Design and Testing of a Light-Weight ROV for Deep-Sea Research and Exploration

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***Abstract*—The scientific community has utilized unmanned underwater vehicles for ocean exploration since the mid-twentieth century, resulting in a well-cultivated and ever-changing discipline used in marine operations. The deep-sea environment presents unique and harsh criteria due to the increased pressure found at depth and the vehicle components necessary to overcome it. The size and weight of underwater vehicles typically increase as operational depth increases, resulting in physically large systems with high operational costs to accommodate deep-sea research. This project demonstrated the ability to reduce the weight and size of an existing 300 meter rated ROV by 8.6% and 26%, respectively, through the replacement of buoyancy foam with hollow carbon fiber structural components, as well as replacement of a twisted pair copper wire tether with a fiber-optic microtether. The resulting vehicle "ROV FiberFish" had a weight in air of 116 newtons and a size of 50,000 cubic centimeters. A system of this size and capability directly serves to increase accessibility to the world's oceans, and provides a baseline model for future design of underwater vehicles attempting to minimize size and implement structural buoyancy to their architecture.**

***Index Terms*—ocean robotics, deep-sea systems, composite materials, additive manufacturing, fiber-optic telemetry**

I. Introduction

In recent years, the scientific community has seen an increased interest in the world's deep oceans [1], [2]. In order to access this region, underwater robots are commonly employed to minimize danger to life and liabilities associated with manned submersibles. Due to this demand and rapid innovation in the growing field of deep-sea robotics, systems with robust optical, manipulative, and maneuvering capabilities have resulted. In order to accommodate a wide variety of tasks, these robotic systems must be individually tailored to prioritize ability in some aspects, at the cost of decreased ability in others. Vehicles designed to operate in the deep ocean are often large and cumbersome due to the need for pressure-tolerant buoyant material at the cost of buoyant efficiency by volume.

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Remotely operated vehicles (ROV's) are defined as ocean robots that utilize a tether for remote control of maneuverability and live telemetry to the surface and operator. ROV's can be divided into three categories based on their physical size: observation, inspection, and work-class vehicles. Observation class ROV's are classified as having a weight limit at 200 pounds in air and a depth rating limit of 300 meters. Inspection-class vehicles have a weight minimum of 200 pounds, to a maximum of 2000 pounds, with a depth rating of less than 1000 meters [3]. Working class vehicles include platforms larger than the previous two, and are outside the scope of comparison for the vehicle developed in this project. The ROV FiberFish offers significant capability upgrades to existing observation-class ROV's, primarily through its use of carbon fiber tubes as integrated structural buoyancy.

Most deep-sea ROV's utilize syntactic foam to provide buoyancy, introducing a common limit in the net buoyancy to weight in air ratio [4]. Syntactic foam is a pressure tolerant volume that uses glass microspheres suspended in an epoxy matrix to supply buoyancy [5]. Recent years have seen research into the alternative use of composite materials for the construction of external pressure housings. Woods Hole Oceanographic Institute (WHOI) assessed the possibility of using ceramic spheres as supplemental buoyancy devices for deep-sea platforms [6]. The results of this research confirmed the viability of construction of pressure-tolerant buoyancy devices with ceramic materials. This success provided the motivation to experimentally analyze carbon fiber in the same role. Pending the results, carbon fiber could then be implemented to the design of a vehicle in order to reduce its weight and size. This project sought to validate the use of sealed carbon fiber tubes as a source of buoyancy and structure to a small ROV, with the goal of minimizing weight in air and size of the vehicle to maximize its mobility and ease of deployment.

II. Methods

To construct the ROV FiberFish, composite materials testing was conducted in order to validate and quantify the use of carbon fiber tubing as structural pressure vessels. The mechanical and structural design of the vehicle sought to incorporate carbon fiber tubing, while also maintaining an emphasis on additive manufacturability of all components. The vehicle was then assessed for basic functionality in a controlled environment, followed by field testing in the Pacific Ocean.

A. Preliminary Materials Testing

To assess the behavior of carbon fiber tubes under simulated ocean pressures, test samples were created and evaluated. Hydrostatic pressure chamber testing of carbon fiber tubing was performed to determine the effects of tube length, diameter, and fiber-weave pattern on failure depth. There were a number of fiber-weave options to choose from, of which the roll-wrapped twill finish and braided finish were selected. The roll-wrapped tubing was selected due to the manufacturer's description, stating it produced the highest bending stiffness at the lowest weight. The braided tubing was selected as a less expensive alternative at $80.31 for a 0.610 m (48") length of 0.0254 m (1") inner diameter tube, compared to $106.39 for the same tube of the roll-wrapped finish. All of the carbon fiber tubing was sourced from DragonPlate[1].

Initial experimentation compared fiber-weave patterns to identify general pressure tolerance and inform material selection for further analysis. Tubes of both weave patterns were purchased, each having a of length 0.610 m (24"), an inner diameter of 0.0254 m (1"), and a wall thickness of 0.0016 m ($\frac{1}{16}$"). They were cut into two 0.305 m (12") length sections. Each set of two tubes were then plugged on both ends by epoxying in custom end-caps made of FormLabs Clear Resin V4. Each tube was then individually placed in a hydrostatic pressure chamber, and subjected to increasing pressure until failure, at which the maximum pressure withstood was recorded for each. This pressure, given in pound-force per square inch, was then converted to equivalent meters of seawater (msw) by a conversion factor of 0.689. The roll-wrapped twill finish tubing performed significantly better, and was selected for further experimentation.

Three lengths of roll-wrapped tube of inner diameter 0.0254 m, 0.0318 m, and 0.0381 m (1", 1.25", and 1.5") were cut by hand with the use of a custom jig and band-saw to lengths of 0.305 m (12") through 0.0508 m (2") at 0.0508 m (2") increments. This resulted in the production of 18 tubes total. A maximum of 0.305 m (12") in length for the tubes was determined based on the physical size of the proposed vehicle. All samples maintained a wall thickness of 0.0016 m ($\frac{1}{16}$"). The ends of each tube were sanded by hand to achieve a smooth finish on the top surface and a slightly rough finish on the interior radius for bonding of the adhesive used to secure the end-caps. Hemispherical end-caps (Fig. 1) were designed for these tubes to be permanently affixed via construction-grade epoxy, and were manufactured via a stereolithography 3-dimensional (3D) printer. Assembled experimental housings (Fig. 2) were independently subjected to cyclical hydrostatic loading within the chamber to a simulated depth of 1000 msw ten times. On the eleventh cycle, the housings were tested to maximum pressure tolerance found at critical failure.

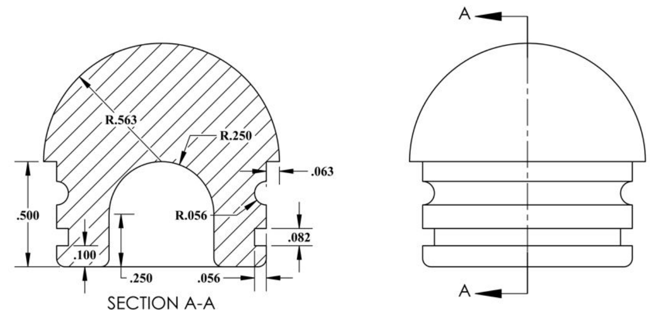

Fig. 1. Dimension drawing of end-cap used in construction of 0.0254 m (1") inner diameter pressure housings.

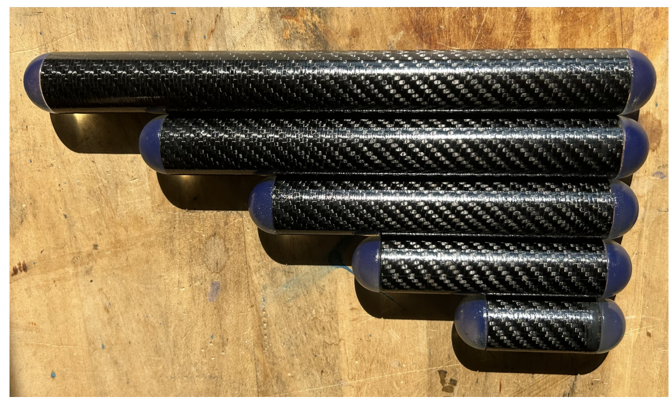

Fig. 2. Fully assembled pressure housings, of 0.0254 m (1") inner diameter tubing, from lengths 0.0508 m (2") through 0.254 m (10") inches.

B. Manufacturing

Additive manufacturing was used for rapid prototyping [7] and final production of mechanical components (Fig. 3). This allowed for research and development to continue in parallel with manufacturing, having design alterations made based on prototyped results the same day. Additive manufacturing of these parts offered freedom in material choice, and weight reduction was achieved by use of FormLabs Tough 1500 Resin with a density of 1.07 g/cm^3, compared to a more traditional material, aluminum, with a density of 2.7 g/cm^3 [8].

C. System Testing

Following the design and construction of the physical system, basic system functions were assessed in a freshwater tank. The vehicle was weighed in air and water, submerged at 3 m for a period of no less than 30 minutes, maneuvered at a low controller gain of 20% in all degrees of freedom available (surge, sway, heave, roll, pitch, and yaw), and maneuvered at

[1] https://dragonplate.com

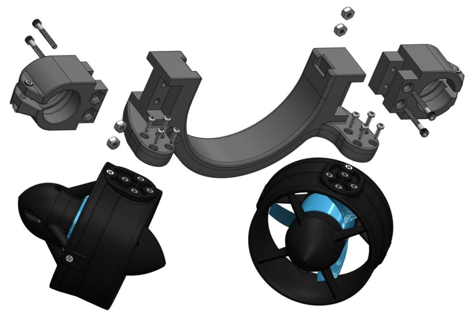

Fig. 3. 3-dimensional model of mechanical system components, used for additive manufacturing.

high controller gain of 100% with rapid directional changes to assess responsivity and structural reaction to shock loading. From this, information regarding the functionality of the tube seals, necessary ballast volumes and placement, vehicle behavior whilst under motion, and the structural integrity of the design under usage were gathered. These tests also served as trial periods for the set-up, usage, and breakdown of the topside control equipment. This involved not only deploying the vehicle, but also deploying the fiber-optic microtether [9], the tether management system (TMS), and the electrical control components used in piloting the vehicle.

The initial deployment of the ROV FiberFish (Fig. 9) in the testing tank provided necessary system information. Through use of a hanging scale, the assembled vehicle was found to weigh 115.7 N in air, and 15 N when fully submerged. Syntactic foam was then cut and affixed to the upper section of the vehicle's frame such that it would be positively buoyant by 1 N. Positive buoyancy ensures the vehicle's return to surface from depth in the event of communications loss or tether sever. A bubble level was used when placing steel ballast weights to ensure uniform placement and a neutral center of gravity in the x and y axis. The ballast weights added, in total, weighed 3.5 N in air. This test also provided a confirmation of structural integrity under variable-speed maneuvering, as justified by the frame remaining rigid, intact with no visible damage, and no hardware loosening throughout. All additional components functioned properly, with full range of motion in the manipulator, full range of intensity in lighting, full range of motion in camera gimbal, continuous high definition live video, and confirmed individual thruster operation.

D. Field Deployment

To validate operational readiness in the field, the ROV FiberFish was deployed to the Gulf of Chiriqui in Panama. The ROV was packed within an armored case capable of being checked as standard luggage (Fig. 4), such that the length, width, and height of the case did not sum to greater than 1.57 m (62") [10]. The topside equipment, including fiber-optic microtether and TMS, were also checked as standard luggage. These cases were then flown on a commercial international flight from Boston, Massachusetts, USA to Panama City, Panama as a series of checked bags. Once on-site, the baggage was placed within a standard rental car, driven to the port, and transferred by hand to the research vessel (Fig. 5). The system was then deployed five times in a series of biologic and bathymetric observation dives at various sites. At these sites the vehicle was equipped with an external conductivity temperature and density (CTD) sensor, along with an external high definition camera in an independent pressure housing. The external camera was held by the vehicle's manipulator, limiting its ability to interact with the environment at depth. As such, it was used in only three of the five deployments, with the other deployments being focused primarily on biologic sampling.

Fig. 4. ROV FiberFish packed into a Pelican 1637 Air case prior to transit. The ROV has been folded down, by design, to fit in this compact space and deploy readily and quickly once removed. An emergency tool kit was fit inside of the case alongside the vehicle.

Fig. 5. Assortment of Pelican cases on the aft deck of the S/Y Eugen Seibold. These cases contain the ROV FiberFish, its necessary tools and auxiliary equipment, the vehicle's tether and TMS, and all topside control equipment.

III. Results

The materials testing yielded results that are useful in the optimization of material and size choice for various depth parameters with a maximum buoyancy-to-weight ratio. A failure depth envelope was created for each of the three inner diameters, as a function of the tubes' length (Fig. 6). It was found that the pressure tolerance of the tubing decreased exponentially as the length increased at all three inner diameters. It was also found that tubes of smaller inner diameter had a greater pressure tolerance than those of the same length with a larger inner diameter. The 0.0254 m (1") inner diameter tubing imploded at 1483 msw at the maximum length tested. The 0.0318 m (1.25") inner diameter tube imploded at 1000 msw with a length of 0.147 m (5.8"), and the 0.0381 m (1.5") inner diameter tube imploded at 1000 msw with a length of 0.132 m (5.2"). A 1.2 factor of safety was applied to this data for a proposed operational depth of 1000 msw, and found that the maximum length of any given 0.0254 m, 0.0318 m, and 0.0381 m (1", 1.25", and 1.5") inner diameter tube was >0.305 m (12"), 0.132 m (5.2"), and 0.112 m (4.4"), respectively. Using this data, a generic design tool was created that quantifies the optimization of buoyancy for weight in air. This was achieved by plotting the net buoyancy and weight in air for each series of tubes, as well as a generic syntactic foam block with experimentally derived values (Fig. 7). The graph shows a stepped line for each of the tubes, and a linear line for syntactic foam. The reason for this is the length limitation of carbon fiber tube due to operational depth. Essentially, the tubes can only increase in length by so much, before requiring an additional tube to be implemented, this length being informed by the design depth of any given system utilizing the tool. In this way, every time the length of a tube reaches its maximum, a new tube of no length (i.e. just end caps) is added and later lengthened. The addition of this tube supplies negative net buoyancy and positive increase in weight in air at first, resulting in the visual steps on the graph. This graph can then be configured to include maximum lengths for each diameter tube based on the necessary design depth, informed by interpolated values from the experimentally generated failure depth curves.

Future work on the ROV FiberFish includes an increase in system depth rating from 300 to 1000 msw. With a proposed operational depth of 1000 msw, an allowable failure depth of 1200 msw was found based on a factor of safety of 1.2. The design tool was thus altered to reflect this new criteria (Fig. 8), resulting in different optimized choices for buoyancy when compared to an unrestricted tube length. The optimum choice for delivering 1 N of net buoyancy for the lowest weight in air was found to be one 0.3048 m (12") and one 0.1524 m (6") tube of a 0.03175 m (1.25") inner diameter when unrestricted. The optimum choice under the proposed restrictions for that same 1 N of net buoyancy became three 0.3048 m (12") and one 0.2032 m (8") tube of 0.0254 m (1") inner diameter. Under both conditions the carbon fiber tubes provide a higher buoyancy to weight ratio at larger amounts of net buoyancy when compared to syntactic foam, regardless of the inner diameter. As such, syntactic foam is not optimized

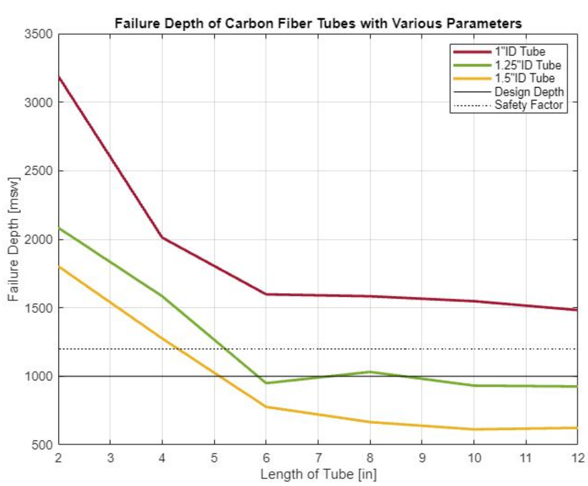

Fig. 6. Graph displaying the relationship between failure depth and length of tube for three series of tubes. Such series had tubes of 0.0254 m, 0.0318 m, and 0.0381 m (1", 1.25", and 1.5") inner diameters. The design depth of 1000 msw is included as a solid line, and the modified design depth to include a factor of safety of 20% is included as a dashed line.

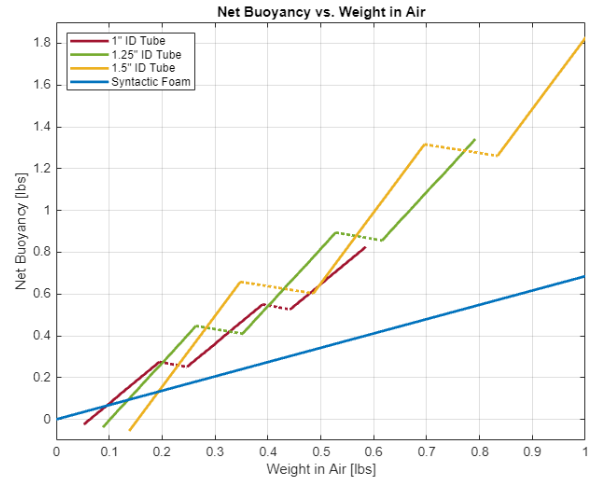

Fig. 7. Graph displaying the relationship between net buoyancy and weight in air of carbon fiber tubes with varying inner diameters. Tubes are limited to the maximum length tested, 0.3048 m (12"), prior to the addition of a supplemental tube.

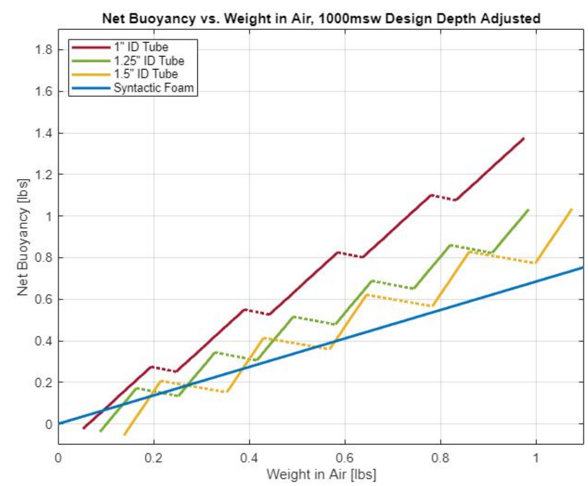

Fig. 8. Graph displaying the relationship between net buoyancy and weight in air of carbon fiber tubes with varying inner diameters. All tubes are restricted in length due to a design depth of 1000 msw and safety factor of 1.2.

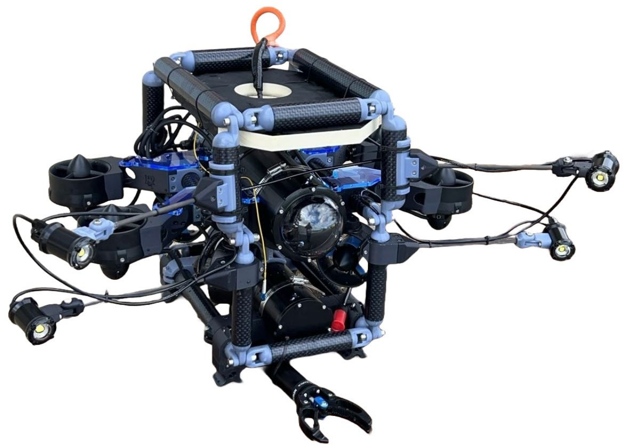

Fig. 9. ROV FiberFish fully assembled. Vertical thruster arms and light booms are in a deployment configuration, and can be collapsed inward for storage.

Fig. 10. ROV FiberFish sitting astern and the TMS with fiber-optic tether on the port stern the S/Y Eugen Seibold during pre-cruise set-up.

to maximize buoyancy and minimize weight in air at a net buoyancy of greater than 0.15 N, tube length unrestricted by design depth, or 0.25 N, tube length restricted for 1200 msw failure depth. When designing a vehicle that requires buoyancy reserves of greater than or equal to these values, carbon fiber tubes provide more buoyancy than syntactic foam at the same weight in air.

The ROV FiberFish was flown to Panama City, Panama for field testing following construction and preliminary testing. There were no issues traveling and flying with the system, and it was able to be checked as a standard size and weight bag at the gate of the airport. Its portability benefited the team when driving the system from the airport to the dock, having the ability to store all necessary cases, as well as three adults and their personal effects, in a standard SUV rental car. The entire system was lightweight enough that two adults could safely and easily carry it on uneven floating docks and load it by hand over the side of a large sailing vessel, the S/Y Eugen Seibold. Once aboard, set-up of the vehicle took less than one hour and the TMS was installed within the same time frame.

The vehicle require two hard-points on the deck for which to strap it securely during transit, as well as a low gunwale or small a-frame to hand-place or lower with rope into the water for deployment, respectfully. Through trial at sea, it was found that the easiest deployment method was to hand-place the vehicle in the water, and the easiest retrieval method was to send a diver out with a rope to affix the vehicle to the a-frame and hoist it out. The TMS required a sturdy fishing rod holder or a sturdy rail on which to affix an accompanying rod holder. The TMS also require one 12-volt lead acid battery. The topside controls, including a laptop, signal splitter, and fiber-optic multiplexer, required a standard 120-volt outlet or power supply and did not need a Wi-Fi connection to a local network.

ROV FiberFish was deployed five times over 48 hours at two unique locations within the Gulf of Chiriqui. The first two deployments were in a region known as Ladrones Bank at an average operating depth of 26.5 m and average operating time of 40 minutes. The first of these dives was targeted towards photography and videography of megafauna, and as such included a secondary external camera. A large biologic diversity was found at depth, and video was used to capture the local behavior of choice animals. One such unique instance was a prolonged observation of an interaction between a stingray and trumpet fish (Fig. 11). Other species were sighted and observed, largely directed by the onboard team of biologic scientists. The second dive of this location was focused on the recovery of coral samples, and saw the removal of the secondary camera to free the claw of obligation. A small specimen from a sea fan coral, specific species unknown, was successfully retrieved and brought to the surface, measuring roughly 25 cm^3.

The third dive of the cruise was in a deep section of a new region know as Hannibal Bank. This was a night operation, with a focus on maximizing depth achieved. ROV FiberFish was deployed and reached a maximum depth of 251.3 m. Shortly after reaching this depth an optical sever occurred in the tether, and all communication with the vehicle was cut. While optically severed, the the tether's outer sheath was still intact and a physical connection to the vehicle remained. The recorded current at this location was 3.3 m/s, resulting in a large horizontal drift as the vehicle descended. This required the tether to be paid out to a great length, ultimately introducing excess stress to the fiber, causing it to break. The vehicle was retrieved through use of the TMS, hauling it in at a slow rate to avoid physical sever due to increased load. The fiber-optic tether was swapped for a spare stored onboard after this recovery, resolving all operational issues of the previous dive. The optically-severed tether was taken to a workstation where a handheld optical fault sensor was used for diagnosis. The site of the sever was found, and the tether was cut back to this point and re-terminated without the use of a fusion splicer, as would be the common practice in a lab.

The next two dives used the field-spliced tether with success.

Fig. 11. View from the secondary camera aboard the ROV FiberFish while observing a stingray and trumpet fish in the Gulf of Chiriqui, Panama.

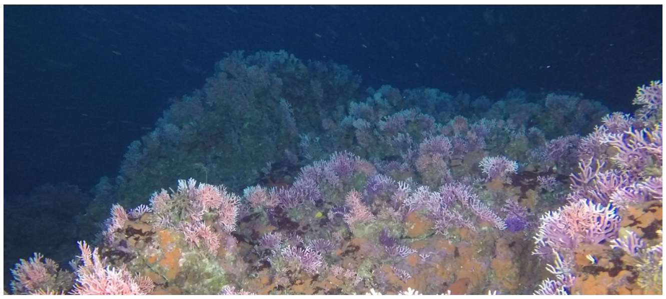

Fig. 12. Still image from recorded video highlighting the biodiversity of corals found at an average depth of 65 m, in the Gulf of Chiriqui, Panama.

They were in Hannibal Bank, following the pattern of observation and then sample recovery for order of deployments. The average depth over these two dives was 65 m, with an average dive time of 30 minutes. An expansive reef was found upon arrival to depth during the fourth deployment, with a variety of species observed. The samples taken during the fifth deployment included a fragment of coral, a live brittle star, and a small live crab of unknown species (Fig. 13). Upon completion of the last dive, the vehicle was disassembled and packed away, along with its accompanying equipment. The video footage was then shared with scientists from the Smithsonian Tropical Research Institute and the Max Planck Institute for review.

IV. Conclusion

Robotic systems are used extensively to explore the world's oceans, and it is necessary to make this technology accessible and robust to ensure continued advancement in understanding of these environments. Current systems used to explore deep-sea regions of the ocean are often large and bulky, in part due to the common use of syntactic foam as buoyancy material in the trimming and design of a vehicle. To address this issue and reduce the weight in air and size of an existing system, an ROV was designed and constructed to integrate net buoyancy to its structural architecture by means of a frame consisting of sealed carbon fiber tubes. Hydrostatic pressure chamber testing of sealed carbon fiber tubes under various configurations was conducted, and provided data used to generate a design tool to optimize the net buoyancy to weight in air ratio of buoyancy material at any given design depth. This design tool, along with validating testing results from the experiment, was used to inform the design of ROV FiberFish's frame. Carbon fiber tubes of various length were cut and sealed with end-caps

Fig. 13. Coral fragment and live brittle star recovered in the Gulf of Chiriqui, Panama by the ROV FiberFish

made via additive manufacturing, specifically SLA-printed. The rest of the mechanical components for the vehicle were designed and manufactured in-house through this method. The resulting vehicle was based around the system architecture of a BlueROV 2 Heavy but saw a weight in air reduction of 8.6%, 13.0 kg down to 11.9 kg, and a size decrease of 26%, from 0.07 m^3 to 0.05 m^3. The ROV FiberFish was then flown internationally and deployed on a series of biologic and bathymetric observation dives in the Gulf of Chiriqui, Panama. Successful completion of this series confirmed the field-readiness of the vehicle, and generated valuable data for scientific scrutinization by professionals associated with the cruise.

The ROV FiberFish represents an innovative prototype capable of deep-sea exploration, while maintaining a lightweight and compact geometry for ease of deployment. It offers a highly packable and rapidly deployable system with the ability to inspect and interact with the deep ocean from a variety of non-conventional vessels. A system of this size and capability serves to increase accessibility to the world's oceans through its versatile deployment and recovery methods, flexibility in transportation options, and ease of setup in-field. Additionally, this project and its data provide a baseline model for future design of ROV's looking to minimize size and implement structural buoyancy to their architecture. Future work expected to be supported by this platform includes a depth rating increase from 300 to 1000 meters through the exchange of the manipulator and viewport components, with validating fieldwork to follow.

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