All three programs are run on a Linux based Gumstix written in C++.

3.b$_1$ Stability Augmentation System

The Hoverfly Pro autopilot onboard the quadrotor will do most of the stabilization by controlling the four motors. There is an 'auto-level' mode that will maintain the desired attitude during flight.

3.b$_2$ Navigation

The 6th IARC Mission poses three navigation problems: maneuvering from the launch point through the window, exploring the corridors of the building, and searching the rooms within the building. The quad-rotor will employ a 'path planning algorithm' similar to 'A*' to figure out the most efficient path by setting its own waypoints as it goes.

An onboard laser range-finder is used to sense walls and obstacles in the surrounding environment while simultaneously mapping the surrounding 5 meters away with 240 degrees coverage. An obstacle avoidance algorithm is loaded on the Gumstix and utilizes the data from laser range finder to avoid obstacles as it navigates.

3.c Flight Termination System

There are two termination systems on Eagle Quad. The GCS off switch will result in a throttle command to zero, and a secondary remote system which cuts power to the motors.

4 PAYLOAD

4.a Sensor Suite

The quad-rotor vehicle carries a sensor payload in addition to its ranging, reference and altitude sensors. Visual data is collected by a single camera. This payload is integrated into the vehicles' other attitude sensors in order to more accurately estimate heading and distance to targets based on the vehicles current position and orientation.

4.a$_1$ Guidance, Navigation and Control Sensors

The quad-rotor platform uses several sensors to determine its current position in the world and move toward its current goal. A laser ranging unit gives the ground station the distance to obstacles around the platform and an inertial measurement unit that returns current attitude information to the ground station.

Heading is provided by the magnetometer contained in the onboard IMU. This 'micro-electromechanical' system (MEMS) sensor is capable of reading variations in the Earth's magnetic field with a precision in the tens of micro-gauss. On-chip data processing, amplification and offset cancellation are all carried out by a custom military grade 32 step Kalman filter that is part of the software package provided internally on the IMU by the manufacturer.

The primary ranging data is provided by a Hokuyo Scanning Laser Ranger Finder with 240° in the horizontal plane of platform up to 5 meter away from the sensor. A unique feature that is taken advantage of is the fact that if a pulse of light is reflected off of a mirror and then an object part of the reflection off of the object will travel back to the source along the original path. This results in an effective altitude sensor by placing a small mirror of known width at a 45° angle toward the ground. In effect this causes a small portion of the scan to be redirected toward the ground, which can then be interpreted as altitude data.

4.a_2 Mission Sensors

Mission sensors for the quad-rotor include the navigation sensors and a camera. The camera is composed of a 640 x 480 digital cameras that are mounted at a known distance from each other. With this data and knowledge about the movement of the pixels and or objects in the two images, the distance to objects can be determined through the use of trigonometry. This distance, along with the position of the object in the image allows for a distance and heading of targets of interest to be determined.

4.a_{21} Target Identification

In order to identify the target the quadrotor employs the onboard camera and off board image processing. Images taken from the onboard camera are sent over the high-speed data link and are subsequently processed in LabVIEW. The image analysis consists solely of image smoothing and simple pattern matching.

4.a_{22} Threat Avoidance

The onboard Gumstix Overo Fire computer reads the ranging information from the laser scanner and generates a local perceptual map. If an obstacle is detected in the flight path prescribed by the ground station, an avoidance vector is calculated, and an avoidance maneuver is initiated. This reactive behavior subsumes any higher-level commands or behaviors until the obstacle has been successfully cleared or flight has been terminated.

4.b Communications

The digital high-speed data link for the quad-rotor system is provided by the built-in wireless chipset on the Gumstix Overo Fire. This is an 802.11 b/g WIFI system that allows two-way communication with air vehicle in order to send movement commands to and receive obstacle data from the quad-rotor platform.

4.c Power Management System

The integrated design of the air vehicle enables a simple power management scheme. Air vehicle power is provided by a 5000 mAh 11.1V lithium-polymer battery. Motor power, voltage regulation, over-current cutoff, and low-voltage cutoff are all provided by the onboard motor controller. Battery capacity permits flight times exceeding the 10 minute mission time limit. Propulsion power is managed by a custom circuit that enables the operator to remotely kill the power going to propulsion system.

5 OPERATIONS

5.a Flight Preparations

1. Plug in battery
2. Connect to Gumstix through serial terminal
3. Start control code in /root/flight_control/controller.bin
4. Remove manual flight lock
5. Start Groundstation
6. Arm Hoverfly
7. Press "Mission Start"

5.b Man/Machine Interface

To interact with the vehicle, a ground control station was created. This software can be run from any computer. A user can monitor and change the state of the vehicle. There are two states for the quadrotor, autonomous and manual. In manual flight a user can input values for altitude, roll, pitch and yaw. These values are then sent to the vehicle, and the onboard computer implements those commands. Autonomous mode, only allows the user to view the state of the vehicle. On the user interface, orientation, altitude, battery life and obstacle range data can be seen on simulated instruments. There is also a first person view video that is displayed. In any state, the user can arm or disarm the vehicle remotely. In future versions, a map of the surrounding and path flown will also be displayed.

6 RISK REDUCTION

Safety has always been a primary concern and the quadrotor system needed to be designed to be safe for everyone who will be in close proximity to it during the competition. Hence our engineering design takes into account risks and hazards that the quad-rotor may impose to be reduced or removed.

6.a Vehicle Status

Similar to a pre-flight check, the team will check for any malfunctions of the vehicle before flight. The battery lifespan must be fully charged for full flight and the autopilot must be armed. Also, all the emergency stops should be function immediately when pressed. The GCS must be receiving all the data from the laser range finder, camera and the inertial measurement unit. Once all are checked, only then will it be able to carry out its task.

6.a1 Shock/Vibration Isolation

During testing, the only vibration produced was from the propulsion system. Nevertheless, the vibration must be maintained at a minimal so that it does not obscure the quad-rotor from performing its mission. Moreover, the quad-rotor is made out of PC/ABS, which has good vibration damping properties. Also the brushless motors were chosen because they did not produce a lot of vibration.

6.a2 Electromagnetic Interference (EMI)/Radio Frequency Interference (RFI) Solutions

The quadrotor has few systems that are directly affected by either EMI or RFI interference, especially the PNI SpaceFusion Point magnetometer. Hence, extensive testing has been done to find the best possible position for each system, so that the noise produced by the motors and the lid cover, which uses magnets to hold itself closed over the sensor hub, would not interfere with the readings.

6.b Safety

Isaac Asimov's first Law of Robotics states that 'a robot may not injure a human being, or through inaction, allow a human being to come to harm'. Having Isaac Asimov's first law of robotics in mind, the aerial vehicle's designs and functions were engineered to abide by it. First and foremost, the Quad-rotor will only operate either remote-controlled or to autonomous mode once the Hoverfly autopilot is armed. Weight was also considered as a safety factor. Thus the robot was made out of a thermal plastic namely, PC/ABS which is light and has a high impact rating. Besides designing the shrouds for better airflow resulting in a more efficient lift, the shrouds also serve as a shield to protect anything from the fast rotating propellers. Last but not least, we have designed an emergency stop just in case any unprecedented scenarios happen. When the emergency stop button is pressed, powers to the electronic speed controllers will be cut off killing the motors and stopping the aerial vehicle from flying.

6.c Modeling and Simulation

The process of Modeling and Simulation is especially important to us to make certain that the flying vehicle does not break when it crashes. Since the airframe was modeled in CATIA, the team was able to use its Finite Element Analysis (FEA) capability to calculate any form of deformation that would happen within the airframe. This allowed the design to be improved so that its strength and resistance to deformation would maintain a certain factor of safety.

6.d Testing

During the preliminary design phase, the motors used to drive the propellers were tested first. A simple test bench was designed to measure the amount of thrust the motor could produce with the R8x4.5 propellers. Then using FEA any deformation and distortion the airframe would experience under certain loads and stress were calculated. The weight limitation is very strict in this competition therefore; the airframe was designed to have limited density and maximum strength. Design iterations were made regularly throughout the duration of the project to ensure the airframe was structurally sound.

After each iteration flight testing was done using remote-control to ensure all the components of the Quad-rotor functioned properly. For the obstacle avoidance testing, the team used a miniature ground vehicle called Omni-Base. This vehicle could drive in any direction, allowing for a close simulation of how the quadrotor would move on an X-Y plane. All code was tested on the

7 Conclusion

The Eagle Quad is a complete and competitive solution to the complex challenges posed by flight inside closed quarter environments. While radical in both construction and concept, the quadrotor inherits the characteristics of a rotary wing aircraft. The inherent simplicity allowed attention to be focused on overall mission requirements and system integration. This approach focusing on simple and robust systems has allowed ERAU to address every aspect of the 6th Mission from ingress to target acquisition.

8 References

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Acknowledgments

The ERAU IARC team would like to express appreciation to Embry-Riddle Aeronautical University College of Engineering and the following people without whom this project would not have been possible.

Christopher Hockley
Rajan Khatri
Charles Breingan
Mike Potash
Bill Russo