Intelligent Radiation Awareness Drone: Creation of an Unmanned Aerial Vehicle with Radiation Hazard-Guided Navigation

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Introduction

Radiation is a threat that is impossible to perceive without proper surveillance equipment, and in extreme cases the efficacy and efficiency of surveying can be life or death. Radiation surveillance may be performed routinely or used in the case of accidents and other unplanned events. Surveying is necessary to understand the radiological characteristics, or background environmental radiation, prior to installation of a nuclear facility or to improve detection of possible future illicit operations. Significant radioactive sources, from therapy machines or used in industrial radiography, may be lost and would need to be quickly located. Initial and continuing investigation of the distriubtion of radioactive material in the environment following nuclear power plants accidents or radiological terrorist events is also best accomplished through radiological surveys. Finally, decommissioning and cleanup operations require extensive radiation surveys of large land areas. With sufficient surveillance technology databases of radiation levels over time can be created. By comparing with historical trends, radiological events can be detected.

Routine surveying allows for necessary databases to be created and maintained, but surveying over large areas is time consuming and resource demanding. The current methods of radiological surveying involves every portion of an area being swept with a handheld detector or random samples of environmental media (soil, water, foodstuffs) collected and analyzed in a laboratory. This requires significant human resources and a near-rectilinear search pattern to be comprehensive. This method of sweeping becomes exponentially more expensive as the size of the surveyed area increases. The cost is a hurdle for any agency or community that wants to survey for radiological hazards. Consequently, surveying is not incentivized, and possible threats are easily ignored because radiation cannot be perceived with the naked eye. Nevertheless, radiological surveying is funded to protect large populations during gatherings or when responding to perceived threats. While the current methods are considered comprehensive, measurements are still confounded by interference caused by physical obstacles, which can lead to an inaccurate picture of the radiological characteristics of an environment.

Surveying can be facilitated using a small unmanned aerial vehicle (UAV) with a radiation-detecting payload. To maximize the UAVs limited flying time, a radiation hazard-guided navigation algorithm can be used to comprehensively survey an area without the need to sweep the entire area using a rectilinear search pattern. Instead, each survey consists of many discrete radiation intensity measurements, called counts, and all available information in each survey can be utilized to make informed decisions about the optimal flight pattern to collect only the data necessary to reconstruct a map of the radiation sources within an area.

In addition, the scattering and shielding issues faced in traditional surveying can be avoided by taking measurements in the air above most obstacles. Autonomous operation of the UAV is possible with the addition of a collision avoidance subsystem, allowing for minimal required human intervention. Using an UAV would eliminate the need for large human resources, and the algorithmic search method would create efficiency without sacrificing quality. The cost of radiological surveying could decrease dramatically, making surveying accessible to more communities, giving them knowledge of their radiological environment, and allowing them to make more informed decisions.

With the rise of drone hobbyists, the resources and knowledge base surrounding drones has increased. An open-source ecosystem for flight controllers and telemetry ground stations is available and used in industry-grade systems. These developments in the drone industry have allowed an interdisciplinary team of undergraduate students at the University of Michigan to begin the development of an Intelligent Radiation Awareness Drone (iRAD). iRAD aims to provide an accessible solution to the issues presented with traditional radiation survey techniques, and provide an interesting platform for undergraduates to develop their skills in engineering and research.

Project Scope

The creation of iRAD is driven by the desire to integrate a currently purely algorithmic solution to surveying into UAV hardware that can be applied in physical spaces. At this stage of development, the problems presented in this project involve systems integration and minimizing overall weight, rather than optimizing the UAVs power consumption or movement. Described in this paper are the efforts of a team of undergraduate engineering students towards creating iRAD. Students were tasked with tackling individual subsystems and integrating the hardware to enable iRAD to serve its intended purpose. All equipment sourced for the construction of iRAD is considered hobby-grade due to its cost and accessibility. iRAD aims to have a total system mass of 4kg, which is near the maximum weight capabilities of hobby-grade systems. Several iterations of the iRAD system are to be expected in its development; this paper details the first of these iterations. For iRAD to be considered complete, several requirements were created involving the hardware, software, and sensors.

Hardware

The essential flight hardware of iRAD needs to be capable of flying for a minimum of 15 minutes, with a preferred flight time of 30 minutes or greater. This benchmark was chosen by comparing iRAD to similar systems and taking into consideration the relatively large system mass.

The motors used to lift iRAD need to be able to produce a total of at least 8kg of thrust to lift the 4kg system and maintain the optimal thrust to mass ratio of 2-to-1. This will ensure iRAD has enough power to maneuver safely and reliably.

Software and Sensors

For iRAD to complete its intended mission, it needs to have flight software integrated with GPS to set the boundaries of a particular survey flight and track the location of each count measurement. A telemetry system is required so the drone can communicate with the mission planner software used to set these boundaries and track GPS movements. In addition, a manual flight mode is necessary for safety while testing, requiring a long range 915MHz radio module and controller to interact with the drone. Nevertheless, iRAD is intended to be an autonomous system requiring very little human intervention. This means the implementation of collision avoidance and terrain holding subsystems is necessary for iRAD to navigate complex environments. A companion computer must be present to process data from auxiliary sensors, and, more importantly, to interface the hazard-guided navigation algorithm with the flight controls software. In addition, the sensing payload must be modular in order to adapt to the two use cases: radiation detecting and Wi-Fi sensing.

Technical Approach

To meet the requirements specified, the first iteration of iRAD was constructed using a heavily modified hobbyist drone hardware bundle featuring the DJI F550 Flamewheel hexacopter frame. Avionics are powered using a 4S lithium polymer (LiPo) battery. The focus of this first iteration was to design and construct the wiring harness for the essential flight hardware of iRAD and achieve full integration with necessary telemetry and radio systems. Subsystems involving the autonomous operation and algorithmic control of iRAD were developed separately without the intention of integrating them. Focusing on a relatively low-cost frame keeps the cost of failure low and the learning opportunities for students high.

Flight Control

An open-source flight control software called PX4 Autopilot runs on a PixHawk4 flight controller which has native GPS, and is used in several applications across industry. The autopilot’s capabilities allow for the nuances of controlling a multicopter to be abstracted to a trusted system, allowing the project focus to be on interfacing with the navigation algorithm. The algorithm will tell iRAD where to go, but the autopilot figures out how to get it there, and the two communicate using custom firmware.

Hazard-Guided Navigation

An on-board companion computer will perform the computations involved with the hazard-guided navigation algorithm. In short, the algorithm takes an intensity measurement at a point then uses the collection of data taken during the survey to predict the location of a radioactive source. Using the communications firmware, the navigation algorithm sends the coordinates of that prediction to the autopilot and iRAD moves to those coordinates. This process is repeated until iRAD reaches a predetermined threshold of certainty that the source has been found. The development of the radiation hazard-guided navigation algorithm is a largely independent project; its implementation will not be discussed in detail in this paper, only its integration into iRAD. In addition to the navigation algorithm, the companion computer facilitates the collection of real-time data for the subsystems necessary for autonomous operation, namely collision avoidance and terrain holding. Collision avoidance involves using a front-facing camera to determine if iRAD is about to hit an obstacle. This data is sent to the autopilot, which already has the controls necessary to avoid the obstacle. Terrain holding involves a down-facing LiDAR sensor whose measurements are similarly sent to the autopilot to ensure iRAD remains the same distance from the ground, even over rough or sloped terrain.

Payload

The modular payload consists of two discrete modules. Only one will be present onboard iRAD at a time. One module contains a line-of-sight radiation detector needed to complete the intended mission of iRAD. The other module has a Wi-Fi detector to measure the Received Signal Strength Indicator (RSSI) from 2.4GHz Wi-Fi emitters as simulated radioactive sources. Because radiation and Wi-Fi are both electromagnetic waves, they both have decreasing intensity proportional to the inverse of the squared distance. This is the property utilized in the navigation algorithm, so a large irradiated environment can be simulated using Wi-Fi emitters with the Wi-Fi detector payload. This allows iRAD to have a large-scale testing environment without having to acquire radioactive sources strong enough to be detected from several meters away or gain access to hazardous environments to test in. Both modules send their respective measurements to the companion computer using the same wiring and communication protocol to ensure consistency between them as they are intended to act identically from the perspective of the companion computer.

Results

The first phase of the iRAD development cycle has resulted in the complete system architecture design shown in Figures 1 and 2.

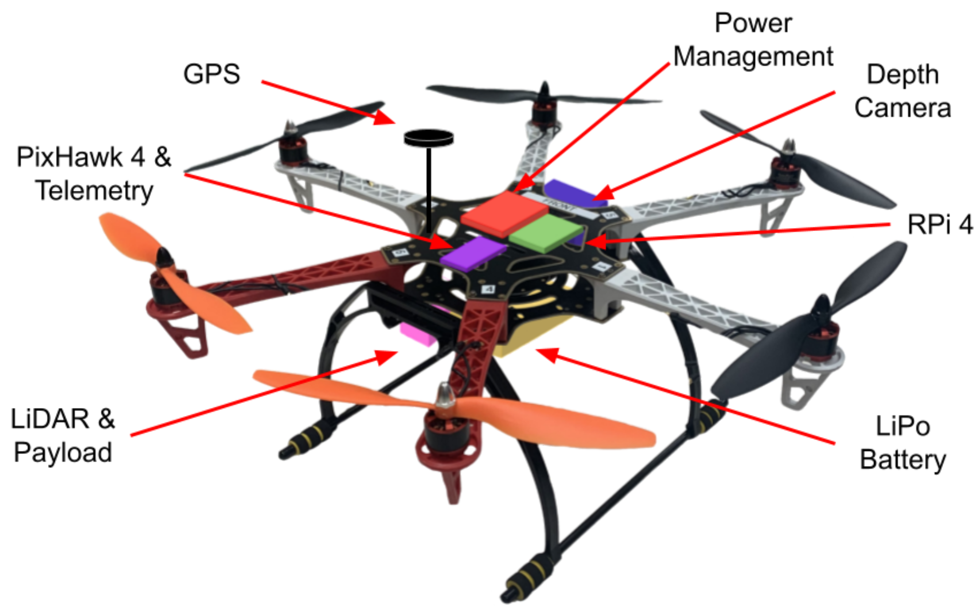

Figure 1: Modified DJI F550 drone kit showing the various components and their approximate location on the drone when integrated into the system.

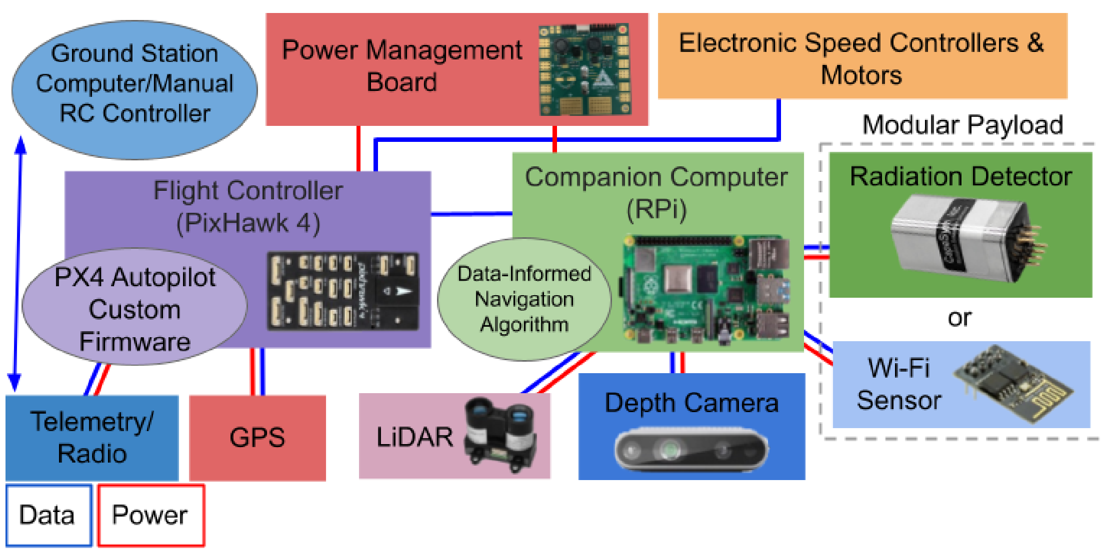

Figure 2: Power and data flow between main components integrated into iRAD.

The first iteration of the multicopter drone with essential flight hardware is assembled and has a system mass of 2.1kg. Essential flight hardware includes the components for power distribution, motors with electronic speed controllers, flight controller with GPS, telemetry to communicate with the mission planner, and a radio system so iRAD can be controlled manually. All subsystems not yet integrated are currently in development. Test flights have confirmed the successful integration of the essential hardware, which means attention can be focused on subsystem development until each one is ready for full integration. The wiring harness onboard iRAD during its first flights is shown in Figure 3.

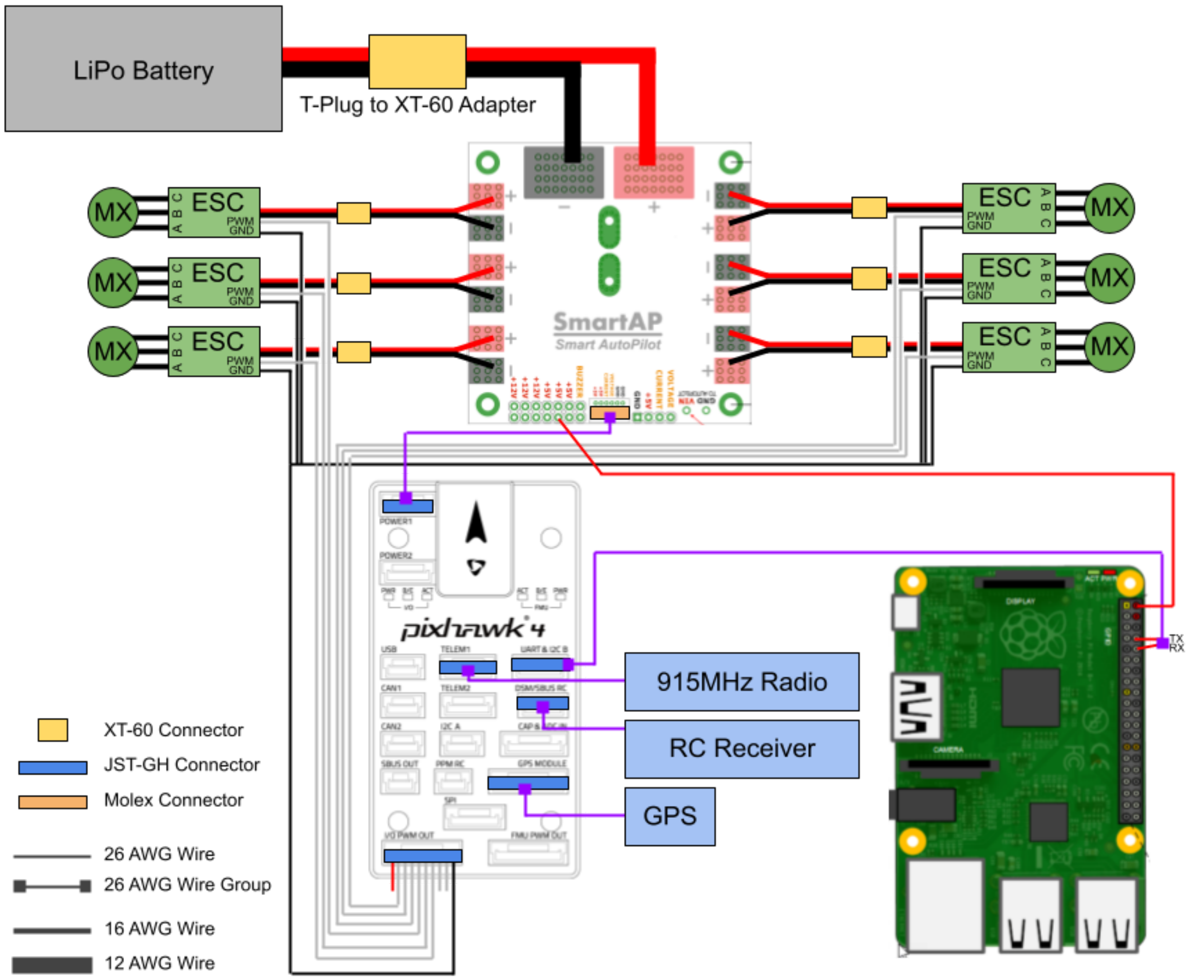

Figure 3: Wiring harness of iRAD essential flight hardware and companion computer.

Frame

iRAD is supported by a DJI F550 Flamewheel hexacopter frame with landing gear from Drones-Xpress, a hobbyist drone-parts supplier. As seen in Figure 4, the frame from tip-to-tip is 23.5 inches and the landing gear has a height of 13.4 inches, providing space below the DJI frame when landed. With 6 motors, a hexacopter can provide more thrust than the more common quadcopter, and was chosen to alleviate the issue of the large system mass. The landing gear is an essential addition because it allows for the heaviest component of iRAD, the battery, to be mounted below the center of gravity of the frame. Lowering the center of gravity provides stability in the air which is helpful because iRAD stops periodically to take measurements. The landing gear also allows room for the downward-facing LiDAR sensor to be mounted below the frame.

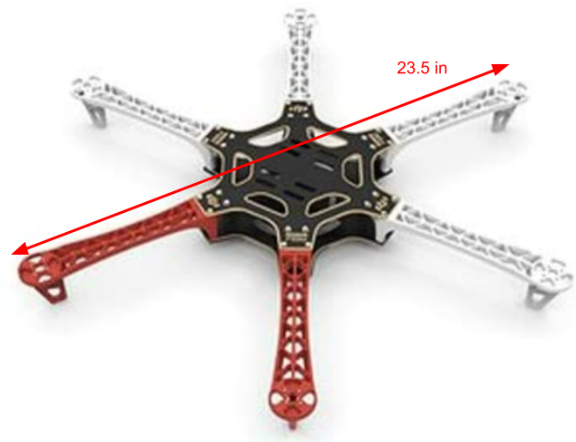

Figure 4: DJI F550 Drone frame used to support the first iteration of iRAD.

Essential Flight Hardware

iRAD is powered using a 4S Lithium Polymer (LiPo) battery, and power is distributed to every component onboard using the Smart AP Power Distribution Board (PDB). All parts of the power system are designed to be reused in future iterations of the drone. Thus, no wired connections from the PDB involve direct soldering and instead use connectors. The PDB itself was chosen due to its versatility and high amperage ratings. If a future iteration of iRAD opts for more powerful hardware or motors, the current power distribution system can still be used without risk of an amperage bottleneck.

iRAD is equipped with 6 2212-KV920 motors, and six Simonk 30A electronic speed controllers (ESCs). The ESCs receive power from the PDB and a signal from the flight controller to set the motor's speed. Each motor is equipped with standard 1045 2-blade propellers capable of creating an estimated 500g of thrust at 100% throttle, creating a total of 3kg of thrust. The most common benchmark for multicopter motor thrust is a 2:1 thrust-to-mass ratio. This ensures the drone hovers at about 50% throttle which optimizes battery life and allows for a reliable margin of thrust available for maneuvering in the air safely. In order to meet the requirement of a 4kg system mass, the motors would have to produce a total of 8kg of thrust at 100% throttle. The current motors do not meet this benchmark, but for the first iteration of iRAD they are adequate to perform rudimentary flight testing. Further iterations of iRAD will need more powerful motors to meet the 8kg requirement.

The flight controller onboard iRAD is the PixHawk 4 with GPS running PX4 Autopilot, an open-source flight control software used by hobbyists and industry professionals. All of the controls software used to fly iRAD is abstracted out to PX4, allowing the focus of iRADs development to be on integrating specific payloads.

The telemetry for control of the drone is made up of two independent systems. First is the automated GPS-guided telemetry. The firmware to run this is pre-loaded onto the PixHawk 4. A computer running QGroundControl, an open-source mission planning software, will send mapping signals to the PixHawk using telemetry antennas and an open USB port on the computer. The data is sent in the form of a Micro Air Vehicle Link message (MAVlink). MAVlink messages range from takeoff directions to GPS coordinate points to heights and speeds and wind information. The PixHawk uses this information to autonomously control the motors and perform calculations based on all other sensors that are connected to the device. The second system is the manual flight control system. This system is connected to a standard remote control. Through a 16-channel 915MHz communication protocol, the pilot can remotely control drone height, yaw, pitch, and roll. The drone is controlled using a FRSky Taranis QX7 controller with an R9M 2019 915MHz Transceiver module. This connects to a R9M Slim+ receiver connected to the PixHawk.

The PixHawk is always prepared to receive signals coming from the manual flight controller, reading any info given and taking it as a priority so the pilot can intervene if a flight becomes unsafe or to avoid a collision. If the connection between the drone and remote controller is severed, the PixHawk will listen for MAVlink messages and process telemetry. If no telemetry data is received, the PixHawk switches to a “return home” directive where it will return to its point of departure by a generated emergency path, and land automatically. Having no manual control of the drone is very dangerous. A severed radio connection can be simulated using the bypass mode on QGround control in order to prepare for such a situation without taking the risk of irreversibly relinquishing control of the drone.

Companion Computing

The companion computer onboard iRAD is a Raspberry Pi 4 Model B running Ubuntu. Having an additional computer onboard allows the navigation algorithm to complete its computations without the need to transmit data to and from a ground station, meaning processes can run in near real-time. This project is unique in that the drone is meant to be controlled algorithmically rather than manually or with a predetermined flight path. Custom firmware is in development to enable serial communication between the controls software and the hazardous-navigation algorithm running on the companion computer. The algorithm outputs coordinates of the next position where iRAD should move to continue its search, and the firmware ensures the PX4 software receives and understands those coordinates. A more detailed explanation can be seen in Figure 5.

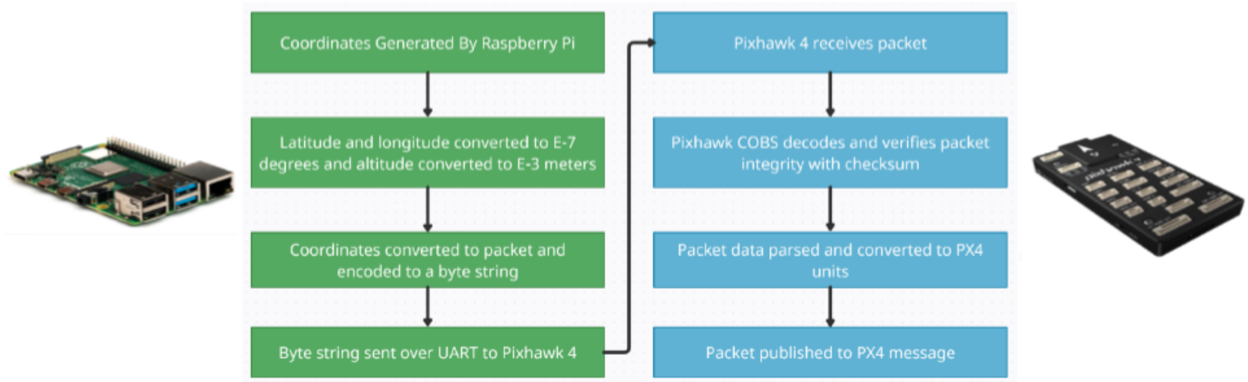

Figure 5: Information flow chart for packet encoding on the companion computer and decoding on the PixHawk 4

The companion computer is also responsible for sending data to the flight controller relevant to the collision avoidance and terrain holding systems. However, custom firmware is not needed for this as PX4 has built-in functionality for both collision avoidance and terrain holding. The hardware simply needs to be connected via a port on the PixHawk.

The collision avoidance subsystem uses a front-facing Intel RealSense Depth Camera D435 to collect data. MAVLink then communicates the data from the companion computer to the flight controller which runs evasive maneuvers if necessary.

The terrain holding subsystems ensures iRAD is low enough for the payload detector to measure effectively, and high enough not to disrupt dirt or other material on the ground. Dispersing radioactive particles into the air when surveying a hazardous environment could confound measurements and pose a safety risk.. A LiDAR-Lite Optical Distance Sensor V3 is mounted facing downwards. Similar to the collision avoidance, the data is run through the companion computer which is then transferred to the flight controller via MAVLink. Based on the received data, the flight controller will move iRAD up or down accordingly.

Next Steps

A second iteration of iRAD is already in development, and utilizes the entire wiring harness assembled in the first iteration of the drone. However, a significant redesign is underway to be able to lift a fully integrated system at a 4kg system mass. This next iteration will include a more robust frame and more powerful motors in a quadcopter configuration. It was discovered during development that 4 motors, rather than 6, is optimal to generate the necessary 8kg of thrust. Using 4 motors with larger propellers requires less current draw to generate the same amount of thrust as 6 motors and smaller propellers. Thus using a quadcopter puts less stress on the power distribution system overall.

The integration of the modular sensing payloads is essential. Testing needs to be completed on several Silicon Photomultiplier (SiPM) Scintillator radiation detectors in order to determine their maximum detection range before a decision can be made. SiPM Scintillators are lightweight and small, but also offer the possibility of identifying the type of source once found. The currently selected Wi-Fi sensor for the alternative payload is a HiLetgo ESP8266, but has yet to be integrated.

Flight testing is needed to characterize the movements of iRAD, determine boundary conditions of operation, and stress test components. Once the Wi-Fi sensor is integrated, large-scale testing can commence using Wi-Fi emitters. This will test the efficacy of the hazard-guided navigation algorithm running on iRAD. Smaller-scale testing with the radiation detector payload will also occur, but it’s unclear at this time if the drone will be flying during them due to difficulties accessing strong radioactive sources.

As development continues past the first two iterations, iRAD will carry exponentially more expensive equipment– notably the radiation detector payload. The system mass of the drone will also double after full integration. To ensure all flight testing is safe and beneficial to the project, members of the team will train to receive their Part 107 licenses to become official drone pilots.

Conclusion

A first iteration of an Intelligent Radiation Awareness Drone has been designed, built, and flight tested. Individual subsystems are in development along with a second iteration of the drone. The efforts of this project will result in a useful UAV system for several application spaces involved with radiological surveying. Utilizing the capabilities of a drone combined with a radiation hazard-guided navigation system can greatly improve on the traditional methods of radiological surveying.

From routine surveying to rapid response to radiological events, iRAD appears to be a viable solution for efficiently and accurately surveying radiologically hazardous environments. Having a more accessible solution will incentivize agencies and communities to survey their environment and be able to make informed decisions about disposing of material and precautions to take.

iRAD is developed by a team of all undergraduate students. Through this project students are being introduced to a variety of engineering disciplines while being encouraged to engage in research, ultimately preparing them for graduate programs.