Development of 'ERAU Raven II' Quad-Rotor System for the International Aerial Robotics Competition 2013

Tim Zuercher,
Ian Price,
Gene Gamble,
Mike Surber,

Embry-Riddle Aeronautical University
Daytona Beach, FL

Abstract

The Embry-Riddle Aeronautical University (ERAU) team presents the ERAU RAVEN II system as a candidate for completing the 6th Mission of IARC. RAVEN II represents a significantly enhanced incarnation of the RAVEN Quad-rotor from the 2012 IARC. RAVEN II is lighter, more robust, and more capable than its predecessor. The vehicle combines a custom internal circuit board with judiciously-selected guidance, control and mission sensors and powerful on-board processing to autonomously navigate through close-quarters environments. Novel navigation algorithms have been developed to enable the system to maneuver in an indoor environment while avoiding obstacles and evading threats, allowing the vehicle to retrieve a flash drive and deploy a decoy flash drive.

1. INTRODUCTION

1.1 Problem Statement

The objective of the IARC 6th Mission is to create an air vehicle that can navigate into a secure enviroment through a 1m x 1m window. RAVEN II must explore the environment 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 being seen by a camera as well as 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, computer, and software engineering students focused on the IARC mission.

1.2 Conceptual Approach

For the third year the team continued to improve upon the ERAU RAVEN quad-rotor. Last year, effort focused on expanding payload area while shrinking the vehicle size. This year the team focused on improving component integration, reducing overall vehicle weight, and increasing robustness. The RAVEN II platform 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 quad-rotor 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 3D printing manufacturing processes has provided many advantages for the team, including the ability to rapidly modify the design to meet changing design requirements and experimental findings.

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 Hokuyo scanning laser range finder, 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 flash drive retrieval, the vehicle incorporates a pick-up and drop-off mechanism for the flash drive and decoy. The system architecture is shown in Figure 1.

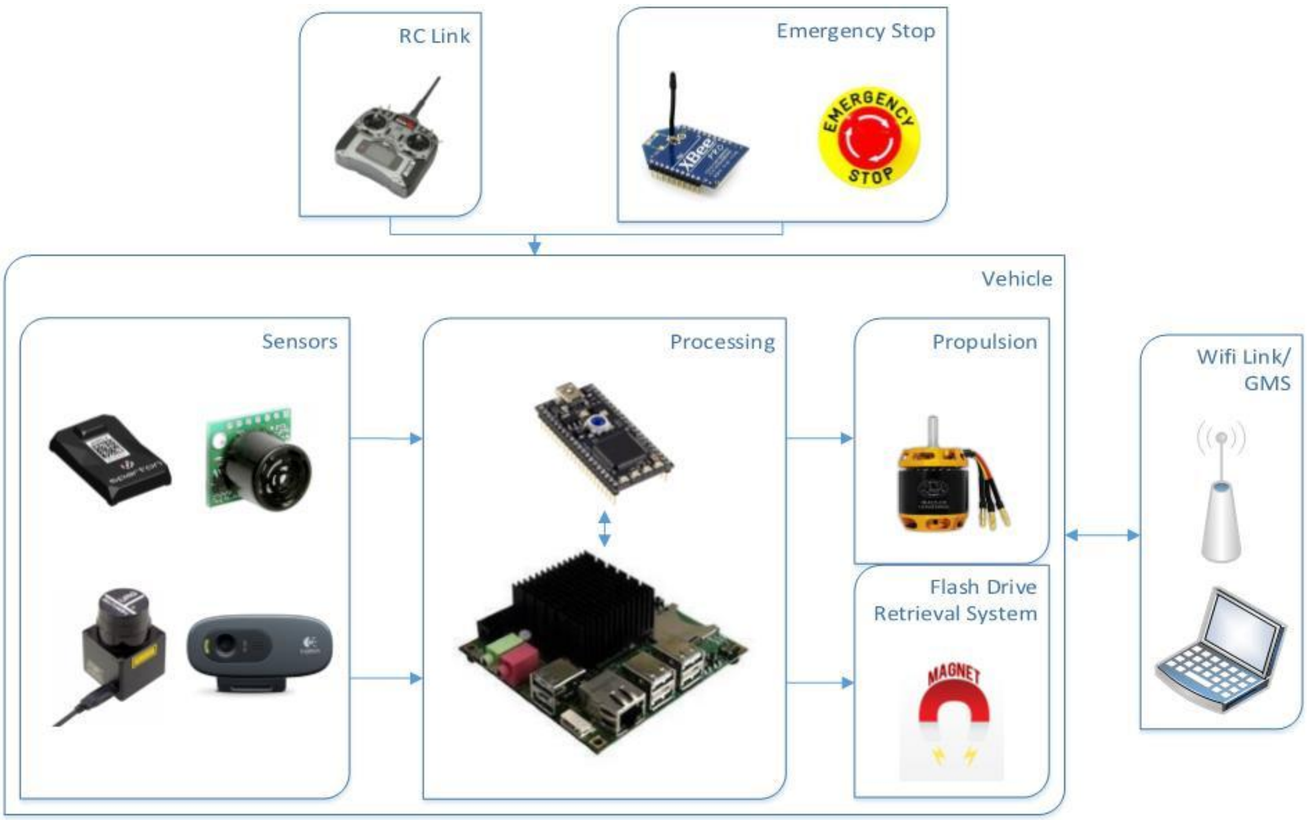

Figure 1: ERAU Raven II System Architecture

1.3 Yearly Milestones

First year development of the RAVEN quad-rotor concept for the 2011 competition digitally manufactured full body structure with ducting for the propellers. The second year 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. A drop-off and retrieval system was also designed and implemented. The current year focused on improving the electronics integration, simplifying the system power supply chain, and the development, implementation, and testing of effective autonomy algorithms. Overall vehicle weight was also decreased by 150 grams to 1300 grams.

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 a Odroid-X2 with Wi-Fi. RAVEN II's sensor suite includes a Hokuyo URG-04LX scanning laser range finder, 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, were inefficient and noisy. To gain improvement in these areas 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 system to be used if the IRIS board stability augmentation fails.

2.2.2 Navigation

Autonomous navigation through unexplored close-quarter environments is essential to the completion of the IARC mission. SLAM (Simultaneous Localization and Mapping) techniques are an appropriate solution to this problem. However, these techniques require significant processing power and suffer from problems with sensor drift. Reactive object avoidance routines also need to be run concurrently with SLAM routines, further increasing processing power requirements.

The ERAU RAVEN platform emphasizes onboard processing. This minimizes the ground station requirements and allows the vehicle to operate during communication brownouts and in RF hostile environments. Over the last three years the processing capability onboard the vehicle has increased by an order of magnitude. The platform was originally powered by a Gumstix Overo Fire embedded processor operating at 750MHz. Last year the Gumstix processor was upgraded to a PandaBoard ES with a dual-core OMAP processor running at 1.2GHz. This year the Pandaboard ES has been upgraded to an Odroid X2 Exynos 4412 Prime 1.7GHz quad-core computer with a quad-core graphics unit. Utilizing this processing power, the team is able to combine our novel Heterogeneous Autonomous Route Determination (HARD) algorithm with a simultaneous localization and mapping (SLAM) algorithm. The team can also process high definition images for better window, threat, and obstacle detection.

The HARD algorithm was developed to aid in navigation without a global location reference by using current sensor information combined with limited apriori knowledge to determine a heading. HARD uses the sensor data to create a local impression of the surroundings. The algorithm converts this information into direction vectors and performs a weighted average of these vectors to generate a navigation vector. 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 is used to generate the threat vector. A goal vector points in the desired direction of travel and receives a middle weight (20%-30%). The previous vector points away from where the vehicle has recently been and receives a low weight (10%-20%). Finally, 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. This is implemented as the bottom layer of the autonomous navigation system, used to keep the vehicle traveling in the desired direction and away from threats.

A goal vector is given to the bottom layer by the upper layer containing the navigation integrator. The navigation integrator analyzes the map created using SLAM as well as inputs from the computer vision. Using a state machine tracking the mission's progress the integrator determines how these inputs should be interpreted and outputs the goal vector. The layout of the autonomous navigation system is shown in Figure 3.

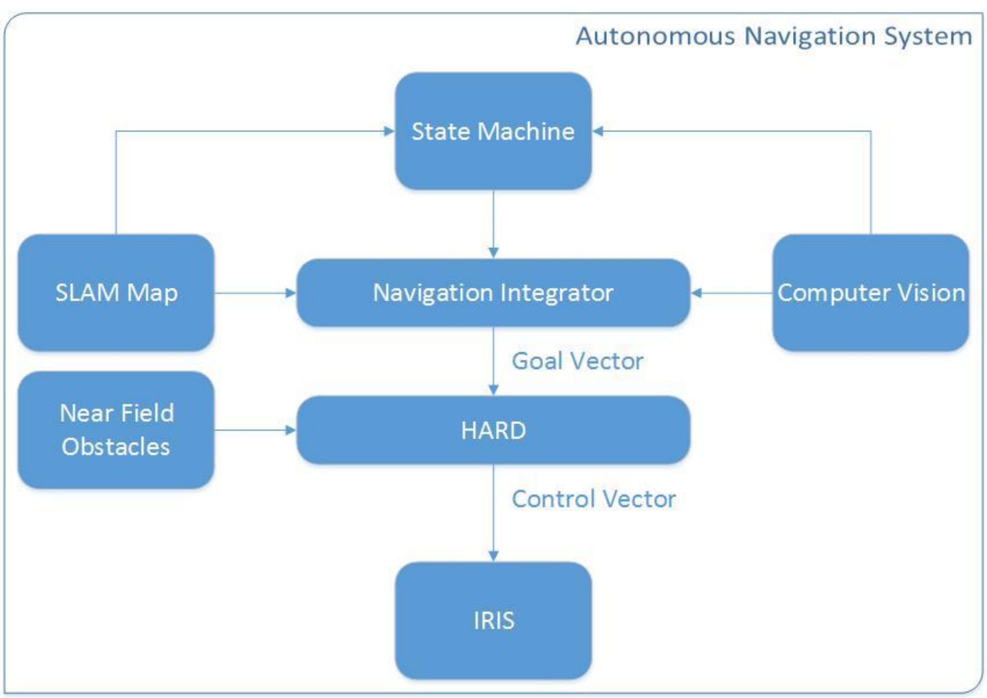

Figure 3: Autonomous Navigation System

2.2.3 Control System Architecture

Figure 4 shows the flow of data through the control system architecture. First, the Odroid X2 processes data from the laser range finder and cameras using the navigation 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-X2 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.

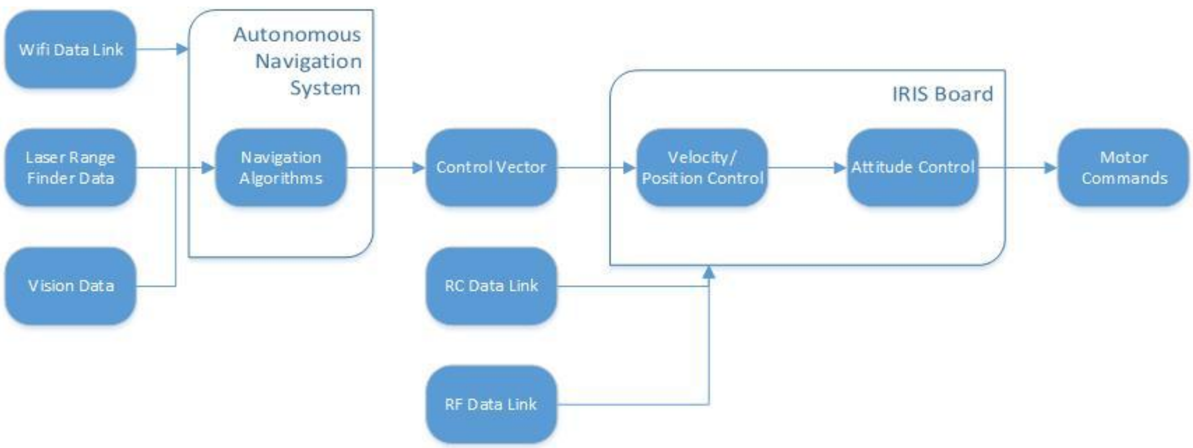

Figure 4: Control System Architecture

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 Flash Drive Pick-up and Drop-off

The flash drive retrieval system consists of electro-magnets inside a cup on the bottom of the vehicle. Once the flash drive is detected using downward facing HD camera, the vehicle will hover above the flash drive and then lower itself onto the drive and lift it off the table. After the flash drive is visually confirmed to be onboard, the drop off servo rotates, releasing the decoy.

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 URG-04LX Hokuyo Scanning Laser Ranger Finder and two Logitech HD cameras along with the IMU and altitude sensor to produce a navigation vector and a map of the environment.

3.1.2 Mission Sensors

Primary mission sensing is performed using a URG-04LX Hokuyo Scanning Laser Range Finder and two Logitech C270 HD Webcams. The Hokuyo is used for object ranging allowing classification of physical features in the mission area, such as the window opening, walls, doorways and any other physical obstacles up to five meters away. Hokuyo data is also used in creating the environment map. Forward and downward facing cameras are used to identify mission-critical landmarks such as the posted signs, the entry window, the window camera, and the flash drive. These tasks are accomplished using the open-source computer vision library OpenCV. The camera is also used to identify obstacles in concert with the Hokuyo. When obstacles such as laser trip wires are detected, the ducts around the propellers allows the vehicle to lightly bump into the deactivation switch to turn off the trap.

3.2 Communications

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. 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.

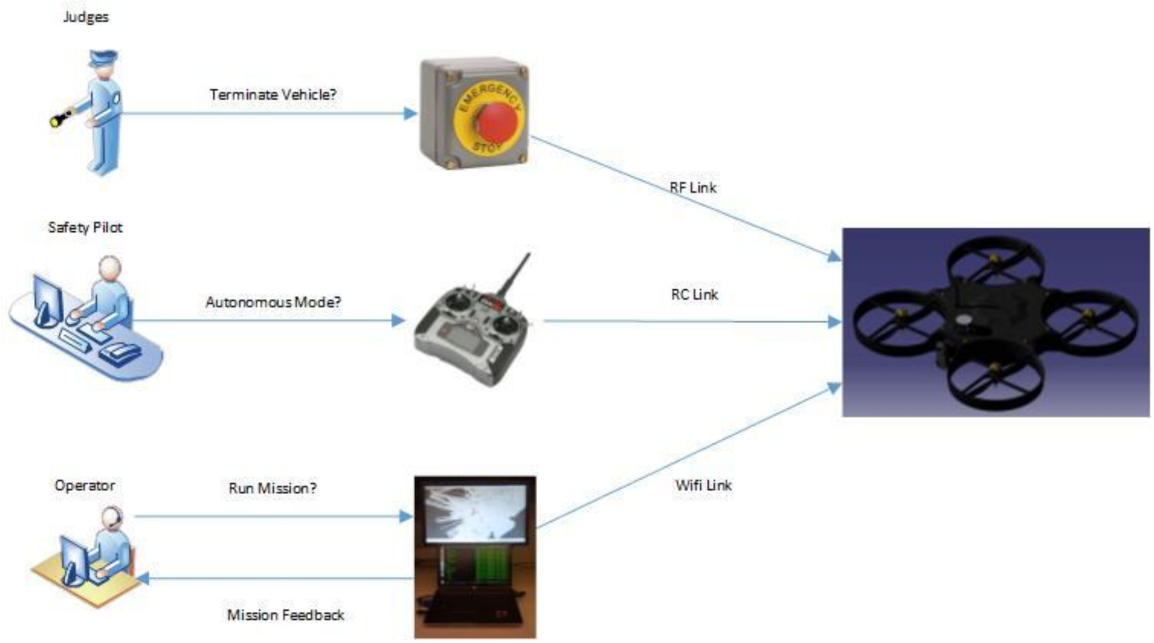

Figure 5: Man/Machine Interface Hierarchy

5. RISK REDUCTION

Safety has always been a primary consideration in all aspects of IARC team and vehicle operation, 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 while providing protection from the rotors. Multiple termination signals were implemented to insure that the vehicle can be shut down and rendered ballistic in case of emergency. The vehicle is designed and manufactured to be able to withstand significant impacts without permanent damage.

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 test for fit and finish 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 building hallways and rooms was performed.

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 by flight inside close-quarter environments. The use of digital manufacturing technology to fabricate the airframe allowed the vehicle to be precisely tailored to the requirements of the 6th mission and the selected sensors, components and subsystems. The team used a systems engineering approach to focus improvements on the mission requirements. 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 RAVEN II system to provide a complete solution for the 6th Mission of IARC.

7. ACKNOWLEDGEMENTS

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

Dr. Charles Reinholtz
Dr. Patrick Currier
Dr. Eric Coyle
Mr. Christopher Hockley
The Boeing Co.
Sparton Corporation
MaxBotix Inc.
Hoverfly Technologies Inc.

8. REFERENCES

[1] Michelson, R., Rules for the International Aerial Robotics Competition 6th Mission, http://iarc.angel-strike.com/IARC_6th_Mission_Rules.pdf

[2] Kennedy, Christopher, et. al., “Development of 'Eagle Quad' quad rotor for the International Aerial Robotics Competition 2011”, 2011 Symposium on Indoor Flight Issues, 9 Aug. 2011

[3] Zuercher, Timothy, et. al., “Development of 'ERAU Raven' Quad-Rotor System for the International Aerial Robotics Competition 2012”, 2012 Symposium on Indoor Flight Issues, 3 Aug. 2012