*Autonomous Unmanned Aerial Vehicle Development*

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*Abstract*— *Unmanned autonomous vehicles have the potential to fulfill an organization’s objectives in a safer and more timely manner. Specifically, for the United States Coast Guard (USCG), unmanned autonomous aerial vehicles can be utilized to accomplish core goals such as search and rescue, migrant interdiction, and drug interdiction through image processing techniques which can help identify people and vessels in the water.* *This paper documents the production of an autonomous unmanned quadrotor in the scope of USCG missions. For three months the Autonomous UAV Capstone group of US Coast Guard Academy Electrical Engineering Department, guided by the Roboboat 2022 competition requirements, has been developing an unmanned aerial vehicle. The developed unmanned aerial vehicle is capable of autonomous and manual flight, including landing, taking off, and delivering payloads autonomously. This device serves as the foundation for a product which may provide the Coast Guard with an inexpensive method to supplement its success in achieving some of its core missions. Using the current prototype, the group has completed successful tests in flight, demonstrating the functionality of computer vision algorithms, real time kinematics, and basic autonomous flight. This project is under continued development to best fit the needs of the service.*

# Introduction

Autonomous unmanned aerial vehicles (AUAVs) are an invaluable tool for accomplishing the goals of an organization while minimizing the number of resources required to do so. The concept of utilizing AUAVs to contribute to the completion of mission objectives of the United States Coast Guard is one of incredible potential. The AUAV capstone project group at the United States Coast Guard Academy has actively been designing an AUAV for several months with the intention to prove such a device’s potential benefit for the service. The team cooperated with another capstone group developing an autonomous surface vessel to meet the requirements of the Roboboat 2022 International Competition. The quadcopter was tested in two environments, primarily in *Gazebo*, a software which allowed for specific simulated testing of the drone so that the group could ensure proper functioning prior to live testing. Testing was completed in both environments to ensure the accuracy of navigation systems, positive buoyancy of the drone, accuracy of color detection modeling and more. Testing was imperative to create a functional product, and in doing so, the team has constructed a quadcopter capable of both remote and autonomous flight.

# Background

Over the last decade, unmanned flights have become a dominant front-runner in the world of aerial advancements. As drone flight continues to increase in popularity among private businesses and governments, research has shifted focus to a new advancement in the industry: autonomous flight.

An autonomous aircraft can be classified as one that “does not require pilot intervention in the management of flight” [1]. This is exactly what the autonomous unmanned aerial vehicle presented in this paper is designed to do. Specifically, the UAV is designed to assist the United States Coast Guard (USCG) in missions such as alien migrant interdiction operations (AMIO) and search and rescue (SAR)

The USCG is currently only using one *unmanned* flight system on a large scale: The Boeing ScanEagle. As a fixed wing drone, the ScanEagle has offered the service advanced capabilities in flying without the need for an onboard pilot. The ScanEagle, however, requires a large area for a dedicated launching system and a remote pilot. This has resulted in the ScanEagle only being deployed on larger platforms, excluding many USCG units. The USCG is certainly interested in other unmanned aerial systems that would benefit smaller platforms; however, budget constraints have prevented the service from acting

TABLE I. REQUIREMENTS MATRIX

|  |  |  |
| --- | --- | --- |
| Operational Requirement | Functional Requirement | Non-Functional Requirement |
| The Vehicle Shall be Capable of Unassisted Flight. | The UAV must be capable of controlled flight in wind. |  |
| The Vehicle Shall Meet Competition Size Guidelines. |  | The UAV must be electronically powered: no battery voltage may exceed 60Vdc. |
| The Vehicle Shall Meet Competition Size Guidelines. |  | Together with the ASV, the dimensions must not exceed 3ft by 3ft by 6ft. |
| The Vehicle Shall Meet Competition Size Guidelines. |  | The criteria include batteries, meaning the total weight must be less than 10 pounds. |
| The Vehicle Shall be Capable of Autonomous Flight. | The UAV must be able to be controlled manually and autonomously. |  |
| The Vehicle Shall Communicate with the ASV. | The vehicles must exchange information about locations and targets of interest. | Wireless communication must utilize legal public frequencies. |
| The Vehicle Shall be Capable of Landing on an ASV Flight Deck. | The UAV must be equipped with cameras/LIDAR/RTK to land on the target. | The flight deck must be a design that is preemptively established in the computer vision module. |
| The Vehicle Shall Enable Transportation of Small Objects. | The UAV must be equipped with a claw capable of carrying and dropping objects. | UAV must be able to detect, move toward, and deliver objects to a designated target area design. |
| The Vehicle Shall Deploy from the ASV’s flight deck. | The UAV must have landing gear. |  |
| The Vehicle Shall Deploy from the ASV’s flight deck. | The UAV must be able deploy while the ASV is moving or stationary. |  |
| The Vehicle Shall Have a Loss of Contact Instruction Set. | Must initiate slow decent within 5 seconds of losing contact with remote control or remote kill. |  |
| The Vehicle Shall Have a Loss of Contact Instruction Set. | Positively buoyant for at least 120 seconds. |  |
| The Vehicle Shall Allow for Immediate Shutdown. | The vehicle shall have a local kill switch onboard the UAV. | The override must be wirelessly capable for 1000 ft. |
| The Vehicle Shall Allow for Immediate Shutdown. | The vehicle shall have a remote kill switch at the control station. | The remote stop function must be separate from the main controller. |
| The Vehicle Shall Allow for Immediate Shutdown. | Both must turn off all motors on UAV within 1 second of being pressed. |  |

Regarding unmanned surface and air systems in March 2021, USCG Commandant ADM Schultz said “We look at commercial-off-the-shelf; following, you know, our other fellow services and seeing what they're doing. We have just got a finite amount of R&D (research and development) dollars… We just don't have a lot of that budgetary maneuver space to take high risks there” [2]. This quote signifies that the Coast Guard is not investing in its own development of an unmanned aerial system let alone an autonomous one. This means that an AUAV for Coast Guard use will only come into the picture after another organization purchases and field tests one. LCDR Dom Bucciarelli, the USCG Short Range UAS Platform Manager, detailed in an email that the Coast Guard is currently looking to implement variants of the Skydio X2D and Parrot Anafi drone platforms (Both are not autonomous). The testing of these drones is coming after their success in use by Customs and Border Protection [3]. This further signifies the Coast Guard’s reliance on off-the-shelf platforms that have already been tested. It is evident that the USCG is not designing its own *autonomous* drone and that the service will only acquire one that has already been developed and tested. The AUAV group believes that the USCG could benefit from its own production of an autonomous drone as it could be suited specifically for service needs and at a much lower cost.

Until recently, hardware limitations only allowed leaders in the drone industry access to develop autonomous aerial systems. Today, however, flight controllers and mission planning software are available at reasonable costs to the public that support autonomous flights. The autonomous UAV capstone team believes that these advances can be used to the USCG’s advantage in the development of aerial systems. Completion of this

project will serve to demonstrate that a small team can achieve autonomous flight at a low cost.

This year’s AUAV project is a continuation of a capstone project from the USCG Academy’s Electrical Engineering Department class of 2021. Due to unforeseen challenges due to the COVID-19 pandemic, last year’s group was unable to make meaningful progress on AUAV development. As a result, the AUAV presented in this paper is entirely the work of this current year’s group.

# Objective

This capstone group in conjunction with the Autonomous Surface Vessel (ASV) will be competing in the International RoboBoat Competition next June. As a part of this competition, the UAV will autonomously take off from the ASV, fly to and detect a specific area where it will deliver an object, then afterwards provide arial video feed for the ASV team to use while navigating their course before returning to the ASV and landing.

After compiling requirements from the RoboBoat

Competition and other stakeholders the group has devised the following requirements matrix shown in Table I.

The most difficult constraintof the project is being able to successfully take off and landon the back of a moving vessel. Both tasks can be accomplished in any manner but must be fully autonomous. Once the UAV is in the air it must fly a search pattern until it finds the specific drop zone. Once detected, the UAV will fly over and hover just above the target before delivering the

Diagram

Description automatically generated

Fig. 1. System Block Diagram

payload. The pay load is described as a ping-pong ball sized object as only required to be delivered and not picked up as it will be pre-loaded on the drone. This has significant design impacts as the system only needs to be designed with a release mechanism rather than a claw which would be used to pick up the object as well.

During the competition, the ASV will be required to navigate a course fully autonomously. After completing the drone specific tasking, the UAV will locate itself above the ASV to provide an aerial lookout. This will come as live video feedback to both the ASV and UAV teams and will be utilizing the UAV’s onboard image processing technology to help the ASV plan its trajectory through the course.

In addition to the above main objectives, the UAV has other niche requirements that must be met to compete. These include all pilots being certified by the FAA, the drone being able to float for 120 seconds, and the drone having a remote kill and various other protocols in place for loss of connectivity.

# System Design

The completed UAV is comprised of several independent subsystems linked through the flight controller, as depicted in Fig. 1. To best understand the overall design, one may view the UAV as a series of physical components supported by connecting software frameworks and protocols.

The hardware components of the drone include the Holybro S500 generic quadcopter frame, motors, electronic speed controllers (ESCs), a physical flight controller, and mechanisms for landing, floating, and transporting small objects. These elements are largely independent of one another with the notable exception of the flight controller. The flight controller is a physical

device that serves as a common link between each component and connects sensors with elements that perform real-world actions.

The UAV specifically relies on the Pixhawk flight controller – a device capable of interfacing with the motors, sensors, and inputs – to enable various forms of flight. PX4 autopilot, an open-source autopilot designed to enable autonomous, manual, and other flight modes, is used in conjunction with the Pixhawk and interfaces directly with each subsystem to include telemetry, sensors, and communications.

Each of these subsystems has distinct inputs and outputs at each stage. The Pixhawk alongside PX4 autopilot are the cornerstone of the UAV as it exists today. Each element, from the onboard communications system to the entirely separate RTK base station, relays its information to PX4 in some way, shape, or form. This allows PX4 to enable various methods of control including manual, offboard, or computer vision driven control.

As part of the Roboboat competition guidelines, a UAV must be positively buoyant for 120 seconds in the event of a water landing (see Table I for a definitive requirement matrix). The objective, however, was to make the drone indefinitely buoyant to minimize damage to electrical components in case of an emergency landing. To meet this requirement, the UAV was fitted with outriggers to each corner of the drone. These outriggers provide, based on density and displacement calculations, over 6 pounds of buoyancy. That is nearly twice the 3.05-pound weight of the drone. Further, the wide spacing of these outriggers was designed to maximize the drone’s stability while on the water.

Testing of all flight software is done in the Gazebo simulation environment. Gazebo is a physics engine that is used primarily to model robots. Gazebo provides an environment to test flight and object detection software, incorporating appropriate forces such as drag, lift and gravity. The UAV presented in this paper can be seen modeled in Gazebo below (Fig. 2).

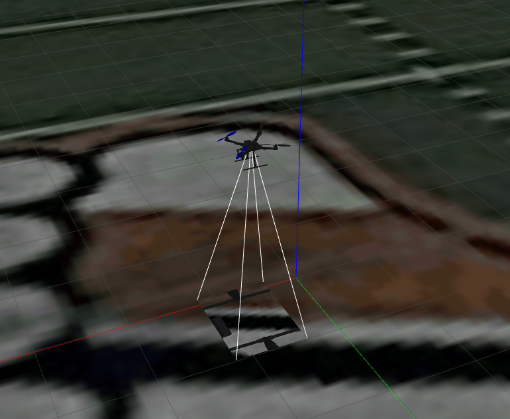


Fig. 2. Model of UAV in Gazebo Environment

An ideal computer vision test scenario was formulated to evaluate the design; from start to finish, the quadcopter would take off and execute a search pattern to discover an ArUco marker. If one is found, the drone would land on top of it. If not, the drone would return to start after exhausting the search pattern. A wrapper of the MAVLINK protocol was created to facilitate this task and manage the drone’s flight modes safely in the event of an error condition [4].

# Results

*A. Physical Platform*

The quadcopter, built according to a preliminary design, served as a primary testing platform for subsequent requirements. The initial analysis of the physical characteristics demonstrated that the drone’s weight of 3.05 pounds and ability to indefinitely remain positively buoyant exceeded the Roboboat competition requirements of less than 10 pounds and 120 seconds, respectively. The foam outriggers used to provide buoyancy were tested in a pool. In Fig. 3 below, the drone is seen floating in the pool while supporting 3000 g (6.61 lb.) of weight. This indicates the drone can support the weight of all hardware; however, a water landing of the drone has not been tested to determine the drone’s stability while moving on water.



Fig. 3. Test of Drone Floatation

The quadcopter’s proportional-integral-derivative controllers must be stable to maintain both manually controlled and autonomous flight. Following the initial configuration, the controllers were iteratively tuned to balance stability with responsiveness. In response to a significant disturbance input—a strong pull on the drone’s tether—the drone’s flight controller maintained stable flight and returned to its previous holding position [5]. Plots demonstrating the effectiveness of the flight controller with yaw, pitch and roll can be seen in Appendix I.

A picture containing text, grass, sky, outdoor

Description automatically generated

Fig. 4. The drone’s maintenance of level flight.

*B. Safety Criteria*

The safety of people and property is a priority of this research group, as well as the Roboboat competition guidelines. Thus, the remote kill-switch and loss of radio control (RC) signal procedures were analyzed during the first test flight. The initial test of the kill switch proved successful, immediately stopping all rotors regardless of the drone’s current position. The first test of the loss of signal failsafe appeared successful but, after further review, the flight controller failed to recognize the loss of RC signal. Instead, the most recent throttle input was maintained indefinitely; by coincidence, this was sufficiently low to result in a gradual descent that resembled a landing. In response, the RC receiver was configured to provide radio signal strength indicator readings to detect a loss of signal. Subsequent testing demonstrated that a loss of RC signal for two continuous seconds prompts the drone to land, as seen in Fig. 5.

Graphical user interface

Description automatically generated

­Fig. 5.The drone’s response to a loss of RC signal.

If the drone was receiving GPS data, the drone returned to its original point of takeoff. If not, the drone slowly landed at its current position.

*C. Computer Vision*

The computer vision algorithms designed to detect the Roboboat competition landing platform were tested extensively. Initially, these yielded a 72% detection rate of the platform under indoor lighting, as seen in Fig. 6.

Graphical user interface, application

Description automatically generated

Fig. 6. Indoor recognition testing of the landing platform.

However, the algorithms failed to properly recognize the landing platform during outdoor test flights under non-ideal lighting conditions, Fig. 7.

A picture containing text

Description automatically generated

Fig. 7. Outdoor recognition testing of the landing platform.

In response to these tests, the proposed landing platform of the ASV was changed to an ArUco marker, a black and white square marker that resembles a matrix. These markers are designed for fast and reliable detection. In Fig. 8 below, one can see the OpenCV script detecting the ArUco marker and outlining it in green. The script alongside the Raspberry Pi Cam can detect the marker out to about 35 feet before detection becomes inconsistent.

A screenshot of a computer

Description automatically generated with medium confidence

Fig. 8. The detection of an ArUco marker from in-flight video.

The AruCo marker system has since been revised again. The ArUco marker itself has been reduced to a 4X4 rather than 7X7 which makes it detectable at further distances. Another issue that was discovered, was that as the during the landing sequence the camera would eventually loose detection when the drone got too close. To combat this a smaller AruCo marker was added in the middle that is detectable even when the drone is on the ground, fig XX. The larger outside marker is detectable at up to 150 ft, and the smaller one is detectable up to 15 ft, which allows for a smooth transition going into the landing.

*D. Autonomous Flight*

Autonomous flight is a key requirement of the proposed autonomous UAV. The Gazebo simulation environment was utilized to test autonomous takeoff, landing, waypoint flight, as well as various search patterns. Following successful simulated results, the same commands were sent to the actual quadcopter. These test flights demonstrated successful autonomous flight, as well as the transfer of commands from the simulated environment to real-world results.

*E. GNSS and RTK Measurements*

Several tests have been performed to provided measurements of observed GNSS accuracy. Standard GNSS signals—a combination of GPS, Galileo, Glonass, and BeiDou—an average deviation of +/- 60cm over the course of 15 minutes, as seen in Fig. 9.

A picture containing light, night sky

Description automatically generated

Fig. 9. Deviation Map of a 15-minute GNSS fix.

This observed accuracy of accuracy from standard GNSS navigation is insufficient for precise adjustments when performing a computer vision enabled landing onboard the ASV: an inaccuracy of 60cm could place the drone beside the ASV rather than above. Thus, an RTK base-station position was measured to an accuracy of 16 millimeters and will be used to send RTCM corrections to the drone, as given in Appendix III. Using the same antenna and receiver, as well as under the same satellite constellation, weather conditions, and location, the observed accuracy of the GNSS-RTK enabled fix was +/- 6cm, Fig. 10.

Radar chart

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Fig. 10. Deviation Map of a 15minute GNSS-RTK fix.

Streaming RTK corrections directly to the GNSS receiver has presented several technical challenges. Troubleshooting this is a primary concern prior to a computer vision enabled landing; however, the overserved accuracy of the GNSS-RTK equipment is well below our objective requirement of 10cm.

*F. Computer Vision Enabled Landing*

The Gazebo simulation environment facilitated preliminary testing of a computer vision-controlled landing. The preliminary controller, which calculated the distance to the center of the marker in pixels, centered the drone over the landing platform and slowly lowered before touching the platform. These distance estimates did not change with altitude, though, and revealed characteristics of an unstable controller. After several iterations, the controller was updated to utilize the drone’s current altitude and attitude to estimate the distance between the point directly beneath the drone and the center of the marker. The resulting computer vision-controlled landing followed a stable path, as shown in Fig. 11.

A screenshot of a video game

Description automatically generatedFig. 12. A simulated computer-vision enabled landing.

Following this initial success, the Gazebo-SITL simulation environment was used to test the computer vision enabled landing sequence contained within the MAVLINK wrapper. When the ArUco marker is within the camera’s field of view, the simulated quadcopter recognizes the marker, centers above it, and begins descending. Below a specified altitude, and when the smaller inscribed marker is identified, the descent rate slows until a landing is detected.

Separately, the wrapper can execute take off and a corresponding search pattern based on a starting coordinate, desired path spacing, and desired altitude. During this time, the drone monitors for ArUco detections; however, the wrapper is not yet capable of transitioning from search to landing states. All testing has been conducted within SITL (Software in the Loop). If the ArUco marker detection falls below a specified threshold, the quadcopter holds position until it reestablishes positive identification or determines the marker to be lost, at which point it returns to its takeoff position.

*G. Payload Delivery System*

From Table 1, the drone shall also be capable of transporting small objects. This task has been accomplished through the creation of a scoop mechanism for payload delivery. The mechanism is powered by an SG90 continuous micro-servo motor. This servo motor provides transmission to a gear system that guides one of the two scoops along a rail, creating an opening for objects to be dropped at the bottom. The mechanism can open to a maximum of 1.8 inches, allowing for the delivery of table-tennis ball sized objects. This mechanism has been tested in the real world and has performed as designed. The payload delivery system can be seen in Figs. 13 and 14.

Diagram, engineering drawing

Description automatically generatedFig. 13. SolidWorks Rendering of Payload Delivery System

A picture containing indoor

Description automatically generated Fig. 14. Payload Delivery System Attached to Drone

# Conclusions

The AUAV capstone group has made great strides in meeting the given requirements of this project as outlined previously. To date, the group has created a quadrotor unmanned aerial vehicle capable of remote and autonomous flight; the group has begun initial testing of computer vision algorithms, and the group has completed several test flights to assess the quality of both. There is still much more to be completed before the group finds satisfaction with the drone’s performance such as the detection of the ArUco marker, utilization of a RTK base station with the receiver on the drone, and the implementation of the Pixhawk alongside PX4. The parts of this project that have been completed must be built upon for the group to complete all necessary requirements. Moving into the next phase of this project, the group has already created a rough timeline and plan for the implementation of the several required portions of the UAV that have not yet been developed. This includes further development of the computer vision algorithm and its communication to a controller to issue commands to the UAV, further optimization of the UAV’s performance, the testing of the drone’s buoyancy, and more. After analyzing the work that has been completed thus far, and the work that has yet to be completed, the group is certainly meeting the timeline objectives to complete this project prior to the termination of the spring 2022 semester. Overall, the group continuethe objectives of the Roboboat competition requirements by creating an autonomous UAV drone, utilizing basic autonomous flight, real-time kinematics, computer vision algorithms, basic autonomous flight, and implementing a payload design. This capstone has been a learning experience to design and construct an inexpensive AUAV that could achieve several of the core missions of the United States Coast Guard in the future.

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##### Appendecies

##### Appendix I

##### Tuning

Chart, line chart, histogram

Description automatically generated

Time

Time

Time

Fig. I.1: Roll, Pitch, and Yaw Angle.

##### Appendix II

##### Observed In-Flight GPS Accuracy

Chart, line chart

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0m 5m 10m 15m 20m

Fig. II.1: GPS Accuracy

##### Appendix III

##### RTK Auspos Post Processing Report

Text

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