Development of 'ERAU Raven' Quad-Rotor System for the International Aerial Robotics Competition 2012

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Abstract

The Embry-Riddle Aeronautical University (ERAU) IARC team presents the ERAU Raven system as a candidate for completing the 6th Mission of IARC. The RAVEN Quad-Rotor was custom designed to meet the requirements of the IARC mission and was fabricated using additive manufacturing technology. The vehicle combines carefully-selected guidance, control and mission sensors and powerful on-board processing to autonomously navigate through close-quarters environments. Custom algorithms have been developed to enable the system to navigate in an indoor environment, avoid obstacles, evade threats, and retrieve a flash drive containing important information.

1. INTRODUCTION

1.1 Problem Statement

The objective of the IARC 6^{th} Mission is to create an air vehicle that can navigate into a secure location through a 1m x 1m window. The vehicle must explore the location in search of a flash drive and, upon finding the device, must pick it up and replace it with a decoy. Then the vehicle must exit the location. While performing the mission objectives the vehicle must avoid a camera and other sensors and traps. The general restrictions on the vehicle are as follow:

1) Must not weigh more than 1.5kg
2) Must not exceed 1m in any dimension
3) Must operate electrically
4) Must have a termination mechanism that will immobilize the propulsion system

To complete these objectives, ERAU assembled a team of experienced aerospace, mechanical, and computer engineering students with a focus on the IARC mission.

1.2 Conceptual Approach

The team continued the implementation of the 3D printed ERAU Raven quad-rotor concept from last year, but with several critically-important improvements. The new vehicle, while similar in general appearance, has been optimized to have a larger payload area for sensors, electronics and batteries, while reducing the largest exterior dimension by ½ inch. The current platform is constructed from PC-ABS plastic. The PC-ABS blend provides an excellent combination of toughness, rigidity and flowability, allowing the new quad to be printed with thinner wall sections while maintaining strength and reducing weight. The Boeing Co. has generously donated the machine time and materials for 3D printing. The 3D printing manufacturing technique has many advantages, including the ability to rapidly modify the design to match changing design requirements and experimental findings. The ERAU Raven concept vehicle structure will be combined with an onboard electronics package consisting of microcontrollers that governs stability, attitude, and velocity control, a primary processor capable of processing information to complete mission requirements, and a data-link to connect with a judge's monitoring terminal and a ground monitoring station.

The electronics package is composed of a suite of sensors including a laser range finder, a digital compass, an ultrasonic rangefinder, a digital barometer, a stereo camera, and an optical flow camera. An RC receiver is included to allow for manual control. The autonomy algorithms will be executed primarily using the onboard electronics package, minimizing ground station requirements. Finally, the vehicle incorporates a pick-up and drop-off mechanism for the flash drive and decoy. The system architecture is shown in Figure 1.

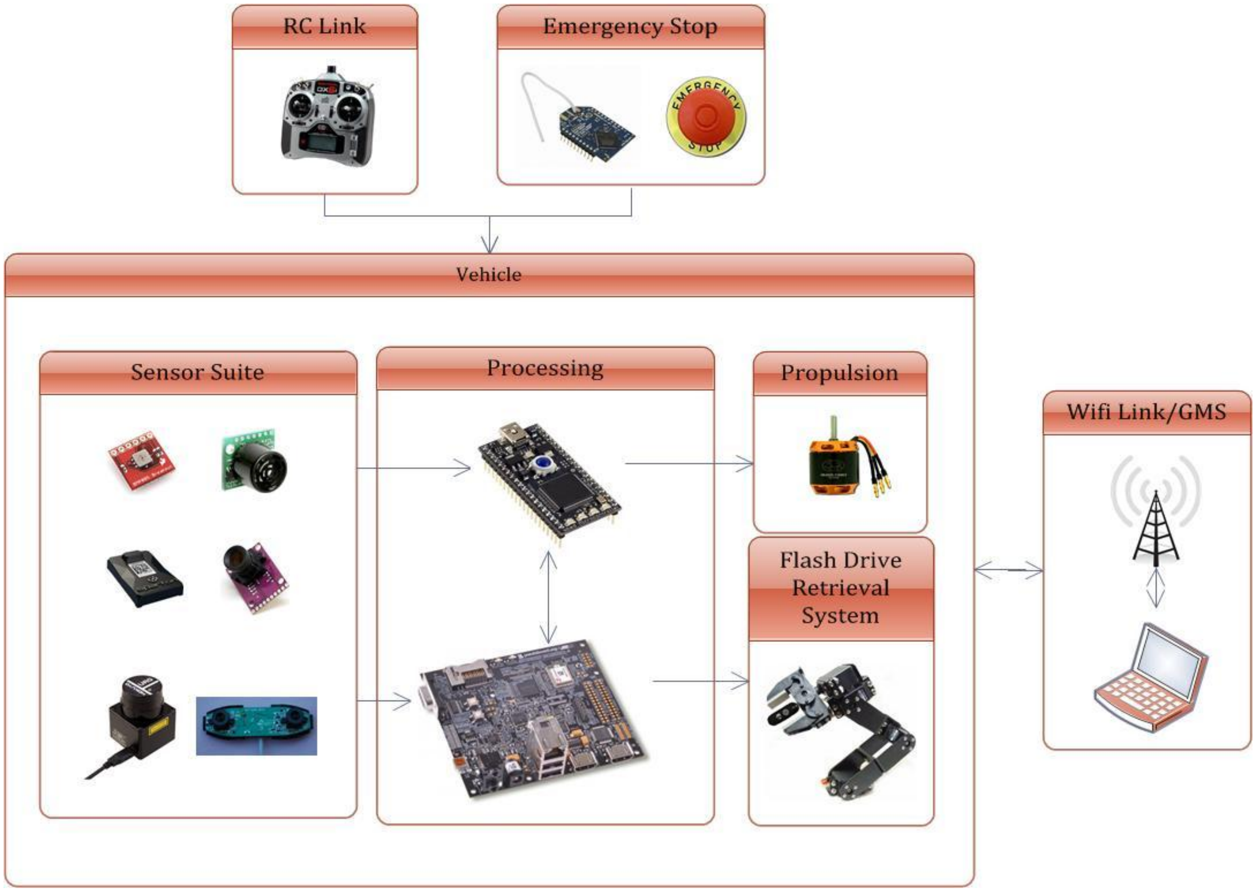


Figure 1: ERAU Raven System Architecture

1.3 Yearly Milestones

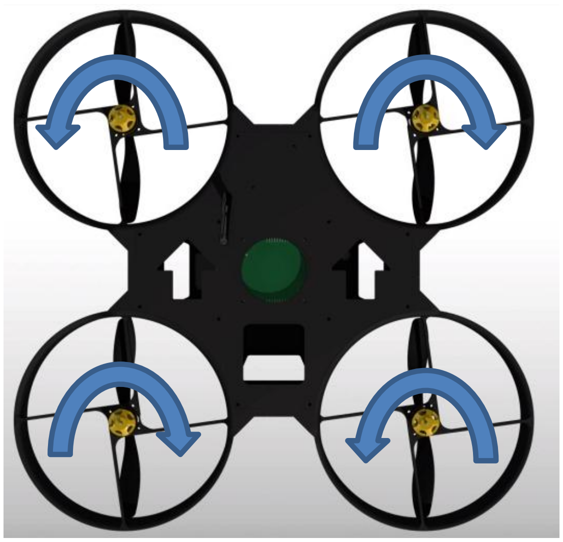
The team reevaluated vehicle requirements for the 6th mission and chose to implement a quad rotor concept. First year development of the quad-rotor concept saw the implementation of a full body structure with ducting for the propellers. This year (the second year) the team focused on implementing the electronics package including the controllers and the sensor suite. Refinements to the structure were made in order to ease electronics integration and reduce maintenance labor and time requirements. A drop-off and retrieval system was also designed and implemented.

2. AIR VEHICLE

The ERAU Raven vehicle is constructed of PC/ABS plastic and features a ducted rotor design for increased safety and efficiency. The electronics package is internalized and consists of an ARM32 Microcontroller, a PandaBoard with Wi-Fi, a Hokuyo URG-04LX laser range finder, an Xbee module, and a Sparton GDEC-6 digital compass. A Hoverfly-Pro autopilot is optional for additional stability and attitude control.

2.1 Propulsion and Lift

A quad-rotor consists of two sets of counter rotating rotors. These rotors provide vertical, lateral (by rolling), and longitudinal (by pitching) acceleration along with yawing motion. These rotors are configured as shown in Figure 2a, and the Thrust vs. RPM curve for the Scorpion SII 2208-1280 kV and Dragonfly 8x4.5 counter rotating propellers is shown in Figure 2b.



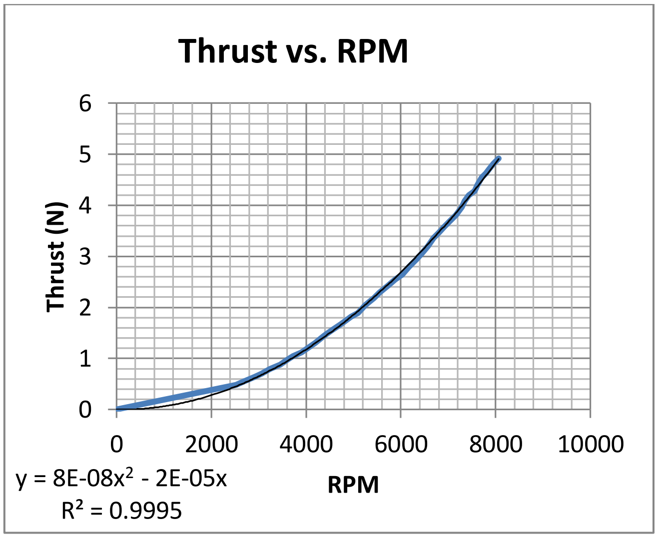


Figure 2: a) Rotor configuration b) Thrust vs. RPM curve for motor/propeller combo

The stall RPM of the Dragonfly propellers is approximately 8800 RPM. At this RPM the Scorpion motor is consuming 155W, which is the maximum continuous power rating of the motor. The motor and propeller combination produces a maximum 5.5N of thrust, giving the ERAU Raven (four rotors) a maximum thrust of 22N. This allows for a thrust to weight ratio of 1.5 with a maximum takeoff weight of 1.5kg. The extra thrust capacity allows for quick maneuvers while maintaining an altitude hold. The motor ESCs (Electronic Speed Controller) are oversized to increase thermal dissipation. Turnigy AE-30A ESCs were chosen because of the high amperage rating (35A) and low weight (20g).

The battery to power the motors was sized to allow for up to 10 minutes of flight. The average current draw on each of the motors is 6A and the draw for the electronics package is 3 to 4 A. A 5000mAh Li-Po battery is used to sustain power for 10 minutes.

2.2 Guidance, Navigation, and Control

2.2.1 Stability Control

There are currently two interchangeable stability control implementations for the ERAU Raven. The first implementation is the Hoverfly Pro autopilot, which was used in the previous design iteration. The Hoverfly Pro is a commercially available autopilot that allows stable flight in isolation of the rest of the system. Commands for Thrust, Roll, Yaw, Pitch, and Altitude hold can be input through PWM signals. The Hoverfly Pro provides excellent stability and attitude control; however it comes at a cost of weight, space, and power consumption. Users also cannot access orientation and altitude data used by the Hoverfly Pro.

The new stability control implementation utilizes extra processing power from an onboard ARM32 microcontroller. The microcontroller gathers sensor data, processes RC commands, manages the RF data-link, and responds to flight termination signals. The microcontroller also acts as the position/velocity controller. Adding the attitude and stability algorithms to the microcontroller and outputting directly to the motors instead of to a Hoverfly Pro allows the team to completely remove the Hoverfly Pro from the electronics package. While this new system has been flown successfully, the microcontroller stability and attitude control algorithms require extensive testing and tuning to gain confidence in their reliability compared to the Hoverfly Pro; therefore interchangeability between the two systems has been maintained to allow the Hoverfly Pro to be easily integrated into the system, if necessary.

2.2.2 Navigation

Autonomous navigation through close-quarter environments is extremely important to the completion of the mission requirements. SLAM (Simultaneous Localization and Mapping) techniques are a popular solution to this problem. However, these techniques require significant processing power and suffer from problems with sensor drift. Object avoidance routines also need to be run concurrently with SLAM routines, increasing processing power requirements.

To solve these problems, the design team at ERAU created a new method to navigate unknown buildings: HARD, Heterogonous Autonomous Route Determination. HARD was developed as a result of trying to navigate without a global location reference by using current sensor information combined with limited prior knowledge to determine a heading. HARD uses the sensor data to create a local impression of the surroundings. HARD converts this information into direction vectors and performs a weighted average of these vectors to generate a navigation vector. Currently there are four direction vectors: Threat, Goal, Previous, and Random.

The threat vector points away from threats and receives the highest weight (30%-50%). A potential threat algorithm creates a field mapping of threat vs. reward using sensor data. This field mapping that is used to generate the threat vector. The goal vector points towards where the goal is presumed to be and receives a middle weight (20%-30%). The previous vector points away from where the ERAU Raven has recently been and receives a low weight (10%-20%). The random vector is randomly generated and also receives a low weight (5%-15%). These vectors are combined to create the navigation vector indicating the desired direction of movement.

HARD allows for many different types of information to be incorporated in a single algorithm. Signs can be read in order to change the goal vector. Laser range finder data can be used to generate the threat map and produce an avoidance vector. Optical flow and accelerometer data can be used to determine previous position.

2.2.3 Control System Architecture

The PandaBoard (Dual Core, 1 GHz ARM32 based Linux computer) processes laser range finder data, vision data, and navigation algorithms, as shown in the control system architecture in Figure 3. The desired control vector produced by the PandaBoard is sent to the ARM32 microcontroller, which performs velocity/position control then attitude stability control and outputs to the motors. The PandaBoard maintains the Wi-Fi data link to the ground station, which can be used to perform additional navigation or image processing tasks as well as monitoring. The microcontroller maintains the RF data link which transmits the termination signal. The microcontroller also receives a signal from the RC receiver, which determines autonomous or manual mode as well as transmitting a termination signal.

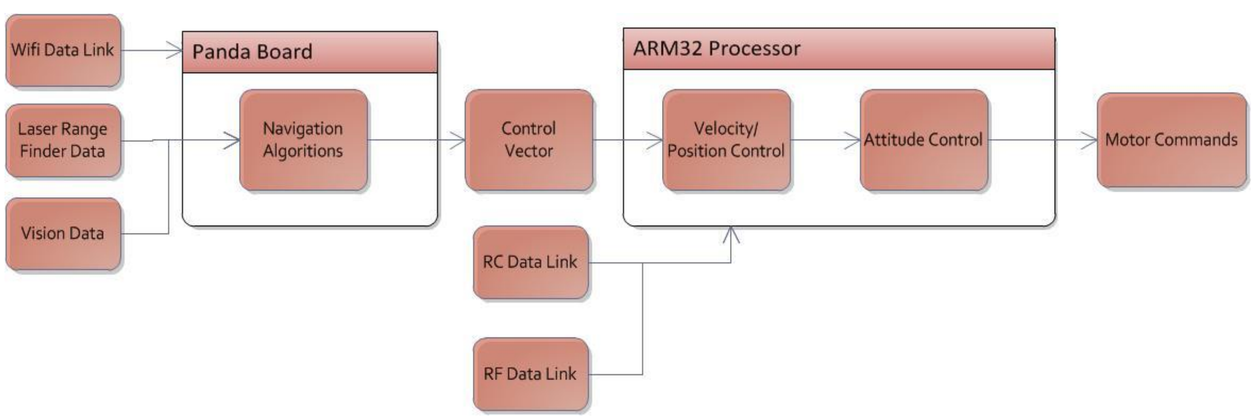


Figure 3: Control System Architecture

2.3 Flight Termination System

There are three separate termination signals for the ERAU Raven. The first system produces a soft termination of autonomy and allows for a user to take control of the system using an RC controller. This system can also act as a hard termination if the user transmits the RC termination signal. The second system is a hard termination signal through the RF data link. This system is controlled by a separate transmitter given to the judges. Once activated, the transmitter immediately stops all four rotors and activates a termination state. The vehicle must be manually restarted to recover from this state. The third system is an on-board termination that occurs if the heartbeat between the primary processor (Pandaboard) and the ARM32 microcontroller is disrupted. This also activates a termination state (Motors inactive with beeping alarm) that cannot be exited until the vehicle is power cycled.

2.4 Flash Drive Pick-up and Drop-off

The flash drive retrieval system consists of magnets inside of a cup on the bottom of the ERAU Raven. Once the flash drive is detected using vision, the ERAU Raven will hover above the flash drive and then lower itself onto the drive and lift it off the table. Once the flash drive is visually confirmed to be onboard, the drop off mechanism releases the decoy.

3. PAYLOAD

3.1 Sensor Suite

3.1.1 Guidance, Navigation, and Control Sensors

The ERAU Raven uses a Sparton Electronics GDEC-6 Digital Compass as the primary attitude sensor. This sensor provides very precise heading information using Sparton AdaptNav technology. The Sparton also provides body acceleration and angular rate information. For altitude measurement, the ERAU Raven uses barometer and ultrasonic rangefinder estimates fused using a Kalman filter. For lateral and longitudinal velocity estimates the ERAU Raven uses an optical flow sensor. The HARD algorithm uses the URG-04LX Hokuyo Scanning Laser Ranger Finder and a stereo camera along with the altitude and velocity sensors to produce a navigation vector.

3.1.2 Mission Sensors

Primary mission sensing is performed using a URG-04LX Hokuyo Scanning Laser Range Finder and a Minoru 3D stereo camera. The Hokuyo is used for detecting distances of objects used for classifying physical features of the mission area, such as the window opening, walls, doorways and any other physical obstacles up to 5 meters away. The primary purpose of the camera is to identify mission-critical landmarks such as the posted signs and the flash drive. The stereo vision features of the camera are used to identify features such as tables, desks, and/or other objects to identify locations where the flash drive would be located. This is accomplished using the open-source computer vision library OpenCV. The camera is also being used to identify obstacles in concert with the Hokuyo. Collected data is then relayed to the HARD algorithm on the PandaBoard. When obstacles such as laser trip wires are detected, the ducted propeller design allows the ERAU Raven to lightly bump into the deactivation switch to turn off the trap.

3.2 Communications

The digital high-speed data link for the ERAU Raven system is provided by the built-in wireless chipset on the PandaBoard. This is an 802.11 b/g Wi-Fi system that allows two-way communication between air vehicle and ground station. A Spektrum 2.4 Ghz Spread-Spectrum RC system provides an interface for manual piloting of the vehicle. Termination signals are sent using a 900 Mhz Xbee RF based off the Zigbee 802.15 via the judges termination interface and/or the RC transmitter.

3.3 Power Management System

The integrated design of the air vehicle enables a simple power management scheme. 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 Turnigy motor controllers. The motor controllers provide power to the electronics package through a 5V line.

4. OPERATIONS

4.1 Flight Preparations

Autonomous flight is initiated by the following procedure:

1) Inspect vehicle hardware: check for flaws in structure, sensors, wire connections
2) Turn on RC transmitter
3) Turn on judges' termination system
4) Connect vehicle battery
5) Activate judges' termination system
6) Power cycle the vehicle to reset termination signal
7) Test motors by manual piloting from RC transmitter
    a. Check propellers for proper spinning direction
    b. Perform manual check take-off and landing
8) Turn on ground monitoring station (GMS)
9) Activate systems test from GMS
    a. Check battery voltage
    b. Check sensor output for correct operation
10) If test completes successfully, activate autonomous mode from RC controller, otherwise unplug battery
11) Activate mission on ground station

4.2 Man/Machine Interface

There are multiple man/machine interfaces that are implemented using the hierarchy shown in Figure 4.

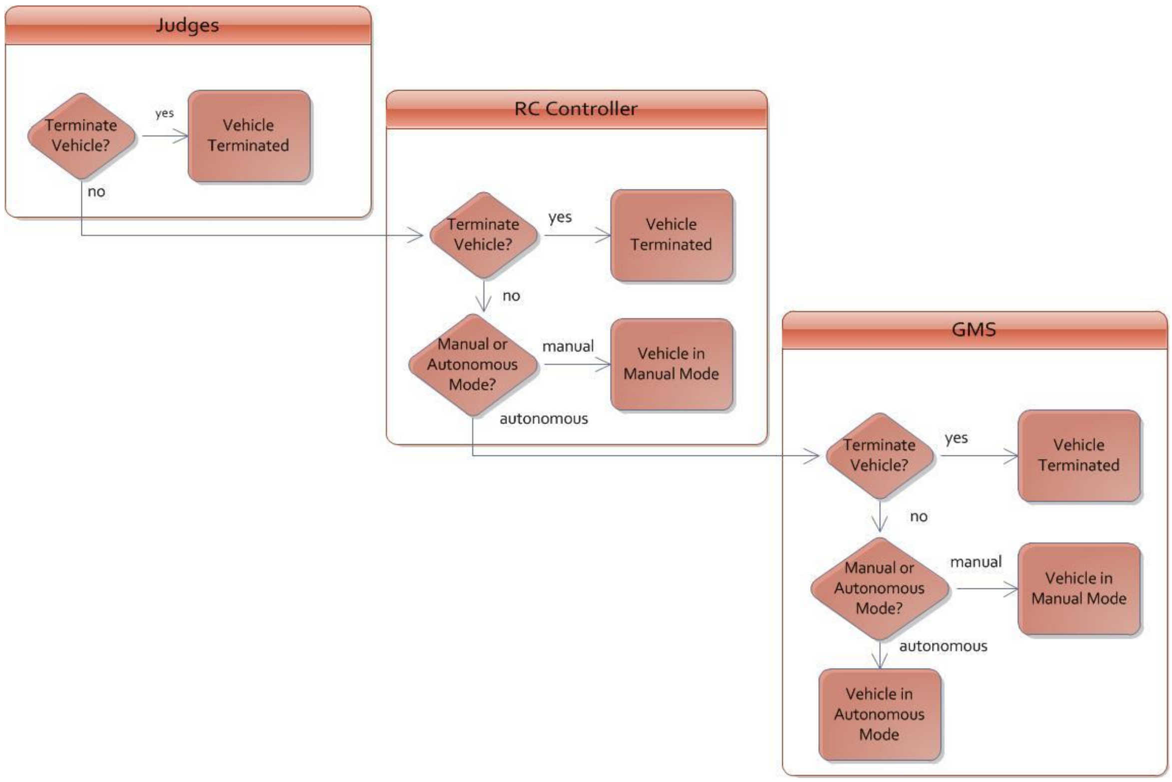


Figure 4: Man/Machine Interface Command Hierarchy

The judge's RF termination signal is at the top of the hierarchy. If a termination signal is transmitted, all of the systems will deactivate and a restart is required. The RC controller is next in the hierarchy. The RC controller can select either manual or autonomous mode. In either mode the RC termination signal can be sent. In manual mode the RC controller can be used to fly the ERAU Raven. Next the ground control station can be used to fly in both manual and autonomous mode (the RC controller must be in autonomous mode). Control commands can be sent to the ERAU Raven from the station and autonomous mode can be activated. A termination signal can also be sent from the ground control station.

If the ground station and RC controller are set to autonomous mode, the ERAU Raven can fly autonomously. Commands from each stage supersede the following stage starting with the judge's RF signal: Judges > RC > Ground Station > Autonomy. If any of the stages implements a termination signal, the vehicle enters a termination mode.

5. RISK REDUCTION

Safety has always been a primary concern, and the system was designed to be safe for all persons in close proximity to it during the competition. Design features such as rotor ducts increase efficiency and provide protection from the rotors. Multiple termination signals were implemented to insure that the vehicle can be shut down and rendered ballistic.

5.1 Vehicle Status

Automated pre-flight tests must be performed to successfully enter autonomous mode. Termination signals must also be active in order to operate in autonomous mode. Finally, telemetry between the ground station and the ERAU Raven must be confirmed before flight. Health monitoring and error reporting data are sent over the Wi-Fi link to the ground station.

5.1.1 Shock/Vibration Isolation

The primary source of vibration onboard the vehicle is the propulsion system. The propulsion system produces low magnitude, low frequency vibration at about 950Hz from the rotation of imperfectly balanced rotors. This vibration has not affected system performance. To prevent future problems due to vibration, damping washers are installed on electronics mounts. The electronics package is also in the center of the vehicle frame, protecting it from damage during a crash.

5.1.2 EMI/RFI Solutions

The ERAU Raven has two systems that could be affected by electromagnetic or radio frequency interference. The Sparton GDEC-6 Digital compass has internal algorithms that compensate for EMI interference. Calibration is also performed to nullify local sources of interference. The data-links may be susceptible to large amplitude RFI; however the ERAU Raven initiates a termination mode when signal over the RF data-link is lost.

5.2 Safety

The ERAU Raven was designed with safety in mind. There are multiple redundant termination switches that allow external users to deactivate the drone. The propellers are shrouded by ducts which help prevent injury from contact with propellers. The ducts also allow the quad-rotor to lightly bump into an obstruction without significant damage.

5.3 Modeling and Simulation

The ERAU Raven has been extensively modeled. The structure was designed and components were modeled in CATIA V5. Finite Element Analysis (FEA) was performed on the structure. The attitude, position, and velocity controllers as well as the navigation algorithms have been modeled and tested in MATLAB Simulink. This modeling was performed to reduce the risk of unexpected failure in any of the systems and to verify the theoretical performance of these systems. Simulink diagrams of each system were created and the navigation algorithms were tested in virtual buildings.

5.4 Testing

Each system has undergone individual and integration testing to determine operational characteristics and functionality. Design changes are tested using the CATIA models as well as the Simulink simulations before being implemented. After implementation, the system was tested using manual control before testing autonomous control.

6. CONCLUSION

This paper has presented the proposed ERAU Raven System developed by the ERAU IARC team as a competitive solution to the complex challenges posed by flight inside close-quarter environments. The use of 3D printing technology to fabricate the airframe allowed the vehicle to be precisely tailored to the requirements of the 6^{th} mission and the selected sensors, components and subsystems. The team used this design iteration to focus on mission requirements, the electronics package, and system integration. The system balances the use of commercial-off-the-shelf hardware for sensing while employing custom algorithms for stability, control and close-quarters exploration. This methodology allows the ERAU Raven system to provide a complete solution for the 6^{th} Mission of IARC.

7. ACKNOWLEDGEMENTS

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