Fishbots: Bio-Inspired Marine Robots Give Students a Hands-On Introduction to Fluid Mechanics

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***Abstract*— Simple biomimetic marine robots were used as teaching tools to introduce students to concepts in fluid mechanics and how they are applied to understanding swimming in fish and other marine animals. These robots, termed FishBots, were used in two educational situations. The first was a project for two undergraduate summer interns at MIT Sea Grant. This experience proved that such robots could be developed by students under the time constraints of a one month internship. Building on that success we used FishBots successfully in an undergraduate freshman seminar class at MIT. In one semester 29 students build 15 FishBots, all were tested in the water and 13 successfully swam. These educational experiences are described in this paper along with the design of several of the student-build FishBots. The paper concludes with future educational paths for the FishBot idea.**

Keywords*— *biomimetic robot; fish swimming; marine robotics; fluid mechanics; hands-on learning

I. Introduction

Fish and other marine organisms are masters at controlling flow for thrust, hovering, steering and braking. This is accomplished through the oscillatory action of fins and/or whole body undulations. Fish, therefore, should make good models with which to learn basic and advanced concepts in fluid mechanics (hydrostatics and hydrodynamics). Unfortunately, live freely moving fish are difficult objects to study, especially by undergraduate students. Fish movements are fast, complex, and subtle making them difficult to see, measure and understand. Instrumenting a live fish is very difficult and often impossible as the method of observation must not impair its motion or harm it in any way. We have overcome these obstacles by using living marine animals as sources of inspiration for students to create marine robots that are simplified versions of their biological counterparts. The key was to challenge students to create a simple marine machines that display, at least qualitatively, the propulsive motions of real marine animals. The availability of submersible radio-controlled (RC) servo motors, microcontrollers, and 3D printers, and laser cutters has made the construction of flapping and undulating mechanisms doable by even inexperienced undergraduate students. By building a bio-inspired aquatic robot (a FishBot), programming its basic motion and, through the iteration of experimentation and reprogramming, optimizing its motion, students can rapidly build an intuitive understanding of the fundamentals of fluid mechanics and how they apply to fish propulsion.

We tested this idea in two steps. First we had two undergraduate summer interns design, build, and test a tethered penguin-like vehicle. This experience proved that undergraduate engineering students could build and experiment with a simple marine animal (in this case penguin) – inspired robot. The second iteration of our idea tested the utility of FishBots as teaching tools in a classroom environment with multiple students. FishBots were used as a project in MIT's freshman seminar class "Mens et Manus" (MIT subject 6.A01). The following sections detail the two implementation of FishBots as teaching tools along with details of the design of some of the student-built robots.

II. The Penguin-Inspired Robot

A. Educational Context

The "penguin robot" was the first FishBot. It was developed by two undergraduate students from the WEBB Institute in their month-long internship at MIT Sea Grant during the summer of 2018. Their challenge was to design, build, and test a simple penguin-like robot. The students worked together on the overall design, then they divided the project into two major tasks, wing design and hull design, that they worked on individually in parallel. The students then combined their efforts to integrate the hull and wings and test the performance of the robot.

Under the supervision of their mentors (the authors of this paper), the trainees were encouraged to follow an experimental engineering approach: i) model the hydrodynamics of the robot; ii) design experiments to identify model's parameters; iii) perform the experiments and analyze the data; iv) design and make prototyped of the components; v) test the components to assess their performance; vi) repeat the loop to move forward in the design process. After iterations on both the hull and the wing design the optimized components were integrated into a working robot.

The MIT Sea Grant 10 meter Towing Tank was the primary experimental tool used by the students to extract design parameters for the robot. They designed and carried out two sets of experiments. The first set measured the drag of penguin-shaped hulls of different sizes at a number of speeds. The second set measured the thrust of flapping wings of different sizes flapping at several frequencies, different motion symmetries, and towed at a number of speeds.

A short course regarding hydrodynamic stability and the effect of the destabilizing Munk moment was given to the students to enable them to make a simple model of the stabilizing fins. Assumptions on the hull shape were made to simplify the calculations. The size of the fins was determined before finalizing the design and fabricating the hull. Experiments MIT Sea Grant's 3000 gal. testing tank validated the stability of the penguin body with fins, and demonstrated simple unidirectional swimming.

B. *Penguin-Inspired Robot Design*

The design began with a hull shape mimicking the body of a Gentoo penguin (Fig. 1). After collecting data from the towing tank tests it was decided to add "rocket fins" for added stability despite their un-penguin-like appearance. The hull was 3D printed with PLA in 6 parts due to the limited build volume of our low-cost 3D printer. Holes and bosses were added for screws that held the assembly together (Fig. 2).

Each wing consists of a plastic spline that acts as a bone and gives the wing some rigidity. It was encased by an elastomeric shell which acts as the "flesh" of the wing (Figs. 3 and 4). The acrylic splines were laser cut while the wings were made of polyurethane polymer poured in a 3D printed two part mold. Two metal rods were glued into the slots on the spline prior to pouring the mold. A 3D printed plastic "shoulder" that acted as the point about which the wing would pivot to feather during operation (Fig. 3). Once printed the shoulder was slipped over the rods sticking out of the wing and secured. One rod served as the axis around which the wing pivoted during swimming. The second rod hit a stop in the shoulder that forced the wing to maintain an orientation perpendicular to the flow during the power stroke of the wing flap. During the return stroke the shoulder permitted the wing to swing into a horizontal, minimum drag, orientation (feathering, Fig. 4). The fins, therefore, acted like oars of a row boat.

The wings were flapped by two HITEC model HS-5646WP submersible RC servos (HITEC RCD USA, Poway, CA) programmed to oscillate on a mirrored trajectory, so the wings would flap symmetrically. The servos were controlled by an Arduino Mega microcontroller. To attach the wings to the servos a part was added to the shoulder which served as an extension and connection to the servo horn (plastic disk or rod attached to the output shaft of the servo). Note that long lever arm added by the wing can lead in some extreme case to the loss of the watertightness resulting in a failure of the servo. Solving this problem requires more advance mechanical design that was not addressed during the internship. The servos were simply epoxied inside the penguin body.

Buoyancy and trim were adjusted using polystyrene foam as floats and steel nuts as weights. A CAT 5 cable (8 #28 AWG stranded wires in 4 twisted pairs) was used as a tether to provide power and RC servo control signals to the robot. Electrical connections were made waterproof with Liquid Electrical Tape (Starbrite, Ft. Lauterdale, FL). The Arduino microcontroller and power supply were outside of the testing tank.

III. *Mens et Manus* Freshman Seminar – the fishbots Project

A. *Educational Context*

MIT offers its freshman a variety of seminar classes to let students explore advanced topics while they are taking their basic science and math classes (the General Institute Requirements). The goal of the *Mens et Manus* freshman seminar is to reinforce the knowledge gained from the General Institute Requirements through hands-on construction and laboratory-based projects. It basically keeps the flame of interest alive in the students while they slog through often dry introductory science and math classes. FishBots fit well with the *Mens et Manus* theme because it related the fluid mechanics concepts learned in first year physics to understanding how fish and fish-like robots propel themselves. FishBots was one of several hands-on projects from which the students could choose. Each project lasted 6 weeks and the students engaged in two projects during the fall semester when the seminar was offered. At the end of the semester the students gave presentations, and often demonstrations, of their projects.

In FishBots we challenged the students to build a working physical model of the marine animal of their choice; they were not confined to fish. By "working" we mean that it propelled itself in a manner similar to the living creature. Unidirectional motion (e.g. straight line forward) was all that was required, maneuvering was an option. The class started with a lecture on basic concepts of hydrostatics and hydrodynamics (Archimedes principle, lift, drag, continuity, vortex shedding). These concepts were then applied to understanding how the undulating body of a fish generates thrust. The functions of the fins in thrust and lift generation, and maneuvering were also presented. The lecture was concluded with a discussion of existing research bio-inspired marine robots from MIT (e.g. the RoboTuna) and labs at other universities.

All *Mens et Manus* students received training in CAD and fabrication techniques at one of the MIT Maker Spaces. FishBots added instruction on basic electronic concepts, Arduino microcontroller programming and interfacing, RC servos, and power. Specific construction topics were also discussed such as frame and hull construction, mechanical coupling of RC servos, and how to waterproof electrical connections. Given the limitations of time and students' experience with fluid mechanics we did not use the towing tank in FishBots. Experimentation, testing and design iteration happened on the lab workbench and in our 3000 gal. testing tank.

The project consisted of six two-hour sessions, once per week, that occurred in the MIT Sea Grant Teaching Laboratory. In addition to the above mentioned lectures, In the first session the students learned how to programm an Arduino to control and RC servo, In the next session the students learned how to control and coordinate multiple servos. These programming exercises gave them the programming core needed for developing the code for their robots.

To construct their FishBots the students were given waterproof RC servos, Arduino microcontrollers, a wide variety of mechanical parts and access to 3D printers and a laser cutter. Each robot were tethered to a topside microcontroller and power supply. This removed the need for waterproof housings that can be time consuming to construct and prone to leakage. The only waterproofing involved was coating the tether to servo electrical connectors with Liquid Electrical Tape. The HITEC model HS-5646WP and D-646WP submersible RC Servos were used, as with the penguin, as the "muscles" of the robots. These servos are IP-67 rated which means they can nominally withstand immersion up to 1 meter depth for ½ hour. In actual experience we have found the servos can operate for many hours underwater at depths greater than 1 meter.

As homework after the first session the students were tasked with A) picking a marine animal to mimic, B) start brainstorming designs for their robot, and C) form a project group (optional, some students worked individually). In the second session each group (or individual) gave a brief presentation on their chosen marine animal, what aspect of its locomotion they planned to mimic, and potential designs for the robot. They then commenced designing, building and testing in the remaining sessions.

Two 6 week projects were run during the 2018 fall semester involving a total of 29 freshmen, many of whom had little to no building experience. Working individually or in small groups a total of 13 vehicles were built, all were water tested and 11 successfully swam! The bio-inspired robots copied a number of basic swimming mechanisms including: pectoral fin flapping (manta ray) using mirror-image oscillations of paired servos (Fig. 5), tail fin oscillation (angelfish, Fig. 6), body undulation (subcarangiform swimming) for thrust generation using serially coupled servos (Fig. 7), fin undulation (cuttlefish) utilizing a crankshaft mechanism (Fig. 8), and whole-body pulsation (jellyfish and octopus) using simultaneously acting servos to contract a symmetrical body (Figs. 9 and 10). Details of these devices are presented below.

B. Manta Ray-Inspired Robot

Two RC servos were mounted in parallel using machined aluminum servo brackets (ServoBlocks, ServoCity, Winfield, KS). The assembly was hot glued into a pentagonal foam block that formed the bulk of the robot's body. A plastic strut was glued along the midline of the foam block to serve as the robot's tail. A length of thick-walled rubber tubing was used as the "skeleton" of each pectoral fin (Fig. 5A). The use of rubber tubing was appropriate in that it mimicked the relatively compliant cartilaginous skeleton of an actual manta ray. These tubes were tightly fitted onto the rod-shaped servo horns. The servos were programmed to oscillate in a mirror image to each other to generate up/down fin flapping. The servo wires were coupled to the tether at the tail end and coated with Liquid Electrical Tape. The robot was covered with a thin sheet of silicon rubber that was stitched around the fins and the body. We found that sewing the silicon rubber was far superior to glue in forming a strong but compliant bond. Most of our FishBots were covered in this way. The 5 meter tether consisted of an RJ-45 cable with a standard RJ-45 connector on the dry "topside" end. The tether was plugged into an RJ-45 to screw terminal adapter that was bolted to a solderless breadboard that also held the Arduino Mega microcontroller. A benchtop DC power supply was plugged into the breadboard and connections were made from the Arduino and power supply to the tether screw terminal adapter. The tether, breadboard, microcontroller and power supply were identical for all the FishBots. The only difference was in the number of servos employed by each robot.

For testing the robot was submerged in the test tank and lightly shaken to remove trapped air. Its buoyancy and trim were adjusted with weights (large steel nuts and small lead fishing sinkers) attached with cable ties. The robot successfully demonstrated forward swimming motion (Fig. 5B).

C. Angelfish-Inspired Robot

A pair of students set-out to mimic a deep body fish that moves by oscillating its tailfin, they were inspired by the freshwater angelfish (*Pterophyllum scalare*) although the resulting robot resembled a discus (*Symphysodon discus*) more than an angelfish. A D-Shaped frame Tygon tubing stiffened with wire and covered with silicone rubber comprised the large laterally-compressed body of the robot (Fig. 6). An aluminum strut bisected the body and served as a mount for a single RC servo. Fixed plastic pectoral fins were attached to the strut to prevent roll. The polystyrene plastic tailfin was attached to a bracket that was screwed on to the servo horn (Fig. 6). The servo oscillated the tailfin and the drag of the body prevented it from counter rotating. The net result was a forward motion in our testing tank.

D. Subcarrangiform Fish-Inspired Robot

Subcarrangiform is a term that describes a mode of undulating body-based fish swimming in which the traveling wave includes the body and the tailfin. Three RC Servos were coupled in series using sheet metal "Servo Erector Set" brackets (Lynxmotion/RobotShop Inc., Swanton, VT) (Fig. 7A). A large "head" was constructed with aluminum channels (ServoCity). Blocks of floatation foam were inserted into the head and in each segment of the body of the robot (Fig. 7B). The Arduino was programmed to run the servos at the same frequency but with increasing phase difference and amplitude running from anterior to posterior. This generated a body undulation that successfully propelled the robot. Note that this FishBot swam at the surface, it did not submerge.

E. Cuttlefish-Inspired Robot

Cuttlefish swim by undulating laterally placed fins, this gives them great maneuverability. The two students who created the cuttlefish robot departed from the construction methods used by the other students and instead used Legos for the body and propulsion system. A crankshaft was built that oscillated 6 fin rays up and down. Each fin ray crossed the midline so the right side of the ray was 180° out of phase with the left side. A rubber sheet was stitched to the rays on either side of the robot (Fig. 8) to create the undulating fins. An RC servo was modified for continuous rotation by removing the internal potentiometer and replacing it with a fixed resistor that was ½ the value of the potentiometer. The servo signal from the Arduino then controlled the direction and the rotational speed of the servo instead of its position. The robot was suspended in the water column by attaching it to two donut floats. With an undulation running anterior to posterior the robot successfully swam in the testing tank.

F. *Jellyfish-Inspired Robot*

A team of three students set themselves the task of making a robot that moves by repeatedly contracting its body in a manner similar to a jellyfish. The dish-shaped body of the robot consisted of a wire ring to which ten wire loops were attached and the entire assembly was covered with silicone rubber. The loops were all interconnected and could rotate perpendicular to the plane of the central ring (Fig. 9A). Two servos were connected with an aluminum plate and mounted in the center of the ring and foam was attached to adjust the buoyancy. An aluminum strut connected each servo horn to loops at the opposite ends of the body. The oscillatory rotation of the servo horns and struts alternately caused the loops to bend to contract the body and then bend in the opposite way to expand the body. This generated pulses of water and caused the robot to move upward. When ballasted to sit on the bottom of the tank the robot successfully "pulsed" its way to the surface (Fig. 9B).

G. *Octopus-Inspired Robot*

Two students wanted to make a multi-armed robot inspired by an octopus, however, for propulsion they chose simultaneous contraction of the arms similar to the bell contraction of a jellyfish. They did not mimic jet propulsion commonly used by octopus and squid. Deepwater octopuses, with webbing between their arms do use this form of propulsion, however. Given the limitations of the tether they opted for 5 arms, each controlled by an RC servo. Each servo horn was connected to a plastic strut that was embedded into an arm. The 5 arms were cast as a single unit made of silicone rubber, essentially a circular 5 fingered rubber glove that was attached to the servo assembly (Fig. 10). The servos were attached to a circular foam cylinder made of stacked foam disks. The cylinder was hollowed-out on its topside and weights were added to make the robot neutrally buoyant. Attaching 5 servos to the 8 conductors of the tether cable proved to be a challenge and taught the students much about power wiring. A servo typically has three wires: power (4.8 – 7.4VDC), ground, and signal (from the microcontroller). To accommodate 5 servos five of the eight tether lines were dedicated to servo signals, two lines for ground and one line for +V. Given the relatively high current draw of each servo (> .5A), the number of servos, the thin wires of the tether (#28 AWG) and the length of the tether, power losses in the tether were substantial caused erratic behavior of the servos. Often only a subset of servos would work and they were generally jittery. This indicated that the voltage was periodically dropping below the working voltage of the servos causing them to stop or otherwise malfunction. The problem was fixed by increasing the voltage a small amount above the maximum and halving the length of the tether. Unfortunately the robot did not propel itself through the water (either vertically or horizontally) rather it simply oscillated up and down. As an educational experience, however, the octopus robot was successful in that the students engaged in a quite detailed analysis of their design and devised potential redesigns for future versions of the robot. Their experience with the power problem gave them a wonderful introduction to the challenges of power and power distribution in robotic systems.

IV. Discussion & Conclusion

Our major goals in this work were 1) to develop the tools and curriculum that will enable students to design, build and test biomimetic robots inspired by marine animals, and 2) use these FishBots as teaching tools to introduce students to concepts in fluid mechanics and inspire them to delve deeper into this important subject. We approached these goals in two steps. First, we fielded a summer undergraduate research project employing two students to build one robot. This penguin robot project taught us many lessons about implementing FishBots in the classroom including:

a. A simple biomimetic marine robot could be designed, fabricated and tested by undergraduates.

b. Selected topics in fluid mechanics can be quickly assimilated by the students to enable their immediate use in the development of their robot.

c. Low-cost components and readily available materials can be used to fabricate the robot.

d. Commonly available tools (3D printer, laser cutter, drill press, hand tools) are adequate to construct the robot.

e. Simple towing tank tests can be performed to facilitate the design process.

f. The availability of a large testing tank (Sea Grant's 3,000 gal. tank) was essential to the design process by enabling the student to rapidly test design modifications and new ideas.

g. The students were motivated by the bio-mimetic topic plus the multidisciplinary fields involved (biology, fabrication, hydrodynamics, hydrostatics, programming, electronics, towing tank experiments).

The second step was to create a class with FishBots as the focus. We ran the FishBots as a project in the *Mens et Manus* freshman seminar class at MIT. Two projects were hosted during the fall semester of 2018, a group of 14 students in the first half and a group of 15 students during the second half of the semester (6 weeks per group). The students worked individually or in small groups on their robots. For the most part these students had little knowledge of hydrodynamics and many had no robot building experience. This forced the curriculum for the FishBots project to be simpler than the tutorials given to the summer interns during the penguin project. It also precluded the use of the towing tank since learning its operation would take most if not all of the time allotted for the whole project. Despite these limitations the students successfully built biomimetic marine robots, most of which swam in our testing tank (11 out of 13 robots). Most importantly, the FishBot students were able to engage in the design/build/test iteration of engineering development just like the penguin robot students who had far more time to work on their project.

Going forward we see the FishBots idea growing in two directions. FishBots would be an interesting and inspiring hands-on experience for high school students. The FishBots seminar class could be readily modified into a high school class, or an addition to an existing high school engineering or physics class. One could also envision a FishBot competition in which teams of students build biomimetic marine robots that are judged on: design, performance and biological fidelity. At the other end of the educational spectrum FishBots could be developed into an advanced undergraduate engineering class and incorporate modeling and advanced testing techniques (towing tank, PIV, etc.). It could be either a stand-alone class or serve as the laboratory for a fluid mechanics class. Robots for more advanced FishBot class could include feedback control and the ability to interact with the environment (e.g. obstacle avoidance) thus enabling the students to integrate and synthesize their broader engineering knowledge in the creation of a complex, challenging and inspiring marine system.

ACKNOWLEDGMENT

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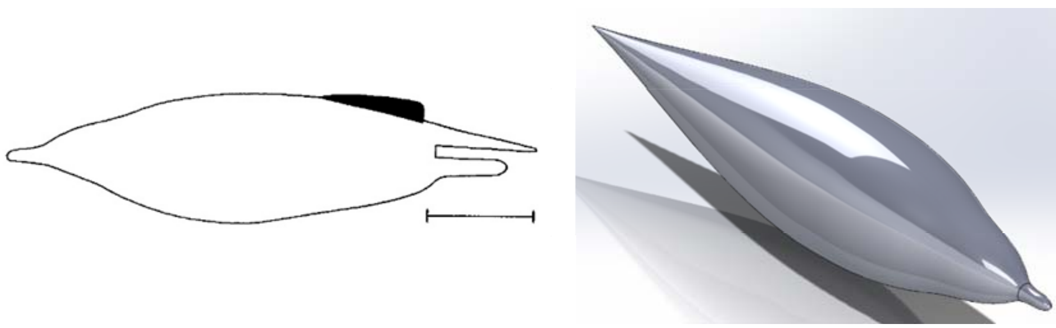

Figure 1. Drawing showing shape of Gentoo penguin body, scale bar = 150 mm (left, Fig. 3D from Ref. 1), CAD rendering of the robotic penguin body (right).

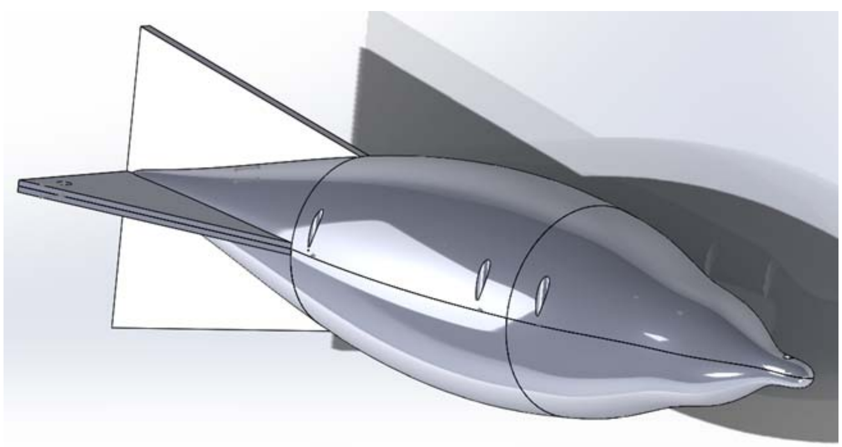

Figure 2. CAD rendering of final penguin robot body design with holes for screws and “rocket-like” rear stability fins.

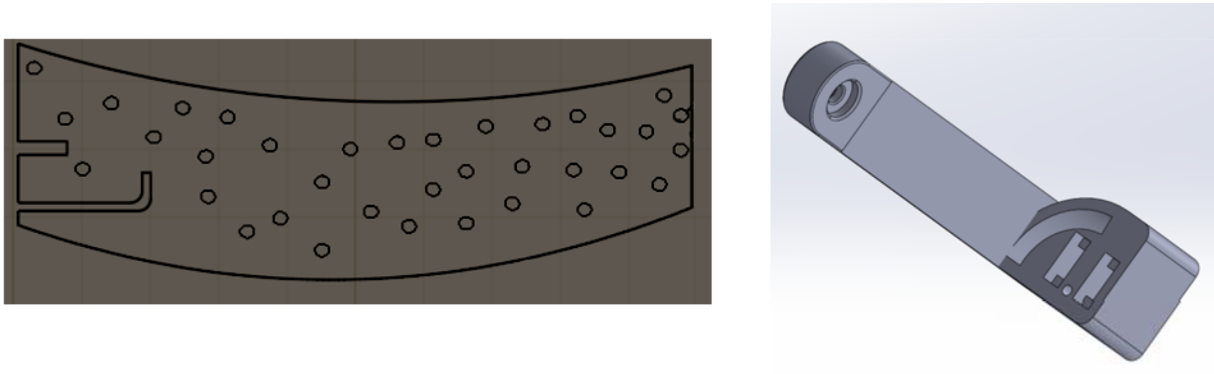

Figure 3. Penguin wing spline drawing (left), and CAD drawing of the shoulder (right).

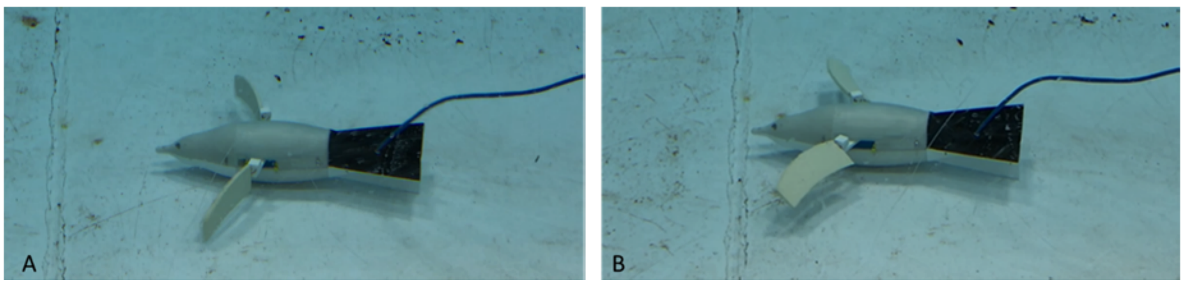

Figure 4. Penguin-Inspired Robot. A. Power stroke of the pectoral fins, B. feather (return) stroke. Length approximately 42 cm.

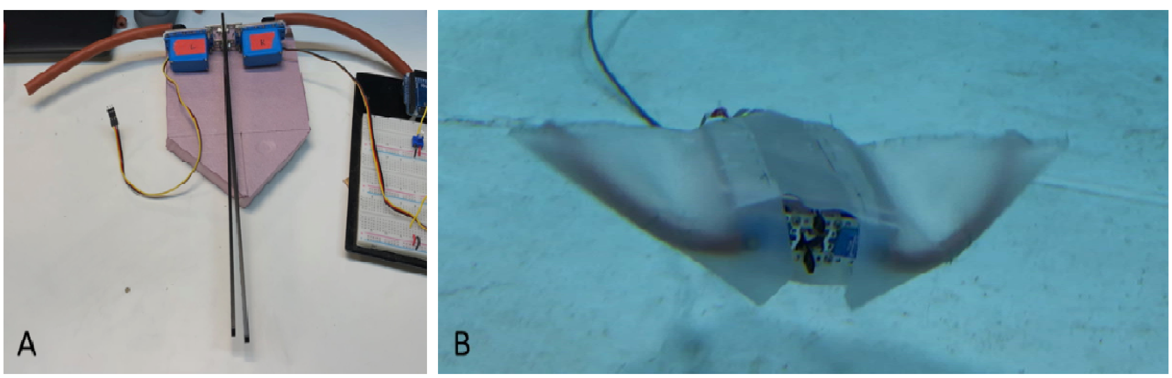

Figure 5. Manta Ray-Inspired Robot. A. Structure of the robot before addition of its flexible silicone rubber skin. B. Manta robot swimming in the Sea Grant Teaching Lab testing tank. Approximately 48 cm between tips of the pectoral fins.

Fig. 6. Angel Fish-Inspired Robot in testing tank. Body to the left, tailfin to the right, blue RC servo in the middle. Approximately 41cm long and 30cm from dorsal to ventral.

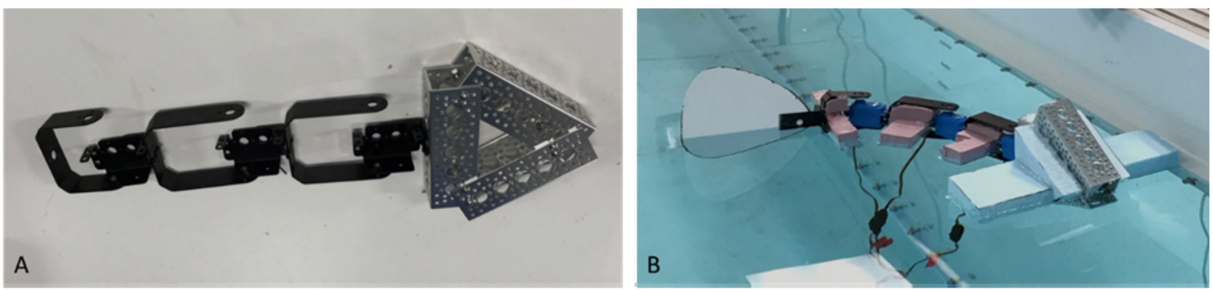

Figure 7. Subcarangiform Fish-Inspired Robot. A. Frame of robot before mounting the servos, tailfin, and buoyancy foam. B. Robot swimming on the surface of the tank. Total length is approximately 61 cm.

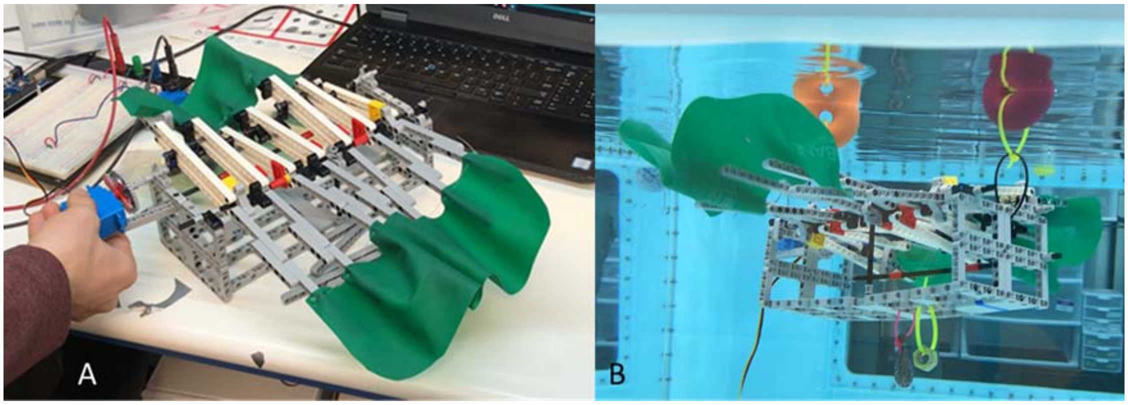

Figure 8. Cuttlefish-Inspired Robot. A. Robot on the workbench, continuously rotating RC servo held in hand. Robot is 34 cm long and 40 cm wide. B. Robot in testing tank, note donut floats on top and weights on bottom to keep it oriented in water column.

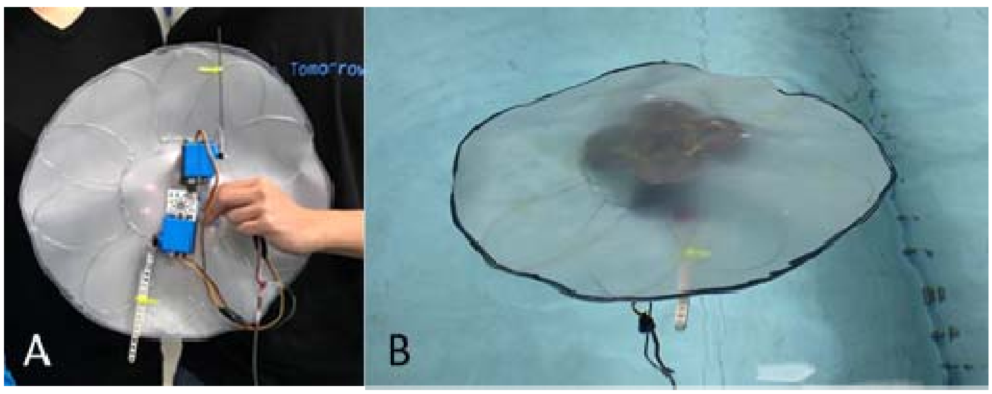

Figure 9. Jellyfish-Inspired Robot. A. Bottom view showing RC servos and wire central ring with 10 attached loops. B. Jellyfish robot in testing tank, diameter is approximately 36 cm.

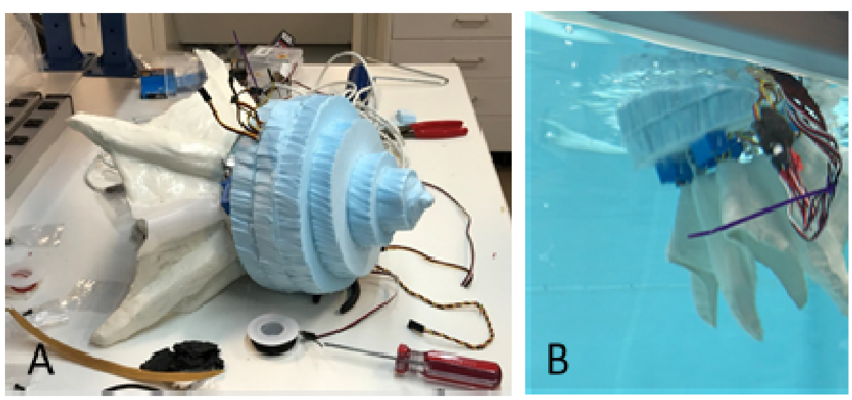

Figure 10. Octopus-Inspired Robot. A. Robot on workbench, foam body has not yet been hollowed-out for weights, diameter of foam body is 22 cm. B. Robot in testing tank, note blue RC servos between arms and foam body.