Yakski: An Electric Waterjet Propulsion System

Technical Capstone Project
Presented to the Faculty of the
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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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ABSTRACT

Current personal watercraft designs leak harmful pollutants into the environment, cannot operate in shallow waters, and are often large and require trailers for transportation. While kayaks lack these disadvantages, they are powered by the pilot alone. The goal of this project is to design and build an electric propulsion system that can be mounted on a kayak. This system will retain the advantages of a kayak over most personal watercraft with the added benefits inherent to an electric propulsion system, such as ease of powering, little to no pollution, and low noise. Secondary goals are to gain experience in the product development process and utilize computer-aided design (CAD) and computational fluid dynamics (CFD) software, 3D printing technology, and laser cutting technology to aid system development and prototyping.

I. INTRODUCTION

Humans have a long history of interaction with freshwater environments. Rivers and lakes have served as sources of water, food, power, and travel. Yet, the last century has seen a dramatic increase in its use as a source of recreation. Recreational boating has become increasingly common and has exacerbated the issue of freshwater habitat destruction (Fontaine & Dunn, 2007). There is a vast array of recreational watercraft propulsion systems, and each has benefits and consequences. Watercraft most notably can be propelled by gas motors, electric motors or humans. Inboard motors that run on petrol, oil, or diesel harm the environment the most by a significant margin. In fact, gas-powered motors add chemicals and metals to water, which can influence the type and amounts of aquatic wildlife (Vermont Water Quality Division, 1999). In his book, *Polluting for Pleasure* (1993), Andre Mele estimated that approximately 150 million to 420 million gallons of unburned fuel is emitted into aquatic environments each year by recreational boats (p. 29). Traditional inboard gas-powered propellers further disturb environments by uplifting sediment. Human-powered boats have limited applications due to their minimal speed, power, and size. Electric outboard motors represent a quiet, emission-free alternative to gas-powered motors while sacrificing price and convenience.

This research team will build upon current electric outboard motor technology to produce an attachable electric outboard freshwater propulsion system for lightweight watercraft. This new propulsion system will be particularly desirable for use in shallow water and where wakes and gas engines are not allowed. The application of this system will be limited to freshwater bodies of water because corrosion from salt is mitigated. This technology will be adjustable for attachment to a variety of lightweight watercraft and will act as an intermittent discretionary replacement for existing propulsion systems. To achieve these goals, the propulsion system will be composed of an electric motor that powers a water jet. Water jets operate differently from conventional propulsion systems due to their use of an impeller. Impellers produce thrust by creating a pressure differential in an internal flow. Water jets operate at and slightly below water which enables propulsion in very shallow water while also minimizing sediment disruption. A variety of jet ski designs will be explored – due to their relevant application of water jets - and research will be explored to determine suitable designs for the water jet. This team has worked to optimize durability, power, and range within price constraints. The final product will be attached to a kayak on the Rivanna Reservoir - where water is shallow and gas motors are prohibited - for preliminary testing. This propulsion system will be referenced to as the Yakski.

II. METHODOLOGY

A. LITERATURE REVIEW

The aim of this report is to detail the team's production of an innovative electric-powered water jet propulsion system that can be attached to a kayak. Thus, the team's review of previous literature is primarily focused on research into optimizing water jet propulsion systems. Three main topics are of primary concern for informing the optimal design of the Yakski: water jet size, impeller/stator design, and flow path design. These reports focus on determining optimal characteristics to maximize efficiency, thrust, and weight.

The first report, "Comparison of Waterjet Performance in Tracked Vehicles by Impeller Diameter," explores the effects of impeller diameter on amphibious military vehicles. The amphibious military vehicles that were studied utilize typical flush axial waterjets which were also used in designing the Yakski. The report explains that larger impeller diameters in a water jet result in greater performance while sacrificing buoyancy. Additionally, the report explains that the pitch and the number of stator blades play an important role in straightening the rotating flow to improve performance. The number of stator blades should outnumber the number of blades on the impeller. After conducting various tests on three water jets with different diameters, the researchers concluded that it is important that impeller/stator diameters are optimized for buoyancy and performance requirements (Kim, Chun, Kim, Park, & Jung, 2009). The conclusions from this report were significant in guiding the development of the impeller and stator. Although this report focused specifically upon amphibious military vehicles, the team believed that the results were generalizable to the design of the Yakski. Thus, the team recognized that the pitch and number of stator blades should be optimized to improve efficiency.

Additionally, the team found that it would be important to optimize the size of the water jet with regard to price, performance, and weight constraints.

A second report, “Analysis of the effect of impeller geometry including blade outlet angle on the performance of multi-pressure pumps: Simulation and experiment,” examined the effects of outlet angle geometry of multi-pressure pump impellers on head and efficiency. Researchers compared the pump head and efficiency for outlet angles of 27, 30, and 33 degrees. Thorough computer-aided and experimental testing led to the conclusion that, at an outlet angle of 30 degrees, losses are reduced and energy transfer is improved which leads to increased pump head and efficiency. In fact, the outlet angles of 30 degrees and 27 degrees had the greatest and lowest efficiencies at all flow-rates, respectively. Both experimental and computer-aided numerical methods yielded the same results; computer-aided simulation is purported to be quicker and cheaper than experimental methods for determining optimal impeller outlet angles (Mohammadi & Fakharzadeh, 2017). This report specifically focused upon multi-pressure pumps, however, the team believed that the analysis should be relatively generalizable to water jet applications. As a result, the team recognized that a preliminary impeller outlet angle of 30 degrees would be reasonable and could be modified using computer-aided simulation testing.

The final report of interest was “Analysis of Convergent and Divergent-Convergent Nozzle of Waterjet Propulsion by CFD Simulation” which explores the differences in water jet efficiency and thrust between waterjets employing a convergent nozzle and a divergent-convergent combination nozzle. In convergent nozzles, the inlet has the largest diameter and the outlet has the smallest diameter. Divergent-convergent combination nozzles differ from convergent nozzles because the middle diameter is greater than the inlet diameter. After testing ten different combination nozzles and five different convergent nozzles, the researchers were able to conclude that convergent nozzles have greater efficiency by eight to twelve percent. In contrast, the thrust from combination nozzles was found to be approximately two times greater than with convergent nozzles. (Budiyanto, Novri, Alhamid, & Ardiyansyah, 2019). From this research report, the team recognized that a nozzle design needed to be picked after weighing the requirements of efficiency versus thrust in the Yakski. Nevertheless, it is clear that the water jets used with the Yakski must have nozzles that exhibit some sort of convergence.

B. DESIGN PROCESS

The final Yakski was developed by leveraging previous technology and research during the design process. The development of the Yakski was divided into five major subsystems and their development was prioritized by their levels of interdependency: water jet (first), propulsion powering system, steering, mounting, and user interface (last). Each subsystem progressed through multiple iterations of design and testing until satisfactory results were achieved. Prior to beginning the design process, a list of functional requirements and design tradeoffs were explored to ensure the development of an effective technological solution.

1. Functional Requirements and Design Tradeoffs

1. Ease of Attachment: The device should enable rigid attachment, adjustment, and removal by the user with relative ease.
2. Weight: The device must not weigh over 170 pounds due to the weight constraints of the lightweight watercraft. The device should minimize its weight to help maximize the ease of attachment and the efficiency of the device.

3. Power and Range: The device must have sufficient power to achieve speeds of at least 5 miles per hour. The device must also have sufficient range to operate for at least an hour of continuous use.
4. Steering and Braking: The device must have sufficient steering and braking capabilities to avoid freshwater hazards.
5. Durability: The device must have a lifespan of five years when operating under typical freshwater and weather conditions. The device must be sufficiently waterproof to protect mechatronic systems.
6. User Learnability: The device must have an interface and attachment system that is easy to learn and operate without requiring a technical background.
7. Safety: The device must be sufficiently waterproof resistant to capsizing to prevent short circuits.
8. Cost: The total cost of this device must be at or below $1,200.

2. Prototyping

SolidWorks, a 3D modeling software, was used extensively to design the waterjet, the propulsion powering, and the steering and the mounting subsystems. In order to properly test and make design improvements, various iterations of these subsystems were 3D printed from ABS plastic with the exception of the mounting subsystem, which was assembled using existing material. 3D printing provided a fast and cost-efficient means to produce prototypes for testing and development purposes.

The SolidWorks flow simulation software was utilized to model the waterjet system and to simulate various iterations of the design prior to printing. Only prototypes that were verified by flow simulation were printed and tested, as time and budget were large limitations in this project.

C. APPARATUS

The Yakski was built to be an attachable electric outboard freshwater propulsion system for lightweight watercraft. This system was specifically designed for attachment to an Eddyline Caribbean 14 kayak. This system is composed of five major subsystems: water jet, water jet powering system, steering, mounting, and user interface. The water jet subsystem is comprised of two sets of housings, impellers, stators and exit nozzles. This subsystem is actuated by the water jet powering system and provides the thrust for the propulsion of the Yakski. The water jet powering system includes two sets of batteries, motors, and shafts. This subsystem is supported by circuitry and code to control the power delivered to the water jets. The steering system is made up of two motors, two steering nozzles, and two batteries which are supported by circuitry and code. This subsystem controls the steering for the Yakski with a combination of differential thrust and fly-by-wire steering. The mounting subsystem is largely composed of 6105-T5 aluminum T-slot structural framing (8020) which is supported by waterproofing, nuts, bolts, and straps. This subsystem connects each Yakski subsystem and allows for the attachment and adjustment of the full system on the kayak. The user interface subsystem consists of the user-accessible controls for launching, accelerating, and steering. The arrangement of these subsystems on the Eddyline Caribbean 14 kayak can be seen below in Figure 1.

Figure 1: Full Yakski assembly

1. Water Jet:

i. Waterjet Housing

The waterjet housing is one of the most important subsystems within the overall waterjet driven propulsion system. This subsystem includes the housing of the waterjet, an impeller, and a stator that provides a streamlined path for water within the system. Inspiration for the housing mainly came from preexisting technologies such as water jets in complex systems like jet skis. To optimize the flow of the water through this housing, many different types of shapes and sizes would need to be considered. The overall shape of the waterjet housing needed to be efficient so that the intake of the water would not be slowed down by the walls or the shape of the housing. Of particular interest were the shape of the inlet, the change in height from inlet to outlet, and inlet area versus exit area. The method for securing the impeller shaft axially and radially was also of concern.

SolidWorks flow simulation was used to evaluate the performance of the various designs. Early iterations employed external flow scenarios, where an initial fluid velocity would be set and a rotating region was created around the impeller to model the system. Parameters of interest were the exit flow velocity and exit mass flow rate. Also, cut plots and flow trajectories of the simulation were used to find inefficiencies in the water jet. These visual tools allowed for the identification of high-pressure regions, rotational flow, and skin friction. While initial simulations were useful, it was found that the model made some inaccurate assumptions that would need to be changed. The simulations were switched to internal flows with atmospheric pressure boundary conditions at the inlet and outlet. This model proved more accurate. The initial design for the waterjet housing using this method can be seen below in Figure 2.

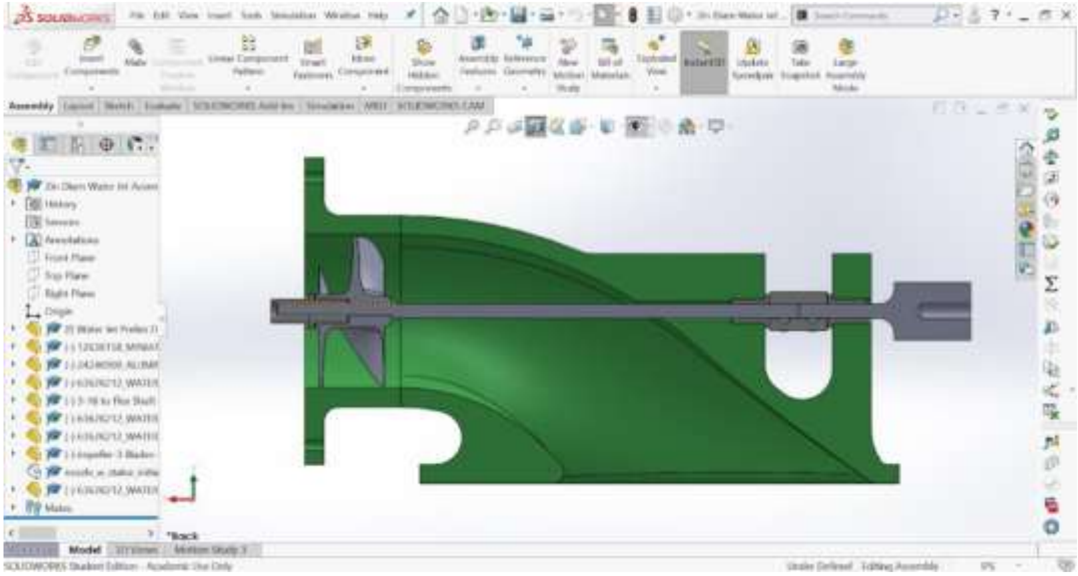

Figure 2: Initial model of waterjet housing

The original waterjet housing shape included some aspects that make it very easy to independently modify while keeping the rest of the system the same. The initial print of the waterjet housing included a two-inch diameter flow path for the water to traverse and a through-hole for a shaft to freely rotate within. This print also included a slot for a sleeve bearing to secure the shaft in the radial direction. The stator was designed directly into the exit nozzle, and this component was designed to be fastened to the face of the waterjet housing so that combinations of exit nozzles, stators, and impellers could be tested rapidly by changing the exit nozzle or impeller. Upon testing this two-inch housing with sleeve bearings, it was quickly determined that sleeve bearings would not be reliable enough to trust for long-term and the two-inch housing combination with stators and impellers was not nearly powerful enough to move a whole kayak.

After consulting Assistant Professor Daniel Quinn who holds a doctorate with specialization in hydrodynamics, it was determined that the waterjet housing needed to consider some drastic changes in order to achieve the goals set out by the group. Professor Quinn suggested that in order to produce more propulsion, the size was one of the biggest factors. Moving forward from the two-inch housing, the general shape of the housing did not change, however, the size of the waterjet housing doubled in size from a two-inch diameter to a four-inch diameter to increase thrust. This four-inch waterjet housing, portrayed in Figure 3, stood as the final design as it proved to be the most efficient after CFD analysis confirmed it was the best waterjet design yet.

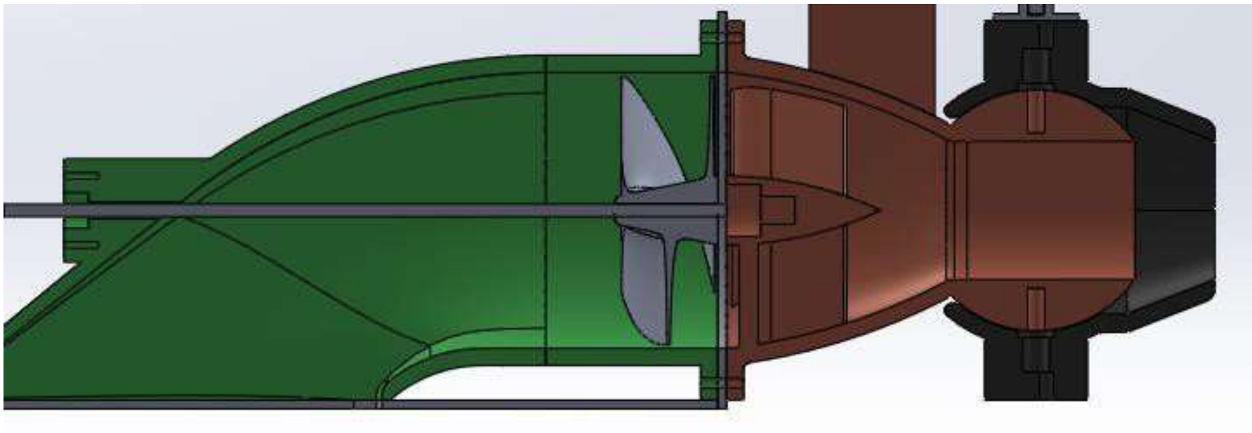

Figure 3: Final 4-inch housing design

Another significant change in the design was the use of sealed ball bearings in place of the sleeve bearings used previously. The new design incorporated two ball bearings: one at the stator end of the shaft, and one at the back of the water jet, where the shaft enters the housing.

The stator bearing was pressed into a 3D printed piece that fits inside the stator hub. This piece is removable, so in the event that a bearing wears out, the piece can be removed, and reprinted, and a new bearing can be pressed into the new piece. The bearing at the back of the water jet was more difficult to implement. To install this bearing, the shaft was frozen, and the bearing was aligned in the appropriate location. This bearing fits into a recess in the back of the housing, and another 3D printed piece is fastened over the bearing to lock the shaft axially.

ii. Impeller

The purpose of the impeller was to create the largest thrust force from the water coming out of the exit nozzle. Impellers are made of two main parts: the blades and the hub as indicated in Figure 4. An impeller is similar to a propeller in that they both push water to propel a vehicle using Newton's third law of action reaction forces. The difference is that an impeller is located snugly *inside* a pipe or housing to create a suction force on the fluid at the inlet by creating a negative pressure difference inside the housing. This differential is caused by the liquid inside the waterjet moving faster than it does at the inlet, making the static pressure inside decrease

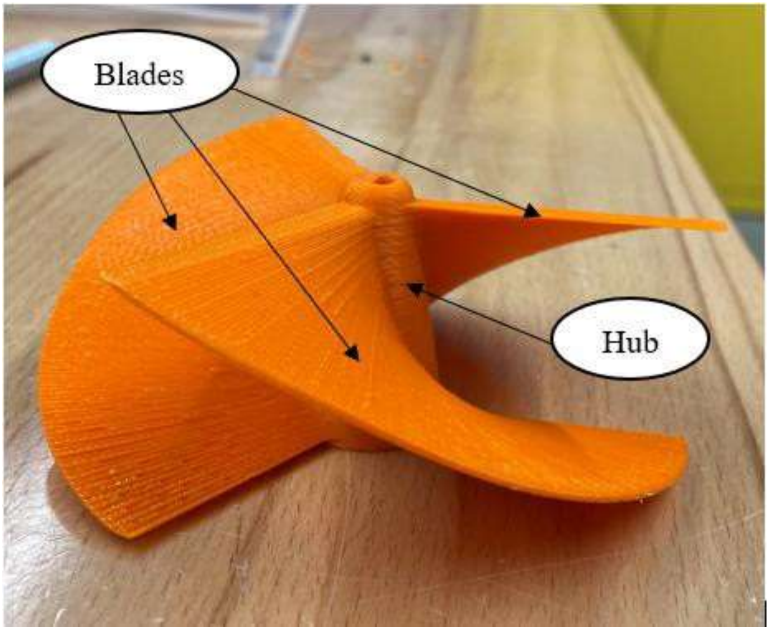

Figure 4: Diagram of a prototype impeller. The hub and blades are highlighted.

according to Bernoulli’s Equation and thus drawing in water from the inlet. The impeller then accelerates the fluid through a combination of its spinning blades and a change in the flow area induced by an increase in its hub diameter. The acceleration of the water results from the transmitted torque and rotation of the motor to the blades pushing on the water, while the decrease in area causes the water to accelerate according to the continuity equation shown below.

$$V_1A_1 = V_2A_2 \tag{Eq. 1}$$

After the fluid is accelerated past the impeller and the stator, it continues through the exit nozzle. According to the integral momentum theorem, the sum of the forces on a system is equal to the momentum flux of the system. The momentum flux out of the exit nozzle produces a force on the water jet which propels the system forward. For this process to work efficiently the impeller must be fully submerged in a fluid. The impeller in the final design was located in the waterjet housing around a D-shaft, as seen in Figure 5.

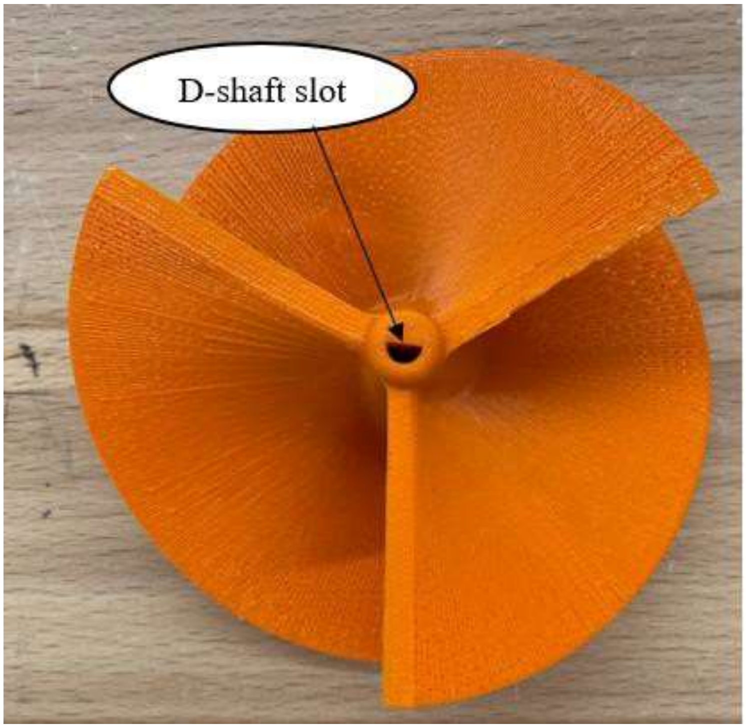

Figure 5: Impeller with D-shaft

The design of the impeller was a result of research into existing technologies and experimental testing. The initial designs were based off of current jet ski impeller designs. Most of these designs incorporated three or four blades, where the end of one blade would overlap underneath the start the next blade when viewed from above. These impellers had a diameter of about 6 inches and were used for jet skis with 60 to 300 horsepower, which is significantly more than the motor capabilities of the motor used for this project, rated at a little more than 1 horsepower. After this research, three-blade and four-blade impellers were designed in SolidWorks and 3-D printed for testing. These initial impellers had a diameter of 2 inches and were 1.5 inches long in the axial direction to fit the initial housing design. The thickness of the blades for each initial impeller and the orientation of the impellers were varied to test the capabilities and strength of the ABS plastic. Upon testing for both rigidity and thrust produced, the optimal thickness was determined to be 0.1 inches, while the three blade impellers performed better across the board when compared to the four blade impellers. Even though the three-blade impellers performed well, it was apparent upon simple observation that there was still not nearly enough thrust created from the 2-inch impellers to propel the Yakski forward. Upon further research on fluid dynamics and impellers, the best way to increase the thrust out of the exit nozzle was to increase the overall size of the impeller and housing. The diameter was increased from 2 inches to 4 inches for the impellers and housing and then tested. After the change of diameter, the mass flow rate increased from 1.6kg/s to 13.7kg/s and velocity increased from 1.7m/s to 6.8m/s from Computational Fluid Dynamics (CFD) simulations in SolidWorks. The large increase in mass flow rate and velocity can be seen in Figure 6. When the flow goes from green to blue it is being accelerated by both the impeller and the change in diameter size. The use of CFDs were used to determine the best impeller by comparing exit velocity and mass flow rate in Equation 2.

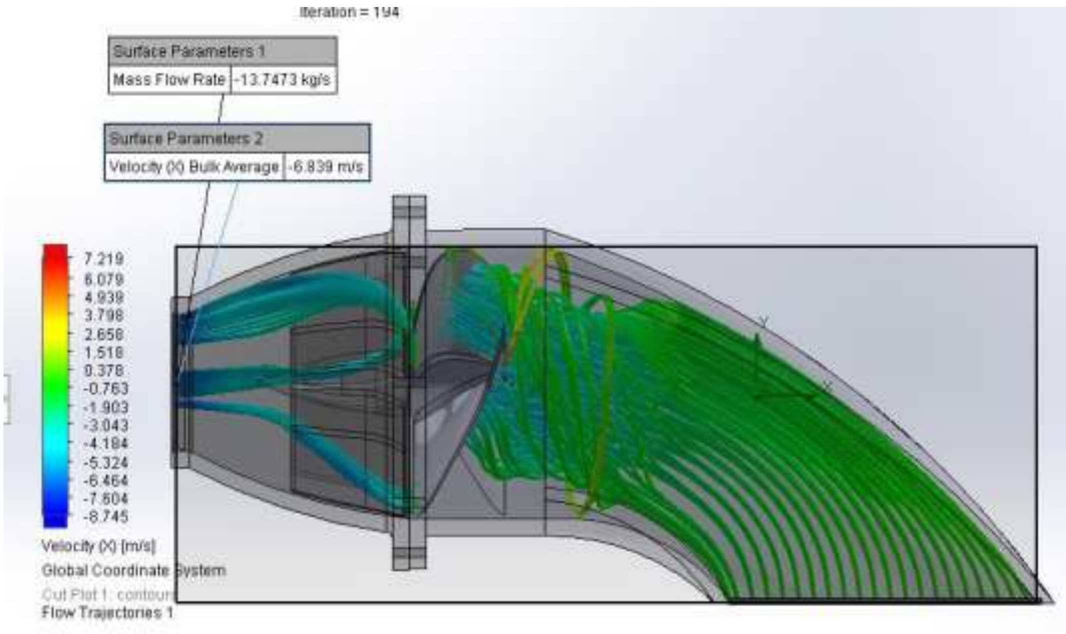

Figure 6: CFD results for optimized water jet. The positive x-axis moves from left to right, so the relevant velocities are shown as negative.

$$F = \dot{m} * V_e \qquad \text{(Eq. 2)}$$

These large increases were seen quickly when physically testing the new impeller and housing.

iii. Stator and exit nozzle

The primary goal of the stator and exit nozzle was to produce the most concentrated and uniform flow path at the exit. Thrust results from the momentum flux out of the system, and any flow in directions other than parallel to the axis of the impeller would result in inefficiency. Additionally, rotational flow would also cause inefficiency. Since the blades of the impeller caused the water flowing from it to have a significant amount of rotational flow, the stator was critical to converting this rotational flow into flow along its axial direction in order to produce maximum thrust. Similar to existing technologies, the stator was located inside of the exit nozzle and adjacent to the downstream side of the impeller hub. In order to maximize the efficiency of the design, various elements of the geometry of the stator and exit nozzle had to be carefully considered. The first of these elements was blade shape. In order to correct the rotational flow of the water, the angle of attack of the blades had to be aligned in a way that was opposite to that of the impeller, as shown in Figure 7.

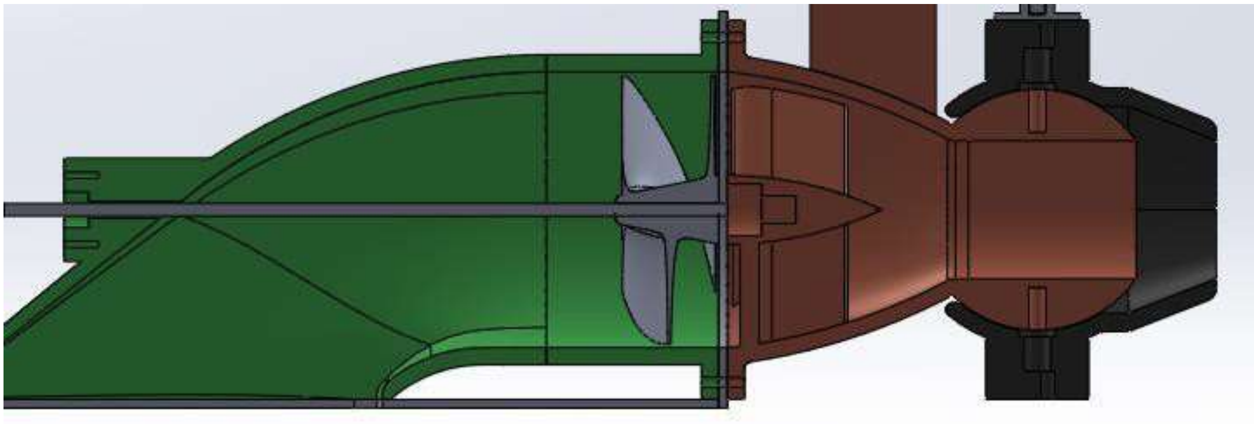

Figure 7: Cross-section of housing with stator

While the directions of the blade pitch of the impeller and stator were opposite, the actual values of the blade pitches were different. If the two values were made to be equal and opposite, the stator blades would act as walls and introduce significant major losses to the water flow. In order to prevent this from happening, the stator blades were made to have a pitch that was much less aggressive than those of the impeller. In order to use as low of a blade pitch as possible, the blades were also made to be much longer than the impeller blades -- 1.75 inches. This added length would introduce more surface area and thus more minor losses due to skin friction, but these losses would be small in comparison to the major losses from rotation that this design eliminated. In order to further reduce any losses that the stator might introduce, the blades were designed to merge with the walls of the exit nozzle so as to eliminate any blade tip leakage flow within the system. The stator and exit nozzle were thus printed as a single part. With these corrections, the stator blades acted to efficiently correct the flow of the water while adding linear velocity at the exit nozzle.

Another element of the stator that was considered was its hub design. In order to guarantee a smooth transition of flow from the impeller to the stator, the leading hub diameter was set to be the same value of the impeller’s trailing hub diameter. Initial designs incorporated a cylindrical hub profile, but flow simulations showed that this design caused high pressure regions directly downstream of the hub as a result of flow separation at the trailing edge. In order to minimize losses from this high-pressure region, the stator hub was redesigned to have a gradual change in its diameter with respect to the axis of the waterjet path before coming to a sharp tip on the exit side of the hub. This was done to reduce the flow separation of the water from the trailing edges of the hub and thus create a smooth, efficient flow at the exit. The final length of the hub was 2.25 inches.

The number of stator blades was determined simply by examining existing technologies and assigning a number of blades to the Yakski that was similar to the number that is typically seen in jet ski stators. This was done in large part because the available 3D printers had to be shared amongst multiple groups and because of the time constraints inherent to completing such a complex project in one semester. Each stator and exit nozzle took about 25 hours to print and considering the available resources, printing multiple exit nozzles and stators solely for the purposes of testing different blade numbers would be inefficient. Typical jet ski stators have anywhere from six to nine blades -- it was decided that the Yakski’s stator would have seven blades.

Another element that was considered was the shape of the exit nozzle, specifically the concavity of its walls and its exit diameter. Initially, the walls of the exit nozzle were designed to be concave, but it was found during testing that concave walls produced a dispersed exit flow. Convex walls were tested and it was found that these produced a more concentrated exit flow. Convex walls acted as a more gradual guide to the flow of the water and would reduce some of the major losses that concave walls would incur on the system. The exit diameter was also changed in various stages of testing. Its value changed as the hub diameter of the impeller did to ensure that the inlet area of the exit nozzle was larger than its exit area. After the various changes to the impeller design, the 2-inch diameter exit nozzle produced the most thrust.

2. Waterjet Powering System

The water jets were driven by electric motors, which in turn were powered by batteries. The motor type was selected first in order to have a basis from which the battery would be selected. Different types of motors were studied that provided similar power to what was required for the Yakski, and ultimately, it was decided to use an electric scooter motor. The selected motor was a 24 Volt, 400-Watt DC brushless motor whose output shaft rotated at 2800 RPM. Two of them were ordered, one for each water jet. A brushless motor was chosen because of its durability, easy integration, reliability, and efficiency, most of which is due to the fact that there is no brush or commutator erosion which increases its life span. One of the main goals of this project was to create a long-lasting product, and having a brushless motor helped to fulfill that goal. Brushless motors also allowed for easy user interface and integration into the rest of the design. The motors included an analog throttle which took a voltage signal from a potentiometer. This allowed for a simple throttle design using a potentiometer, or a more elegant control system that allowed for digital control of thrust to aid steering.

For initial testing, the throttle was a simple 10kΩ potentiometer. However, the final steering system incorporated differential thrust, so a more complex control system was required. This system still incorporated a 10kΩ potentiometer, but this potentiometer fed into a channel on the TLC 2543 12-bit multiplexing ADC. The ADC would send a value between 0 and 4095 to the propeller chip, which would multiply the ADC value by 0.062271 and effectively convert the 12-bit value to an 8-bit value between 0 and 255. This value was sent to two MCP41100 digital potentiometers which were connected directly to the analog motor throttles. While the system was redundant in converting from analog to digital and back to analog signals, it provided the advantage of being able to control the throttle in different situations, such as a case where the power to the two motors is varied to aid steering.

Once the motors were chosen and ordered, the requirements were set for a battery. The biggest concerns when choosing a battery were weight and water resistance. The Eddyline kayak had a set maximum weight restriction of 400 pounds overall, but 350 pounds after taking the weight of the kayak into consideration. Factoring in the weight of an average-sized human, an absolute maximum of 170 pounds was allocated for the water jet. Due to the weight restriction, the battery could not be too heavy. Initially the design only involved having one battery. Through additional research it was found that a lithium-iron-phosphate battery was most ideal. It as comparatively lightweight and contained the power to run the water jet at full speed for approximately ten minutes. The problem of water contamination remained, but due to the nature of the project, it had to be addressed through waterproofing techniques in the design. While finalizing the final battery to be used, an external power source, plugged into the wall, was used for all testing. After all testing and final designs were complete a battery was decided. However, shipping issues resulted in the delayed arrival of the battery, and two 12V lead-acid batteries were purchased in order to facilitate testing. They were wired in series to produce the required 24 volts, and although they weighed nearly twice as much as the purchased battery, they were suitable for testing.

For the connection between the motor shaft and impeller shaft, multiple designs were considered. Because the water jets were to be mounted outside of the kayak, the motors could not be placed in line with the impeller shaft, as they would be exposed to water and would require a complex waterproofing design. Instead, the motors were to be mounted above the water level. The first design was a flex shaft that is commonly used on line trimmers, shown in Figure 8.

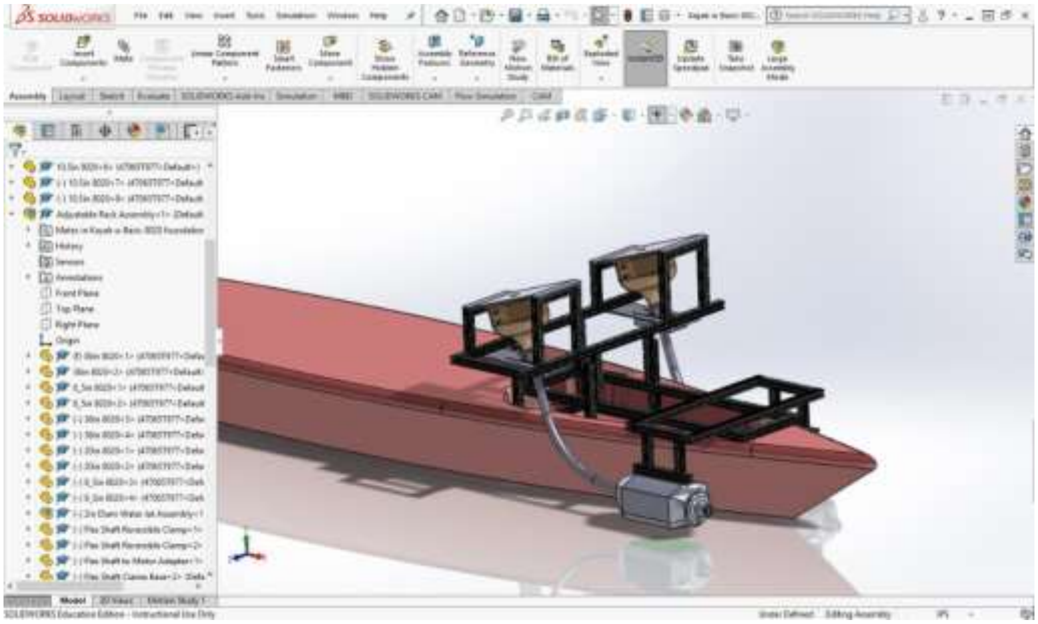

Figure 8: Model of initial mounting scheme. Flex shafts required the motor to be mounted at an odd angle.

This shaft design allowed for the motor to be bolted onto the kayak while the water jet system sat at the water level. It worked efficiently and lasted throughout design testing. However, the shaft produced large vibrations at high speeds. The shaft needed to be held with multiple hands during testing. This amount of vibration likely would have caused premature failure of various components. The flex shaft also proved to be difficult to mount. It required the motor to be mounted at an inconvenient angle. The initial design gave little support to the motor and increased the risk of exposure to water. A thorough redesign of the shaft connection followed. A ninety-degree drill adapter was incorporated in place of the flex shaft in the final design. The shaft vibration decreased and the mounting mechanism was greatly simplified. The final mounting design is discussed in a later section.

3. Steering

In order to develop an effective steering system that is capable of changing the direction of outlet flow and allowing the battery-powered kayak to turn, three main aspects needed to be considered: how the flow can effectively be changed, how the system is controlled and the necessary changes to the water jet housing.

One mechanical and one mechatronic steering concept was considered. The mechanical concept involved the use of push-pull cables to change the relative positioning of a steering nozzle that would be mounted to the exit nozzle. The mechatronic concept would incorporate a fly-by-wire system featuring a potentiometer feeding in an analog signal to an analog-to-digital converter (ADC) that would determine the position of a brushed DC motor with a quadrature encoder. This motor would attach to a steering nozzle mounted on the exit nozzle of the water jet housing. A reversing mechanism was also proposed to increase the maneuverability of the kayak in all directions, and while a number of designs were proposed, time and budget constraints prevented the team from developing a successful mechanism.

With regards to a mechanical push-pull system, the system would impose restrictions that deterred the team from selecting this option. While the system offered an advantage in simplicity of integration, limitations include rust, cost, and the subjectivity of the analog push-pull impulse person-to-person. The mechatronic steering concept was chosen for its ease of use and elegance, and cost-effectiveness. The Parallax Propeller Mini would be the microcontroller used to control the system.

Motor selection was of primary importance. The best option to complete this task was a DC brush motor configured with worm gears and a quadrature encoder. The worm gears and the quadrature encoder provided important advantages for the system. The worm gearing provides holding torque for the system so it could withstand the large force of the exit flow without the use of extra energy that a servo motor would require. The quadrature encoder allowed for positioning of the motor and easy control by an H-bridge circuit.

The steering was designed to be controlled using a potentiometer that would deliver an analog signal into one of the channels on the TLC 2543 Multiplexing ADC. From there, 12 bits of binary, ranging 0-4095, the signal is read into the Propeller Chip and, using floating-point math, divided by a factor to give the maximum range of steering. The quadrature encoder had magnets at intervals of 7.5 degrees, corresponding to 48 magnets total, and with a gear ratio of 340:1, 16320 counts would occur per one revolution of the output shaft. It was discovered experimentally that the nozzle had a maximum range of approximately 52 degrees of range, which corresponds to 2360 encoder counts. The motor system incorporated one limit switch to which the motor would home at startup. Once homed, the encoder program would begin and the potentiometer would give positions between 0 and 2360. From there, the motor is given direction and speed commands through a DRV 8801 H-bridge chip based on a comparison of the encoder count and potentiometer position. The circuit diagram used to control throttle and steering can be seen in figure B of the appendix.

With the motor controls determined, the next challenge became how to change the design of the exit nozzle so that the flow can effectively be changed using the worm gear motor. With regard to the nozzle, the design of the stator was changed in order to have a bulbous shape downstream of the original exit location. The bulbous profile was necessary to allow for sufficient range of the steering nozzle. The new bulbous profile of the stator allowed for the steering nozzle to remain flush with the exit nozzle, which limited the loss of thrust from leakage between the steering nozzle and exit nozzle. The steering nozzle, visible in Figure 9, consisted of two halves that were fastened with 6-32 screws, and rotated on two brass pins with sleeve bearings. The top half had an aluminum flange with set screws to pinch the steering motor d-shaft.

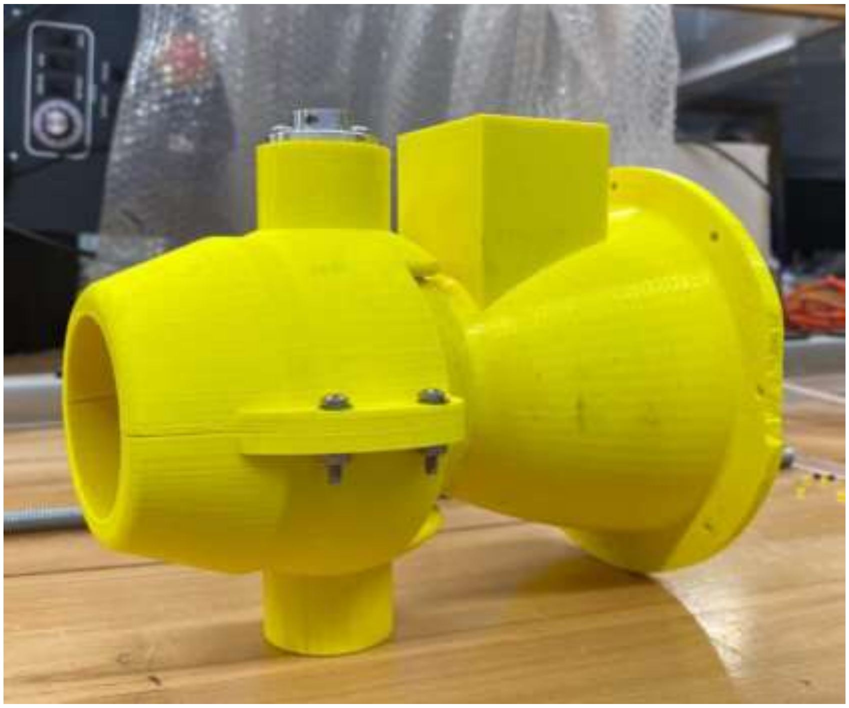

Figure 9: Final steering nozzle design

Waterproofing was a critical component of the steering design. The motor and motor housing were placed above the turning nozzle and stator so that the motor’s output shaft could connect directly to the turning nozzle. Both the motor and limit switch needed a waterproof housing, because they would be mounted inches above the waterline. The waterproof housing consisted of an aluminum bottom plate with holes for mounting to the stator, 3D-printed rectangular walls that were epoxied to the aluminum plate, and an acrylic cover that screwed onto the walls. The acrylic cover had a hole through which wiring could pass. Initial designs incorporated waterproof joints that would eliminate the need for tape, but time constraints prevented the use of these components, and tape was used to seal the hole.

Another facet of the steering system was the implementation of variable thrust to make the steering also rely on the use of changing the motor thrust of one of the water jets in order to improve turning. Initial testing of the Yakski system included the use of variable thrust only for steering, as the steering electronics were not ready. Instead of controlling the angle of the steering nozzles to turn this system simply cut off power to the appropriate water jet motor. This was determined by the input of the ADC. For example, if the pilot turned the potentiometer to the left, the left motor power would be cut off, and the right motor would apply a torque to the kayak and turn it. While this steering method did function, the turning radius was much too large, so it was decided that a combination of differential thrust and mechatronic steering would produce the most effective steering.

4. Mounting

A custom mounting system was designed to secure the Yakski onto the Eddyline Caribbean 14. The largest considerations for the attachment apparatus design were weight, balance, and waterproofing. The Eddyline’s overall weight capacity was 350 pounds. Considering the weight of an average-sized male to be approximately 180 pounds, an absolute maximum of 170 pounds could be allotted to the waterjet system. Given that mass is inversely proportional to speed and acceleration, the weight of the mounting system took the largest precedence during the design process. Balance and stability were then considered, as the combined center of mass of the Yakski had to be maintained on the central axis along the length of the kayak in order to prevent the kayak from tipping. The distribution of the weight was also key to keeping the kayak balanced in the water. Lastly, the mounting system had to be designed in a way that kept the areas where the electronics and batteries are held waterproofed. Secondary considerations, such as drag and ease of construction, were also considered but only after the initial designs were created.

The final mounting scheme was constructed primarily out of 1x1 inch 8020 aluminum beams as shown in Figure 10. 8020 beams were chosen because of their lightweight nature, workability and anti-corrosion characteristics. The frame was constructed using custom cut aluminum brackets, secured with 8020 specific screws and nuts. The waterjet housing was mounted on top of an aluminum plate and secured to another plate that was perpendicular to the surface of the water. The stator was also mounted on this perpendicular plate, and fastened with 6-32 nuts and bolts.

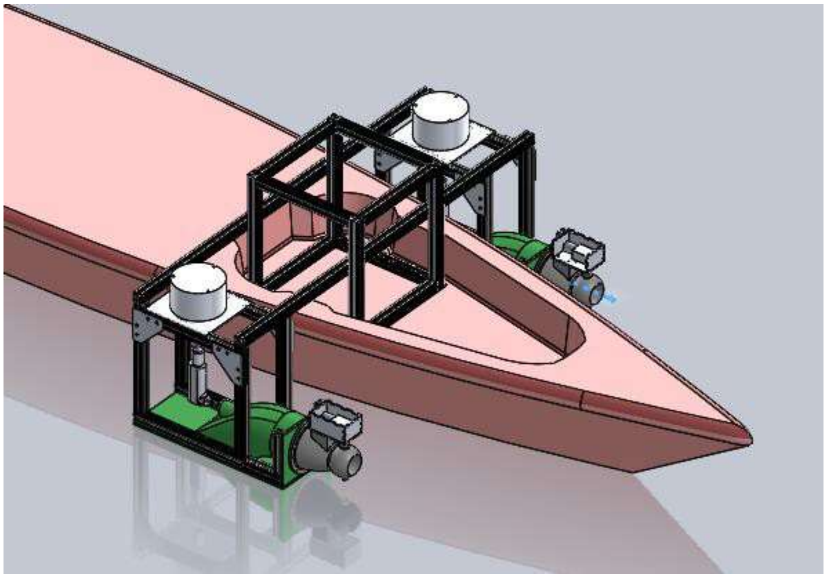

Figure 10: Final mounting design

The final design, in Figure 11 below, used a 90-degree drill adaptor to transfer the rotational power from the motor onto the steel shaft. This was chosen instead of the flex shaft, as mentioned above, because of its ability to be mounted using 90-degree brackets. The 90-degree drill adaptor connecting the rotating steel shaft to the motor is held into place by a 3D-printed part mounted on the bottom plate. This part not only secures the drill adaptor in place but also absorbs much of the linear force from the impeller. The motor is mounted directly about the drill adaptor, screwed into a custom cut aluminum plate that is secured on two 8020 beams.

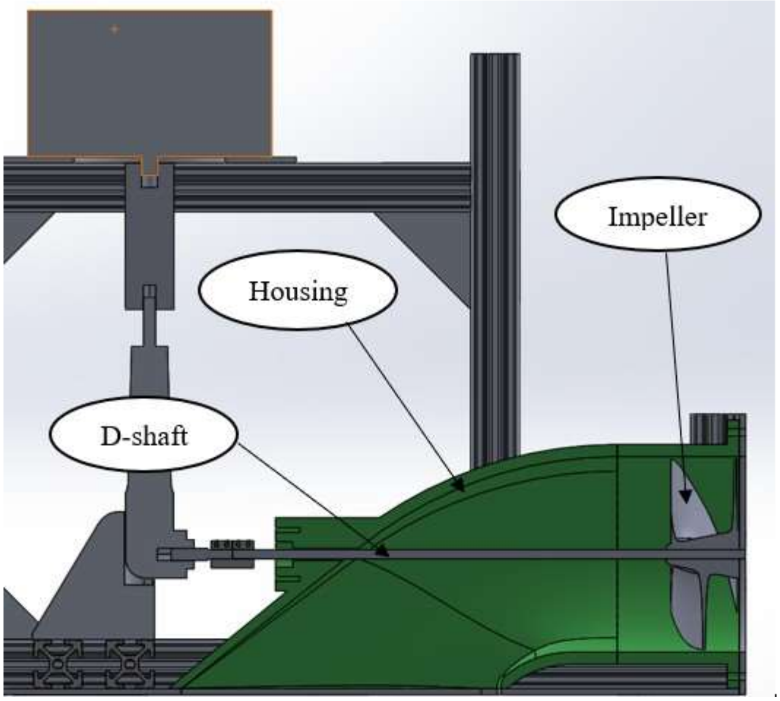

Figure 11: Final water jet mounting scheme.

The batteries were placed in the front compartment of the kayak. This was done to better distribute the weight throughout the body of the kayak. This front compartment is also waterproof, which is very important as the batteries are unable to get wet. A hole was drilled in the front compartment container to feed the wires through the hull of the kayak. The hull is underneath the passenger seat and not at risk of becoming wet. The wires traversed the whole hull and were fed out of the back to be connected to the motor.

The mounting system was secured to the back of the kayak using two bolts going through the bottom of the kayak. The system is symmetrical which keeps the kayak balanced and reduces the risk of capsizing. Two triangular foam cutouts were mounted in front of the waterjet to reduce drag and further streamline the system. Due to time constraints on the project, the mounting scheme was heavier than planned, but all other considerations were met and the water jets were properly secured onto the kayak.

5. User Interface

The Yakski is controlled by the control panel box shown in Figure 12. The control panel box was laser cut out of acrylic and super glued together. Tape was placed around the edges to further waterproof the wires inside. The box is secured to the top right side of the kayak, within arm's reach of the passenger seat. The steering is controlled using the circular knob in the bottom left corner of the box. This knob is a potentiometer and controls the steering via the fly-by-wire circuit explained above. As the passenger turns the steering knob, the nozzles move in the same direction of the rotating knob. The throttle is controlled with the linear potentiometer along the right side of the box. When the stick is at the end closest to the passenger, the motors are off. As

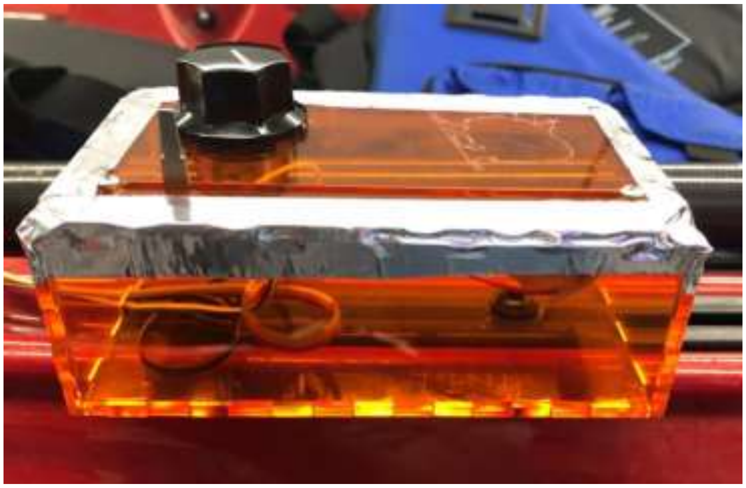

Figure 12: Control panel box

the throttle stick is moved in the direction away from the passenger, the rotational speed of the motors increased, with the maximum speed occurring when the potentiometer is at the point furthest towards the front of the kayak. This user interface allows for any passenger to easily control the Yakski.

III. EXPERIMENTATION

An experimental setup was created to test the thrust of the water jet and to validate the results of the CFD simulations. The test rig, in Figure 13, consisted of a large plastic tank filled with water, and a structure of 8020 aluminum with two vertical rods, one of which had a hinged connection to the cross rod. This rod had an acrylic plate attached to the bottom. The other vertical rod had a fish scale attached to it. The fish scale had test line tied to one end and the line tied around the other rod. This setup allowed for the calculation of thrust by using a sum of moments equation to determine the force on the plate. The derivation of thrust from the test can be seen in Figure 13 of the appendix. While this setup was far from an accurate method of determining thrust, it gave an approximate estimate and allowed for the comparison thrust between different designs.

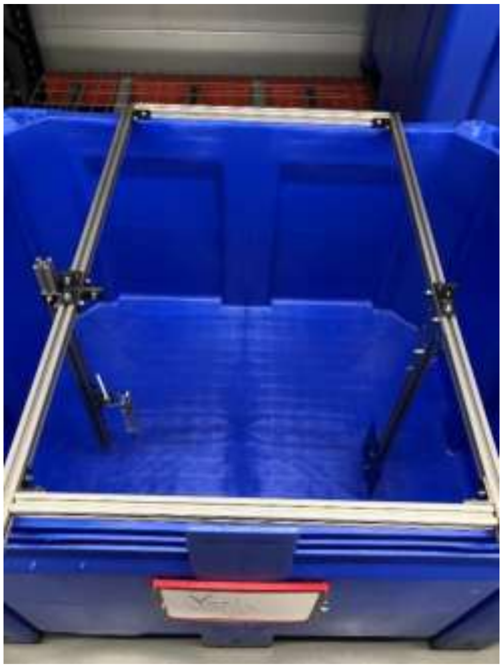

Figure 13: Test rig used for evaluation of water jet performance.

The first test of the Yakski was conducted at the Dell pond in Charlottesville, VA. This test was conducted to observe how the water jets performed and to test the variable thrust setup.

The steering nozzle system was not testing during this experiment as it was not reliably working at the time of the test.

Once the kayak with the Yakski attached was brought to Dell pond, the batteries were placed in the front compartment and connected to the wires. It was important to connect the batteries and seal up the hatch before bringing the kayak close to the water as the batteries cannot get wet. The breadboard circuit was placed in a plastic container and secured on top of the mounting system to keep it away from the water. The container was sealed with tape as well to prevent any splashing from making its way onto the breadboard.

When the batteries, circuit board, and mounting system were all secured and properly set up, the whole system was tested to ensure there were not any problems. Once confirmed that the motors worked and were able to be controlled, the Yakski was placed in the water. The passenger was equipped with a traditional kayak paddle to steer and paddle the kayak in case problems with the Yakski arose while testing.

The water jets were able to create suction and propel the kayak forward. The kayak traveled slower than anticipated, but was able to pick up speed and cruise at a pace of around 7 mph. The variable thrust system worked as well, with the kayak able to turn itself when running. The test confirmed that the Yakski system would work, given that no major problems were encountered. It was clear that a lighter design was necessary if the speed of the kayak were to be increased. This test was an important step to see what could be optimized for the final test.

The second and final test to place at the Ragged Mountain Nature Area water reservoir in Charlottesville, VA. The same procedural set up and safety precautions were taken as before. For this test, the steering nozzle system was in place and ready to be tested. The motor and steering controls were tested out of the water to ensure all components were set up correctly and working properly. After confirmation that the motors and steering system were functioning, the kayak was moved into the reservoir.

After running for a few seconds, the motors appeared to stop and waterjets stopped propelling water through the stator. The passenger noted that the motors were turning very slowly and the steering system wasn’t working. After being unable to fix the system in the water, the kayak was brought out of the water to be inspected. It appeared that circuit was shorted out by a loose wire in the touching one of the H-bridge chips in the breadboard. Unfortunately, testing on the steering system had to conclude because the circuit was not operational after being shorted out.

As an additional test, the motor throttles were wired directly to the potentiometers as was done during experimental testing. The system performed in a similar manner as during the Dell pond test before the left motor experienced problems. The inconsistency with how the Yakski ran could be attributed to the cold temperatures, but due to the conditions and time constraints, the Yakski could not be fixed in time for another test at the reservoir. Like the Dell pond test, it could be concluded that all components of the Yakski work together in a vacuum. Due to real world conditions and time constraints, a full working test was unable to be conducted, but the proof of concept was able to be confirmed, as each part worked at some point during the test.

IV. DISCUSSION

The testing of the Yakski system showed that the machine was functional, but did not meet all of the intended design goals of the project. The team succeeded in developing an efficient water jet propulsion system that is powered by electric motors that effectively propelled the kayak. The design includes a functional steering system. The system is easy for the user to control, and the entire device can be completely removed or mounted onto the kayak in under 15 minutes.

Although the project resulted in a number of successes, there were a great number of shortcomings. The kayak did not reach the speeds for which the team had hoped, and the turning system was underdeveloped. There are a number of possible reasons why the kayak did not reach higher speeds. During testing for thrust using the test rig, the team was able to manipulate the height of the jet to produce maximum force. During testing, the height was set and could not be changed once the kayak was moving. Given that temperatures were below 45 degrees for both water tests, it is possible that the batteries were at too low of a temperature to provide the required current to run at full throttle.

The mounting system was too heavy for the amount of thrust that the system could produce, and the portion of the mounting that sat in the water was not hydrodynamic and was not verified by flow simulation. The electronics were brought to the prototype level, as they were proven to work in the lab and for a limited amount of time, but a more robust wiring and container design would have prevented the premature failure of the system during testing.

There are a number of improvements that could be implemented through future work. A lighter and more elegant mounting scheme would result in higher top speeds, a more aesthetically pleasing appearance, and easier mounting and dismounting. The soldering of a perf board would prevent shorts and decrease the overall size of the electronics, which would allow for better waterproofing for durability. A reversing mechanism would give the system added maneuverability, but would require a more complex water jet housing or mounting design to accommodate the mechanism. The addition of a switch in the control box to turn power from the battery on and off would make the powering of the system much safer and easier. A more effective waterproofing of the battery container would make the system safer in the event of capsizing.

V. ACKNOWLEDGMENTS

The goal of this project was to design and build an electric propulsion system that would propel a kayak. This goal was achieved to an extent, and valuable experience in product development, machine design, CAD, CFD, and project-based work were gained. We would like to thank multiple University of Virginia Engineering faculty and staff for their support in our completion of this technical project: Gavin Garner -- Associate Professor and Director of Undergraduate Studies in the Department of Mechanical and Aerospace Engineering, Daniel Quinn -- Associate Professor in the Department of Mechanical and Aerospace Engineering, Sebring Smith -- Engineering Technician and Lewis Steva -- Engineering Technician.

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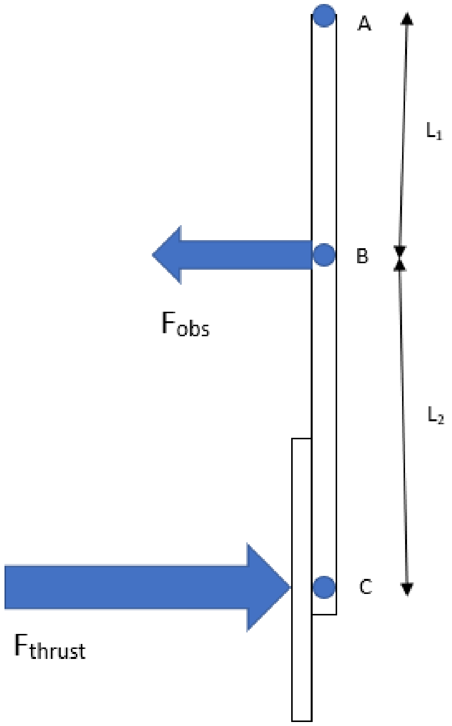
VII. APPENDICES

Figure A: Test Rig Model



Thrust derivation by sum of Moments:

$$\Sigma M_A = M_{Thrust} + M_{obs} = 0$$
$$M_{Thrust} = F_{Thrust}(L_1 + L_2)$$
$$M_{obs} = F_{obs} L_1$$
$$F_{obs} = m_{obs} g$$
$$F_{Thrust} = \frac{m_{obs} g L_1}{(L_1 + L_2)}$$

Figure B: Final Circuit Diagram