Resident AUV Design for Deployment at Kilo Nalu Observatory

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***Abstract*—Near-shore environments are important to oceanographers because of their relationship to the biogeochemical and anthropogenic processes which occur on land and at sea. Their proximity to land makes them convenient to study long-term using undersea infrastructure, which can supply oceanographic sensor arrays with power and data connections. However, such infrastructure is fixed and cannot adapt to interesting chance events like autonomous underwater vehicles (AUVs) can. AUVs, on the other hand, cannot stay in the water forever and need intervention before embarking on new missions. Here, we present the design of a resident AUV coupled to the undersea infrastructure at Kilo Nalu Observatory (KNO), a near-shore observatory off the south coast of Honolulu, Hawaii. We modify the BlueROV2 Heavy, a commercial ROV sold by BlueRobotics, to create our relatively low-cost resident AUV. Among the novel features we add to our resident AUV are a larger pressure vessel, a gimbaled camera, larger thrusters, and an inductive charging module to be paired with a docking station connected to KNO's undersea infrastructure. In the future, we will field test the AUV to fully overcome the challenges of autonomous docking and charging in near-shore environments and demonstrate the feasibility of long-term resident AUV deployment. Moreover, we intend to remove the AUV's reliance on undersea infrastructure and move towards resident AUV operation in information-rich, low accessibility areas.**

***Index Terms*—autonomous underwater vehicle, cabled observatory, docking, inductive charging, marine robotics, near-shore environments, resident AUV, vehicle design**

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I. Introduction

Owing to their location, near-shore environments contain a wealth of interesting information related to the biogeochemical and anthropogenic processes which occur in the surrounding land and sea. For example, the nutrient influxes and hydrological conditions in these environments support complex ecosystems throughout the year and contribute 14-30% of total oceanic primary production [4]. The proximity of near-shore environments to land lends itself to the study of these environments using undersea infrastructure. In particular, numerous cabled observatories worldwide use fiber-optic and power cables to support oceanographic sensor arrays that observe marine life year-round, even during times when weather conditions render field measurements impossible [4]. The long-term nature of undersea infrastructure enables researchers to collect long-term temporal data in the ocean wherever the infrastructure is present. However, said infrastructure is fixed. It cannot capture data at any spatial scales other than those permitted by its stationary sensor array, and it cannot adjust its sensors to react to the interesting, chance events that occur in these environments.

Resident autonomous, underwater vehicles (AUVs) can complement undersea infrastructure and provide more complete pictures of near-shore environments when both are used in tandem. Resident AUVs are AUVs which permanently reside at underwater locations and perform multiple missions at a given site of interest without needing physical human intervention [5]. Because of their small size, deployment speed, lower costs, and autonomous operation, resident AUVs can react to events of interest and capture information at the finer spatial and temporal scales not captured as well by undersea infrastructure. Moreover, the infrastructure which supports scientific instruments underwater can also support resident AUVs, which require ways to recharge themselves and upload and download data before embarking on new missions [1], [5].

This paper presents the design of a low-cost resident AUV for operation at Kilo Nalu Observatory (KNO), a near-shore ocean observatory off the coast of Honolulu, Hawaii. We modify the BlueROV2 Heavy, a commercial ROV, to create a resident AUV for KNO that demonstrates successful autonomous docking and inductive charging. Here, we summarize the upgrades and novel features we add to the BlueROV2 Heavy and present the results from a preliminary design analysis on the AUV. We also discuss our plans for the AUV in the future.

II. Design Features

The original BlueROV2 Heavy robot forms the basis for our resident AUV. We show computer-aided design (CAD) models for the BlueROV2 Heavy and our resident AUV in Figure 1. It is convenient to use the original BlueROV2 Heavy as a platform since it is already compatible with other components from BlueRobotics. Moreover, the BlueROV2 Heavy runs on open-source software, and we have already developed an autopilot mode for the unmodified robot. We will use the BlueROV2 Heavy's Raspberry Pi, navigator flight controller, and SD card to navigate the AUV, control the thrusters, and collect data. However, because of our upgrades to the AUV, we replace the power components and the basic electronic speed

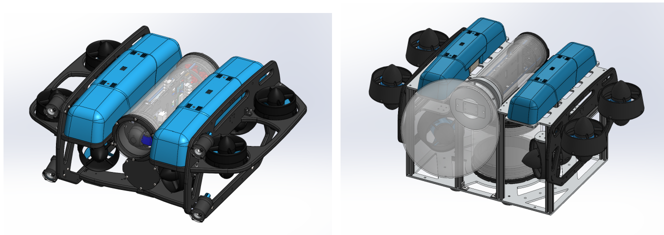

Fig. 1. Solidworks computer-aided design (CAD) models for the BlueROV2 Heavy (left) and our resident AUV (right).

Fig. 2. The WiBotic transmitter (left) and onboard charger and receiver (right), along with their corresponding antenna. Figure adapted from [6].

controllers (ESCs) which control the original thrusters with new components. We detail these changes in this section.

A. Autonomous Docking and Inductive Charging

We design our resident AUV to dock autonomously and to charge using an on-board inductive charging module paired with a docking station. Inductive charging methods are wireless, making them safer, more convenient to use, and more compatible with autonomous systems when compared to their wired counterparts [7]. We will use a wireless charging module sold by WiBotic specifically for robotic platforms. The module includes a transmitter circuit and antenna which will connect to the cabled infrastructure at KNO and an onboard charger and antenna installed within our AUV to receive power, as shown in Figure 2. The onboard charger will charge LiPo batteries within the AUV, which will then supply power to the AUV during a mission. The WiBotic automatically starts charging once the two antennas are sufficiently close to one another, and we can monitor and configure the charging using WiBotic's control panel software. The choice of transmitter and charger determine the output voltage to the batteries, the maximum output power, and the output current of the system. Table I shows these parameters for transmitter-charger model pairs given by WiBotic. The specific charging module and batteries we use depend on the other electronics installed on the AUV, which we are still finalizing.

For the AUV to charge, the two charging module antennas must face each other at a close enough distance and line up [6]. To facilitate this, we design the AUV to mount to a docking station using six magnets mounted to the AUV's bottom, aluminum plate. These six magnets are the six dark gray circles arranged hexagonally in Figure 3. The magnets will line up to six other electromagnets on the docking station. These electromagnets will only activate when the vehicle has

TABLE I
SPECIFICATIONS FOR TRANSMITTER-CHARGER MODEL PAIRS RECOMMENDED BY WIBOTIC [6].

Transmitter	Onboard Charger	Output Voltage to Battery (VDC)	Max Output Power (W)	Output Current (A)
TR-110	OC-110	7.92 - 30.1	90	0.5 - 5
TR-110	OC-210	12.03 - 36.0	125	0.5 - 10
TR-300	OC-250	12.03 - 36.0	250	0.5 - 10
TR-300	OC-300	0 - 58.4	300	0.5 - 30

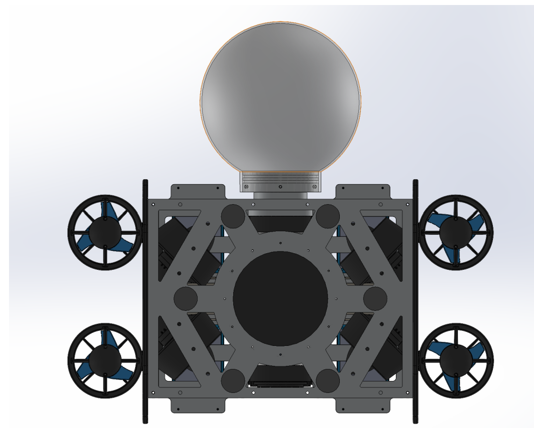

Fig. 3. A bottom-up view of our resident AUV. The AUV magnets are the six dark gray circles attached in a hexagonal pattern to the bottom of the AUV's bottom aluminum plate.

come close enough to aligning with the station. The magnets will help the AUV align and lock into place when docking, facilitating the process.

B. Gimbaled Camera System

We upgrade the camera system on the original BlueROV2 to help the AUV position itself while docking. Our docking station uses an ultrashort baseline (USBL) acoustic system to track transponders on vehicles. However, the system cannot track vehicle positions accurately enough for vehicle docking, which is why we consider camera upgrades. The original BlueROV2 comes with a low-light camera which looks out from the front of the ROV, but the camera is recessed into the top pressure vessel. We want the camera to have enough range of motion to look downwards at the base of our AUV during its docking procedures, which the original BlueROV2 camera arrangement cannot do. So, we replace the original BlueROV2 camera with a camera attached to a gimbal and replace the original BlueROV2 camera dome with a custom-made polycarbonate dome that gives the gimbaled camera a nearly 360° view of the AUV's surroundings. Figure 4 shows the camera dome arrangement. The spherical part of the dome has an outer thickness of 0.36 cm and supports an internal, 29.53 cm diameter spherical cavity for gimbal movement. The cylindrical part of the dome has an outer thickness of 0.48 cm and supports a cylindrical opening of diameter 14.29 cm and height 3.81 cm to allow us to insert the gimbal into the dome. We will use the Namaste three-axis gimbal sold by Gohstand Designs for our AUV. When fully extended, the Namaste

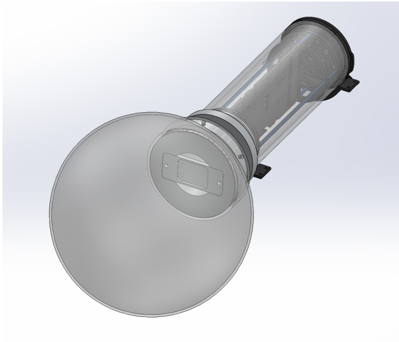

Fig. 4. The camera dome attached to the top pressure vessel via a custom-made, aluminum part. The rectangular plate within the dome holds the gimbal mount, which in turn holds the gimbal and camera.

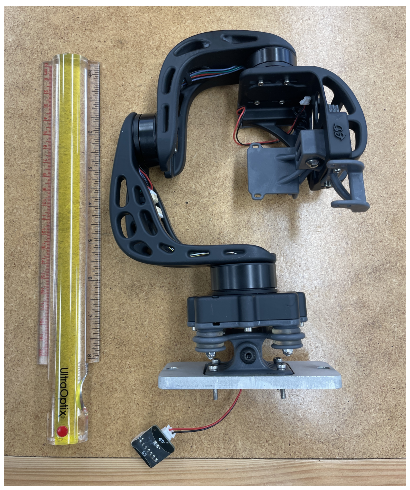

Fig. 5. The gimbal, gimbal mount, and rectangular aluminum plate in the camera arrangement. 20 cm ruler for scale.

gimbal is about 22.86 cm (9”) tall. Moreover, the moving components on the gimbal require a spherical space with a diameter exceeding 17.88 cm (7”) to move freely. The gimbal mounts to a plastic part provided by Gohstand Designs. We fasten the gimbal mount and gimbal to the AUV’s top pressure vessel using an aluminum plate and a custom aluminum part as shown in Figures 4 and 5. We plan to control the gimbal using a SToRM-32 microcontroller. The microcontroller will stabilize the camera’s motion while the AUV moves around and incorporate information captured by the camera into a control algorithm that lets the AUV mate with its docking station underwater.

C. Enlarged, Bottom Pressure Vessel

The bottom pressure vessel on the original vehicle is too small to accommodate the inductive charging components. Therefore, we replace the original, bottom pressure vessel with a pressure vessel from BlueRobotics’ 8” series watertight enclosures. The new pressure vessel has an inner diameter of 20.32 cm (8”), an outer diameter of 22.225 cm (8.75”), and a height of about 21.59 cm (8.5”) when all the components are assembled. The BlueRobotics pressure vessel is a good choice

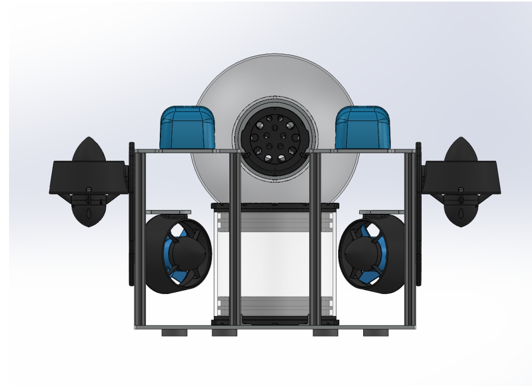

Fig. 6. A back view of the AUV. The AUV’s bottom pressure vessel lies on top of the AUV’s bottom aluminum plate and in the center of a T-slotted rail frame. The thrusters which lie within the T-slotted rail frame provide thrust in the surge and sway directions.

for the upgraded AUV because it is easy to purchase, already compatible with the BlueROV2 Heavy, and comes with all the necessary components for assembly. This new pressure vessel will hold the inductive charging components, the AUV batteries, and a CPU. We show the bottom pressure vessel in relation to the other AUV components in Figure 6.

D. T-Slotted Rail Frame

We use a combination of commercial, T-slotted rails and waterjetted aluminum plates to connect the new pressure vessel with the original BlueROV2 Heavy. The new pressure vessel is fixed to a 49.72 cm by 37.20 cm by 0.635 cm rectangular plate. Eight 30.48 cm (12”) long T-slotted rails then extend upwards from the bottom plate and connect to two other aluminum plates which themselves are connected to the original BlueROV2 pressure vessel. These two plates then hold buoyancy foam and fairings from the original BlueROV2 Heavy configuration to make our resident AUV more buoyant underwater. The connections between the bottom pressure vessel, T-slotted rails, and aluminum plates can be seen in Figures 1 and 6.

E. Upgraded Thruster Capacity

Because of the bigger payload, our AUV is heavier than the BlueROV2 Heavy. Moreover, the original thrusters on the BlueROV2 Heavy are not strong enough to maneuver around and dock in the rougher wave conditions of the near-shore environment, especially with the larger payload to handle. To account for these two facts, we upgrade the thrusters used for our AUV. The original BlueROV2 Heavy uses eight T200 thrusters from BlueRobotics, whereas our resident AUV uses eight T500 thrusters. Table II compares the thrusts and current draw of the two thrusters at their maximum operating voltage.

We mount four thrusters inside the T-slotted rail frame to propel the AUV in the surge and sway directions. These four thrusters lie next to the bottom pressure vessel in the four corners of the AUV, as shown in Figures 3 and 6. Each internal thruster is attached to the T-slotted rail frame via an aluminum

TABLE II
A COMPARISON OF THE TWO BLUEROBOTICS THRUSTERS AT MAXIMUM VOLTAGE. THRUST AND CURRENT VALUES ARE FOR THE THRUSTERS AT FULL THROTTLE [8], [9].

Thruster Type	Maximum Voltage (V)	Forward Thrust (N)	Reverse Thrust (N)	Current (A)
T200	20	65.7	49.5	32.0
T500	24	158	103	43.5

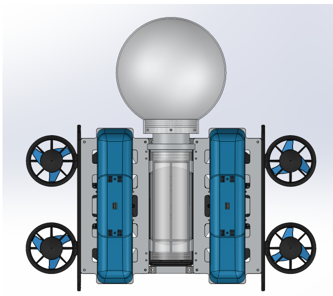

Fig. 7. A top-down view of the AUV. The four thrusters seen on the left and right sides of the AUV are mounted to the original BlueROV2 Heavy walls and provide thrust in the heave direction.

plate. We mount the remaining four thrusters on the outside of the robot, as shown in Figure 7. These thrusters propel the AUV in the heave direction and are mounted on the side walls of the original BlueROV2, which themselves attach to the T-slotted rails via mounting brackets. The original thruster hole pattern on the walls are compatible with the T200 thrusters but not the T500 thrusters, so we drill the larger hole pattern shown in Figure 8 in order to fasten the T500 thrusters to the side walls. Using the original side walls allows us to attach BlueROV2 components originally attached to the vehicle's outer walls, such as the subsea lights. We control all eight T500 thrusters using upgraded ESCs which replace the original ESCs in the original BlueROV2 Heavy. The vertical position of both the inside and outside thrusters are designed to be adjustable in the heave direction so that we can adjust the AUV as needed depending on the equipment onboard. Specifically, we can move the inside thrusters such that they lie at the same level as the AUV's center of gravity, preventing the inside thrusters from generating any undesired pitching and rolling torques from desired surge and sway forces.

F. Preliminary Buoyancy Analysis

Finally, we want the AUV to remain stable underwater and for the AUV to be positively buoyant. These two properties ensure that we need no extra thrust to operate the AUV and that the AUV floats to the ocean surface in case of malfunction. Furthermore, positive buoyancy means the AUV must thrust downwards instead of upwards to maintain its depth, preventing the thrusters from disturbing seafloor sediment and clouding visual docking cues. To these ends, we present the results of preliminary buoyancy analysis on the AUV using our CAD models for two configurations: an "old dome" configuration with the original BlueROV2 Heavy dome and camera

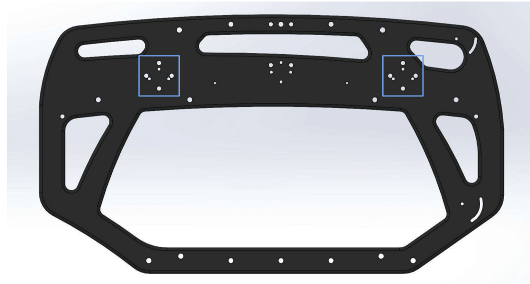

Fig. 8. The side walls to which we mount the AUV's external thrusters. We drill out a larger hole pattern for the T500 thrusters, as seen in the blue boxes.

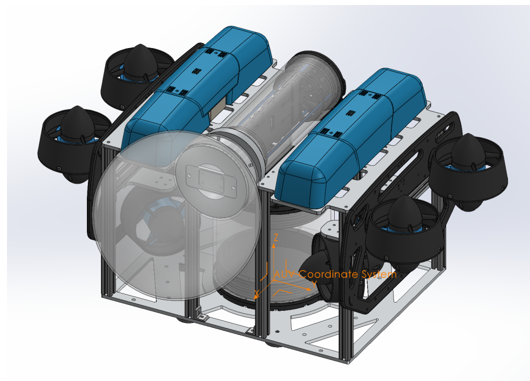

Fig. 9. The coordinate system in which we calculate the vehicle's center of mass and buoyancy. The origin of the system lies at the center of the top face of the bottom aluminum plate in the plane where the plate and bottom pressure vessel touch. The positive x-, y-, and z-axes correspond to the positive surge, sway, and heave directions respectively.

and a "new dome" configuration with the polycarbonate dome and gimbaled camera. Both configurations include the other BlueROV2 parts used and the frame which holds the bottom pressure vessel. Tables III and IV show the total mass, center of mass position, displaced water mass, and center of buoyancy position estimated for the two AUV configurations. Figure 9 shows the coordinate system which we use to calculate the center of mass and buoyancy positions. To move the AUV's center of mass further below the center of buoyancy and make the AUV more stable, we have multiple unused holes in the AUV's bottom plate to which we can attach ballast or flotation foam.

G. Current State

To date, we have finished the mechanical design of the AUV, and fabrication of the custom frame pieces. Moreover, we have

TABLE III
THE MASS PARAMETERS FOR THE AUV WITH ITS ORIGINAL AND NEW DOMES RESPECTIVELY. HERE, "COM" REFERS TO THE VEHICLE'S CENTER OF MASS. THE ORIGIN OF THE COORDINATE SYSTEM IS AS DESCRIBED IN FIGURE 9.

Configuration	Total Mass (g)	CoM X-Coordinate (cm)	CoM Y-Coordinate (cm)	CoM Z-Coordinate (cm)
Old Dome	24,959.46	0.57	0	17.50
New Dome	28,340.98	3.56	0	19.32

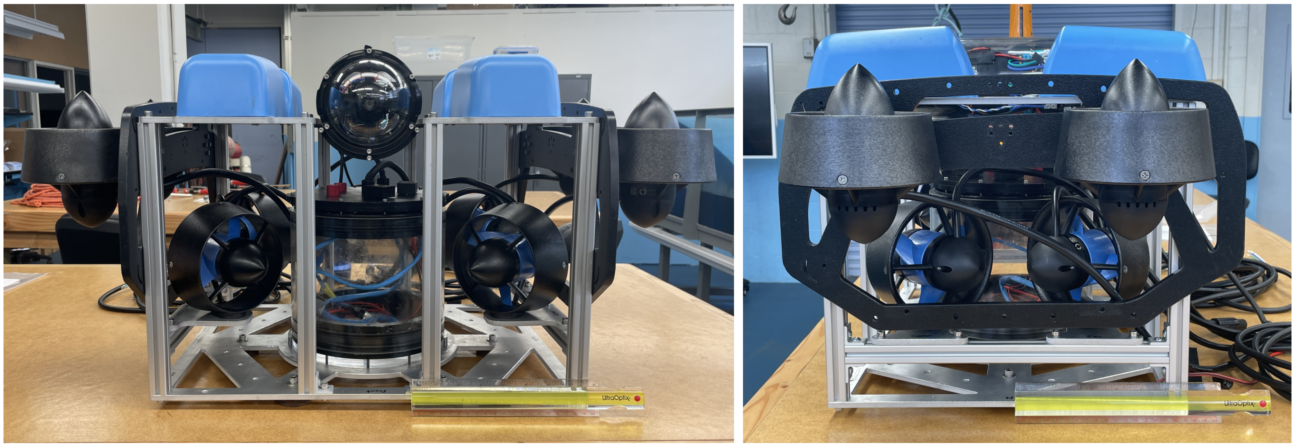

Fig. 10. Front (left) and left side views (right) of the current AUV assembly. 20 cm ruler for scale.

TABLE IV
THE BUOYANCY PARAMETERS FOR THE AUV WITH ITS ORIGINAL AND NEW DOMES RESPECTIVELY. HERE, "COB" REFERS TO THE VEHICLE'S CENTER OF BUOYANCY. THE ORIGIN OF THE COORDINATE SYSTEM IS AS DESCRIBED IN FIGURE 9. IN THE CALCULATION FOR DISPLACED WATER MASS, SEAWATER DENSITY IS ASSUMED TO BE 1.025 G CM^{-3}.

Configuration	Displaced Water Mass (g)	CoB X-Coordinate (cm)	CoB Y-Coordinate (cm)	CoB Z-Coordinate (cm)
Old Dome	21,938.69	0.37	0	20.69
New Dome	36,612.37	14.38	0	25.72

assembled the AUV in its "old dome" configuration, as shown in Figure 10. Fabrication and shipping delays have prevented us from assembling the AUV in its "new dome" configuration and attaching some buoyancy components. However, we demonstrate the validity of the mechanical design with the successful assembly.

III. CONCLUSION AND FUTURE WORK

In summary, we present the design and current state of a resident AUV for Honolulu's Kilo Nalu Observatory. We upgrade BlueRobotics' BlueROV2 Heavy with new mechanical components and plan to incorporate inductive charging, a gimbaled camera, and autonomous docking onto the AUV. Once we assemble the AUV and finalize its electronic components, we will configure the AUV electronics for autonomous docking and prepare tests for the AUV at Kilo Nalu Observatory. This project will pave the way towards the creation of resident AUVs for other near-shore areas like KNO.

Here, we note that the infrastructure used to support resident AUVs in this matter need not be tethered to a cabled observatory. Though cabled observatories lend themselves to powering docking stations for AUVs, a wave-energy-powered, self-charging docking station could in principle operate alongside a resident vehicle anywhere, including more remote, information-rich areas unsuitable for long-term, manned missions [2], [3]. One such area is the polar regions, which ice renders inaccessible for research cruises during the winter months. Thus, we eventually want to remove our AUV's reliance on cabled infrastructure and facilitate extended AUV operation in information-rich, low accessibility areas.

ACKNOWLEDGMENT

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