Unmanned Autonomous Object Retrieval: Old Dominion University 2013 International Aerial Robotics Competition Entry

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This paper describes the design implementation of a Quadrotor Unmanned Aerial Vehicle (UAV) with the capability of exploring indoor locations without the assistance of external aids. For relative position, the use of a laser range sensor, an optical flow sensor, and sonar sensor combined allows for the vehicle to generate mapping information. With relative position in mind, the vehicle uses vision algorithms to recognize immediate obstacles, sign, and entry ways to allow for quick movement responses and object recognition. A proportional-integral-differentiator controller allows for flight stability and mitigation in the tight confines of the indoor spaces. A mapping algorithm allows for the quick evacuation of the location without interacting with previously detected obstacles and walls. This vehicle is designed and intended for Old Dominion University's Unmanned Aerial Vehicle Team's entry for the 2013 International Aerial Robotics Competition.

INTRODUCTION

Governments worldwide have begun to prioritize the indoor surveillance of enemy territories during battle in means for gaining an advantage during wartimes. For a completely unnoticed reconnaissance, an unmanned aerial vehicle is an optimal design over the land based autonomous designs due to the UAV's ability to travel in three dimensions instead of two. A three dimensional travel range is preferred due to unknown obstacles within and easier avoidance of detection with the ability to levitate out of sight. Using current technology, the aerial systems are for the most part reliant on satellite positioning, which is unreliable on the interior of buildings. Even with the significant increase of indoor reliability, the specific goals of the

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competition state that the global positioning system is not a readily available resource for the vehicle to use due to its variable reliability. For surveillance purposes, the design must be small and lightweight, but high in efficiency with a low cost. In case of exposure, the team could easily ditch the vehicle, possibly with an algorithm to clean the device's system and immediately leave the area. The small design also allows for easier navigation of cluttered environments and unnoticeable movements within the indoor environment.

Problem Statement

The sixth mission of the International Aerial Robotics Competition clearly states that a UAV weighing no more than 1.5kg must have the ability to enter an unknown environment through a window, navigate, and map the afore mentioned environment in an attempt to locate a pre-designated target within the building [1]. The location of the target is unknown, so the vehicle must show the ability to recognize signs located throughout the building while avoiding security systems and detection. Once the object is found, the vehicle must retrieve and immediately evacuate the environment. All of this must be completed in less than a ten minute timeframe.

Conceptual Solution

The Old Dominion Unmanned Aerial Vehicle Team, ODUUAV, has designed an indoor autonomous vehicle with the ability to enter and navigate through unknown interior airspace without the use of satellite navigate. The vehicle is designed from a modified preconfigured quadrotor platform. An ArduPilotMega, APM, 2.5+ is mounted on the platform for on-board system operations and communication. An unique algorithm for navigation is ran through the base station, which is necessary due to the amount of processing, with the communication from the laser range detector, optical flow sensor, and sonar sensor, which will form accurate measurements for navigation in order to allow for full avoidance and movement within the facility. In addition to the navigation algorithms, the vehicle will be equipped with a PID control that assists in movement of the vehicle in order to fully maneuver the vehicle as needed for the mission.

Yearly Milestones

The ODUUAV team continues its development of a stable custom UAV capable of completing the sixth mission. The vehicle will have the ability to explore and map the indoor environment, detect all vision aspects of the competition, and extract the target flash drive. Additional milestones are exploring the indoor facility without detections as well as integration of guidance and vision systems to improve mapping algorithms. Previous years, reliance on the vision systems were primary, but with the addition of the laser detector, vision system will be used as a catalyst for improvement of the navigation system. In 2012, a series of ultrasonic and infrared sensors with the camera were utilized simultaneously in hope to gather the proper information for accurate mapping and navigation. For 2013, reliance on the laser detector will be primary goal for interior of the facility movements.

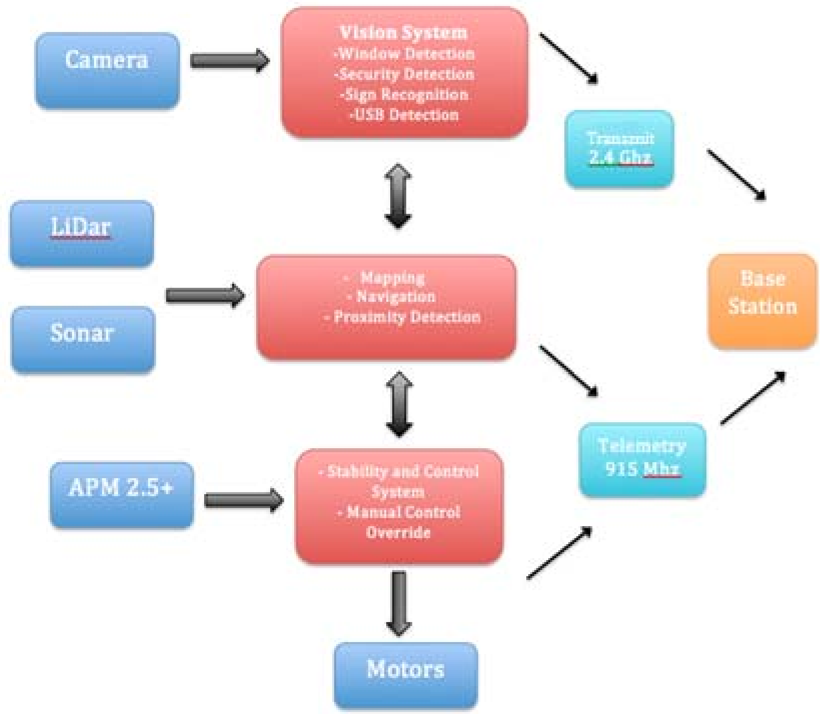


Figure 1. The ODUUAV System Architecture

AIR VEHICLE

Structural Flight Design

The quadrotor design of the unmanned aerial vehicle seems to be one of the most commonly used design present for autonomous designs. Due to its simplicity of design, the vehicle can be oriented in either an x- or plus-configuration. Stereotypically, the x-configuration is chosen over the plus configuration due to its ability to prevent saturation of the motors [2]. The team's choice to use the x-configuration allowed for a simple build algorithm for stabilization and movement control, but more extensive calibration testing of the system due to multiple varying motor speeds. The actual vehicle itself was a custom build from a pre-built frame with multiple parts purchased separately. Two custom vehicles are in development for the 2013 competition, one being the Tarot Iron Man 650 quadrotor frame and the other, X-4 8 Quadro Copter. The vehicle gains lift and propulsion from four Turnigy D2836/8 Brushless Outrunner Motors. With the x-configuration, each diagonal set of motors will offset their relative thrust to control movements in pitch, yaw, and roll.

(a) Tarot Iron Man 650 Platform (b) X4-8 Platform

Figure 2. The 2013 ODUUAV Team chose to use the X4-8 and Tarot Iron Man 650 platforms.

A third vehicle was in development for the initial design to allow for minimizing risk to the main design frames. With this frame for testing, the possibilities for design failure and development were increased, but allowed for minimal risk to the main systems to increase cost effectiveness. This vehicle was separately provided by another student due to its relative weight to the actual frame design, which allowed for semi-accurate calibration in the initial development phases. All of the frames are designed using carbon fiber sheets for the main body and carbon fiber rods for the arms. Due to the scarce availability of machinery for in-house development, the vehicle are purchased via hobby shops, so risk minimization is at the top of the team's priorities.

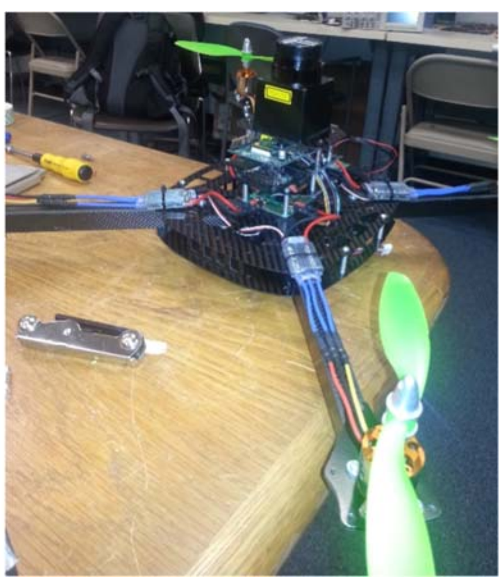


Figure 3. The X4-8 modified frame for competition

The current vehicle weight approaches 1.475 kg with the following components mounted to the frame: four motors, two sets of propellers, four speed controllers, Xbee transceiver, APM

2.5+, Turnigy Camera, receiver, power regulator, transmitter, Light Detection and Ranging, LiDaR, sensor, ultrasonic sensor, optical flow sensor, telemetry kit, and a LiPo 3250 4-cell battery. The heaviest items are the battery pack, 327 g, LiDaR, 160 g, and the four motors, 280 g cumulative. The specific battery chosen will provide just enough power for the vehicle to fly for the required ten minutes to complete competition with the motors at maximum thrust, which is approximately 4520 grams of thrust, which is more than adequate enough for lift, hovering, and maneuverability. With all of the above materials, only 25 grams are available to develop and attach a retrieval system for the flash drive.

Guidance, Navigation, and Control System

Guidance System

With the use of on-board sensors, the vehicle will relay the retrieved information to the home station and generate a map from the series of readings. Of the on-board sensors, the LiDaR will be the most reliable sensor for the generation of the map. The LiDaR will send out its ray, which will reflect back at each intersection. The scans will be continual and the guidance system will take all of the points of reflection into reference of previously generated points. The importance of this is to gain a proper accuracy of the surroundings with multiple checks instead of trusting only a few points. If a previous node is reflected back, then the map will represent it in the previous location on the system.

For the actual mapping of the system, the vehicle will be taking into account previous locations within the environment. Because of the wide scanning array of the device, the sensor is able to capture a total of 240 degrees around the forward part of the vehicle [3], which allows for recognition of previous nodes within the facility. Due to the continual processing of the sensor data, the vehicle will be consuming more data processing than need be, so the team is currently optimizing this error in the system with built in waypoints from the reflection points.

Stability Control System

Without an input control system, the quadrotor would not have the ability to maintain stabilized while in flight. Due to additional add-ons to the frame, the initial stability of the flight was horrific and destructive. Due to its difficulty to control, the calibration of flight requires the addition of multiple sensors of proper orientation and control during flight times. The APM attached to the vehicle actually comes with an on-board gyroscope and accelerometer to aid in the calibration of the control system. For the change in attitude and creation of stabilization, the team is utilizing a proportional-integral-differentiator, PID, controller.

While calibrating the PID, the system will provide responses with our physical change in pitch and roll. The accelerometer data is translated into vector coordinates along all three axis. These translated vector outputs are sent back to the console, so that the responses are compared to the output motor values. From there, calibration can be continued using the comparison of responses to those desired by using the proportional part of the algorithm. Once the proportional response is calibrated properly, then the differentiator is next for calibration. The differentiator and integral are similar in that they are the time for the proportional response, so they are similar in calibration meaning that once the proper time response is achieved, then both components are as desired.

Navigation System

The vehicle's navigation system is based from the above designed guidance map. Originally, SLAM [4] and Robot Operating System [5] were in development for the navigation system within the building. However, due to the frame design, the navigation system became a series of commands that generate the map and follows avoidance protocols from the sensors and camera. Specifically from the camera input, the vehicle will discover the sign for each room and identify the proper room to proceed into while taking into account all obstacles surrounding the vehicle through laser detection. For the laser detection aspect of navigation, once the vehicle enters the facility; the initial readings will command the vehicle to travel within one meter of the right-hand wall of the facility.

From this point, the vehicle is commanded forward throughout the facility keeping the one meter distance while mapping forward and left of the vehicle location. This is optimal due to the laser's wide range and its high accuracy. The continual flow of the laser sensor allows for easy reaction to the upcoming obstacles and easy avoidance protocols. A local generated map will provide an optimized path based upon the restraints of the vehicle and around the vehicle to travel from door to door for the sign recognition part of the objective. Once the proper door is located, the vehicle will proceed into the room and repeat the same technique as when it first entered the facility.

As for the escape from the facility, the vehicle will uses the previously generated map and optimize the path out of the facility while allowing for obstacle avoidance. The algorithms and actions taken by the vehicle are completely an in-house creation.

Flight Termination System

There are two ways of termination for the vehicle flight installed within in the vehicle. The first one is a function built within the main algorithms of the vehicle. During testing, it became difficult to disconnect the battery if the PID values were improper. After several changes to the system, a series of character inputs will recalibrate the entire PID controller, the motor speeds, and the vehicle power system. The importance of all of these system changes as it pertains to the motor speeds is for ease of discovery of the needed motor values for each aspect of flight. Once the minimal values were found for hover, the PID values were estimated and the system restarted. If the PID values were incorrect, the values were able to be calibrated in flight causing an ease and speed up of calibration. With the one key power kill, there was a dampening of human risk in the physical testing.

The second form of termination was provided by the IARC. The provided circuit board is directly connected into the power board to the vehicle as an intermediary from the battery. The last part of the board is connected into a receiver, so that the vehicle can be killed remotely without need from the on-board microcontroller. The reason for this method is to provide an option for the system to terminate that will not need the processing time that the algorithm would need.

PAYLOAD

Sensor Suite

For the ODUUAV entry, the primary purposes of the sensors are for navigation, stability, and control. The devices include the APM 2.5+, LiDaR, optical flow sensor, and sonar sensor. Most importantly is the APM because it includes several on-board sensors including a three-axis gyroscope, a three-axis accelerometer, a magnetometer, and a barometer. For the indoor usage of this device, the only sensors utilized are the gyroscope and the accelerometer. The specific chip on the APM is the MPU-6000 family, which is a programmable chip for both the gyro and accelerometer portions of the board.

The LiDaR utilized on the vehicle is the Hokuyo URG-04LX-UG01. This specific model was chosen because of its cost effectiveness and accuracy. The device has a range of 5.6 meters with a 240 degree viewpoint. For the navigation and mapping portion of the milestones, this device proves to be more than enough to fulfill its purpose especially with an accuracy within 30 millimeters of true value. Even with all of these characteristics being within the perfect setting for the experiment, the power consumption was by far the most important for the selection. A low-power consumption is mandatory due to the limited time frame and small battery for competition purposes.

The last two sensors, optical flow and sonar, are the only sensors mounted on the bottom of the vehicle. The sonar sensor used is the LV-MaxSonar-EZ4, which was chosen because of its accuracy and quick availability to the team. The purpose of the sonar sensor for the vehicle is for altitude control of the vehicle. Once initially started, the vehicle will spike upward into the air to the desired setting, which is found and relayed by the sonar to the base station. For the optical flow sensor, the team is utilizing the ADNS-3080 optical sensor. The team chose this sensor because it was relatively cheap and would serve the purpose for speed calibration. Because the optical flow sensor relays the change in pixels detected, this will allow for the algorithm to take into account this flow to assist in minimizing the issue of possible collision with obstacles.

Communication

The communication between the base station and the vehicle is controlled by a telemetry kit directly linked into the APM. The camera will portray its vision to the home station though a transmitter mounted to the vehicle and a receiver directly linked into the base station. As for the LiDaR, the information is passed from the LiDaR to a Raspberry Pie, which is only being used to process the laser data. The Raspberry Pie is linked into an XBee communication device that communicates with its mate at the base station. With all of these forms of communication, they all transfer via different bandwidths, so no interference has been noticed.

Power Management System

The entire vehicle is powered by a four-cell 14.8 volt LiPo 3250 battery. The battery is fed through a controller board, which will in turn power the motors and devices mounted on-board. For the Raspberry Pie, a voltage divider circuit is implemented to prevent ruining the board, which will in turn provide the power to the LiDaR at the proper level. The batteries have been continually tested through flight and examination as to its length of operation time. The specific battery chosen will run for just about twelve minutes before shutdown. An alternate battery was utilized during testing phases, but it only lasted six minutes, so it was inadequate for the competition purposes.

OPERATIONS

Flight Preparations

For each flight test, calibration test, or competition trail, a checklist of preparations has been mandatory for the team to follow. Table 1 depicts that specific checklist.

Table 1. Flight Checklist

Steps completed days prior to flight	Charge LiPo batteries Validate that all sensor connections proper Verify all equipment present
Steps completed day of flight	Set up ground station Check structure of vehicle Verify center-of-gravity
Steps completed before each flight	Cover safety protocols for in-flight testing Upload code Recheck vehicle integrity
During Flight	Have coder present to input commands for change and shutdown Make sure that IARC kill switch operates properly

Man and Machine Interface

The base station designed for the man and machine interface was an in-house set of codes based from previous experiences with other vehicles. It has the ability to retrieve and analyze all on board data into an easier understood user interface.

RISK REDUCTION

Vehicle Status Monitoring

The vehicle will continually run its mapping and guidance protocol to detect potential obstacles using the on-board LiDaR system. Any and all obstacles will be broadcasted back to the base station for proper monitoring and map generation.

Shock and Vibration Isolation

The devices mounted on the vehicle have the inherent ability of variable voltages. The team decided that it was important to install specific voltage divider systems to assist in minimizing the risk of destroying any component mounted. For vibration of the vehicle, the team is utilizing a several tier mount on the top half of the vehicle for the APM, Raspberry Pie, and LiDaR. The LiPo battery is directly attached to the center of the bottom of the vehicle, which assists in the equalization of the vehicle's balance. The use of the tier allows for a series of spacers with springs to absorb the shock of the vehicle's movements. For the lower mounted sensors, shock did not present any type of problems during testing, so no extra precautions were made for these sensors.

Electromagnetism Interference, EMI, and Radio Frequency Interference, RFI

As the team built the vehicle, previous designs from the ArduCopter libraries [6] discussed the use of brushless motors to reduce the EMI signature along the device. The APM and motor control board were mounted on the center of the vehicle, the APM on the top and the motor control board on the bottom. This assisted in the reduction of the EMI that could possibly be developed between the motors and circuitry boards. In addition to the previous precautions, the addition of multiple voltage regulators and dividers were added along the vehicle to assist in the dampening of any possible EMI produced.

To reduce the possible RFI with the vehicle, the transmitter and receivers on board operate at a variable bandwidth ranging in the 2.2-2.4 GHz range. The video transmitter specifically is a 2.4GHz that broadcasts the video link back to the base station. For the APM and data processing, the telemetry kit will broadcast the information and sensor values to the base station. The last communication device on the vehicle is the XBee, which will send the LiDaR data to the system for processing to a map. Luckily, all of these devices interact at different bandwidths, which reduces majority of the possible errors with miscommunication between devices.

Safety System

The main safety function utilized for this devices is our variable algorithm that allows control of motors, power, and PID controller. There are two options to guarantee safety for those around; cut the power to the system or to reduce the motor speeds substantially to the point where flight is suspended. As for the physical design of the vehicle to reduce risk, the arms lengths of the frame were reduced to assist in stability as well as the top mounter sensors being taller than the motors. The increased height will assist in possible prevention of being hit straight on by the vehicle. The LiDaR will hit the person before the motors do in most cases. The last assistance to bystander safety is the IARC provided kill switch, which will bypass all operations and suspend power to the vehicle and motors.

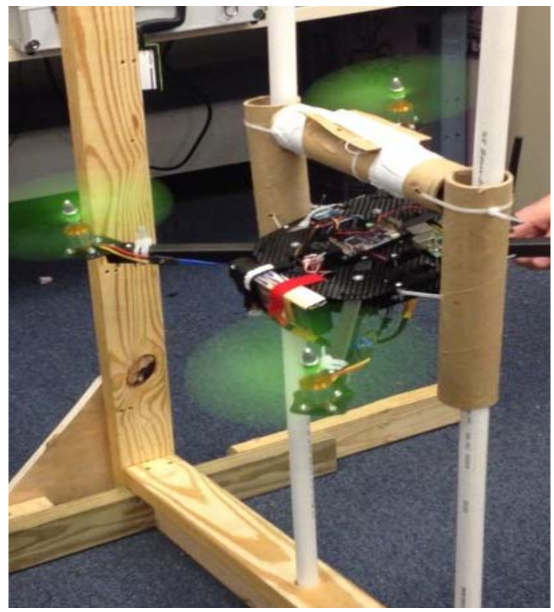
Modeling and Simulation

Due to an issue with timeframes, the simulation and modeling section of our development was actually minimal. The communication system and sensors were the only part of the vehicle simulated before the actual testing began. Due to software and lab constraints, the team focused more on the testing phase of experimentation and guaranteeing that that phase was performed with full safety for the lab and testers.

Testing

Initial testing was performed with a vertical "hangman" style frame, meaning that the only restraint on the vehicle was a vertical placed rope around a wooden frame above the vehicle. After that testing had begun, another testing frame was developed for proper safety measures. Below in figure 4, the left frame was the horizontal testing of the vehicle movement versus the right frame being our PID controller calibration frame.

(a) Horizontal Test Frame



(b) Vertical Test Frame

Figure 4. ODUUAV Calibration Testing Frames

The PID frame was utilized specifically for calibration of the pitch and roll of the vehicle. The way the vehicle mounts to the frame allows for full range movement along only one axis at a time. Beginning with pitch, the vehicle is calibrated using the gyro, accelerometer, and motor values for a physical change to the vehicle controlled by the team. As each value is found for the vehicle, the tension of the vehicle to the frame is lessened, which allows the vehicle to move with more freedom along the axis. Each time the vehicle gains more freedom, the vehicle requires more calibration. This exact system was repeated for roll calibration.

Once the PID was calibrated, the vehicle was attached to the horizontal frame to test the sonar and LiDaR responses to the system. The vehicle started from a rest, gains lift, and then an object is introduced below the sonar sensor. The proper reaction of the motors is to increase proportionally to proper altitude desired by the algorithm. As for the LiDaR, the team introduced an item within the half meter safety zone of the vehicle. The response is for immediate hover of the vehicle or movement opposite of the obstacle.

For the competition portion of the testing, the team built an entrance window exactly 1 meter by 1 meter. The vehicle has two ways tested for entry to the facility. Option one is to utilize the visual library functions built for the camera to detect the center point of the entryway. The vehicle will proceed forward slowly into the facility and once entered into the facility begin the navigation and guidance protocols. The second option for entry is utilizing the LiDaR to find the left and right edges of the window. From the generated map, the vehicle will proceed forward through the center point of the mapped edges thus allowing for the vehicle to begin the facility protocols.

The next part of the team's focus was to detect whether the security system is online or disabled. The team uses the OpenCV libraries generated by the camera to detect a blue LED. If the LED is recognized, the security system is online and the vehicle must disable it; otherwise, the vehicle begins its mapping and navigation systems. Also, the team must focus on sign recognition along the hallway to find the proper room for entry to find the flash drive. Using Haar-like features, the vehicle compares all images to the database on the base station. If the proper sign is recognized, the vehicle will proceed indoors to find the flash drive.

The flash drive will also be recognized using the Haar-like features from OpenCV. The flash drive image will be placed on the base station for comparison as well. If the vehicle recognizes the flash drive, it will proceed to retrieve the flash drive using a magnet. Once retrieved, the vehicle will immediately evacuate the facility.

Individually, all of these aspects have been tested and properly followed. As a total, the test run is still being calibrated for mission success.

CONCLUSION

The team designed and presented the details of a Quadrotor Unmanned Aerial Vehicle designed for exploring indoor environments. The specific frame for competition was a mass produced design with one of the most practical microcontrollers for flight electronics. Data gathered from the LiDaR, APM, optical flow, and sonar sensors is relayed to the base station to control, navigate, and guide the vehicle through the indoor environment without external aids. An in-house algorithm utilizing theories similar to SLAM and ROS allows for the vehicle to gather enough information to generate maps and proper navigation through the interior of the facility. These maps are sent to the control architecture, which allows for the proper movement of the vehicle through the facility with proper avoidance of obstacles and walls within the facility.

A series of PID controllers generates the proper reaction and movement of the vehicle in accordance to the generated map and entryways. Along with advanced control for specific parts of the vehicle, the vehicles reactions can be augmented with a simple press of a button. These specific control systems undergo severe testing to guarantee proper reactions to every movement along the entire vehicle.

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