ASME IAM3D Hovercraft Challenge

Oregon State University

The Flying Beaver

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1. Individual CAD Additive Manufacturing

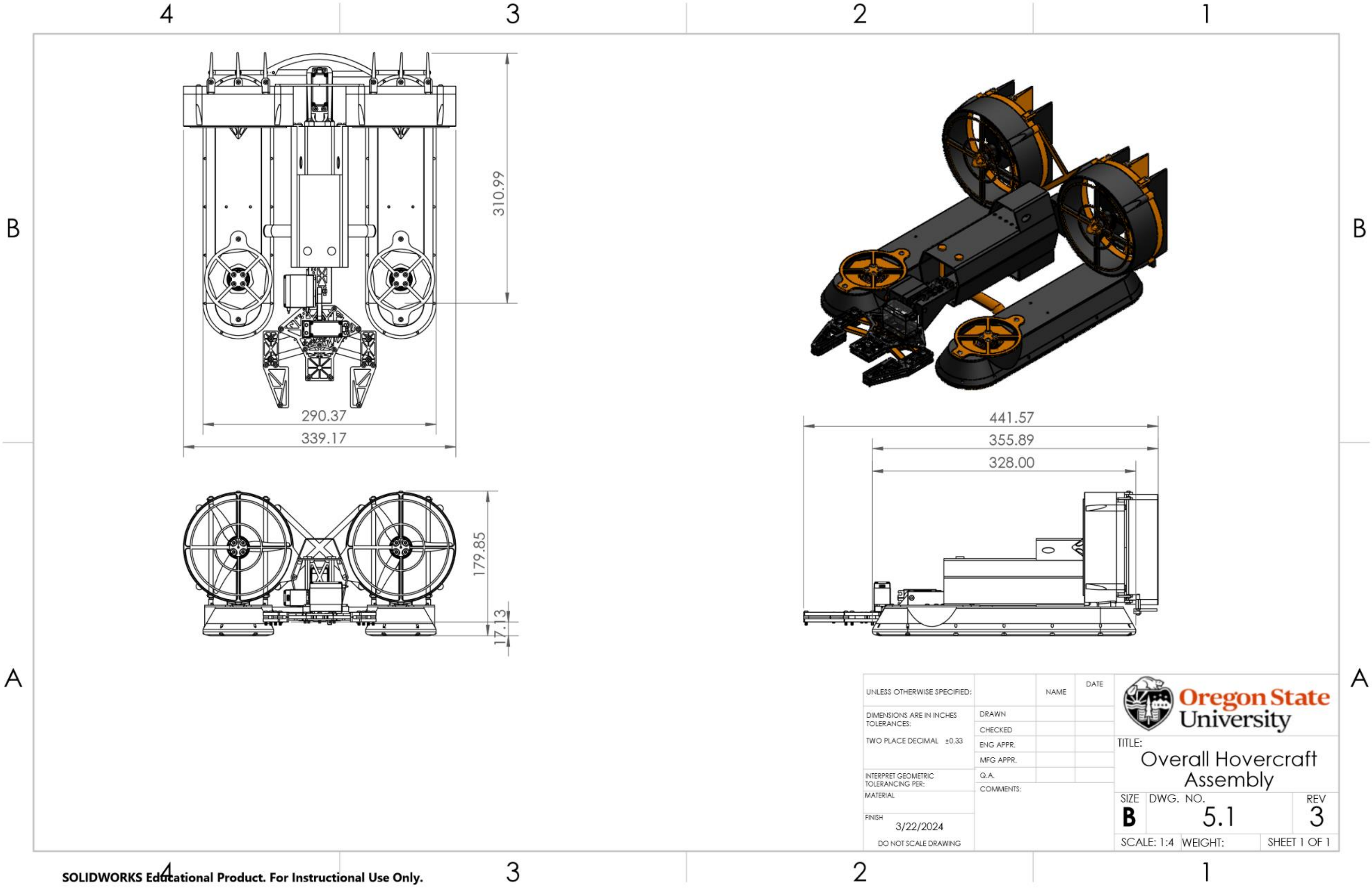
Individual CAD drawings for every part created using additive manufacturing are attached in the Appendix and provided in Table 1.

Table 1: List of all additive manufactured component part numbers, names, and number on assembly.

Part Numbers/Names		
Part Number	Name	Total # for Assembly
1.1	Pontoon Outer Shell	2
1.2	Pontoon Inner Shell	2
1.3	Pontoon Fan	2
1.4	Drag Skirt	4
1.5	Motor Brace	2
1.8	Wire Guide Base	2
1.9	Wire Guide Cap	4
2.1	Thruster Shroud	2
2.2	Steering Ring	2
2.3	Long Aileron	2
2.4	Short Aileron	4
2.5	Aileron Link	2
2.6	Steering Connection Link	1
2.7	Servo Link	1
2.8	Servo Horn	1
2.9	Front Thruster Screen	2
2.12	Rear X Brace	1
3.1	Center Body	1
3.2	Front Pontoon Leg	1
3.3	Pontoon Leg Body Connector	1
3.4	Battery Tray Pins	1
3.5	Servo Mount	1
3.6	ESC Tray	1
4.1	Grabber Claws	4
4.2	Grabber Upper Mounting Plate	1
4.3	Grabber Lower Mounting Plate	1
4.5	Grabber Motor-Driven Gear Arm	1
4.6	Grabber Idler Gear Arm	1
4.7	Grabber Four-Bar Outer Arm	2
4.8	Grabber Joint & Hard-stop	1
5.1	Overall Hovercraft Assembly	-
5.2	Exploded Hovercraft Assembly	-

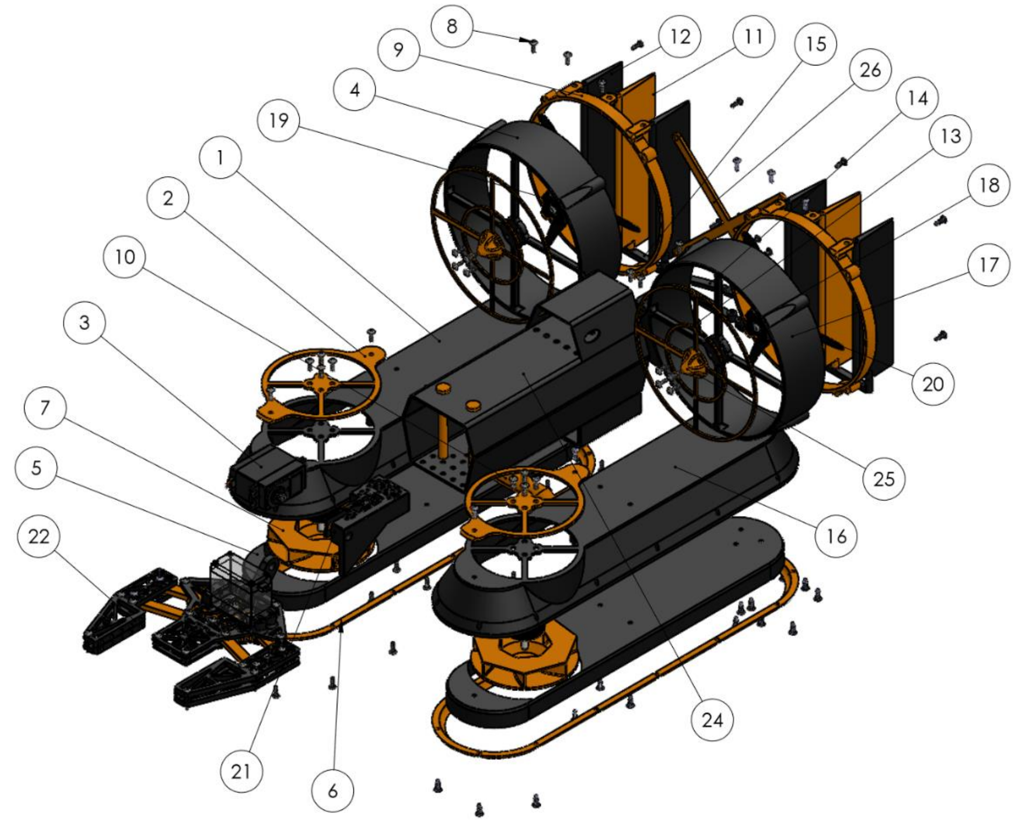
2. Formal Vehicle CAD

Formal vehicle CAD drawing with a bill of materials



Section 3: Exploded CAD Assembly

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Part 1.1 Pontoon Outer Shell		1
2	Part 1.5 Motor Brace		1
3	MG996R_SBORKA_v1		2
4	Part 2.1 Thurster Shroud		1
5	Part 1.2 Pontoon Inner Shell		1
6	Part 1.4 Drag Skirt (Half)		4
7	Part 1.3 Pontoon Fan		1
8	M3x0.5 Button Head Hex Driven Bolt 8mm	Button Head Hex Drive Screw	85
9	Part 2.2 Thruster Steering Ring		1
10	Part 3.2 Front Pontoon Legs		1
11	Part 2.3 Longer Aileron		2
12	Part 2.4 Shorter Aileron		4
13	Part 3.5 Servo Mount		1
14	Part 2.6 Steering Connection Link		1
15	Part 2.5 Aileron Link		1
16	Part 1.1 Pontoon Outer Shell MIRROR		1
17	Part 2.1 Thruster Shroud MIRROR		1
18	Part 2.7 Servo Link		1
19	Part 1.6 XING2 Motor		4
20	XING2 51466 Propellers		2
21	Part 4.8 Grabber Joint & Hardstop		1
22	Simple Claw Assembly		1
23	Part 2.8 Servo Horn		1
24	Part 3.1 Center Body		1
25	2.9 Front Thruster Screen		2
26	Part 2.12 Rear X Brace		1



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Oregon State University

TITLE: Exploded Assembly with Bill of Materials

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4. Analyses

4.1 Component Specifications

When forming our design, a lot of thought was put into the use of fasteners, electronics, and additive material to be used. By selecting certain materials and standardizing our components, we were able to produce a design that is both functional, and easy to manufacture and assemble. This section aims to provide a comprehensive overview of the specifications of our components, materials, and overall design.

For additive manufactured components of the hovercraft, we have selected “PLA Professional” from OVERTURE (also called PLA+). This material is both durable but ductile while also being relatively affordable. In conditions outside the competition, traversing harder terrain would be difficult using a material that would react harshly to repeated impacts. The properties of the PLA+ formulation allow for higher strength with no particular loss to the ductility of PLA, making it the perfect choice for this application. Additionally, unlike other plastics used in additive manufacturing, PLA is a renewable and compostable plastic. With this in mind, any broken components that cannot be repurposed into more filament can either be recycled, composted, or decay naturally if not recovered.

While the goal of the IAM3D challenge is to use as much additively manufactured components as possible, we used a large number of fasteners in our design. While there are alternative methods of fastening components with additive manufacturing, such as clips or buckles, we believed that these methods would succumb to failure under repeated impacts and loads. Additionally, mechanisms like the grabber which are compact cannot fully take advantage of these processes. Because of this, we standardized our design to use primarily M3 button-head bolts, as this allowed for us to reduce overall cost due to fasteners and keep the same level of rigidity and integration that bolts provide.

For our choice of motors, we went with *iFlight XING2 2306 16V/20W* motors. Due to our initial prototype’s larger weight, it was important to find motors that could provide enough lift force to create a frictionless surface. With the 51466 propellers attached, the XING2 creates roughly sixteen-hundred grams of force. This motor/propeller combo was used for the thrusters. The same motors are also used with the lift fans to produce the pressurized pocket underneath the lift pads. Combined with a horizontal fan optimized for the space within the pontoon, the enough pressure is produced to lift the vehicle creating a frictionless air cushion.

4.2 Performance Analysis

The success of any hovercraft design relies on its ability to navigate the terrain it is exposed to, whether that be sandy or swampy. By scrutinizing the key aspects of our design that are integral to the performance on the field, we were able to make necessary design adjustments that affect our real-world capabilities. The purpose of this section is to clearly define our expected capabilities and provide an analysis.

To determine the top speed of the hovercraft, an excel spread sheet was used in order to both calculate and chart our top speed given a set a real-world variables. For this calculation, we assumed that the surface was a frictionless flat plane in order to simplify our calculations. We used the relationship between the drag force and the thrust force to solve for the theoretical maximum speed, and this relationship can be observed in Figure 1 which graphs the hovercrafts acceleration in relation to the drag force. When the positive acceleration due to the thrust force is in equilibrium with the negative acceleration due to the drag force, the hovercraft enters a steady state scenario, and the velocity remains constant.

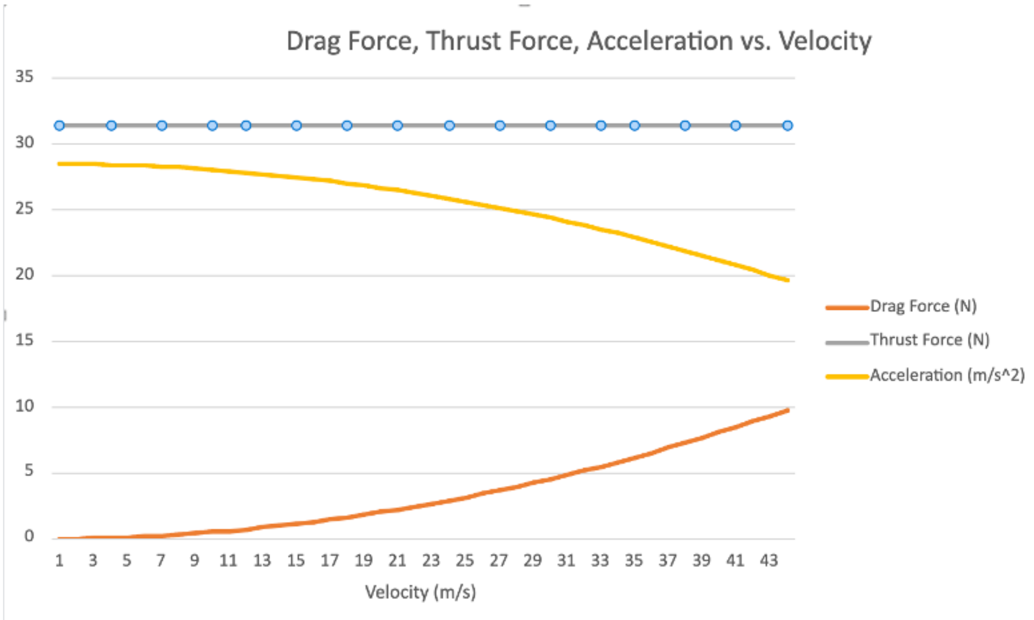

Figure 1: Theoretical performance chart for the hovercraft.

The thrust to weight ratio in relation to approximated drag coefficient results in a vehicle with outrageous performance. Since the motors have a thrust force of 1651 gram-force at 100% throttle, this was converted into Newtons and used for our calculation of top speed. To determine our opposing force from drag, we used the equation:

$$F_d = C_d \times \frac{1}{2} \times \rho\, U^2 \times\ A \qquad [1]$$

Where C_d is the drag coefficient, ρ is the density of air, U is the flow velocity relative to our object, and A is the surface area experiencing the drag force. By assuming the velocity of air is zero and solving for the flow velocity, we can find our maximum velocity. If we assume in our calculation that the relative object is stationary and calculate the flow of air, this velocity can be applied to a moving vehicle when the air is at a steady state.

Using this formula, we were able to determine a maximum speed of 176.31 miles per hour, or 78.82 meters per second. Air density was determined from a table provided by the University of British Columbia, where the density of air is 1.225 kgm^{-3} at room temperature and zero elevation [2].

Section 5: Design for Manufacturing and Assembly Analysis:

Design for Manufacturing and Assembly (DFMA), a process pioneered by Geoffrey Boothroyd and Peter Dewhurst, is an important tool that engineers use to reduce cost, decrease time, and increase the effectiveness of manufacturing methods [3]. There are many considerations that go into DFMA such as selecting the appropriate materials, reducing part count, reducing complexity of designs, and potentially designing more parts with standard manufacturing methods in mind.

Designing for manufacturing focuses on designing parts that decrease the cost of manufacturing by reducing the need for multiple work pieces, reducing waste by conforming to workpiece specification, increasing utilization of material, and decreasing cost. Additionally, designing parts with simple and uniform geometries can significantly improve manufacturability. Complex shapes and features may require specialized machining processes, which can lead to increased machining time and overall cost. By simplifying part geometry, designers can benefit from standard manufacturing processes and ensure that there will be minimal risk during the manufacturing process. Additionally, considering proper tolerances and taking advantages of principles like press fit and close fit can reduce the number of fasters required and increase reliability of mechanism. Standardizing components is also a major factor to consider when designing for manufacturing. By reusing the same components throughout a design, machinists can utilize the same stock more efficiently and decrease cost. Standardization also encourages interchangeability, making it easier to maintain and repair mechanisms due to fatigue or damage. In relation to an additive manufacture, designing for manufacture required DFAM (next section) where parts are designed to minimize print times and material utilization.

Designing for assembly focuses on designing parts to be easily assembled, modular, and accessible. The fundamental aspect for designing for assembly is reducing the number of total parts. Regarding this project, certain components such as washers or spacers can be combined into one part by merging them with, perhaps, a build plate. Modularity is also an important aspect of designing for assembly, as being able to remove smaller assemblies without destroying the integrity of others can make maintenance and replacing components much easier in the lifecycle of a product or mechanism. Finally, accessibility during assembly is crucial for both initial assembly and disassembly or maintenance. By using a large amount of fasteners and making certain components harder to access, this can dramatically increase the cost of repairs or assembly, and therefore increase the cost for both the manufacturer and the end user. It was decided that varying lengths of M3 screws would be used as a standardized part. This choice results in a more uniform design with lowered costs as screws can be pulled off previous iterations or purchased in bulk.

Overall, applying DFMA to our hovercraft was an extremely important aspect of our design process. Since the real-world application of our design will be used in humanitarian scenarios and third-world areas, having less complicated mechanisms and standardized fastening can be the difference of being able to maintain the vehicle and having to leave it in disrepair.

For our initial design, the goal was to use the least number of components while maximizing control system options. This design utilized the max diagonal area of the print bed on an Ender CR-10 which enabled us to print the large pontoons as one single component rather than as multiple components that would have needed assembly. This design was simple and effective at producing initial functional results that guided towards future iterations. It also allowed us to test a variety of motors for both our propulsion and lift mechanism in order to determine the proper amount of power required from our motors. However, we began to face challenges in our ability to iterate this design. Since the plenum chambers, which can be seen below in Figure 2, were both designed as one large piece, we were not able to quickly replace them or iterate upon them due to the print time and lack of modularity. One issue we immediately ran into was that when we tested our design on abrasive surfaces, it became a challenge to generate consistent air pressure. Furthermore, the impacts to the vehicle were repaired rather than components replaced given the over-built nature of the parts. There was a tradeoff where the thick plastic on the first iteration of the pontoons extended print times but also allowed for repairability using plastic welding. In contrast, thin plastic would have likely warped if plastic welding was attempted, but would also be much quicker to print. Because of this, in our second iteration, we decided to create replicable skirts that are bolted together.

Figure 2: Image of our first iteration hovercraft design (February 21st, 2024)

Additionally, the initial design used far more material than required. The pontoon was formed with an inner and outer skirt creating a momentum curtain; however, this initial design required a change in angle (or large curve) to be able to be manufactured as a single component. That extra space within the pontoon required the fan to move significantly more air than our weight and surface area would have otherwise required. By reducing the size of our plenum chamber in the future iterations, we were able to reduce overall weight of the vehicle and decrease the power required to create consistent, uniform lift.

Initial development of the grabber mechanism produced an assembly with more individual components than anywhere else on the hovercraft (See Figure 3). However, DFMA was kept in mind during the design process.

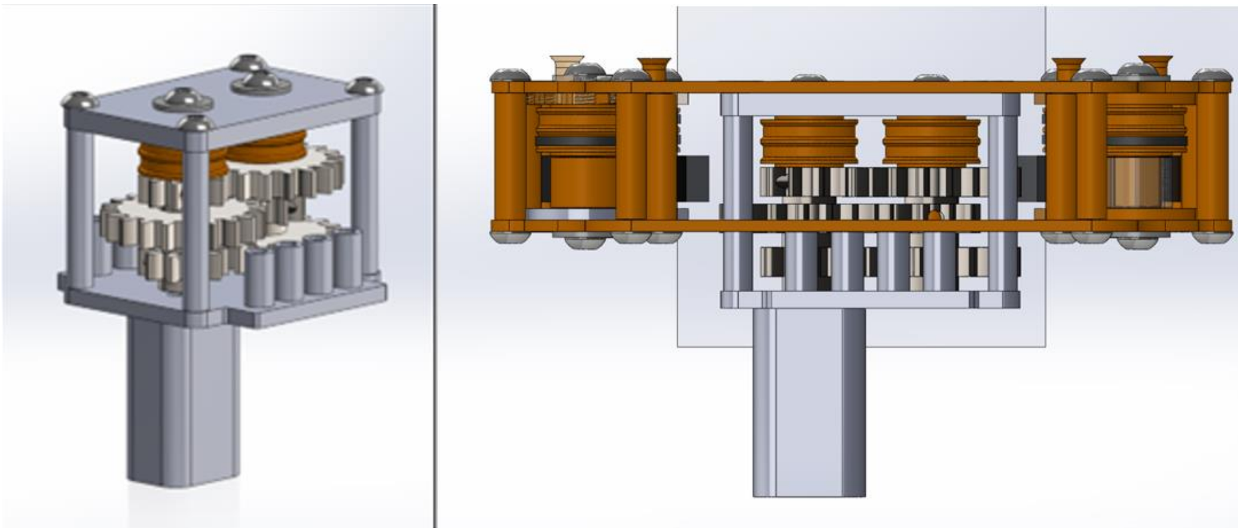

Figure 3: Image of grabber gearbox (left) and assembly (right)

Modularity was important to make this design possible, however, it quickly became apparent that this design was the opposite of DFMA. Removing and assembling the gearboxes was more complicated than anticipated because modularity was poorly implemented. The design required the gearbox to be assembled along with the entire grabber, rather than it being assembled separately, and integrated afterwards. By allowing the gearbox to be inserted from the bottom of the backplate and integrated post-assembly, it made it much more accessible to repair and replace the gearbox assembly. Figure 3 shows the complexity of the gear box and implementation into the grabbing mechanism. This design was dropped in favor of a much simpler design as seen in Section 7.8.

DFMA was incorporated in future iterations as the design became more refined and we were able to understand what was working and what needed to be changed. As detailed in Section 7.1, the pontoon design made slightly smaller and was separated into several parts since the motor mount position changed. This resulted in faster manufacturing times.

Additionally, the thruster design incorporated DFMA in the design of the steering ring mounted to the rear of the shroud. On several occasions the motors needed to be removed. This design decision remained for all iteration and made it easier to assemble the hovercraft thrusters.

Finally, as we became more competent with our CAD program, we were able to verify fitment of the entire assembly as well as simulate motion of the steering assembly. Incorporating this overall assembly view and fitment step prior to manufacturing resulted in the fasted iteration cycle that had the least amount of rework. Overall, DFMA proved incredibly useful, and many lessons were learned on how to better utilize this methodology for future projects.

6. DFAM

It is essential to understand DFAM when 3D printing. DFAM is the methodology of creating, optimizing, or adapting the form and function of a part, assembly, or product to take full advantage of the benefits of additive manufacturing processes [4]. In other words, every decision made around the design should keep in mind how it is going to print. It is important to understand load direction, what side to print on, and the limitation the printer has when printing certain surfaces. It is also desirable to have a part that doesn't require any support since it uses less material and will print more reliably. DFAM leads straight into the overall iterative approach for this team. We decided to design everything to be modular given the desire to test multiple control systems for the first iteration. The second iteration, however, refined components that worked, and changed those that didn't as lessons were learned through testing. The third iteration, or more aptly referred to as V2.5, was the final one for this team. That iteration emphasized further refinement of the second iteration including wire management, greater handling, and overall streamlining to produce an elegant product. DFAM was incorporated through the entire process as every part had to be printed. Standardized hole diameters were used with the M3 screws. Holes that needed to be self-tapped were designed to have a diameter of 2.8mm. Holes that were a slip fit allowing the part to rotate around the screw (such as the link mounted to the aileron) had a diameter of 3.2mm. On occasion, part quality differed requiring post processing. A 3mm drill bit was used to ensure tolerances were met.

Another part of DFAM is the use of engineering design tools. Part of the competition requires the use of Altair Inspire. This software simulates forces on components and uses a generative design algorithm to that modifies the component. It can be tailored to minimize weight of a part or maximize stiffness. Altair Inspire is demonstrated in Section 9. Another design tool that was used was the airfoil tool in Fusion 360. This tool was utilized heavily when iterating though many versions of the lift fans for the pontoons. It creates optimal airfoil sketches that considers 3D printer surface quality limitations. The ideal airfoil shape is a hard challenge to solve given the iterative nature of fan design. This airfoil tool saved time and had parameters that could be set within our application. After 7 generations in just the first iteration of the hovercraft, the design finally met expectations. However, since the placement of the fan changed significantly between vehicle design iterations, many more generations of lift fan were designed using this tool to eventually achieve a fan that met the needed tolerances and performance.

Figure 4: Five of the six fan iterations (4 pairs seen above) produced during the first vehicle iteration.

Additionally, adaptive cubic infill was selected as the ideal infill for inner structures. It works by increasing in density along wall adding extra support for edges while also leaving large empty spaces in the middle [3]. The infill results in considerable strength, weight saving, and lower print times. However, it is not always an option depending on the slicer program. Rectilinear infill was used on some occasions.

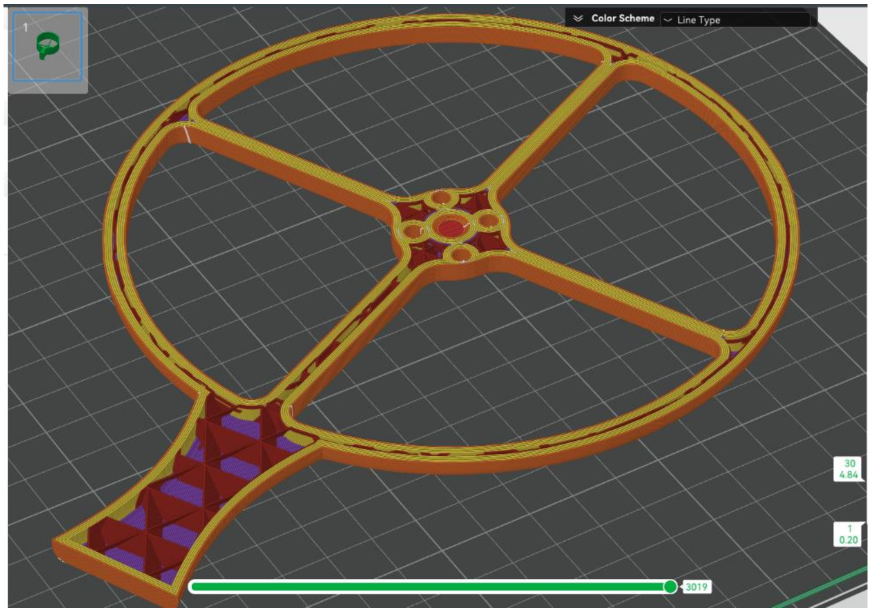

Figure 5: Sliced look at the thruster shroud for the first hovercraft iteration.

For example, the fan shroud sliced in Bambu Studio shows the adaptive cubic infill (in red) inside the base of the shroud. Print settings are crucial to the strength of the print. The bolt holes have support that connects fluidly between the motor mount and the beams that connect it to the shroud. The first print may have used more wall layers than needed, however, a sturdy design was desired given the unknown load scenarios with different motor-propellor combinations. The depth of the shroud can be seen in Figure 4. It has a flat face on the back for the steering linkage to mount to. That may seem like a good surface to print from, however, the center motor mount would have to be supported for the entirety of the print which will increase print time, cost and risk of the print failing. Ideally, a side or plane should be designated at the start of a design so it can be flush with the print bed lowering the risk of detaching from the print bed or warping. The design will also be more aesthetically pleasing when it prints as expected with little flaws. Additionally, a rule of thumb is that a design should not have more than a 45-degree angle unsupported since the filament needs the previous surface to adhere to [5].

7.1 Design Process and Iteration

The design process began with research focused into three categories: the history of hovercrafts, previous competition hovercrafts and additive manufacturing. Through researching the history of hovercrafts, the team found a design feature known as a momentum curtain, it was created by English engineer Christopher Cockerell [6] and will be a large efficiency gain for the hovercraft. Reviewing the history of hovercrafts revealed an undecided portion of the vehicle design. Since its creation in 1959 the hovercraft has been controlled by nearly every form of motion control humans have invented. Hovercrafts have used turbines, propellers, cables pulled by winches and even tires under their skirt. Even though nearly every control surface and method has been used on a hovercraft, none have become standard. A large propeller like an airboat is the most common, even among this style though you will find a huge amount of variation. This shows that while hovercrafts have been around for over 60 years, an ideal control method has still not been found.

With the beginning ideas of a hovercraft formed the team began to research previous attempts at the competition. The competition restricts vehicle size to fit within a 2”x2”x2” rectangular prism, many of the hovercrafts created for this competition are much larger than they need to be. Those that are small and agile while still maintaining a strong influence of the Cube tend to be outliers as faster vehicles in the competition. In 2019 Eastern Washington University did a great job of creating a maneuverable vehicle. They used this hovercraft to have a first place and final round finish in the 2019 IAM3D Hovercraft competition year [7]. Watching the video of their competition run you can see the vehicle has power, but the controls are very sensitive, the vehicle wants to over rotate whenever it tries to turn. This shows again that making the vehicle float is the simple part, and controlling a frictionless vehicle is where the challenge lies.

The vehicle is challenged to be made with as much additive manufacturing as possible. This means the team needs to have a thorough understanding of how additive manufactured parts handle stresses. Unlike machined components, additive manufacturing components are stronger in the plane of the print bed than they are in the direction tangent to the print bed. This is due to each layer cooling at different rates, as the material is squeezed out of a nozzle and printed in a line there is a temperature difference coming from the print head. The farther one gets from the print head the cooler the part is. This means that when a layer is finished, and the next layer begins there is a large temperature difference between the new material being added and the material already placed. This difference causes a weaker bond between the layers of material normal to the print bed. The software used for additive manufacturing also has a large variety of settings all which have an impact on the overall strength and performance of the final part [8].

Once the team had finished adequate research, the team began to work on the down selection process. This process began with a house of quality. This was done primarily to keep the teams’ stakeholder needs in mind as they work towards a final design. With this complete the team knew their focus was to create a vehicle using additive manufacturing effectively, creating effective and natural feeling control methods, while being capable of transporting the defined cargo. The team decided next to create a morph matrix, this was used to purchase initial supplies as it allowed them to define common components that would be needed no matter the final design of the vehicle. The morph matrix then led to three primary designs. A single float mono propeller hovercraft, A dual float dual propeller hovercraft, and a quad float dual propeller hovercraft. The team took these designs and using a decision matrix proved the dual float dual propeller vehicle to be the most versatile option.

7.1.1 Pontoon V1

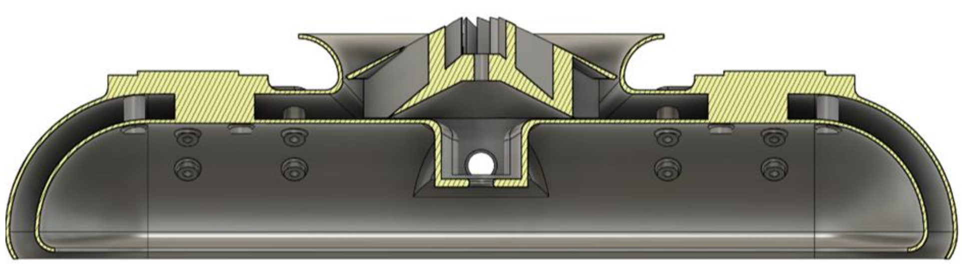

Figure 6: Half-cut Analysis of Lift Pontoon

The first generation of the lift pontoon shown in figure 6 was designed to test multiple different control methods. To achieve this the design features two universal mounts at either end with a central lift fan and motor mount section in the middle. The design is a single print and took 65 hours to print as well as used

154 grams of support material. The design was used to understand fan development and identify which control methods we will use at competition. The motor used for this design was initially a 1700kv A2212 drone motor. To connect this motor to the lift fan this utilized a collet. This design would slip at high loads or extended run times. To remedy this the next design changed the motor to an iFlight Xing2 2306 1755kv motor. This is a much more compact, powerful, and lighter motor with a more effective connection method.

7.1.2.1 Pontoon V2

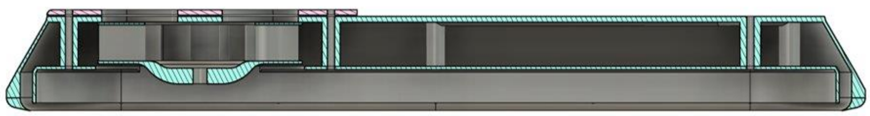

Figure 7: Half cut longitudinally of pontoon

The second generation of lift pontoon shown in figure 7 focuses on reducing weight and designing for the specific control methods the team decided to move forward with. These being rear ailerons and reducing lift to either side of the vehicle. The new motor was mounted inverted directly in the incoming airstream to maximize the potential cooling to the motor. The pontoon was designed to be printed using minimal supports needing only 17 grams of support material to complete the print. Refining the design and focusing only on the control methods described previously the design was reduced from 65 hours to 16 hours to print the complete design. This generation utilizes multiple component design to reduce print times but, it also allows the team to print spare parts for specific failures as well as focus design efforts on the specific components that need refined.

7.1.2.2 Inner Skirt

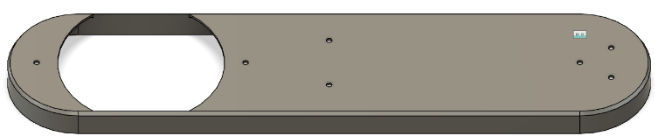

Figure 8: Inner skirt

The inner skirt's main purpose is to create an inside barrier to help with the momentum curtain effect the vehicle relies on to hover.

7.1.2.3 Wire Keeper

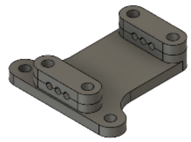

Figure 9: Wire keeper

A simple wire guide to ensure wires remain away from moving components and other possible dangers.

7.1.2.4 Lift Motor Brace

Figure 10: Lift motor brace

The motor brace acts as a wire guide and reinforces the top of the vehicle where the lift motor mounts. This area often experiences large stresses while under temperatures that weaken the base material. This large brace reinforces this area as it slots onto the top section of the device. It also serves as part of the centrifugal fan system. The smaller center diameter acts to cover the sections of the lift fans that otherwise would be exposed releasing pressurized lift air in a direction the team does not want.

7.1.2.5 Lift Fan

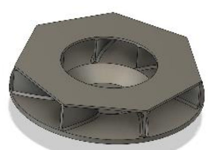

Figure 11: Lift fan

The component is spun to create the lift pressure that the vehicle rides on.

7.1.2.6 Hard Skirt

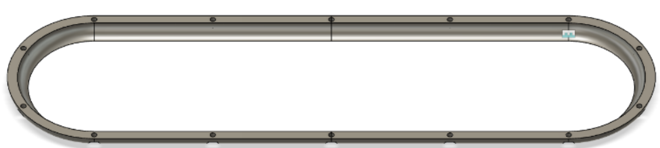

Figure 12: Hard skirt

The base of the vehicle is our skirt. This is printed in two pieces separated at the center. This component serves two purposes, the inner curve directs the lift air to create the momentum curtain that the vehicle relies on for lift. The outer curve gives the vehicle a bumper to get over obstacles higher than the vehicle's lift.

7.1.2.7 Outer Shell

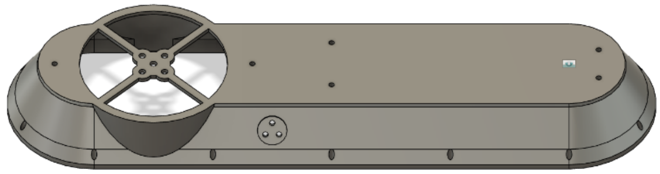

Figure 13: Outer pontoon body

The outer ponton is the most complicated part of this component. It serves as the central mounting point for every other component as well as the exterior shell of the air curtain creating lift for the vehicle. It has reinforcement underneath the top to reinforce the mounting locations of other components.

7.2.1 Lift Fans for Pontoon v1

The team initially planned on using 3" drone props for lift fans. The first attempt to drive the vehicle quickly showed this would not work and showed the team they would need to design their own. Fans are organized into three categories axial, centrifugal and mixed flow. All of these are in reference to where the air comes in and where the air exists. The team initially was planning on using axial fans and therefore had created large ducts on the intake to help draw more air in. After the drone props failed to produce adequate lift, the team switched to centrifugal fans as it was less restrictive to air flow within the pontoon. These showed a drastic improvement over the initial drone props. The team experimented with both backwards curved, and forwards curved centrifugal fan blades and found the forwards curved blades to have more consistent performance compared to the reverse curve. After the fifth design revision the lift fans were tested for an extended duration. This extended run time showed that due to the fan design the motors were not receiving enough airflow and therefore began to overheat and warp the ponton body. This testing forced the design into a mixed flow design to allow for more airflow over the motor. The initial design worked but it was very difficult to 3D print and remove the supports afterwards. The mixed flow fans were then redesigned to have a thicker base to the axial flow stages, and this created a much stronger final product with easier to remove supports.

7.2.1.1 1st Generation

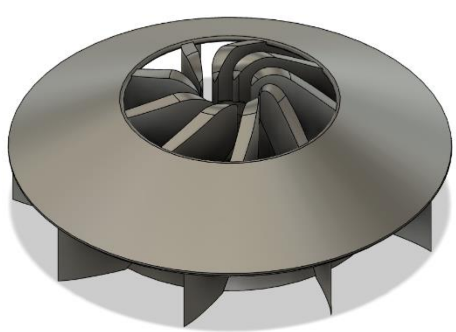

Figure 14: 1st Generation of Lift Fan

The First Iteration of the lift fan was functional but, had areas of high turbulence and looked as if they could be improved.

7.2.1.2 2nd Generation

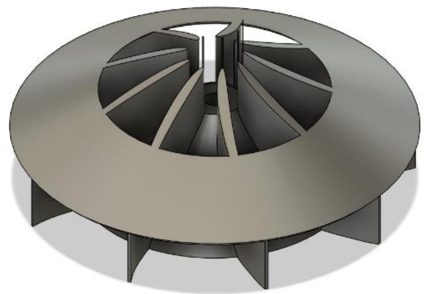

Figure 15: 2nd Generation of Lift Fan

The second iteration of the fan design focused on reducing the number of blades on the fan. This created a higher rpm fan that had better performance but, the team felt we could improve it by reducing the chord length of the fan blades.

7.2.1.3 3rd Generation

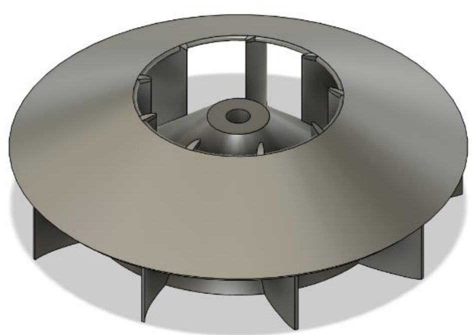

Figure 16: 3rd Generation of Lift Fan

The 4th iteration showed a dramatic increase in performance, the vehicle previously would be about 4mm above the surface of the floor with the 4th generation the vehicle at max lift maintains about 7mm of lift.

7.2.1.4 4th Generation

Figure 17: 4th Generation of Lift Fan

The 4th generation of fan took a step back, increasing the blade count of a forward curved centrifugal fan. This showed better performance than the previous generation, achieving about 10mm of lift.

7.2.1.5 5th Generation

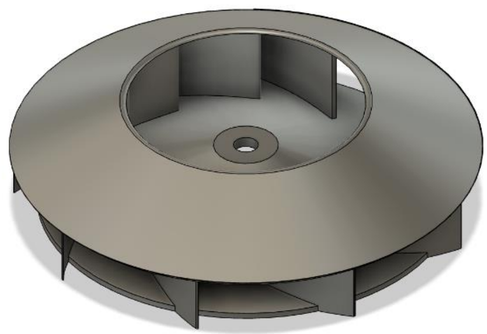

Figure 18: 5th Generation of Lift Fan

The 5th generation was the first to achieve less performance than the previous generation. This was designed as a reverse curved centrifugal fan. This produced less thrust than the previous two generations. The fan though did show that the motor was heating excessively causing the motor mounts to warp and fail.

7.2.1.6 6th Generation

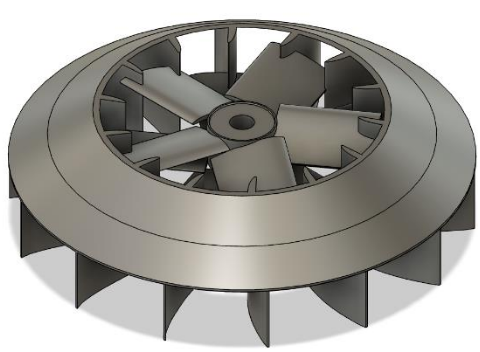

Figure 19: 6th Generation of Lift Fan

The 6th generation of lift fan is the team's first mixed flow design, it utilizes the same forward curved centrifugal fan as generation 4 but replaces the center section with a small two stage axial flow fan. This had slightly reduced lift then the 4th generation but, maintained healthy motor temperatures. The design though is very fragile and difficult to remove supports from without destroyin the fan itself.

7.2.1.7 7th Generation

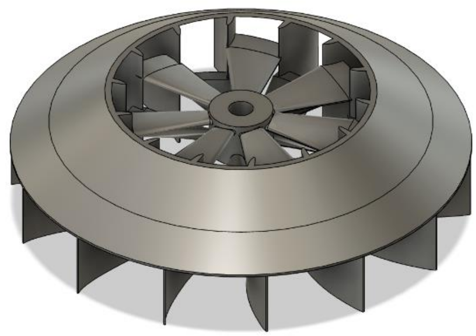

Figure 20: 7th Generation of Lift Fan

The 7th generation fan has slightly reduced performance from the previous generation. This fan though has a thicker base portion of the axial section of the fan. This makes the design much stronger and easier to print.

7.2.2 Lift Fans for Pontoon v2

Pontoon V2 is a much smaller design, this restricts the diameter of the fan prop for this series. The pontoon inverts the motor to force it to be in the incoming air stream. This improves cooling for the motor and allows the team to use a more traditional centrifugal fan design. The first design for this series was a 14 blade forward curved fan with a rather high amount of camber. This fan design was difficult to print as well as making the motors heat up excessively. The design was reduced in mas by reducing the number of fan blades as well as using an airfoil with less camber and an overall much thinner design. This design change created a weak and unstable fan. The following revisions reinforced this design in the needed areas to print well and be structurally stable.

7.2.2.1 8th Generation

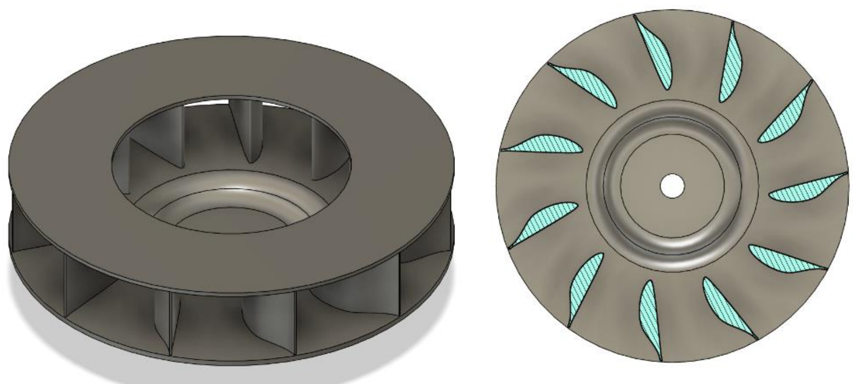

Figure 21: 8th Generation of Lift Fan

The 8th generation lift fan was redesigned for new motors and for the motor to be mounted inverted compared to our previous design. The fan itself though has tolerances too tight for operation. In less than 10 seconds of initial operation the fan seized completely.

7.2.2.2 9th Generation

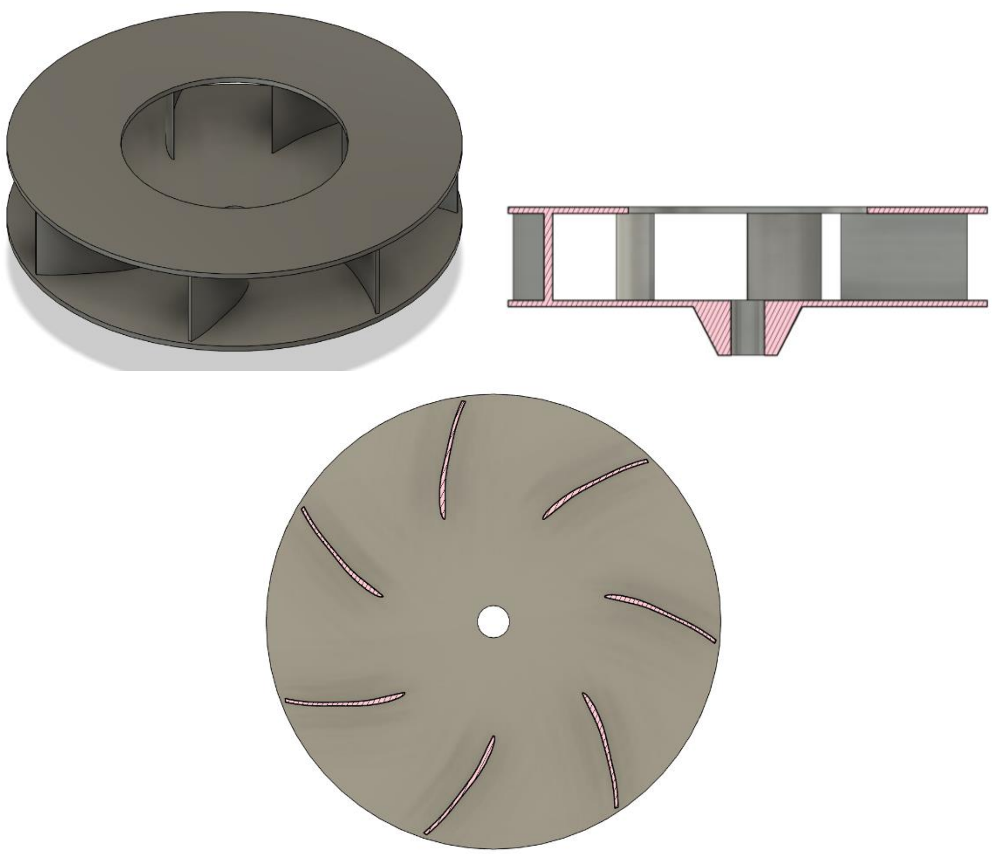

Figure 22: 9th Generation of Lift Fan

The 9th generation of lift fan was reduced in fan height to allow larger tolerance between the fan and nearby components. The airfoil was changed to one with much less camber to help reduce rotational mass, the number of airfoils was reduced for the same reason as well.

7.2.2.3 10th Generation

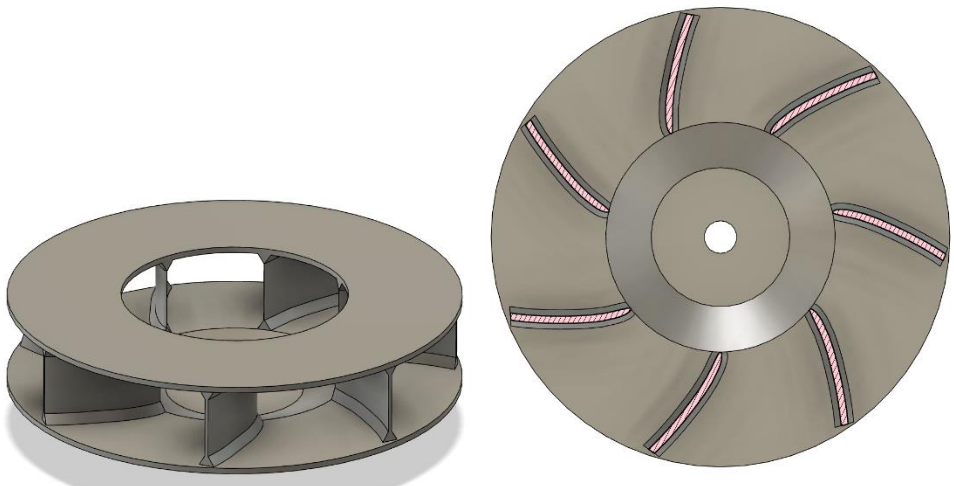

Figure 23: 10th Generation of Lift Fan

The 10th generation lift fan thickened the airfoil as the previous design often broke removing supports.

7.2.2.4 11th Generation

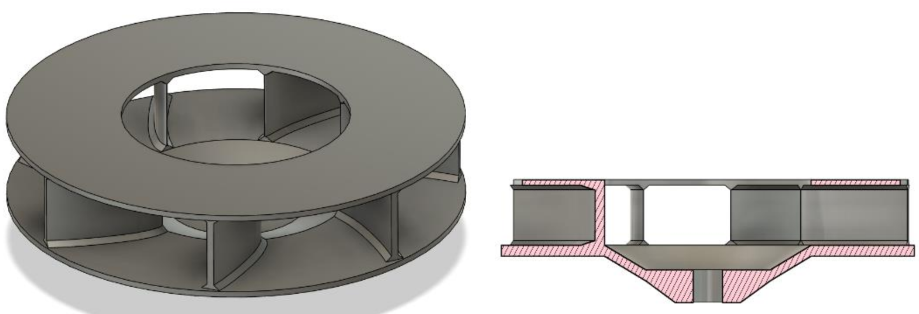

Figure 24: 11th Generation of Lift Fan

The 11th generation reinforced the fan with a thicker base this reduced the height of the airfoil but greatly improved the printing success and strength of the part.

7.2.2.5 12th Generation

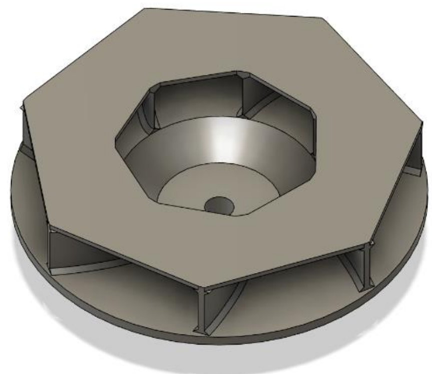

Figure 25: 12th Generation of Lift Fan

The 12th generation fan is the same as the previous with the exception that the edges have been removed to create straight perimeters on the print. This allows for more consistent prints with effective bridges. If the final shape is circular the printer struggles to bridge the gap in a curve. If it is a straight line, the printer can under extrude and as the material cools it will pull tight creating the bridge.

7.3 Front Ailerons

To get the front of the vehicle to lead when turning into a corner the team has designed front ailerons for the vehicle shown in figure 26, in a turning event they turn towards the corner, while in equal proportions the rear ailerons turn away from the corner. This creates a situation in which the front ailerons are always perpendicular to the direction of thrust. This creates drag biased towards a single side of the vehicle. This drags in combination with the rear thrust create a moment around the vehicle center allowing the vehicle to turn while taking a corner. While this showed promise and tested to be effective, when combined with reducing the speed of the lift fan inside the corner would create an excessive moment on the vehicle. This would cause the vehicle to spin instead of turning, preventing it from completing the corner. Further testing showed that the vehicle had better overall handling, reducing the front ailerons and only relying on reducing lift to create a moment while cornering.

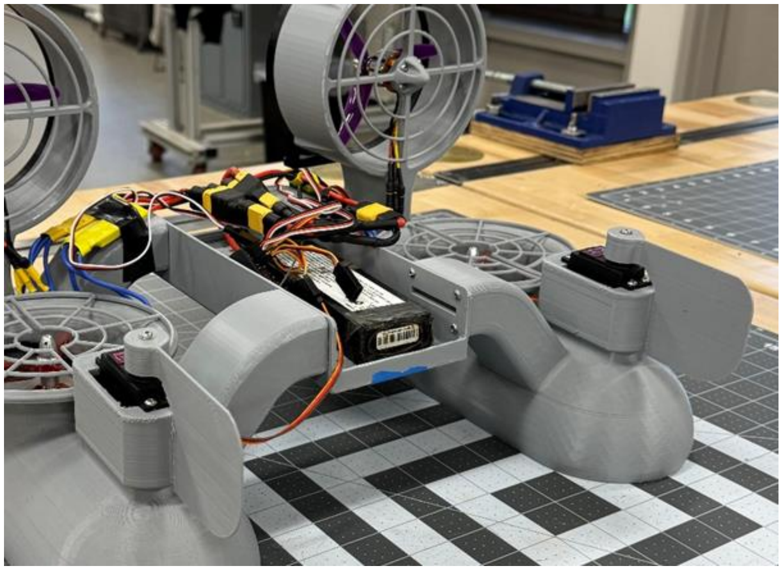

Figure 26: Front ailerons mounted on hovercraft.

7.4.1 Thruster Assembly V1.0

The thruster shroud shown in Figure 27 was the initial design for the first iteration of the hovercraft. Across all three thruster iterations the use of a central motor mount and elongated shroud that connects to a ring that holds the rear ailerons remains the same. The rear ailerons are then connected to a servo-actuated linkage. Different aileron sizes and configurations were also be tested as the control system was refined around operator preference. It was decided that two thrusters were going to be used at the concept selection stage. This decision allowed for independent testing of differential thrust steering, aileron steering, and a combination of both.

The overall design kept in mind DFMA and DFAM decisions, but was built to be stronger than necessary to ensure it survives impacts and any propeller failure. Survivability leads to more testing time when mistakes are made. The steering linkage was mirrored allowing for all of the components to remain the same except for the servo mount.

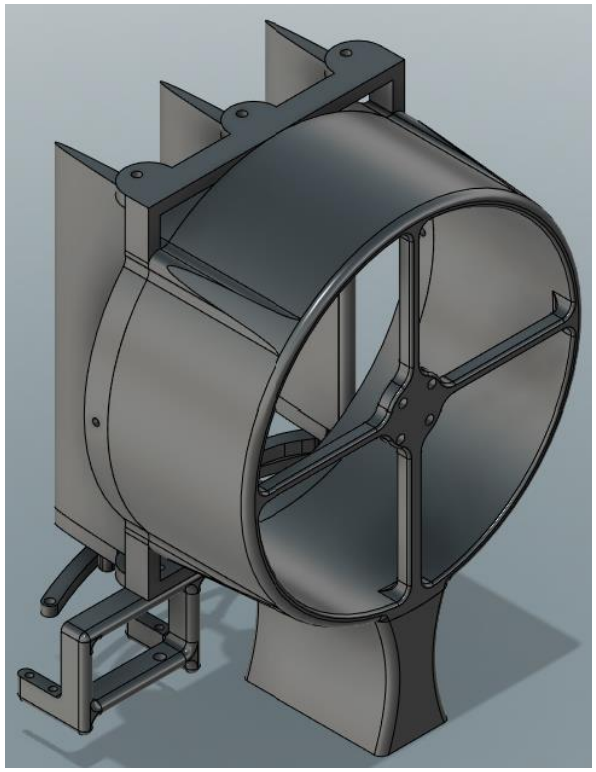

Figure 27: Render of Thruster Shroud with Rear Aileron attached.

The first iteration was designed to be robust. After completing assembly, it worked well enough to merit testing and modification. There were two glaring issues with this design. The first involved the servo mount being too narrow for the servo requiring the person assembling to force the servo and needing at least two of the four screws to hold it in place. The second issue that needed improvement was the linkage system itself. It lacked tight tolerances which lead to misalignment between the two sets of ailerons. A slight toe-in of the ailerons is desired for stability at speed, however, this thruster design wasn't optimal for that level of adjustment. Several servo links were printed to adjust the alignment of ailerons.

Another issue that occurred was the lack of thought in designing the aileron extensions. As seen in Figure 27, the aileron extends down slightly beyond the bottom of the steering ring. This design would have allowed for full motion, however, the ailerons hit the steering ring semi-circles. The ailerons had to be trimmed because of this misunderstanding of geometry. Additionally, this link bar wasn't far enough below the steering ring even with the aileron extensions leading to collisions with the screw heads underneath.

The bolt holes on this thruster worked for the A2212 motor originally used, however, the pattern was rectangular instead of square. When we transitioned to the XING 2306, with its square bolt pattern, the motor mount was modified using a drill to fit the new motor on. This change resulted in an increase in thrust from about 400g to 1600g per thruster.

7.4.2 Thruster Assembly V2.0

The goal of the second iteration was to build off the success of the first iteration while dramatically cutting weight and attempting a different linkage structure. It became slightly more complex in design out of necessity. The overall vehicle assembly also changed as the thruster became more central to the vehicle structure requiring a mounting plate to be added. This change increased the stiffness of the structure, which was needed since everything became thinner and lighter, and more flexible. The shroud wall thickness was made significantly thinner from 5mm to 2.5mm and it was reduced in overall length. The pontoon mounting bolt pattern changed along with the height of the mount and the switch to new motor mount bolt pattern. That reduction in diameter and lowered height resulted in a decrease in weight from 390 grams to 152 grams per thruster. The steering ring proved very useful at simplifying thruster assembly by consolidating the steering ring, ailerons, and aileron link separate from the shroud where they could bolt on/off when the motor/propeller need attention. The steering ring was also modified to remove the top bar, in Figure 28, which lowered drag. This change, however, resulted in a switch to two aileron sizes with a taller one in the middle, and two shorter ones on each side. Any change to control authority with the reduction in aileron length was negligible. The aileron link was extended up to meet the shorter aileron. The geometry around the aileron extension was verified prior which removed any risk of the link colliding with the underside aileron bolts.

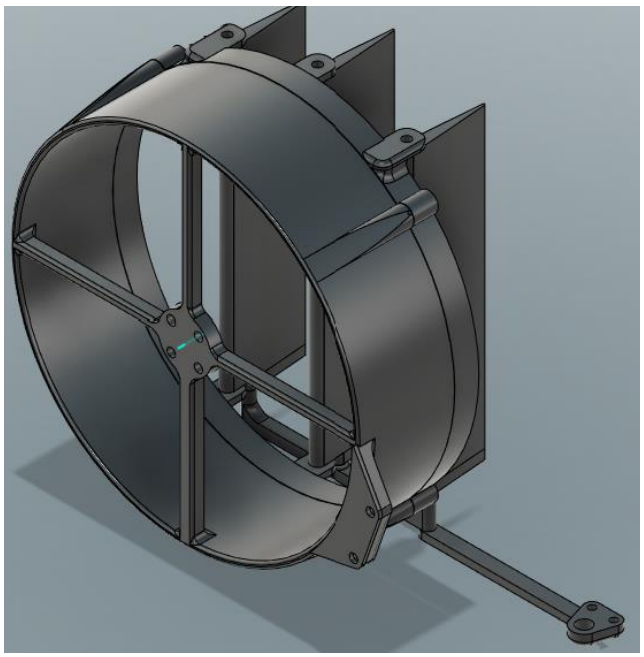

Figure 28: Render of second iteration of thruster

The largest change to the steering system was switching to a single servo to actuate the ailerons on both thrusters. The central servo mount would eliminate the weight of a second servo. It was also a decision that resulted in significant streamlining. Furthermore, combining the linkage would allow for more adjustment with the servo and optimized toe-in. However, the custom servo horn with two mount locations immediately led to binding and misalignment with the steering system. This was fixed in the next iteration.

A significant challenge with this iteration was the increased rate of print failures due to how thin some of the components were. The ailerons consistently failed many times at the same location. They required additional bed adhesion to print successfully, however, a modification was also needed too. It was discovered that designing the aileron link hole to be at the same depth as the start of the aileron extension increased the rate of failure. Too many changes to that layer contributed to its failure. Increasing the hole depth caused the slicer to change its pattern removing that discrepancy and increasing print success.

Ultimately, this design incorporated many good changes, however, the servo horn and link assembly resulted in a thruster that was barely useful.

7.4.3 Thruster Assembly V2.5

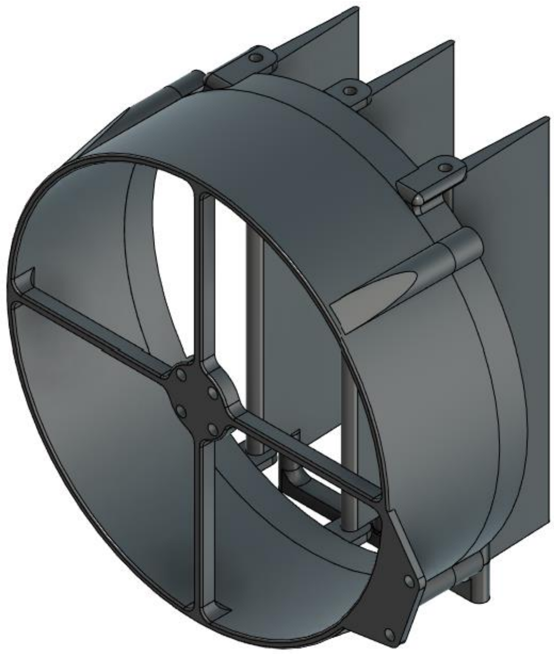

Figure 29: Final iteration of thruster assembly.

Figures 29 and 30 show the final iteration of the thruster assembly. It is referred to as Version 2.5 because the changes are more of a refinement than a full iteration. The shrouds were made 2.4mm thick to print better with the 0.6mm nozzle we switched to. Multiple test prints were made to narrow the tolerance between the inner shroud and the propeller. The propeller is approximately 129.5mm while the previous shroud iteration was 138mm. A couple test prints were made of small rings with internal diameters of 130mm, 131mm, and 132mm were printed. The propeller was placed within the ring and the fitment was visually checked. The 132mm provided a satisfactory level of clearance while limiting the risk of propeller strike if the shroud flexes.

Figure 30: Final steering assembly.

With this final version, the ability to dimension components easily was kept in mind. Needless splines on the ailerons were replaced with straight edges. Components such as the ailerons and steering link were slightly increased in size to reduce the risk of catastrophic failure and ensure they print successfully. M3 screw holes were given a boss which creates a stronger aileron that prints more easily since vertical supports are needed all the way to the to the boss to transition the overhang.

Furthermore, the single servo design in Figure 30 incorporates a drag link and connecting bar. This differs from previous iterations but was the improvement needed to make this system ideal. This linkage scheme turned out to be much more effective and provides the confident steering that was desired by the operator.

7.5 Rear Aileron

This control method is what one finds typically on a hovercraft. It is a feasible control method but, typically, is an inaccurate control method. It will allow the user to point the vehicle roughly where it needs to go but has very little control over the orientation of the vehicle in respect to the direction of travel. This is seen watching commercial hovercrafts operate. They are typically only used in wide open areas as the vehicle will drift and float in strange directions due to wind, ground slope, and changes in lift. The team's design features three splines and a standard 1/10 scale Remote Control (RC) servo to actuate the ailerons. The component is shown above in figure 6.

7.6.1 Body V1

For the first iteration of the vehicle this was the component that had the most uncertainty in its design. It needs to hold the vehicles battery and most of the electronic components. The body show in figure 31 ties the two lift pontoons together and serves as a central mounting point for the grabber mechanism. To allow for the most adaptability in the design the first body design is simply an open basket shown in figure 7, with a universal mounting pattern on the bottom. This allows the team to test multiple iterations of electronic packages and mounting configurations before finalizing on a body design.

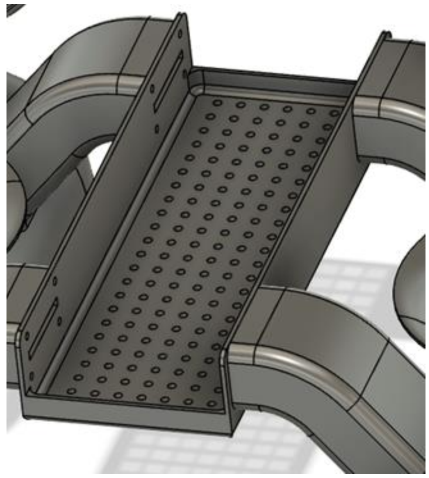

Figure 31: Render of Hovercraft Body

7.6.2 Body V2

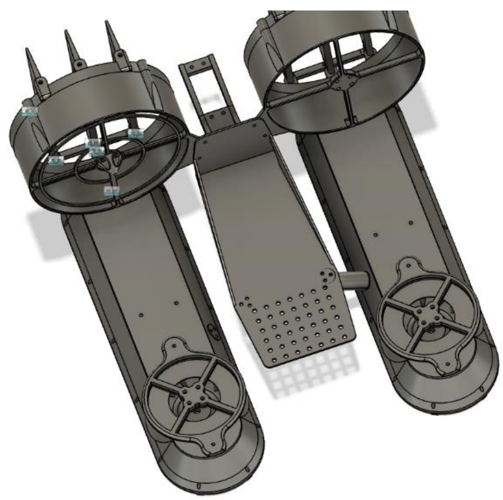

Figure 32: 2nd Generation of Body

The 2nd generation of the vehicle body shown in figure 32 was very similar to the first. The main difference is that this removes the lower mounting point and replaces it with a mounting location on the thruster. This helps reduce the mass of the overall vehicle. The thruster shrouds changed the servo location from each independent shroud to a central servo mounted to the body. The overall size of the body was dramatically reduced as well as the mounting options were reduced to only the front of the vehicle.

7.6.3 Body V3

Figure 33: 3rd Generation of Body

The third generation of the body shown in figure 33 was designed after the battery size was finalized for competition. This body was designed with specific mounting locations for specific electronic components. The ESC's will reside in a tray in the lower section of the body. The battery is held in the large central chamber and is retained with two printed pins. The servo mounts to a removable mount on the back of the body and the top section is to mount the receiver and vehicle BEC. The frontal mounting method was changed from a strut style to a clamp more like handlebars on a bike.

7.7 Initial Grabber Mechanism Design

The team's grabber mechanism shown in figure 8 needs to be able to effectively grab and hold the 2" 100g polylactic acid (PLA) cube. It needs to be able to fully support the Cube and prevent the Cube from making contact with any surface It would be beneficial as well if the grabber mechanism can grab the Cube at any orientation. To do this the team has designed a grabber mechanism that uses two DC motors to spin the below wheels using thermoplastic polyurethane (TPU) printed belts. The design would allow for some slip to prevent the motors from burning out. The device would be spring loaded to be able to compensate for different orientations of the Cube.

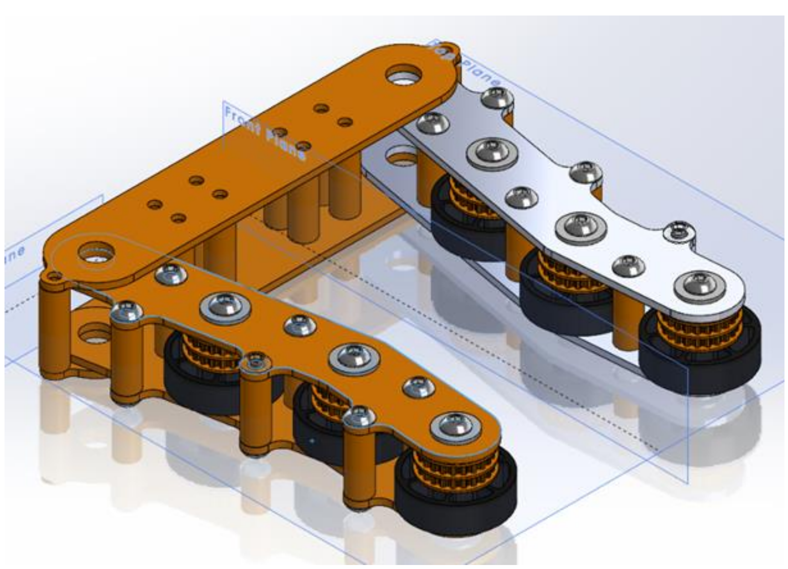

Figure 34: Initial Grabber Mechanism Design V1

However, complications in this design arose from a variety of factors. One major issue that arose was the manipulation of the arms and creating a satisfactory, constat force on the Cube. Since the ideal design would allow for joints of the arms to rotate and allow the width of Aquisition to adjust for the cubes position, motors could not be used for this application. For prototyping, springs were used to create this effect but could not maintain a satisfactory grip on the cube. Additionally, many motors available to us were not large enough to create satisfactory torque, and because of this a gearbox was designed and implemented. While the gearbox could spin properly, extra torsional forces due to friction may have been applied and caused issues with the wheel movement. Due to these factors and many others, we decided to pivot to a simpler, more reliable design for the second revision of our hovercraft design.

7.8 Final Grabber Design V1 & V2

The design our team ultimately pivoted to was a four-bar style claw mechanism. By pivoting to this design, we forfeited many of the design elements we hoped to implement in our original design including acquisition from multiple orientations. However, this design was far easier to iterate and make changes to for purposes of optimization.

By using 1.5 module gears as the fundamental mechanism for rotation, this allows us to create a claw where both joints move parallel to each other while being controlled by a single servo motor. Additionally, by adding a second linkage to each claw, both claws remain parallel to one another, ensuring an even grip on the cube and allowing for more secure acquisition. The components that make up the claw are parallel to one another in the model, making iteration much easier by being able to edit a single part and changing each component in the assembly.

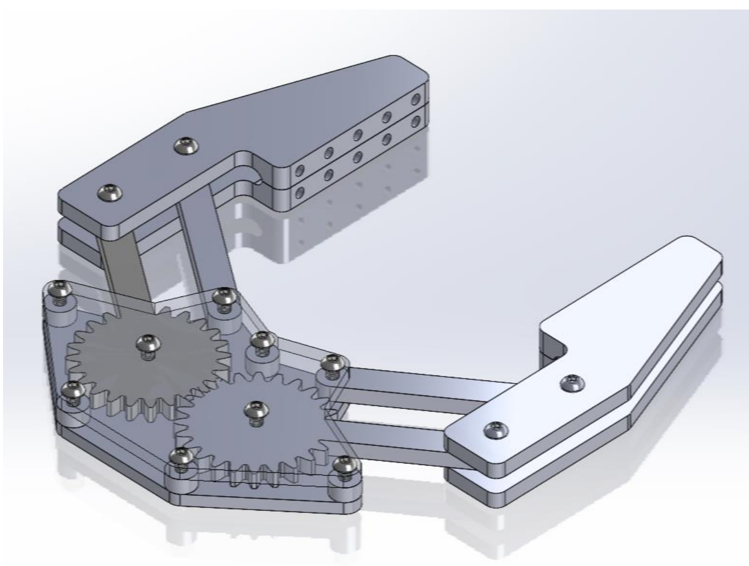

Figure 35: Initial iteration of grabber design.

There were many flaws our team was able to detect quickly with the initial design. The main concern was that the Cube may end up being trapped in the back of the assembly due to the geometry, thereby inhibiting its ability to acquire it. Additionally, issues arose with engaging the servo motor with the “Gear Arm”, which was slightly press-fit and used an additional set screw. This was done in favor of using a manufacturer provided servo horn for reasons of tolerances and spacing, but this design lacked the ability to properly engage the servo under necessary load. Issues with the claws also arose, as they lacked any standoffs in the assembly to reduce rotational movement, which caused grip on the Cube to be inconsistent. Besides these primary issues, other problems such as unforeseen spacing issues and other minor tolerance errors were also observed and addressed accordingly in the second iteration.

In iteration two of our design, the major design flaws were addressed. To ensure proper acquisition of the cube, a flat backstop was implemented to keep it in optimal position. The press-fit hole size was reduced to 5.8mm on both the mounting joint and the Gear Arm in order to increase contact stress and secure the servos; M3 bolts were also used to secure the servos with preload. Additional standoffs were added to the claws to keep the planes that contact the Cube as coincident as possible.

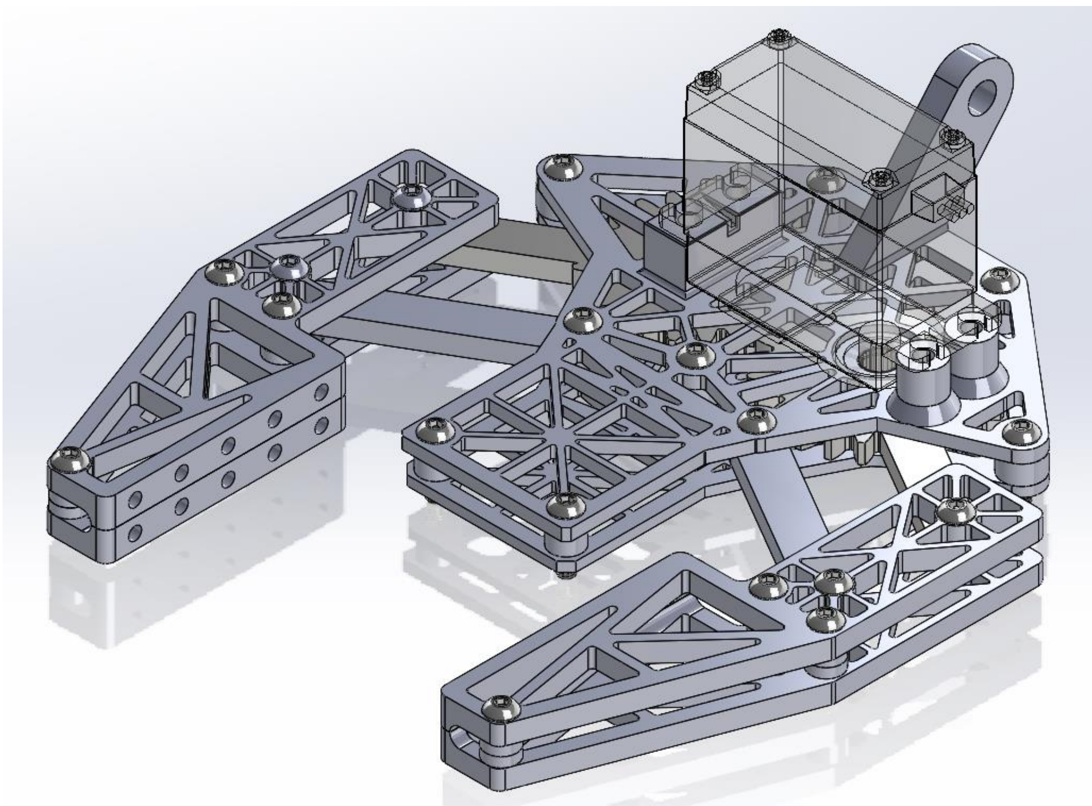

Figure 36: Isometric grabber assembly view with servo

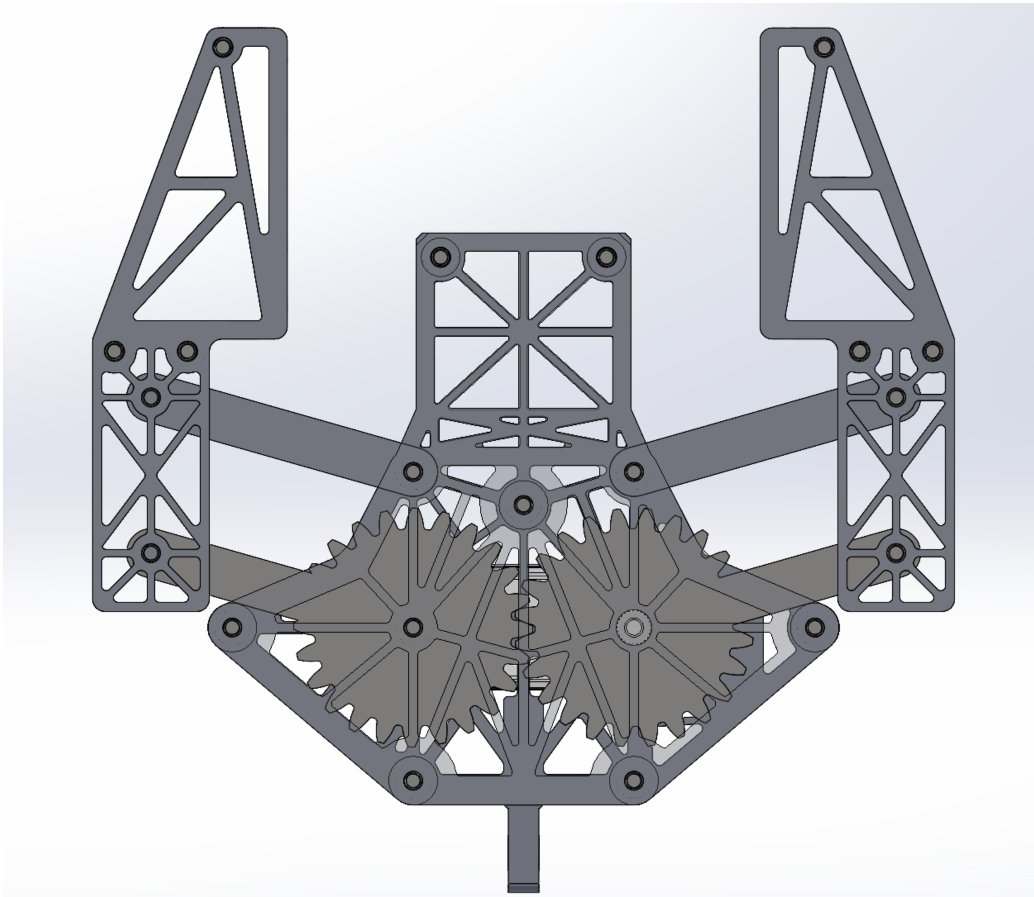

Figure 37: Grabber Assembly

Another major change made to this iteration of the design was the skeletonization of most components. A large risk in any potential design is the moment applied to the servo motor on the joint that makes the wrist mechanism. If too much load is applied to the joint, the motor may burn-out or fault during our competition run, causing time delays and a major loss of points. By skeletonizing the design, weight of the additively manufactured components was reduced by approximately fifty percent, reducing the weight to 49.2 grams from 97.5 grams plus or minus a tolerance of 5 grams. This reduction in weight allows for the mechanism to be more consistent in testing and more reliable overall; however, more testing and analysis of structural integrity will need to be done between this submission of this document and the final competition.

7.9.1 Full Assembly V1

Each of these components add up to the team's overall vehicle shown in figure 38. By designing a system with excessive mechanical control elements, each can be tested individually. This allows the team to find each component's individual contribution. This data can then be used to tune down each individual control method until the vehicle handles as we expect in a predictable manner. As the old saying goes slow is smooth and smooth is fast.

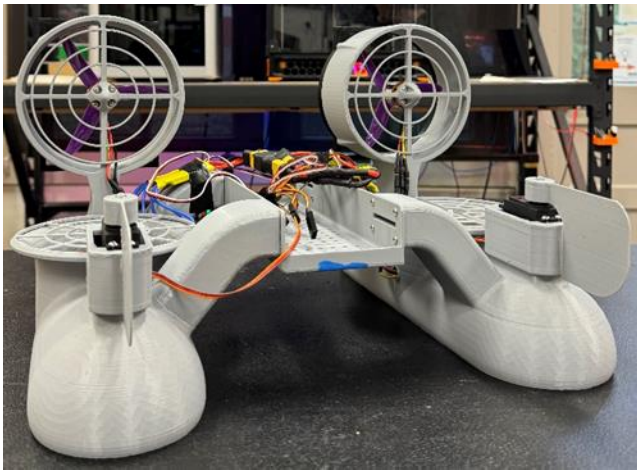

Figure 38: Fully Assembled Hovercraft (Grabber Mechanism and Rear Ailerons not attached)

7.9.2 Full Assembly v2

Figure 39: Physical assembly of functional hovercraft.

Slow is smooth but, this thing is just fast. The second iteration of the team's vehicle uses much more powerful motors with more efficient propellor and a massive reduction in vehicle weight. This iteration of the vehicle shown in figure 39 took the step from a learning device to a racing vehicle. It is designed to go very quick on a flat surface and not notice the load it is carrying. The main challenge remaining for v2 is refining the control tuning to keep this beast in control.

8. Testing

Due to budget constraints the team was restricted to basic tools to collect data on the vehicle. The primary tools used to collect data were spring scales, length measuring equipment, and personal interpretation of the vehicle's response. Using these limited tools, the team tested and iterated through a design process heavily assisted by academic research along the way.

8.1 Basic Operation Testing

Every component on the vehicle goes through basic operation testing. This is when we cycle the component through the operation it is designed for. If the component is static within the assembly, then the main procedure was to fully the component assembly and verify fitment. If everything fits as it should the part is approved as finished for that iteration. If the component is in a more dynamic environment, the component is cycled by hand initially. The component is then connected to power and initially tested at a slow speed with electronic components. If the component passes this check, it is operated at full competition speed or load. The component must pass a five-minute operational test to be approved for use. This method of testing allowed us to find many minor assembly issues before the whole assembly was printed allowing for the problem to be rectified before the rest of the assembly was printed. This procedure minimized downtime and resulted in more productive testing sessions. The two largest examples of this are generations eight through ten of the lift fan design phases. Each of these components would seize with mildly increasing operation times. The initial design barely lasted 10 seconds while the tenth generation failed in just over 2 minutes. The designs worked in assembly but under load for an extended period would fail. This drove the design to be reinforced until the eleventh generation. This version had necessary clearances and reinforcements to operate successfully for over 10 minutes. A static example of fitment testing involved a minor dimensioning issue with the thruster shrouds. This caused the vehicles rear of the pontoons to be closer together than the fronts. This forced an offset in the steering and limited vehicle operation. The issue was found when half the assembly was printed and was easily rectified before the rest of the assembly had printed. This test procedure was used to identify early issues in assembly and verify operation of mechanical linkages, often leading to design improvements and slight modifications to our steering system.

8.2 Thrust Testing

Thrust data involving certain combinations of propellers and motors often are not commonly available. If the team needed to find these values, they utilized a 3d printed motor mount and a spring scale. The test was conducted remotely to reduce the risk of injury. This simple test proved very valuable to allow the team to calculate vehicle performance expectations.

8.3 Control Mechanism Testing

The hovercraft tested a variety of control mechanisms: front ailerons, rear ailerons, independent thrust changes and independent lift changes. The team isolated each control method and tested them independently. The team then noted the various influences the control method had on the vehicle. Then, the team would test each possible combination of control methods and noted what the resulting influence was on the vehicle. This testing led to questions on individual control component modification. To test these ideas the team created multiple variations of the aileron systems. The front ailerons were made with three different surface area sizes to test the effects of increasing or decreasing the drag caused moment of the vehicle. The rear ailerons tested larger size ailerons in smaller quantities to see if a similar influence could be achieved. The team also tested each size of aileron in each possible configuration. This at one point required a redesign of the servo linkage so it could operate a single aileron instead of a set. After testing control methods independently, the team shifted to testing combinations of the control elements and noting if these had different effects than the sum of effects from the vehicle's individual components. As this test series required multiple different control schemes it also gave the team the chance to learn and refine the mix tuning of the Fly Sky G7P controller. The controller greatly reduces the response time of the team's vehicle in comparison to a microcontroller system. This comes at a cost though in that the team cannot rewrite the code to adjust for changes in the vehicle. The vehicle must be tuned and controlled through the mixing channel system native to the controller's firmware. The device has a large amount of tunability allowing us to dial in these adjustments, however the user interface can be hard to understand and often does unexpected things. Once these settings are decided the system works well but it requires an individual familiar with the device to adjust. This early test phase gave the team the opportunity to work through this learning phase. The team continued to test every combination of control methods until it was evident which control scheme to use. Many combinations resulted in similar influences and these combinations wouldn't allow us to simplify the control scheme. By February 25, the team tested the vehicle using rear ailerons and 75% lift reduction. This combination created a vehicle that responded nearly as expected and was easy to control. It would accelerate, turn sharply and enter a corner with the proper vehicle orientation. Further testing revealed this to be the best control method for the operator, and it was decided this would be our focus for the second design iteration.

8.4 Lift Testing

To test the lift the vehicle created the fans would be attached to the fully assembled vehicle. The vehicle would be then restrained and with full throttle applied. The team would then use a measuring stick to measure the height caused by the air cushion. This method was used to refine fan designs throughout each generation.

9. Altair Lightweighting

Altair Inspire is an optimization program that can be used to analyze load cases on parts and simulate optimal geometry to meet those load cases. It is especially useful when loads are defined, and part restrictions are well understood. One can create parts within the program or import designs from other programs.

The OSU Flying Beaver team made the decision to demonstrate the capability of this program on a low - risk component. This was determined in part due to the short timeline this team had to participate in this competition (began in early January), the complex nature of the design outside of Altair Inspire, and limited resources with 3D printing. The design iterations generated by this used conventional additive manufacturing strategies to maximize component print viability. Even still, there were many print failures. Adding complex geometries for critical components was not a risk this team was willing to take for this section of the design report.

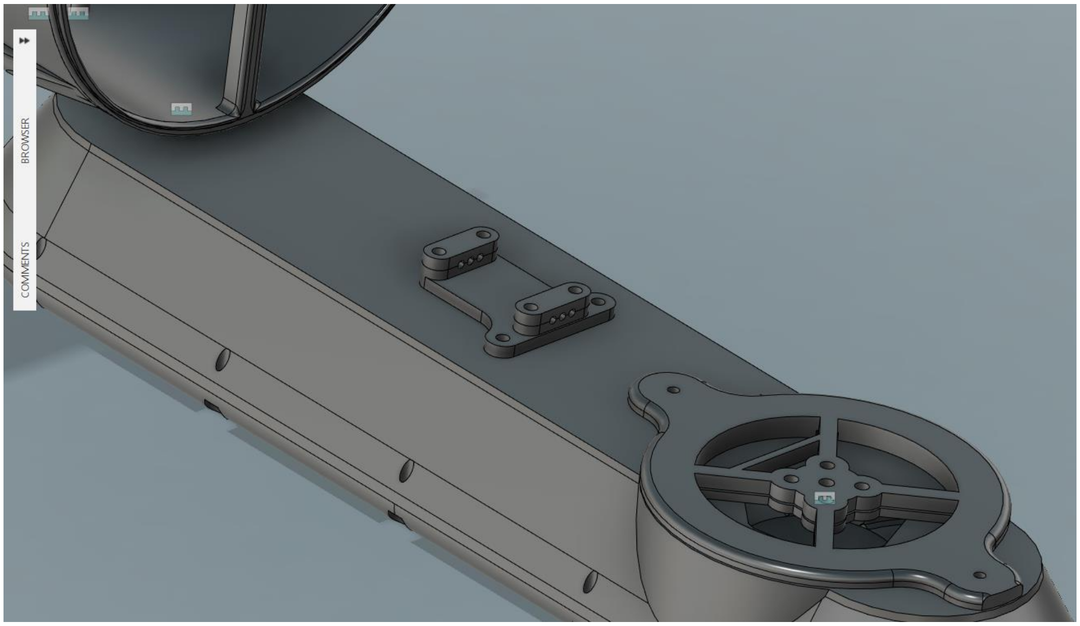

Figure 40: Render of wire retainer on pontoon.

Figure 40 shows the component selected for analysis. It is a wire retainer used to group together the thruster and lift fan wiring. Excess wiring could have been directed separately to the individual ESC's, however, a consolidated wire path to the ESC location was an engineering decision this team decided to make out of preference. The lower half component has two bolt holes that mount it to the outer shell of the pontoon and troughs for the three wires from each motor to pass through and then redirect inward to the body. The upper retainers are neglected in the rest of this analysis.

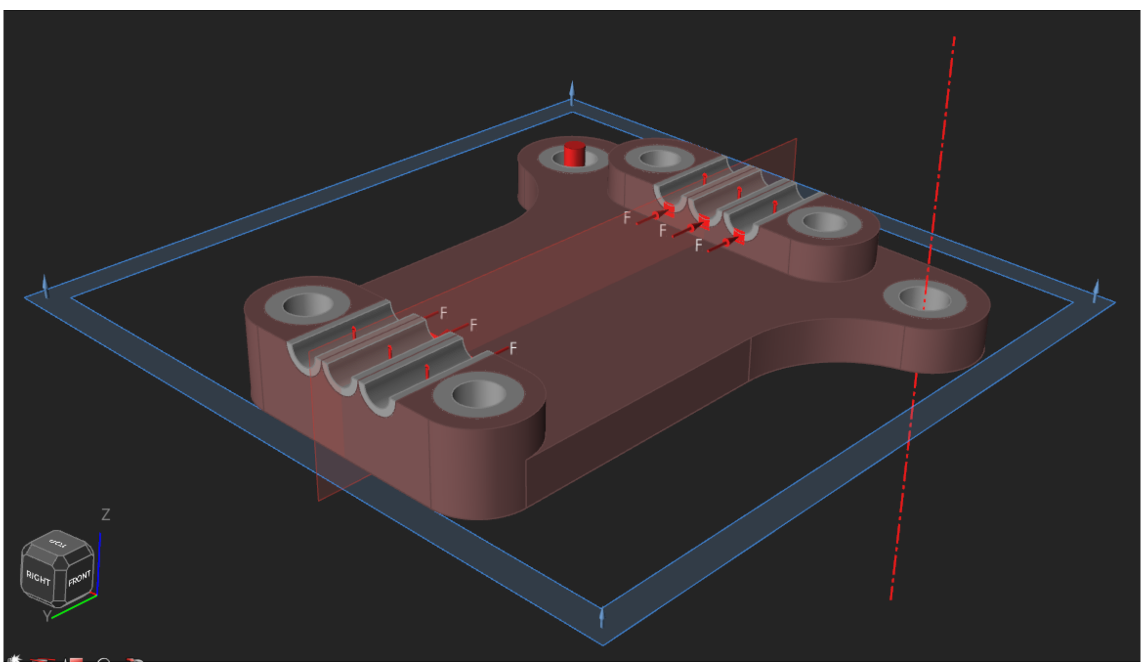

Figure 41: Load cases and section view of the lower half of the pontoon wiring retainer.

Going forward, the lower half of the three-component wire retention assembly will be referred to as the wire retainer. This part was recreated in Altair Inspire and given structural conditions as seen in Figure 41. The first step was to determine which sections of the design to remain the same. The wiring troughs and bolt holes were given suitable material to ensure successful printing. Load cases are minimal in the actual use of this part, however, to be able to use Altair to optimize a component clear criteria are needs to be defined. Given the nature of the part, wiring will be clamped in between the trough which is why the load arrows are facing down into those components. Additionally, lateral forces pulling the component apart were used to approximate a worst case where wires are tugged on. All forces were given the value of 10 Newtons (each force is roughly the weight of the hovercraft). Furthermore, the two bolt holes that fix the wire retainer in place on the hovercraft were used as supports within the program. A symmetry plan was used to ensure the part is universal for use on both sides of the hovercraft. Finally, the Single Draw plane under Shape Control was used to optimize the component for Fused Deposition Modelling (FDM) printing.

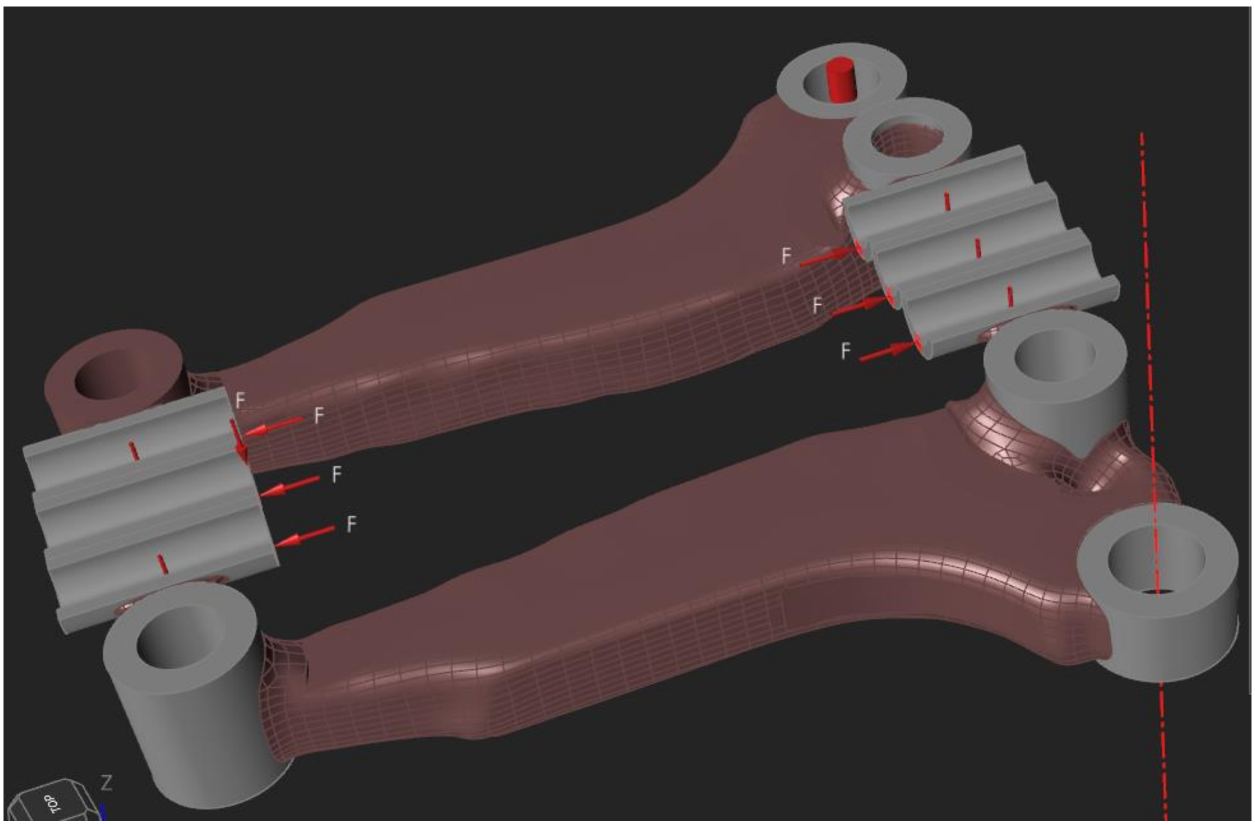

Figure 42: Optimization of the wire retainer.

Material properties for PLA Plus were found online and entered into Altair Inspire as its own material. The part was optimized to maximize stiffness while targeting a mass of 25% of the original part. Minimizing mass could be used instead, however, maximizing stiffness will yield a more robust part. Figure 42 shows the optimized shape where loads are being transferred to the bolt holes and material exists to support what is needed.

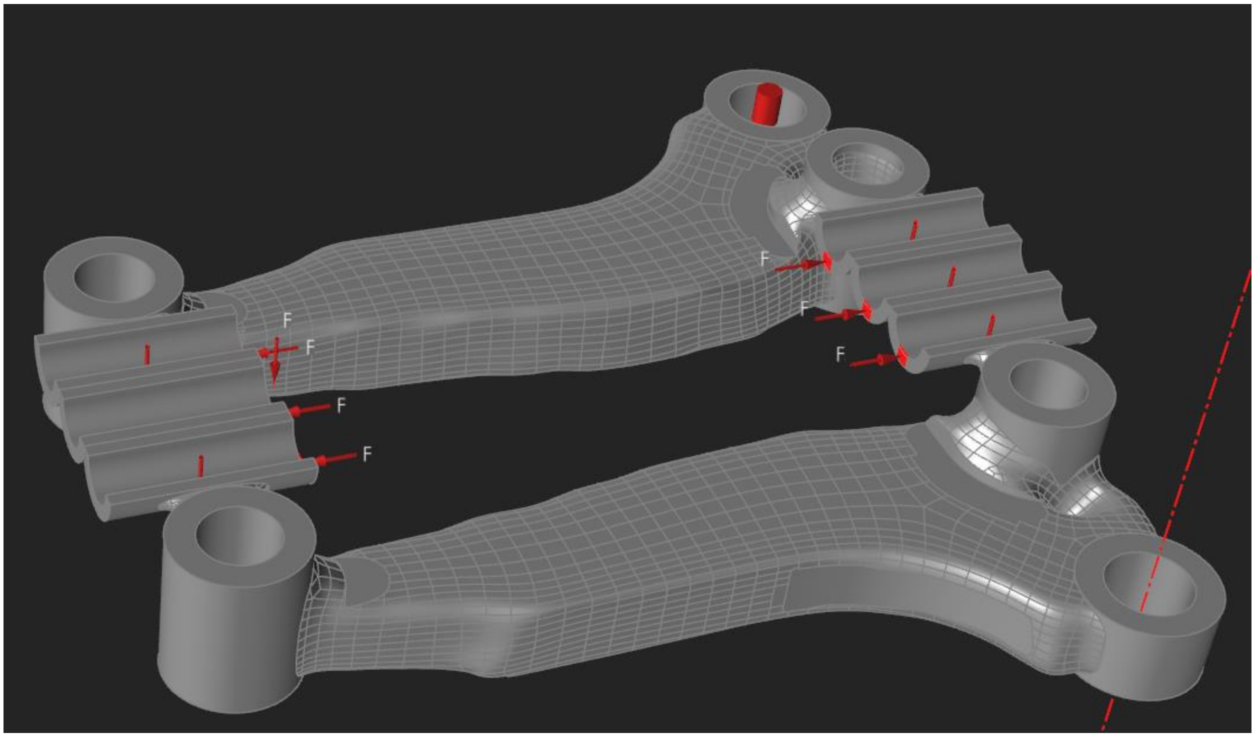

Figure 43: PolyNumbs view of optimized part.

Figure 43 shows the final refinement using PolyNURBs to smooth out the shape and make it more continuous. This simulation produces a lower cost part that will be able to achieve the same purpose as the original.

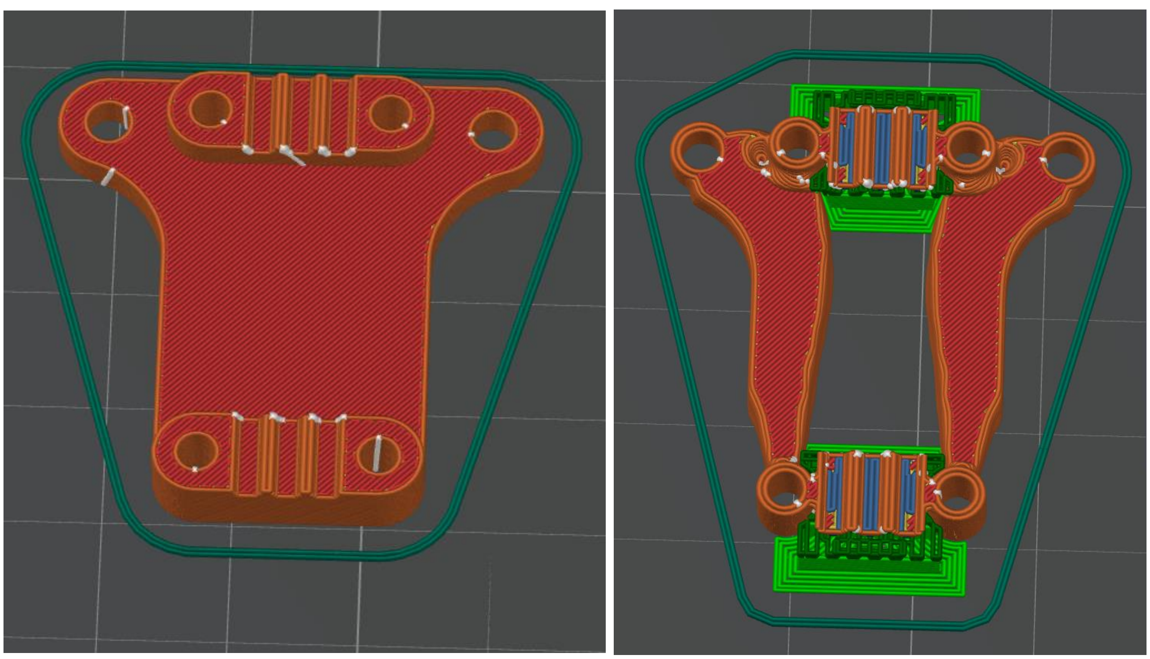

Figure 44: Sliced STL files of lower wiring retain before (left) and after (right) using Altair Inspire

Figure 44 shows the sliced file in Bambu Slicer. The new design requires supports to bridge the floating wire troughs; however, the supports use less filament than the material that would have been in its place. A generic 0.4mm nozzle will be used to print this component. The part went from 3.17g to 2.03g of material. Altair Inspire was an effective weight-saving tool.

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APPENDIX

All additive manufactured component CAD drawings are included in the following pages.