Unmanned Water Testing Vehicle

Final Report

IGEN 230

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Introduction

Our student team was formed to tackle challenges associated with ecological protection by developing tools to monitor the quality of bodies of water in a more convenient and accessible way. After discussing various applications that require water monitoring solutions, it was decided that an ideal candidate was mining tailings ponds. This allowed us to define a smaller set of primary stakeholders that we could consult with during our project's design and testing phases. Current standards have mines taking real-time sensor samples at a single location with varying depths (T. Tedford, personal communication, February 14, 2022). We envision that a finished product would reduce the time and cost of water monitoring, allowing for more frequent testing, and allowing potential problems to be detected and corrected quickly. We also intend to deliver a product that will improve the safety of mine employees that conduct water testing by eliminating the need for personnel to board watercraft themselves. A broader audience of stakeholders could also be affected by the project, such as the oilsands industry or scientific groups that conduct water quality assessments. We expect the project's impact to be similar across all these stakeholder groups.

We determined that to fulfill stakeholder needs, a watercraft must be able to vary the depth of a multi-use sensor at a single location on the tailings pond to collect and store real-time data. However, we will not include the sensor in our project due to budgetary constraints but will allow interested stakeholders to implement their own. Therefore, we determined a list of requirements and objectives that a watercraft would have to fulfill to produce desirable results. These are as follows:

Requirements

- The watercraft must be able to withstand wave patterns of tailing ponds (including shallow waves and large waves near the shore)
- The watercraft must be durable and be able to sustain impacts while traveling at it's cruising speed
- The watercraft must have sufficient battery power and speed to travel 10 kilometers in 45 minutes
- The watercraft must be capable of operation in a wide range of potential environmental conditions, including in fresh and brackish waters, in winds of up to Beaufort 4 (~16 knots), and in temperatures ranging from 1 to 30 degrees celsius
- The watercraft must be able to be deployed and operated by a single person
- The watercraft must be able to lower a package of sensors to a user-specified depth, with a maximum depth of 50 meters
- The watercraft must be capable of storing sensor readings with the time, depth and location of each reading

Design and Implementation

Our design consists of a fibreglass-hulled catamaran, with dual electrically-driven propellers and dual rudders situated aft of each hull. A wooden deck supports radio and testing equipment on its surface while protecting navigation hardware and batteries below the deck. For water data collection at depth, a winch system can lower a sensor array from the deck level to a depth of 50 meters directly below the boat.

Hull

The design of the hull, decided on through the use of WDMs (Refer to *Appendix A: Table I*), is a catamaran. The design required for the application is a cruising catamaran that can sustain a large load. We ended up with a model 80 cm long, 56 cm wide, and 21 cm tall (seen in figure 1). This design was mainly chosen because we are required to carry a heavy load, and we only need to perform basic navigation.

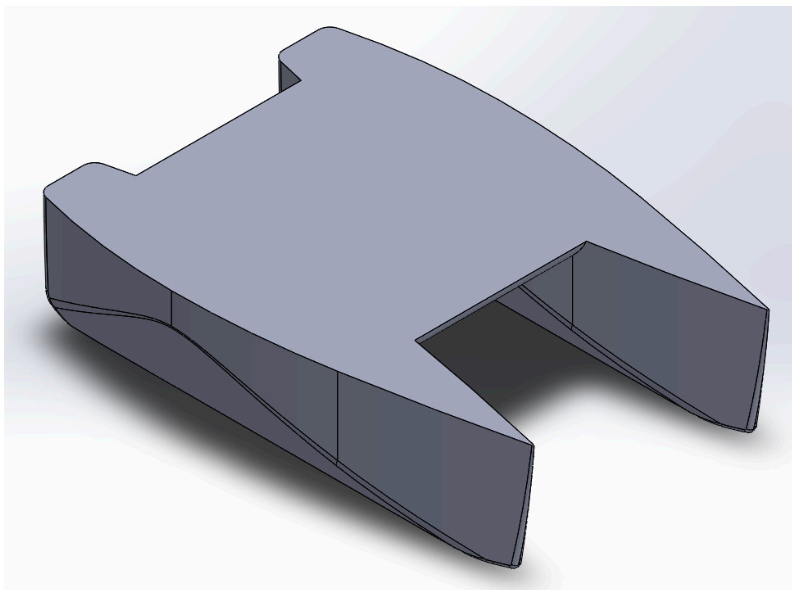


Figure 1. 3D model of catamaran hull V2

After an iteration of the first version, we arrived at V2, the final design for the boat (figure 2). This version had larger hulls and thus, could carry more weight. To fabricate the hulls, the team initially decided sheet metal was the best material to reduce cost and increase performance, specifically in the area of impact resistance. However, we were made aware that we had the resources at IGEN to fabricate the hull out of fibreglass. The material is strong, lightweight, and durable. More importantly, using fibreglass reduces the complexity of fabrication significantly. The team quickly changed our plan and we started researching how to fabricate fibreglass.

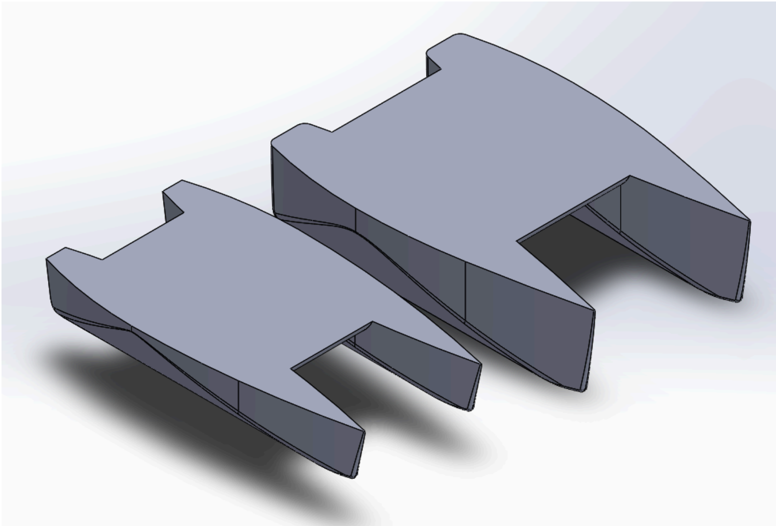


Figure 2. CAD of V1 (left) and V2 (right) side by side

After research and consultation with Marvin (IGEN 3D printing manager) as well as Zach (IGEN shop manager) we decided to 3D print a negative mould of a single hull used for fabrication. This mould would be used twice to create the two hulls of the catamaran. Due to the size of a single hull, we had to print seven different pieces and attach them with tape and hot glue before fabrication (Figure 3).

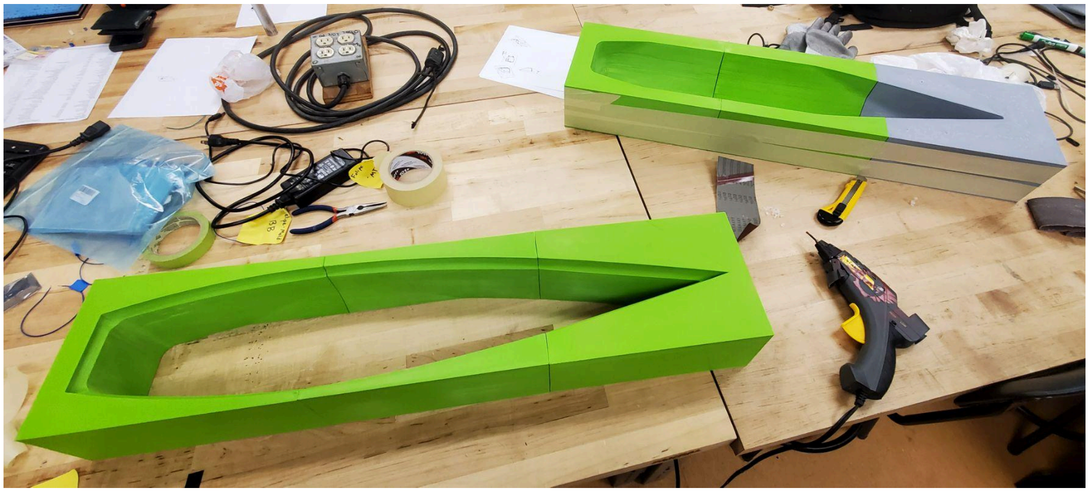


Figure 3: Negative mould of a single hull prior to fabrication of the hulls.

Considering our team's experience with fibreglass, both hulls came out in very good shape. We had issues with the plastic we used as mould release as it caused us trouble down the line, however, overall, the fabrication was successful. Soon after, we filled and sanded both hulls 6-8 times before we were content with the shape and smoothness of the surface. In the meantime, the deck was sanded to fit. Finally, after patching leaks and spray painting the hulls, the hardware was installed.

Winch System for Water Data Collection

The winch system consists of the following components:

1) Stepper motor
2) A4988 driver module
3) PVC arm
4) Pulleys mounted by paracord
5) 3D printed spool
6) Vertical support and bearings
7) Sensor guide
8) Sensor - replaced by a model sensor in prototype

A microcontroller and motor driver are used to control the stepper motor, which then control the direction the spool spins and whether the probe attached to the high-strength fishing line is extended downwards or retracted to a maximum depth of 50m. PVC conduit was used to build an arm with two pulleys. Refer to *Appendix C: Diagram I* for the diagram of the design.

A shaft was needed to mechanically link the stepper motor and the spool so that the spool could spin. First, a shaft was connected to the stepper using a coupler, and then the spool was glued into place. The shaft coupler was used to connect the 5mm stepper motor shaft to an 8mm diameter steel rod because it would provide tolerance for shaft misalignment and introduce mechanical flexibility. This would lower the likelihood of uneven wear on the bearing from equipment vibration or other mechanical issues during the building process.

The stepper is controlled using the Arduino linked to the Raspberry Pi and an A4988 stepper driver. The potentiometer on the A4988 driver was adjusted to limit the current going through to the specifications of our stepper. The A4988 driver was chosen because it was available at no cost and provided sufficient power and stepping resolution for our needs. The stepper and its power and data leads were soldered onto a project board to ensure the reliability of the connections. Additionally, a capacitor was put between the positive and negative terminals of the power supply to prevent voltage spikes.

A bearing with a 3D printed insert was used on the other side of the shaft. Refer to *Appendix D: Diagram II* for the diagram of the design. The sensor probe is attached to the high-strength fishing line, wrapped around and attached to the spool. This winch system is designed for the RBRduo^3 & RBRconcerto^3. A fake sensor was made out of steel tubing and cut to the size of the RBRduo^3. To prevent the sensor from swinging, the sensor was set to sit partially lifted through the hole in the deck. To ensure the sensor would not get caught on the bottom of the deck when pulled up, a conical sensor guide was 3D printed for the top of the sensor.

Navigation and Propulsion

Our watercraft is propelled by two water-cooled 2950Kv outrunner brushless motors. These motors interface to separate electronic speed controllers, which are connected to a flight controller. Before our upgrades, each motor was attached to a two-bladed nylon 1.5cm propeller. According to our calculations, the current propellers were sufficient to meet our speed and thrust requirements, however, we upgraded to three-bladed 3.0cm propellers to improve performance. Refer to *Appendix E* for details of our calculations. These new propellers provide increased torque and power from starting to low speeds. This is at the cost of a reduced top speed as the larger, three-bladed propeller will produce more drag in the water. Given our research on water quality testing applications, we believe that this is an appropriate tradeoff.

In addition to differential thrust produced by the propellers, twin servo-actuated rudders provide additional attitude control. The rudders were printed with tough resin to allow for higher toughness and impact resistance. Since the rudders deflect water flow, this material was used because of its great load-bearing ability compared to PLA. As with the motors, these are connected and controlled through the flight controller.

The steering and propulsion system is powered by two 1300mAh 11.1V LiPO batteries. We estimate that these batteries will provide 10-15 minutes of charge under typical use (RCExplained, 2020). This estimate decreases to roughly 4 minutes at sustained open-throttle. Our hull design provides sufficient weight-bearing capacity for additional or higher capacity batteries to be added, but due to budget constraints, they have not been included in this iteration.

The navigation system consists of a flight controller and associated sensors that receive signals from a Raspberry Pi (Pi). This Raspberry Pi is connected to the operator on-shore via a 2.4 GHz telemetry connection. This allows the operator to view live telemetry data, change the mission plan while a mission is in progress, or take manual control of the watercraft. GPS and compass functionality has been implemented to allow the flight controller to autonomously move to a testing location and location stamp readings. Using the GPS and flight controller IMU data, the watercraft can maintain positional accuracy within a 1.5-meter radius of user-defined waypoints. In a future revision of the design, we anticipate the addition of a depth-finding sensor to ensure that the sensor is not lowered in shallow water or when an obstruction is present. Due to the cost of these sensors, we will not be able to include one in this iteration of the design. A block diagram of all of the control hardware used in the watercraft can be found in *Appendix F.*

The flight controller firmware is ArduPilot Rover, an open-source project that interprets telemetry data to make real-time navigation decisions. It uses a 3 level hierarchical control system to determine the correct settings for the propulsion and steering system. The L1 controller interprets sensor data to determine the desired heading, and the L2 and L3 controllers make specific decisions about the speed and attitude of the motors and rudders.

The Raspberry Pi runs custom-written software that enables the networked link to the ground computer and remote access software and MAVProxy. This open-source telemetry handling tool logs and forwards mission data. Our Arduino, connected to the Pi, runs a custom-written script that handles the raising and lowering of the winch. This software enables remote operation and contains safety checks to ensure that the winch is not overrun or deployed in unsafe conditions and prevents stalls. The Arduino was chosen due to its ability to produce accurate PWM signals, a capability that the Pi lacks. Finally, our ground computer (a Windows 10 laptop) runs remote viewing software and Mission Planner, an open-source project. Mission Planner provides a real-time interactive display of all available telemetry data. It is used to create and upload detailed mission maps, coordinate autonomous tasks, calibrate sensors, and take manual control of the boat with a joystick.

Validation and Verification

Hull Validation

During the design process, we used buoyancy calculations (Refer to *Appendix C*) based on the estimated weight of all the components combined in order to validate that the design fit our requirements. This process assured that the hulls were able to perform as required and could also bear the weight of the fully assembled boat.

Propulsion Validation

After we consulted with UBC Civil Engineering Research Associate Ted Tedford, we determined that given the oval-like, narrow shape of tailings ponds, and relatively small average size of $10km^2$, a specification goal of travelling 10 kilometres within 45 mins would be adequate to meet stakeholder needs. Varying weather conditions are another factor we considered, as remote mine sites in British Columbia often have unpredictable weather. Because of this, designing a robust propulsion system to mitigate any risk of damage or performance failure during these conditions was an important requirement to satisfy stakeholder desires. Additionally, considering the remote, often solo operation of water quality testing, we decided upon a requirement to build a craft that can be easily operated and transported by a single user.

Winch Validation

Our consultation with Ted Tedford, a UBC Civil Engineering Research Associate, told us that mines are looking for depth-specific testing of temperature, salinity, and dissolved O_2. From this, we determined the most effective sensor use would be the RBRduo³ or RBRconcerto³. This is due to data being saved in the sensor unit, removing the need for a data cable, automatic calibration and its onboard clock and depth measurement functionality. It is also modular, allowing for tests of conductivity, fluorescence, ORP, PAR, pH, transmissance, turbidity, and other parameters (RBR, n.d.).

Hull Verification

To verify that the hull's buoyancy calculations were correct, a 3D printed scaled-down model of the hull was tested. Using Solidworks, we calculated the depth at which the model sat in the water, respective to the load it supported. The model was then placed in a bathtub with the respective load on top. When stable, it was spray-painted so that once out of the water, the waterline was visible, and the depth could be calculated. This proof of concept (Refer to *Appendix B: Screenshot 2*) was successful as the model carried the load almost identically to the prediction from Solidworks. This verification process assured that the calculations previously conducted were correct and the hull would perform to the project's requirements. Similarly, to guarantee the reliability, once both individual hulls were fiberglassed, filled, and sanded, we did a variety of leak checks. During this process, we patched major holes with a makeshift mix of fibreglass and epoxy and used more filler for minor ones, verifying the hull’s life-long performance.

Propulsion/Electrical System Verification

To test that our watercraft met our initial propulsion-related requirements, we ran a series of tests in the UBC Fountain and the lakes at Jericho Beach. Because of the waves created by the large jets in the fountain, we could test and note our craft's handling and propulsion systems in varying environmental conditions. We noted that the boat could operate at sufficient speed and with acceptable turning ability despite the rough waters. During our nighttime test at Jericho Beach, our craft was faced with moderate rainfall in dark conditions. Here, we tested the autonomous function of our craft. This test was successful as the boat could navigate itself to pre-programmed waypoints in less than ideal weather conditions.

Fig. 4: Float and electronics test at UBC fountain

Although, due to budget constraints, we could not meet our minimum distance in a given time requirement. However, if we could obtain multiple larger batteries, we believe that this requirement can be met, given the excess weight capacity of the watercraft. Our current batteries can achieve 10 minutes of run-time at an average speed of 11 km/h. This means our craft can travel roughly 1.8 kilometres before needing a recharge or battery swap. If we upgrade our 1300mAh batteries to 5000mAh units, we should expect about 30 minutes of run time and a travel distance of 7.5 kilometres. After a battery swap, the craft should easily reach an additional 2.5 kilometres within the remaining 15 minutes to meet our requirement.

Our tests at the UBC Fountain and Jericho Beach included frequent transportation of our vessel. The craft can be relatively easily placed into a vehicle and driven to the site by a single user. The rudders and propellers have been strategically placed higher up on the back of the hulls to mitigate the risk of damage during transport. We tested placing down and picking up the watercraft numerous times, with little to no damage to our propulsion system. The unit can safely be lifted by a single individual.

Winch Verification

We ran several dry tests with a metal replica of the RBRduo^3 & RBRconcerto^3 the same size, 35.5cm by 6.325cm, though slightly under the specified weight. These tests verified that the sensor could be lowered to a specific depth but could not be brought back up. After reducing the size of the metal sensor, we verified that the sensor could be lowered and raised. This means that we had insufficient amperage going to the stepper motor for the winch. If we were able to get a better power source, we believe this problem would be solved.

Conclusions and Future Work

Our team has been able to successfully build a watercraft designed for water testing in copper mine tailing ponds. Our final design can withstand wave patterns of tailing ponds, sustain impacts, has sufficient battery power and speed to travel 10 kilometres in 45, can be deployed and operated by a single person, and can lower a package of sensors to a user-specified depth, with a maximum depth of 50 meters. Although these requirements have been met, several improvements can be made to improve usability and functionality.

Firstly, the hull fabrication process could be improved significantly. With no previous experience in fibreglassing, we made a number of mistakes when making the hulls. Many of them can easily be corrected if we repeat the process. Primarily, with a larger budget, we could've made the mould out of high-density polyurethane foam, as opposed to the plastic that was used to form the prototype's hulls. Furthermore, we'd use better mould releasing techniques and avoid air bubbles in the resin and imperfections in the fibreglass. Additionally, we could prioritize sealing leaks after installing the motors, particularly through the propellor shaft.

While the prototype's hull performance was satisfactory, future iterations could be improved by placing additional focus on the boat's hydrodynamics. This could reduce drag, thus increasing the efficiency of the boat and the operational time on the water.

Due to insufficient amperage to the stepper, the winch could not lift the model sensor built to the weight of the recommended sensor unit without being connected to a bench power supply. However, the winch lowered and raised a reduced-mass payload while on battery power. With a bigger budget, we would get a better power source. Another option also includes implementing a design with reduction gearing. Another improvement aspect for the winch is designing a mechanism that evenly distributes the fishing line along with the spool to reduce the risk of tangling or uneven tension along the line. These issues could ultimately lead to the drum being unable to freely wheel because the winch line is pinched under the upper coils. A design with a traverse spool/self-reversing screw is a suitable option and would allow for level winding to mitigate these problems. Currently, our design has no clutch implemented into the stepper, and if it lost power, it would drop the sensor. This would be beneficial to implement in future designs as an added safety mechanism.

Due to budgetary constraints, our team could not test the watercraft with a real sensor. We would like to obtain an RBRduo^3 or RBRconcerto^3 for testing for future work. Similarly, with increased funding, we would aim to implement an improved flight controller and RTK GPS and a depth sounder to improve the autonomous functionality of the craft and increase the amount and accuracy of data provided to the user. The use of a sonar depth sounder could also allow for automated topographical mappings of the bottom of tailings ponds. We would also obtain additional batteries to improve the run time of the boat. The team was able to find a camera for the watercraft, but we lacked time to mount it to the deck and test the associated software. With additional time, we could allow the user to view a camera feed off the craft's bow and could implement some form of automated object avoidance. Our current electronic hardware is compatible with all of the above equipment. Our software has been designed so that only minor modifications would be needed to interface with the added components. Finally, when looking at the use of our project outside of mine applications, we would develop a water collection system to work with the real-time sensor to increase functionality.

References

RCExplained. (2020, June 30). *Selecting a Brushless Motor, ESC, LiPo Battery and Prop for an RC Boat* [Video]. YouTube. https://www.youtube.com/watch?v=2tuvoAfPMYU&list=LL&index=2&t=1277s&ab_channel=RCexplainedF

RBR. (2021, November 5). *RBRvirtuoso³ and RBRduo³ | Ocean Sensor Systems*. https://rbr-global.com/products/standard-loggers/rbrvirtuoso-rbrduo

Appendices

Appendix A: WDMs

Table I. Weighted Decision Matrix for fibreglass hull design

Criteria	Weight	Single hull	Catamaran	Semi-submerged
Lightweight	3%	5	4	6
Handling characteristics	26%	8	5	4[1]
Performance in adverse conditions[2]	42%	3.5	6.5	6.5[3]
Durability[4]	17%	3.5	4	2[5]
Ease of maintenance	4%	5.5	5	7
Cost	9%	5	4	7.75[6]
Total	100%	491	534	520

Total for each design is multiplied by 100 for ease of comparison.

Note: Due to the expected difficulty in manufacturing, sheet metal was screened out in favour of fibreglass.

[1] The semi-submerged design is the least compact out of all designs, thus its turn speed and acceleration is the lowest.
[2] Including various waveforms, weather, etc.
[3] Although the semi-submerged hull is more difficult to control, much force is required to destabilize it.
[4] Including resistance to corrosion and tolerance to temperature change.
[5] Assuming it is made of foam, the submerged part which carries hardware and samples is prone to hitting the bottom of the pond in shallower parts.
[6] Assuming the semi-submerged hull is made of foam, it will cost the least out of all designs.

Table II. Weighted Decision Matrix for Propulsion Design

Assuming the hull is a catamaran (highest score from previous WDM):

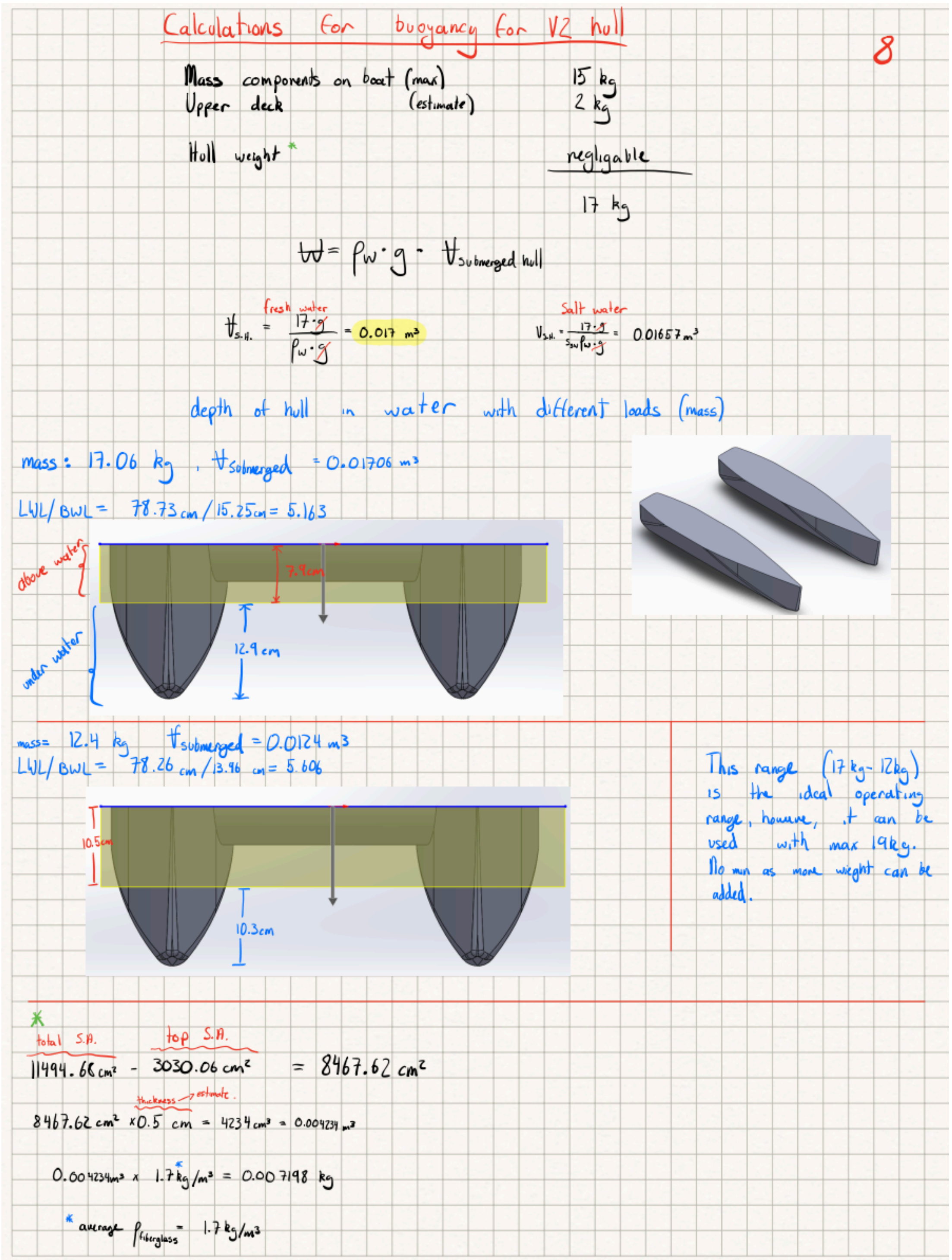
Criteria	Weight	Single propeller with dual rudder	Double propeller with single rudder	Double propeller with double rudder	Fan propeller
Handling	34%	5[7]	7	7	3.5[8]
Power draw	13%	8	6[9]	6.5[10]	5[11]
Durability	5%	6	6[12]	5[13]	8[14]
Reliability (fault tolerance)	36%	3[15]	5	6	3
Cooling	9%	6[16]	4	4	9[17]
Cost	3%	6[18]	4	3	7
Total	100%	483	573	607	434

Total for each design is multiplied by 100 for ease of comparison.

[7] A single propeller increases the difficulty in handling the boat, especially a catamaran.
[8] Long blades of the fan can be affected by wind.
[9] This is scored lower compared to the single propeller since sufficient power must be delivered to both propellers for stability and speed.
[10] The extra rudder decreases power draw by a small amount.
[11] Since the fan is above water, significant power is required to propel the watercraft through water.
[12] If the single rudder malfunctions, steering will be lost.
[13] If one of the propellers breaks down, steering and propulsion can be maintained. However, if one of the rudders is stuck at turning position, all control of the boat will be lost.
[14] Since the fan is above water, there will be no corrosion, collision, or fouling.
[15] Propulsion is dependent on one element (low redundancy leads to low reliability). Thus, the two designs with a single propeller are scored the lowest, and the double propeller with double rudders is scored the highest.
[16] A single propeller needs one cooling system, while two propellers require more cooling.
[17] No cooling is required since the fan is in air.
[18] The single propeller designs will cost less than the double propeller designs. Since the fan does not require cooling, it will score higher, despite a higher power draw. The single rudder will cost less than the double rudder system.

Appendix B: Hull - Buoyancy calculations and verification

Screenshot 1: Buoyancy calculations hull V2



Screenshot 2: Buoyancy Verification

Buoyancy Verification with scale model

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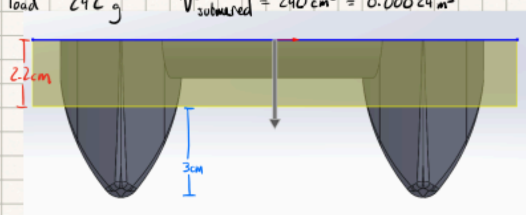
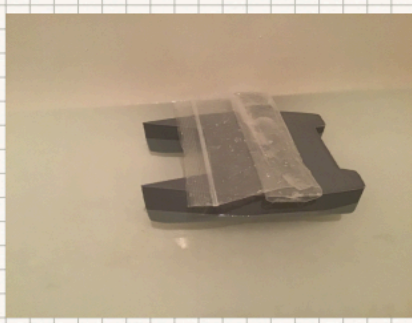
Testing to see whether the calculations on buoyancy are accurate is important in order to prove that the boat would handle the load we planned to put on it. To do this I 3d printed a model scaled down to 0.25 of the original. The model itself weighs 182 grams. Adding 60 ml (1/4 cup) of water in a plastic bag will make the total weight 242 grams, equivalent to 15.5 kg on the real size model. To see if it's accurate, on the cad model of the scaled down version I'll calculate theoretical depth of hull and then measure what depth it went to. If it's close enough then we can safely assume the real hull will bare the weight that was calculated above in page 8. Since the models weight is distributed unevenly between the bow and the stern, not all points will be submerged equally. That's why the reading will be taken at the midpoint of the boat

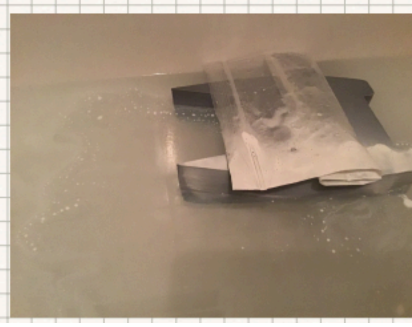
load 242 g $\forall_{submerged} = 240\ cm^3 = 0.00024\ m^3$

$* \ 0.242\ kg \times 4^3 = 15.488\ kg$



To measure the depth I spray painted the boat while in the water. Once out of the water I could measure up to the point where the paint started.





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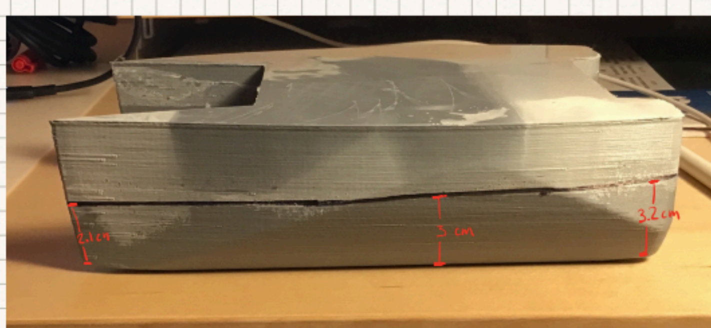


The depth of the boat was almost identical through the length of the hull. Despite thinking it would be much deeper at the back, it stayed pretty even thoughout. This was especially due to the back and front having a lip curving up (it can be seen on the side view of the hull V3 on page 7). This helps us comfortably say that the real sized hull will support the load that has been calculated in page 8.

Sources for equations:

Lee, J. L. (2019). *CIVL 215 Buoyancy* [Slides]. Canvas. https://canvas.ubc.ca/courses/82947/files/19208213?module_item_id=4201981fL

Appendix C: Prototypes and Sketches

Diagram I: Winch System for Data Collection

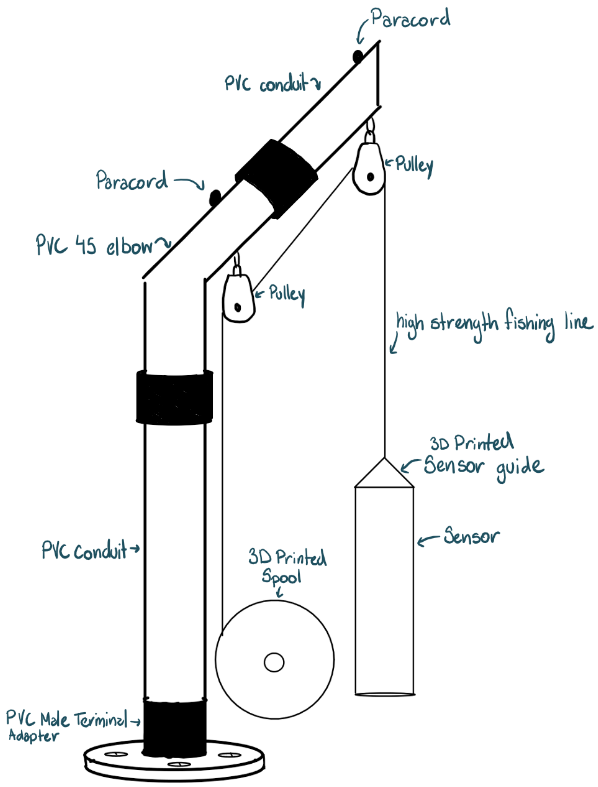
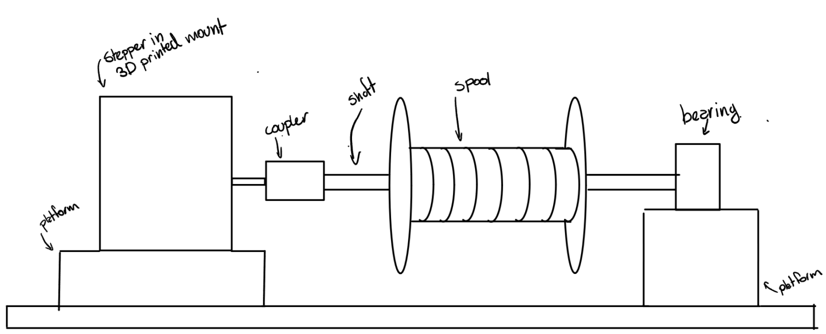


Diagram II: Spool and stepper design for water data collection



Appendix D: Project Budget

Budget	Item Name	Price	Count	Final Price
Propulsion/Navigation	Motors	-	2	-
	ESCs	-	2	-
	Rudder Servos	-	2	-
	Rudder Blades	-	2	-
	Flight Controller	76 USD	1	105.54
	GPS Module	34 USD	1	49.67
	Batteries	-	2	-
	Battery Charger	15.99	1	16.79
	Mission Computer	-	1	-
	SD Card	15.99	1 x 64 GB	20.25
Hull	Hull Mold	-	1	-
	Fiberglassing	-	N/A	-
	Silicone	-	N/A	-
	Decking (Wood)	-	1 80x56 cm	-
	Metal Sheeting	-	1 50x30 cm	-
Water Collection/Testing	Stepper Motor	-	1	-
	Bolts	-	Assorted	-
	Arduino	-	1	-

Budget	Item Name	Price	Count	Final Price
	Stepper Driver	-	1	-
	Winch Bearing	-	1	-
	Winch Carriage	-	1	-
	Winch Cabling	-	50m	-
	Sensor Array	-	0	-
	SONAR module	-	0	-
Misc.	Shipping Pickup	4 USD	N/A	5
	Adhesives	2.75	N/A	2.75
Total Cost				$200

Appendix E: Propulsion and Motor Calculations

For 1 motor

- $K_v = 2950 \frac{RPM}{V} \approx 309 \frac{rad/s}{V}$

$\omega_{rad} = 309 \frac{rad/s}{V} \cdot \underbrace{11.1V}_{\text{battery voltage}} = 3430 \frac{rad}{s}$

- $K_t = \frac{1}{K_v} = \frac{1}{309} \frac{V}{rad/s} = \frac{1}{309} \frac{Nm}{A}$
- Max torque = K_t · max ESC current $= \frac{1}{309} \cdot 20A = 0.065\ Nm$
- Assuming motor is ≈ 80% efficient at max current

Corrected torque = Max torque $\cdot \sqrt{0.8} = 0.058 Nm$

- $P_{out} = \underbrace{\tau}_{\text{torque [Nm]}} \cdot \underbrace{\omega_{rad}}_{\text{angular velocity in rad/s}} = 0.058Nm \cdot 3430 \frac{rad}{s} \approx 200W$
- for two motors we have 400W (≈ 0.54 horsepower) of power ⇒ sufficient to propel boat
- Note: at max current, our batteries would last: 1300mAh @ 20A

h ≈ 0.065 hours

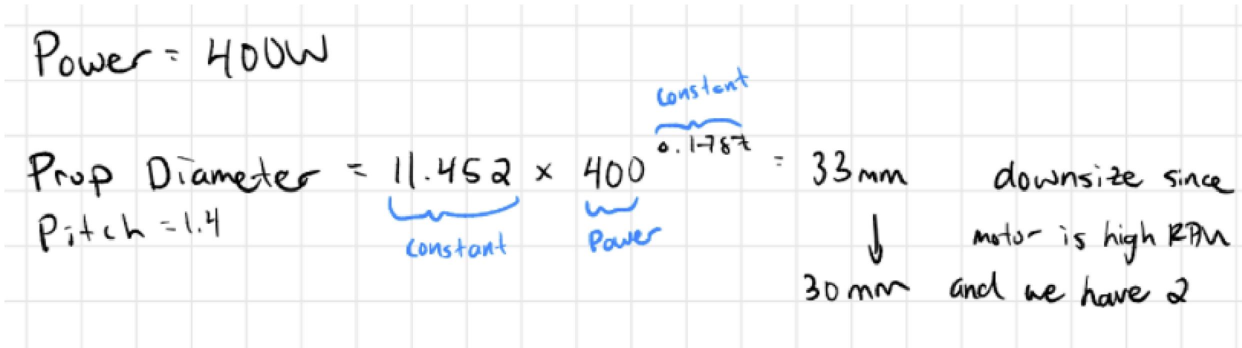
≈ 3.9 mins

3.9 mins @ sustained max throttle

(in reality would be less since batteries are old)

formula valid for hull length

20in – 50 in



Source for equations:

RCExplained. (2021, May 11). *RC Brushless Motor Actual vs Calculated Torque Output* [Video]. YouTube. https://www.youtube.com/watch?v=x6NIlsPAfAk&t=433s&ab_channel=RCexplined

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Appendix F: Hardware Block Diagram