Object Retrieval from Secure Unknown Interior Spaces Using Autonomous Unmanned Aerial Vehicles

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ABSTRACT

This paper describes an autonomous unmanned aerial vehicle (UAV) designed to participate in the 23rd annual International Aerial Robotics Competition. The UAV is equipped with onboard sensors and a Harvard architecture 8-bit RISC microcontroller to monitor and locally control its flight telemetry. Additional sensors (and an additional microcontroller) are used for detecting and mapping of structural and environmental objects while the UAV is in flight. The microcontrollers are interfaced with wireless communication modules for transmitting flight telemetry and structural/environmental data to a ground control station that sends the UAV command and control signals required for the mission objectives. The UAV platform is built upon a quad-rotor helicopter (quad-copter) design that utilizes open-sourced hardware and software, and is equipped with hobby grade sensors, actuators, vision systems, and wireless communication components thereby reducing the cost of UAV research by an order of magnitude.

INTRODUCTION

The autonomous unmanned aerial vehicle (UAV) described in this paper will be presented as an entry into the 23rd annual International Aerial Robotics Competition (IARC) held from 31 July through 3 August, 2012 in Grand Forks, North Dakota. The competition challenge is to deploy a UAV that is capable of entering a structure with an unknown interior floor plan; locate and retrieve a pre-defined object while avoiding detection from, or disabling, interior and exterior security measures. The UAV team's goal is to be the first group to successfully complete IARC

Mission 6 and showcase the innovation and engineering prowess of Old Dominion University's Frank Batton College of Engineering and Technology.

To accomplish this goal, the team has translated the competition guidelines [1] into engineering guidelines and designated the systems and sub-systems required to achieve them. Using a design/build approach, the team has begun the process of design, implementation, and testing of several of the key components and sub-systems of the UAV. Our design specifications are based upon the IARC Mission 6 goals and competition rules that are described in the following subsections.

IARC Mission 6

IARC Mission 6 is a simulated covert intelligence operation directed against a hostile group occupying a secure compound with task orders [2] directing our team to penetrate the compound, locate the security office, find and retrieve a USB flash drive, and exit the compound undetected by exterior and interior security measures. The mission must be accomplished using an autonomous UAV that meets the IARC design specifications and is capable of complying with and completing the Mission Critical Elements for the competition [1].

Mission Critical Elements

From the IARC 6th Mission Rules [1], the Mission Critical Elements are:

- The UAV must be fully autonomous and capable of self controlled flight within a confined environment.
- The vehicle will first be required to enter the building through a one square meter (minimum) open window.
- The vehicle will launch from a designated area not less then three meters away from the window.
- The vehicle must search for the target area while avoiding un-briefed obstacles such as wall, columns, and furniture.
- The vehicle must avoid detection by security systems such as an exterior video camera and an interior laser barrier.
- The vehicle must detect and recognize several signs indicating the route to the security office.
- Upon locating the security office, the UAV must find and retrieve a USB flash drive and leave a blank 'decoy' drive in its place.
- The UAV must exit the compound with the retrieved USB flash drive to complete the mission.
- The entire mission must be completed in less than ten minutes.

Design Specifications

The IARC 6th Mission Rules [1] lists the following design specifications:

1. The vehicle must be unmanned and autonomous.
2. Any number of vehicles may be deployed so long as the gross aggregate weight of each vehicle does not exceed 1.50 kg.
3. Computational power need not be carried by the UAV.
4. Data links by means of radio must utilize legal radio bands for the arena location.
5. Aerial vehicles can be of any type.

6. Vehicles must use electric motors powered by batteries, capacitors, or fuel cells.
7. No more than two non-line-of-sight navigation aids may be used external to the designated flight area.
8. GPS is not allowed as a navigation aid.
9. A manually-actuated remote kill device must be provided for each vehicle or group of vehicles.

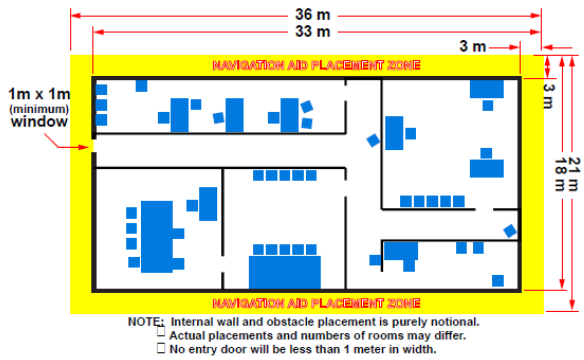

Figure 1: Competition area dimensions.

Competition Area

The competition area will be a structure that is 30 m long and 15 m wide. The walls of this structure will be 2.5 m tall and the interior will be divided into various rooms and hallways similar to the layout in Figure 1.

The structure interior will be constructed of 2.5 meter cubes arranged in different configurations to create rooms and hallways that the UAV must travel through to complete the task. Each cube will be made up of twelve 8 foot long PVC pipes, connected by four corner couplers. The walls of these cubes are made out of DuPont c Tyvek and hung by tie wraps. Holes are cut into to some of the walls to represent windows or doors in the structure. The resulting structure will look similar the one shown in Figure 2.

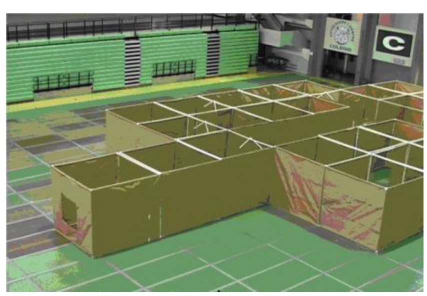

Figure 2: Example Competition Area

DESIGN

The UAV team is Old Dominion University's newest student driven competitive robotics team and is currently in its first year of competition. Therefore, the team has no a priori knowledge of aerial robotics, nor any systems or data to utilize as a baseline for our design. Thus, the team elected to use a rapid application development paradigm and a design-build methodology to facilitate rapid prototyping of our aerial vehicle and all of its sub-systems. Furthermore, due to our limited resources and time, we elected to utilize readily available components and systems as the core for our robot and to tailor our engineering design approach to a systems integration or system design process. From this approach we were able to quickly identify existing solutions for many of our hardware and software subsystems.

UAV Platform

The competition requirement for controlled flight within confined spaces limits the choice of aerial platforms to lighter-than-air or rotary-winged aircraft. The time and size limitations of the competition make the use of lighter-than-air aircraft impractical, leaving only rotary-winged aircraft as a viable choice. To minimize the mechanical complexity of the aircraft and thereby increase its reliability, we elected to select a quad-rotor helicopter (quad-copter) rather than a traditional helicopter design. As shown in Figure 3, a quad-copter has only four moving parts - the motors that drive each propeller - mounted at the extremities of its cross-arms.

Figure 3: Typical quad-rotor helicopter.

The quad-copter's simplicity in mechanical and electrical design and construction lends itself well to a student-lead research project. Primary flight control and stabilization of the quad-copter is accomplished by means of an embedded microcontroller and an array of on-board sensors (gyroscope, accelerometer, barometer, magnetometer, etc.). Many commercially produced hobby, professional, and research grade quad-copters are available, however, most of them significantly exceed any realistic budget expectations of the team, and most utilize proprietary hardware, software, and human-machine interfaces. One solution that the team found, the 3DR Arducopter, is produced by 3D Robotics [3] and is based upon and open-sourced solution produced by the DIY Drones on-line community [4]. The Arducopter's control system - known as the ArduPilotMega or APM - uses an Atmel ATMega2560 microcontroller [5] that is compatible with the Arduino Mega development board and the Arduino integrated development environment (IDE) [6], it has a full range of sensors for flight stabilization and control, and fully configurable hardware and software for user interfacing. Furthermore, the Arducopter meets the team's size and weight requirements, our budget, and is well supported via the on-line community. Therefore, the Arducopter was selected as the platform for our UAV.

Proximity Detection Subsystem

The Mission Critical Elements of the competition rules make it clear that the UAV will have to be equipped with an on-board camera and interfaced with a vision processing sub-system for image recognition and visual object detection. However, a single camera cannot provide the depth of field required to determine the UAV's spacial orientation or its proximity to or from an object. Therefore, we must rely on a separate sensor sub-system for proximity detection.

Looking to our Arducopter's on-board sensors and the hobbyist market, two solutions appeared: ultra-sonic and infra-red sensors produced by MaxBotix and Sharp [7, 8]. Both sensors fit the criteria of low cost, power, and weight, while meeting the maximum and minimum sensing ranges that will be encountered in the arena.

Mapping and Navigation

The navigation sub-system of the UAV will be a complimentary design with the purpose of maneuvering through a building while simultaneously mapping the structure, tracking the location of the UAV's location within the structure, and plotting the shortest route available for exiting the building after recovering the USB flash drive. The principle operation will be a 3-state algorithm that takes inputs from the various sensors on-board the quad-copter. The algorithm we will use makes decisions based on the distances calculated from the sensors, and locates the exit point of the room or hallway that the UAV is occupying. The exit point will be any opening not the same as the entrance. The overall position of the UAV will be determined by a parallel set of arrays that compute local and global position relative to the vehicle's launch point. The local position is local to the room that the vehicle is presently is exploring. The global position is relative to the building that the room exists within. The global position is used to make a decision for multiple exits.

For the Navigation system, several highly developed algorithms are being considered. One is the wave front algorithm which, using the data gathered from the sensors available, makes a grid of the surrounding area using a two dimensional array. A target cell within the room is assigned based on predefined constraints from the programmer. The vehicle will travel towards the target cell, constantly updating its map and shrinking the size of the cells that represent the interior space of the room. Eventually, the robot finds a precise location of the target and the navigation portion is completed. The downfalls of this method are that the limitations of the algorithm come from the technology available. For this method to be precise, typically there is a trade-off between speed and money. They are inversely proportional.

Command and Control Structure

Because the competition rules give the option of the computational equipment not being carried by the air vehicle, the group decided that all flight control computations will be performed at the base station to keep the vehicle's weight and power requirements to a minimum. The primary purpose of the command and control function is to provide a central location for the data collected from the navigation and vision subsystems and to serve as the only line of communication between the vehicle's subsystems and the Arducopter's piloting firmware. This will prevent erroneous flight commands due to conflicting data from the various subsystems of the UAV.

In order to become familiar with the APM firmware, the team will read the code and documented each line using Doxygen. Doxygen is an open-source documentation program that can extract the source code comments (of a wide variety of languages like C++, C, Java, etc.), and analyze the declarations of the code to create a HTML document of the code in one simple click [9]. This program will help the team familiarize themselves with the firmware in the short time frame that this project has for completion because the code has complex data structures for every operation that the Arducopter has to do. The Mavlink protocol is embedded into the APM firmware and is used for sending and receiving data from the base station to the UAV. Mavlink is a standard protocol that the team had to become familiar with in order to implement its Application

Programmable Interface (API). Mavlink is used to collect the data from the vehicle's motors, GPS, altitude sensors, battery, ground speed indicator, and compass module, and send this data to the Base Station. Typically, the Base Station program will translate the data into a human readable form on a Graphical User Interface (GUI) application. The data transmitted via the Mavlink protocol is encoded in UTF-8 (RFC 3629), which is "a multibyte encoding for text that represents each Unicode character with 1 to 4 bytes, and is also backward compatible with ASCII [10] ." In order to complete this project, we will have to understand the Mavlink protocol so that we can use it to establish a stable link to the UAV.

Vision Subsystem

The vision subsystem is a mission critical element for this project. From the Mission Critical Elements [1], the team has identified that this subsystem must be capable of accomplishing several specific tasks such as:

- Detect a USB flash drive and provide tracking information to the command and control subsystem.
- Detect and recognize several signs indicating the route to the security office.
- Detect visible security measures such as:
  - Simulated video surveillance camera - a blue LED will indicate that the camera is active.
  - Laser barrier - a warning sign will indicate the location of the barrier and a pressure plate that will deactivate it
- Aid the mapping and navigation subsystem by:
  - Detecting doors and windows and providing tracking information to the command and control subsystem.
  - Detecting objects of interest and providing tracking information to the command and control subsystem.

As previously mentioned, the team has elected to move the UAV's computational systems off of the vehicle to a ground control station. Therefore, the vehicle must be equipped with a means to collect and transmit images to a receiver attached to the ground control station.

Digital Camera

A digital camera affixed to the vehicle will capture images for transmission to the ground station. The image sensors used in digital cameras are divided into two main categories: Charge-Coupled Devices (CCD) and Complementary Metal-Oxide Semiconductor(CMOS). The image sensors convert optical signals into electrical signals and image hosting. While both of them use photodiode for optical-electrical conversion, they have a different structure and effect[12, 13, 14]. CCD is a mono-crystal semiconductor and CMOS is a Metal-Oxide-Semiconductor. In a CCD, the charge data in every pixel will be sent to the next pixel and released at the last pixel. Amplification and conversion is the next and last step in the process. In a CMOS, every pixel is linked to a transistor, which amplifies and converts the signal after being read from each individual pixel. CCD and CMOS have many differences in performance and application due to the differences in data path. First, the CCD and the CMOS both have micrometer unit class pixel size, but CCD only has one amplifier for the whole chip. This is while a CMOS has same number of amplifiers as pixels. Due to this construction, the CCD can have more pixels than the CMOS for the same size. The difference of amplification causes an array of character:

1. CCD requires higher voltage supply for pushing charges in every pixel unit to only one amplifier. The CMOS can use lower and wider voltage to power and less energy for millions of parallel amplifiers.
2. CCD has lower noise and better linearity because all charges travel through the same amplifier, while CMOS has millions of amplifiers, each with different amplification characteristics.
3. CCD has lower image distortion than CMOS because of CCDs single amplifier, compared to the millions of amplifiers of CMOS. Image data from CCD is easier to reduce.
4. All charges in CCD have to go through one amplifier. It is much slower than CMOS where every pixel has its own amplifier. Therefore, CCD has lower capture speeds than CMOS.

The UAV team will choose a CMOS image sensor because CMOS has higher capture speeds and lower energy consumption than CCD. Higher capture speeds reduce the ghosts and drag when the UAV is moving resulting in lower energy consumption therefore increasing the endurance of whole system. CCD image sensor has higher resolution, but more pixels will cost more time to compute, more bandwidth to transmit, and more space to store. This will increase the difficulty to design the whole system. The team will use gray scale images rather than color to increase computing speed, so image noise is not a significant problem for the project. Additionally, the team will use a camera that can provide a standard Electronics Industries Association (EIA) RS-170a composite video output signal [15] for compatibility with available radio transmitters and receivers, and available video capture devices.

Transmitter & Receiver

The team will use a compact DPCAV 5.8 GHz/ 200mW A/V Transmitter. This transmitter has a composite video input, a 5.8 GHz radio frequency band that will not interfere with other radio frequency signals employed by the UAV, and it is capable of operating from power sources ranging from 7 to 15 VDC. This allows flexibility in the teams selection of batteries used to power the UAV. The matching video receiver is the DPCAV 5.8 GHz / 12V Micro Receiver.

Video Capture Device

The composite video signal delivered to the ground station computer is an analog signal and can therefore provide lossless real time video input. However, the computer is a digital machine and cannot process the video stream without a peripheral device capable of converting the analog input into a digital format. The team selected a Hauppauge 558 ImpactVCB PCI Video Capture Card because it met the following requirements:

- Low cost: less than $50
- PCI interface: matching available expansion slots on the ground station computer
- Drivers available for the Linux operating system: matching the operating system used on the ground station computer

Vision Algorithms

For each of the primary tasks assigned to the vision subsystem, a unique algorithm has been created for processing the incoming video stream.

Surveillance Camera Detection

To detect the blue LED that indicates that the surveillance camera is active, this algorithm will transform the video stream data from a red, green, and blue (RGB) color space to hue, saturation, and intensity (HSV) color space. HSV color has Hue value that separates dark from bright and can eliminate the affect of ambient light [14]. The algorithm will then locate all pixels in the blue wavelength range. Next, a filter will erode and dilate each image in the string to delete most of noise. The erode filter can delete all noise under a number of pixel. The dilate filter can balance the effect of the erode filter by increasing the size of all existing pixel area. After this filter, all small noise will be deleted. Finally, a blue color threshold contour will mark the LED source.

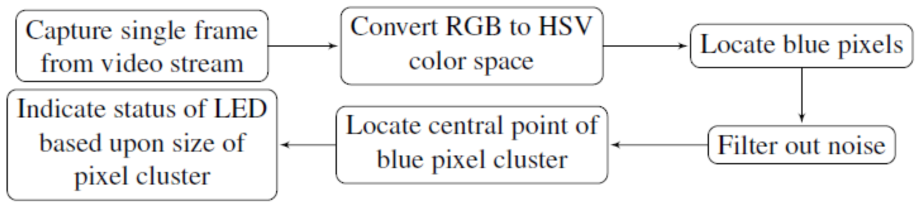

Figure 4: Flowchart Showing Algorithm to Detect Blue LED

Sign Recognition

To detect and recognize the signs within the competition arena, a gray scale image will be created from a reduced-resolution color frame. This can reduce the size of data and increase the computation speed of the image processing. The sign recognition algorithm will then use machine learning and an artificial neural network to learn and recognize frames captured under different angels, distances and light conditions.

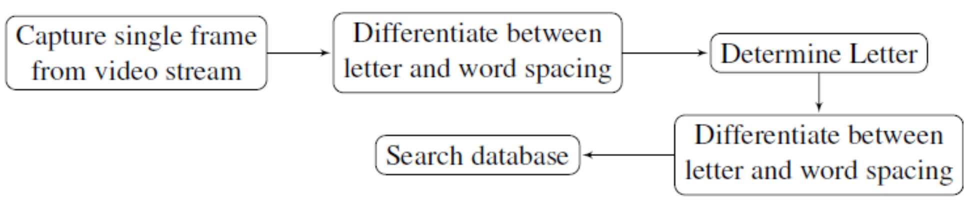

Figure 5: Flowchart showing algorithm to detect and recognize signs.

USB Flash Drive Detection

The USB flash drive detection algorithm will employ two color filters that will analyze the image and build thresholds for the two possible colors of flash drive. Contour images will be built from an edge image detection algorithm and will be searched for contours with two pair of parallel lines. A boundary tracing will then be used to mark the target. From reading the target's pixel size, and comparing it with the expected size of the flash drive, the program will determine if the target is the flash drive.

Object Retrieval Subsystem

The retrieval and replacement of the USB flash drive accounts for 1500 points of the total scoring for the IARC competition therefore the design and implementation of the object retrieval subsystem is crucial to the overall performance and success of the team during the event. In designing this system, the team must consider two important design constraints, weight and size. The competition rules state the UAV must weigh no more than 1.5 kg. This is a very limiting constraint for retrieval system because the UAV's current design, with the other subsystems attached, weighs in at approximately 1.3 kg, limiting the retrieval system design to no more than 200 g. Another constraint is the size of retrieval system with regard to the overall size of the UAV. The competition requires that the UAV must fit through a 1 by 1 meter window to enter the building. Because the UAV is approximately .915 m at its widest, the design of the retrieval system cannot extend much further than the arms of the UAV. Currently, two designs are being developed to complete the task.

Both designs appear to be viable solutions that meet the constraints outlined above, but further testing will be needed to determine the appropriate final design for the competition.

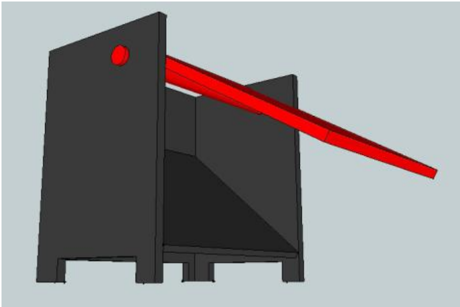

Figure 6: Conceptual drawing of retrieval mechanism.

The retrieval system can be divided into two unique mechanisms: The retrieval mechanism and the delivery mechanism. Our concept of the retrieval mechanism is a basket that will simultaneously retrieve the target object and deploy the decoy object. Figure 6 shows a conceptual sketch of the retrieval mechanism. The basket will be attached to a delivery mechanism that will lower it over the target thumb drive. When fully lowered, the basket's front door will be pushed open when it hits the surface of the desk, allowing the stored decoy object to slip out. At the same time, the target object is acquired by the use of double-sided adhesive tape affixed to the bottom of the basket. The bottom of the basket will have small legs to avoid inadvertently adhering to anything other than the target object.

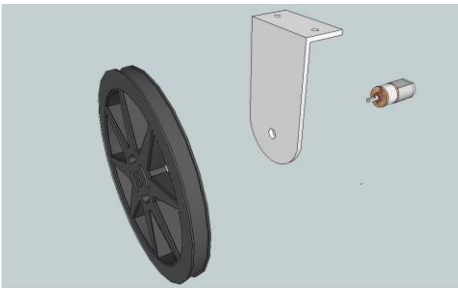

Figure 7: Conceptual drawing of delivery mechanism.

As shown in Figure 7, the current delivery mechanism is a cable & winch mechanism that will use a string to raise and lower the basket. The winch will use a brushed DC motor that will be controlled by an H-Bridge circuit as shown in Figure 8. Control signals from our microcontroller will determine which transistor pair to turn on, allowing the motor to operate in the forward or reverse direction based on the transistor pair selected. The advantages of this design are that it is simple, light, and easy to construct.

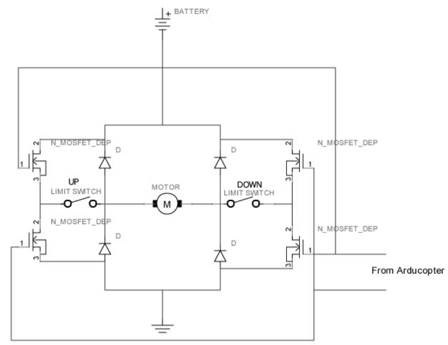

Figure 8: H-Bridge circuit drawing.

CONCLUSION AND RISK ASSESSMENT

The UAV Team faces many realistic constraints upon our design and implementation for our entry for the IARC competition such as deadlines, budget, health and safety, manufacturability, sustainability, and design specifications. The results of our efforts will be determined by our ability to address each of these constraints and produce guidelines, time lines, and procedures as required as well as adapting to and changes that may be necessary due to unforeseen events.

In addition to constraints, it is the team’s responsibility to ensure that this project results in a UAV platform and control system that is safe, reliable, reproducible, and easily manufactured. To aid in the completion of the project on-time and onbudget, we have implemented several engineering standards as part of our design. These Standards defined terms and reference designations for components, parts, and equipment that we included in our design and implementation. They have also provided guidance for personal, property, and electrical safety.

Our commitment to the environment led us to include Standards for assessment of the environmental impact of our project, and the large amount of programming that this project requires led us to include Standards for implementation of programming languages. Due to our design/build approach we also employed a standard guide for rapid prototyping. Finally, the UAV is a flying machine and as such must be in compliance with federal guidelines. The team kept these all of these guidelines and standards in hand while developing the designs.

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