

Acrobatic Low-cost Portable Hybrid AUV (ALPHA): System Design and Preliminary Results

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Abstract—This paper reports the progress towards the development of a highly maneuverable affordable portable AUV, called ALPHA. The ALPHA has a diameter of 10-inch, an overall length of 1.5 m, and a total weight of about 30 kg with flooded areas for wet sensors. The research aims to provide an accessible underwater vehicle platform that is highly customizable to lower the barrier-of-entry to conduct research and education in underwater robotics. In this paper, the details in AUV system design will be presented. Field tests have conducted in Narragansett Bay to validate the performance of the guidance, navigation and control system with preliminary results shown and discussed in the paper. A suite of science sensors (an CTD, an optical dissolved oxygen sensor, and an optical chlorophyll sensor) is also integrated on the ALPHA for water property assessment during the field trials.

Index Terms—Autonomous Underwater Vehicle (AUV), Marine robotics, Open-source robotics

I. INTRODUCTION

Over the last several years, the price of commercially available AUVs has gradually decreased because of the advancements in manufacturing and integrated circuits. Small-size AUVs and micro-AUVs (such as ecoSUB [1] and YUCO by SEABER) are becoming affordable at a cost of about \$20k to \$50k. Small and low-cost AUVs offer simple logistics for deployment and recovery, opening the potential of distributed multi-AUV operation [1]. However, there are some limitations on the existing small-size and micro-AUVs. First, the majority of them are designed with a single pressure housing. As a result, limited space is available for wet sensors for simple integration. Second, small-size AUVs are usually steered using control surfaces, concerning the system efficiency. As a result, they are under-actuated; especially, at slow speed [2]. Such a disadvantage prevents these AUVs from sophisticated applications such as underwater inspection and low-altitude seafloor imaging.

To overcome the aforementioned disadvantages and further expand the usage of small-size AUVs in ocean research, several highly maneuverable small-size (50kg or less) AUVs have been developed by various groups. In UK, Delphin2 AUV has been developed [3]. This flight-style AUV is equipped

with multiple tunnel thrusters and control surfaces, allowing efficient cruising and hovering capability. The portability accelerates the software and algorithm development since field tests could be arranged relative simple compared to large AUVs, e.g., their Autosub AUVs. The team has conducted field tests to validate the low-altitude terrain following [4] capability and bottom imagery missions [3]. Sparus II [5] is another flight-style hovering-capable AUV from Spain. The AUV is equipped with differential thrusters for surge and turning, and a vertical thruster for depth control. Sparus II has been involved in many applications including underwater inspection [5] and seabed imaging [2], and underwater cave explorations [6]. Another highly maneuverable flight-style AUV, called SAM AUV, is recently invented by the researchers from KTH Royal Institute of Technology. The concept was introduced in 2019 [7] with the field test results presented in [8]. Instead of using tunnel thrusters, SAM AUV has a vectored stern thruster and several internal movable trimming systems that actively reposition its center of gravity. In [9], the author has demonstrated complicated maneuvering, helix maneuver, turbo-turn maneuver and tight looping maneuver. There are also several highly maneuverable small-size AUVs designed in box-like shapes. For instance, [10] presented a low-cost ((under \$30k) 6000-m rated AUV. HATTORI-2 was developed for coral reef studies [11], and a hovering-capable underwater robot equipped with 4 rotatable thrusters is presented in [12].

In this paper, we present the development of a new small-size highly maneuverable AUV, called ALPHA which stands for acrobatic low-cost portable hybrid AUV. The system is developed to make the AUV scalable, customizable and affordable. This in turn allows for easy adaptation by the users. This paper is organized as follows. In Section II, the vehicles design is presented. Outdoor tests have been conducted to validate the system functionality and science sensor integration, and we present the results in Section III. In Section IV, we conclude the paper and discuss our future works on the ALPHA.

II. VEHICLE DESIGN

Figure 1 depicts an overall system schematic of the ALPHA. The overall weight of the vehicle is about 30 kg with an external diameter of 25cm and a length of 1.5m. The vehicle

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body is designed to be flooded to provide extensive space for wet sensors. There are two pressure vessels in the vehicle body, one for electronics and one for the battery packs. The vehicle is equipped with two 250 Wh battery packs with an approximated endurance of between 3 to 6 hours (sensor and speed dependent). The current version of the ALPHA is equipped with three thrusters, one for surge, one for pitch/depth control, and one for steering(yaw). The control surfaces are eliminated because the ALPHA is intended to be used for high latitude operation where a flash freezing may cause malfunction on the control surfaces, as well as the dynamic seals may fail at low air temperature (i.e., -30°C). Moreover, the thruster array provides enhanced maneuverability in comparison to conventional torpedo-shaped AUVs. For instance, the vehicle could descend at a steep-angle (up to almost 90 degrees) with pitch controlled by the vertical thruster, it could hold its heading, pitch, and position simultaneously, or perform surveys at slow speeds (less than 0.3 m/s). However, the overall system power consumption will be several times higher compared to the conventional flight-style AUVs steered by rudders and fins.

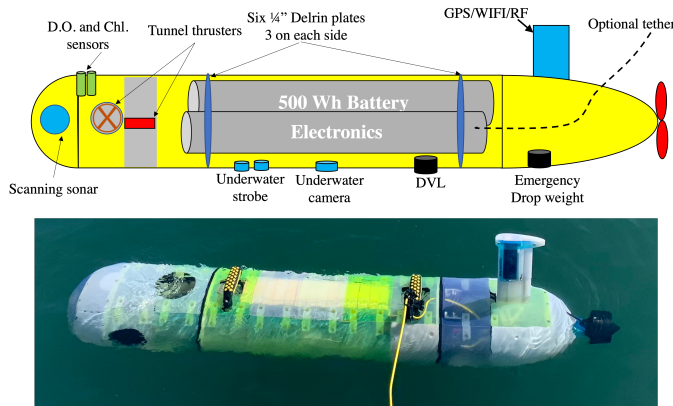


Fig. 1. ALPHA system overview. Top: system schematics; bottom: a photo of ALPHA in the water.

As list in Table I, the ALPHA used commercially available components, including the thrusters, battery packs, pressure vessels, navigation sensors, and single-board computers. The electronics assembly is customized with power distribution, power sensing, and motor controller integration. We leveraged accessible fabrication machines (including laser cutter and resin 3D printers) and standard parts for designing the customized components. For instance, we custom-made the drop-weight system and the mast (shown in Fig.2). The customized drop-weight system is designed using a permanent magnet from APW Company. The electromagnet is encapsulated in a 3D printed resin casing and is capable of holding about 250 grams of steel disc. The mast is fabricated in a similar approach where a 2.4GHz USB WIFI module, a XBee 900 MHz RF module, and a GPS are encapsulated in a 3D printed hydro foil. For modularity and customizability, the main frame of the vehicle is made out of four 20-mm square aluminum T-slotted frames and six 1/4" laser-cutted Delrin plates (3 on each side as shown in Fig. 1), and the external fairing panels are solid and fabricated using LCD 3D

resin printers that are widely available in the market place. The fabrication process and the design allows us and other users to mount wet sensors, ballast weights, and foam blocks at different places on the frame. The fairing can also be easily reproduced for customized sensor shapes.

Core Systems, Total: \$13.6k		
Parts	Source	Cost
Thrust	Blue Robotics T200	\$600
Pressure sensor	Blue Robotics	\$100
Pressure housings	Blue Robotics	\$1,200
Battery	Blue Robotics	\$700
DVL	Water Link A50	\$7,000
Computer	Raspberry PI-4	\$100
IMU	XSENS MTi-630	\$1,300
Tether	Blue Robotics	\$400
Electronics assembly	Customized	\$150
GPS/RF/WIFI Mast	Customized	\$150
Dropweight	Customized	\$100
Main Frame	Customized	\$500
Resin fairing	Customized	\$300
Underwater cables	Various places	\$1,000
Payload		
Parts	Source	Cost
Scanning sonar	Blue Robotics	\$2,500
Underwater camera	DeepWater Exploration	\$280
Underwater strobe	Blue Robotics	\$325
CTD	Star-oddi	\$3000
D.O. optode	RBR	\$5,000
Chl. optode	Turner Design	\$2,000

TABLE I
COMPONENTS AND COST BREAKDOWN.

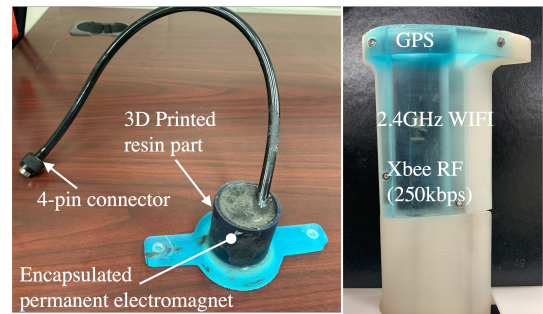


Fig. 2. Customized parts (left: The drop-weight system; right: the AUV mast.). Electronics are encapsulated in thermal conductive epoxy resin.

The ALPHA software is built upon the Robotic Operating System (ROS) middle-ware using the Marine Vehicle Packages (MVP) [13] which is developed in parallel by the authors. The open-software (GNU GPL v3 license) ROS-MVP framework allows us to easily configure the ALPHA system, including thruster allocation matrix, thruster curves, and proportional-integral-derivative (PID) controllers, using Unified Robot Description Format (URDF) and YAML files. This can all be achieved without changing or recompiling the source code. The MVP navigation stack leverages the widely used robot localization package [14], and MVP has built-in multi-input-multi-output PID controller and common behaviors (such as trajectory following and depth tracking). More information about the MVP is available in [13].

For software and algorithm development, a simulation environment is created using the open-source Stonefish simulator

[15]. We have modified the Stonefish ROS interface such that it is compatible with the ROS-MVP framework and avoids license conflict with the COLA2 software (owned by the IQUA Robotics). Figure 3 shows an assembled picture of the virtual simulation tools we used. While the Stonefish simulates the vehicle dynamic and the environment, we have setup a RViz interface to show the vehicle mission status. For example, the desired path and the current tracking line segment are shown in different colors, and the time elapsed vehicle track is also presented for assessing the vehicle performance. The vehicle model (the red model in the zoom-in view in Fig.3) is imported into the RViz allowing us to visualize and observe the vehicle's orientation changes when testing the low-level controller.

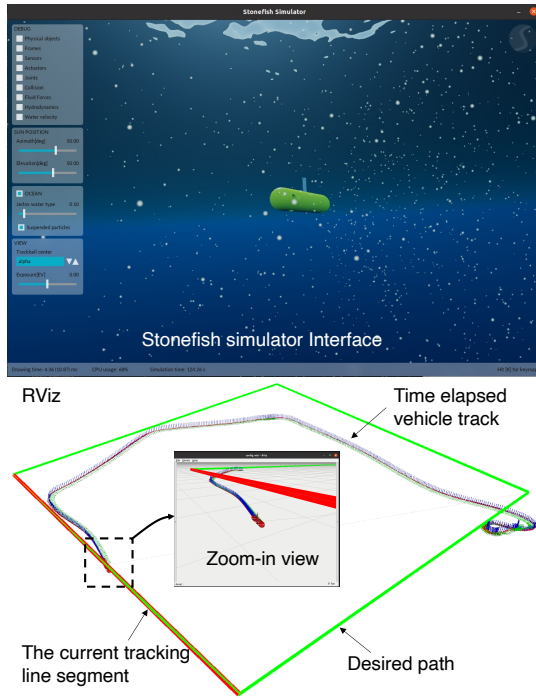


Fig. 3. Simulation setup screenshots. Top: Stonefish interface, bottom: RViz visualization.

III. PRELIMINARY FIELD TEST RESULTS

A series of field trials has been conducted in a freshwater pond and in the Narragansett Bay in Rhode Island, as shown in Fig. 4. In these tests, a 100-m long tether (single twisted pair) is attached to monitor the vehicle status for debugging and controller tuning purposes.

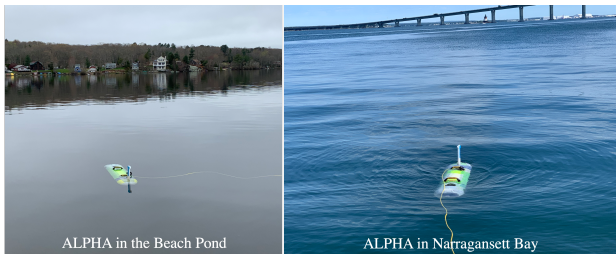


Fig. 4. The ALPHA in the Beach Pond (left) and Narragansett Bay (right)

In the trial, we have validated the low-level controller performance, navigation stack, and several common guidance behaviors, and the mission planner. An example result of path tracking at depth is shown in Fig.5. The top panel of Fig.5 depicts the vehicle trajectory in relation to the desired path in the planar plane. As shown in the figure, the ALPHA has successfully followed the 4 path segments in the counter-clockwise direction. During the path following, the vehicle's desired heading is computed using the line-of-sight (LOS) [16] guidance law to minimize the cross-track errors. The forward-looking distance of the LOS is set to 5 m and the waypoint acceptance radius is configured to 3 m. Meanwhile, the depth tracking behavior also used the LOS guidance law, but was transformed into the vertical plane. However, we limited the desired pitch angle to be within ± 15 degrees. The desired heading and pitch from the guidance behaviors are relayed into the low-level vehicle controller, which uses the multiple-input-multiple-output PID control law to obtain the desired thruster commands. The second plot in Fig. 5 presents the vehicle depth change during this mission. Oscillation is observed that may due 1) improper PID tuning for the pitch controller or 2) the pitch instability induced by the Munk moment. For a better depth tracking performance, we plan to integrate another vertical thruster in the rear section of the vehicle or add fixed hydro-plane near the tail. During the test, we have also enabled the periodical surfacing behavior which overwrites the desired pitch angle from the depth tracking behavior, and it sends the desired pitch angle of 15 degrees to the low-level controller in order to bring the vehicle to the surface for obtaining GPS fixes. The gray regions in the second plot in Fig. 5 highlights the periods when the surfacing behavior is active. Once the vehicle has transit through all the waypoints, the mission state will be switched from *survey* to *start* which will bring the vehicle to the surface and wait for another user-triggered state change for a new mission.

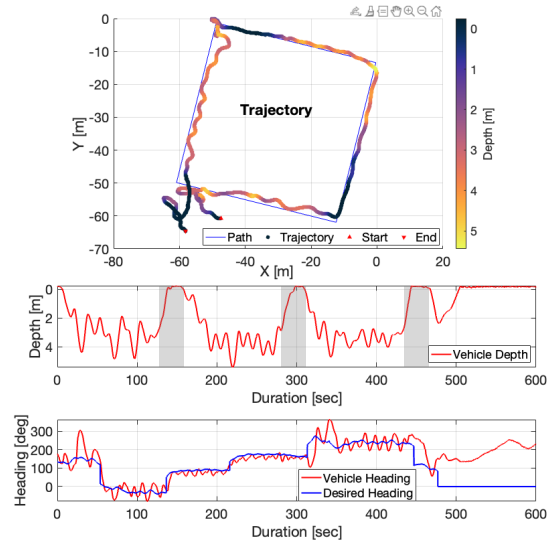


Fig. 5. Field result from the outdoor trial.

For the Narragansett Bay test, we have installed multiple

scientific sensors in the nose to collect water property measurements. A Star-odd online CTD is installed to measure the conductivity and temperature at different depths. After data analysis, we found that the conductivity reading is unrealistic while the temperature and the depth reading are reasonable compared to the ALPHA's pressure sensor (with temperature reading). A RBRcoda Optical Dissolved Oxygen sensor is also integrated to measure the dissolved oxygen saturation in the water, while an optical chlorophyll sensor from Turner Design is used to collect chlorophyll measurements. The processed sensor measurements are presented in Fig. 6 for a series of tests done in Narragansett Bay on July 11, 2022. All the dives are conducted in the same area. Worth noting that, the variations in the dissolved oxygen seems mainly caused by the pressure changes. However, the oxygen decreases observed in the first several dives did not appear in the last 6 dives (between 1pm to 3pm) where the chlorophyll measurements are also slightly increased.

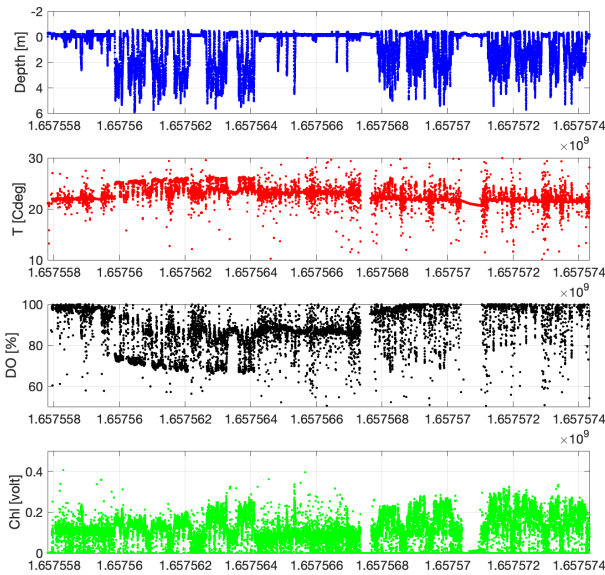


Fig. 6. Measurements obtained from the science sensors.

IV. CONCLUSION AND FUTURE WORK

This paper has presented our recent development on an affordable and highly maneuverable AUV, called ALPHA. The current version of the ALPHA is controlled by three thrusters, one vertical tunnel thruster, one horizontal tunnel thruster, and one surge thruster in the stern. The vehicle has an external diameter of 10-inch (or 25cm) with an overall length of about 1.5 m and a total weight of about 30 kg. A simulation environment is constructed leveraging the open-source project, Stonefish simulator and ROS environment and tools, allowing easy validation of the autonomy software and algorithms prior field tests. Field tests are conducted in a freshwater pond and in Narragansett Bay where we have successfully validated the performance of low-level controller and guidance behaviors. Gained from the field tests, further tuning in controller parameters, and additional pitch stabilizing

systems (such as two hydroplanes or another vertical thrust in the rear) are planned for a better depth and pitch control on this particular ALPHA.

With the acceptable performance and the experience gained from building the prototype, two additional ALPHAs are planned to be constructed with different actuation systems and sensor suites for different purposes. One ALPHA will be equipped with a differential thruster instead of a single stern thruster. On this ALPHA, one of the stern thrusters will be made rotatable for better control in roll, pitch and depth. This vehicle will mainly be used for underwater inspection applications. Thus, a forward-looking imaging sonar and multiple cameras will be installed. The other ALPHA will be equipped with an interferometric sonar, acoustic modem, and optical modem for collaborative underwater mapping applications. Compared to the prototype presented in this paper, this ALPHA will be made longer to accommodate more sensors and more onboard battery. Also, two vertical thrusters will be integrated for a better depth and pitch control. All of these changes and renditions of our ALPHA platform hope to offer a low-cost, yet customizable, versatile, and most importantly affordable future to small-size AUVs.

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