Low-Cost Unmanned Underwater Vehicles for Multi-vehicle Autonomy Testing

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***Abstract*—Recent years have seen an increase of autonomy algorithms designed to enable multi-robot collaboration to accomplish tasks over different domains and time scales. While autonomous collaboration is highly desirable in the underwater domain where communication is limited, the validation and deployment of multi-vehicle autonomy is hindered by the high cost of underwater testing platforms and the significant number of vehicles required to demonstrate swarm capabilities. Currently available low-cost platforms tend to be specialized for specific tasks and lack the flexibility that is needed to evaluate multi-vehicle autonomy. Even the smallest underwater vehicles, which are on the lower end of the cost spectrum, can cost over $10,000 each, making the purchase of multiple vehicles prohibitively expensive. This paper describes the design of a low-cost micro unmanned underwater vehicle (μUUV), named the BlueJacket, for use as a development and testing platform of multi-vehicle autonomy algorithms in the underwater domain which cost less than $2,000. Initial results from field testing of the BlueJacket design are also presented and discussed.**

***Index Terms*—Low-cost UUV, Multi-Domain Autonomy, UUV**

I. INTRODUCTION

Unmanned Underwater vehicles (UUVs) have become an area of increased focus for both civilian and military missions over the last decade leading to the development of many different types of UUVs [1] [2]. However, these UUVs tend to be large and expensive due to the sensors, communication, power, computation, and ballasting which are required to operate in the underwater environment. This means that low-cost UUV designs need to analyze possible trade-offs to reduce costs while maintaining the capabilities necessary for autonomous underwater operation and multi-agent collaborative tasking. To navigate these trade-offs, low-cost UUVs are often designed with a single task in mind, such as sea floor imaging [3], and lack some of the enhanced capabilities, such as communication and depth rate, that are needed on a robust multi-vehicle autonomy platform.

In order to establish a platform for testing autonomy algorithms on hardware, as well as verifying and validating simulation results, the BlueJacket was built as a low-cost and flexible platform capable of running an autonomy stack in an underwater environment. The focus was on developing a simple yet extensible system that could integrate with a range of sensors and run a diverse set of missions to support autonomous vehicle research and development. Furthermore, it was important that the design of the vehicle was simple enough to be manufactured quickly and inexpensively, leveraging rapid prototyping methods, such as 3D printing, and commercial-off-the-shelf (COTS) components when available.

The initial concept for the test platform was based on the designs and bill of materials (BOM) for a low-cost μUUV test platform shared with Georgia Tech Research Institute (GTRI) in a collaboration with US Navy researchers. After analyzing the design, it was decided that the tail cone could be modified to allow for a greater depth rating and that the overall design was missing key electrical components for swarm operations, such as an acoustic modem for underwater communication. Similar to the shared design, the BlueJacket leverages the use of COTS parts from Blue Robotics[1] (a low cost, remotely-operated vehicle (ROV) company), but iterated the design resulting in a platform that is better suited for multi-vehicle autonomy testing.

Each evolution of the BlueJacket was focused on developing a platform with specifications that enable it to perform more complex autonomous tasks not accessible to other low-cost autonomous vehicles. Efforts were focused on increasing the depth rating, communications reliability, and navigation capabilities of the BlueJacket. Through testing, failure points were identified for future iterations of the BlueJacket platform. Results of the BlueJacket development are pictured in Figure 1.

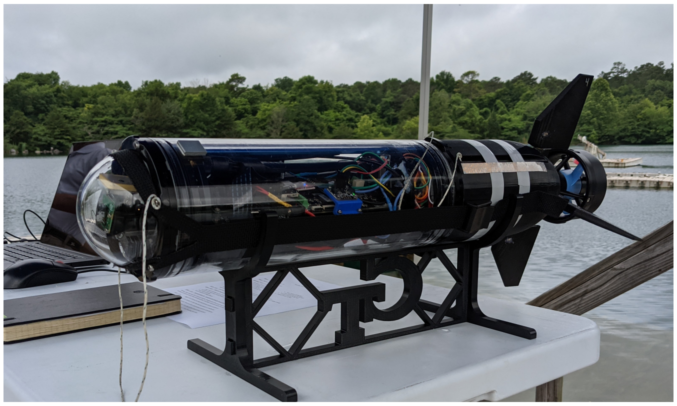

Fig. 1. BlueJacket UUV prototype

Currently, five BlueJacket UUVs have been built to show-

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[1] https://bluerobotics.com/

case swarming capabilities and have been tested for their individual and collaborative capabilities. Testing focused on ballast, depth rating, waterproofing, RF and acoustic communication, and mechanical functionality. Each platform is approximately 2 feet long (0.65 meters) and four inches in diameter (0.101 meters), weighting about 10 pounds (4.54 kg), making them easily portable, and able to achieve depths of at least 125 feet (38 meters). The construction of multiple UUVs allowed for an exploration of modularity within the system. A few different sensors were successfully tested, such as an ultra-short baseline navigation system and a different inertia measurement unit (IMU), without disrupting the overall testing efforts. The resulting group of UUVs has been proven to be capable of running a variety of missions in pool and freshwater lake environments.

II. HARDWARE DESIGN

The BlueJacket UUV can be broken down into two main sections; the pressure hull and tail cone. The pressure hull is a sealed section handling the computation, sensing, and other electronic components of the UUV while the tail cone primarily houses the mechanisms for motion control. These two sections are designed to be interchangeable between UUVs. Interchangeability provides the ability to test different designs during a single testing event and quickly recover from damages to the equipment. A two section design also allows for heterogeneous sections to be designed that can be swapped on and off of a vehicle based on testing needs.The weight of both sections was accounted for and adjusted so that the overall ballast of the UUV was slightly positively buoyant for easy recovery during testing. These and many of the other decisions made while designing the BlueJacket were driven by cost, reliability, and simplicity of construction.

A. Pressure Hull

Vital to autonomously operating a UUV is the pressure hull which houses a majority of the electrical components. Blue Robotics's 4-inch diameter acrylic watertight enclosure[2] was selected as the pressure hull for the BlueJacket due to the low cost, depth rating, and reliability. The Blue Robotics enclosure's size and shape were the main constraints while selecting electronics.

Part selection for on-board components of the vehicle was highly constrained and required planning to optimize the performance of the BlueJacket. Ship building principles were used to design the layout of the components with maximum vehicle stability. Mostly COTS parts were used and each was evaluated for size, weight, and power. Primary electrical components required to handle computations are the Jetson Nano[3] and Teensy 4.0 microcontroller[4]. Original sensors included the Blue Robotics depth sensor[5], RF radio, and IMU. The whole UUV is operated using a single Lithium-Polymer (LiPo) battery[6].

While the original sensors were sufficient for basic UUV operations, they were inadequate for collaborate autonomy. Collaborative autonomy is highly dependent on vehicle communication to share world and vehicle information [4]. RF communication is ideal for surface operations but quickly degrades over even very short underwater distances [5]. Acoustic communication can supplement this issue as it is capable of communicating over large distances underwater but at significantly lower data rates. A mesh acoustic modem and transducer were added to the BlueJacket to increase communication channels between vehicles from solely RF communication to RF and acoustic communication.

Localization of the vehicle is also critical for collaborative autonomous missions. Relative positioning could be achieved using the IMU and dead reckoning, however absolute positioning was desired while on the surface. GPS was added to the vehicles for global position on the surface. Underwater localization was also explored through the integration of an ultra-short baseline system into one of the UUVs. An exploded view of the final pressure hull electronics can be found in Figure 2.

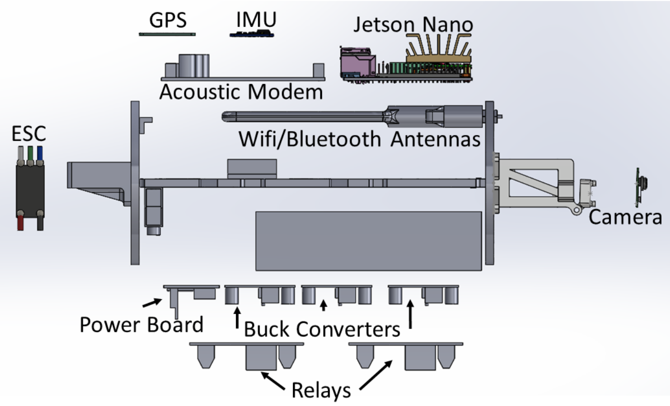

Fig. 2. Each of the electrical components in the BlueJacket pressure hull. Major components include a Jetson Nano, Acoustic Modem, ESC, and camera.

B. Tail Cone

Designs for the tail cone were initially based on models shared through a collaboration with US Navy researchers. The design consisted of a conical housing manufactured using a rapid prototyping process called 3D printing. Attached to the housing were a Blue Robotics T200 motor and four waterproof servos. Figure 3 shows a CAD model of the initial design and the following tail cone iterations. Design evaluations discovered that this design had either an extremely limited depth rating or was expensive, depending on which waterproof servos were used. There was also no space for the addition of a transducer for the acoustic modem.

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[2] https://bluerobotics.com/store/watertight-enclosures/wte-vp/#tube

[3] https://developer.nvidia.com/embedded/jetson-nano-developer-kit

[4] https://www.pjrc.com/store/teensy40.html

[5] https://bluerobotics.com/store/sensors-sonars-cameras/sensors/bar30-sensor-r1/

[6] https://zeeebattery.com/products/zeee-lipo-battery-111v-8000mah-100c-3s-lipo-battery-with-deans-plug-for-rc-car-truck-rc-truggy-fpv-airplane-boat-buggy-254

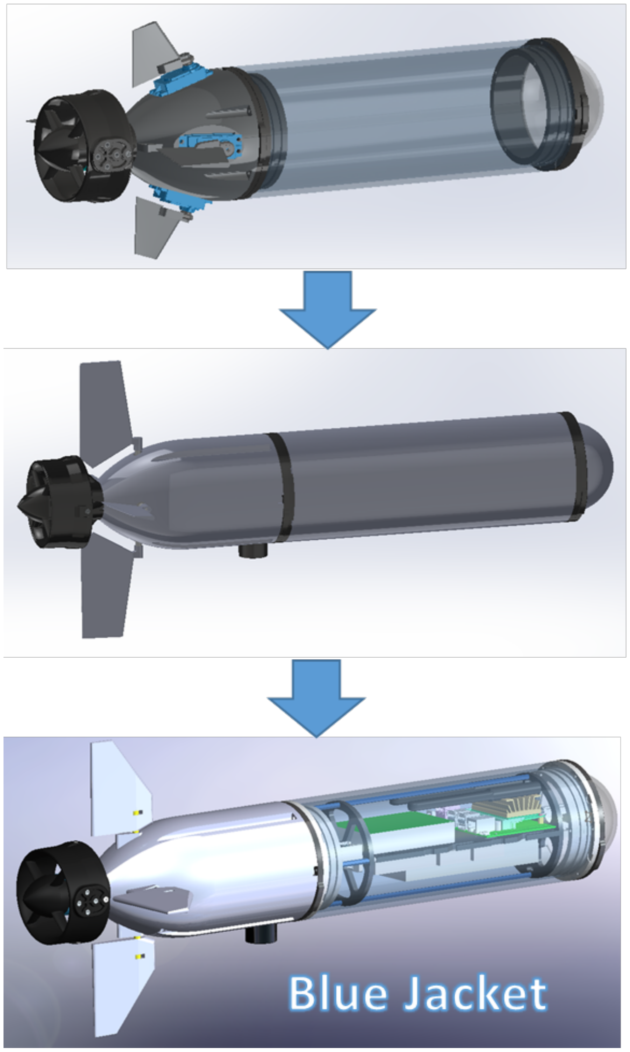


Fig. 3. Evolution of the overall BlueJacket Design. Top image is the initial design shared by US Navy Researcher. Middle image show the first iteration of the BlueJacket design. Bottom image displays the final BlueJacket design.

First iterations of the tail cone focused on addressing design concerns from the initial tail cone evaluation. Limiting factors for the initial tail cone depth rating were a result of the waterproof servos. Investigation of servos concluded that most low-cost COTS waterproof servos were only rated for submergence up to 3 feet (1 meter) for 30 minutes. A design spiral was performed to generate a waterproof system to actuate the fins at greater depths. Results yielded a waterproofed servo box containing two 180 degree servos. A shaft is attached to the servo horn and the rotational motion is converted into linear motion extending outside of the servo box. A dual joint system shown in Figure 4 is then used to connect the servo box shaft to the elevator and rudder shafts. Angular losses occurred but the depth rating increases from 3 feet to approximately 300 feet (100 meters). Full functionality of UUV fins can be considered achieved with less than ±40 degrees of rotation [6]. The trade-off between angular losses in the fins for increased depth rating was sufficient to proceed with the design.

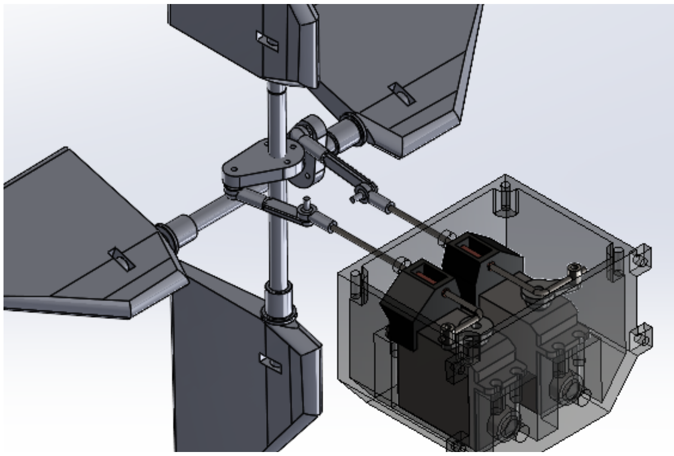


Fig. 4. Servo Box drive shaft connection to the elevator and rudder fins.

Further tail cone iterations addressed the fin design and addition of a transducer. A four-fin system was used to control the UUV. Two sets of fins are aligned to create two dive planes; the rudder and elevator. Figure 3 shows the progression of fin designs as the tail cone evolved. First designs had to be revised due to breakage around the shaft and fin connection. The latest fin design has proven to be robust. Final adjustments to the tail cone were limited to an indent placed on the underside of the tail cone with a slot to mount the transducer.

C. Servo Box Design

The servo box went through several design spirals in order to create a simple, robust, and cost-effective design. The resulting CAD design of the first design spiral for the servo box can be seen in Figure 5. Key results of this design spiral were the use of COTS RC boat stainless steel shaft dimensions and the layout of the servo-to-shaft connection as seen in Figure 4. Switching from the original stainless steel shafts allowed for higher shaft strength while significantly decreasing the cost. The servo-to-shaft connection resulted in a ±40 degrees range of motion for the control surfaces. However, the servo-to-shaft connection layout limited the servo range to ±80° before bending the drive shafts. Safety measures were implemented in the software, however testing proved this design to be too fragile.

A second design spiral focused on changing the servo pressure hull to allow for the servo to be able to rotate a full ±90 degrees. In the first iteration, the drive shaft was centered on the servo horn which resulted in interference between the servo horn connector and the drive shafts at the limits of the servo. This version of the servo box shifted the drive shafts closer together, off-center from the servos, and the servos further apart to remove that interference. This iteration allowed us to use the full 180 degrees of motion from the servo and maintained the ±40 degrees of motion for the control surface. However, normal operational forces continued to cause bending in the drive shaft resulting in a high failure rate during testing.

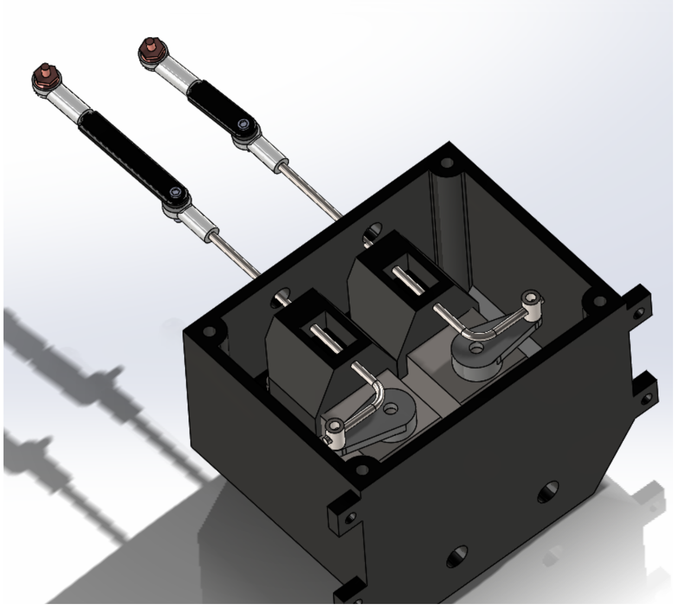


Fig. 5. Initial servo box design

The high failure rate of the second iteration led to another design spiral to make a simpler and more robust servo-to-shaft connection. This design replaced the original 0.078 inch (2 mm) drive shaft with a 1/4 inch (6.35 mm) diameter shaft to prevent any bending. Bronze tubing with an inserted oil sleeve bearing replaced the linear converter from the first two iterations, as seen in Figure 6. Two seals were placed around the shaft for redundancy in waterproofing. This final iteration, shown in Figure 7 has proved robust throughout testing and was able to withstand initial testing at a depth of 125 feet.

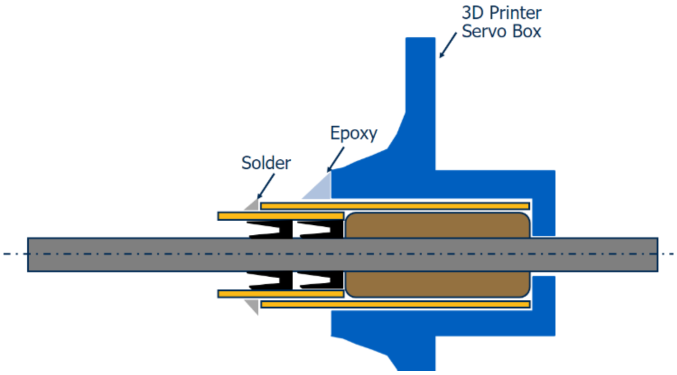


Fig. 6. Linear converter design for the final iteration of the servo box

D. Waterproofing

Principles of waterproofing were used to achieve operation at depths of 300 feet (100 meters) or more. In the pressure hull, this was achieved through a use of a flanged seal with double o-rings for redundancy. Tail cone designs only required waterproofing of the servo box for operation. The servo box was designed as a secondary pressure hull separate from the main hull to protect it against leaks due to actuation. 3D printing was used to manufacture the servo box. However, simply using additive manufacturing was insufficient due to the small spacing left between material inherent in the process which would allow for leaks, especially under pressure. This challenge was overcome by coating the entire servo box in epoxy except for around the shafts. Servo shafts were initially sealed with a pushrod rubber seal to allow for actuation while preventing leaks and then in later designs sealed using a double o-ring seal for redundancy. Oil filling the servo box was explored, but significant ballast shifts occurred introducing an excessive amount of drag to the system. It was decided that desired waterproofing could be achieved without the need to oil fill the servo box.

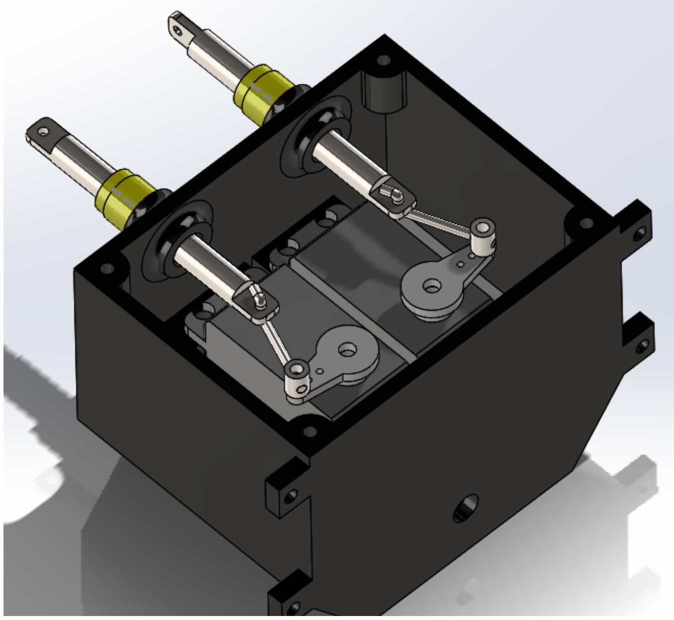


Fig. 7. Final servo box design

III. BASIC CONTROLS

The creation of a custom UUV required development of low-level autonomy to perform the actuation necessary to follow high-level control commands as well as autonomously recover from failure states. The developments described in this paper include enabling the platform to dive and resurface autonomously, maneuver to GPS waypoints on the surface, hold reference depths as well as heading, and enact safety routines to prevent damage to the platform if and when the vehicle enters a potentially hazardous state. These algorithms and controllers are implemented on the Teensy 4.0 microcontroller with an interface to modify, call, and control them through ROS messages.

The rudder and dive planes of the platform are controlled by two independent servo motors. This constrains the orientation control of the platform to pitch and yaw. With this constraint in mind, the low-level control architecture has been designed to follow global heading commands with respect to the magnetic field of the earth and depth commands. This is achieved through a proportional integral derivative (PID) controller of the form,

$$u(t) = k_p e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \tag{1}$$

where $u(t)$ is the output control value at time t, k_p, k_i, and k_d are strictly positive real number gains, and $e(t)$ is the error between the desired state of the system and its current state. To implement this controller in hardware, a class was created with a discretized approximation of 1,

$$u(n) = k_p e(n) + k_i \sum e(n)\Delta t + k_d \frac{e(n) - e(n-1)}{\Delta t} \tag{2}$$

where Δt is a sampling time of the controller and n is the discretized time step. The time step and control gains may be set to achieve desired performance. Due to not having a dynamical model of the BlueJacket, the controller tuning was done manually.

For heading control, the rudder angle is controlled with a PD (e.g. $k_i = 0$) version of Equation 2. An integral component may be desired to reject external disturbances, like currents. However, it was found experimentally that any substantial integral gain slowed the controller response and would sometimes induce undesired oscillation during surface operation when the UUV would operate in choppy waters. The controller reference, or desired state (heading), is chosen to be a compass heading with respect to the Earth's magnetic field and is compared to the current heading estimated from a sensor fusion algorithm returned from the onboard IMU. It should be noted that this reference can be augmented to follow a heading in the UUV's local coordinate frame by adding the desired heading in the coordinate frame local to the UUV's current measured heading with respect to the Earth's magnetic field.

Pitch control can be achieved in a similar manner to heading control. However, holding a specific elevator fin angle is not as useful directly and is instead leveraged to hold desired depths. Thus, the challenge is to convert the error between the UUV's current depth and desired depth to a reference pitch for the platform to follow in order to drive the depth error signal to zero. This is achieved using a look ahead controller, where the desired pitch is calculated to a point projected ahead of the agent at the desired depth set point. Figure 8 displays this look ahead controller and labels the relevant variables associated with it. In this scenario, the desired depth (d_d) and look ahead distance (L) are provided to the controller and the current depth (d_c) and current pitch (φ_c) are estimated from onboard sensors.

The desired pitch for the UUV to follow is then calculated as,

$$\varphi_d = tan^{-1}\left(\frac{L}{d_d - d_c}\right) \tag{3}$$

and passed as a reference to calculate the error in Equation 2. For the depth control, a full PID controller is used, as integral action is required to compensate for the positively buoyant design of the UUV. It should be noted the selection of the look ahead value (L), used in Equation 3 is important as it is another design variable that interacts with the PID controller and plays a role in how quickly the UUV will achieve the desired depth. If chosen too aggressively (small) this distance can cause the system to become unstable but if chosen too cautiously (large) the system will be unable to achieve the desired depth. Users have the option to bypass these depth and heading controllers and interface with the control surface actuators directly. The provided depth and heading controllers can be individually disabled and replaced by servo angle commands. This has been done to simplify implementations of some behaviors, like loitering, where the UUV circles at a desired depth by using the autonomous depth controller and setting a static rudder angle. This provides the opportunity for future users to design different controllers that may better suit their needs.

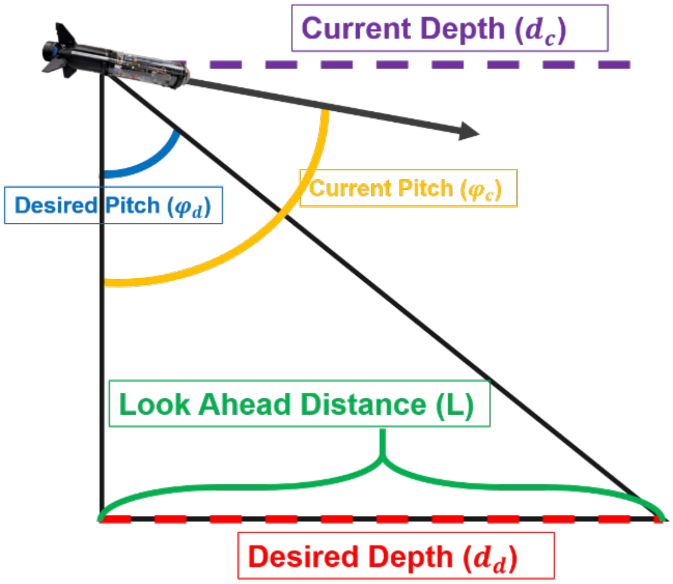


Fig. 8. Diagram of pitch control to hold desired depth.

The low-level controllers have been leveraged to develop a short distance autonomous dive routine. This is significant as it enables the BlueJacket to dive to operating depths without requiring a long "runway" that other UUVs often require. A block diagram overview of this behavior is shown in Figure 9. A user specifies a safety timeout time, surface time, and minimum depth that is considered a successful dive. With this information the UUV holds a constant acceleration value to its maximum speed over the surface time provided by the user. During this time, the rudder is manually set to its nominal position and the elevator is manually set to provide maximum pitch upward in order to keep the thruster underwater. After the UUV achieves its maximum speed, the elevator is manually set to provide maximum downward pitch to dive straight to the depth that is desired by the user. If this is successful, the rudder is manually controlled to one extreme to hold a tight spiral and the elevator is automatically controlled to achieve a desired operating depth before handing off to the mission controller. If the dive does not hit successful depth before the user provided safety timeout the UUV returns to the surface.

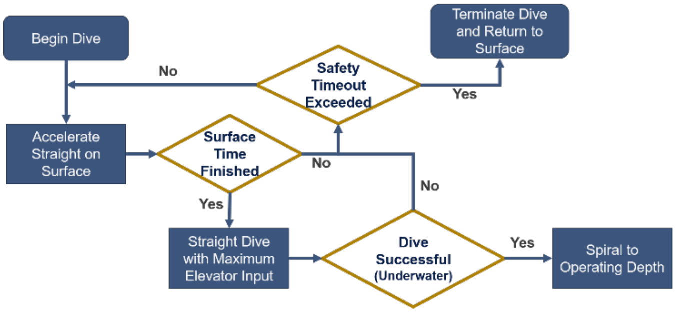


Fig. 9. Block diagram of short autonomous dive routine.

Beyond the autonomous dive, autonomous safety routines have also been developed to protect the BlueJacket if it enters undesired or hazardous states. The first safety routine simply turns off the thruster and returns the control planes to their nominal position if the UUV comes within a user-defined distance of the surface after diving. Routines that return the UUV to the surface if a user-defined maximum operating depth is exceeded have also been developed. This is done by enabling the autonomous depth control and assigning the desired depth to 0 while manually assigning the rudder to an extreme in order to keep the ascent in a tight spiral. However, if a control plane is inoperable or a sensor has malfunctioned, an additional routine has been created that kills all power to the thruster and control planes if a maximum depth is exceeded. This relies on the positively buoyant design of the system to return it safely to the surface after failure.

IV. FIELD TESTING RESULTS

In-water testing leveraged low-level controllers and behaviors to validate the performance of the BlueJacket for autonomous missions. Different sensing capabilities were explored in conjunction with behavior testing to inform future autonomy behaviors. Testing was done in a diverse set of environments. Primarily locations being the Georgia Institute of Technology dive pool and recreational open water dive park called Kraken Springs.

A. *Dive and Loiter control*

One of the first behaviors developed and tested was to loiter at depth, where the UUV would drive straight on the surface holding a heading for a set amount of time then autonomously dive to a desired depth and hold for a set amount of time. Figure 10 shows the result of a loiter behavior performed at Kraken Springs where the BlueJacket was tasked with holding a heading for 60 seconds on the surface before autonomously diving to a depth of 10 meters and holding that depth for 60 seconds before returning to the surface. This data show that the loiter behavior is functional and more importantly that the autonomous depth controller is able to achieve and hold desired depths within a very fine error envelope (<2%). It should be noted the difference between the time to depth and time to resurface is most likely due to the buoyant design of the platform.

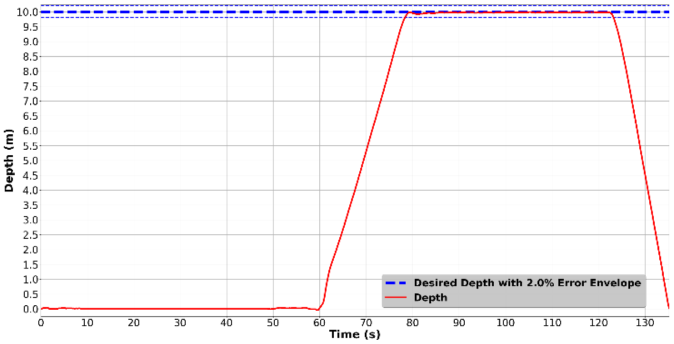


Fig. 10. Depth achieved by BlueJacket during a loiter behavior.

B. *Lawnmower Pattern*

After validating the autonomous dive routine and depth controller, a simple lawnmower behavior was developed. The logic of the lawnmower is described in Table I. The lawnmower behavior was tested at Kraken Springs with a 3 minute long mission at a depth of 2 meters, where the initial heading was due north (0 degrees) and the straight legs of the lawnmower were held for 10 seconds. Turning was based on UUV angular positioning. At the end of each leg, 90 degrees were added to the current heading, held for 0.01 seconds, and then another 90 degrees were added to start the next leg. The estimated heading of the UUV during this mission is shown in Figure 11. These results show a successful behavior and good performance of the autonomous heading controller.

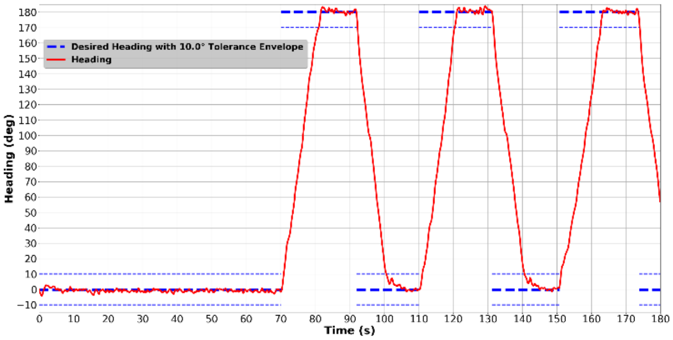
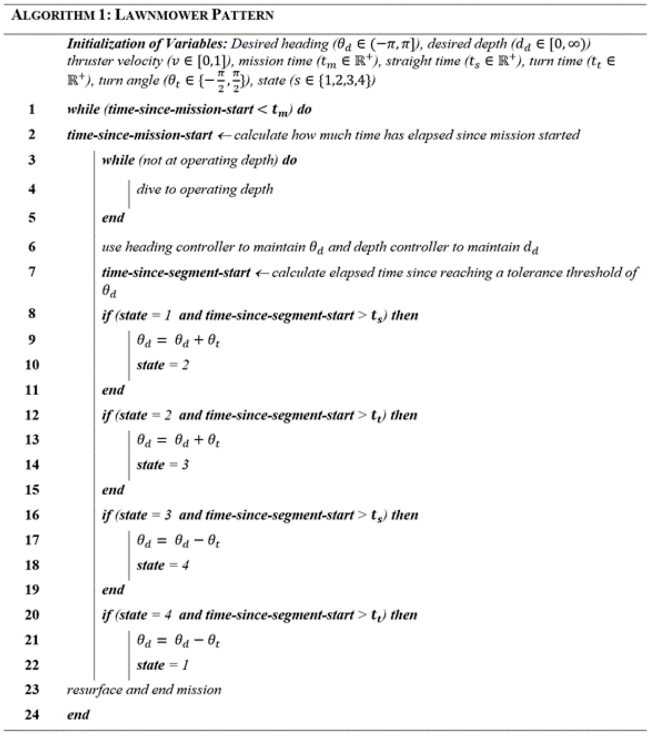


Fig. 11. Heading of the BlueJacket during a lawnmower behavior.

C. *GPS Waypoint*

The final behavior tested was a GPS location following algorithm. This was done via a surface heading controller following global headings calculated between the BlueJacket's measured GPS location (in UTM coordinates) and desired GPS location (in UTM coordinates). This was successfully done for tolerances of 3 meters.

TABLE I
LAWNMOWER PATTERN



ALGORITHM 1: LAWNMOWER PATTERN

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Initialization of Variables: Desired heading ($\theta_d \in (-\pi, \pi]$), desired depth ($d_d \in [0, \infty)$) thruster velocity ($v \in [0,1]$), mission time ($t_m \in \mathbb{R}^+$), straight time ($t_s \in \mathbb{R}^+$), turn time ($t_t \in \mathbb{R}^+$), turn angle ($\theta_t \in \{-\frac{\pi}{2}, \frac{\pi}{2}\}$), state ($s \in \{1,2,3,4\}$)
while (time-since-mission-start < $t_m$) do
time-since-mission-start ← calculate how much time has elapsed since mission started
    while (not at operating depth) do
        dive to operating depth
    end
    use heading controller to maintain $\theta_d$ and depth controller to maintain $d_d$
    time-since-segment-start ← calculate elapsed time since reaching a tolerance threshold of $\theta_d$
    if (state = 1  and time-since-segment-start > $t_s$) then
        $\theta_d = \theta_d + \theta_t$
        state = 2
    end
    if (state = 2  and time-since-segment-start > $t_t$) then
        $\theta_d = \theta_d + \theta_t$
        state = 3
    end
    if (state = 3  and time-since-segment-start > $t_s$) then
        $\theta_d = \theta_d - \theta_t$
        state = 4
    end
    if (state = 4  and time-since-segment-start > $t_t$) then
        $\theta_d = \theta_d - \theta_t$
        state = 1
resurface and end mission
end
```

D. Collaborative Missions

Successful execution of each of the previous autonomy behaviors lead to testing with multiple vehicles operating at once. Initial testing focused on two vehicles running a lawnmower pattern on the surface together. One vehicle was given a heading of due north (0 degrees) while another vehicle was given a slightly offset heading (10 degrees). All other mission parameters were kept the same between vehicles. Both vehicles were able to simultaneously implement a lawnmower pattern. Further testing had two vehicles drive out at slightly offset angles and then dive and loiter for 60 seconds. This mission was also able to be successfully demonstrated in multiple tests.

V. CONCLUSIONS AND FUTURE WORK

Our development effort resulted in a simple, low-cost μUUV design capable of hosting collaborative autonomous missions in the underwater domain. Vehicles were equipped with critical components for collaborative autonomy such as RF and acoustic communication, as well as GPS. Low-level controllers and behaviors were implemented on multiple vehicles and demonstrated in both pool and lake environments. Vehicle costs were significantly lower than similar μUUVs currently available. The original cost breakdown to build one BlueJacket UUV can be found in Table II. Further work is planned to investigate implementing an acoustic localization solution and more complex autonomy behaviors.

TABLE II
BLUEJACKET COST BREAKDOWN

Blue Robotics Parts	$480
Jetson Nano*	$99
Sensors & Electronics	$164
Tensy Microcontroller	$25
Misc. Hardware	$42
Acoustic Modem	$1100
Total Cost (w/o) Acomms	∼ $900
Total Cost w/ Acoms	∼ $2000

*Pricing of components from 2020

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