Development of 'ERAU Raven II' Quad-Rotor System for the International Aerial Robotics Competition 2015

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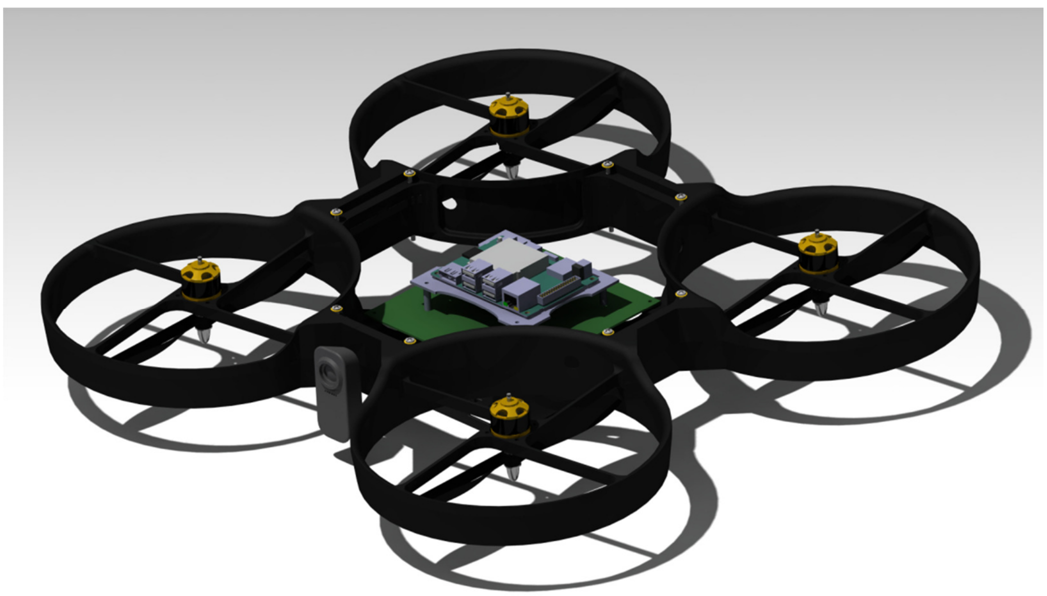

Abstract

The Embry-Riddle Aeronautical University (ERAU) IARC team presents the ERAU RAVEN II system as a candidate for completing the IARC Mission 7 challenge. RAVEN II currently ~~exists in~~is a modified version of the platform that was first created for the 6th Mission of IARC. The vehicle combines a custom internal circuit board with carefully selected vision and control sensors and powerful on-board processing to autonomously navigate around ~~an open room within given limits~~in the Mission 7 environment. Algorithms have been developed to enable the system to maneuver through its environment while tracking, following, and modifying the trajectory of autonomous ground vehicles, allowing the vehicle to herd them towards set goals.

1. INTRODUCTION

1.1. Problem Statement

The objective of IARC Mission 7A is to create an air vehicle that is able to autonomously roam an open area. In this area, it must identify and interact with autonomous ground vehicles so as to guide them towards a specific, recognizable goal. The area is populated by roaming obstacles, which must be avoided, and ground vehicles, which must be managed to prevent them from leaving the set area through non-ideal paths. The general restrictions on the vehicle are as stated below:

1) Must not exceed 1.25m in any dimension
2) Must operate electrically
3) Must remain within bounds of arena
4) Must have a separate and portable ground station and termination device.

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

1.2. Conceptual Approach

This is the third year that the ERAU IARC team has depended upon the RAVEN II unmanned aerial vehicle. Much of the design has gone unchanged, as we have made efforts to focus on the software development component of the competition. ~~The~~ RAVEN II is fabricated on a 3-D printer from a Polycarbonate and Acrylonitrile Butadiene Styrene (PC-ABS) plastic blend. This blend provides an excellent combination of toughness, rigidity and flow-ability, allowing the quadrotor to be manufactured with thinner wall sections while maintaining strength and reducing weight. The Boeing Co. has generously donated the machine time and materials for manufacturing the vehicle. Using the 3D printing manufacturing processes has provided many advantages for the team, including the ability to rapidly modify and replicate the design, both to meet changing design requirements, and to facilitate rapid repairs should damage be incurred.

The RAVEN II concept combines a robust vehicle platform with an onboard electronics package consisting of a custom printed circuit board, a Linux based computer to enable onboard processing of mission data, and a data link to connect to the ground monitoring station. The mission and flight sensors include a Sparton digital compass, a MaxBotix ultrasonic rangefinder, and two Logitech high definition cameras. An RC receiver is included to allow for manual control and flight termination. The autonomy algorithms will be executed primarily using the onboard electronics package, minimizing ground station and data link requirements. To meet the mission requirements for ground vehicle interaction, the vehicle incorporates several rare-earth magnets to activate the magnetic influence sensor on their tops. These components are shown in Figure 1.

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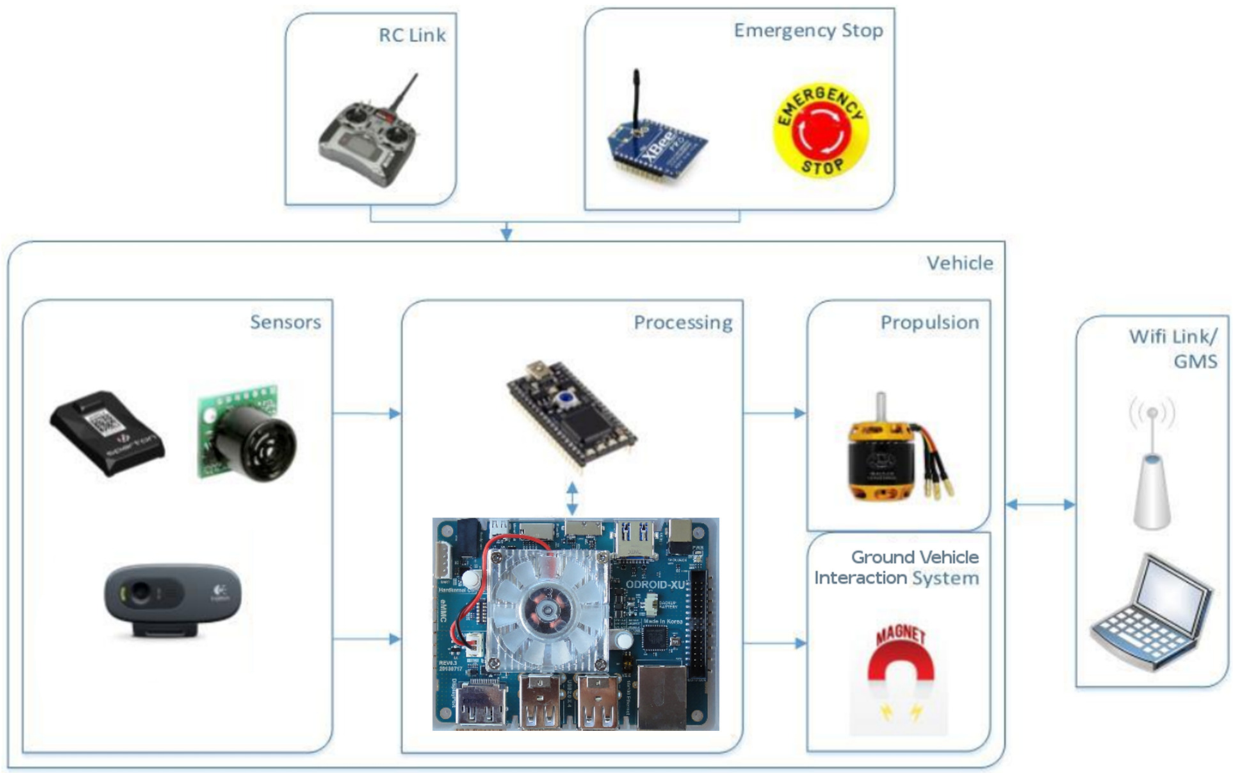


Figure 1: ERAU RAVEN II System Architecture

1.3. Yearly milestones

First year development of the RAVEN quad-rotor concept for the 2011 competition resulted in a digitally manufactured full--body structure with ducting for the propellers. The second year of development focused on integrating the electronics package and mission payload. Refinements to the structure were made in order to ease electronics integration and reduce maintenance labor and time requirements.

2. AIR VEHICLE

RAVEN II is constructed of PC/ABS plastic and features a ducted rotor design for increased safety and efficiency. The vehicles electronics package is integrated using a custom printed circuit board and consists of an ARM32 Microcontroller and an Odroid-X2 with Wi-Fi. RAVEN II's sensor and communication suite includes an Xbee RF module, a Sparton AHRS-8 digital compass, a MaxBotix ultrasonic rangefinder, and two Logetech C270 HD webcams.

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.

In previous years the team used Scorpion SII 2208-1280 kV brushless motors with either Dragonfly 8x4.5 plastic propellers or Gemfan 8x4.5 carbon-nylon propellers (Figure 2 Top). These propellers worked adequately, but they were inefficient and noisy. ~~To gain improvement in these areas t~~The team manufactured new blades by sculpting Gemfan 12x4.5 carbon-nylon propellers down to 8 inch propellers (Figure 2 Bottom). This provides a wider propeller blade and tip, and allows the tip to be shaped to better fit the quad-rotor ducting. The results of these modifications were an average decrease of 6W per rotor in power consumption during flight. The new propellers also produce less noise and a lower pitch, less offensive noise.

Figure 2: Top) 8X4.5 Gemfan carbon-nylon propeller
Bottom) 8x4.5 modified propeller

The motor and propeller combination produces a maximum 5.5N of thrust, giving RAVEN II (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. Having additional thrust capacity allows for quick maneuvers while maintaining altitude hold. Castle Creations Phoenix 25A ESCs (Electronic Speed Controller) were chosen because of the high amperage rating (25A) and low weight (17g). The motor ESCs are oversized to increase thermal dissipation. Each motor draws less than 5.5 amperes on average, allowing the ESC's to stay below 31 degrees Celsius in continuous operation. The average current draw on each of the motors is 5.5A and the draw from the electronics package is 1.5 to 2.5A. Considering that the team had a vehicle flight time requirement of 10 minutes, a 4400mAh battery was selected for RAVEN II. This battery been verified to provide sufficient power for 10 minutes of flight in laboratory testing.

2.2. Guidance, Navigation, and Control

2.2.1. Stability Augmentation

The RAVEN II platform uses a custom circuit board dubbed IRIS to manage power resources, enable sensor connectivity, perform stability augmentation, and house flight termination circuits. The embedded ARM32 microcontroller on IRIS gathers flight 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. Stability augmentation algorithms utilize the Sparton AHRS-8 and extra processing power from the IRIS's microcontroller. In previous years, the vehicle has relied on a Hoverfly Pro autopilot for stability augmentation. Hoverfly Pro is a commercially available autopilot that allows stable flight in isolation of the rest of the system. 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 internally by the Hoverfly Pro, requiring extra on board sensors to obtain this information. The IRIS board has maintained backwards compatibility with the Hoverfly Pro, allowing ~~this~~ the Hoverfly system to be used if the IRIS board stability augmentation fails.

2.2.2. Navigation

Autonomous navigation in a sterile environment is essential to the completion of the IARC mission. In this case, sterile refers to the ~~lack~~ absence of walls that ~~may~~ might otherwise be used to create an environmental map ~~from~~, as well as the prohibition of GPS technology.

The ERAU RAVEN II platform ~~utilizes~~ uses a combination of optical flow sensing and line detection to identify the direction being traveled, ~~as well as~~and it ~~accurately~~ ~~determining~~ determines ~~the~~ distance traveled based on the floor grid. Since the creation of the platform in 2013, the processing on board has migrated from an Odroid-X2, with an Exynos 4412 Prime 1.7GHz quad-core processor, to an Odroid-XU, with an Exynos5 Octa Cortex CPU. This CPU utilizes the ARM big.LITTLE technology, and two quad-core processors, to create a much more energy efficient platform, vastly ~~expanding~~ increasing our maximum runtime. This efficiency comes without a sacrifice in performance, as the Cortex-A15 Quad core processor on the XU model ~~vastly outpaces~~ outperforms the Cortex-A9 processor on the X2 model.

Object avoidance is a minimal issue in Mission 7, as all obstacles can be avoided ~~from~~ during traversal by maintaining ~~a~~ sufficient altitude~~,~~. ~~and t~~The risk of the vehicle coming down upon ~~the~~ a mobile obstacle~~s~~ can be minimized by detecting the color of the ground vehicle. Additional altitude also provides a greater field of view, with the sacrifice of resolution. This issue has been minimized by the selection of sensors used for the optical detection.

In the IARC Mission 7 rules, it is stated that should a ground vehicle leave the arena through any means, it is removed from play. To counter this loss of scoring possibility, the current navigation algorithm prioritizes herding exiting ground robots.~~minimizing this occurrence~~. Upon being placed in the autonomous control mode, RAVEN II will navigate so as to place itself directly above a corner of the field. Based on the colors of the two adjacent sides, it will navigate inward from the edge to maximize visible area, and then migrate along the three sides of the field through which ground vehicles can be lost. Upon locating a ground vehicle, RAVEN II will analyze its movement, estimating its trajectory and predicting whether it will leave the arena or not on its next movement cycle. If so, it will move to intercept, basing the type of interaction, front or top, on the angle of movement in relation to the edge of the field. If the ground vehicle is predicted to be staying within the field, RAVEN II will continue onward along the three sides of the field.

2.2.3. Control System Architecture

Figure 4 shows the flow of data through the control system architecture. First, the Odroid-XU processes data from the cameras using the navigation and task priority algorithms. The resulting control vector is sent to the IRIS board microcontroller, which performs velocity/position control then attitude stability control and outputs commands to the motor controllers. Simultaneously, the Odroid-XU maintains the Wi-Fi data link to the ground monitoring station while the IRIS microcontroller maintains the RF data link that relays the termination signal. The microcontroller also monitors signals from the RC receiver, which determines autonomous or manual mode as well as relaying a termination signal.

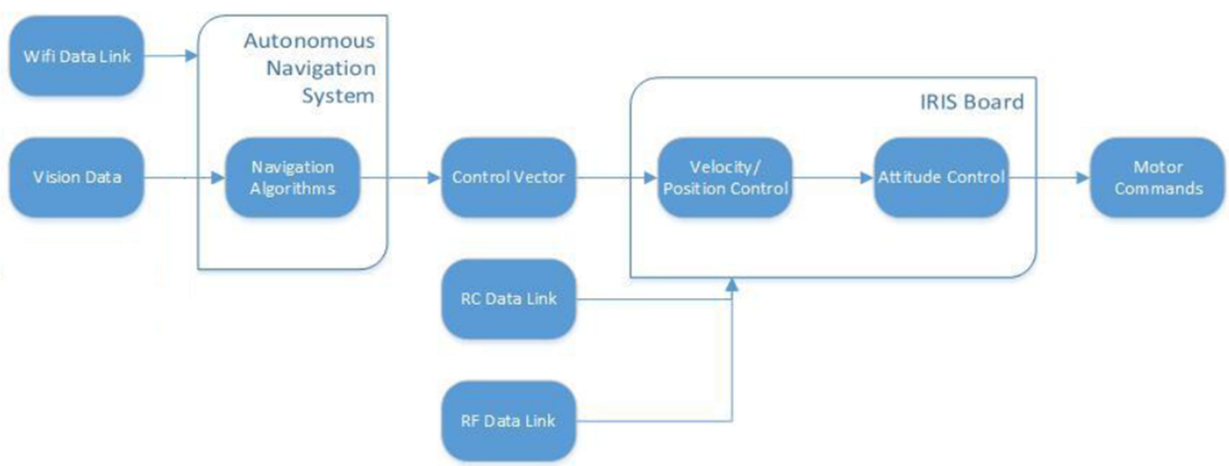


Figure 3: Control System Architecture

2.3. Flight Termination System

There are three separate termination signals for RAVEN II. The first signal is operator triggered produces a soft termination of autonomy, allowing for the operator to take control of the system using an RC controller. This signal can also act as a hard termination if the operator transmits the RC termination signal. The second signal is a hard termination signal through the RF data link. This signal is controlled by a separate transmitter given to the judges. Once activated, the signal immediately stops all four rotors and activates a termination state. The vehicle must be manually restarted to recover from this state. Finally, if the heartbeat between the primary processor (Odroid-X2) and the IRIS board microcontroller is disrupted, the third signal is activated and an onboard termination occurs. This also activates a termination state (Motors inactive with beeping alarm) that cannot be exited until the vehicle is power cycled.

The 2013 IARC competition introduced a suggested common kill switch for all vehicles. One of these kill switches was purchased by the team for testing and reference. The kill switch circuit implemented on the IRIS board is similar to the suggested configuration with increased current capacity to reduce thermal heating that occurred when operating with the common kill switch.

2.4. Ground Vehicle Interaction System

The ground vehicle interaction system consists of a series of rare-earth magnets placed in the undercarriage of the airframe, used to trigger the magnetic influence sensors in the ground vehicles. Additionally, the frame of the quadrotor can be used to trigger the bump sensor on the front of the ground vehicles. These two methods are used in tandem with an algorithm that analyzes the trajectory of the ground robots, and determines the degree to which their course needs to be changed by. The magnetic trigger is used for minor (~45°) adjustments, while RAVEN II will land in front of a ground vehicle when a 180° adjustment would be preferred.

3. PAYLOAD

3.1. Sensor Suite

3.1.1. Guidance, Navigation, and Control Sensors

RAVEN II uses a Sparton Electronics AHRS-8 Digital Compass as the primary inertial measurement unit (IMU). This sensor provides precise attitude information using Sparton's AdaptNav technology. The AHRS-8 also provides body acceleration and angular rate information. RAVEN II uses a Maxbotix ultrasonic rangefinder fused with linear accelerations from the IMU using a Kalman filter to determine its altitude. The autonomous navigation algorithm uses the two Logitech HD cameras along with the IMU and altitude sensor to produce a navigation vector and track the floor markings to determine relative location in the arena.

3.1.2. Mission Sensors

Mission sensing is performed using two Logitech C270 HD Webcams. Forward and downward facing cameras are used to identify the ground vehicles and floor markings, track the vehicle's position in the arena, and calculate trajectory of the ground vehicles. These tasks are accomplished using the open-source computer vision library OpenCV.

3.2. Communication

The digital high-speed data link for RAVEN II is provided by a USB wireless receiver. This is an 802.11 b/g/n Wi-Fi system that allows two-way communication between RAVEN II and the ground monitoring 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 protocol 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 4400 mAh 11.1V lithium-polymer battery. Motor power, voltage regulation, over-current cutoff, and low-voltage cutoff are all provided by the IRIS circuit board. Motor power is sent from the IRIS board to each ESC.

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 rotation 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 restart vehicle
11) Activate mission on ground station

4.2. Man/Machine Interface

There are multiple man/machine interfaces that are implemented using the scheme shown in Figure 5. The judge's RF termination signal is top priority. If a termination signal is transmitted, all systems will deactivate and a restart is required for the system to run.

Next in the system is the RC controller, which can select either manual or autonomous mode and terminate flight. The ground control station can be used to fly in both manual and autonomous modes, as well as issuing termination commands.

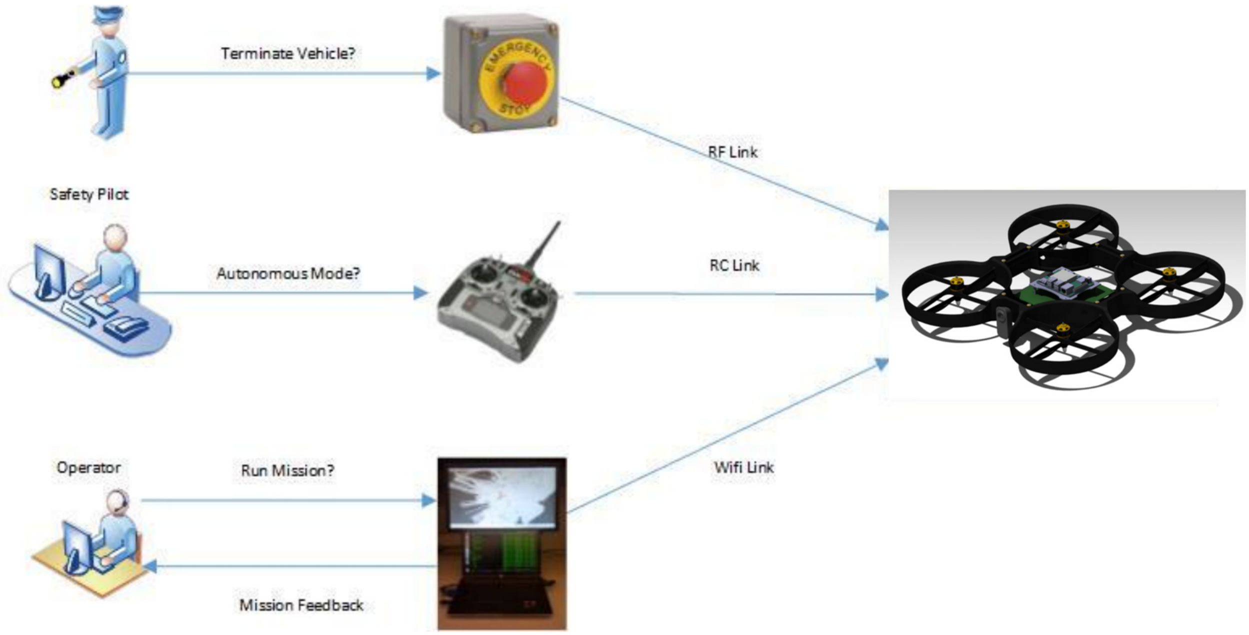


Figure 4: Man/Machine Interface Hierarchy

5. RISK REDUCTION

5.1. Vehicle Status

To enter autonomous mode, pre-flight motor and data link checks must be logged successfully by the vehicle. Motors are tested for proper installation and propeller seating. Each data link is monitored using a heartbeat signal. If the heartbeat is not received properly the vehicle activates the associated termination signal. 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. Quadrotor propulsion systems produce vibration due to turbulence generated by the rotors as well as vibration from imperfectly balanced rotors. To minimize potential problems due to vibration, damping washers were used to mount the electronics to the frame. The electronics package is also installed in the center of the vehicle frame, protecting it from potential damage in the event of an impact.

5.1.2. EMI/RFI Solutions

RAVEN II has two systems that could be affected by electromagnetic or radio frequency interference, namely the digital compass and the data links. The Sparton AHRS-8 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; which would cause the RAVEN II to initiate a termination mode when signal over the RF data-link is lost. This possibility has been minimized through careful selection of the radio systems, proper antenna placement and through extensive range testing in noisy RF environments.

5.2. Safety

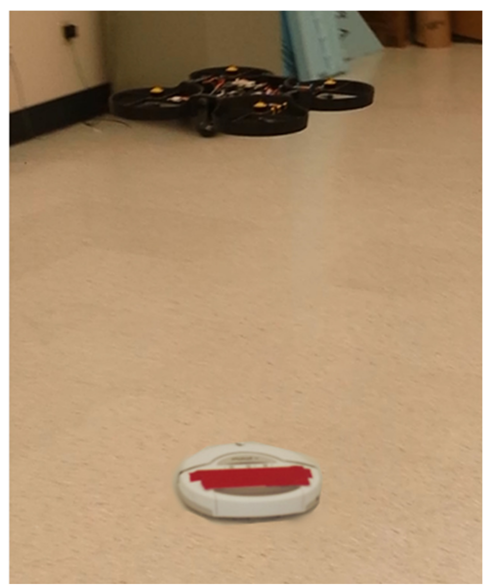
The RAVEN II was designed with safety in mind. There are multiple redundant termination signals that allow external operators to deactivate the drone. The rotors are shrouded by ducts which help prevent injury and damage from propeller strike. The ducts also allow the vehicle to lightly bump into an obstruction without damage.

5.3. Modeling and Simulation

RAVEN II has been extensively modeled using the CATIA IV 3D product lifecycle management software suite, CATIA supports multiple stages of product development including design (CAD), manufacturing (CAM), and engineering (CAE). The structure was designed in CATIA V5 and perfected over more than a dozen design iterations. This iterative empirically based optimization process was made possible by the use of rapid digital manufacturing technology (3-D printing) and by using parametric design tools available in CATIA IV. The system and subcomponents were also modeled and analyzed using the ABAQUS Finite Element Analysis (FEA) solver in CATIA. The attitude, position, and velocity controllers as well as the navigation algorithms have been modeled and tested in MATLAB and 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 before real flight were performed.

5.4. Testing

Each system and subsystem has undergone ~~rigorous~~ testing ~~in order~~ to determine characteristics, functionality, and system failure states. Mechanical testing for ~~for~~ fit and ~~finish~~ durability were was first undertaken in CATIA and then using 3D printing prototypes. Software was tested using a virtual reality simulation created in MATLAB and Simulink. Full system testing was performed in a closed laboratory environment before full scale testing using floor markings and analogous ground vehicle stand-ins.



6. CONCLUSION

This paper has presented the RAVEN II autonomous vehicle developed by the ERAU IARC team as a competitive solution to the complex challenges posed air/ground vehicle interactions. The existence of a stable, versatile platform made it possible for the team to focus on the more important aspects of this challenge, namely the navigation and tracking of ground-vehicles. The system balances the use of commercial-off-the-shelf hardware for sensing while employing custom algorithms for stability, control and ground-vehicle interaction. This methodology allows the RAVEN II system to provide a complete solution for the 7th Mission of IARC.

7. ACKNOWLEDGEMENTS

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