MATE 2023 Technical Documentation for *Chameleon Diver*

Hackley Aquatic Engineers (H.A.E)

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I. Introduction

A. Abstract

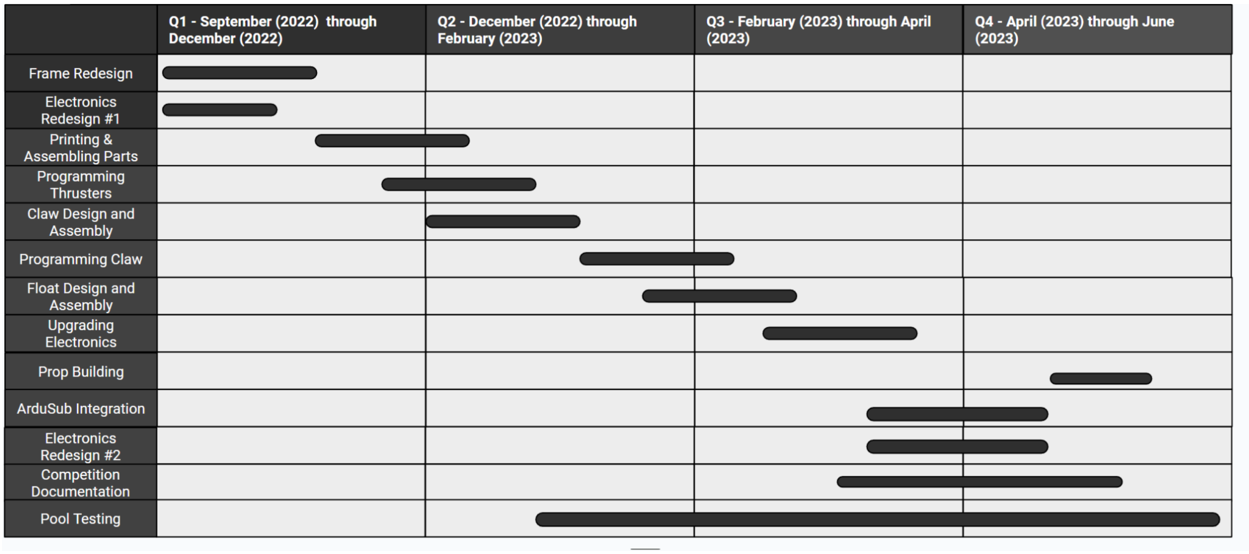
Fig. X Our robotics team at the 2023 MATE regional competition at the Massachusetts Maritime Academy. Team members Sam Nadol, Aiden McComiskey, Vihaan Dheer, Kiran Marfatia, Jaden Bayrooti, and Melissa Boviero (coordinator) are shown from left to right.

H.A.E. has been working on designing and building Underwater ROVs for seven years. Initially having close to no budget, we were faced with the challenge of developing a low-cost yet effective ROV. This forced us to think creatively and use the few resources we had at our disposal. This has carried through the years despite our budget growing as we were able to secure funding and additional members, leading to our ROV, *Chameleon Diver*. An affordable but highly modular ROV, *Chameleon Diver* has been specifically designed with the UN decade of the ocean in mind, and has the potential to quickly adapt to new situations, allowing us to better face complex tasks. Using our experience of 7 different MATE competitions, H.A.E has been able to develop unique solutions to solve the various challenges presented in the 2023 MATE missions. The *Chameleon Diver* is equipped with the necessary tools to be able to handle heavy loads and be very precise in the construction of renewable offshore energy, while having the maneuverability and speed needed to pilot through rivers and streams in all terrains. The technical documentation below describes the full capabilities and history of *Chameleon Diver.*

B. Team Schedule

To accomplish our project goals, stay on task, and work as efficiently as possible, we developed a team schedule at the start of this year that we adhered to closely (See Table 1). The company CEO helped direct the team effort, assigning tasks according to each person's specific capabilities and creating a detailed plan for the completion of *Chameleon Diver.* At the end of every worksession, we had a team debriefing session in which we discussed everything we had completed in the day, brainstormed solutions to issues, and created a list of tasks to complete. This allowed us to maintain communication between all team members, ensuring we were all on the same page and working as efficiently as possible.

Table 1 H.A.E Schedule throughout the year.



	Q1 - September (2022) through December (2022)	Q2 - December (2022) through February (2023)	Q3 - February (2023) through April (2023)	Q4 - April (2023) through June (2023)
Frame Redesign	▬			
Electronics Redesign #1	▬			
Printing & Assembling Parts	▬	▬		
Programming Thrusters	▬	▬		
Claw Design and Assembly		▬		
Programming Claw		▬	▬	
Float Design and Assembly		▬	▬	
Upgrading Electronics			▬	
Prop Building				▬
ArduSub Integration			▬	▬
Electronics Redesign #2			▬	▬
Competition Documentation			▬	▬
Pool Testing		▬	▬	▬

II. Engineering Design

A. Engineering Design Rationale

We designed our ROV's physical aspects with the primary goal of it being affordable, flexible, and intuitive. Its highly modular frame allows for many different thruster, gripper, and camera configurations. Moreover, switching between them takes only a few minutes. This allows the ROV to — almost instantly — switch from being very robust with a high payload capacity, to being smaller, faster, and more maneuverable. Having this capability on our ROV allows it to satisfy our missions and goals very well. For instance, if our robot is being used for the maintenance of marine renewable energy systems, we can convert it to the light-weight, maneuverable mode, in which it has finer claw control over small electronic components, and can fit into tighter spaces. If, on the other hand, the bot is used for a large-scale and more general survey of a bigger water body, we could use the heavy-duty operation mode, with which we can move much faster, carry heavier loads and utilize more sensors for more accurate measurement. In addition, this mode allows our robot to communicate with and deploy our custom-built float, which can autonomously complete certain surveying tasks itself.

Building such a versatile, modular, and functional robot required various design principles and decisions. These are outlined in the sections to follow, along with an overview of the mechanism by which each individual component operates. In particular, Sec. II.B describes the physical attributes and advantages of the frame design we chose. Secs. II.C and II.D discuss the choices for thrusters and claws we made, respectively, as well as our own customized additions to each of the two systems. In Sec. II.E, the buoyancy choices we made for each component of the robot are explained. Finally, Sec. II.F outlines our newly-designed float and its operational principles.

B. Vehicle Structure

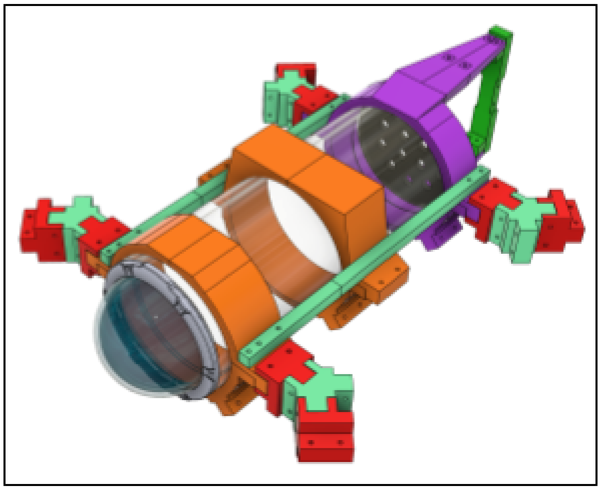


Fig. 1 A rendering of the ROV's major frame components. All pieces are 3D printed with the exception of the central tube.

Our ROV's frame adheres closely to our central themes and missions of our company, especially reproducibility, modularity, and cost-effectiveness. Firstly, the frame (see Fig. 1) — with the exception of the central acrylic tube — is entirely made out of custom-designed 3D printed parts. Each piece is printed out of either PLA or our homemade PET, then coated in a layer of XTC-3D resin finish, which protects the plastic from water corrosion and debris while filling in print striations to create an almost perfectly smooth frame surface. Although there do exist some types of filament which are more waterproof, they are very expensive in comparison to our plastics. We were then able to print the entire frame for under 100 dollars. Furthermore, using this kind of fabrication made the robot much lighter than some of the alternatives, which weighs only 7.14 kilograms with all parts mounted, permitting for easy transportation to and from potential test sites.

We custom make our PET filament using a homemade Polyformer. This is an open-source system that is built mostly of 3D printed parts that takes disposable plastic bottles and converts them to PET filament. As we only recently completed this project, we have only replaced some of the parts on *Chameleon Diver*, but are continuing to do so.

Another key feature of the frame is its modularity. It has been, and it will continue to be, our constant goal to continue improving our ROV — yet even while adding various components such as new motors, an additional claw, and a second camera, we have not needed to change the underlying structure of the frame. Our design relies on three fundamental pieces: large circular brackets (see Fig. 1, in orange), 90 degree mounting adapters (in red), and dual connectors (in green). With these three parts, we are able to mount any devices to the frame no matter how large or small. For example, after the creation of a second, custom claw, we only needed to add a circular bracket to the center of the tube. This design also allows operators to change the configuration of *Chameleon Driver* mid-mission, switching from a high-payload configuration with many thrusters and equipment to a faster and nimbler design with as few as three thrusters.

C. Propulsion

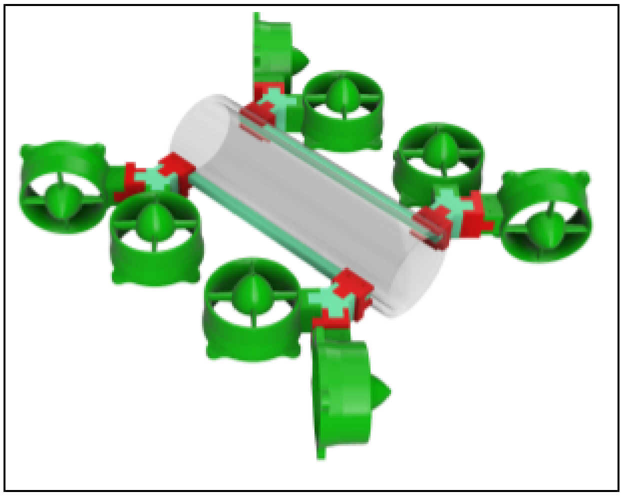


Fig. 2 A 3D rendering of the eight thrusters placed on the central tube.

We employ two kinds of thrusters on the robot: 1) Blue Robotics T200 thrusters, and 2) custom-built thrusters. While the T200s offer a large amount of thrust force, they are expensive to purchase and maintain, and they are difficult to modify. Therefore, because of our eight-thruster design, we decided to use the more powerful T200s for the horizontally placed thrusters — which are placed at a 45 degree angle to one another to allow for gyration about all three major axes — and the thrusters custom-built from Turnigy drone motors on the vertical axis, all facing upwards. In the past, we had used a six-thruster design with only two on the vertical, but we noticed that more power especially for lifting objects would be helpful. In particular, even if the robot was able to pick up an object, it would tilt forward a lot. With the additional two upwards thrusters, we are able to balance the load torque that the object imparts upon the robot, which maintains the pitch of the ROV and allows the driver to more easily maintain control. For this reason, the 4 + 4 model is a cost-effective but still-powerful compromise.

Each T200 thruster, if powered at 12V but without any current limit, produces 36.38 N of thrust force if driven in the forward direction, and 28.64 in the reverse direction. The four horizontal motors, because of their placement, allow for lateral movement in *any* spatial direction without requiring turning. Depending on the angle, though, different maximum thrust forces can be achieved (see Fig. 2). Our thruster placement also allows high-powered rotation about its center of mass — this is useful for quick movement in case the camera also needs to be turned in the direction of motion. In either the counterclockwise or clockwise direction, the thrusters can impart a maximum torque of 32.51 Nm at 12 V (which will draw approximately 70 A). Our custom thrusters made from drone motors, which are used for vertical translation, each have a maximum thrust force of 21.22 N forward and 16.40 N in the reverse direction. Based on our configuration, this allows for 65.60 N upwards and 84.88 N upwards. In addition, these motors can create a maximum torque of 10.76 Nm about the axis through the length of the tube (in either direction). Of course, using combinations of the lateral and vertical thrusters, extremely

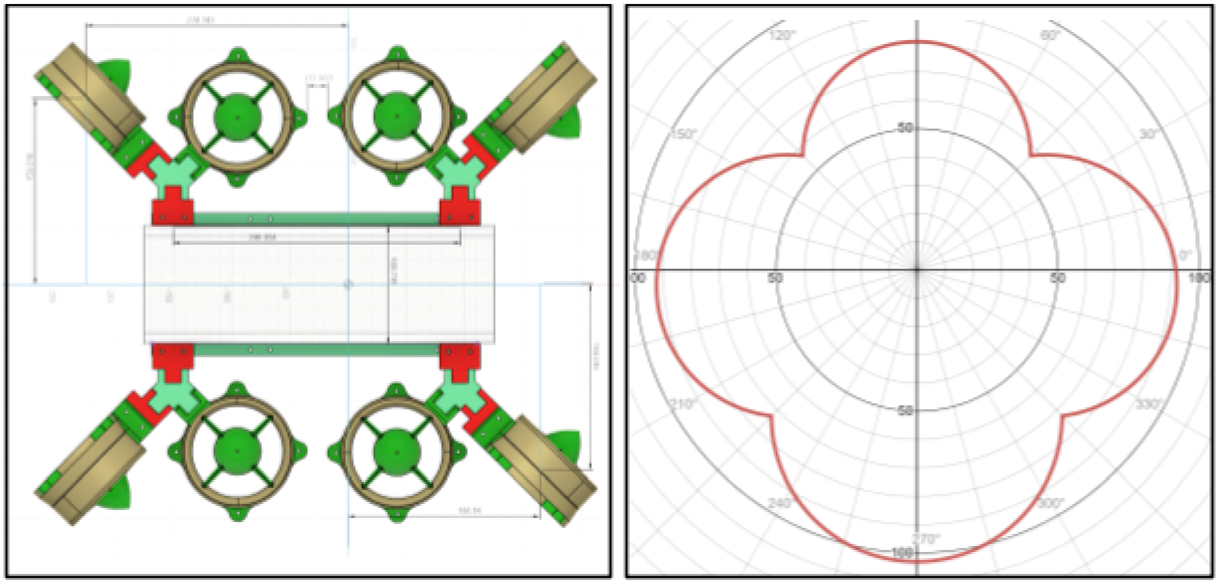


Fig. 3 A schematic diagram (left) of the robot's eight thrusters with measurements in millimeters. A radial graph showing (right) showing the maximum lateral thrust force in each direction in Newtons. The thrust force in the left and right directions is 91.97 N. The force forwards is 81.01 N, and the force backwards is 102.90 N.

complex paths can be traveled along with varying forces.

Because of our vehicle structure (see Sec. II.B), especially due to our separated 3D printed components, we are also readily able to increase or decrease the number of thrusters on the robot based on power specifications. If a lower supply voltage is given and/or a fuse of lower amperage is required, our robot can be installed with as little as three thrusters each running in a low-power operation mode. If higher power is allowed, over ten thrusters may be utilized. For instance, with little work eight thrusters could be installed in the horizontal direction and four in the vertical direction. As the central tube can always be swapped for a larger tube if there is not space left, there are few limitations as to the amount of thrusters the ROV's frame can handle.

D. Buoyancy

Neutral buoyancy is an extremely important and useful aspect of our ROV. Manufacturing our robot with a total density of exactly 1.00 g/ml gives preliminary stabilization and ensures that no power is wasted keeping the ROV either up or down. In addition, modularity being one of our key focuses, we realized that the constant removal or addition of new parts could affect the buoyancy of the robot, which would force us to redo buoyancy testing each time we upgraded it. Thus, we decided to make *each* major component on the robot neutrally buoyant on its own. Although this takes some extra work while designing new pieces, it saves us a huge amount of time, and allows us to complete oceanside part-switches. Having this ability means that our robot can handle a variety of situations without needing to return to a lab for adjustments.

Throughout our years working with the robot, we have encountered various buoyancy challenges for which we have created innovative solutions. Before using a frame with a watertight enclosure like this one, we had worked solely with standard water-filled PVC frames, which were by default positively buoyant, and thus required adding foam pieces to ensure neutral buoyancy. Once we transitioned to the tube, the robot's total density became much lower than 1 g/ml due to the air in the tube, which forced us to redesign other components to rebalance the buoyancy. The biggest tool we used to accomplish this was printing with various infill densities to have exact control over the density of the ROV. As an example, to offset the negative buoyancy of the watertight enclosure, the main frame pieces were printed at a high infill so that together, the total density was that of water. All other components, such as the custom thrusters, motor mounts, custom claw, etc. were all printed at the right infill to ensure neutral buoyancy. Finally, normally the weight of the tether would also contribute to the overall buoyancy of the robot — to prevent this, we chose a neutrally buoyant tether. In these ways, the fact that we have made each individual piece of the robot neutrally buoyant has both made sure that the robot as a whole is neutrally buoyant, and maintained the modularity of the overall design.

D. Grippers

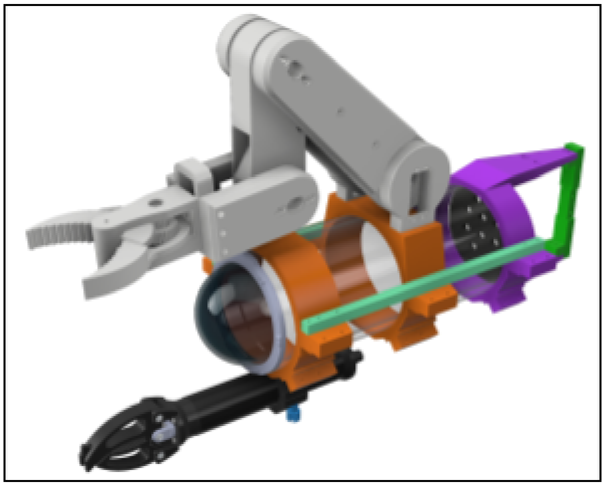


Fig. 4 A rendering of the the two grippers mounted onto the frame. The custom-made jointed claw (white) is placed on top of the robot, while the Newton Subsea Gripper (black) is mounted to the bottom.

Our robot is equipped with two distinct kinds of grippers, each with different strengths and purposes. Firstly, there is a Newton Subsea Gripper placed on the underside of the tube whose claw component is directly in the line-of-sight of the main camera. The focus of this gripper is robustness, strength, accuracy, and safety. Next, we have a custom-designed jointed claw — built only with servo motors and in-house 3D printed parts — that is designed with the opposite goal in mind: speed, maneuverability, and lessened power consumption. While each individual claw has tradeoffs and compromises, almost any task can be completed by using them in conjunction. For instance, the Subsea Gripper might be used to hold in place a nut, while the custom claw is used to fasten a screw thereto. In addition to function, using these two different gripper designs has kept our robot affordable and reproducible. Finally, because of our highly modular frame, more claws could in theory also be added without much additional work.

Firstly, our Newton Subsea gripper is perfect for tasks which require a lot of strength, precision, or delicacy. It has 124 N of grip force, which allows the robot to pick up almost anything from inside a body of water regardless of shape. In addition, as this is greater than the maximum thrust force, essentially anything that the robot can transport will be held by the Subsea Gripper. Another important feature is its precision gripping, which allows us to specify the grip width at the scale of 3 millimeters, which could be crucial if the robot needs to operate underwater electronic systems. Finally, the Subsea gripper is equipped with sensitivity control via force sensors, which allow it to detect resistance from the object it is clamping upon and stop closing in at an appropriate time. Fig. 5 shows this process in action. For gripping delicate components or even wildlife, this makes our robot a very safe option that still provides standard claw capabilities. If gripping hard/solid objects, this feature ensures that neither the gripper (nor the object) is damaged in the clamping process.

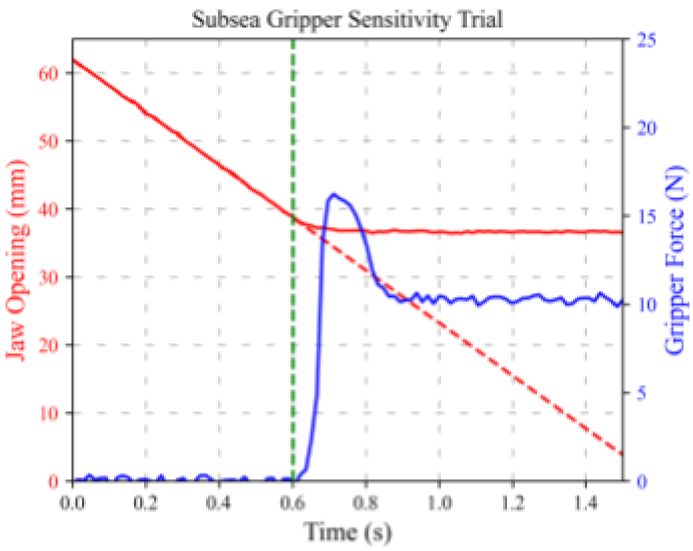


Fig. 5 An object was placed in the Newton Subsea Gripper's general claw path, and the Gripper closed upon on the object; the Jaw Opening and force exerted by the Gripper were both recorded. The object is encountered at $t = 0.6$ s, at which point the force sensor prevents the Gripper from closing further.

As mentioned, the robot is also equipped with a custom-designed, more light-weight, and more versatile claw. The custom claw is equipped with four joints, each made with underwater servos, and an additional servo is used to open and close the actual gripper, giving it 5 degrees of freedom. If necessary, we also designed a base component for the claw which would allow the entire apparatus to rotate with a stepper motor, giving it 6 degrees of freedom — although we have decided not to use it given our power limitation, it could be easily installed onto the ROV. The custom claw is very helpful for grabbing various objects in the vicinity of the robot, but comes most in handy when used in conjunction with the Newton Subsea Gripper. For instance, Fig. 6 demonstrates how the pair could be used to tighten a screw into a nut. Having this functionality is crucial for tasks such as maintenance of underwater electronics systems.

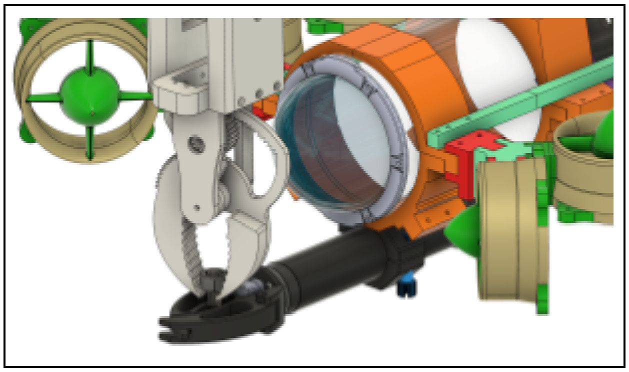


Fig. 6 A rendering of the custom claw working with the Newton Subsea Gripper to fasten a screw to a nut.

F. Fish Carrier

When designing the fish carrier, we opted for a very simple design. Essentially, just a box with a handle, the fish carrier is a very simple basket that can be easily held by either of *Chameleon Diver's* grippers. Upon reaching the desired location, the carrier has a simple door mechanism that is powered by a single servo motor, allowing the fish to be released into the proper environment and away from the thrusters of the ROV.

G. Float

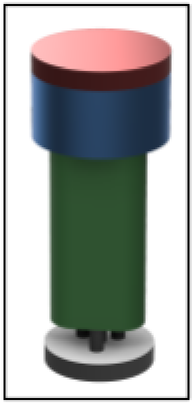


Fig. 7 A 3D rendering of the float is shown. The bottom-most piece represents metallic weights added to the float's main body to increase the weight. These ensure that the float is neutrally buoyant at the half-filled position.

Our custom-designed float complements the ROV perfectly by adding additional functionality whilst maintaining the main goals we had in mind for our robot. The float is fully 3D printed (with the exception of metallic weights and electronics), is able to autonomously sink to the bottom of a body of water and back to the surface, and finally can transmit information to the main ROV, and thus to the engineers at the surface. This is very practically useful as it allows one to take various kinds of readings and measurements at, for instance, the sea floor in a particular location, such as temperature and pH level, and even take a sample of water up to the surface. Since our design relies on buoyancy principles rather than any motors, very little power is used, and the entire apparatus — including the transport mechanism and the internal electronics — can be powered by a single 9V battery (and a small AAA battery that prevents needing to manually turn on and off the float). Finally, the float communicates wirelessly with the main robot and the base station when above the water level; because of this, the float may be used relatively far from the robot and collect data from much deeper than a tether would allow.

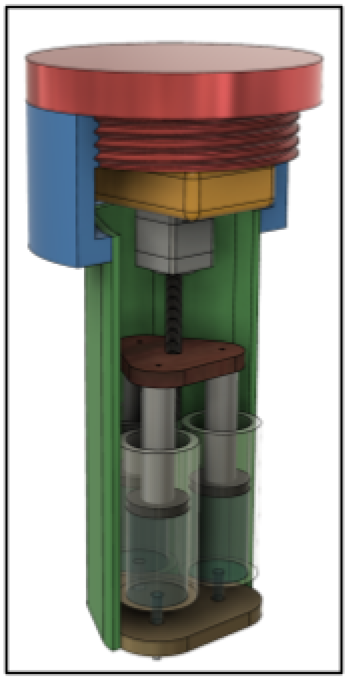


Fig. 8 A rendering of the float cut out so the internal components are visible. The threading on the float cap ensures that any parts of the float outside of the syringe bodies are completely water tight. A rubber gasket (not pictured) is also used to maintain water-tightness. A Raspberry Pi microcontroller (pictured in yellow) is used to actuate the stepper motor and communicate with the base station when above water. The motor rotates the threaded bolt, which translates the syringe plungers, either drawing water in or out.

Our float relies on the fact that objects below the density of water float, while those with densities above that of water sink. We use syringes in the float to expel/pull in water, effectively decreasing or increasing the density of the device.

We have manufactured it to be almost completely neutrally buoyant, so that this change in density is enough to induce floating or sinking, respectively. In more detail, a stepper motor is utilized to actuate water-tight plungers which either draws water into or pushes water out of the three syringes in the float (see Fig. 8). Buoyancy testing has been done when each syringe is filled halfway with water, which is taken as the starting position of the float. To sink the device, water is drawn into the remainder of the syringe volume, compressing the rest of the air in the float. This adds approximately 122 grams to the total mass of the float without changing its volume, inducing a gravitational force downwards greater than the buoyant force upwards. Once the float reaches either the ground or the desired depth, the stepper motor will be used in the opposite direction to expel water from the syringes. Up until the halfway fill point, this won't have an effect on the height of the float. After this point, though, the stepper motor will expel all of the water in the syringe, which will reduce the mass (from the neutral buoyancy point) by 122 grams, creating a strong buoyant force upwards, causing the float to return to the surface.

In addition to moving, the float also wirelessly communicates with the base station. As wireless communication while underwater is nearly impossible, we decided to limit all communication to the period when the float is above the water, and run the rest of the motion cycles on a timer. We used a Raspberry Pi with a wireless extension module (see Sec. III.D for details regarding the electronics in the float) to allow for data transfer back and forth between the base. So, for example, if a temperature reading was needed from the bottom of a water body, the technician at the base station would initiate a float sequence to descend to the sea/ocean floor, wait for a fixed time during which a few temperature samples would be recorded, and then ascend. Once the float rises to the surface, the data collected would be transferred back to the base. This entire procedure needs only a 9V battery to run, which lasts for at least 20 cycles. To conserve energy between cycles, a wireless power module is used which runs on a small AAA coin cell battery. When this module receives a signal from the base, it turns on the Raspberry Pi and other electronics systems in the float (see Sec. III.D). Because of this feature, we do not need to retrieve the float to unplug the battery each time we are finished using it.

III. Electronics Design

A. Electronics Design Rationale

Almost every component of our robot relies on an electronic system designed and programmed by our team members. In doing so, we have maintained focus on giving our ROV as much capability as possible within the power requirements and other safety limitations set by the competition. In addition, we have continued to keep in mind our goals relating to reproducibility, cost-effectiveness, and ecofriendliness. For example, almost all parts have been built out of small chips and IC boards that cost under $10 (the only more expensive system being the Pixhawk flight controller). For each component we have made the proper choices as to minimize the cost while still providing as much function as possible. For instance, in our Float's electronics system we employ an Arduino Micro — which costs under $20 — rather than using the more common Uno version to save money where possible. Because almost all of the components were designed by us, the robot could with little difficulty be recreated and the code simply be transferred. This setup is so useful because it allows for simple and cheap maintenance and upgrades as well. Finally, we have ensured that our design is as environmentally conscious as possible by choosing lower-powered, and more energy-efficient devices for each part of the electronics system. In particular, although each major mechanical component supports a large power output, we have taken care to programmatically limit power usage to a reasonable level. For these reasons, we believe that our electronics systems are optimized to strike the balance between low cost, functionality, and efficiency, providing for a better robot as a whole.

The following sections lay out exactly how we have done this along with the designs and their respective rationale for each electronic system on the robot. The most important one, the electronics on-board the ROV, will be split into two sections, namely Sec. III.B and Sec.C, in which the various components will be listed and explained, and then a more detailed description and SID will be provided. Sec. III.D will discuss the electronics on the surface and provide an additional SID for more clarity. In Sec. III.E we will explain the relevant details regarding all of the peripheral components, and in Sec. III.F our novel Float's electronic system will be explained. Throughout this discussion, both the power usage when each machine is idling and when it is at a maximum (often limited by us) will be described.

B. On-board Electronics

Each part of the electronics system on-board the robot was chosen carefully to fit our previous choices (see Sec. II) for the thrusters, claws, and other important components. To begin, the central computer running all of our on-board electronics is a Raspberry Pi 4B+. In comparison to other widely-known microcontroller boards, we found the Pi's low price, high degree of software customizability, and large number of GPIO pins available to be the right balance to run the various systems connected to the ROV. In addition, when not powering other devices, the Pi only requires about 40 mA to run, creating a low idling cost regarding power consumption. To power our eight thrusters, we have eight corresponding Electronic Speed Controllers (ESCs) specifically designed for each kind. For our four T200s, we use the Blue Robotics 30A

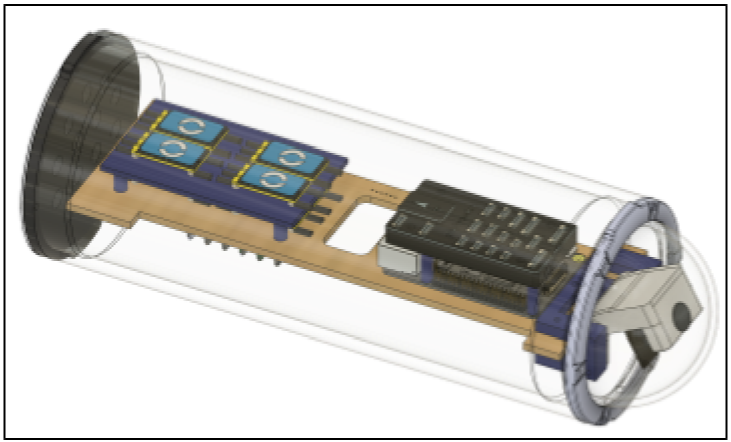


Fig. 9 A top view of the ROV's on-board major electronics systems.

ESCs running BLHeli_S firmware. For our custom motors, we use the Turnigy AE-20A Brushless ESCs. In past years, we have controlled these devices directly with the PWM output pins on the Raspberry Pi. This year though, we decided to add the Pixhawk 2.4 Flight Controller to our setup, with the main purpose of using the open-source ArduSub software. ArduSub is a control software which works with the Pixhawk's many sensors (like its gyrometer and accelerometer) to, among many other useful things, stabilize the ROV using the motors. Therefore, this year we have connected our Pi to the Pixhawk, which then controls the motors with input from ArduSub. Another advantage of using the Pixhawk is that it can control our Newton Subsea Gripper, which is thus also connected thereto. The Raspberry Pi, though, also controls some other aspects of the on-board electronics. Firstly, both cameras employed by our robot use USB and are connected to the Pi directly. Secondly, our custom claw (see Sec. II.D) relies on six servo motors, and we have a seventh servo which controls the pitch angle of the camera inside the main tube (see Fig. 9). Because of this, we decided to use the low-power DS3225mg servo controller which uses the I2C protocol to allow control of up to 16 servos while only using two microcontroller pins. To operate, the board only needs 20 mA of current, whereas the servo motors each use approximately 1A at the most. The Servo controller is itself controlled by the Raspberry Pi. Finally, the Pi is also connected by ethernet cable to a Blue Robotics Fathom-X Tether Interface, which is then connected to our tether. The details by which this allows the robot to communicate with the base station are explained in Sec. III.D.

C. Systems Integration Diagram (SID)

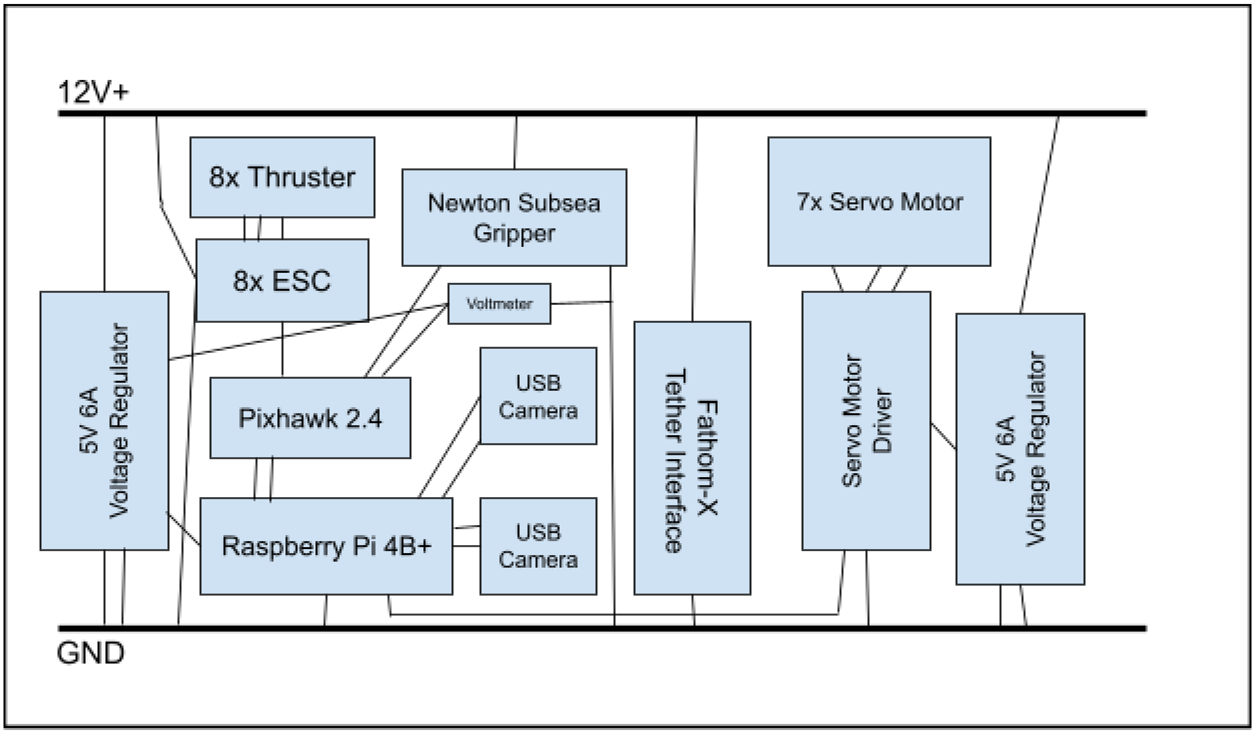


Fig. 10 A high-level SID for the ROV's on-board components.

Fig. 10 shows the major electronic components located within the tube. A high-power wire bundled together with our Fathom-X tether goes from the surface to the robot, transferring 12V power and data to the ROV, respectively. The 12V supply is connected directly to the Fathom-X Tether Interface, all eight ESCs, and two identical 5V 6A voltage regulators. One regulator is used to supply 5V power to the Raspberry Pi (which itself powers the Pixhawk and two cameras), while the other supplies voltage to the power line of the Servo controller. The Fathom-X tether interface, as discussed, is connected via ethernet to the Raspberry Pi to provide data from the surface. Finally, a voltmeter chip and a pressure-depth sensor, powered by the 5V regulator output, is connected to the Pixhawk for additional sensing capabilities.

D. Control System

In previous years, our electronics system was based on Serial communication between the robot and the control system at the surface. Unfortunately, this limited the possible electronic components and sensors we could use on the robot, because our setup allowed for a small number of ports. In addition, adding more ports would have been costly and taken away time from other research and development. Because of these factors the previous design was not scalable. To solve this challenge, in this year's robot we decided to employ ethernet communication between the surface-level electronics and the robot, which allows for an essentially unlimited amount of data to pass through our tether, using just two of our tether wires. Because of this, we were able to add more on-board components, but also allow for communication from the robot to the base station. For example, we were able to employ two cameras on the robot using this setup instead of one.

The control system for our ROV consists of a few major components: firstly, a Fathom-X Tether Interface identical to the one placed in the main electronics housing in the robot. Having this interface on either side allows us to use ethernet communication to send data back and forth from the base to the robot. Secondly, we have a standard Windows laptop running the QGroundControl software. Since the majority of our on-board systems are run with the Pixhawk flight controller, we employ the corresponding QGroundControl application on the surface which interfaces seamlessly with the Pixhawk. For instance, this makes it very programmatically easy to drive the thrusters or the Newton Subsea Gripper — we need only to connect an Xbox controller to the laptop. In addition, the QGroundControl software allows us to see both cameras installed on the robot. To control our on-board systems which *don't* use the Pixhawk, we have a separate Raspberry Pi 4B+ also connected to the Tether Interface. This Pi primarily serves to control the seven servo motors on the robot. In addition, we use this Pi to send and receive signals from our Float (see Sec. II.G and III.F). Fig. 11 shows a more in-depth

SID displaying the electronics stationed at the base.

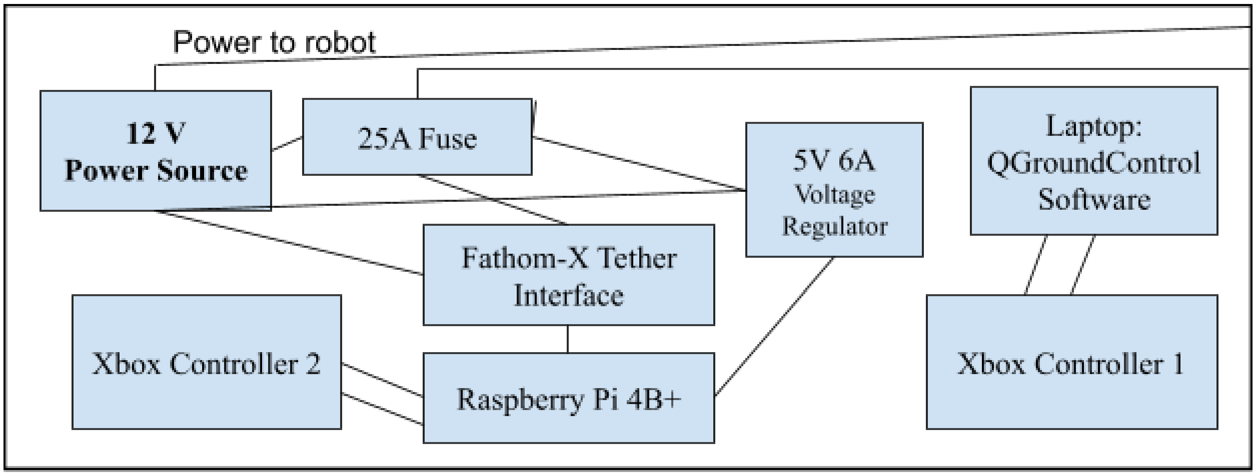


Fig. 11 A standard SID showing the electronics placed at the base station to control the various systems on the ROV.

F. Float Electronics

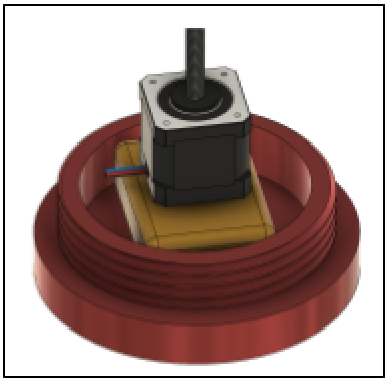


Fig. 12 A rendering of the Nema 17 45 Ncm Stepper mounting just below the electronics housing within the Float cap.

As discussed in Sec. II.G, our custom-designed float acts as a buoyancy engine by using a stepper motor to change the density of the object, while also receiving data from our control station and transmitting back various sensor readings. Our main constraints when choosing the electronic components for the float were that 1) it had to be powered independently of the robot, but with a small enough battery that fits in the housing, 2) it had to be able to send *and* receive data wirelessly to and from the base station, 3) the electronics were small enough to fit in the limited space in their closed container, and 4) the motor was powerful enough to allow the robot to descend into higher pressure regions and to do so quickly given the strict time limitation of the competition. Firstly, to achieve this last goal we chose a NEMA 17 two-phase stepper (see Fig. 12), which is a fast, high-torque motor which can run on a 9V power supply and draws about 1.9 A of current while actuating. To support this motor, we decided to use a Duracell 9V alkaline battery; in addition, the motor's relatively large size limited the size of the electronic housing (see Fig. 12, in yellow) to only 80mm x 57mm. Therefore, we decided that a normally-sized microcontroller would not fit, and instead opted for the Arduino Micro, which has dimensions 48mm x 18mm, leaving space for the other necessary components. Next, as we needed two-way communication between the Arduino and the base station, we chose a 2.4 GHz dual-direction transceiver; this firstly allows the float to receive and interpret the signal to initiate the control sequence (see Sec. II.G), and also lets it send data to the main base station such as sensor or timer readings.

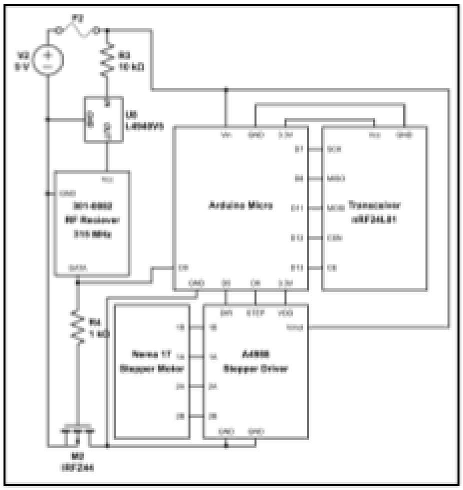


Fig. 13 A circuital schematic diagram for the electronics within the float.

Another big consideration for the Float electronics was power consumption. Firstly, the powerful Nema 17 uses almost 2A while in operation, which is very high when compared to the normal specifications of the Duracell 9V. Thus, we wanted to minimize the amount of power used by the rest of the control system such as the Arduino, transceiver, and stepper driver (see Fig. 13). But based on the necessity for water tightness, we did not want to have to open and close the Float frequently to replace the battery. Therefore, we created a unique power circuit using a MOSFET transistor and a second RF receiver module which we could use to turn our system on and off; this secondary circuit only uses about 0.5 mA, and thus can run almost indefinitely. The specifics are shown in Fig. 13. Essentially, when the Float is not being used, a small, low-power 315 MHz receiver is used to search for a signal at that frequency. Because of a 10 kOhm resistor in this circuit, almost no power is actively being used for this. Once we send the necessary signal to this receiver from a transmitter at the base, the receiver activates the MOSFET transistor, which completes the rest of the circuit, powering the motor, driver, transceiver, and the Arduino Micro. Once it is powered, a digital pin on the Arduino is used to complete the MOSFET circuit so that the control 315 MHz signal may be turned off in operation. Once we are ready to turn off the device, we send a signal through the transceiver to the Arduino to deactivate this digital pin, returning the system to its original state. This separated power setup is highly energy-efficient while still allowing us to maintain complex functionality in the float.

IV. Safety & Testing

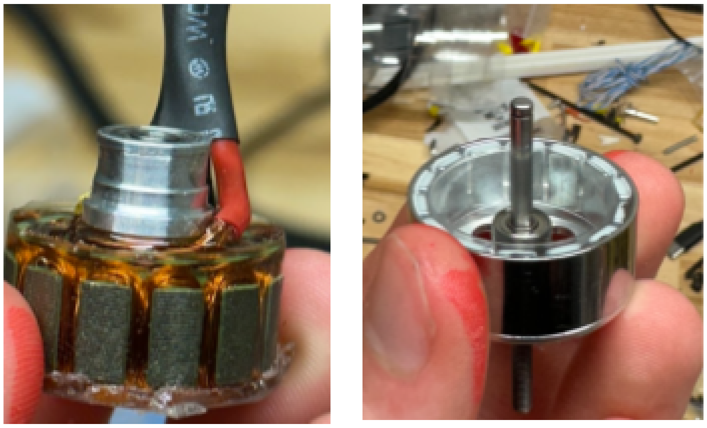


Fig. 14 **(a)** An image depicting the rotor and copper wiring of the brushless motor coated in epoxy. **(b)** The stator shown, coated in epoxy.

A. Safety Features

We deeply believe, and have made it our safety philosophy, that *Chameleon Driver* should leave its environment having harmed no person, wildlife, or equipment. In order to do this, we've developed a suite of safety features. The thrusters are shrouded and marked with a bright red color to alert people of their presence. Our grippers feature an auto-stop feature which senses when they have gripped something and automatically stop, preventing any harm. Additionally the inside of our grippers are lined with neoprene to soften them, providing cushioning as well as additional grip. We have a pressure relief valve in the primary enclosure to prevent any build up of pressure inside the ROV. Finally, we have many smaller safety features such as a handle at the back of the ROV allowing operators to easily pick up and carry *Chameleon Driver* without risking going near any potentially dangerous parts. Our four custom thrusters have been coated in epoxy in accordance with MTB-001 in order to prevent any corrosion or electrocution. Both the rotor and the stator have been coated with epoxy by wrapping a layer of plastic around each part to isolate the sections to be coated with epoxy, and then injecting the epoxy from a syringe to form a hardened shell (See Fig. 14). The float is also designed to maximize safety, featuring a pressure relief plug to prevent the float from exploding if any pressure build up develops. All electronics in both *Chameleon Diver* as well as the float are carefully waterproofed and stress relief is applied to all cables. Finally, prior to operating the ROV, we always follow our safety checklist (See Table 2).

B. Testing & Troubleshooting

We spent most of the year regularly testing our ROV and its various components. The first thing we tested was the acrylic enclosure, which we tested for waterproofing by leaving it in the pool overnight. We then attached the electronics, unpowered, and let that sit in the tube for a few hours, which did lead to some water appearing in the tube. We diagnosed where the leak was by compressing the air in the tube using the caps and looking for air bubbles. We then replaced the corresponding o-rings and added a lubricant, which solved the problem. Our next step was to get the ROV neutrally buoyant, which we did by fixing custom weight containers that attach to our frame, and allow us to compensate for any tilting. After a couple months of testing, our parts began degrading due to the water exposure. To fix this, we reprinted the pieces and coated them in XTC epoxy. We also began the switch from PLA to our homemade PET filament, which does not degrade when exposed to water. *Chameleon Diver's* initial design did not have the secondary gripper. This only came about when we realized that we weren't able to complete some of the missions (specifically the mission where we take a fluid sample from a syringe, and the mission where we have to hold a flashlight while being able to turn it on or off.

We also rigorously tested the float. After assembling the float we placed it underwater for 48 hours. This allowed us to test for any water leakage, implying an improperly coated part before putting in any of the sensitive electronics. We then installed the electronics and operated the float in the pool, and to our delight, it worked very well.

C. Safety Checklist

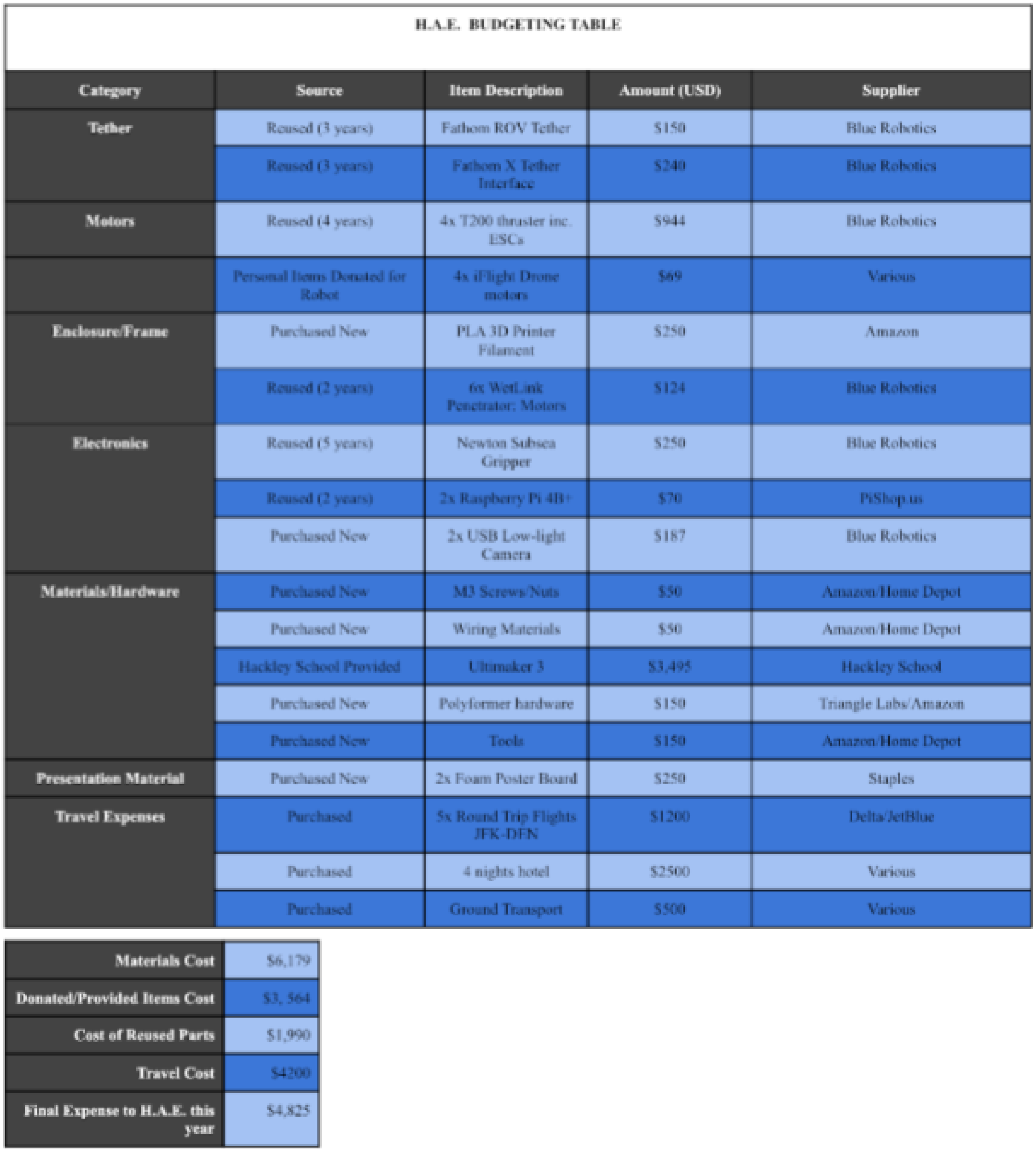
Table 2 Safety Checklist used prior to every entrance of *Chameleon Diver* into the water.

HACKLEY AQUATIC ENGINEERS SAFETY CHECKLIST		
Category	**Description**	**Completed (Y/N)**
ROV - Physical Aspects	All items attached to ROV are secure.	
	Hazardous items are identified and protection provided	
	All propellers are completely shrouded to IP-20 standards.	
	Mesh size is less than 12.5 mm	
	No sharp edges or elements of the ROV design could cause injury to personnel or damage the pool surface.	
ROV — Electrical Aspects	Tether has proper strain relief at the ROV.	
	There are no exposed motors.	
	There is no exposed copper or bare wire.	
	All wiring is securely fastened and properly sealed.	
	Any splices in tether are properly sealed.	
	Single attachment point to the power source.	
	Anderson powerpole attachment to power source.	
Surface Controls — Electrical & Physical	Properly sized inline fuse within 30 cm of power supply attachment point.	
	All wires entering and leaving the surface control station have adequate strain relief and wire abrasion protection as the wires pass through the enclosure.	
	The surface control station is built in a neat and workmanship-like manner. No loose components or unsecured wires. All electrical components are covered inside an enclosure.	
	All connectors utilized are properly rated for their application	
Pre-Operation	Operators check for people, wildlife, or equipment near the ROV	
	Tether Operator verifies no tangles	
	(When possible) Diver verifies they can clearly see ROV and that no leaks are present	

V. Budget & Cost Management

A. Budget

Table 2 The total costs of H.A.E.. We would like to thank Hackley School for their financial support.



H.A.E. BUDGETING TABLE

Category	Source	Item Description	Amount (USD)	Supplier
Tether	Reused (3 years)	Fathom ROV Tether	$150	Blue Robotics
	Reused (3 years)	Fathom X Tether Interface	$240	Blue Robotics
Motors	Reused (4 years)	4x T200 thruster inc. ESCs	$944	Blue Robotics
	Personal Items Donated for Robot	4x iFlight Drone motors	$69	Various
Enclosure/Frame	Purchased New	PLA 3D Printer Filament	$250	Amazon
	Reused (2 years)	6x WetLink Penetrator: Motors	$124	Blue Robotics
Electronics	Reused (5 years)	Newton Subsea Gripper	$250	Blue Robotics
	Reused (2 years)	2x Raspberry Pi 4B+	$70	PiShop.us
	Purchased New	2x USB Low-light Camera	$187	Blue Robotics
Materials/Hardware	Purchased New	M3 Screws/Nuts	$50	Amazon/Home Depot
	Purchased New	Wiring Materials	$50	Amazon/Home Depot
	Hackley School Provided	Ultimaker 3	$3,495	Hackley School
	Purchased New	Polyformer hardware	$150	Triangle Labs/Amazon
	Purchased New	Tools	$150	Amazon/Home Depot
Presentation Material	Purchased New	2x Foam Poster Board	$250	Staples
Travel Expenses	Purchased	5x Round Trip Flights JFK-DEN	$1200	Delta/JetBlue
	Purchased	4 nights hotel	$2500	Various
	Purchased	Ground Transport	$500	Various

Materials Cost	$6,179
Donated/Provided Items Cost	$3, 564
Cost of Reused Parts	$1,990
Travel Cost	$4200
Final Expense to H.A.E. this year	$4,825

B. Budget Management

Maintaining a low cost and keeping the robot accessible was a huge point of interest kept in mind when designing each of its components. In order to do so, we developed a budget plan early on and stuck to it, occasionally modifying it as needed. We tried to build in-house as many of our components as possible, only buying parts we believed were necessary to buy in order to have as effective an ROV as possible. This often meant using 3D printers, and more recently using the filament generated by our Polyformer.

V. Acknowledgements & Funding

A. Acknowledgements

We would like to thank our project coordinator Ms. Melissa Boviero for all of her help and advice in designing, building, and testing our robot, as well as for her support over the last seven years. We would like to thank Hackley School for its continued support for our underwater robotics club. Finally, we would like to thank our friends and family for their encouragement over the years and for coming to the competitions to support us.

B. Funding

We would like to thank the Hackley Upper School for funding our project throughout the last four years

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