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Sim Wheel Hand Controls For Disabled Users

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Abstract

The Sim Wheel Hand Controls kit is an open-source project for disabled individuals to experience simulation racing. The project converts a Thrustmaster TX foot pedal set into hand-operated brake and throttle controls. The module uses elements from the pedal set, a 3D printed housing and commonly available hardware. The Do-It-Yourself nature of the project allows the product to be inexpensive and accessible compared to its single competitor. A website was created to share the 3D printing files, detailed instruction manual and resources provided free by the University of Akron. The team found the module to be ergonomic, durable, realistic, and comfortable for several hand sizes of users. Most importantly, this product gives racers the ability to remain competitive against those who are racing by traditional means. This report details the product development process, testing procedures, results and community outreach involved in creating and distributing the Sim Wheel Hand Controls kit.

Acknowledgments

Throughout the final two semesters of their 5th year in Mechanical Engineering, the four students found incredible support from the University of Akron and Akron non-profits. The team members would like to express great appreciation for Dr. Nadkarni for organizing the Honors Research Project course as well as supporting the SWHC team with enthusiasm. The team is particularly grateful for the guidance given by Dr. Sawyer. As the advisor for this self-initiated project, Dr. Sawyer backed the team with advice to overcome obstacles and provided encouragement through monthly meetings. The team would like to say a special thanks to Aaron Trexler, ASEC Printing Lab's Sr. Engineering Technician, for his constant support with 3D scanning and 3D printing. The team is thankful for being one of the first teams to use the 3D scanning resources which became available in January. The University of Akron resources and Aaron's willingness to support the team with printing prototypes ensured the success of this project. Dr. Kannan also made an impact on the team, as he provided measurement tools for the team that were not originally at UA. His willingness to provide resources for the project made a massive, positive difference in the verification process. Additionally, the team is grateful for Kee Sin, Sr. Development Engineer from Robin Industries, for providing the team with injection molding knowledge and mold quotes regarding the theoretical commercialization of the product.

The team would also like to thank Dr. Felicelli, Professor and Chair of the Mechanical Engineering Department, for being willing to offer free 3D printing services to the first 25 people who reach out about creating the SWHC kit. Community outreach and support could not have been possible without Mike Firtha, President of the Akron Inclusioneers, and Haylee Desonne, Leader of Summit DD. The team is grateful for their time to learn more about the SWHC kit and willingness to support the use of the product with real people in the community. With the collaboration between the SWHC team and the Akron non-profits, the simulation racing hobby can grow and become more diverse and inclusive, especially here in Akron, Ohio.

Contents

1. Introduction

The Sim Wheel Hand Controls kit, or SWHC kit, seeks to break down exclusive barriers within simulation racing. To accomplish this, the four mechanical engineering students from the University of Akron have focused their energy on product design and development over the past two semesters. The team sought to develop a hand control module attachment for a common entry-level simulation racing set-up so that even disabled gamers who cannot use their legs to activate the traditional foot pedals can enjoy the hobby. Since there are limited options on the market for adapting simulation racing set-ups, disabled people are having to spend hundreds of dollars more than anyone else just to try out the activity. If they do not want to spend the money, people try to create their own systems, often unreliable and thrown together, to activate the foot pedals. Most often, gamers are simply deterred from trying simulation racing because of the lack of products that make the systems accessible; therefore, the SWHC kit enters as the keystone for an inexpensive, easy-to-use, accessible 'Do-It-Yourself' kit that preserves the real-life thrill of racing.

Much of the coursework from the University of Akron contributed to the steps of the design process, which can be viewed in Figure 1. First was the conceptual design phase, in which the team began brainstorming concepts, gathering resources and understanding their objectives through decision matrices. This phase was heavily inspired by the coursework in Concepts of Design. Most of this work was completed from September 2020 through November 2020. Next came the embodiment design phase, in which the team began more detailed 3D designs via SolidWorks as well as creating a mathematical model via MATLAB to theoretically prove that the concepts would work. The team also researched materials, manufacturing processes and industry standards. The team found support from the University of Akron's ASEC 3D printing services: 3D printing became a large portion of the prototype process and became the goal for the final product's manufacturing process. This phase heavily used knowledge from Design of Mechanical Components, Dynamics and Vibrations. The team executed the embodiment stage from mid-November 2020 to February 2021. Finally, the last phase was the detail design phase, in which the final design was converted into engineering drawings, instruction manuals for the DIY and a website. This phase was done from February 2021 to April 2021.

Throughout each of the design phases, coursework from Basic Electrical Engineering and techniques learned in Mechanical Engineering Lab were used to complete verification testing. From understanding force curves via the force gauge tests, testing the potentiometers used in the modules and completing the comparative racing trials, the team was able to verify that the module was efficient, ergonomic and still allowed users to remain competitive compared to people using foot pedals. Additionally, the different project costs are a vital part to acknowledge, as there are costs associated with estimated labor a company would encounter, actual costs of the project the team faced, and the estimated costs for the SWHC module for the consumer. The team also detailed the cost of proposed commercialization of the SWHC kit via injection molding.

Overall, the team worked diligently to design and test a product to fill this need, but the true goal was that the product could be used by real people. The team included customer outreach and community interaction as a main block in the diagram because they reached out to non-profits in the community as

well as made the effort to connect with people around the world via the popular Reddit community. They created a manual, a website and other detailed instructions for anyone to make this DIY product with confidence. The team has already proven an impact as they have collaborated with Akron non-profits, the Inclusioneers and Summit DD, to build and use many SWHC kits for the local youth within schools, libraries and events.

The block diagrams in Figure 1 outline the overarching steps to complete the objectives set forth by the team early on in the process. The team planned to design hand controls compatible with a Thrustmaster TX wheel base, which is a common, entry-level set. The design needed to be realistic and have a high-quality feel to the controls. It was important that the module be compatible with the wheel base without outside software or calibration so as to be easy to assemble for users. The design was created to be the most economical choice on the market. The process would need to include 3D printing prototypes and completing initial testing on these prototypes. The production of the final version would also be using 3D printing. Due to the goal for an open-source product, the team needed to create a means to share downloadable 3D print files free to the public, which turned out to be a website. On this website, the team needed to compile a list of extra hardware and tools needed to complete the DIY project at home. The manual and website include detailed documentation. The team also designated researching how to create a commercial-grade product. Each of these objectives from the proposal were satisfied throughout the semesters and will be detailed throughout the report.

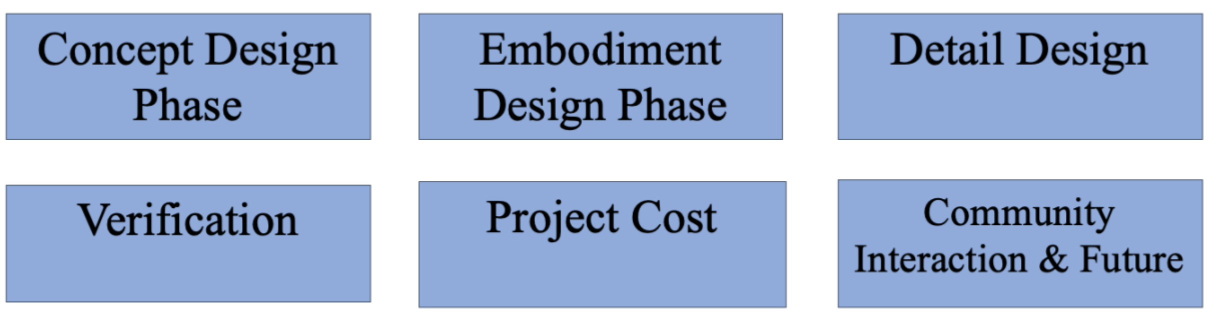

Figure 1: Block diagram to break down sections of project report

1.1 Background

The SWHC kit is focused on the accessibility of E-Sports. Simulation racing, commonly referred to as sim-racing, is an E-Sport enjoyed by many people around the world. The hobby provides a real-world racing experience in one’s home using a motorized wheel and pedal set connected to a computer, Xbox or Playstation. These gaming systems can be configured with a variety of different wheel and pedal set makers. The most common wheel and pedal set is the Thrustmaster TX ecosystem. Any of the sim-racing systems currently break down barriers to connect people all across the world; however, the simulation industry does not tackle one of the most relevant barriers of all: disabled individuals who are unable to use their legs to operate foot pedals. This could include amputees and paraplegics who are disabled from the waist down. Currently, there are several paraplegic and other disabled professional racing drivers who inspire many and prove that a disability should not prohibit the racing experience. Any person, regardless of their disability, should have the opportunity to race virtually through simulation.

Due to the COVID-19 pandemic, Formula 1 and NASCAR held virtual races using simulation wheels. This catapulted the interest in the hobby within the United States and across the world, as new racers were introduced from the comfort of their own homes. From April of 2020 to July of 2020, much of the simulation racing equipment was sold-out from every manufacturer due to the increase in public interest; therefore, there is a desperate need in the market for this type of product. Interested gamers have flocked to the online forum called Reddit to discuss the lack of diversity and need for adaptive hand pedals. There are currently 145,000 members of the r/simracing community. Through posts and comments on this forum, many people have expressed the desire for accessible products, and the SWHC kit delivers.

1.2 Principles of Operation

The final product designed from this project is a simple, easy to use system on the surface. As a product with intended DIY use in mind, this is critical. However, below the surface reveals a more complex system that has been designed with certain aspects in mind. The underlying core of the product is an electro-mechanical system that is controlled by the user. Pulling either paddle toward the user activates the system by turning a rotary potentiometer, similar to pressing the standard pedal set. A potentiometer, which is a type of variable resistor, acts as a voltage divider. By pressing the paddle, the 3.3V from the motor's circuit board is divided by the potentiometer. Thus, the board is able to measure how much the paddle has traveled based on the voltage being applied back to board through the wire harness. Due to this operation, ensuring that proper rotation of the potentiometer can be achieved was crucial throughout the design process. In fact, the team held this so high on their importance list that it was checked with every design iteration. This process is outlined later in this report in section 3.2.

1.3 Product Definition

The final product created is an easy-to-assemble, DIY modification for the existing Thrustmaster TX 458 Italia Edition wheel. The main assembly is created from 3D printing and consists of four main components. The module consists of four elements: a top bracket, a bottom bracket, a throttle paddle and a brake paddle. Each component can easily be printed using the open-source 3D files presented on the website, which is detailed in section 5.1. In addition to the brackets, the system is easily assembled with simple hardware including extension springs, self-tapping screws and machine screws. Once all of these parts are combined, the final product allows users to completely control sim-racing wheels with only their hands.

1.4 Preliminary Market Research

The availability of adaptable systems for entry-level disabled simulation racers is dismal. There are currently no commercially available hand-controlled wheel mounting systems on the market. The only currently available products that aid a disabled individual with sim-racing are from 3rd party vendors: 3DRap and Simability. Their products have a hefty price tag; furthermore, adding additional fees on top of the $350 entry cost makes the hobby even more exclusive.

The first product, from 3DRap, is a handheld module that allows a user to control the brake and acceleration with one hand [1]. According to an article in The Patent Invention Magazine, "The controller, completely printed through a 3D printer, is equipped with two levers managed by the thumb that replace the pedal of the accelerator and the brake in a practical and intuitive way" [2]. This product is distributed from Italy, so the initial $90.00 price quickly increases with shipping and handling costs to the

US. The controls with the 3DRap device do not link with the steering system and require extra calibration through external software. This 3D printed product may not have the level of comfort users need for hours of playing, as the plastic material wrapped around one's hands can become irritated and uncomfortable. This product also forces users to only use their thumb, which may be restrictive and tiresome throughout a session. This product also has the potential to not offer the same quality of life. It is made out of a 3D printed material, which is light-weight, but not as durable for the intense regular usage long-term.

The other company, Simabilty, used to supply high-quality wheel mounting systems, but they are no longer in business. When they were still in business, they sold adaptable hand controls systems made from carbon fiber and aluminum [3]. For the same Thrustmaster TX wheel and base, their product cost nearly $250.00. This price is over half the general cost to start the hobby, which puts disabled gamers at a disadvantage. Simability's use of high-quality materials may improve product life, but the initial cost and cost to repair are prohibitive to disabled racers. This option also requires a large amount of modification to install, including the removal of the quick release collar of the wheel. It seems this option is more suitable for an experienced user who already has equipment; however, since they are out of business, they are not a competitor by any means.

The functions and general purpose of the SWHC kit compared to its market competitors can be viewed in Figure 2 below. In this table, one could see the price for the SWHC is significantly less than the other companies. The SWHC kit will require some disassembly and assembly but will be available open-source with detailed instructions so anyone can build this DIY project. The realistic feel is high with the SWHC kit, as many real NASCAR and FORMULA1 race cars use similar hand control systems. 3DRap may not provide a realistic feel by just controlling the brake and accelerator with one's thumb. Additionally, because of the DIY nature of the product, replacement parts for the brackets and paddles can be easily made and replaced. Other products would require purchasing an entirely new module; however, the SWHC product can easily have new hardware elements like screws and springs, as well as the 3D printed elements, replaced without much additional cost.

Product /Features & Specs	3DRAP	Simability	SWHC Kit
Cost	$90.00	$180-460.00	$25.00 or less
Usability	- Hand Held -Non-adjustable paddles or breaks -Careful Calibration required of the axes in the windows peripheral management	-Adjustable Breaks -Adjustable paddles -Use thumb only	little to no calibration
Assembly required	- Does not attach to wheel, grip around palm	Yes - Disassemble wheel from base -"medium level of installation effort using basic tools.	Hand tools to mount to base Disassembly of stock pedals
Availability	Made it Italy, high shipping cost	Out of Stock - Last website updated said next avaliability Oct. 2019.	Online 3D printing file, small list of simple additional
Combatibility Range to Different Wheels	Not wheel dependent	T300 PlayStation, Ferrari GTE F458, Leather 28 GT, VG Ferrari 599XX EVO	Stock Tx
Combatibility Range to Thrustmaster base	Not dependant	No modification needed for T300/TX servo	Direct plug-in to wheel base
Realistic feel	Medium	High	High
Material Quality	Low - all 3D printed plastic	High - Carbon Fiber and aluminum	Medium - Some 3D printed parts

Figure 2: Comparing SWHC kit and competitors' product features and specifications check formatting of table

Overall, 3DRap and Simabilty are missing a major market for encouraging new people to join the sim-racing community. Since the current products are expensive and do not provide a realistic feel, this market needs attention. Interested racers should not be excluded from this hobby, should not have to pay far more or find lower quality racing experiences just because they have a disability. The SWHC kit will solve this. By going through preliminary market research, the team understands how the proposed SWHC will improve the market and meet end user demands.

2. Design

With a clearly defined vision, list of goals, and a need in the simulation racing community, the team built on the foundation of their ideas to create a robust, tangible final product to test and later share. This product followed three stages of design in order to develop the final solution presented in this report. Firstly, the team spent considerable time in the conceptual design phase where several rough sketches were brainstormed, evaluated independently, and compared in order to set the initial trajectory of the design. This design was then defined more clearly in the embodiment design phase where discrete components with separate functions were identified, eligible materials were analyzed, and the design was modeled mathematically to estimate and optimize the forces acting on the system. Lastly, the design was then brought into the detailed design phase where each component was closely scrutinized for areas of improvement and various elements of the design were tested and iteratively adjusted to maximize the effectiveness and ease of use of the system.

2.1 Conceptual Design Phase

The intention of the conceptual design phase was to produce several sketches of potential hand control designs in order to gauge project feasibility and assess design challenges. Through brainstorming and discussion on the goals of this project, four initial concept drawings were created as well as a list of general requirements and objectives to achieve. This part of the design process aided the team in determining the project scope and provided several ideas with which to enter the embodiment design phase.

2.1.1 Expanded Design Brief

In order to better explain the design for the SWHC hand control module, the team found real vehicles adapted for disabled drivers as sufficient examples. Several designs exist that include gear boxes and levers off of the steering wheel. One such example can be found in the US Patent 3373628A, called *Hand control for motor vehicles*. The patent report, explaining the benefit of its hand control product, said that other lever-controlled options suffer from the disadvantages because "they require one hand of the operator to be taken from the steering wheel all the time the hand control is being used"[4]. Since many existing adaptations for vehicles require users to have their hands focused on different tasks to active pedals, safety and ergonomics become a concern. So, the SWHC team made their focus on a module that allows a sim racer to keep both hands on the wheel to activate the acceleration and brake.

Above all else, the product design ensures drivers are comfortable with both hands on the wheel. The paddles are contoured around the existing wheel so that the hands will stay in a comfortable position. The brake and accelerator paddles are offset next to the shifter paddles so that both can easily be reached at any moment for the fastest reaction times. Since every user may have different sized hands and preferences for hand location on the wheel, the SWHC module works for a variety of hand positions and sizes by incorporating large paddles. Due to these large paddles, there is not a forced hand position, so the product is not restrictive and does not become tiresome after hours of playing. Anyone has the option to use their index finger, middle finger, ring finger or pinky, and can be alternated while playing to ensure comfort.

Additionally, customers who will be using their hands for brake and accelerator desire a realistic feel similar to the amount of resistance a driver would feel using foot pedals. However, the team realized that a reduction in force was needed due to the strength comparisons between hands and feet. This resistance had to be implemented in a safe manner, keeping any pinch points away from the user's hands. This was achieved by placing the anchor point to the oversized paddles, keeping any pinch points far from the user.

The SWHC kit is aimed towards gamers who want to try sim-racing, so most new drivers use the Stock TX wheel. Keeping this compatibility in mind, the top and bottom brackets mount directly behind the wheel. This mounting style allows complete access to the existing buttons of the stock steering wheel. All of these features are what make the SWHC kit unlike no other product on the market.

2.1.2 Overall and Detailed Function Structure Diagrams

As briefly outlined in Section 1.2, the underlying system operates using an electro-mechanical system. Figure 3 outlines the basic inputs/outputs of the system and how they are achieved. Since the scope of the project involved recreating the standard foot pedal system into a hand-controlled system, it was critical to understand how the system worked. Described below in Figure 3, the two decision making structures in the system are the human user and the circuitry within the wheel base. Once the human user decides on an input and presses the pedal, there is a chain reaction that has several effects. As the potentiometer is turned and voltage is divided, the wheel base detects this change. Once detected, the wheel base tells the computer to accelerate the vehicle in the game and directs the motor within the wheel base to act accordingly. As the goal of the project was to modify how the user interacts with the existing system rather than modify the system, the function structure diagram remained the same for the standard pedal set and the SWHC kit. After understanding the function of the system, the project team set out to visualize different ways to achieve this within the constraints of the working area.

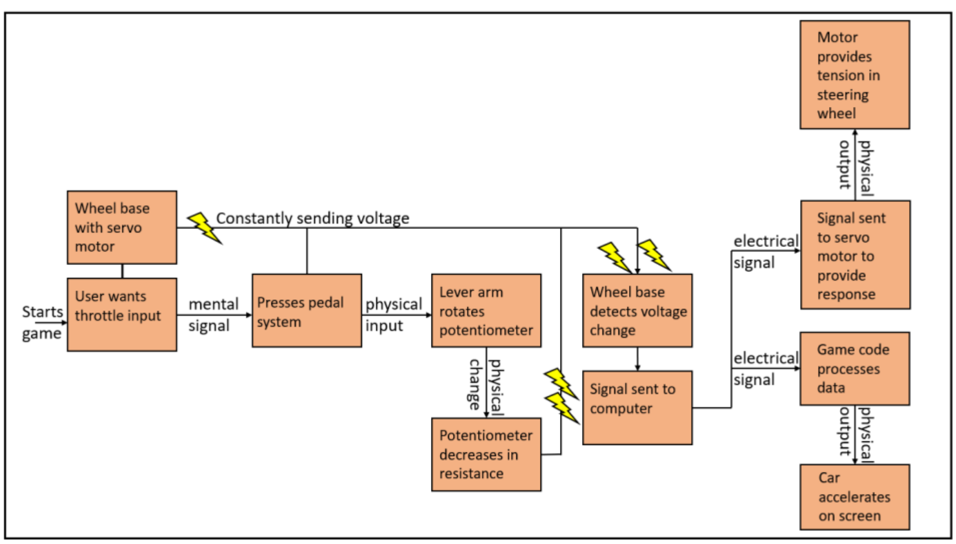

Figure 3: Function structure diagram of wheel-pedal system

2.1.3 Objective Tree

When the team initially met in the Fall 2020 semester to discuss the scope of the project, three primary objectives were developed with secondary objectives stemming from them, seen below in Figure 4. The first two objectives were decided from the team's desire to produce a final product that was easily accessible and intuitive for users. The team felt that the final product needed to be affordable and aimed specifically to be the most economical product available. The team decided that the best way to pursue this goal was to offer the 3D print files as free, open-source resources that anyone could have printed. In the design, the team also attempted to utilize as much hardware from the chosen pedal kit as possible and to minimize the number of purchased components required for installation. The second objective was that the final product was simple to set up and use in order to maximize the user's convenience. The team limited the design to the Thrustmaster TX wheel base most commonly purchased by novice racers in order to ensure that the design could be relevant for the most users, and a set of instructions for installation and use were created to improve the user experience as much as possible.

The third and final objective came out of the team's desire to produce a final product that was enjoyable to use, so in the design the team put an emphasis on the quality of the final product's look and feel. The design was implemented as directly onto the steering wheel as possible to make the hand controls feel like an extension of the existing setup, and the design of the paddles and spring mounts were evaluated for proper stiffness and a proportionate degree of resistance to input as the paddles were engaged. Overall, these objectives assisted in setting the trajectory of the team's design and increased the overall quality of the final product through specific focus on areas the team deemed important.

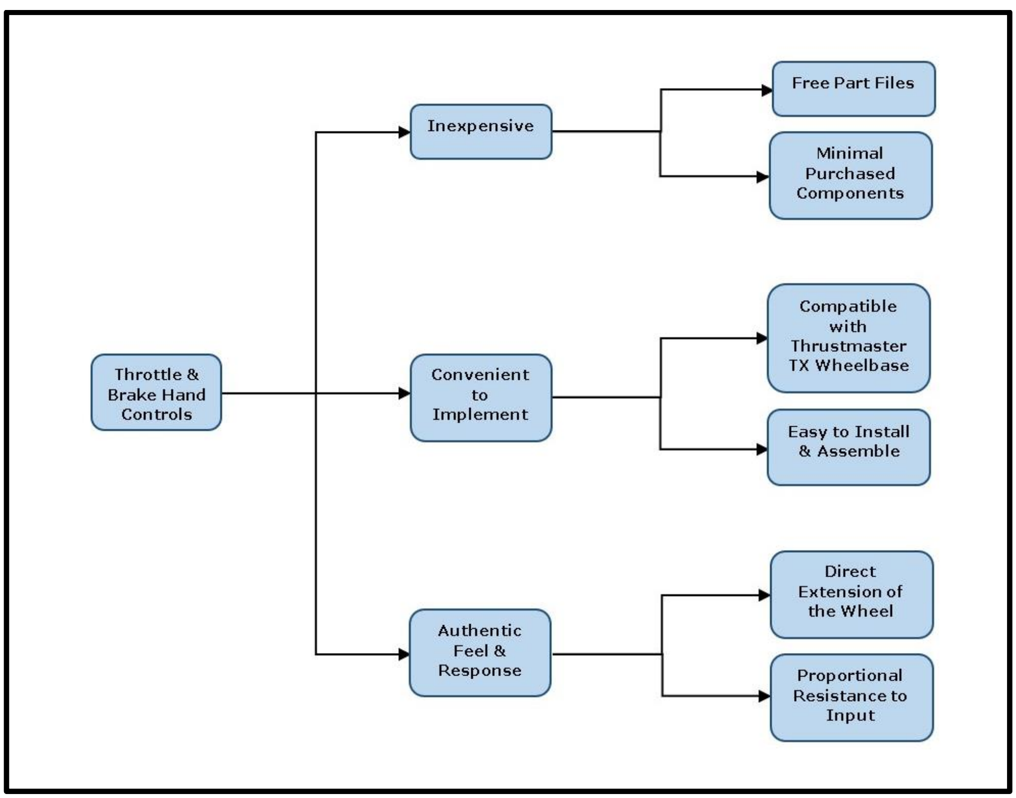

Figure 4: Objective Tree Diagram for Sim Wheel Hand Control Kit

2.1.4 Concept Sketches

The first concept, labeled "Hand Lever Angle on Overlaying Wheel Grip" and pictured in Figure 5, located the potentiometers and paddles in front of the steering wheel at the 10 o'clock and 2 o'clock hand positions. The potentiometers were designed to secure to the wheel at the horizontal spokes with a slight inward angle to allow the user to comfortably push each paddle towards the front wheel face with their thumbs and palms. The paddles were sketched to be tall and to directly overlap with the wheel ring so that the user retained easy access to the wheel while turning it and changing hand position.

Figure 5: Hand Lever Angled on Overlaying Wheel Grip

The second concept, shown below in Figure 6 as the "Lever Inside Ring of the Wheel Grip" design, also maintained the 10-and-2 o'clock hand position with a similar tall paddle design as in the first concept. In this design, however, the potentiometers were placed high up on the wheel ring in order to move them away from the control buttons found on the wheel face. The intent was that as the user gripped the wheel, the paddles would be primarily operated by the user's thumbs and would be pushed into the empty space in the upper half of the wheel.

Figure 6: Lever Inside Ring of the Wheel Grip

The third concept introduced a different direction of paddle travel than the first two concepts by positioning both paddles on the lower half of the wheel behind the wheel ring. The potentiometers were to be mounted to the steering wheel base located behind all other controls in order to allow the paddles to be pulled toward the user for throttle and brake to engage. For this design, the large throttle paddle and small brake paddle were placed in the 5-and-7 o'clock positions to correspond with the existing control buttons on the wheel face. Both paddles were also sketched to completely overlap the wheel ring profile to keep the controls within easy reach of the user while turning the wheel. The schematic of this concept can be seen below in Figure 7.

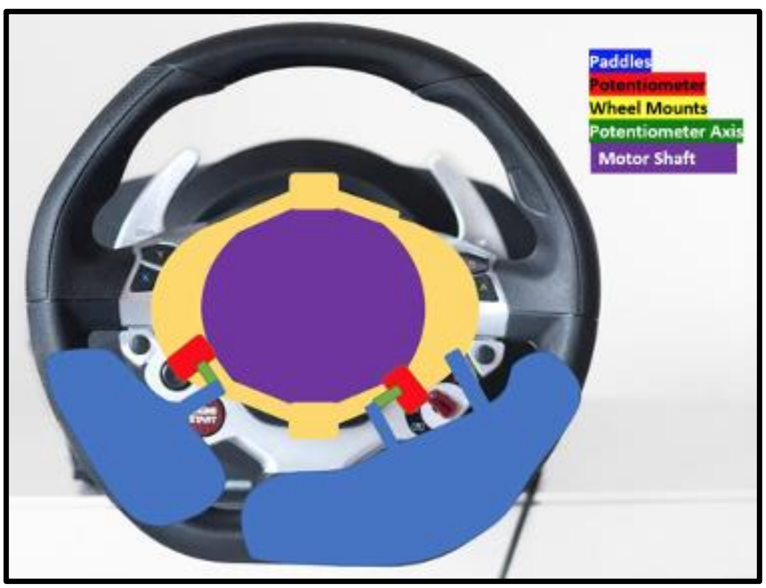

Figure 7: Hand Paddles Behind the Wheel & Below the Shifting Paddles

The fourth and final initial concept, shown in Figure 8 as the "Hand Paddles in Front of Wheel" sketch, placed the paddles fully inside of the upper window of the steering wheel accessible at the 10-and-

2 o'clock hand positions. The design intent was that the user would depress the paddles with their thumb and retain unrestricted access to the shifter paddles as well as the controls on the wheel face. Suspending the potentiometers from the top of the wheel ring reduced the bulkiness of the design and also introduced the possibility of making the paddle set compatible with multiple wheel sizes and styles.

Figure 8: Hand Paddles in Front of Wheel

2.1.5 Weighted Decision Matrix

Two different weighted decision matrices were used by the team to help guide the decision making process throughout the conceptual design process. The first matrix, outlined in Figure 9, covered the four initial concepts outlined in section 2.1.4. As the initial concept sketches for the project, the matrix focused on the general goals and thoughts that the team wanted to achieve. The scoring criteria, a total of nine unique categories, are outlined in the top of the matrix. These criteria were brainstormed based on what the team felt would fit the goal of a DIY, inexpensive, plug and play system. Using the matrix scores, the team decided to pursue the sketch outlined in Figure 7.

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	Criteria 6	Criteria 7	Criteria 8	Criteria 9	
Simwheel Hand Pedal Design	Little to no modification of the wheel	Cost less than $20.00 for DIY print	Use materials/components already provided from factory TX kit with minimal additional materials needed	Potentiometer full 45° range is possible	Ease of use for at least 2 hours without hand fatigue	Maintain full access to existing buttons	Provides most options to use the pinky, index, ring finger, palm or thumb	Safe location for wiring harness possible	Apply throttle quickly out of sharp turns	
Level of importance	*Desired*	*Required*	*Highly Desired*	*Required*	*Required*	*Required*	*Desired*	*Desired*	*Required*	
Scoring:	**3** - Exceeds Critera Expectations		**2** - Meets Criteria Expectations		**1** - Partially Meets Criteria Expectations			**0** - Criteria Not Met		WEIGHTED SCORE
OPTIONS	Criteria 1 SCORES	Criteria 2 SCORES	Criteria 3 SCORES	Criteria 4 SCORES	Criteria 5 SCORES	Criteria 6 SCORES	Criteria 7 SCORES	Criteria 8 SCORES	Criteria 9 SCORES	
3.4.1 Hand lever angled on overlaying wheel grip	3	1	2	1	3	2	1	1	3	17
3.4.2 Lever inside ring of the wheel grip	2	1	2	2	3	1	1	2	2	16
3.4.3 Hand paddles behind wheel below shifting paddles	3	2	3	3	2	3	3	2	3	24
3.4.4 Hand paddles in front of wheel	3	1	2	2	1	3	1	1	2	16

Figure 9: Weighted Decision Matrix Assessment of Four Design Concepts

The result from the first weighted decision matrix became the team's underlying design directive. Taking this into account, the team split up into pairs and created their own simplified 3D models of how to accomplish this directive. From these 3D models, the second weighted matrix, seen below in Figure 10, was created. This was done as both models were unique and offered different benefits to the team's overall objective. The criteria for this matrix focused more on the manufacturing process rather than the team's general goals. This decision was made as the team felt the 3D models followed the design directive based on the team's original matrix (Figure 9). Thus, if the directive was followed then the resulting design would accomplish everything outlined in both matrices. By using this newly created criteria, the team came to a near deadlock. From a scoring viewpoint Dimensional Concept 1 was the victor, but it was decided to morph the two designs into one due to their close scores. The final result was the design that entered the embodiment design phase.

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	Criteria 6	Criteria 7	
Simwheel Hand Pedal Design	Sturdy Mounting Point/Axis Contacts	Use Existing Potentiometer Wiring Harness / Location of potentiometers advantageous for wire placement	Use materials/components already provided from factory TX kit with minimal additional materials needed	Potentiometer full 45° range is possible	Maintain full access to existing buttons	Limited use of external hardware	Provides most options to use the pinky, index, ring finger, palm or thumb	
Level of importance	*Required*	*Desired*	*Highly Desired*	*Required*	*Required*	*Required*	*Desired*	
Scoring: **3** - Exceeds Critera Expectations **2** - Meets Criteria Expectations **1** - Partially Meets Criteria Expectations **0** - Criteria Not Met								WEIGHTED SCORE
OPTIONS	Criteria 1 SCORES	Criteria 2 SCORES	Criteria 3 SCORES	Criteria 4 SCORES	Criteria 5 SCORES	Criteria 6 SCORES	Criteria 7 SCORES	
Dimensional Concept 1	3	3	2	2	2	2	3	17
Dimensional Concept 2	2	1	2	2	2	2	2	16

Figure 10: Weighted Decision Matrix between dimensional concepts

2.1.6 Design Screening Criteria

Both Dimensional Concept 1 and 2 refined the design of placing the gas and brake paddles around the existing shifter paddles. The intent of the design was that as the gas and brake paddles were engaged through their range of motion, the respective upshift and downshift paddles would be exposed. Since shifting up is typically done while applying the throttle and shifting down is typically done while applying the brake, both renderings of the design sought to model a comfortable, intuitive control system that integrated seamlessly with the steering wheel.

Although Dimensional Concept 1 was the optimal design according to the weighted decision matrix shown in Figure 10, several aspects of Dimensional Concept 2 were integrated to improve the overall functionality of the design. From Dimensional Concept 1, the axis of rotation on each paddle was tilted inward at 22.5° from vertical to match the rotational axes of the shifter paddles. This angle, along with the wraparound geometry, allows the movement of the throttle and brake paddles to closely match the shifter paddle movement. This design choice is helpful to users because it helps provide awareness of paddle location without looking away from the virtual track. The second feature retained from Dimensional Concept 1 was the addition of a second attachment point for each paddle. This design choice added rigidity to the paddle so that the spring and hand forces produced less elastic deflection under load, and it also insured greater precision in the alignment of the paddle. The third element of Dimensional Concept 1 included in the embodiment design was the position of the potentiometers near the top of the

wheel rim. This allows for easy installation of the potentiometers in a location that does not require any wires to be lengthened.

For Dimensional Concept 2, the paddle axes of rotation were placed as far apart as possible to reduce the paddle radii. This was done to reduce the distance between the outermost part of the paddle as it rotates the 45° range required to fully engage each potentiometer. The space between the steering wheel and the wheel base naturally restricts this distance, and Dimensional Concept 2 optimizes the paddle radii to fit this space. This optimization improves the user experience by allowing the paddle path to be as linear as possible. For the embodiment design, Dimensional Concept 1 was modified to maximize the paddle radii using the methodology implemented in Dimensional Concept 2.

2.1.7 Gathering Resources

During the conceptual design phase, the team gathered resources needed to complete the project. First, it was determined that the working area would be a combination of the University of Akron's Mechanical Engineering Computer Lab and Weston Davis's home. The computer labs allowed for a comfortable space for the four members during the Covid-19 pandemic, as well as enough computers equipped with SolidWorks for the team, as this was the program used to design the parts. Additionally, the team used Davis's home, as he had a simulation racing set-up of his own that the team could use for testing.

Next, the team needed tools for their on-going verification testing. The team approached Dr. Kannan for a force gauge to complete the pedal force testing in October. The university did not have one already on hand, so Dr. Kannan ordered one. The team deemed a gauge with at least 200 N would be sufficient. The order gauge was a Shimpo FGE-100XY Digital Force Gauge with a measuring range of 100 lb/50 kg/500 N, a 4-Digit LCD Display and 0.2% Accuracy.

After beginning the initial 3D model concepts, there was a need to recreate the Thrustmaster steering wheel in SolidWorks. Since the team was unable to replicate the complex wheel with accuracy, they sought out resources to 3D scan the steering wheel to ensure the best accuracy of the hand paddle design. 3D scanning allows for a physical, 3 dimensional object to be scanned and turned into a 3D model with real-life dimensions in SolidWorks. In early November, the team reached far and wide to understand the resources available for the team. Several people were contacted to understand the resources at UA: ASEC Printing Lab's Sr. Engineering Technician Aaron Trexler, UA MakerStudio's Sean Kennedy, 3D printing and modeling researcher Dr. Choi, Senior Design Advisor Dr. Sawyer, Senior Design Project coordinator Dr. Nadkarni, the Think[box] at Case Western Reserve University and a local engineering consultant, Jim Parish, who spoke to the team's Senior Seminar course. Though the team had several networking opportunities through making these connections, most leads did not result in securing a 3D scanner resource.

Since the university was not scheduled to have their own 3D scanner until the Spring 2021 semester, the team set the goal of seeking local companies who would donate their time and 3D scanner resources. In early November, the team connected with Pam Szmara, the CEO of Pamton 3D in Youngstown, Ohio. This company specializes in 3D scanning, printing, modeling and other similar fabrication needs. The company committed to working with the team on a volunteer basis. The team dropped off the wheel on November 13, but after a month of trying to get a scan, the process was

unsuccessful. Because the wheel is large for Pamton 3D's scanning mechanism, the scan of the entire wheel was not possible. Also, the shiny plastic of the shifter paddles, the mat plastic of the front surface and the rubber wheel grip led to an inconsistent scan: their scanner had trouble with a variety of materials. This 3D scanning was the biggest challenge the team faced throughout the design process.

The team stayed in touch with Dr. Farahad and Aaron Trexler since they planned to implement 3D scanning in their lab sometime in the Spring. Fortunately for the team, the scanner was larger and more detailed than the machine at Pampton 3D, so scanning the wheel was not an issue. The machine was up and running at the beginning of January, so the team was able to complete the scanning at this point.

Lastly, the team sought out 3D printing services. The team met with Aaron Trexler and assistant Blake Bowser to understand the 3D printing capabilities and best material for the process. The lab has capabilities for high resolution prints using vat photopolymerization and Stratsys 3D printers which use nylon or polycarbonate. The team considered the objective of the project is to create a product that can be printed by anyone in the world. It was decided that the print will be made out of ABS or PLA on the smaller printers. Throughout February and March, Aaron Trexler completed the three prototype prints and the fourth print for the final design.

2.2 Embodiment Design Phase

With the 3D scan obtained and a solid design concept generated from the team's two weighted decision matrices, the team entered the embodiment design phase. In this phase, the design concept was evaluated in order to define the specific features and functions of each component, and the team continued advancing and improving the 3D model with these functions in mind. The 3D scan of the steering wheel was crucial to this stage of modeling for two reasons. Firstly, it allowed the team to create a virtual working area for the project to fit inside of which prevented unnecessary interference between the components and their surroundings. Secondly, it allowed the design to flow around the wheel and integrate as seamlessly as possible with the existing controls. This phase of the design process significantly advanced the initial concept from the conceptual design phase and prepared it for the final detailed design phase.

2.2.1 Design Challenges

The project offered several challenges that had to be overcome by the team. While some were related to the specific objectives set-out by the team, others were inherent to the system being used. The challenges that were created from the team's objectives related to keeping the cost to produce down. For example, a goal was to carry over as many parts from the original pedal set to the new design. This included components such as torsional springs, screws, gears and dowel pins. While originally planning to use the torsional springs to add resistance to the paddles, the springs turned out to be too strong to also achieve the goal of reducing the force required to operate them. At first, the team tried to design around this by increasing the moment arm of the paddle. However, it was determined the force required would break the 3D printed parts. Thus, the team had to decide a spring type that would work with the system.

Another big challenge the team had to face was inherent to the small size of the system. With the wheel attached there was only 1.5" of clearance between the motor base and wheel, with this value

increasing with further distance away from the center of the wheel. However, the complex structure of the wheel made it difficult to determine how much exact clearance existed at different positions. By using the precise scan of the wheel, the team was able to accurately determine what clearances needed to be kept at specific positions for the system to function properly. While the clearance issue was solved with the 3D scanned wheel, the tight workspace caused many more design challenges all revolving around the limited space. The team wanted to have paddles big enough that would be comfortable for a variety of people without being so large to interfere with operation. Another concern for the tight space was how to safely mount the springs away from the user's hand to avoid any pinching issues.

Perhaps the biggest challenge of all was a culmination of all the space constraint challenges in one. The team had to design the paddles to achieve proper rotation of the potentiometers while fighting all of these concerns just mentioned. The regular pedal set is a separate system without any of these constraints. However, the team had to fit an equivalent system that was previously designed in a 12" x 8 " x 6" box into the 6" x 6" x 1.5" workspace. All wiring, hardware and structure elements were fit in this new workspace to achieve the team's original objectives.

2.2.2 Product Architecture

To begin the embodiment design phase, the team determined the product architecture of the hand controls by separating the confirmed initial concept into six components organized within two subsystems. The first subsystem, composed of the mechanical elements of the design, includes the top and bottom brackets, the paddles, the extension springs mounted between the paddles and the bottom bracket, and the hardware required to install the hand control assembly. The second subsystem, created for the electrical elements of the design, contained the potentiometers extracted from the pedal set.

Next, the team determined a list of functions considered necessary for the success of the design. In order to satisfy these functions, the team decided to use a hybrid product architecture approach utilizing modular-integrated components. A standard modular component approach prioritizes the independence of each design element from the next, and it allows designs to be broken down into their base pieces. The team valued both the ability to replace components and the freedom of shape that modular architecture allows. The team also wanted to maximize the simplicity of the design by minimizing the part count and achieved this by drawing elements from integrated product architecture. This methodology shares each design function among several components and allows all of the pieces to more seamlessly connect into the final product. For instance, the top and bottom bracket serve collectively to hold the potentiometers, paddles, and extension springs as well as mount the entire assembly to the steering wheel base. The components, subsystems, and required features are all detailed below in Figure 11.

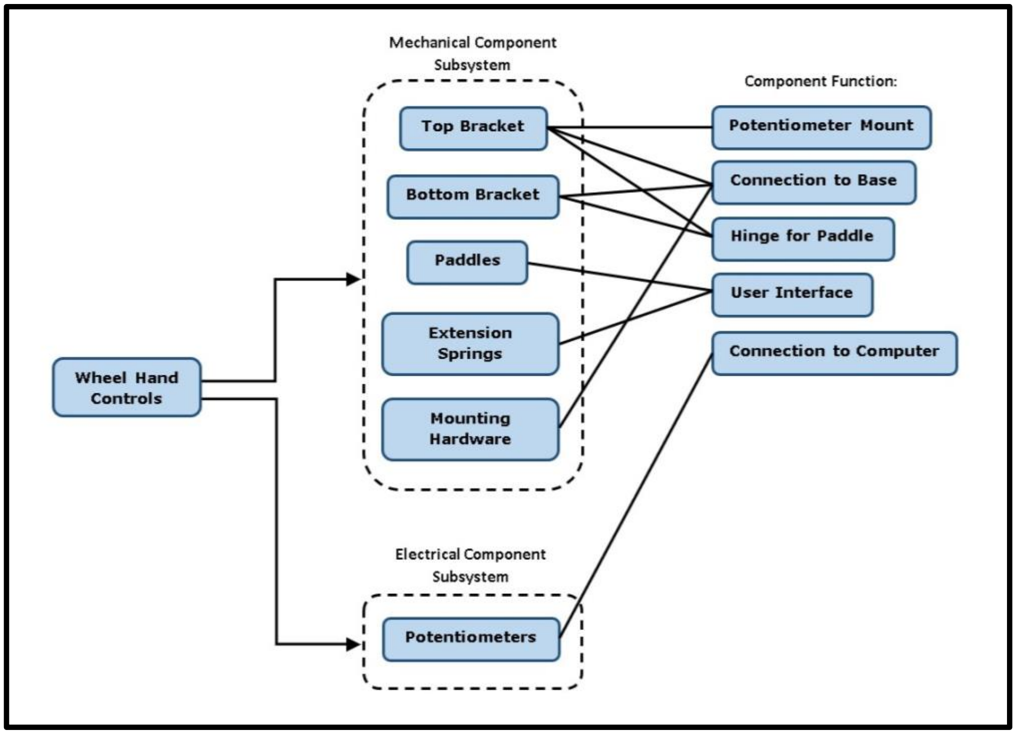

Figure 11: Product component subsystems and function diagram

2.2.3 Component Interfaces

As part of the modular-integrated product architecture, the team devoted a considerable amount of time and thought towards the mechanical connections between all of the components. The design required unique connections for three areas: holding the top and bottom brackets together, mounting the paddles onto the potentiometers, and supporting the paddles at a secondary axis point. Each interface came with its own challenges, but the team successfully developed each one during the embodiment design phase to be as effective and advantageous to the design as possible.

The first interface addressed by the team was the joining of the top and bottom bracket. This connection method needed to provide rigidity to both bracket pieces since this subassembly acted as the base upon which all other components were brought together, and it also needed to fit securely onto the steering wheel base. Since the surrounding geometry of each bracket consisted of two half-circles clamping down on a circular section of the wheel base, two mirrored flanges were modeled on each bracket to provide eligible geometry offset from the half-circle profiles. In the desire to keep all joining hardware as inexpensive and accessible as possible, the team decided to implement two ¼-20 cross-recess (Philips-head) bolts and corresponding ¼-20 hex nuts to hold the top and bottom bracket together. On the top bracket, clearance-fit through-holes were modeled into the flanges to allow bolts to pass through, and hexagonal blind holes were modeled into the bottom bracket flanges to improve ease of installation and prevent the hex nuts from spinning in place. Each flange was extruded at an appropriate thickness so that even a partial-infill 3D print of the brackets would not collapse under mild compression between the bolt

head and hex nut faces when tightened. An exploded view of these flanges can be seen below in Figure 12.

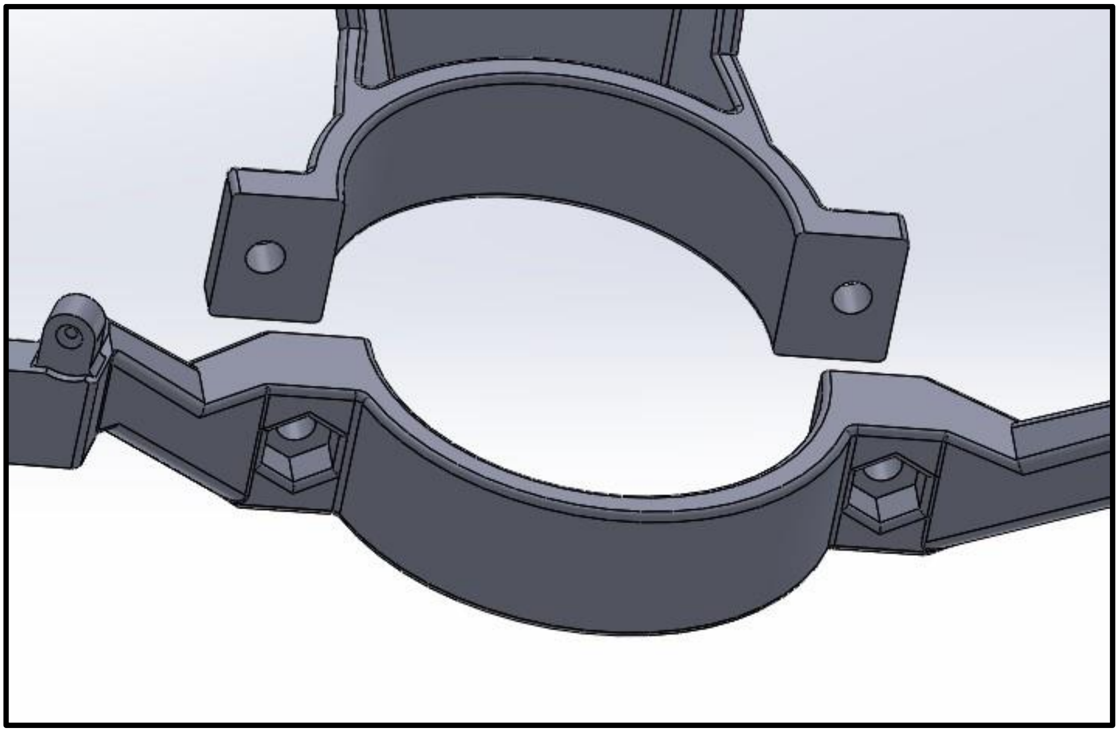

Figure 12: Exploded view of top and bottom bracket flanges

The second interface dealt with was the attachment of the throttle and brake paddles to the potentiometer shafts. The team decided that a tight fit between each potentiometer and its respective paddle was necessary in order to prevent any error between an input in the form of a paddle rotation and an output in the form of a voltage from the potentiometer. In addition, the team decided to use the potentiometer shafts as primary supports for the paddles. This design decision required both that the potentiometers be rigidly attached to the top bracket and that they locate and hold the paddles at their intended angle and orientation. On the bracket side, a similar clearance-fit through hole was modeled for each potentiometer, allowing the use of a hex nut and washer included in the pedal set for mounting. On the paddle sides, an extruded profile was cut out of each paddle end to match that of the round potentiometer shaft with a locating flat. The original foot pedal design implemented injection-molded plastic gears that press-fit onto each potentiometer shaft, and the team determined that these gears would be useful in capturing each paddle onto its respective potentiometer. In the 3D model, the assembly was ordered such that the paddles were pushed onto the potentiometer shafts and then the press-fit gears were pushed onto the exposed remainder, essentially sandwiching the printed paddles between the preexisting pedal components. See Figure 13 for a cutaway view of this subassembly.

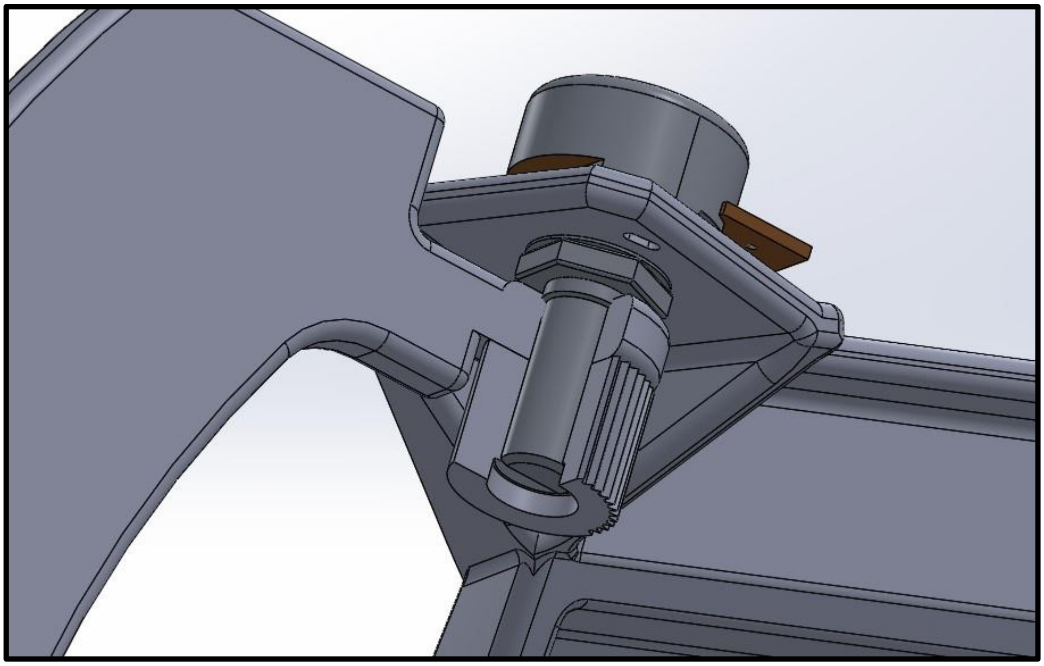

Figure 13: Potentiometer, bracket and paddle subassembly

The third interface addressed by the team was a secondary axial support for each paddle. The team deemed this feature necessary to the design for two reasons. Firstly, the forces exerted from the driver's hands were estimated as a point load at the middle of each paddle, and a support at the bottom of the paddle opposite to the potentiometer greatly reduced the elastic deflection of the paddle. The goal of maximizing the rigidity of the paddles served both to reduce stress and extend the life of the 3D printed components and to improve the end user experience by striving to attain the stiffness properties of higher-quality materials. The second reason the team included the bottom paddle joint was to prevent the paddles from falling off of the potentiometers. Specifically, the required orientation of the potentiometers forced the entire weight of the left paddle onto the press-fit gear keeping the paddle mounted to the potentiometer, and the team determined that this connection was insufficient for long-term use. By including the bottom paddle joints, the majority of the paddle weight was transferred to the bottom bracket and off of the potentiometers. This joint was designed so that the paddle side could elastically flex open enough to seat into the bracket side, where the conical profile centered the joint while allowing easy rotation with little friction. Figure 14 below shows an exploded view of this hinge design and Figure 15 shows an assembled view. During lap testing of the design, discussed in Section 3.3.2, the team determined that the introduction of this joint removed the necessity of the press-fit gear on the potentiometer shafts. In the vein of simplicity, the press-fit gears were eliminated from the assembly before the model entered the next phase of design.

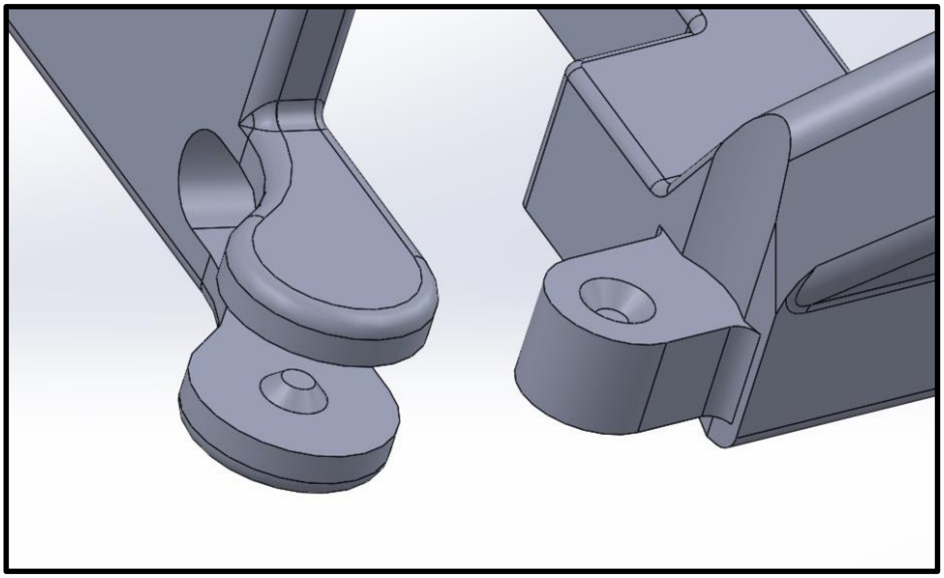

Figure 14: Exploded view of hinge design

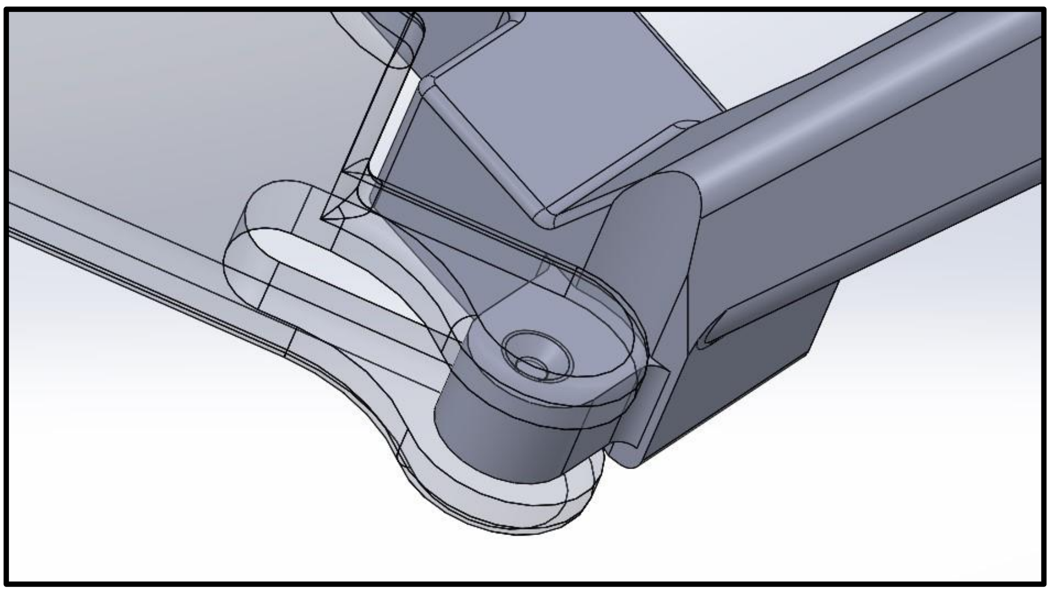

Figure 15: Assembled view of hinge design

2.2.4 Selections of Materials and Manufacturing Processes

The design of the SWHC kit was optimized for 3D printing which is an additive manufacturing process that is growing in accessibility and affordability for the public. Parts are created via application of successive thin layers of melted material that cool and harden at room temperature. 3D printing enables both internal and external features and geometries to be manufactured due to its iterative approach to shape-forming; other processes are not able to achieve this. This aspect of additive manufacturing gave the design team unique opportunity and freedom to design the kit components without traditional limitations found in injection molding or machining processes.

The material selection for the manufacturing process needed to be easily accessible for individuals making this DIY project. The team discovered that Polylactic Acid - PLA - was strong, inexpensive and widely available which suited the needs for this project. PLA has a low printing temperature which reduces the likelihood of part warpage as the layers of plastic cool and, and it allows for accurate printing of complex geometric shapes. The tensile strength is 37 MPa, elongation is 6%, and the density is 1.3 g/cm^3 [5]. PLA has a low stiffness when compared to other materials and even a low stiffness for 3D-printable materials, so the team's design relied heavily on shape and overall geometry for rigidity and reinforcement. If a community member were to only have the access to Acrylonitrile Butadiene Styrene - ABS - this would also be an acceptable option. ABS is strong and ductile.

When 3D printing the four pieces, there were a few required settings for optimal prints, including a layer height of 0.25 mm and an infill density of 20%. Support material was used on all of the parts since the portions not directly contacting the build plate needed support material to build upon. In Figure 16, Figure 17 and Figure 18, the support material contacts the red highlighted surface on the part. These figures also show the optimal orientation of the part on the build plate. The support material density was set to 8% to minimize waste. These specifications were discovered with the help of Aaron Trexler from the UA ASEC 3D printing labs.

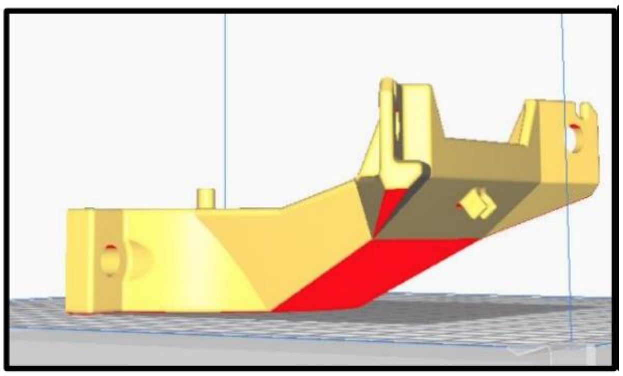

Figure 16: Top Bracket's orientation on build plate

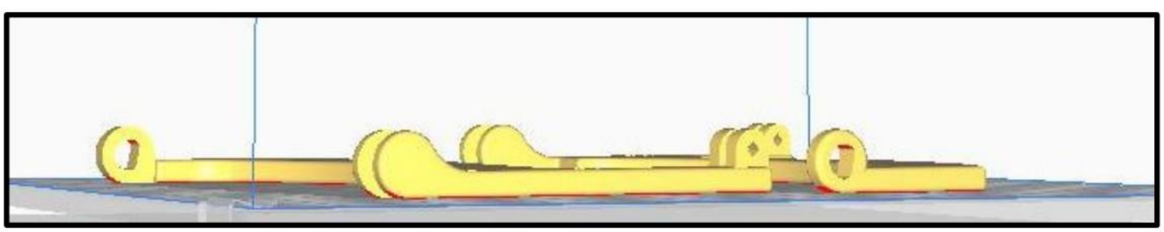

Figure 17: Brake and acceleration paddles' orientation on build plate

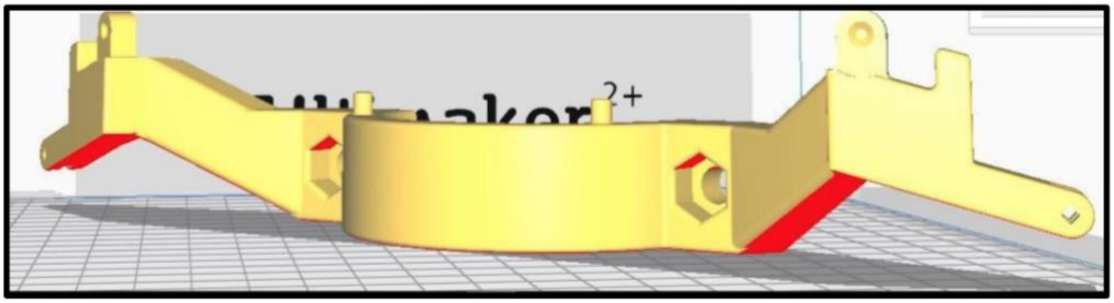

Figure 18: Bottom Bracket's orientation on build plate

The entire printing process took about 9 hours. The top bracket took about 3 hours, both paddles on one build plate took about 2.5 hours, and the bottom bracket took about 3 hours. These times were found by using the 8" x 8" x 8" Ultimaker2 machines in the UA printing lab. The top bracket and the bottom bracket were printed separately, while the paddles were printed together on a single machine. This Ultimaker2 machine is the average size for a 3D printer, but if one is to print on a bigger machine, like a Ultimater 5s, then all prints could be done on the same build plate.

2.2.5 Mathematical Model

While the main goal of the SWHC design was to develop a set of hand controls for disabled sim-racers, the team recognized that a well thought-out design should be competitive or even marginally better against traditional foot pedals when it comes to comfort, performance and ease of use. Rather than designing the hand pedal assembly blindly, the team developed a mathematical model to mathematically iterate the dimensions of the design and experiment with different springs. The ability to mathematically represent the design allowed the team to find possible design options and understand how they behave without taking the time to fully design it using CAD. The mathematical model was used as a tool to guide the design process and allowed the team to find suitable springs and dimensions to make an optimized assembly.

In order to develop a mathematical model, a basic idealized diagram with assigned length and force vectors had to be created. The idealized diagram required the team to decide on the basic orientation of the paddle, potentiometer, frame, and spring of the assembly so an accurate diagram could be developed. From the initial design concept, the design includes a potentiometer that rotates at the anchoring base of a paddle, and a frame that connects both the end of the extension spring and the potentiometer and paddle pivot. Figure 19 shows the idealized paddle assembly at rest, which incorporates a top-down view of one side of the assembly. The yellow axis represents the axis of the potentiometer and the axis that the paddle rotates on. The black L-shape represents the frame. While the shape of the frame is not important in the mathematical model, the perpendicular and parallel distances relative to the axle are important in determining the spring's behavior and stretch. The green bar represents the paddle. While the paddle's shape does not need to be a flat plate with one point of attachment, the cross-sectional points that the user grabs the paddle and the spring attachment point relative to the axis of rotation are important. There can be multiple axes of rotation for the paddle, as long as the axes align from a top-down view.

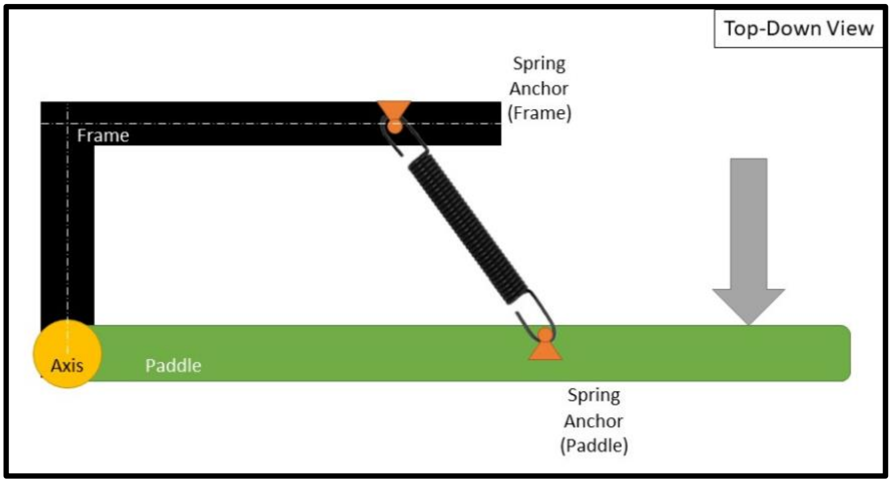

Figure 19: The idealized top-down view of the paddle assembly at rest

Along with representing the assembly from rest, an idealized diagram of the assembly in a stretched position allows for representation of lengths in their proper orientation through operation of the assembly. Figure 20 displays the idealized top-down view in a stretched position.

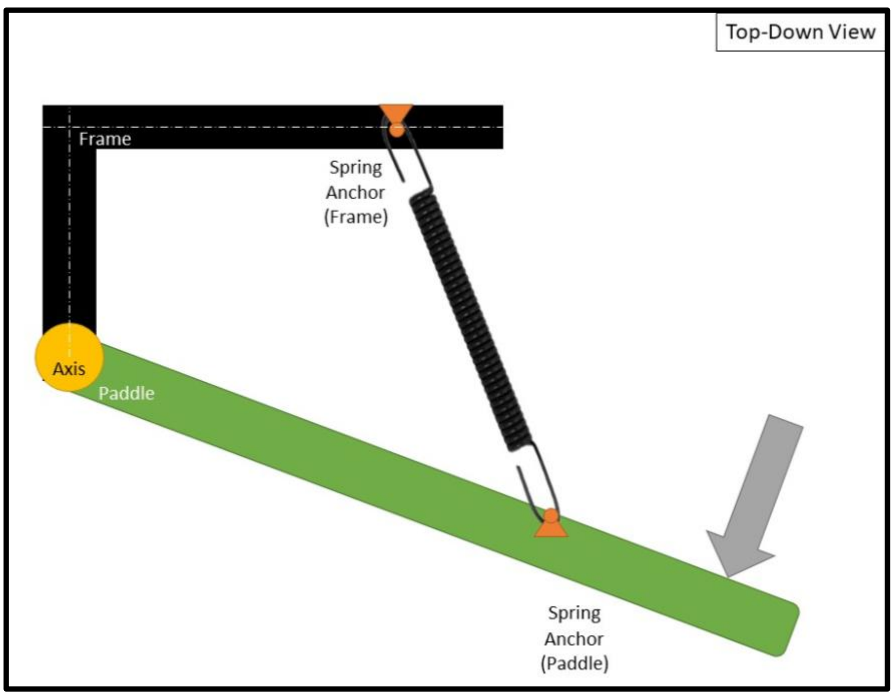

Figure 20: The idealized top-down view of the paddle assembly stretched

After creating the idealized diagram of the paddle assembly, the team assigned lengths and angles of importance to be able to create a dynamic model of the assembly. The lengths and angles were assigned based on the variables the team thought important to be solved in the mathematical model. The team also assigned lengths and angles to the model if the parameters were able to be measured in the 3D model easily, or are part of the design's assumptions for operation. Figure 21 and Figure 22 show the assigned lengths and angles for the design from both an at-rest view and stretched view.

The angles assigned to the assembly include Θ_P, Θ_S, and Θ_A. Angle Θ_P is the angle of the paddle relative to the position of the frame and was assigned as part of the design's assumptions. The potentiometer shafts must rotate 45 degrees for full throttle and braking, and this necessary rotation became the iterative driving variable of motion in the mathematical model. Since the potentiometers are mounted inline with the base of the paddle, the paddle's rotation is equivalent to the rotation of the potentiometer shafts. The idealized diagram displays Θ_P as 90 degrees at rest, but the final model has the paddles slightly less than 90 degrees at rest. The initial angle of Θ_P is not the driving iteration of the motion of the design and does not change the equations, the iteration of Θ_P over 45 degrees from rest is the driving iteration of motion of the SWHC mathematical model. Angle Θ_S is the angle of the extension spring relative to the paddle. Angle Θ_S is important to the design because it is used to project the extension force of the spring perpendicular to the face of the paddle and provide a resistive torque about the paddle's axis. Figure 22 shows that Θ_S decreases through the rotation of the paddle from rest. Angle Θ_A is the angle between the paddle and the force applied by a user's hand. Since different users may grip the paddle differently throughout rotation due to hand size and personal preference, Θ_A is assumed to remain at 90 degrees since iterating it would likely make little difference in the results of a design and the value changes with each user's method of gripping the paddle. Figure 22 shows the 90 degree assumption for Θ_A remaining in the stretched position.

A total of seven lengths were assigned to the idealized model, some of which were intended to be used as design inputs to the code while others were used to solve the forces and torques in the design. Lengths L_F, L_P, L_s, L_D, L_T, L_L, and L_V were used in the design. Length L_F is the distance along the paddle from the axis of the paddle to the point at which a hand applies force. Length L_F is used to determine the moment created by the applied hand force about the paddle's axis. Similar to Θ_A, L_F is an approximation and the distance can vary based on how different users grab the paddle. Just as the applied force has a moment arm, so does the extension spring force. Length L_P is the distance along the paddle from the axis to the spring anchor on the paddle. Length L_P is used in conjunction with the projected force of the extension spring to create a moment about the paddle's axis in the opposite direction of the one from the applied force. Length L_S is the length of the spring parallel to the body of the extension spring. Length L_S is directly proportional to the spring force created by linear extension springs. Length L_S is used in the mathematical model to find a total spring extension range over the full 45 degree rotation of the paddle and to define the force being created by the spring. Length L_D is the vertical length between the axis of the paddle and the spring's anchor on the frame. The team defined L_D as a design input that could change based on the desired design. Length L_D affects the initial spring length and the angle of the spring. Length L_T is the same dimension as Length L_P when Θ_P is 90 degrees. However, while L_P measures the distance from the axis to the paddle spring anchor along the paddle, L_T measures between the same points but measures the distance horizontally throughout rotation of the paddle, as seen in Figure 22. Length L_T is used for solving L_s, which solves for the spring force. Length L_L is another dimension the team used as a design input, but it also is used to find spring stretch and angle. Length L_L is defined as the horizontal distance between the axis and frame spring anchor, and is constant throughout rotation of the paddle. Finally, L_V is the vertical distance between the paddle spring anchor and frame spring anchor. When Θ_P is 90 degrees, L_V is equal to L_D. As the spring begins to stretch, L_V changes but L_D does not, as seen in Figure 22. Length L_V is used to find the spring's stretch.

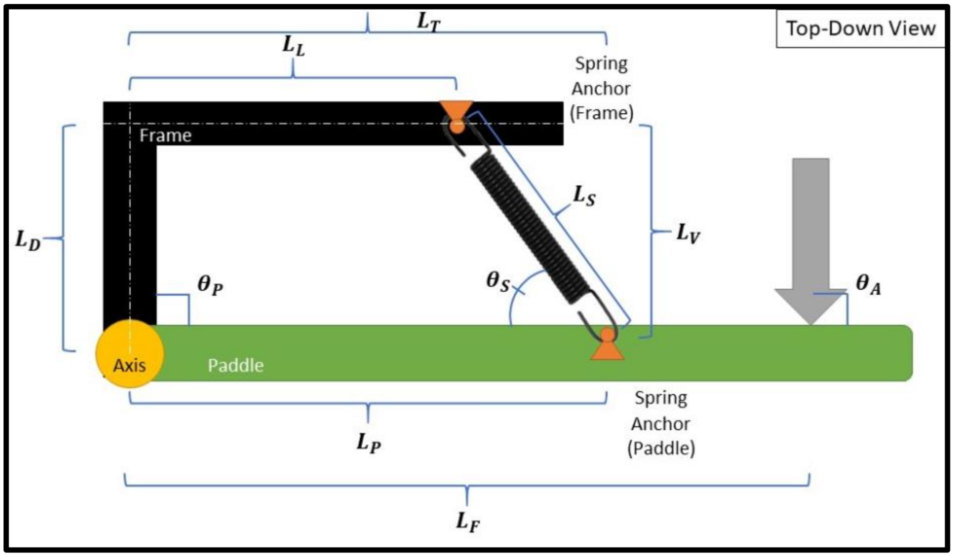

Figure 21: At rest view of the idealized model with assigned lengths and angles

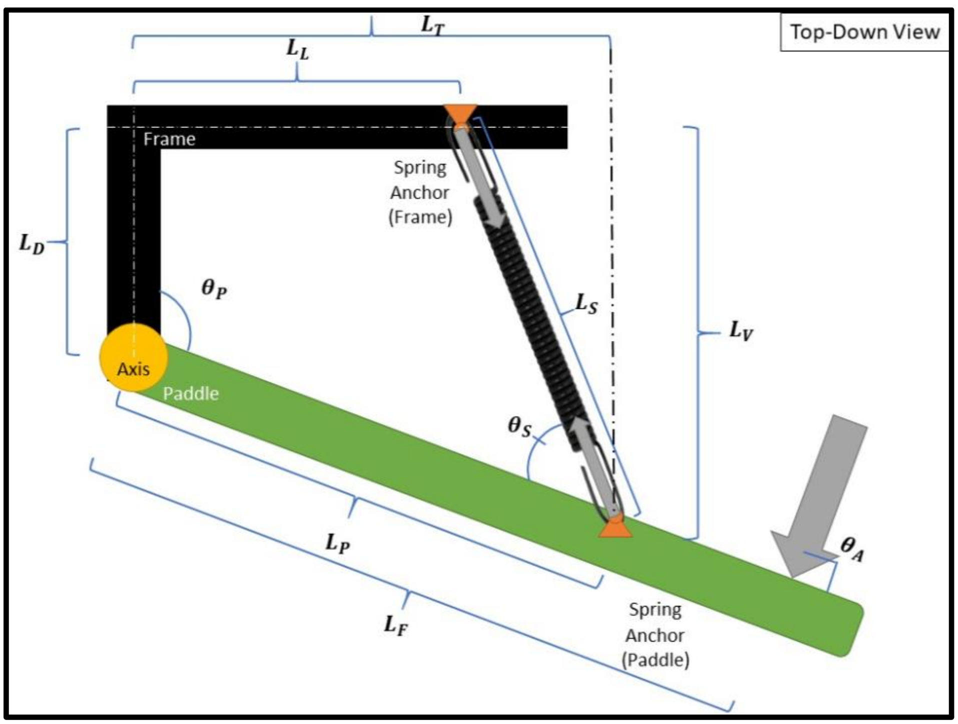

Figure 22: Stretched view of the idealized model with assigned lengths and angles

Once all lengths and angles were found, the team decided which parameters would be used as design inputs and which parameters would be solved for in the code. The design inputs are measurements that could easily be taken on the 3D design, do not change as the paddle rotates, and are used to solve for the non-input parameters. Design inputs were used as inputs to the code to see how differently dimensioned models would behave. Figure 23 and Figure 24 provide a color code to the lengths and angles based on whether or not they are design inputs. Measured design inputs are purple, while the parameters that are solved for are colored red.

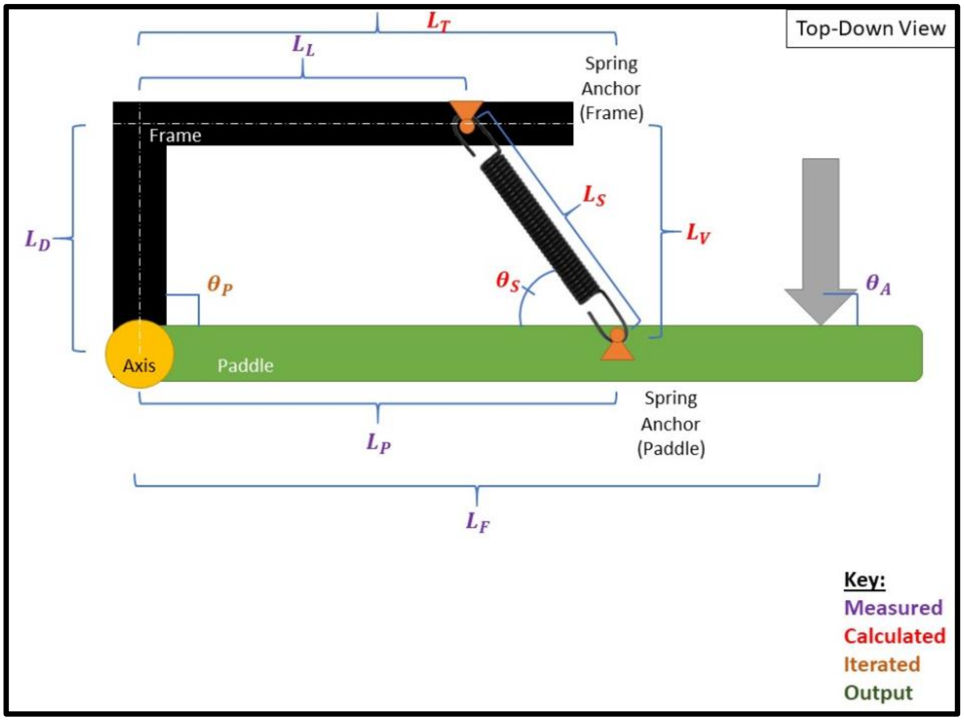

Figure 23: Idealized model at rest with lengths and angles according to how they are solved or measured

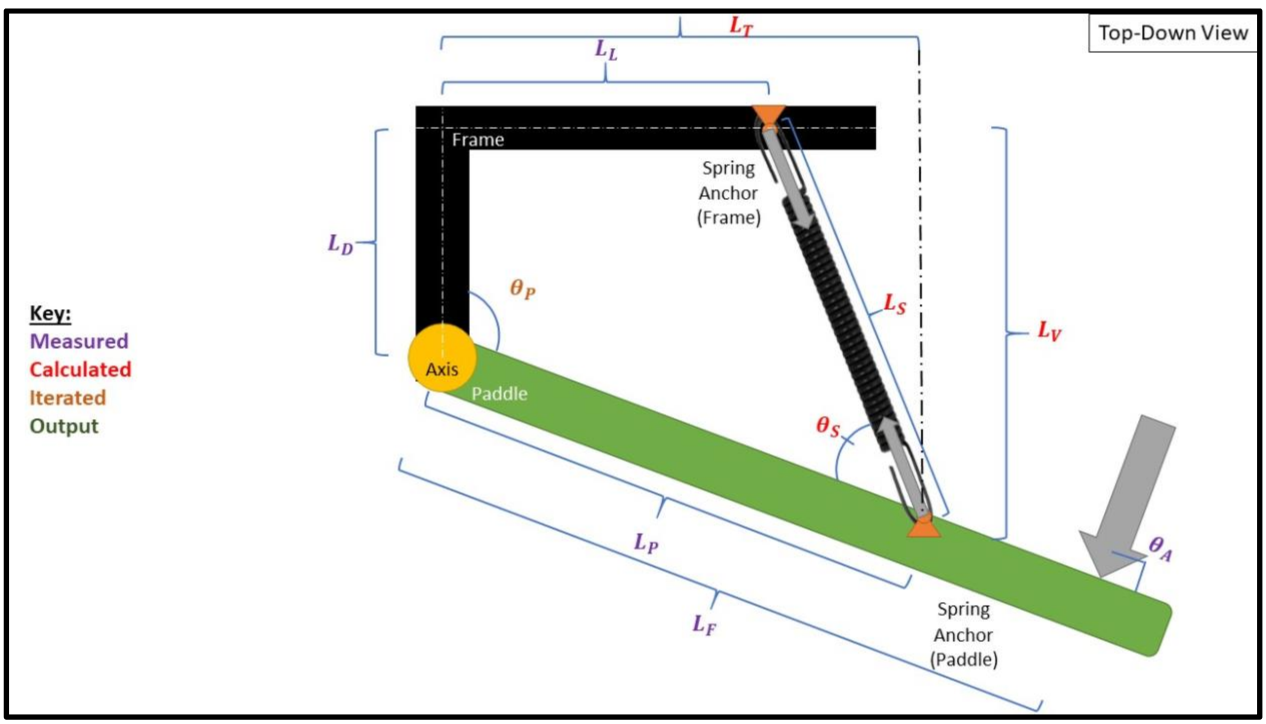

Figure 24: Idealized model stretched with lengths and angles according to how they are solved or measured

Θ_P is the only gold colored parameter because it is the driving iterative force of the system. Angle Θ_P controls the motion of the paddle, and therefore controls the dynamic forces, angles, and lengths of the system. Angle Θ_A is an input because it assumes that it is a constant 90 degrees. Lengths L_f, L_P, L_D, and L_L are purple because they are the inputs of the system. Lengths L_f, L_P, L_D, and L_L do not change length throughout rotation of the paddle, and are not dependent on the type of spring used. Lengths L_f, L_P, L_D, and L_L can all be easily measured and iterated in a 3D model, which makes these four lengths ideal as inputs. On the other hand, parameters L_V, L_S, L_T, and Θ_S are calculated parameters because they are dynamic and do not remain constant throughout the rotation of the paddle. Lengths L_V and L_T are used to find L_S and Θ_S which are used to find the force created by the spring an project it perpendicular to the paddle.

The assigned lengths and angles were used to solve for the forces and torques of the design. Figure 25 and Figure 26 display the torques and forces of the idealized design. The paddle has three main forces acting on it; $\mathbf{F_P}$, $\mathbf{F_S}$, and $\mathbf{F_A}$. The force $\mathbf{F_S}$ is the internal force created by the extension of the spring. $\mathbf{F_S}$ is directly related to the extension of the spring and the spring rate. Force $\mathbf{F_P}$ is a projection of $\mathbf{F_S}$ perpendicular to the paddle's surface. Force $\mathbf{F_P}$ is a function of the spring's extension and the spring angle through the rotation of the paddle. Finally, $\mathbf{F_A}$ is the applied force by the user's hand and the main output of the mathematical model. While $\mathbf{F_P}$ and $\mathbf{F_S}$ are solved within the system to define a resistive torque, $\mathbf{F_A}$ is the force required for the user to create an equal and opposite torque.

From two of the forces on the paddle, two torques about the paddle's axis create torques $\mathbf{T_A}$, and $\mathbf{T_S}$. Torque $\mathbf{T_S}$ is the resistive torque created by the spring. Torque $\mathbf{T_S}$ is a function of $\mathbf{F_P}$ and the length between the axis and paddle spring anchor. The resistive torque is opposed by $\mathbf{T_A}$, the torque created by applied force $\mathbf{F_A}$. Torque $\mathbf{T_A}$ is calculated in equilibrium with $\mathbf{T_S}$ so that the output force $\mathbf{F_A}$ creates an equal and opposite torque to rotate the paddle.

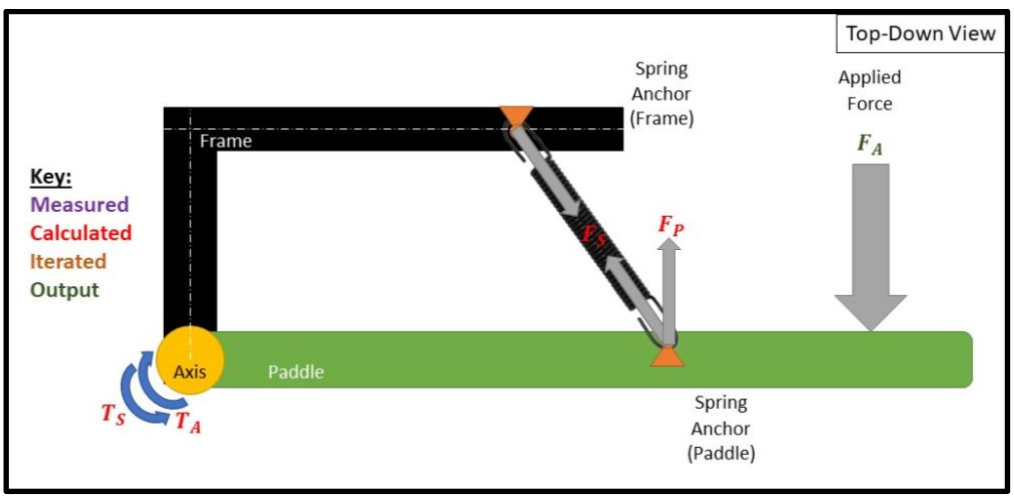

Figure 25: Assigned forces and torques of the idealized model at rest

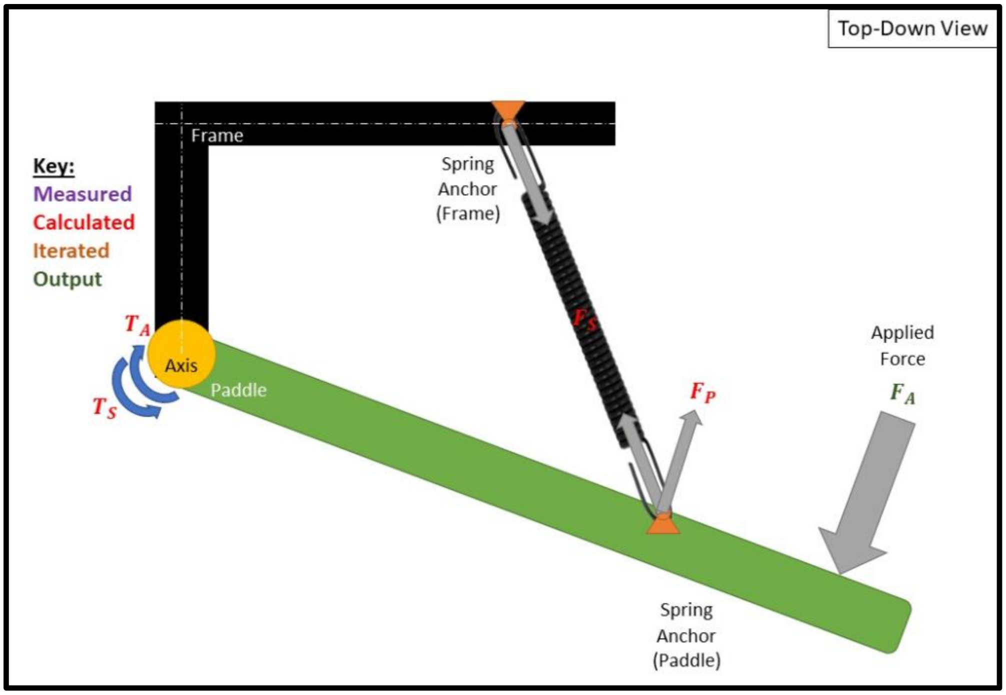

Figure 26: Assigned forces and torques of the idealized model stretched

After defining the parameters of the idealized design, the team derived formulas to solve for the calculated parameters using the measured values of the design. A total of 9 formulas were used to find the calculated parameters of the idealized model, seen in Figure 28. The majority of equations were solved using law of sines given by

$$\frac{Sin\ (a)}{A} = \frac{Sin(b)}{B} = \frac{Sin(c)}{C} \tag{2.1}$$

where capital letters represent the side lengths of a triangle and the lower case letters represent the supplementary angles on the inside corners of a triangle. The team also used trigonometry and Pythagorean theorem to solve a majority of the equations, which follows the four equations and the diagram outlined for a right triangle in Figure 27.

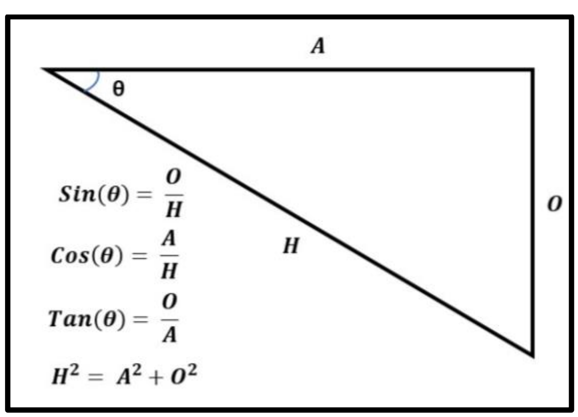

Figure 27: Trigonometric equations used to develop the mathematical formula. Θ represents an angle, while O, A, and H represent the lengths of the opposite, adjacent, and hypotenuse sides of the triangle

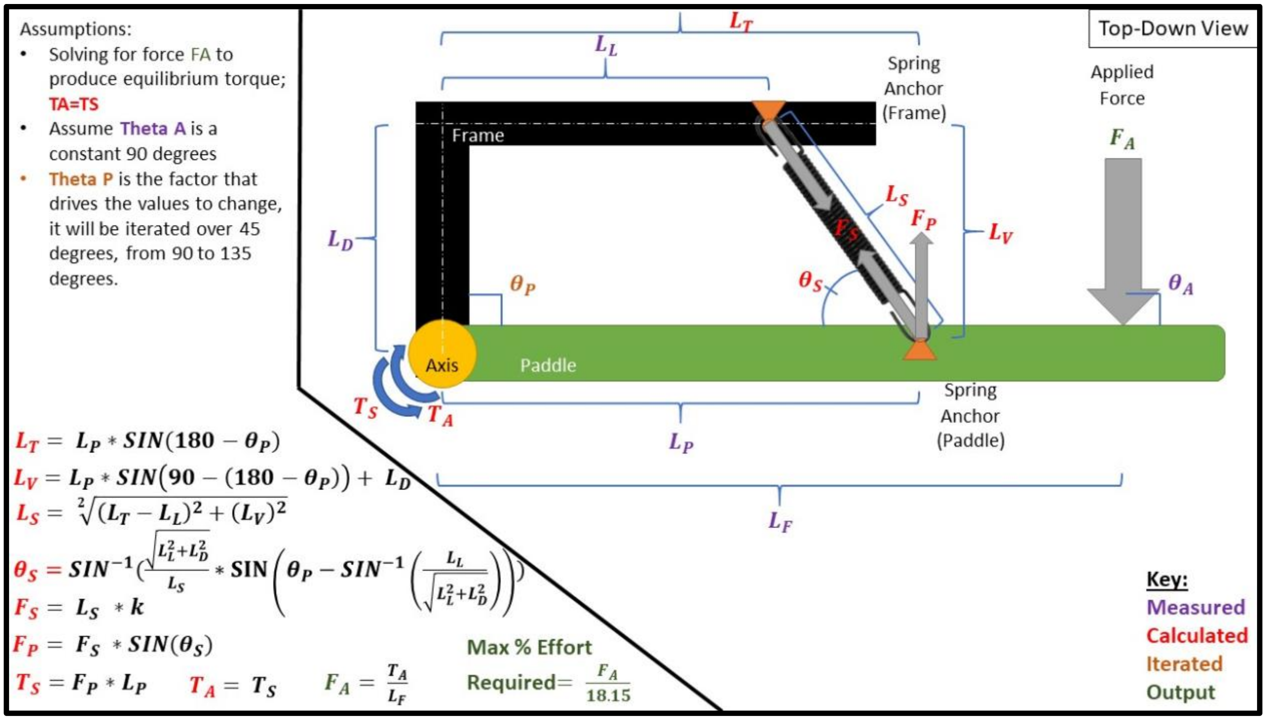

Figure 28: Formulas and assumptions used to create the mathematical model of the idealized design

The first parameter solved for was L_T, which is the horizontal stretch of the spring. One of the vital elements of the design is the overall stretch in the spring and the force created by it through the paddle's rotation. L_T and L_V are vertical and horizontal dynamic lengths used to calculate the spring's overall stretch L_S. Length L_T is essential in finding the spring's length, and the team solved for its length using

$$L_T = L_P * SIN(180 - \theta_P) \tag{2.2}$$

where L_P is the distance along the paddle from the axis to the spring anchor on the paddle and Θ_P is the angle of rotation of the paddle. Figure 29 displays the method for deriving Equation (2.2) . By setting the paddle in a stretched position and connecting L_T with a vertical length, a right triangle can be represented as seen in Figure 29. The right triangle has an acute angle on the left side that is equivalent to the current value of the paddle's angle minus the paddle's angle at rest (assumed to be 90 degrees). Because of this connection, if Θ_P is 90 degrees, the angle is zero and L_T is equal to L_P since both are horizontal. From the created right triangle, an adjacent side of length L_T and a hypotenuse side of length of L_P can be used with the cosine equation from Figure 27. By adding 270 degrees to the angle in order to convert to a sine function and rearranging the equation using algebra, the equation simplifies to Equation (2.2). Length L_T is dependent on the design's input of L_P and the dynamic rotation of the paddle.

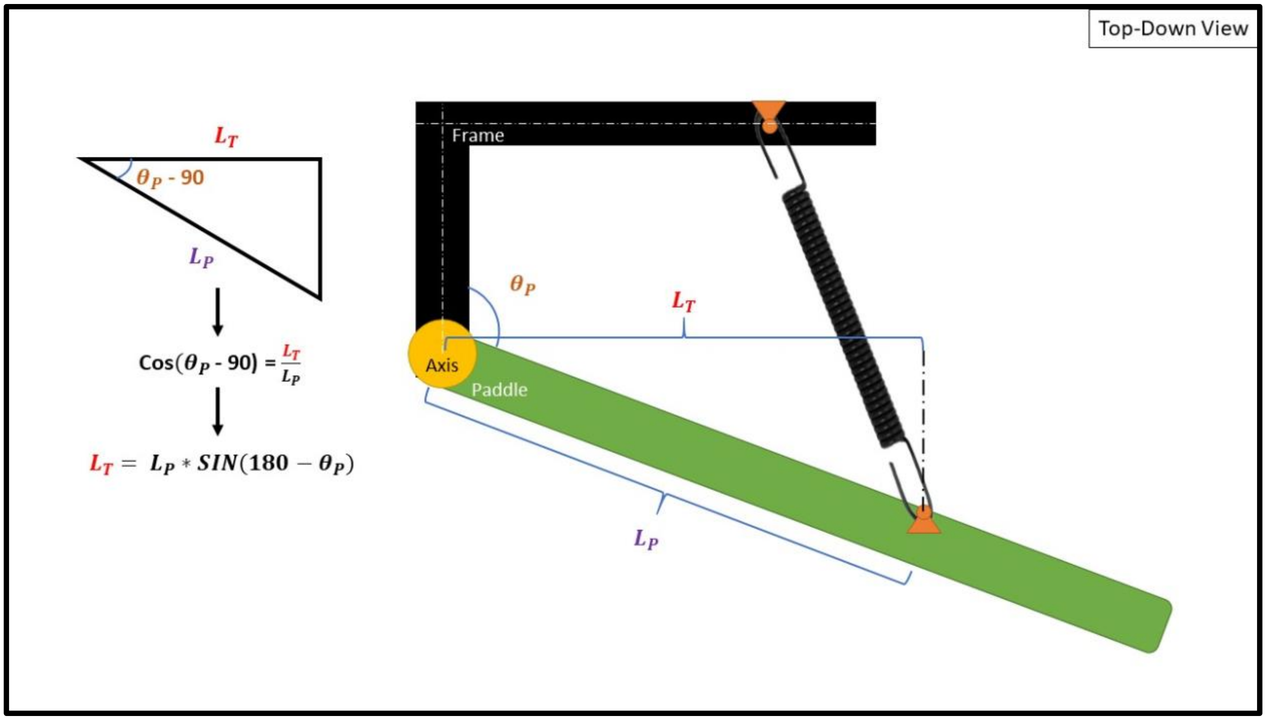

Figure 29: Methodology for solving Equation (2.2)

The other component necessary to calculate the spring's stretch is the vertical spring stretch, L_V. Length L_V is calculate using the same triangle made for L_T using

$$L_V = L_P * SIN((\theta_P) - 90) + L_D \tag{2.3}$$

where L_P is the distance along the paddle from the axis to the spring anchor on the paddle, L_D is the vertical distance from the axis to frame spring attachment and Θ_P is the angle of rotation of the paddle. Figure 30 displays the methodology for deriving the equation for L_V. As mentioned, L_V's derivation uses the same triangle from the derivation of L_T. Unlike L_T, L_V involved using the opposite side of the triangle from the defined angle. The opposite side was defined using the difference between L_V and the constant length L_D. The sine equation from Figure 27 was applied to the triangle and rearranged to solve for L_V. Length L_V is dependent on the design's input of L_P and L_D and the dynamic rotation of the paddle.

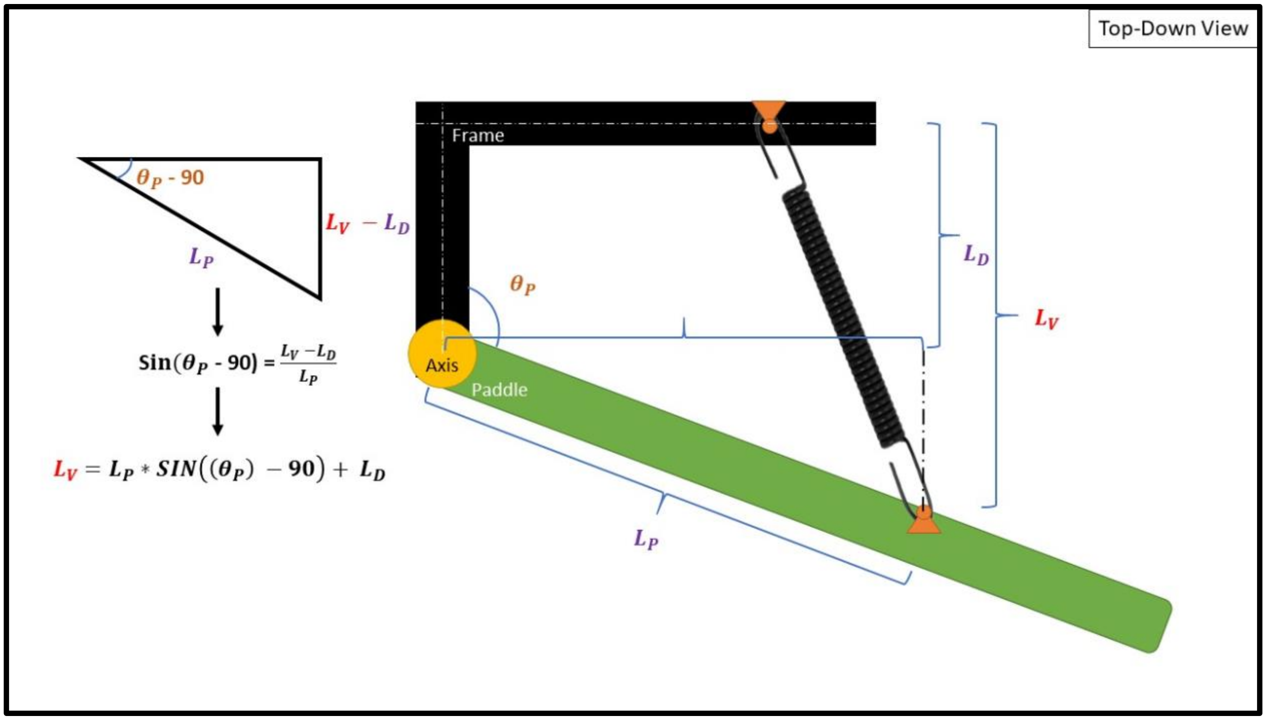

Figure 30: Methodology for solving Equation (2.3)

After solving for L_T and L_V, the team found an equation to find the overall extension of the spring, given by L_S solved using

$$L_S = \sqrt[2]{(L_T - L_L)^2 + (L_V)^2} \tag{2.4}$$

where L_V and L_T are the dynamic lengths solved above, and L_L is the horizontal distance between the axis and the frame spring anchor. Figure 31 displays the methodology used to derive Equation (2.4) . The length L_S is solved by making a new right triangle with L_V as one side and using L_S as the hypotenuse. The final side of the triangle is the difference between horizontal lengths L_T and L_L. Since the triangle is a right triangle and all sides are known, no further information is required and the Pythagorean theorem can be directly applied and rearranged to solve for L_S . Length L_S is dependent on the factors that control L_T and L_V as well as the design's input of L_L.

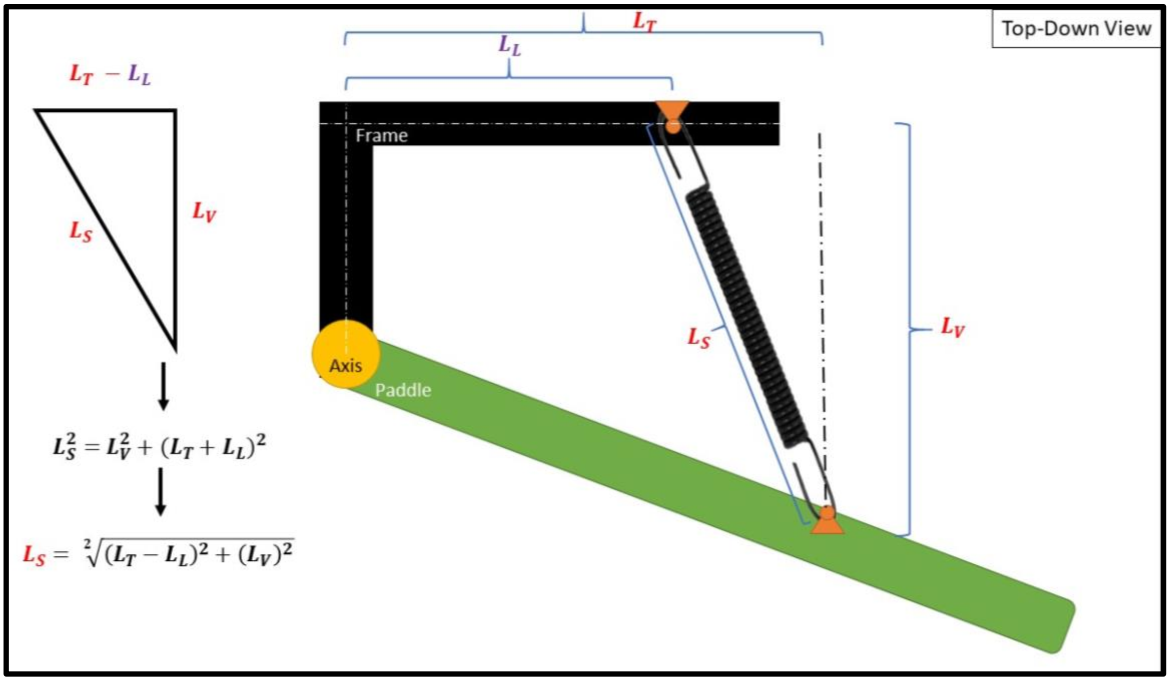

Figure 31: Methodology for solving Equation (2.4)

Once the team developed a formula for the spring length, the force exerted by the spring could be derived from L_S and the spring constant. F_S can be found using

$$\boldsymbol{F_S = L_S * k} \tag{2.5}$$

where L_S is the extended length of the spring, and k is the spring constant. A diagram of the derivation for $\mathbf{F_S}$ is in Figure 32. Force $\mathbf{F_S}$ assumes a linear extension spring with constant spring rate k. The spring constant is an input to the system depending on the constants of available springs that fall within the operating extension range of L_S. The spring constant could be iterated based on the available springs for a dimensional design to find a spring for the design with ideal extension and resistance. The force $\mathbf{F_S}$ is dependent on all factors that affect L_S and the input k for the design.

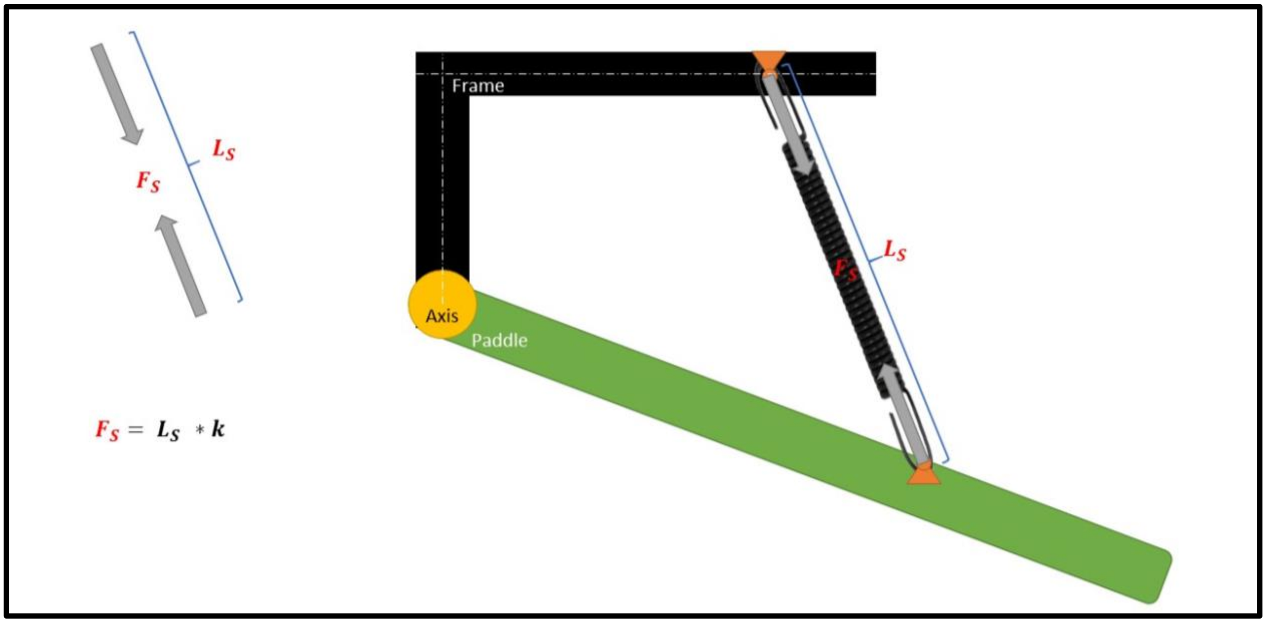

Figure 32: Methodology for solving Equation (2.5)

While the force created by the spring is available through $\mathbf{F_S}$, the team needed to be able to project the force using a spring angle. Angle Θ_S was the most difficult and complex formula to derive, it is calculated using

$$\theta_S = SIN^{-1}\left(\frac{\sqrt{L_L^2+L_D^2}}{L_S} * \mathrm{SIN}\left(\theta_P - SIN^{-1}\left(\frac{L_L}{\sqrt{L_L^2+L_D^2}}\right)\right)\right) \quad (2.6)$$

where L_L and L_D are horizontal and vertical design inputs from the axis to the frame spring anchor, L_S is the spring's extension length, and Θ_P is the angle of the paddle's rotation. Deriving Equation (2.6) involves using the law of sines on two separate triangles that shared a side. Figure 33 displays the origin of the two triangles while Figure 34 derives the equation for Θ_S using the triangles. The derivation involves a right triangle and a scalene triangle with a common side that is the hypotenuse of the right triangle. The hypotenuse can be solved for using direct application of Pythagorean theorem since the other two sides of the right triangle are of known constant length. The scalene triangle has two known sides, the side it share with the right triangle, and the side clockwise of Θ_S, which is L_S. With the triangles together, Θ_P is split by the common side between the two triangles at at unknown angle. A temporary angle alpha is assigned to the right triangle angle that splits Θ_P and in turn the scalene triangle has the angle assigned as Θ_P minus alpha. Alpha is a temporary variable that is eliminated when the equations from each triangle are combined.

The derivation involves two separate laws of sines equations, one for each triangle. The two laws of sines equations create a system of equations that solve for two unknown variables: alpha and Θ_S. Figure 34 shows the two equations, separated by boxes. The top box is the law of sines equation for the right triangle. The law of sines derivation for the right triangle solves for alpha by creating a law of sines equation between the hypotenuse and L_L sides of the triangle. The angle opposite the hypotenuse is a right

angle, and the angle opposite side length L_L is alpha. The law of sines equation was solved for alpha using algebra as seen at the bottom of the top box. The bottom box solves a law of sines for Θ_S using the scalene triangle. The law of sines for the scalene triangle was set up using the side of known length L_S and the side it shares with the right triangle, also of known length. The equation was solved for Θ_S using algebra, and the equation for alpha from the right triangle was input into the final equation for the scalene triangle, eliminating alpha and yielding Equation (2.6) . The angle Θ_S is essential in projecting the spring force created by stretching the extension spring, and is dependent on the design inputs L_L and L_D as well as the rotation of the paddle and stretch in the extension spring L_S.

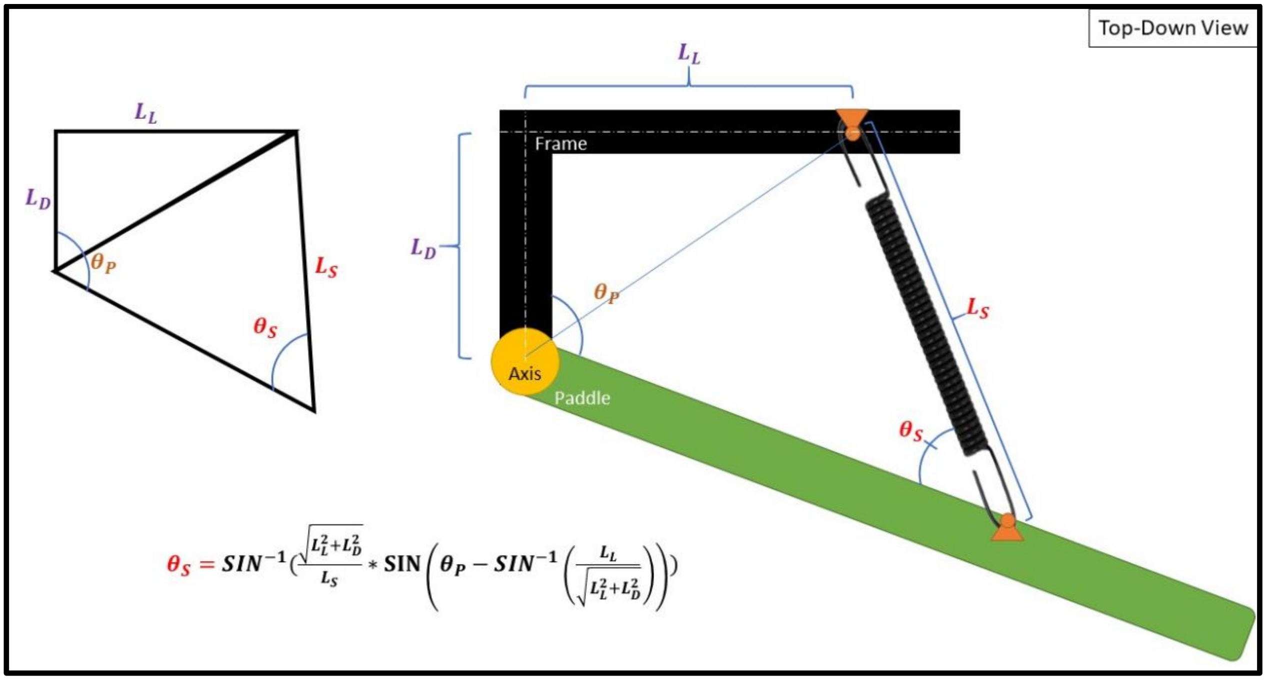

Figure 33: Derivation of triangles used to solve Equation (2.6)

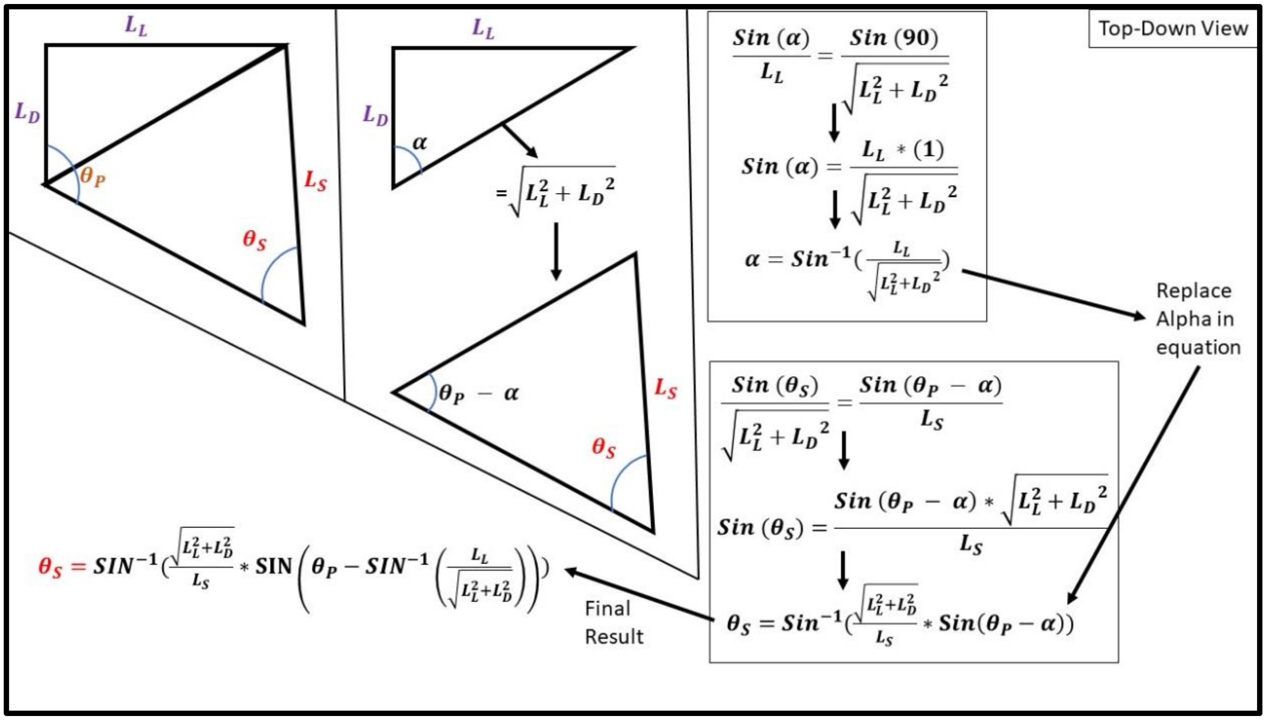

Figure 34: Derivation of Equation (2.6)

Once the team had developed equations for the spring force and angle, an equation for the projected spring force perpendicular to the paddle's surface was derived

$$F_P = F_S * SIN(\theta_S) \tag{2.7}$$

where $\mathbf{F_S}$ is the force inline with the extension spring created by spring stretch and Θ_S is the angle between the body of the spring and the paddle. Figure 35 displays the methodology for deriving Equation (2.7) . From the magnitude of the spring force and the spring angle, a triangle was made to project the force perpendicular to the paddle's surface using the sine function. By assuming $\mathbf{F_P}$ is the O side and $\mathbf{F_S}$ is the H side from Figure 27, the sine function can be applied and solved using algebra to yield Equation (2.7). The projected force $\mathbf{F_P}$ is dependent on the factors that affect the spring angle and the spring's stretch.

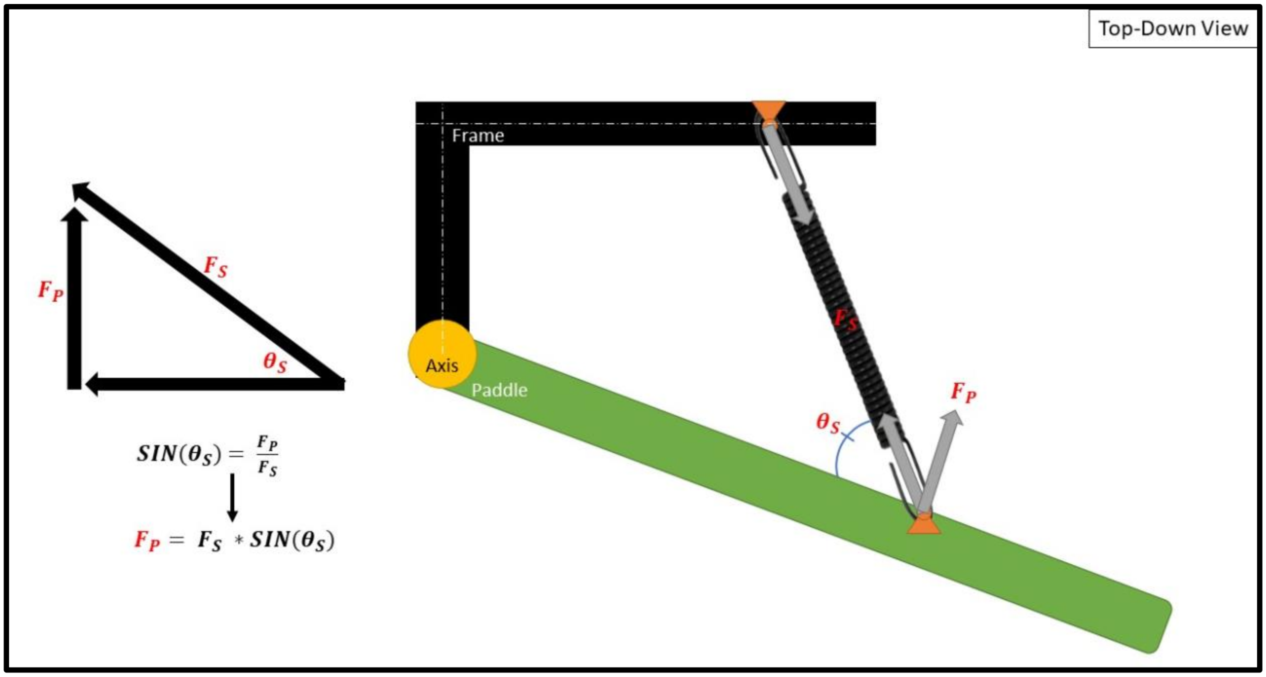

Figure 35: Methodology for solving Equation (2.7)

The projected force creates a resistive torque that acts against the force applied by a hand moving the paddle, given by

$$\boldsymbol{T_S = F_P * L_P} \tag{2.8}$$

where L_P is the design input length along the paddle from the axis to the paddle spring anchor point, and $\mathbf{F_P}$ is the projected spring force perpendicular to the paddle's surface. Figure 36 displays the methodology for creating Equation (2.8). Length L_P creates a moment arm along the paddle and perpendicular force $\mathbf{F_P}$ creates a positive torque on the axis of the paddle that is the main resistive element of the design. $\mathbf{T_S}$ is dependent on the spring force and the design's input for L_P.

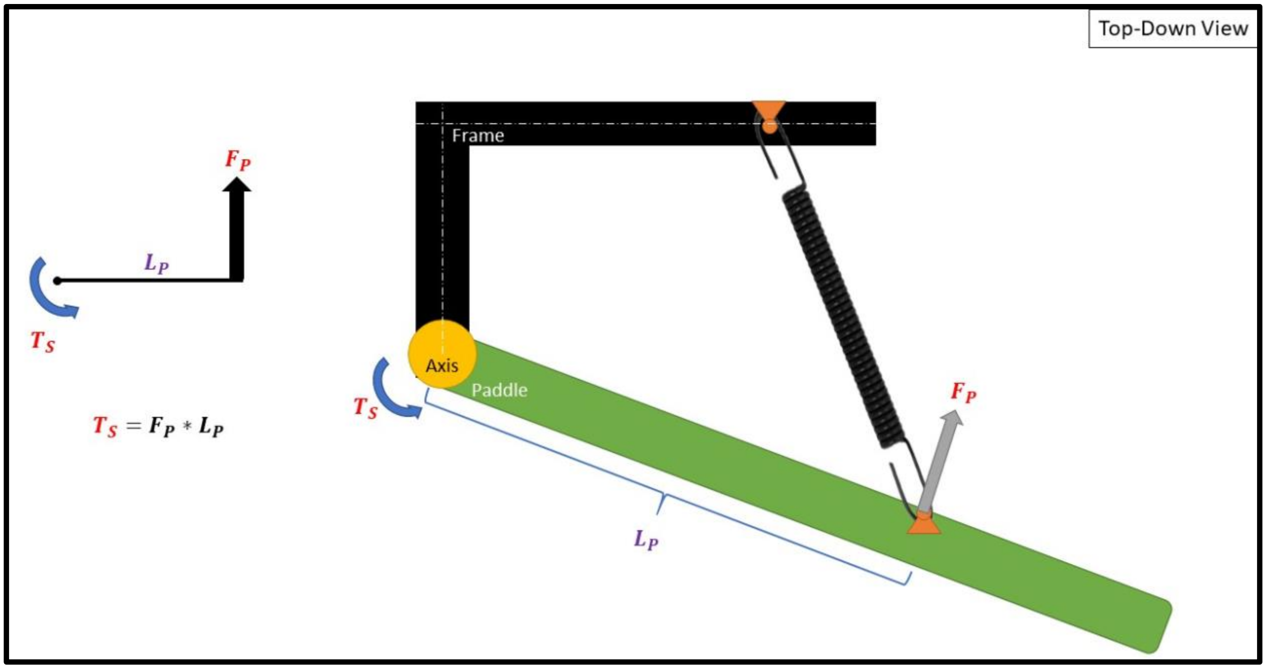

Figure 36: Methodology for solving Equation (2.8)

The torque created by the spring must be met by an opposite torque created by the application of hand pressure such that

$$\boldsymbol{T_A} = \boldsymbol{T_S} \tag{2.9}$$

where $\mathbf{T_S}$ is the previously solved resistive paddle torque and $\mathbf{T_A}$ is a torque created by the user's hand. Torque $\mathbf{T_A}$ is on the same axis as $\mathbf{T_S}$, and the equilibrium equation assumes the minimum force required to move the paddle against the resistance of the spring is the torque equal to the resistance of the spring. Equation (2.9) stems from a sum of moments equation since the two torques are in opposite directions.

The torque created by the user applying force to the paddle has a different moment arm and force than $\mathbf{T_S}$, but is of equal magnitude in torque. The force required for a user to apply a torque equal and opposite to $\mathbf{T_S}$ is defined by

$$\boldsymbol{F_A} = \frac{\boldsymbol{T_A}}{\boldsymbol{L_F}} \tag{2.10}$$

where $\mathbf{T_A}$ is a torque equal in magnitude to $\mathbf{T_S}$ and L_F is a design input length from the axis to the point of applied force along the paddle. the assumption that Θ_A is a constant 90 degrees avoids the need to project the applied force based on an angle of application. Figure 37 displays the development of the final output of the mathematical model, Equation (2.10). The equation is similar to Equation (2.8), but solved for the applied force instead of the torque since the force is the only unknown value. Force $\mathbf{F_A}$ is the final parameter to be solved for in the mathematical model and is dependent on all previously solved parameters and input lengths. Force $\mathbf{F_A}$ is used to gauge the effectiveness of a possible design, as it represents the connection of the design to the user and how it will behave.

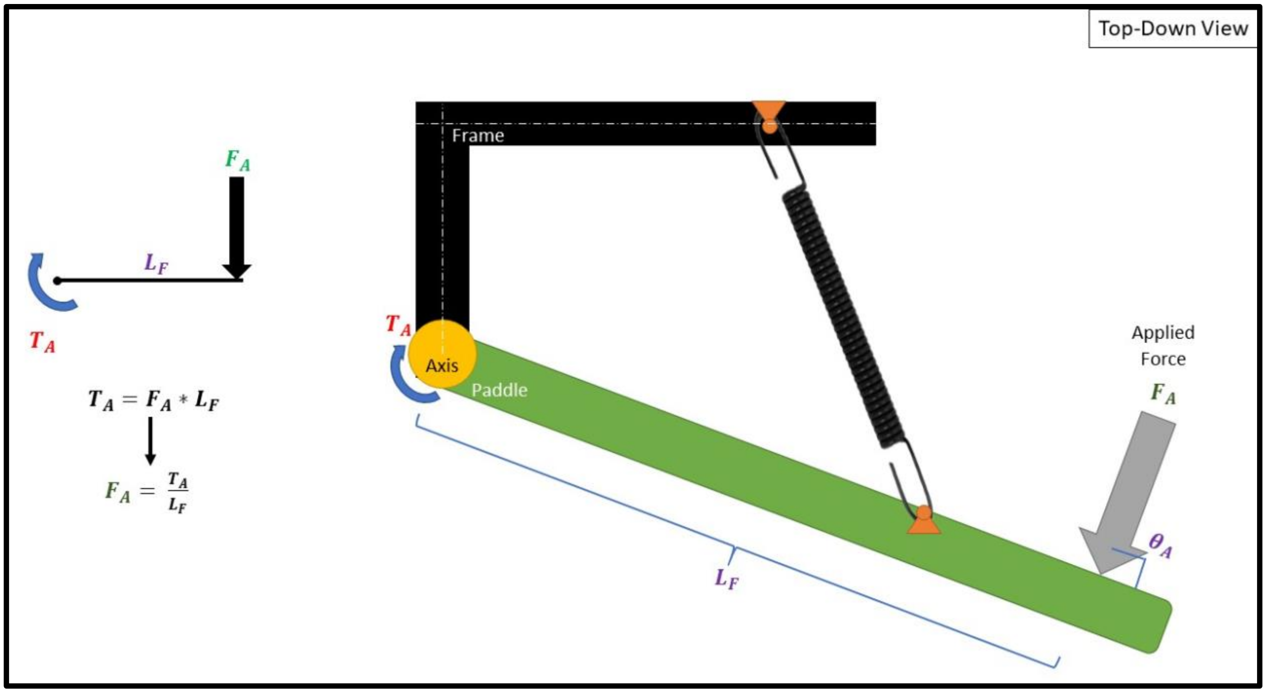

Figure 37: Methodology for solving Equation (2.10)

After defining all variables of the system, the team set out to develop a mathematical model using MATLAB. Figure 38 displays the MATLAB code including the final design's input dimensions. The first few lines of the code include the inputs to the functions, which are defined by the lengths of the proposed design, the initial angle of the paddle, and the spring constant of the proposed spring for the design. After the inputs, the code had to be created in a way such that the order of equations would not create an error. Only variables that are already defined are used to solve for new variables. After the inputs of the function and converting units, the code defines the driving motion of the system; the paddle's rotation over 45 degrees. After the paddle's rotation was defined, L_T and L_V are solved since they depend only on the input variables and rotation of the paddle, all of which are defined in the lines above. Length L_S is solved next in the code since its formula relies on lengths L_T and L_V defined above it. The spring angle was defined next since all variables it relies on are solved above it. After defining the spring angle, the code solves for spring forces $\mathbf{F_S}$ and $\mathbf{F_P}$ which are the spring force and projected force, respectively, using the spring constant and spring angle. Finally, the sum of torques equation is defined after the spring torque $\mathbf{T_S}$. After the sum of torques equation the spring torque is used to solve for the applied force, which is output as a matrix of forces over the rotation of the paddle. The maximum applied force value was displayed by the output of the code.

```
%HAND CONTROLS FOR DISABLED SIM-RACING
%Mathematical Model for Paddle Effort
clc, clear all

%INPUTS FROM SW MODEL ASSEMBLY, REFERENCE DIAGRAM, LENGTHS IN MILLIMETERS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
LD = 20.71;
LL = 41.94;
LP = 78.61;
LF = 50;
po = 1.67; %angle between paddle axis and spring mount
%SPRING CONSTANT K
k = 0.9; %(lbs/in)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%conversion from lbs/in to N/M
k = k*175.1338;
%Conversion to Meters
LD = LD/1000; LL = LL/1000; LP = LP/1000; LF = LF/1000;
%Paddle angle THETA_P iteration over 45 degrees, from 90 to 135
THETA_P = (90-po):(135-po);
%Calculated Lengths
LT = LP*sind(180-THETA_P);
LV = LP*sind(90-(180-THETA_P)) + LD;
LS = sqrt(((LT-LL).^2) + (LV.^2));
%Calculated Spring Angle
THETA_S = asind((sqrt((LL^2)+(LD^2))./LS).*sind(THETA_P - asind(LL./sqrt((LL^2)+(LD^2)))));
%Calculted Spring Forces
FS = LS.*k;
FP = FS.*sind(THETA_S);
%Calculated Torques
TS = FP.*LP;
TA = TS;
FA = TA./LF;
%Required Effort (output) plotted against paddle angle
plot(THETA_P,FA)
grid on
xlabel('Paddle Angle (degrees)')
ylabel('Applied Force (Newtons)')
%Max Force (N) and Force Reduction(%)
Applied_F_Max = max(FA)
Effort_Reduction_Percentage = (1 - (Applied_F_Max/18.15))*100
%Spring Length initial and final (mm)
Spring_Length_initial_inch = min(LS)*1000/25.4
Spring_Length_final_inch = max(LS)*1000/25.4
Spring_Elongation_Total = Spring_Length_final_inch - Spring_Length_initial_inch
```

Figure 38: MATLAB code for the SWHC mathematical model

The matrix of applied force values was plotted in a ‘force curve’ of paddle angle versus force applied. Figure 39 displays the force curve of the SWHC final design. While the final design’s force curve is very linear, other designs the team ran through the mathematical model had varying force curves. Some curves were parabolic with the peak force towards the middle of the rotation at different angles and magnitudes. The force curve characteristics stem from the spring angle and the projected spring force. As the paddle rotates, the spring angle decreases, which decreases the projected force perpendicular to the paddle. However, as the paddle rotates the spring stretches which linearly increases the magnitude of the spring force. Depending on the system being defined and the spring being used, the force curve exhibited

a peak force before full rotation of the paddle because beyond the point of peak force the spring angle was so little it decreased the sinusoidal projection of the force. Overall, the team tried to achieve a linear force curve since this would give feedback most similar to using a spring loaded pedal and would provide predictable resistance.

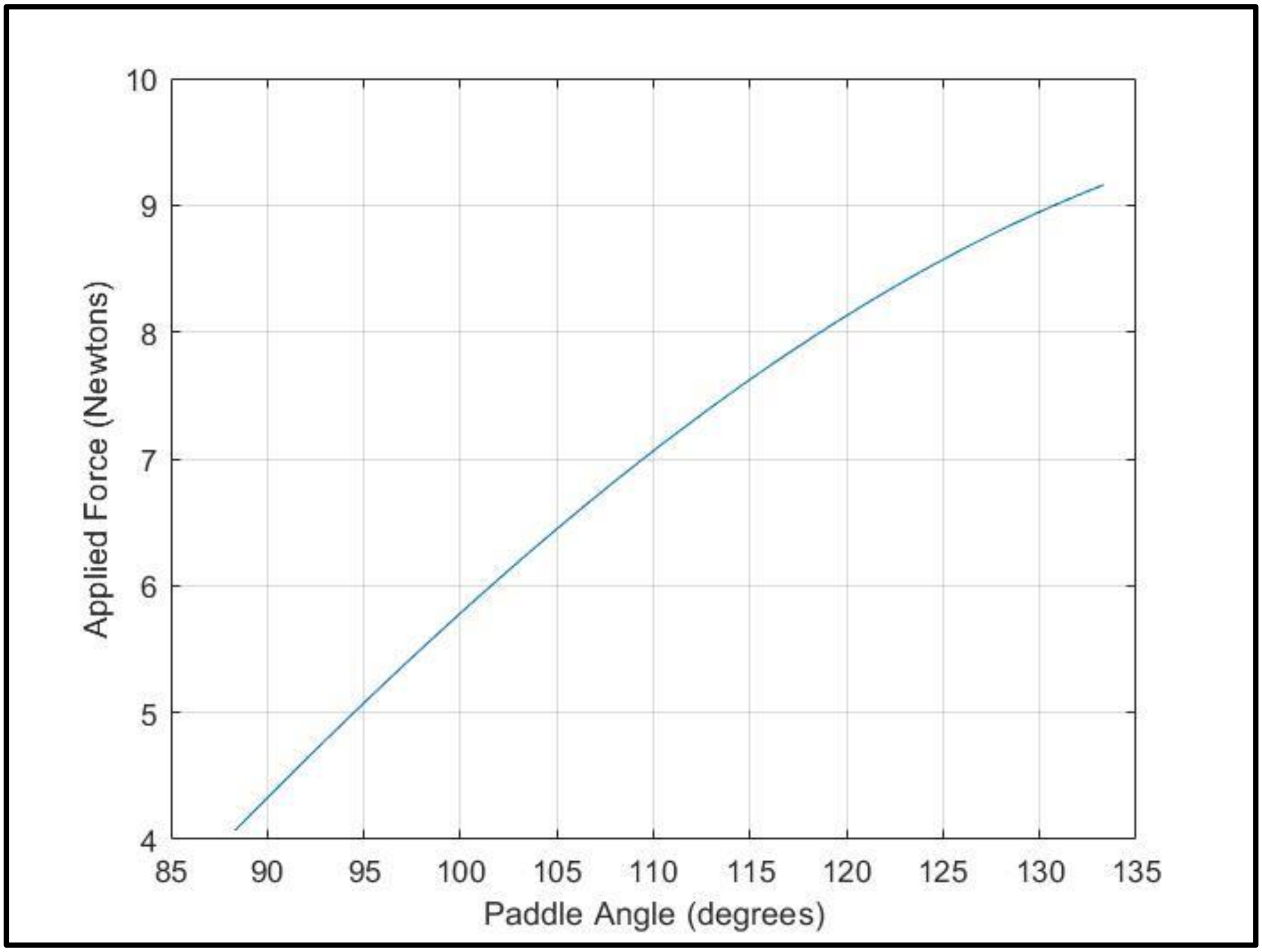

Figure 39: Applied force versus angle of the SWHC final assembly design

Along with the force curve and peak force as outputs to the code, the code outputs the initial and final spring length as well as the spring elongation from the spring length vector. The spring length values are used to find an appropriate spring that doesn't have too short an initial length or is overextended at final length. Finally, the code outputs a force reduction as a percentage of force from the foot pedal force testing. Through design iteration and testing, the final results of the SWHC assembly create an ideal force reduction and linear force curve. The final design outputs are in Figure 40 with force in Newtons, force reduction in percentage, and spring lengths in inches.

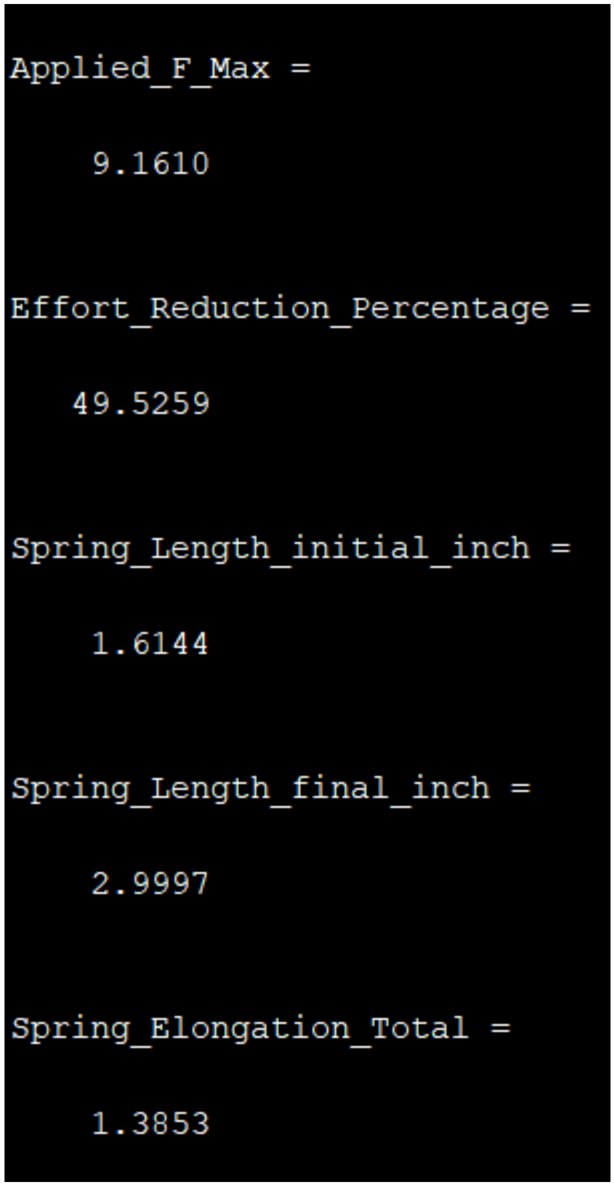

Figure 40: Final design outputs of the SWHC assembly including peak applied force, force reduction from foot pedals, and spring length

2.3 Detailed Design

Once the team determined that the embodiment design phase was complete, the 3D model entered the detailed design phase. In this phase, each component of the control system was evaluated for structural integrity, ease of 3D printing, and fit and finish in order to produce the highest quality hand controls using the team's engineering knowledge and experience. This phase of design was accompanied by strength tests where applicable and by usability testing on a simulation racing setup, covered in the next section. Once the detailed design phase was considered complete, the team focused their efforts on additional product testing and creating an easy installation experience for future end users.

2.3.1 Final Design Elements

The team discovered that the points of highest load in the SWHC design are the attachment points for the extension springs. The extension springs carry all the reactive forces of the design and are meant to extend between two parts made of 3D printed PLA. Due to the relatively low strength of PLA, the team found it necessary to design a spring attachment bracket with exceptional strength to withstand continuous use and the risk of overextending the spring.

The team set out to design a spring anchor point that could be used on the lower frame and on the paddles of the assembly. The team decided to design a capture-style attachment point for the spring instead of a hook-style design since a hook design would require the additional hardware of steel hooks or rely on the strength of a 3D printed hook shape. Additionally, a hook design has a higher chance of allowing the spring to disengage from the attachment point while a capture design guarantees attachment of the spring and distributes the load of a pivot point over two anchoring sites that can have high strength yet be lower profile than a large hook shape. Part of the scope of the SWHC project is utilizing parts from the original pedal set in the new adapted hand controls kit. Along with using the potentiometers from the pedal set, the team found that the small machine screws could be utilized as pivots for the spring anchor points.

The team developed a capture style attachment point for the extension spring eyelets. The spring anchor utilizes a small machine screw from the pedal set that self-taps into a pilot hole. The two extruded features create a middle gap that is large enough for a closed spring loop to fit; see Figure 41. The spring is secured by placing the closed eyelet between the two features and threading in the machine screw which captures the eyelet. The top curved faces create smooth surfaces to allow the spring to rotate about the machine screw's axis without interference of the mount. Overall, the anchor is very small and fits both on the frame of the assembly and the paddle itself. The team 3D printed the anchor concept seen in Figure 41 to test the ultimate strength of the anchor using a force gage. The max spring force used for comparison is based on the final dimensional model from the mathematical model.

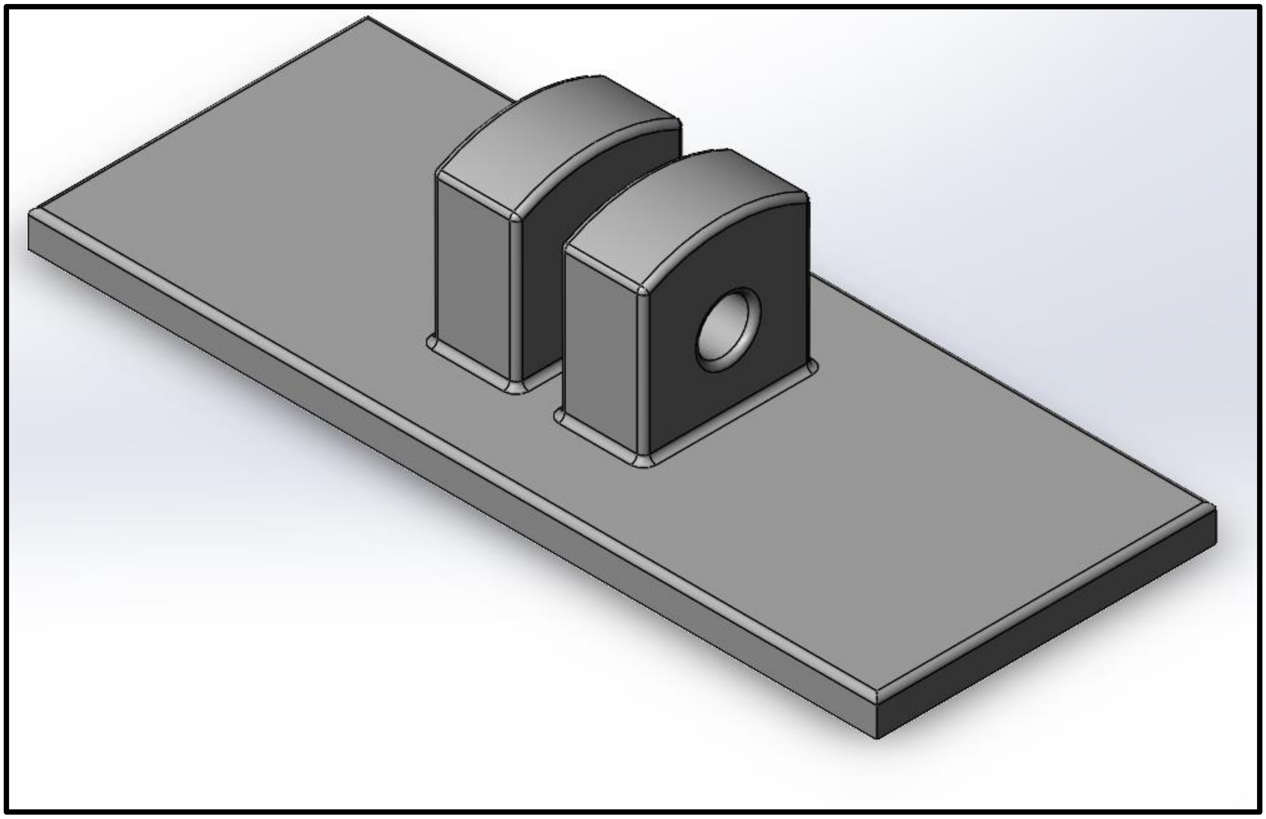

Figure 41: Spring anchor design

After printing several samples of the spring anchor design, the team used a force gauge to test the ultimate strength of the anchor point and ensure it could be utilized into the design. Figure 42 shows the testing apparatus. A small wire clip was inserted into the gap and the machine screw from the pedal set was threaded in to capture it. The apparatus was pulled apart, and the max force on the force gauge was observed upon failure or at the maximum force on the scale. The test was repeated over five printed samples, the results of which are seen in Table 1.

Figure 42: Using a force gauge to assess the strength of the proposed spring anchor design

Sample	1	2	3	4	5
Breaking Strength	93.6 N	98.8 N	96.3 N	106.7 N	108 N
Break Location	On base	On base	On base	On base	No Break

Table 1: Results from testing the spring anchor with a force gauge

The results of the spring anchor testing showed a very high break force for the design, at which the design typically failed at the base of the pivot, similar to what is seen in Figure 43. It is worth noting that one sample maxed out the force gauge and did not break at all. The strength at the base of the pivot on the printed samples was of little concern to the team since the base that the pivot actually uses consists of the lower frame or the paddle, both of which offer a much higher thickness and strength. Nonetheless, an inherent safety factor of the pivot can be calculated by dividing the maximum internal force of the extension spring and the average break force of the sample spring pivots.

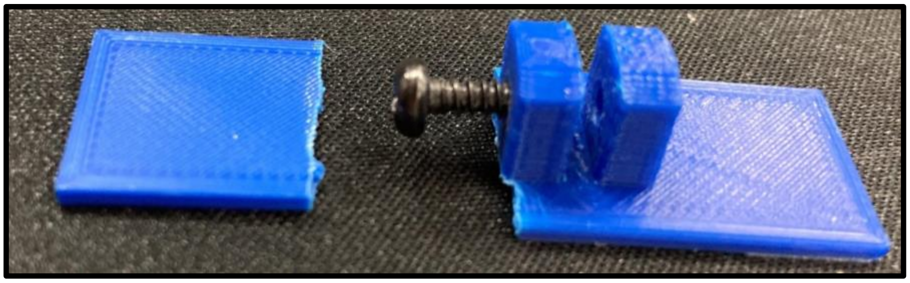

Figure 43: Successful strength test of spring pivot, breakage at base with over 100 N of force

By combining the failure force of the pivot testing and the maximum spring force in the final mathematical model, an inherent safety factor for the spring attachment points is calculated by

$$SF = Fb/Fs \qquad (2.11)$$

where **Fs** is the maximum force exerted by the spring in the final design, equaling 12.2 N at full extension, and **Fb** is the average break force from samples one, two, three, and four in Table 1, equaling 98.85 N. The safety factor of the spring anchor points was calculated using Equation (2.11) and resulted in an excessive safety factor of 8.1. Such a high safety factor ensures the longevity and durability of the highest stressed area of the design and opens the opportunity to use stiffer springs if the user would like to. A high safety factor also protects against improper use of the design, such as overextending the spring or the use of multiple springs per paddle.

2.3.2 Design Components and Standards

The final design consists of a small list of components that can be easily assembled with simple hand tools. The detailed list of needed 3D components, hardware and tools are outlined in the instruction manual in the Appendix A, which is also available on the SWHC website. The components can be broken down into two different types of components. These types are the 3D printed parts and hardware components. There are four separate parts that fall under the 3D printed components. The top and bottom brackets are the main pieces of the assembly which all remaining components are attached to. This includes the final 3D printed parts, the left and right paddles which are attached to the potentiometers, and the bottom bracket. 3D printing, a type of additive manufacturing is covered under the standards imposed by ASTM52910-18 which covers the guidelines for designing with additive manufacturing [6].

The second type of component consists of various types of hardware. Machine screws are used to clamp the two brackets together around the wheel base. Once clamped together, the potentiometers and self-tapping screws are taken from the original pedal set to begin mounting the paddles. The most important piece of hardware is the extension spring which is used to apply tension to each paddle.

As a project touted as an open-source, DIY product there are several standardized parts that are contained within the assembly. These standards are essential with ensuring that anyone around the world can take hardware off the shelf and the assembly will still fit together properly. The most notable standardized parts within the assembly are the machine screws and nuts that clamp the two brackets to the stock steering wheel. These parts are held to standards through the American Society of Mechanical Engineers (ASME). Specifically, the B18.6.3 standard covers all the dimensional specifications for machine screws used in the United States [7]. Another standard, B18.2.2 covers all the specifications for

hex nuts [8]. If these parts were to have large tolerances, then the 3D printed parts would have to be modified specifically to what each user had on hand. Additionally, engineering standards were used in combination with these hardware specifications. For example, the clearance holes for the top and bottom brackets follow the standards outlined in ASME standard B18.2.8 which covers clearance holes for all bolts, screws and studs [9]. Another general standard followed by the project team was ASME standard Y14.5 that covers dimensioning of 2D engineering drawings [10]. The drawings created by the team tried to follow these standards as they would be in actual industry practice. Without these standards and specifications, any design work would become much more difficult and almost impossible to fully produce worldwide.

2.3.3 Iterative Design Process

The team took an iterative approach to printing each version of the paddle assembly, making small changes with each print that improved compatibility, clearance and ergonomics. The iterative approach was accomplished by analyzing the fitment and function of a current print and noting any changes to be done to the digital model before printing again. The subsequent print had improved fitment and the process repeated. Through several iterations, a perfected design was eventually printed with proper fitment and function. The iterative approach was the best approach since 3D printing parts is much more cost-effective and faster than iterating with machined, extruded or molded parts. The areas of the SWHC assembly that needed the most attention during the iteration process were more often areas that hardware attaches, through holes, and keying features, as many digital model dimensions measure differently once 3D printed.

One area of the SWHC design that had to be iteratively changed is the clamping face of the top and lower frame onto the base of the steering wheel, seen in Figure 44. The faces of the top and lower frame were at first too large, creating a loose fit and some slip when turning the wheel. The slip between the wheel and frame made the assembly shift independently of the wheel when turning, creating interference between the shifting paddles and printed paddles of the assembly. To mediate the loose fit, the radius of the faces was reduced. The reduced radius improved the fitment at the base of the wheel, but under quick turning the assembly still shifted. The final iteration includes anti-slip extrusions, seen in Figure 45, that lock the assembly with the geometry of the wheel, assuring zero slip throughout all usage.

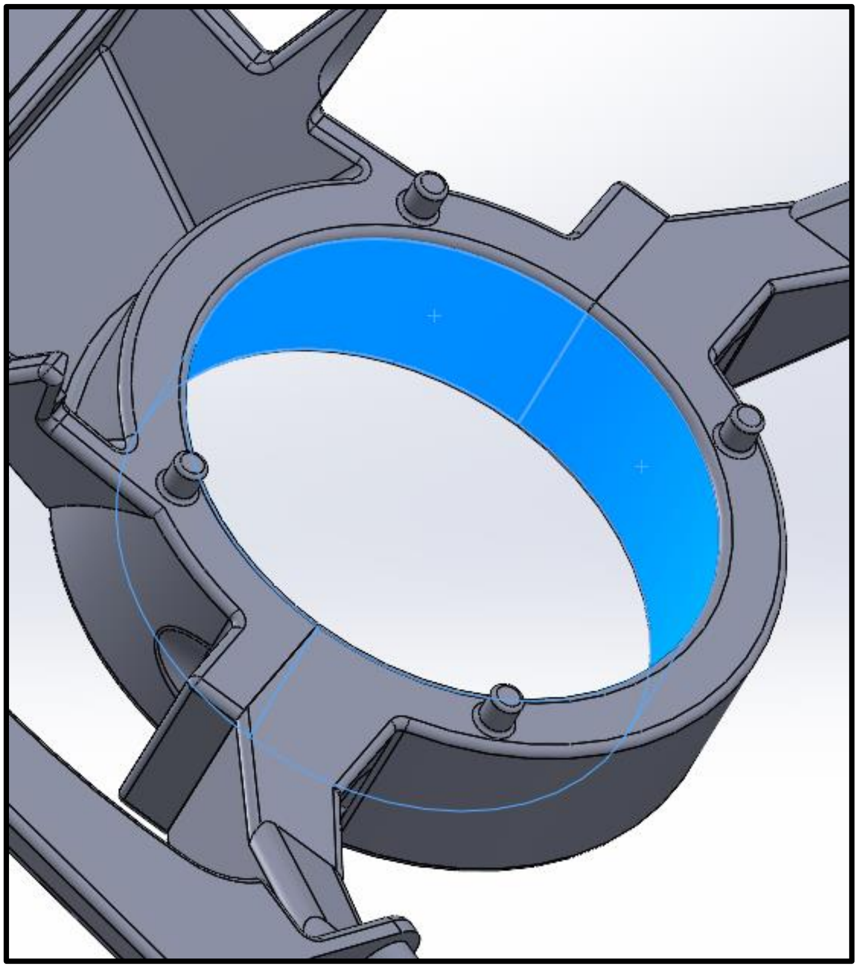

Figure 44: Clamping face of upper and lower face were iterated for proper fitment.

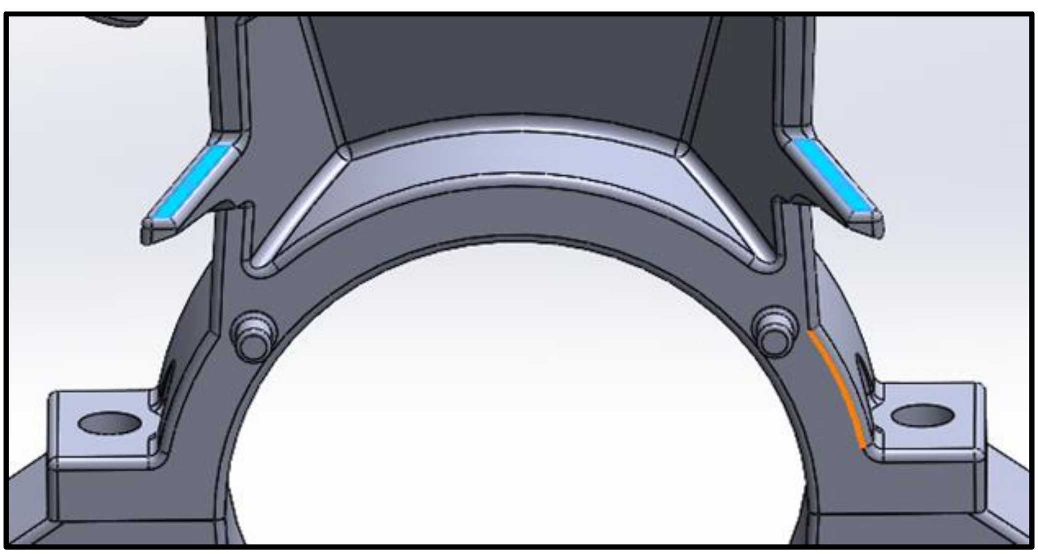

Figure 45: Anti-slip extrusions developed for the final design to lock the assembly to the base

Along with the faces of the upper and lower brackets, the mounting holes that clamp the upper and lower brackets together had to be iterated through prints. The mounting holes include two through-cuts for ¼-20 bolts and a hex cutout to mount a nut flush to the bottom face of the bracket, seen in Figure 46. In the first printed iteration, the through hole printed smaller than dimensioned and the hex cut printed larger than dimensioned. To improve fit, the through hole diameter was increased by 0.015” and the hex width was decreased by 0.015”, resulting in an excellent printed fit of the ¼-20 bolt and nut.

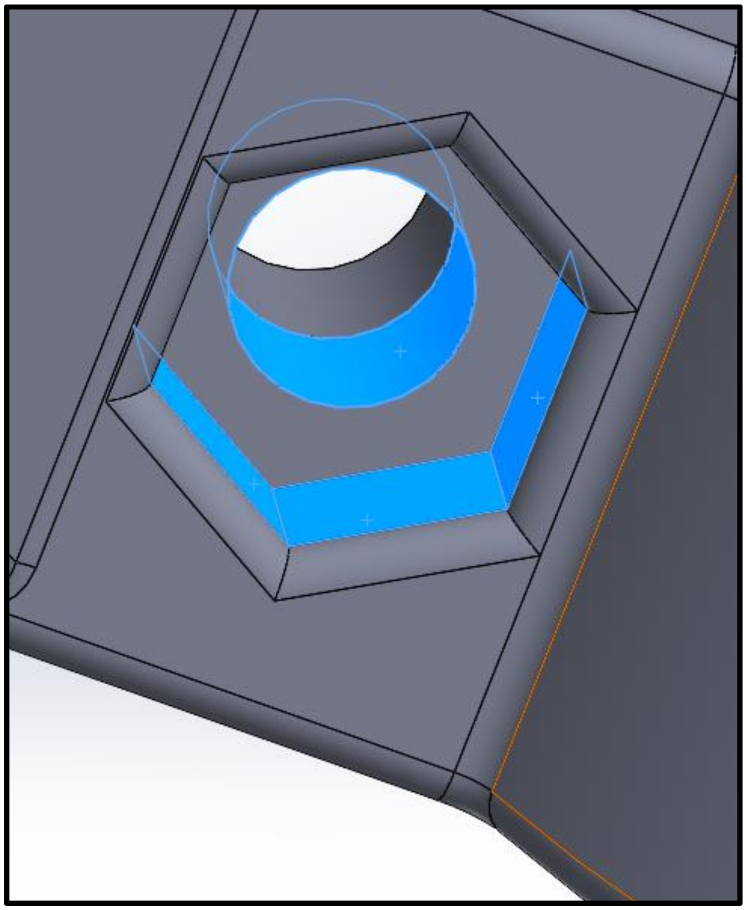

Figure 46: Bolt through holes and hex cutouts for nuts

One of the most difficult areas to develop proper clearance was the potentiometer mounting to the top of the paddles. The clearance in the area of the top of the paddles was difficult because it is the connection of three parts rather than the typical connection of two parts, seen in Figure 47. Since the potentiometer was sourced from the original pedal set, the dimensions of its mounting locations could not be changed, and the team had to develop parts that fit the existing potentiometer geometry. Since both potentiometers rotate in the same direction, the potentiometers are inverted on each side of the assembly. The inversion of the potentiometers created unique connections on each paddle, further complicating proper fitment. Both paddles took advantage of the keying features of the shaft of the potentiometer seen in Figure 48. In the initial print, the paddle holes were too small and the flat feature of the holes was spaced improperly for fitment. The hole was increased by 0.015” and the offset of the flat was changed by 0.010”. Along with keying into the paddles, the potentiometers have a threaded portion that requires a

through hole in the upper frame, seen in Figure 49. The through holes printed small on the initial print, and their diameters were increased by 0.015”. Another print proved the holes too small, and the hole diameter was increased by an additional 0.030”. The potentiometers also have keying tabs to prevent rotation of the potentiometer body, and a feature to accommodate this locking tab had to be incorporated into the upper frame. Figure 50 displays the locking tab features, which had to be increased in size after the first print.

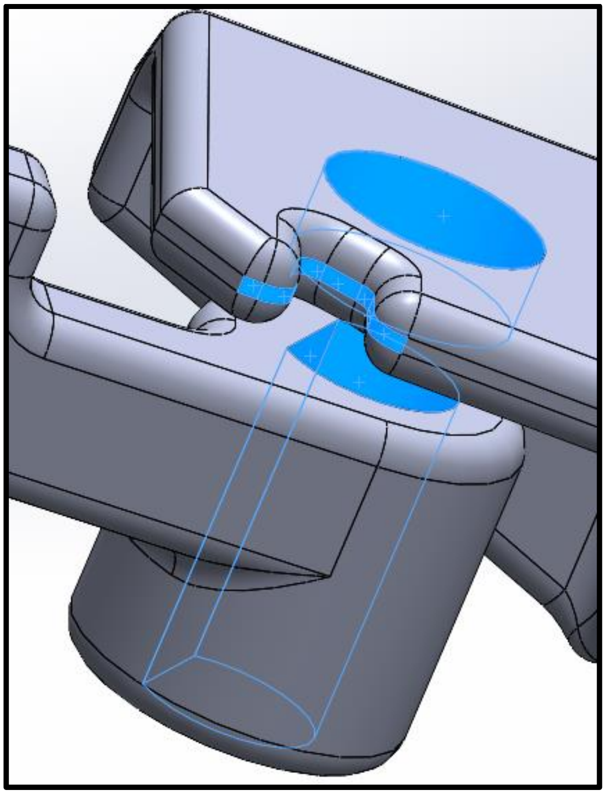

Figure 47: Top paddle connection clearance faces for potentiometer

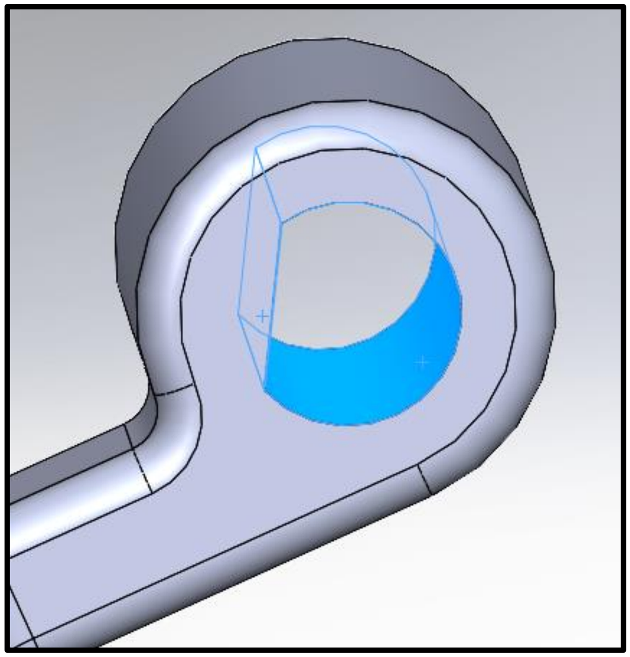

Figure 48: The upper paddle attachments take advantage of the potentiometer shaft keying features

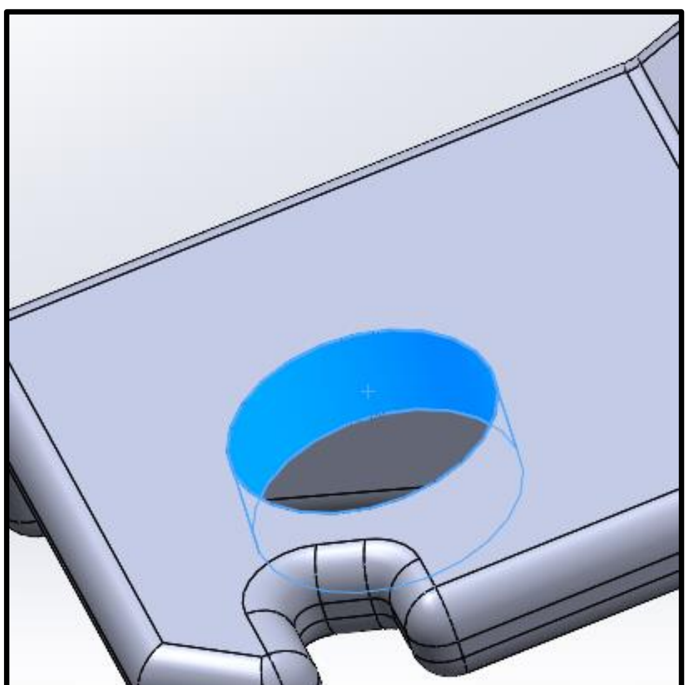

Figure 49: Upper frame through holes for potentiometer threaded portion

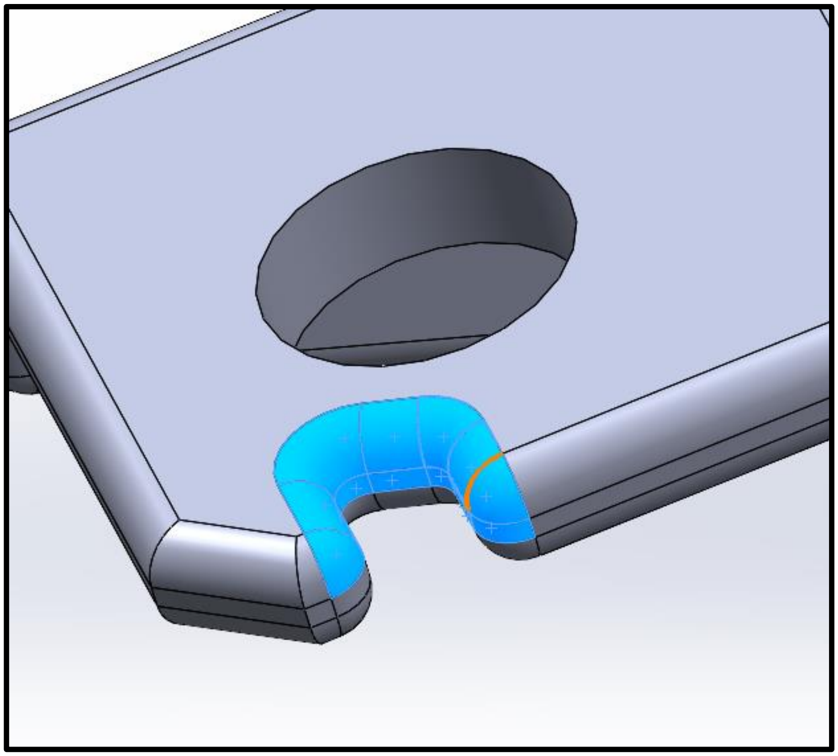

Figure 50: Potentiometer locking tab feature

While the top of the paddles attaches through the potentiometers, the bottom attachment point for the paddles includes a clip-on axis that flexes two tabs over and into a socket, seen in Figure 51. The dimensioning of the paddle tabs was critical, as tabs that were too thin would flex too much and over time walk out of the socket, but tabs that were too thick would have likely broken while trying to flex open. The first few prints found the tabs spaced too far apart, creating a loose fit on the bottom of the paddle and a tendency for the tabs to walk out of the socket. The hinge was edited to provide a better fit that can be assembled easily and remains in the socket.

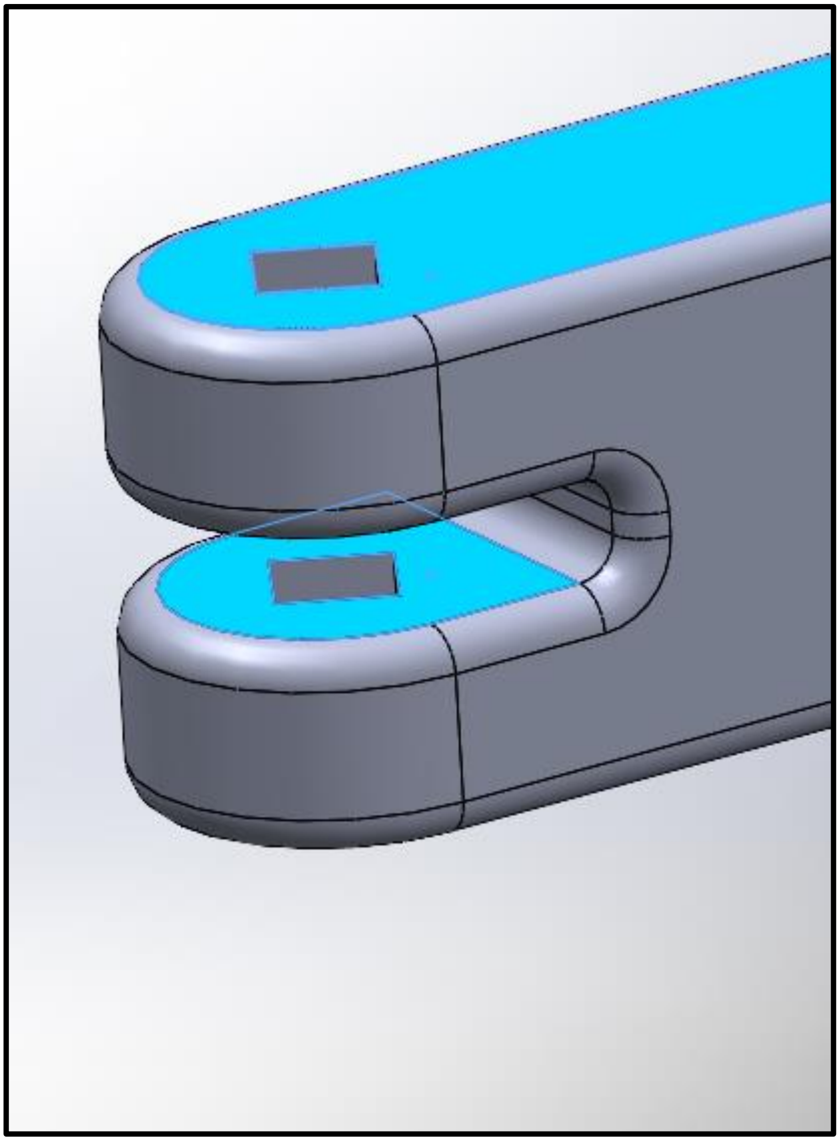

Figure 51: Clip on axis locking tabs had to be iterated for proper fitment

Finally, the team had a clearance issue in the initial print involving the shifter paddles. The inner radius of the printed paddles, seen in Figure 52, contacted the outer edge of the shifter paddles, creating an interference that would prevent the user from using any paddles. To mediate the interference, the next iteration was printed with a larger cut on the inner radius of the paddle, creating clearance between the printed paddles and the shifter paddles.

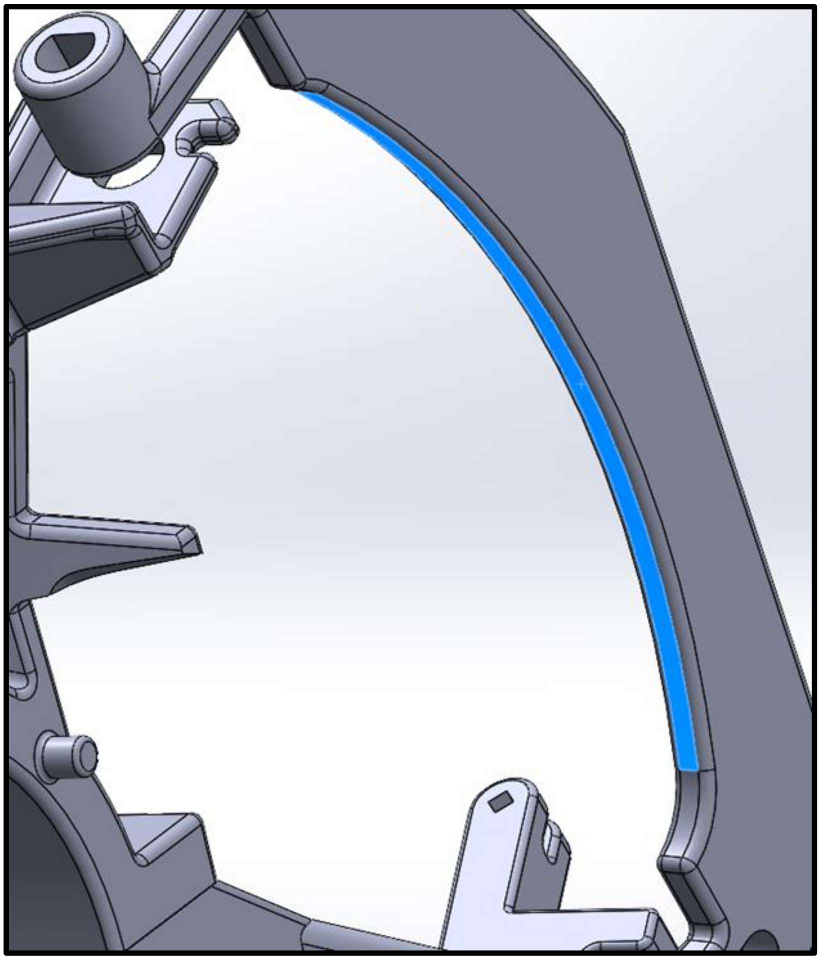

Figure 52: The inner radius of the paddles had to be iterated to create clearance with shifter paddles

2.3.4 Detailed Drawings

After the necessary dimensions were iterated, the team added several features to each component as a final step to bring them to completion. Firstly, every eligible part edge in the assembly was given a radius to improve the quality of the 3D print and to remove potential sharp corners for safe installation and use without part cleanup. Secondly, the team modeled embossed text onto each paddle identifying the left and right hand orientation and the paddles' respective uses for throttle and brake. The team determined that the paddles were the only components requiring this identification, because the top and bottom frames were sufficiently distinct from each other. Technical drawings of each component can be seen below as Figure 53, Figure 54, and Figure 55.

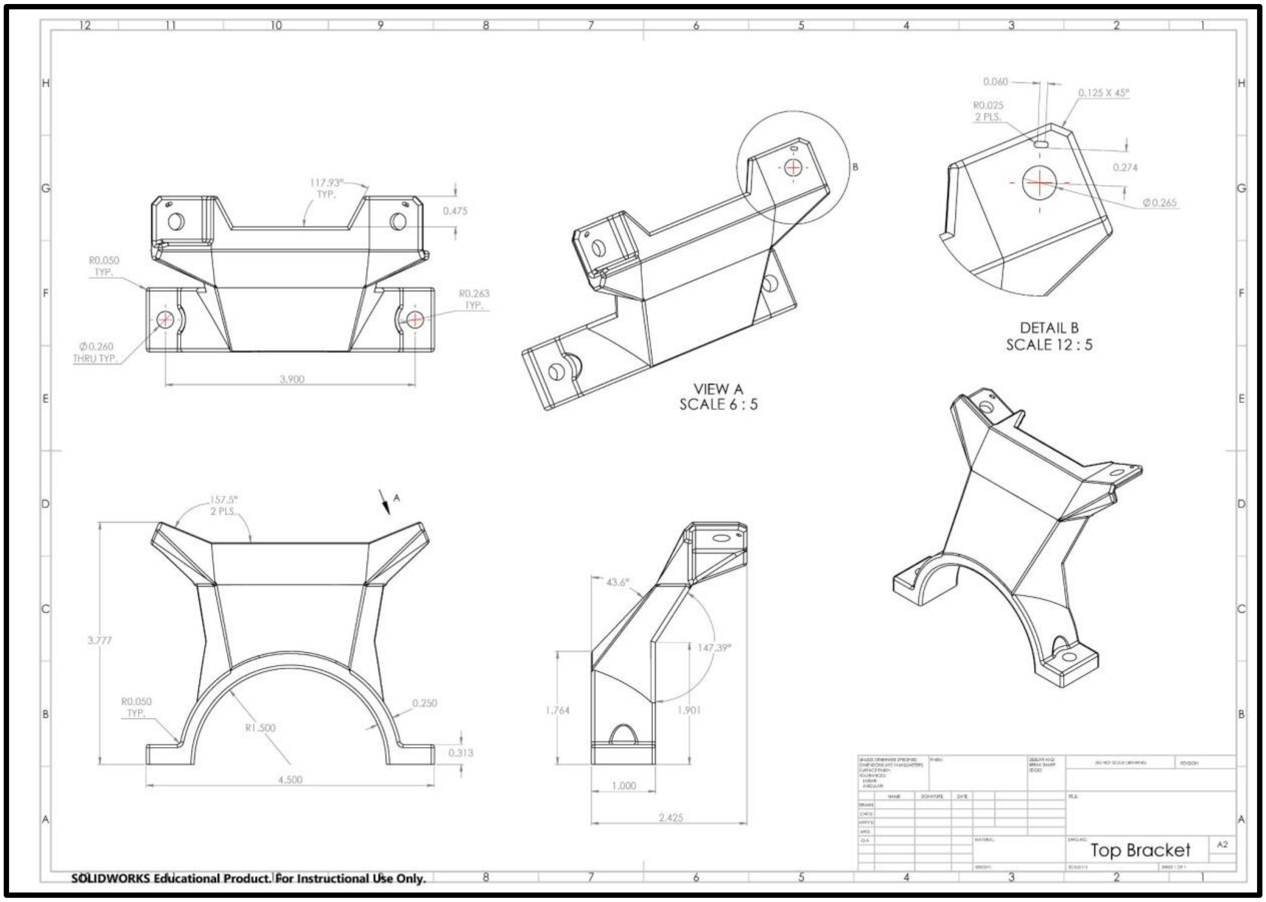

Figure 53: Detailed drawing of top bracket

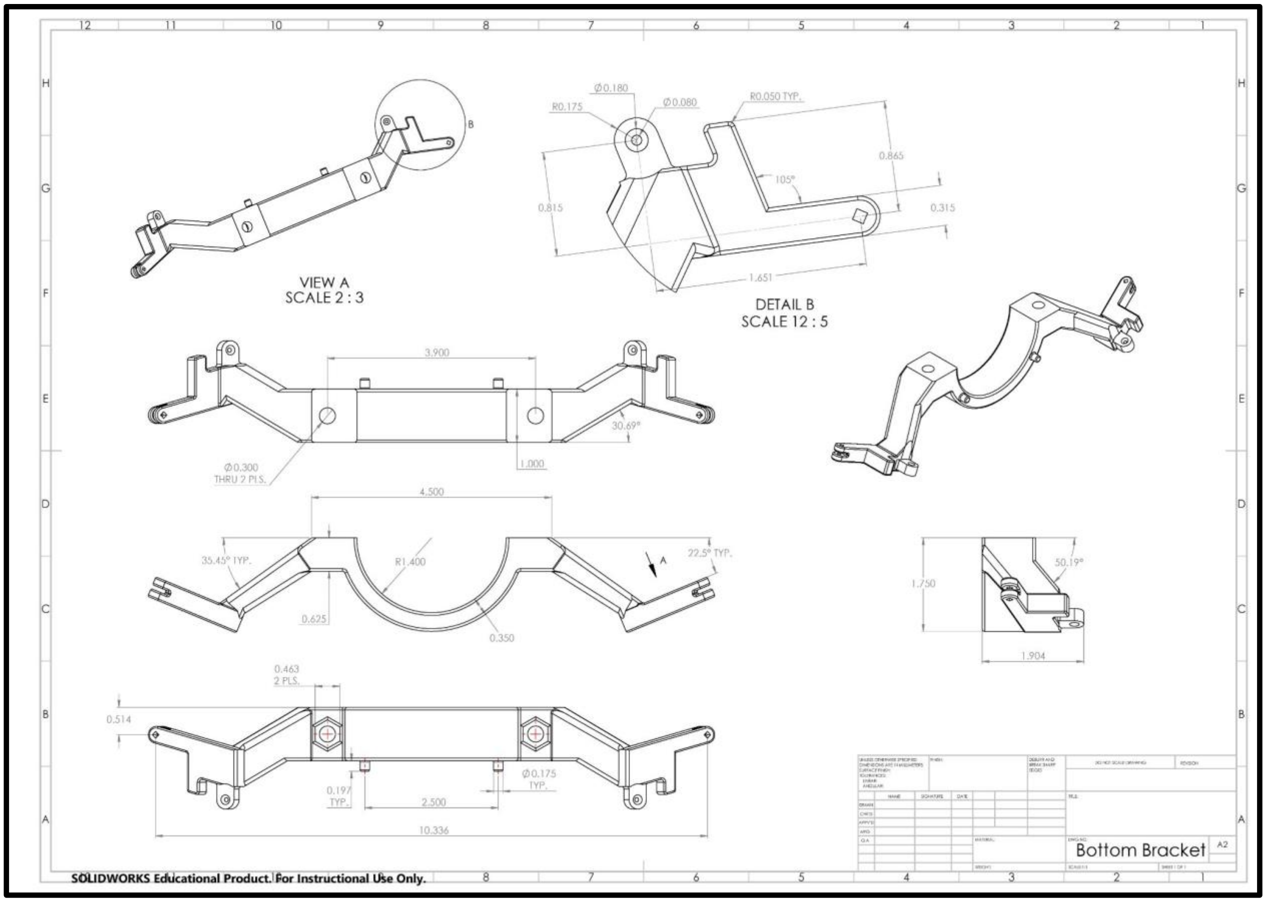

Figure 54: Detailed drawing of bottom bracket

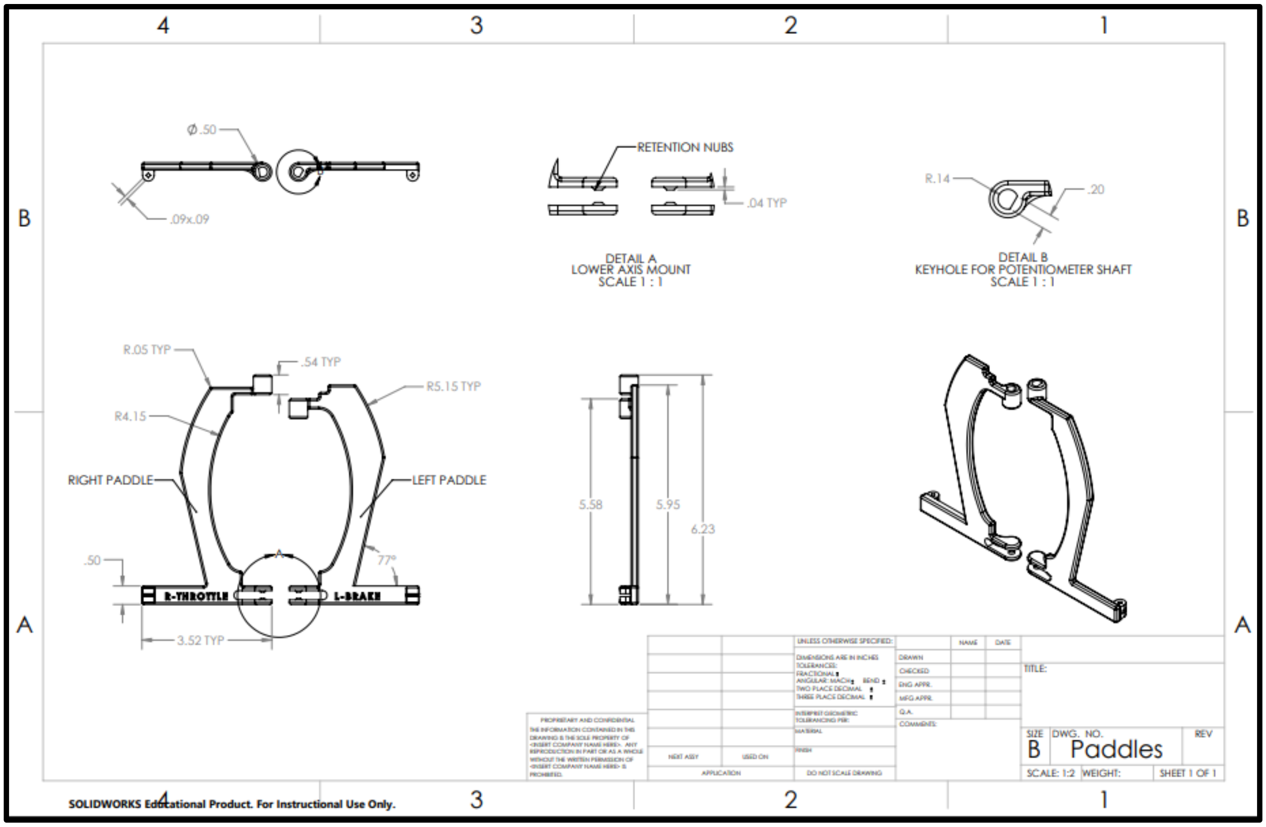

Figure 55: Detailed drawing of paddles

Upon the completion of the 3D model and the technical drawings of each component, the team deemed that creating an assembly drawing would aid as a reference, if necessary, in creating the installation instructions. A bill of materials was used to keep track of each component, and an exploded view drawing was included to provide a visual schematic complete with all the hardware required for assembly. This drawing can be seen below as *Figure 56*.

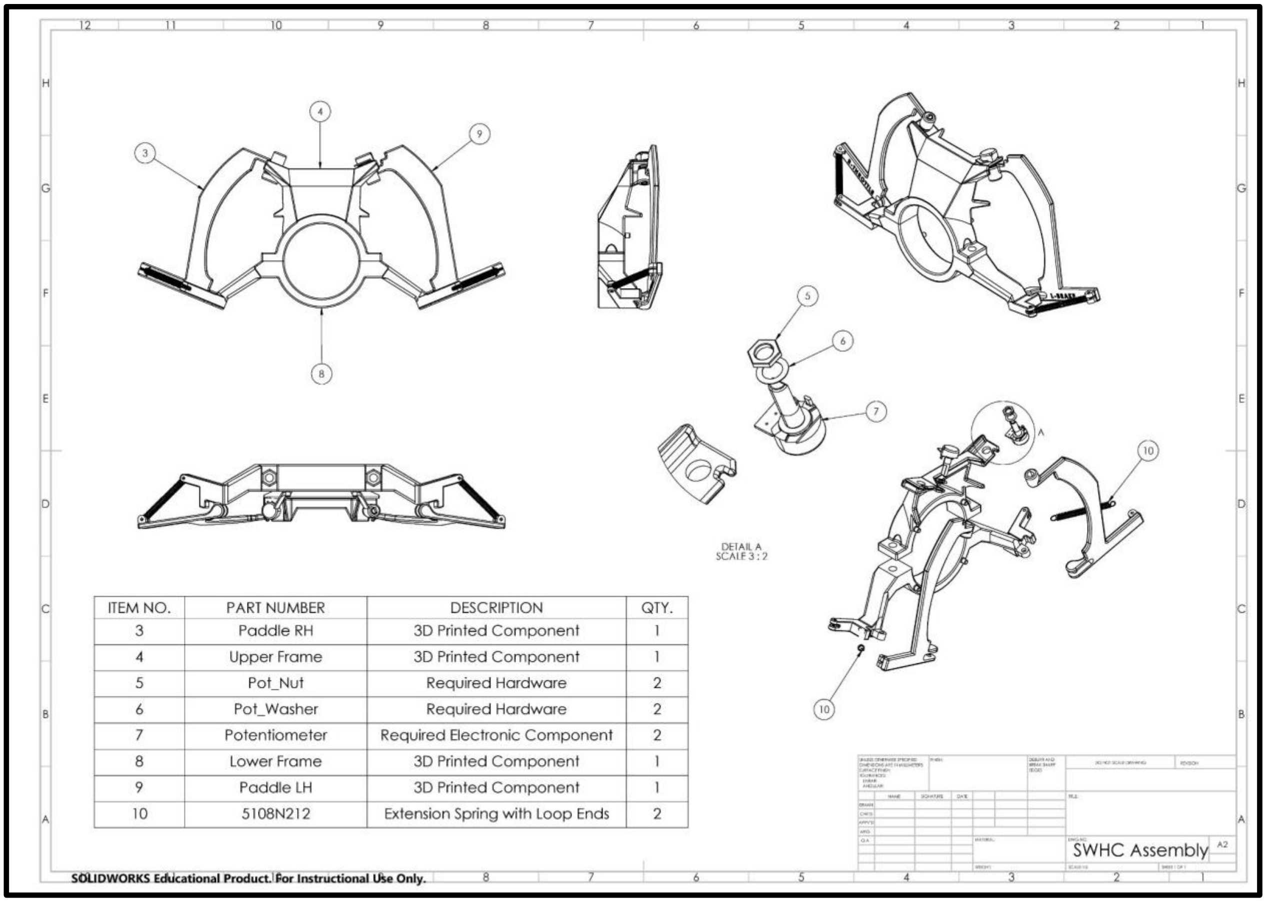

Figure 56: Detailed drawing of assembly

3. Verification

As a project that revolved around product development, it was crucial to verify several different items that pertained to the team's design. The verification process involved a number of tests created by the project team to confirm function or check accuracy of calculated numbers. These tests were completed at various stages of the project and helped the team to iterate the design to its final stage. This section of the report aims to describe and analyze the results of each test as they were performed by the project team.

3.1 Force Gauge Foot Pedal Test

One of the goals of the sim wheel hand controls project was to develop a product that is user friendly and can be enjoyed for hours at a time gaming without any fatigue or discomfort. While a pedal assembly offers users comfort and natural intuition from driving an actual vehicle, the hand pedals had to be designed in a manner that allowed enough resistance from the paddles to be responsive and enjoyable to use while also avoiding hand fatigue with prolonged use. In order to better understand the proper force required for the design, the team first analyzed the resistance of the stock pedal set.

The foot pedal was tested to obtain the force needed to rotate it from rest to the floor, a total rotation of 45 degrees. The force required to radiate the pedal is a function of the line of action (moment arm) and stiffness of an axial spring. Using a force gauge, the force required to rotate the pedal was taken in 10 degree increments and at the full 45 degree position. Figure 57 shows a schematic of the foot pedal force testing increments, where **F** is the force reading on the digital force gauge at each point of rotation. It is worth mentioning that a torque with constant line of measurement *L* as seen in Figure 57 exists on the axis of rotation for the pedal, but since the testing is concerned with effort, the force to rotate the pedal was the primary concern for data gathering.

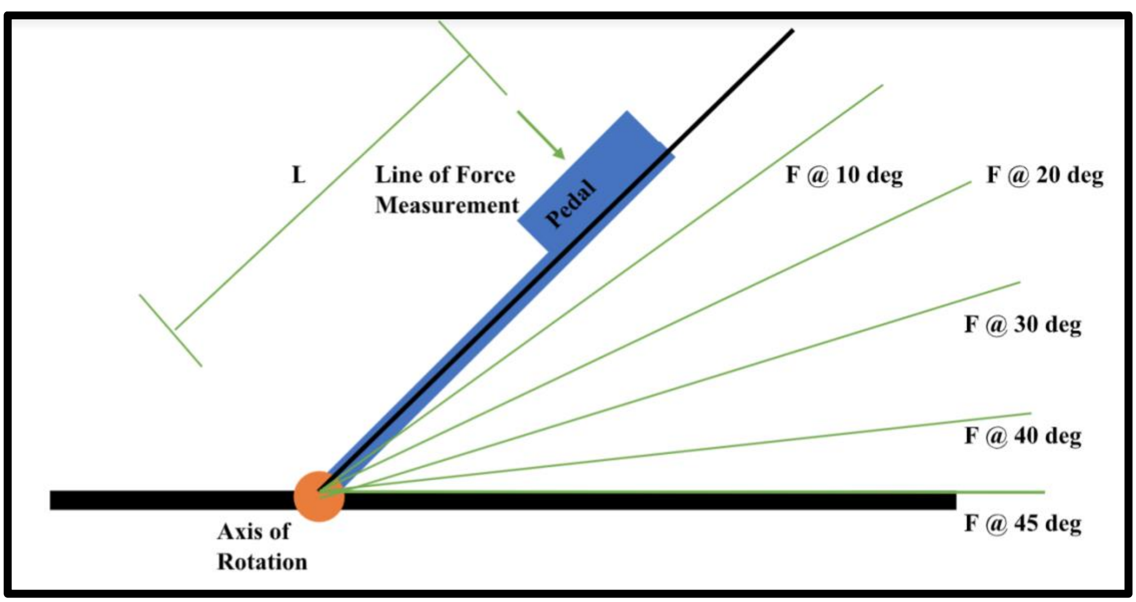

Figure 57: Visual of measurements needed for mathematical model

Since the pedal set came with two pedals that the team wished to convert to hand paddles, both brake and throttle pedals were measured for required effort throughout the 45 degrees of rotation for each. Table 2 shows the tabulated results from the force testing, with Spring 1 representing the slightly stiffer spring in the brake pedal and Spring 2 representing the torsional spring in the acceleration pedal. The team decided to implement equal effort on both paddles in the hand controls design to prevent fatigue in non - dominant hands. An average peak force at 45 degrees of rotation of 18.15 N, seen in Table 2, was used for force reduction.

Angle (Deg)	Spring 1 (N)	Spring 2 (N)	Average (N)
10	8.3	5.1	6.7
20	12	8.7	10.35
30	15.5	12.4	13.95
40	17.3	15.4	16.35
45	20.2	16.1	18.15

Table 2: Force measurements of various springs

To confirm the accuracy of the data measurements and the relationship of the spring, data points were plotted of the measured results. The torsion spring was expected to exhibit the properties of a linear spring. A linear spring relationship by the torsional springs in the pedal set would allow a seamless integration of extension springs in the final design since both behave similarly. Linear springs have a spring constant that is independent of the amount of force being applied. A torsional spring creates a torque about its axis of rotation depending on how far the spring is rotated. The relationship of the torsional springs was confirmed to be linear in Figure 58, which displays the plotted data for each pedal as well as the average rotation versus force curves. Since the moment arm in this case is constant, the force is linearly proportional to the rotation of the pedal. As expected, the plot in Figure 58 shows a very linear plot with a high R-squared value.

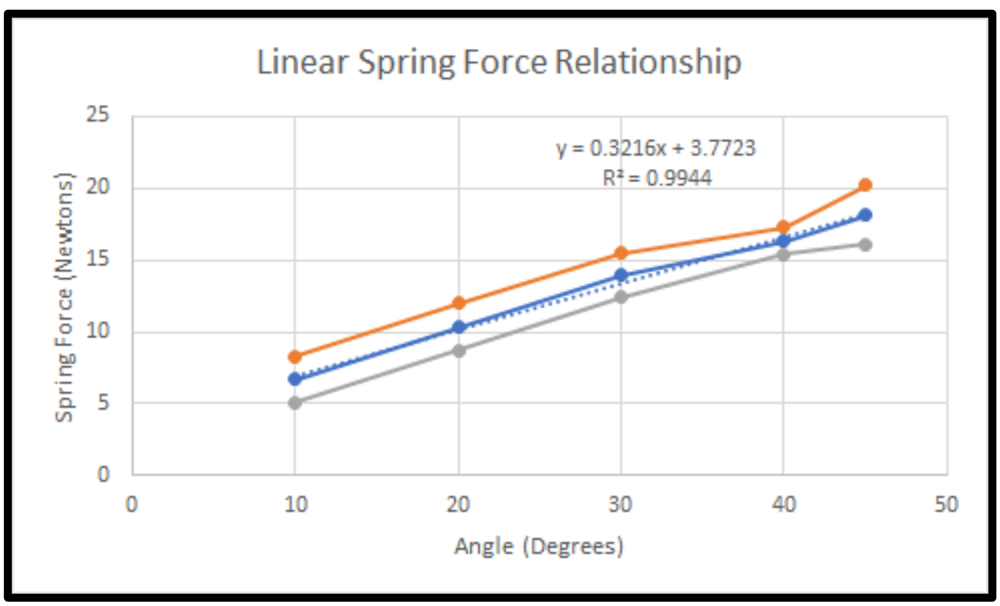

Figure 58: Spring Force Plot showing linear relationship

3.1.1 Pedal Force Reduction Test

While testing the force required to rotate the pedal set, the would be required when converting from foot pedals to the hand paddles. A reduction of peak force of 40-60% gave enough force to provide responsiveness and resistance to use the paddles, but ultimately would be easy to use and not fatiguing for the user. Allowing a 20% range between 40% and 60% gave the team flexibility in finding a compatible spring using the mathematical model. Through iteration and trials of several springs, the team found that a force reduction of 50% was the best option for the design and implemented a spring that gave 49.53% force reduction in the final design.

3.1.2 Comparing Model to Physical Product

The mathematical model the team implemented accounts for all critical dimensions as inputs while also making assumptions in order to calculate an appropriate applied force and spring deflection. From the dimensions input into the MATLAB code from the Solidworks model and the same spring to be used in the prototype, a maximum applied force of 9.16N equating to a 49.53% force reduction from the foot pedals was given by the code. Once the prototype was built, the maximum force on the hand pedal was measured at 8.9N using a force gage, as seen in Figure 59. The results from initial testing resulted in an error of 2.8% between the peak force value in the mathematical model and the actual measured peak force value in the prototype. The team felt that this is an acceptable error, as there are many assumptions made in the mathematical model that would be difficult or impossible to measure for such a small difference in results. Along with assumptions, there are multiple sources of error that arise between the digital model and the assembled printed one.

Figure 59: Force gauge testing resistance of spring

The MATLAB mathematical model makes certain assumptions to simplify the calculation of the hand paddle assembly. All of these assumptions are made knowing that without them the results would only slightly differ and not affect the overall result of the calculation. An example of an assumption that the mathematical model makes is that the force applied to the paddle is always perpendicular to the paddle as seen in Figure 60 below.

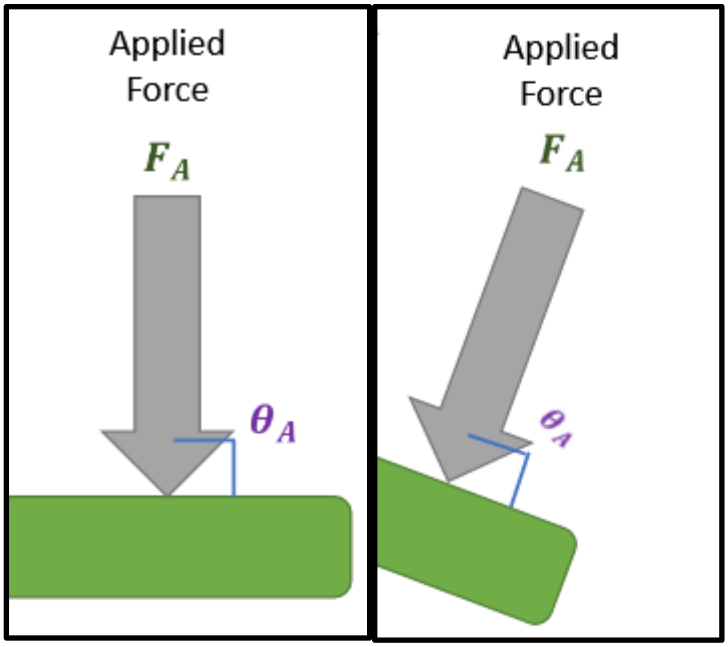

Figure 60: Applied forces on paddle

The assumption that Θ_A remains 90 degrees throughout rotation is difficult to maintain when measuring the physical prototype with a force gage, as this requires the measurer to rotate the force gage with the paddle throughout the paddle's movement. Measuring the force in a situation by which Θ_A is not a constant 90 degrees could contribute to the 2.8% error found going from the mathematical model to the prototype. Another assumption the mathematical model makes is that force is applied to the paddle at a specific point, given in Figure 61 below as L_F.

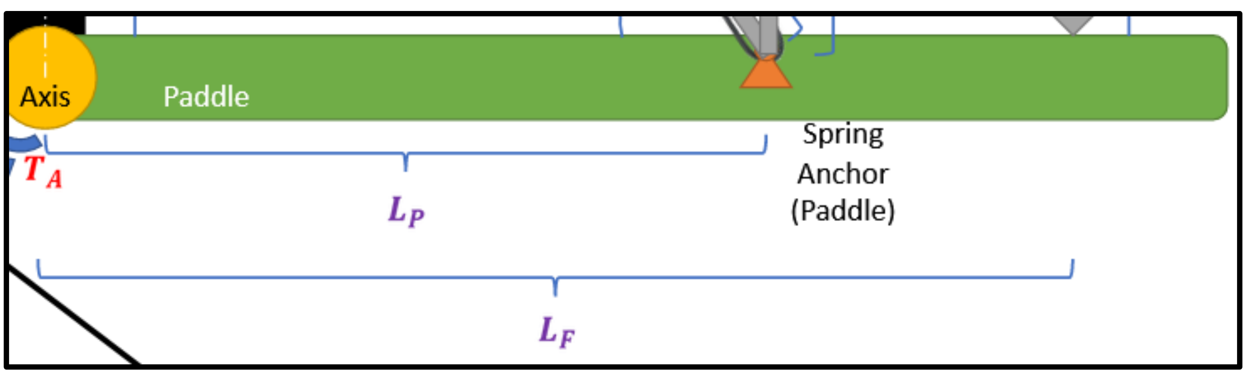

Figure 61: Identifying point of force application, Lf

If the peak force required to rotate the paddle was measured at a different point on the paddle than L_F, it would have changed the moment arm of leverage on the paddle, resulting in a different force. The mathematical model ignores all parasitic losses in the assembly such as friction. While the effect of these forces is likely very minimal, it is worth mentioning that the friction that can accumulate in the pivot points of the paddle and pivot points of the spring was ignored, which may contribute to the small error seen between the mathematical model and the actual prototype. The mathematical model assumes that the body of the spring has zero contact with the frame and paddle throughout use, and the only points of the

spring touching the rest of the assembly are the eyelet mounts. However, the team noticed that the spring coils actually contact the frame and paddle on the ends of the spring. While this likely has little to no effect on the results, it is worth noting that the mathematical model does not account for this interference.

Along with assumptions, there is propagation of error when going from a digital design to a printed one. A degree of error propagated in the actual spring rate of the acquired springs. While the mathematical model assumed that the springs have the same rate that is reported by McMaster Carr, the spring rate likely fluctuates in the actual product from the reported specification. More error propagated in the difference in dimensions that occurred when printing a part with a 3D printer. Due to layering material, the dimensions of 3D printed parts naturally fluctuate from the actual designed values. Since the mathematical model depends on precise dimensions of lengths given by the Solidworks model, the printed lengths of these dimensions may vary, contributing to the 2.8% error going from the mathematical model to the physical one.

3.2 Potentiometer Rotation Test

One of the major challenges of this design was fitting all the required elements into the small workspace. From the principles of operation outlined in Section 1.2, the design must be able to fully rotate the potentiometer from its "initial" state to the "fully-applied" state. These states were defined by the team during initial testing to determine the properties of the potentiometers. The potentiometers included in the original pedal set are listed as B-type potentiometers at 25 kOhm resistance and 45 degree activation band. By using a multimeter, the team was able to determine the real-world properties outlined in the Figure 62 below. From the graph, the potentiometer matches it's B-type resistance curve. That is, the angle-resistance relationship is linear. From this curve, the team defined the initial and final states as 11.3 kOhms and 0 Ohms. Thus, any design created by the team would have to achieve these states when fully depressed.

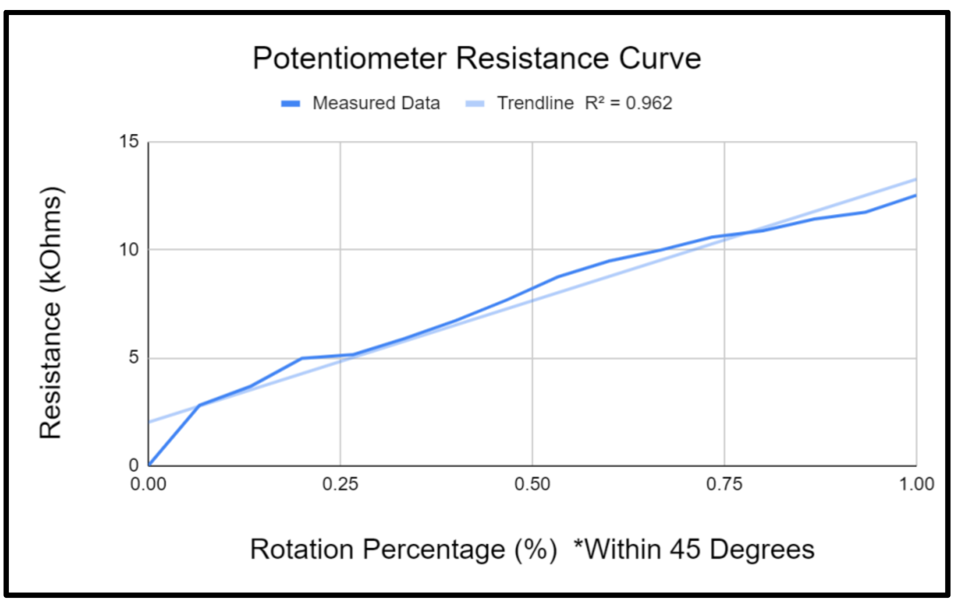

Figure 62: Linear relationship between rotation angle and resistance

These states were confirmed at the beginning of each design iteration. Once the prototype was fully assembled, a multimeter was used to check the resistance of both potentiometers. This was essential in iterating the potentiometer shaft hole on each paddle. If the paddle holes were not aligned with the flat spot of the potentiometers at the angle just before the potentiometer enters its 45 degree activation zone then the system would not work correctly. This was confirmed by fully pressing the pedal and checking the resistance again with the multimeter to make sure it was close to 0 ohms. Any of the prototypes that did not pass this test were revised before completing the next test.

3.3 Real-World Lap Testing

One of the original objectives of the project team was to create a product that was ergonomic while maintaining competitive performance against standard foot pedal users. To ensure this objective had been achieved, the following test procedure was created. First, three of the team members completed a series of laps using the standard foot pedal set. For testing, the Acura NSX GT3 car was used to complete laps at the Circuit of the Americas track on the Project Cars 2 video game. This was kept constant for all real-world testing to make the controls the only variable. The target was for the two systems to be within 0.3 seconds of each other to be considered competitive. The results from this test are outlined below in section 3.3.1. Then, when the design was completed the same members of the team completed the same number of laps but with the hand controls setup. The results from this testing is outlined in section 3.3.2. Additionally, as part of the real world testing, a team member planned to use the hand controls for an extended period of time to ensure that it was comfortable and ergonomic.

3.3.1 Foot Pedal Lap Test

Table 3 illustrates the results from the standard foot pedal testing. The average of each driver's five lap times was taken to set a baseline for each member's performance. Each driver will be compared separately to ensure driver skill is not a factor in the final result. This average was then used as a baseline to compare lap times taken once the hand control laps were completed. If any driver spun or had an accident during the lap it was invalidated and not recorded.

Foot Pedal Lap Times (seconds)			
Lap #	Driver A	Driver B	Driver C
Lap 1	112.38	111.31	95.52
Lap 2	109.82	107.23	94.53
Lap 3	106.30	109.59	94.72
Lap 4	102.32	101.95	93.80
Lap 5	101.90	101.91	93.27
Average	105.09	105.17	94.64

Table 3: Results from the foot pedal testing

3.3.2 Hand Controls Lap Test

Table 4 contains the final results from the hand control testing with the final design. The lap times were recorded in the manner as the foot pedal test. The delta was calculated by taking the difference

between the average from both tests. For example, the delta for Driver A was found by subtracting the foot pedal average, 105.09 seconds from the hand controls average of 106.04 seconds.

Hand Controls Lap Times (seconds)			
Lap #	Driver A	Driver B	Driver C
Lap 1	107.76	102.04	97.17
Lap 2	105.25	106.71	96.76
Lap 3	104.26	105.88	96.06
Lap 4	106.90	103.89	96.64
Lap 5	117.40	107.38	95.65
Average	106.04	105.18	96.46
Delta	0.96	0.01	1.81

Table 4: Results from the hand control testing

3.3.3 Real-World Testing Conclusions

The delta averages outlined in Table 4 offer mixed results as two drivers had a delta significantly higher than the goal of 0.3 seconds. However, when ignoring the averages, each driver had a lap faster or within the set target compared to their foot pedal times. The inconsistent lap times are what led to a higher average than expected and can likely be attributed to being new to the hand control system. While not every driver had done sim-racing before, they had all driven a car in real life. Thus, each driver was more comfortable with the foot pedal set compared to the hand controls. With that being said, the test did confirm that each driver was able to set a competitive lap time. Due to this, it was determined that the team's original goal had been satisfied. The secondary goal of creating an ergonomic interface was also achieved, as Driver C used the system for nearly two hours without any discomfort.

4. Costs

In breaking down the cost of this design project, there are two different types of cost to consider. The first is the physical cost, or the cost it takes to produce the prototypes and ultimately what it takes to physically build the final product. The second type is the theoretical cost, which is an estimation of what it would cost a company to develop this product.

4.1 Physical Costs

The physical cost of this project can be broken down into two sections. The cost the team spent on the product development efforts and the actual cost of the SWHC DIY kit for customers. First, Table 5 shows the total cost to develop the product, which was $93.21. The team purchased a pedal set, a variety of springs to test and bolts/nuts.

Part	Vendor	Actual Cost ($)
Pedal Set	Ebay	45.00
Spring 5108N071	McMaster-Carr	9.31
Spring 5108N32	McMaster-Carr	13.31
Spring 5108N212	McMaster-Carr	13.31
Shipping & Tax	-	9.76
1.5" Bolts/Nuts	Home Depot (Everbilt)	1.26
1" Bolts/Nuts	Home Depot (Everbilt)	1.26
Total	-	93.21

Table 5: Process Development Costs

As part of the goal for designing this product, the team stated that it must be inexpensive and have common hardware that is easily accessible for anyone around the world. Due to this goal, the DIY project should cost no more than $25.00 to produce as seen in Table 6 . The project should cost at least $15.00 to produce, but the cost of 3D printing services and shipping hand handling for the online ordered components will vary depending on location. The design uses easy-to-access bolts and springs that could be purchased at any hardware store, but the team provides suggestions of online stores. Due to a collaboration with Dr. Felicelli, the university is offering free 3D printing services to at least the first 25 individuals who reach out for interest in this DIY project.

Part	Vendor	Actual Cost ($)
Spring 5108N212	McMaster-Carr	13.31
1/4 in.-20 x 1 in. Combo Round Head Zinc Plated Machine Screw (4-Pack)	Home Depot (Everbilt)	1.26
Estimated Shipping & Tax	-	10.00
Total	-	24.57

Table 6: Cost for Customer Final Product

4.2 Labor

The labor for this project is a theoretical cost. The cost for the product development process involves estimated time and payroll needed to develop the final design. The project took about eight months to complete, between September 2020 through April 2021. The team put in an average of 10 hours per week. The total amount of weeks in eight months is about 72, which equates to 720 hours. With an estimated salary of $70,000 shared among the members, the monthly pay would be about $5,833, weekly pay would settle around $1,346, and an hourly wage would be $33.65. This means the total cost of labor for each member would be around $24,228. Overall, for eight months of product development, the cost would be roughly $96,912 collectively.

4.3 Commercialization via Injection Molding

A major consideration for cost would be if the SWHC kit was commercialized. Although the team specifically designed the modules to be optimized for 3D printing, the team valued researching the costs and necessary steps for traditional injection molding. On February 26, 2021 the team met with Kee Sin, the Sr. Development Engineer from Robin Industries. A member of the team had a connection with Sin from co-op rotations. One of Sin's roles at the Robin Research and Development Center is to design prototype molds and quote them for customers; therefore, the team was able to ask questions about molding orientations, parting lines, materials and costs for the SWHC kit.

Although there are many types of traditional molding practices, injection molding was suggested as the most applicable to the SWHC kit: injection molding has design flexibility, fast production, lower scrap rates and using inserts allows for through holes and unique contours (K. Sin, personal communication, February 26, 2021). A single cavity was recommended for each part, resulting in four molds necessary for mass production. Since the design was optimized for 3D printing and not molding, the mold price is expensive without changes to adhere to traditional molding needs.

When assessing each part based solely on the current 3D models, the most conflicting factors in determining the ability to create a mold and its price are thickness of the part walls and placement of holes. First, looking at the paddle models, the parting line would be across the midsection of the thin wall with its molding orientation as seen in Figure 63. Two injection points would be at the top and bottom surfaces of the paddle. The two paddles, which are similar but are different due to lengths, have issues with the current potentiometer holes because they are not in the line of draw. There would need to be a

core that comes in from the side to make those holes, which causes the mold to be more expensive. Additionally, since the potentiometer hole is not round, it would need to be keyed, which also increases the price. The paddles can be molded in its current state, just expensive, landing at around $60,000 for a single cavity. If the holes were altered to be round, added radii to all outlines and have the letters spelling "Throttle" and "Brake" to be extruded instead of embossed, the price of the paddle molds would decrease to $35,000 for a single cavity.

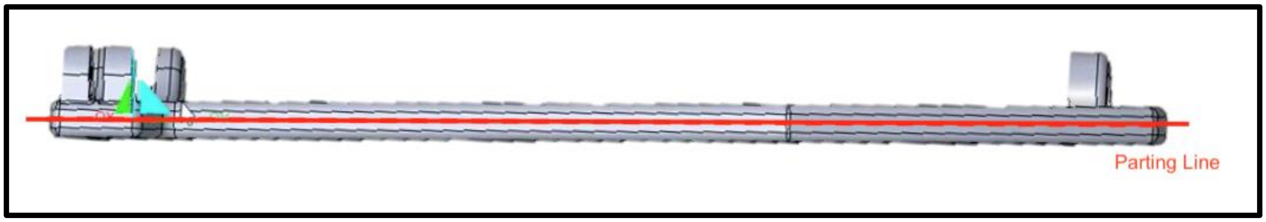

Figure 63: Parting line for molding on paddle

Next, the bottom bracket molding orientation and parting line are shown in Figure 64. The injection molding process is possible with the current state of the bottom bracket; however, due to the extending arm not being at a right angle, the holes are not aligned. Since the spring screw holes and bolt holes are not in the same plane, the price to create cores in the mold would increase. Additionally, this part could experience flow and cooling issues due to inconsistent thickness on the part. The thicker part of the bracket arms would take longer to cool. With the current model, the bottom bracket would cost $55,000, but if the bracket arm parallel was parallel with the mount arm and had a more uniform thickness, it would cost about $35,000 for a single cavity.

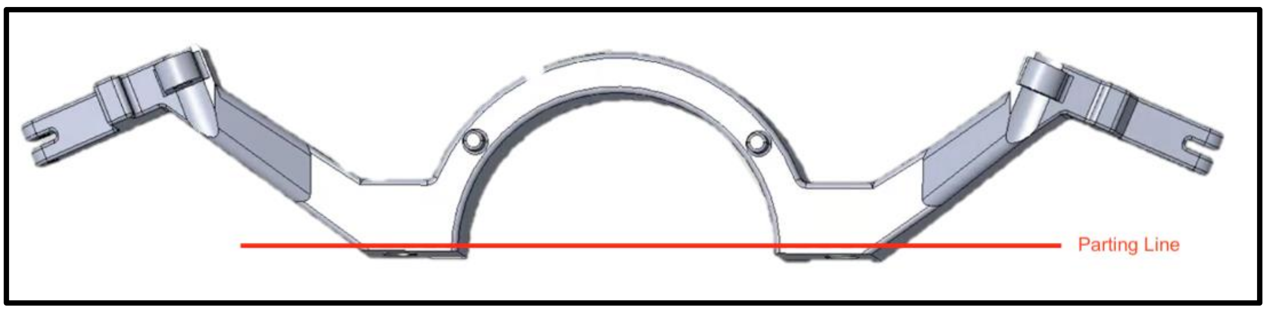

Figure 64: Parting line for molding on bottom bracket

Lastly, the top bracket in its current state also has an issue with holes not being aligned along the same axis, but the thickness is desirable and uniform. In Figure 65, the molding line and part orientation is shown. The top bracket would cost $45,000 in its current state, but if holes were aligned, it would cost about $20,000 for a single cavity.

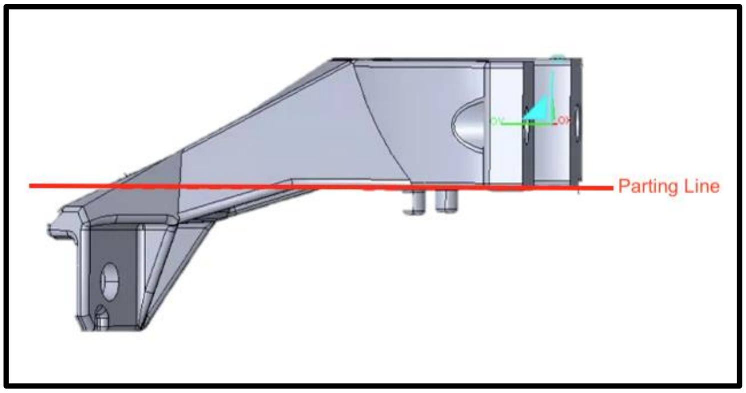

Figure 65: Parting line for molding on top bracket

For all of the pieces - top bracket, bottom bracket, and paddles - drafts would need to be added. A draft is a portion of the part perpendicular to a parting line that allows for the part to be removed from the mold. The recommended material for the molding process is ABS, which is inexpensive in mass production. If using ABS, the designs could be further altered by reducing some of the wall thicknesses since this injection material is stronger than 3D printed PLA. The drafts and reduced material were assumed as part of the estimated costs, as shown Table 7. Table 7 shows all of the proposed costs of molding, both for the current models that are optimized for 3D printing and for the suggested changes to optimize for injection molding. With the redesign, a company could save $95,000. It is important to note that if these changes were made to adhere to injection molding principles, then testing and verification would have to be redone. It would be wise to start from square one with a new design with the goal to optimize it for injection molding rather than trying to change the current SWHC modules to suit injection molding. Creating an entirely new design specifically for injection molding could result in a much lower mold cost and possibly more capabilities not limited to a single cavity. Nevertheless, it was still a valuable experience to learn more about injection molding.

Part	Current Design Mold Cost ($)	Redesigned Mold Cost ($)
Left Paddle	60,000	35,000
Right Paddle	60,000	35,000
Top Bracket	55,000	35,000
Bottom Bracket	45,000	20,000
Total	**220,000**	**125,000**

Table 7: Commercial Single Cavity Injection Mold Costs

5. Conclusion

Throughout the entire product development process, the team worked together to break down the exclusive barriers within simulation racing. From the early conceptual design phase, to the embodiment design and finally with the detail design phase, the team was able to create, test and verify that the SWHC kit is a reliable, ergonomic and realistic product for disable, entry-level racers. This inexpensive, DIY product was created so that anyone in the world can join the hobby, regardless of physical limitations with one's legs. The decision to develop an open-source, DIY product allowed this senior design project to be readily available to real people, as opposed to making a theoretical product. No longer will people be held back by lack of adaptable products on the market and the additional costs current products induce. Those who are interested in simulation racing gaming now have access to a product that will allow anyone to enjoy the adventure and competition of sim-racing like never before.

5.1 Accomplishments

The most pertinent accomplishment the team achieved is the creation of the Sim Wheel Hand Controls website. The website is valuable since this project is open-source and DIY, so all information to create the complete solution is available to anyone who wishes to join sim-racing with this product. The website, ***https://simwheelhandcontro.wixsite.com/simwheel***, has five sections. First is the 'Home' page, which is an introduction to the product. The 'Home' page includes a promotional video, photos of the product in use by the team and the key words of the product: Adaptive, inclusive and thrilling. The second is the 'About' page, which includes a description of the purpose of the product and how it works as well as additional details about the technical side for those interested in learning more about how the team created the product. The third page is called 'What You'll Need,' and it includes information about what is required to create this DIY project. It provides details on compatible gaming systems, recommended racing games and a link to the Thrustmaster TX wheel and foot pedal set. It also provides details about tools needed for the DIY, advice about 3D printing services, the STL files needed to print the parts and links to the external hardware elements, springs, nuts and bolts, needed to complete the project.

Possibly the most important page is the 'Instruction Manual' which provides a downloadable PDF file for the complete guidelines on how to do each step of the process. The manual can be viewed on the website and within Appendix A. The instruction manual includes four detailed sections, all equipped with pictures and step-by-step instructions. The first section details the necessary supplies needed for the project, listing the external hardware part numbers and specifications, elements from within the foot pedal that will need to be reserved and repurposed into the hand controls and lists the tools needed for the project. The next section is the 3D Printing Guide, which gives all of the information related to 3D printing the hand paddles and brackets. It details the materials, infill density, layer height, print time and part orientation that someone will need to supply to his or her local printing resource. This section also includes instructions for how to successfully remove support material from the finished 3D printed parts. The next section is the Disassembly of Foot Pedal Kit, which provides instructions on how to safely take apart the Thrustmaster TX foot pedal set, and lists what elements need to be reserved for hand controls assembly. The last section is the Hand Paddles and Bracket Assembly, which gives instructions on how to put together the 3D printed model with the elements from the foot pedal kit and additional hardware. This section explains how to place the hand paddles and bracket assembly onto the Thrustmaster base. Lastly, the website includes a 'Contact' page that provides an email - SimWheelHandControls@gmail.com -

where the four engineering students who created the project can aid anyone through the process and address questions or concerns without giving out personal information of the team members.

After completing the project and the website, the team reached out to Mike Firtha, President of the Akron Inclusioneers and Halyee Desonne, leader of Summit County Developmental Disabilities Board. By showing the nonprofits the team's website and sharing the product outcomes and goals, some incredible collaborations formed. The SWHC team gave permission for these nonprofit organizations to use the open-source, adaptable product in a variety of different capacities. First, the organizations have moved forward with buying materials to replicate at least five of the sim-racing set-ups with the SWHC adaptations. The team has donated their completed product; furthermore, the nonprofits will replicate more by following the instruction manual on the website. The plan is to allow people at the library to rent a time slot to use the sim-racing set-up. There can also be the option to rent just the module if people in the community have their own sim-racing set-up. Additionally, those who are hosting events geared towards disabled individuals could rent the entire sim-racing set-up.

The Inclusioneers, Summit DD and the SWHC team made plans to couple experienced engineers who volunteer for the nonprofits with high school students from Hoban and Hoover to build the five kits. This will introduce engineering concepts to these high school students, and show the students what kind of experiences can await them at UA. Then, these set-ups will be placed in local libraries. Interest has been solidified from the Akron Public Libraries for an adapted sim-racing machine in their facility. Ultimately, this collaboration is a major accomplishment as this is getting the SWHC product directly to the Akron community and breaking down the exclusive berries on sim-racing. With the help of Kelly Bray, the Director of Marketing and Communications for College of Engineering and Polymer Science, the accomplishments of this project can be shared with the community. Each of these efforts will result in introducing engineering and STEM careers to young students and promoting the University of Akron and bringing awareness to disable racers. With all of the combined efforts, there can be an increased participation in sim-racing within the Akron community, which could ultimately increase the popularity of the E-Sport and finally let disable people feel included.

5.2 Uncertainties

The largest uncertainty of the team's design is the fatigue on the 3D printed parts. The team thoroughly and strenuously tested the final design through several drivers and driving styles which revealed no issues. The long term fatigue testing of the design over several months or even years of use is an uncertainty that is unavoidable, since the team does not have that long to test the final design. The team is very confident that the design can stand up to long term use; however, it is worth mentioning the likely areas to experience wear over a long period of hard use. There are certain components of the design that would likely not be affected by long term use, such as the top bracket. The top bracket's purpose is to support the top half of the clamp on the wheel shaft and house the potentiometers in the upper component of the paddles. It would likely experience little wear compared to the other components because it has no contact with moving parts, as the upper part of the paddles do not touch the top bracket. The clamp attachment does experience torque, but the torque is shared by the bottom bracket, which would experience more wear because it houses one of the two anchor springs. Through cyclic loading on the bottom bracket's spring anchor, some fatigue in the form of stretching may show up in the arm that holds the spring anchor. Overall, the paddle's lower pivot point and faces are likely to show the most wear, as

the faces are regularly pressed on throughout use of the assembly and the lower pivot is a direct contact of 3D printed material between the bottom bracket and the paddle. Over cyclic loading and thousands of rotations, the bottom paddle attachment may loosen from wear and attempt to slip out of the socket; however, the team did not see any wear in the pivot area throughout testing.

Another area of fatigue on the design is the wear on the extension spring. Since springs are wound coils of wire, cyclic loading over a long period of time may weaken them. To minimize the chance of weakening the spring, stretching the spring only to it's working range and not overextending the spring will maximize its lifespan. The team made sure to source a spring that would only be used in it's operating range of extension on the design. While the team did not experience any spring weakening during testing, over a long time of use the spring may weaken and need replaced with a new set. Luckily, the McMaster-Carr spring pack comes with 5 springs, so the user will have replacements when needed.

5.3 Ethical Considerations

The first ethical consideration relates to the 3D printing necessity of the project. There may be places in the world that do not have readily or commonly available resources for 3D printing. The team understands that some areas have less resources available, so they collaborated with the UA Mechanical Engineering Department to find a way to alleviate this stress. Dr. Felicelli, professor and chair of the department, gave permission for free 3D printing services to at least the first 25 individuals who have an interest in building this DIY project. Aaron Trexler also got on board, as he would be the one printing the parts for the community. There are email links to the SWHC account and the university printing services on the SWHC website so that community members can make use of the free printing services.

The second ethical consideration relates to environmental factors. This project uses PLA plastic, which is biodegradable. This thermoplastic is "derived from renewable resources such as cornstarch or sugarcane. PLA is stable in general atmospheric conditions and will biodegrade within 50 days in industrial composters and 48 months in water" [5]. This product can positively affect anyone around the world by making sim-racing more accessible, so this product could be widely produced and used. With worldwide applications, this product could have global environmental impacts. Since PLA is biodegradable, the project will not make a negative impact on the environment. Additionally, the product comes in four parts with different strains and loads interacting during each use; therefore, some elements may deteriorate quicker than others. New printed parts can replace worn out ones, so the entire module will not be disposed of at the same time. The rate at which parts are disposed should not exceed the rate at which they biodegrade.

5.4 Future Work

The future of the SWHC project is wide reaching. Global impact is possible with the use of Reddit. Reddit is a form of social media where users may post links, images, text posts, videos and more. The app is used for discussions, debates and has built a wide variety of communities. One such community is for disabled sim racers [11]. The forum discusses personal adaptations and expresses many frustrations of the exclusive nature of the hobby. The team plans to post the SWHC website and detailed information about the project to this forum so that Reddit users within this community can finally have access to an inexpensive, reliable product.

Continued local outreach is possible with the support of Summit DD and the Inclusioneers. The SWHC kit will see a variety of different opportunities in the near future. During the last meeting with the non-profits, the team became aware of an opportunity with the Reel Abilities Film Festival. This event debuts films about or created by people with disabilities. During the intermissions between shows, activities are available for attendees. A simulation racing station adapted with the SWHC kit would fit in well during the event. It would be entertaining and introduce the hobby to a wider audience.

The Inclusioneers and Summit DD have also invited the team to be a part of the Fall 2021 Akron Maker Faire, which features engineers, artists, scientists and crafters who share their hobbies, experiments, and projects. More details can be viewed on their website at https://akron.makerfaire.com. This event includes booths and activities where young people are able to participate in games and activities to find inspiration, feed their creativity and discover new hobbies. The SWHC team plans to participate in order to offer some activities for the disabled attendees to enjoy. This will also be an incredible opportunity to share the project, expand the sim-racing community and prove that sim-racing can be for anyone.

Lastly, the collaboration with Summit DD and the Inclusioneers could lead to a connection with Akron's Lock 3. Lock 3 is a family friendly entertainment center which currently includes an amphitheater for summer concerts, a putt putt course, an outdoor ice skating rink and more can be viewed on their website at https://www.downtownakron.com/go/lock-3. There has been spoken interest in having an adapted version of a sim-racing machine available on their site. If the SWHC kit can be used to modify a racing set-up for public use at Lock 3, the hobby may be enjoyed by a wide range of people who may not be able to purchase the materials on their own. In combination with the sim-racing that will be available at the local libraries, the sim-racing hobby can become an accessible, thrilling experience for everyone to enjoy.

The team will continue to collaborate with Summit DD, the Inclusioneers and keep up with Reddit. The team will be donating their completed project to the nonprofits on May 3, and will support the groups with any questions and concerns they may have while replicating kits with the high school students. The team will also stay on top of their emails and website feedback, as the students will be the main source of answering questions and connecting people to printing services at UA. The team intends to continue being a support for anyone in the public interested in building the project. With the support of the University of Akron, local publicity, Summit DD and the Inclusioneers, Sim Wheel Hand Controls has the potential to make an ever greater impact than the team could have ever imagined at the start of the project.

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Appendix

A: Instruction Manual

*Begins on next page

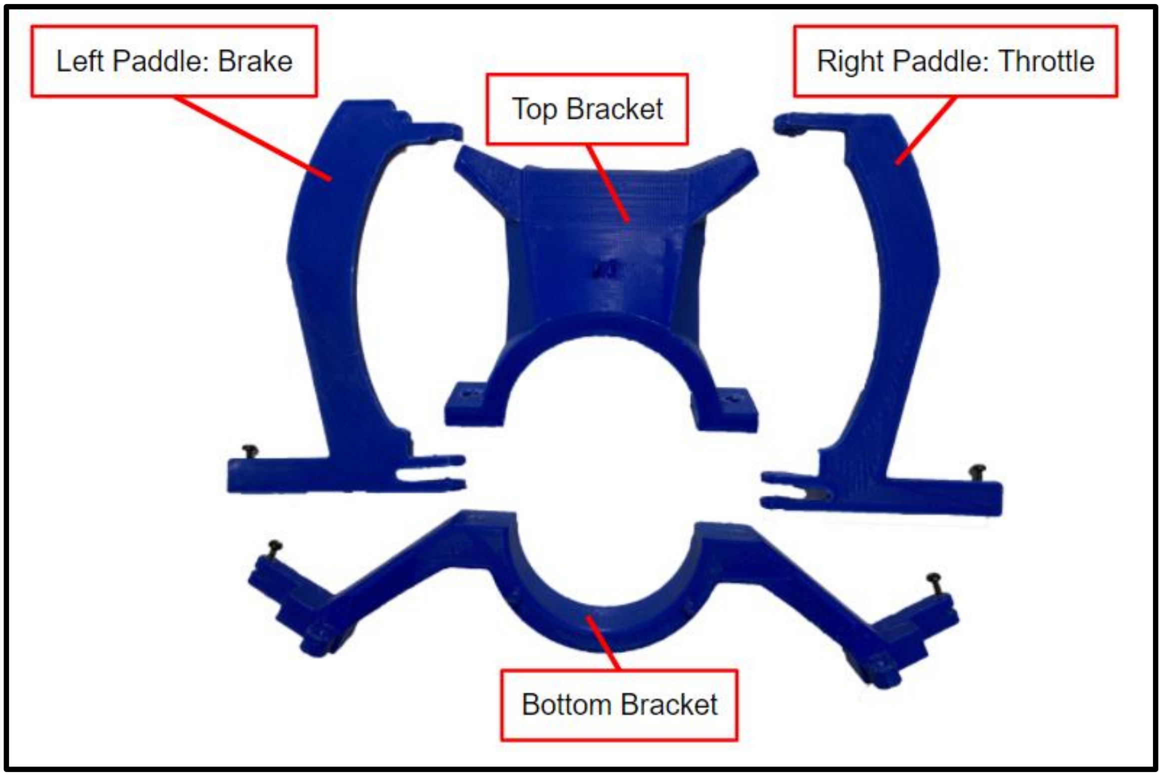
SIM WHEEL HAND CONTROLS KIT

Instruction Manual

Presented by University of Akron Engineering Students - Weston, Josh, Duncan & Jade

NECESSARY SUPPLIES

- **3D Printed Elements:** Top Bracket, Bottom Bracket, Right Paddle (Throttle), Left Paddle (Brake).
  - See details in '3D Printing' on PG 3



- **Assembly Hardware:**
  1. **(Purchased)*** Two 1/4-20 Thread Hex Nuts
  2. **(Purchased)*** Two 1/4-20 Thread x 1 Inch length machine screws
  3. (**Purchased)*** Pack of Extension Spring with Loop Ends. Product Number: 5108N212
     a. *Note: All (**Purchased)** items can be bought from the links on our website's 'What You'll Need' page
  4. Potentiometer set attached to wires **from Foot Pedal Kit**

a. See details in 'Disassembly of Foot Pedal Kit' on PG 9

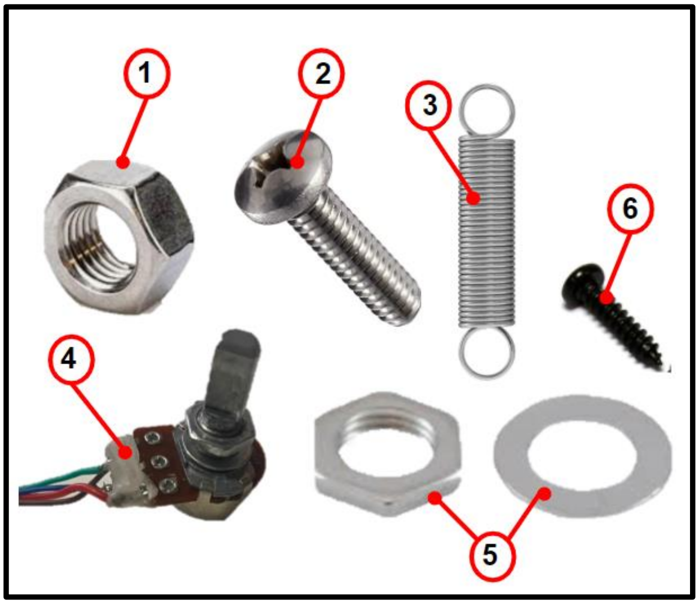
b. Note: The throttle potentiometer has yellow and white wires. The brake potentiometer has green and blue wires.

5. Two washers and two nuts for potentiometer **<u>from Foot Pedal Kit</u>**

    a. See details in 'Disassembly of Foot Pedal Kit' on PG 9

6. Four black phillips head screws **<u>from Foot Pedal Kit</u>**

    a. See details in 'Disassembly of Foot Pedal Kit' on PG 9



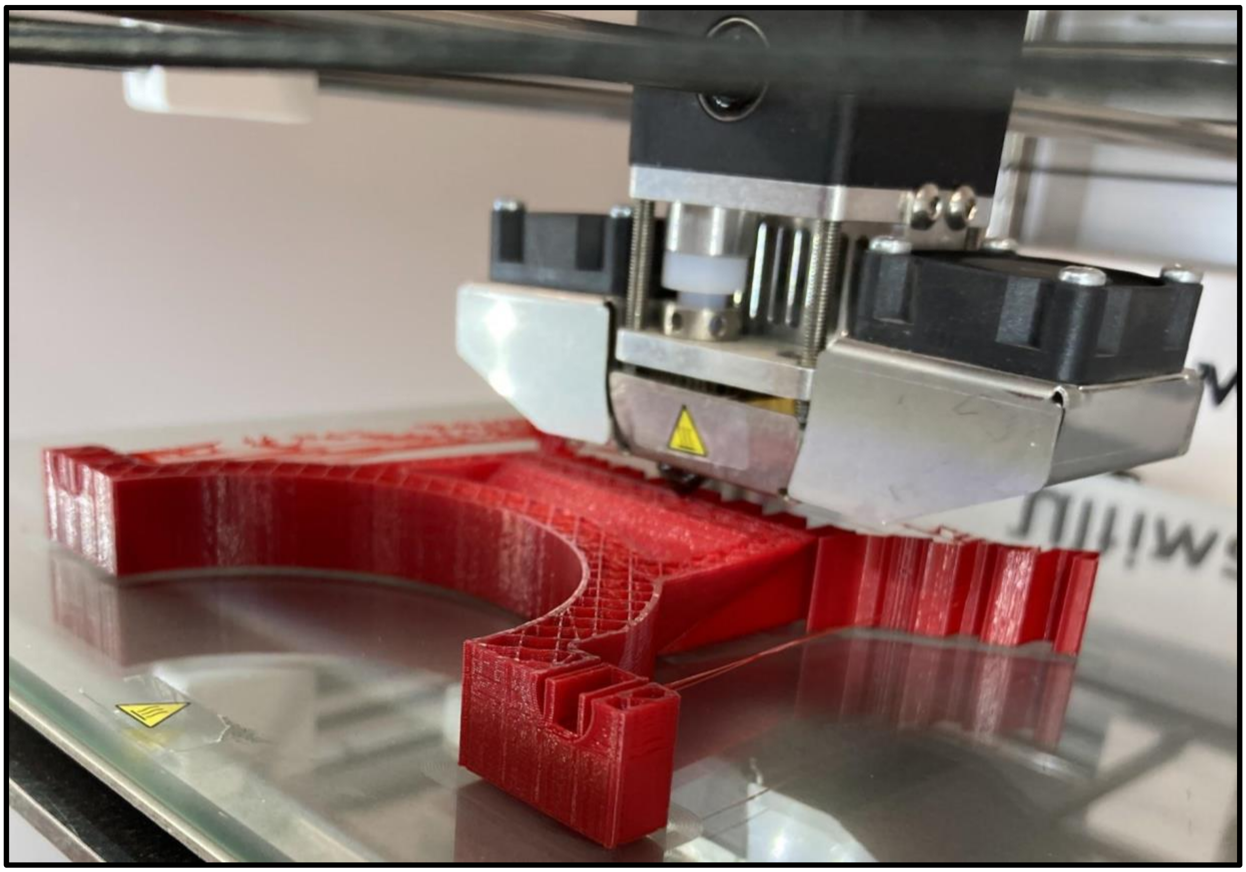
- **Tools for Assembly and Disassembly:**
    - A Phillips head screwdriver
    - Groove joint pliers
    - Exacto or pocket knife

Optional:

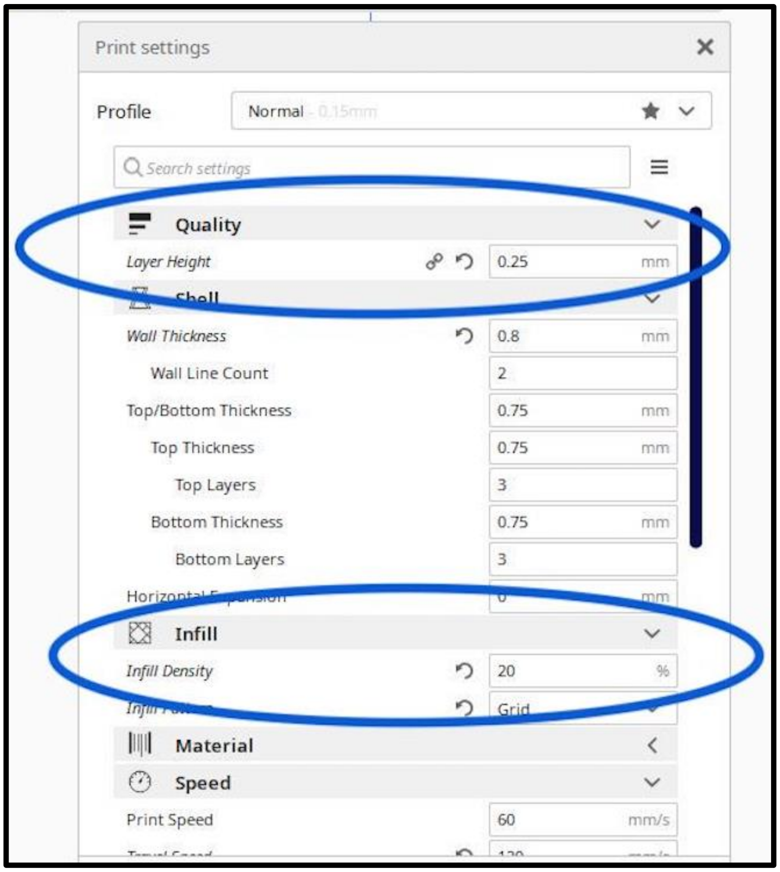
- Needle nose pliers

3D PRINTING

Find a local establishment with 3D printer services: Libraries, universities, local businesses. Find locations near you via a Google search.



- Use .STL files provided on “What You’ll Need Page” on website for printing.
- **Print Setup:**
    - Material: Preferably use a PLA plastic filament.
    - Layer Height Setting: 0.25 mm
    - Infill Density Setting: 20 % infill



- Support Material Setting: Use support on all the parts. Use a support density of around 8%.

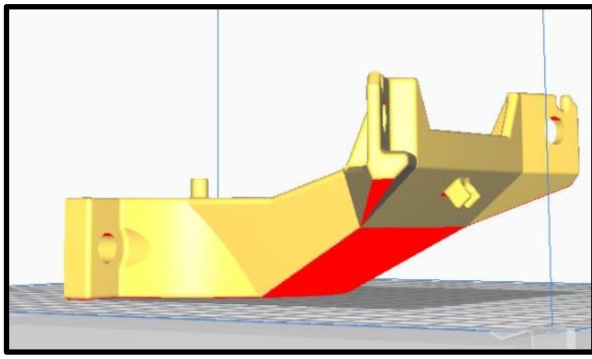
- **Estimated Print Time**:
  - Top Bracket: ~3 hours**
  - Both Paddles: 2.5 hours**
  - Bottom Bracket: ~3 hours**

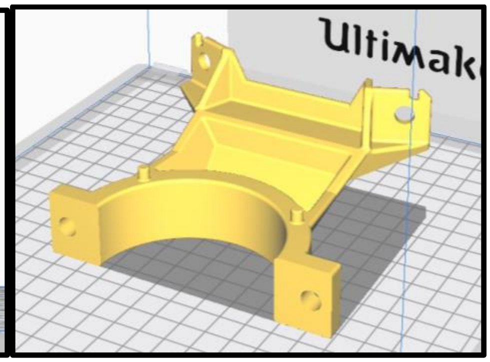
The print time will change depending on the printer, infill density and layer height as well as the size of your build plate - **see below.

- **Build Plate Information**: A standard 8 x 8 x 8 inch desktop 3D print machine will require three separate prints. One print for the top bracket, one print for the lower bracket and one print for both of the paddles at the same time. If printing on a larger machine, it may be possible to fit each of the 4 parts on one build plate.

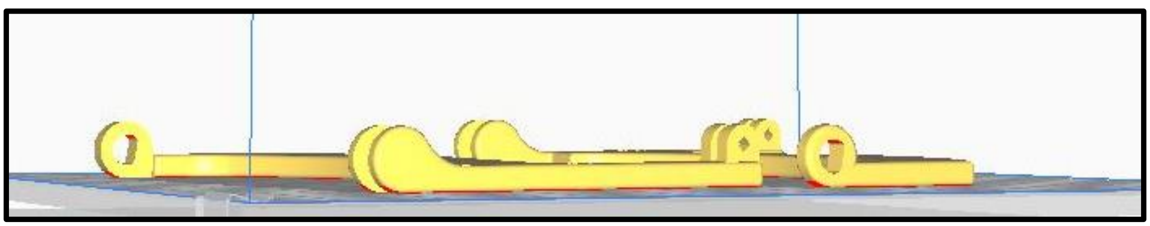
- **Part Orientation on Build Plate**: See images below to correctly orient the parts on the build plate as well as other notes about settings. The build plate is represented by the grey grid.
  - Notice: The red areas on the yellow parts show where the support material will touch the part during printing.

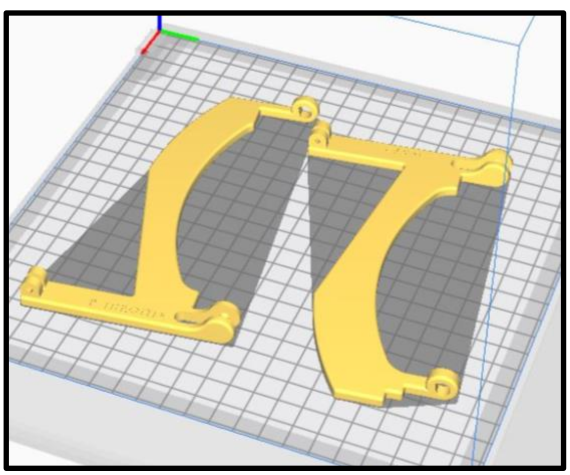
Top Bracket Orientation



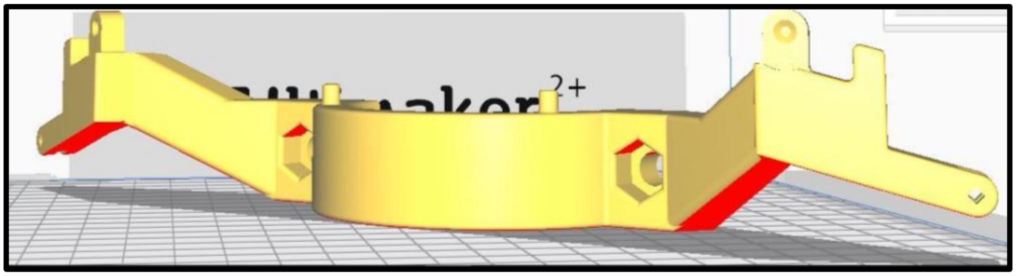


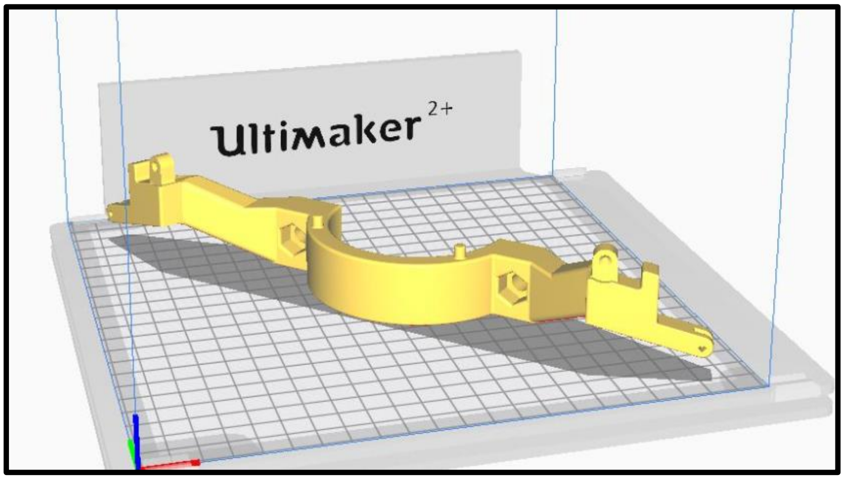
Left and Right Paddles Orientation



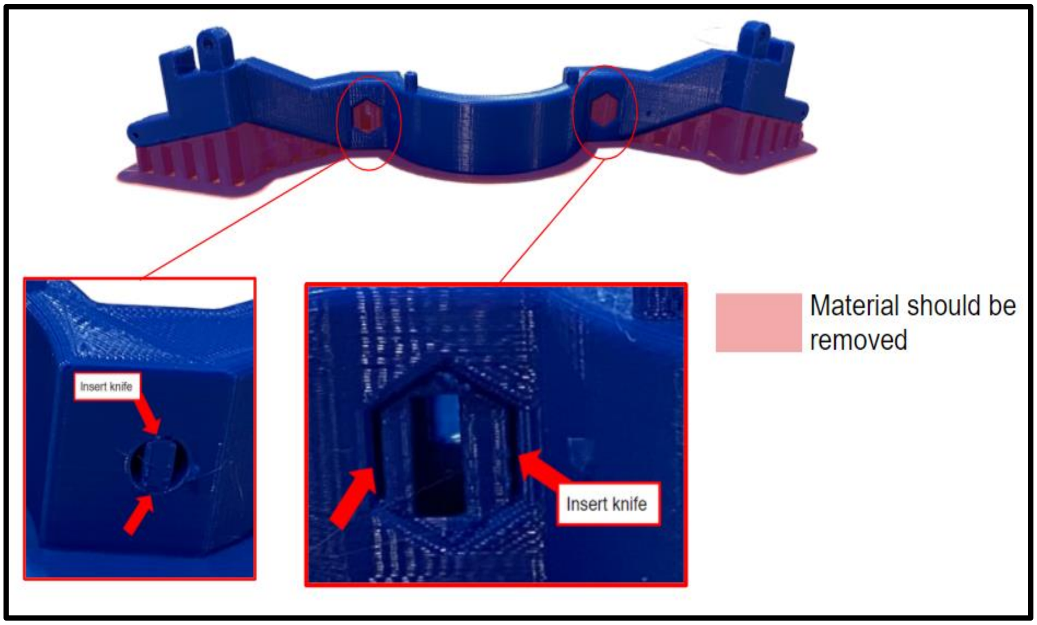


Bottom Bracket Orientation

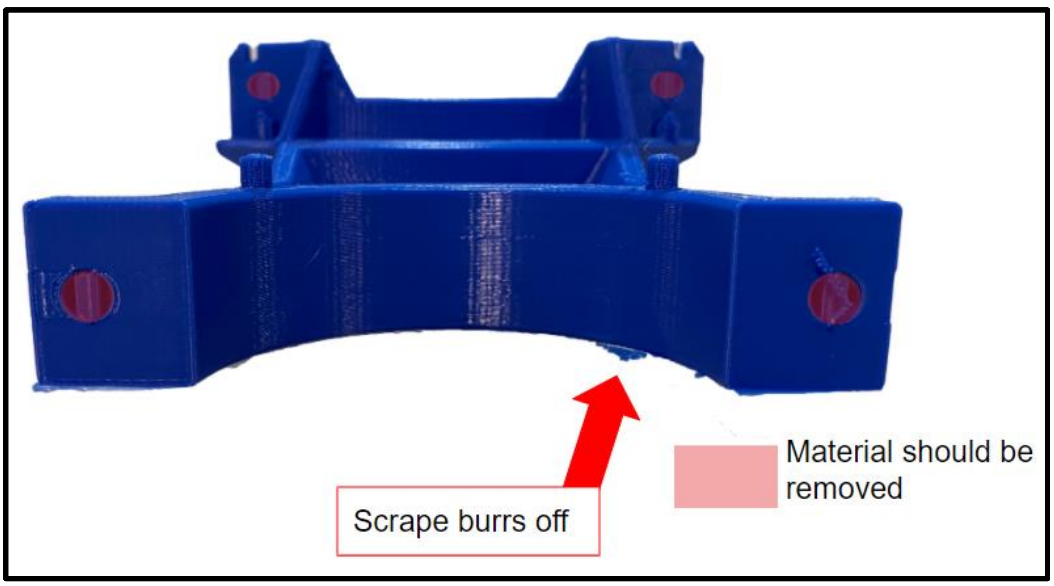




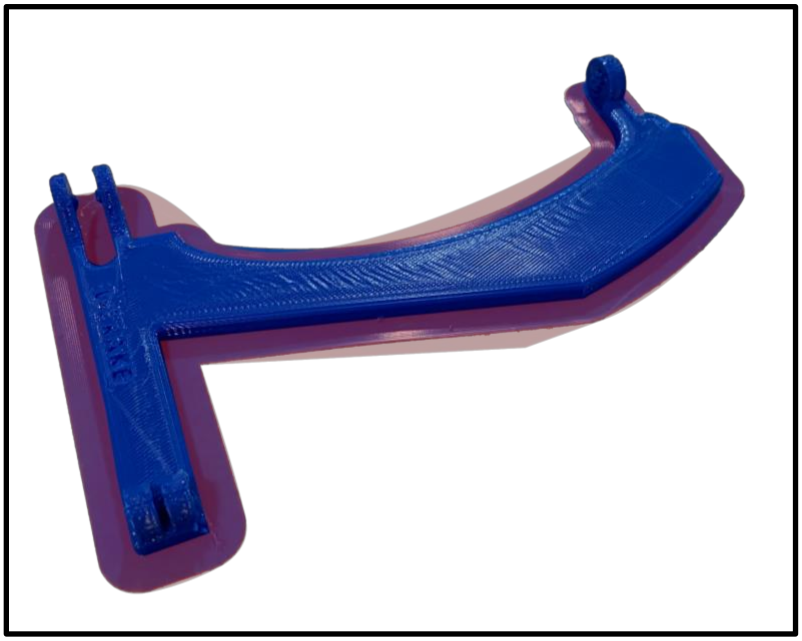
- **Post Processing:** Before assembly can begin, the prints must be prepped by removing the support material. For this, grab the exacto/pocket knife and optional needle nose pliers.
    - Bottom bracket: Remove the support material from the base where it contacted the build plate. This should easily break off, any sharp edges can be scraped off with the knife. Next, remove material on both sides of the two through holes. Be sure to clear any material that could stop the hex nuts from fitting into the slot. This can be achieved by inserting the knife between the support material and twisting to break it loose. Once loose, press your needle nose pliers through the hole to push any material out.

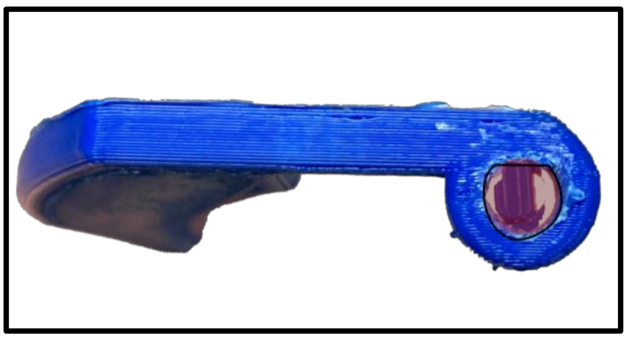


- Top bracket: Remove support material from each through hole. Use a similar technique to what was outlined for the bottom bracket.



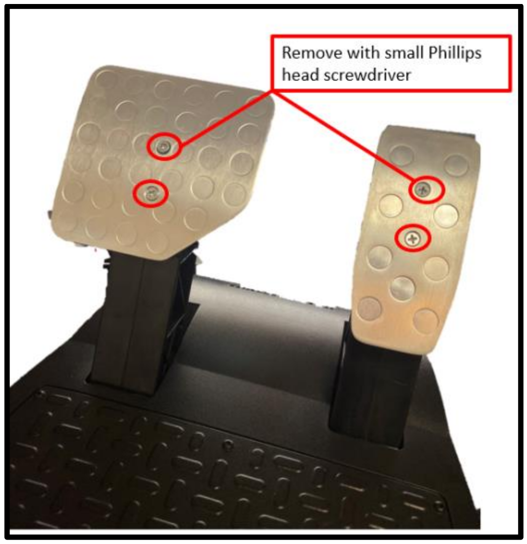
- Paddles - Remove support material from the base where contacted the build plate. Remove support material from the keyhole. Ensure not to damage the flat spot of the hole.





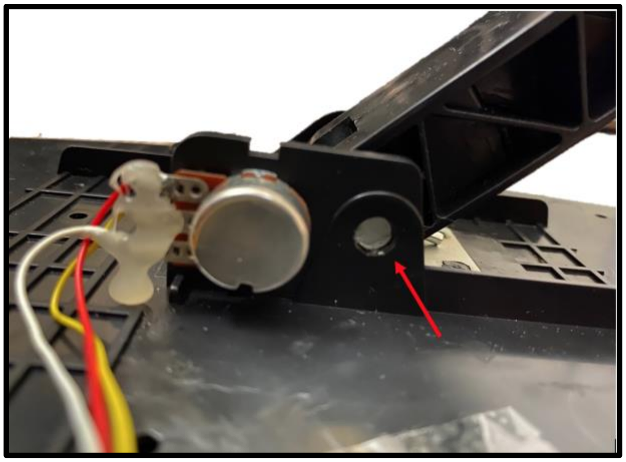
DISASSEMBLY OF FOOT PEDAL KIT

1. **Begin by removing both pedal plates from each lever arm.**
    - Two phillips head screws per plate

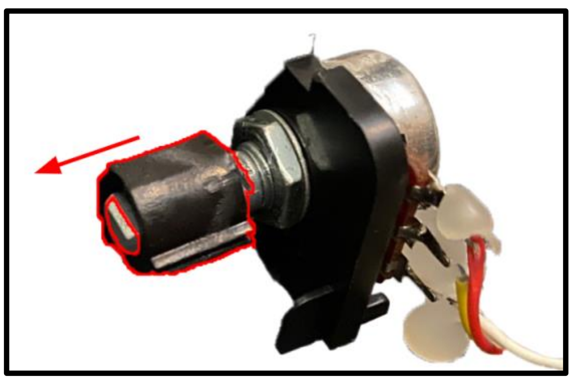


2. **After removing the plates, unscrew the thirteen black phillips head screws on the bottom side of the pedal assembly.**

3. **Once all screws are removed, carefully separate the two plastic shells.**
4. **Next, there is a dowel pin holding each pedal arm to the plastic base.**



5. **Remove it by pushing from the inner side of the pin.**
    - The pedal should easily lift out once the pin is removed
6. **Then take off the plastic gear to access the nut that holds the potentiometer.**

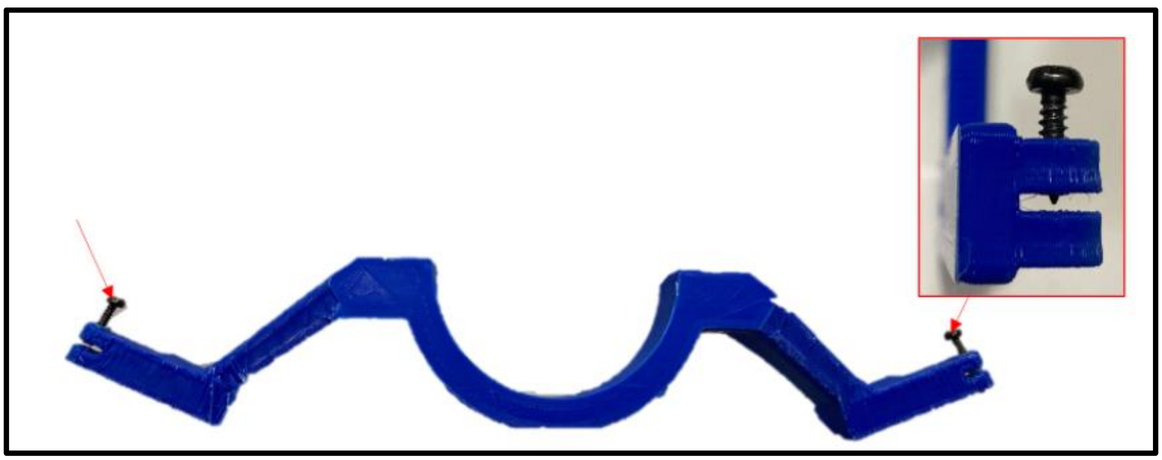


7. **Unscrew the nut, being careful not to over-twist the potentiometer shaft.**
8. **Slide the potentiometer out of the plastic housing, making sure to protect the wires.**
9. **Remove the tape and hot glue holding down the wiring harness.**
10. **Lift up and pull the harness free from the plastic base.**

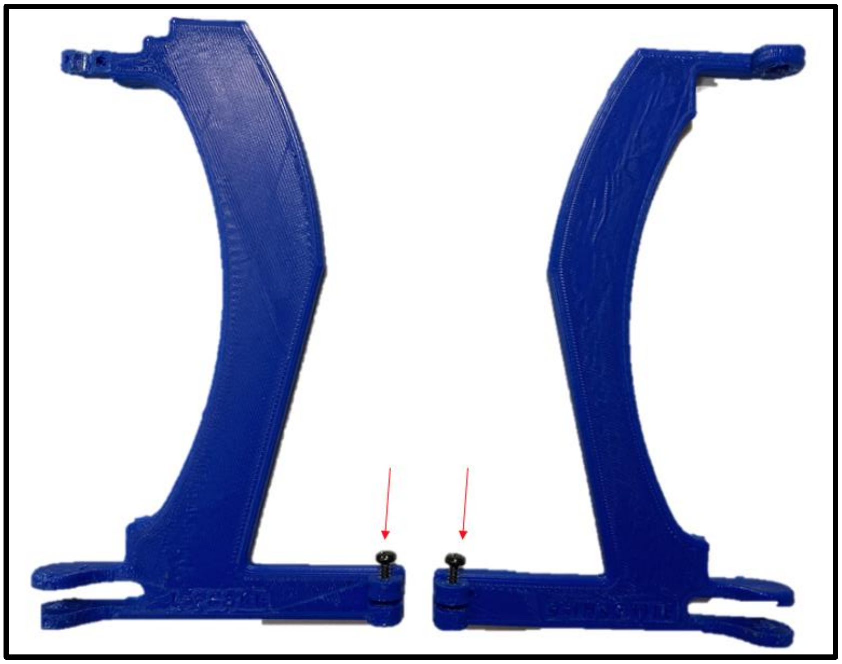
HAND PADDLES & BRACKET ASSEMBLY

1. After removing all support material, press the hex nuts into the cavities of the bottom bracket using the groove joint pliers.

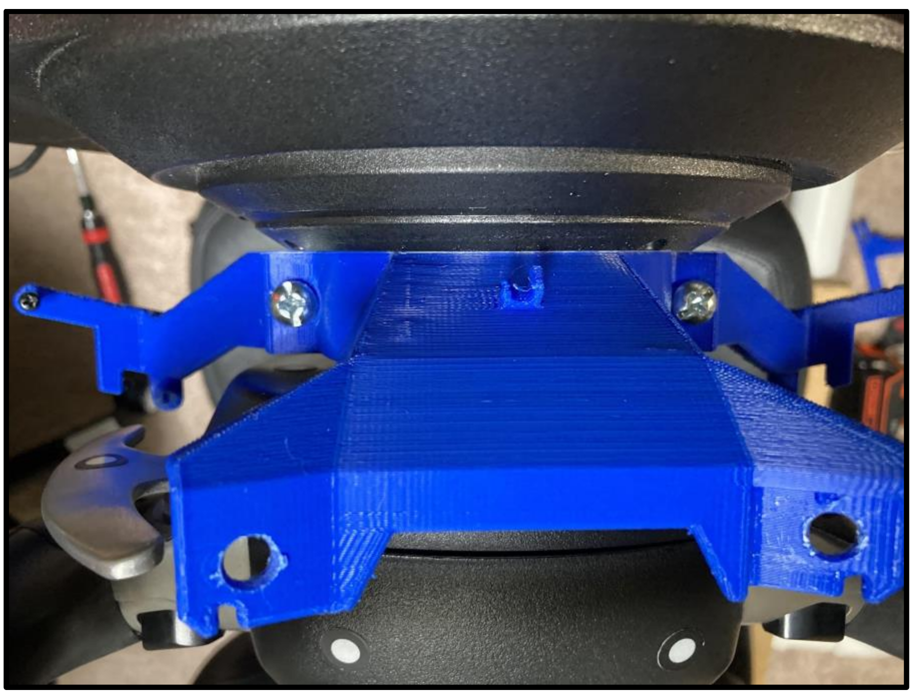
2. Use two of the thirteen black phillips head screws and screw them into both sides of the lower bracket. Only screw in until the black phillips head screws are just though the first nub.



3. Use one of the thirteen black phillips head screws for each of the paddles. Only screw in until the black phillips head screws are just though the first nub.

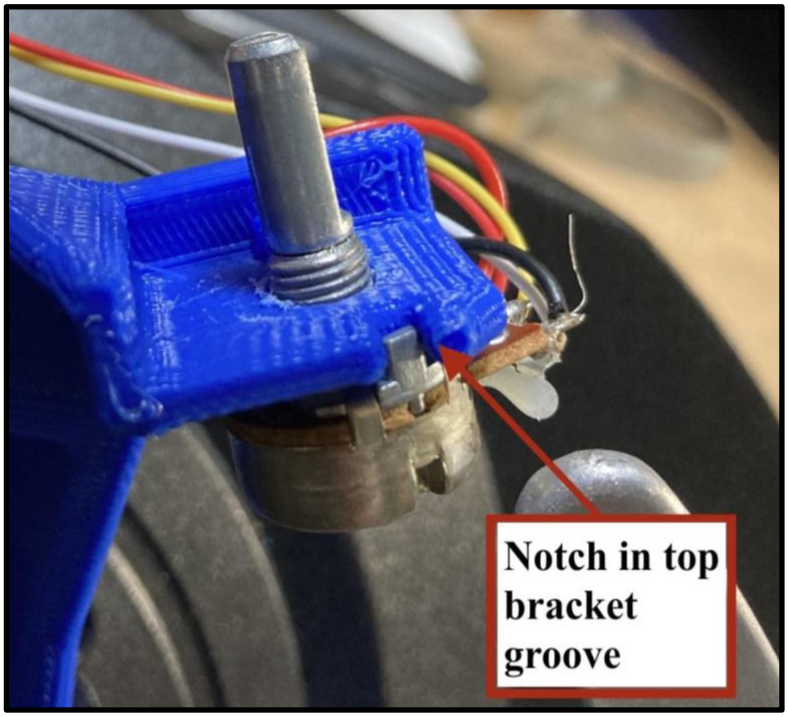


4. Use the two 1/4-20 bolts to secure the top and bottom bracket to the wheel/motor shaft of the Thrustmaster.



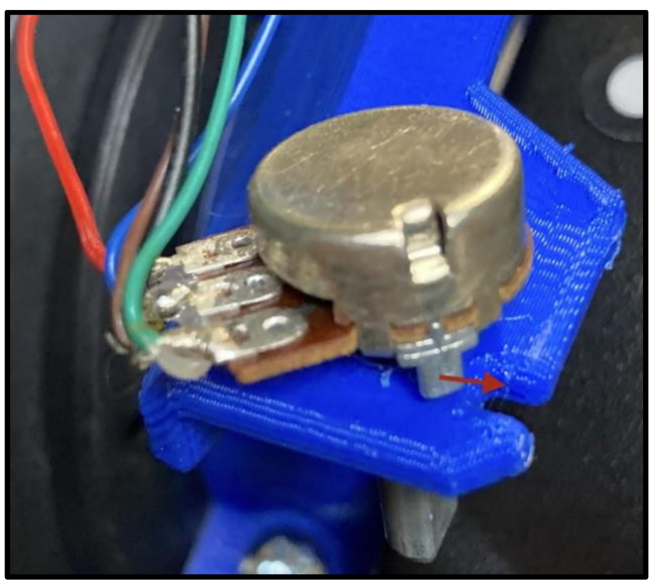
5. Install the right potentiometer with the shaft pointed up through the underside of the top bracket, ensuring to set the notch in the top bracket grove.

- Note: The right side potentiometer has yellow and white wires

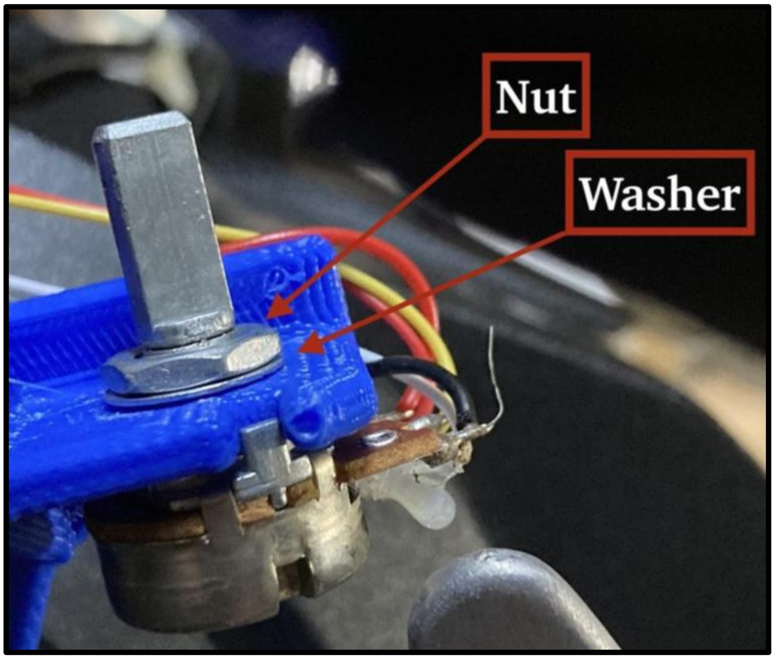


6. Install the left potentiometer with the shaft pointed down through the topside of the top bracket, ensuring to set the notch in the top bracket grove.

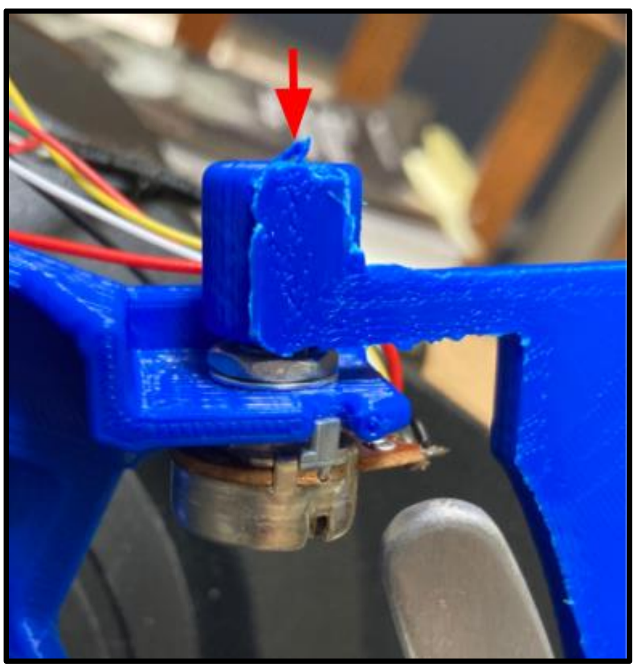
- Note: The left side potentiometer has green and blue wires.



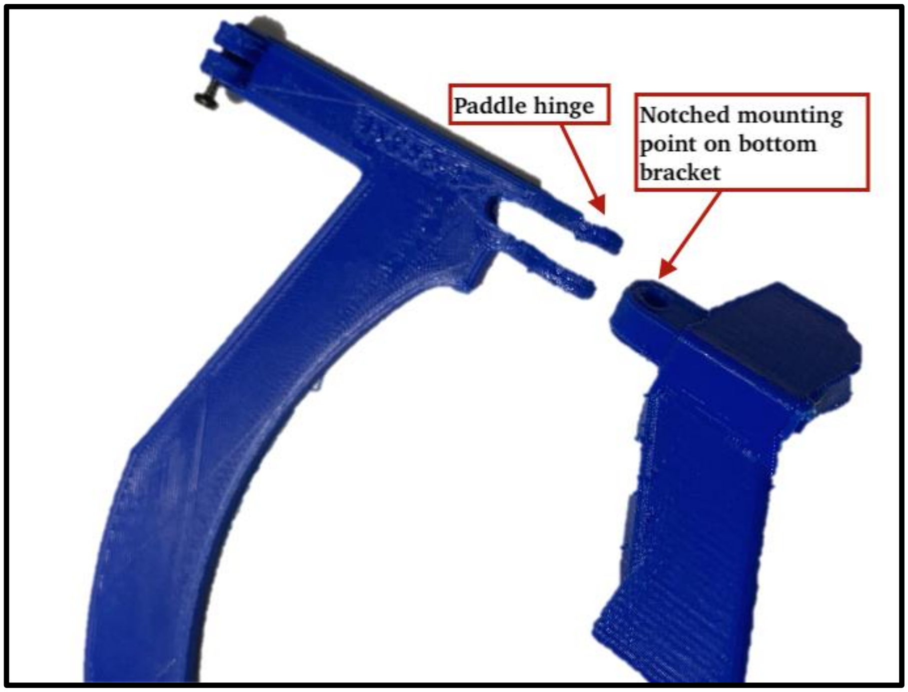
7. Place the washer and thread the nuts onto each potentiometer shaft.

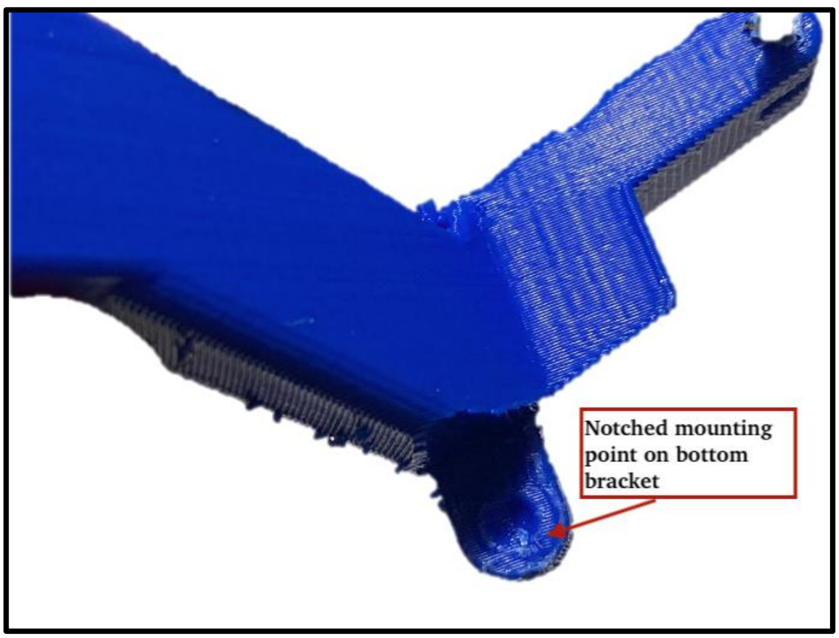


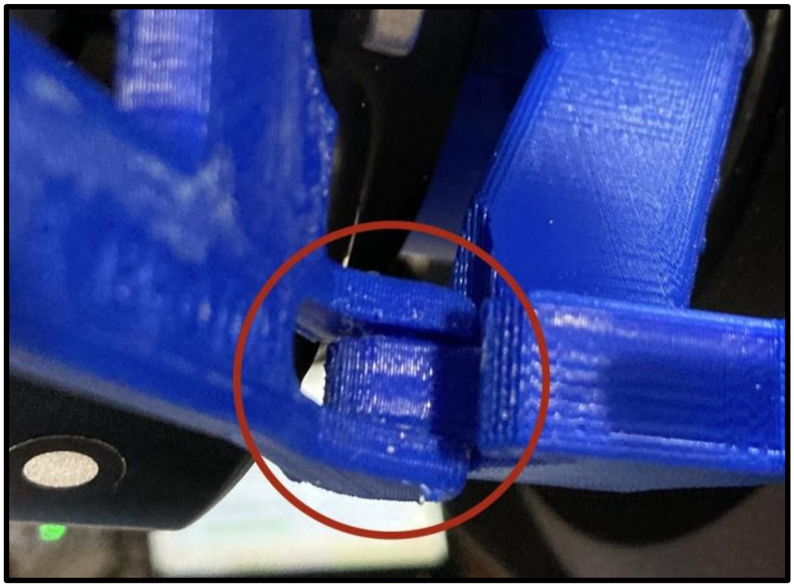
8. Starting with the right side, press the top of the paddle onto the potentiometer shaft, keeping in mind the bottom of the paddle should not be contacting the bottom bracket.



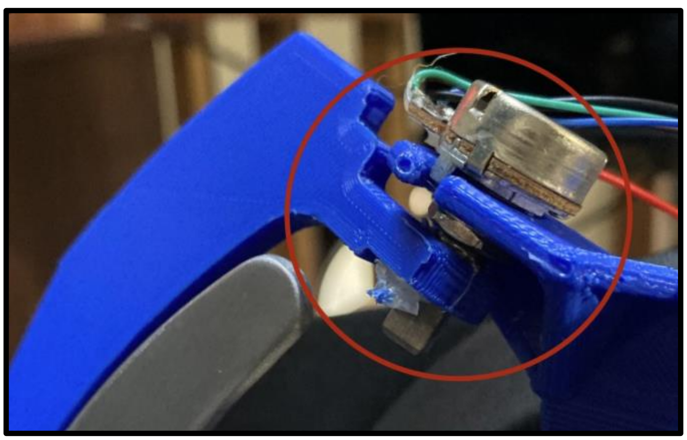
9. Next, for the right paddle, press the paddle hinge onto the notched mounting point located on the bottom bracket.

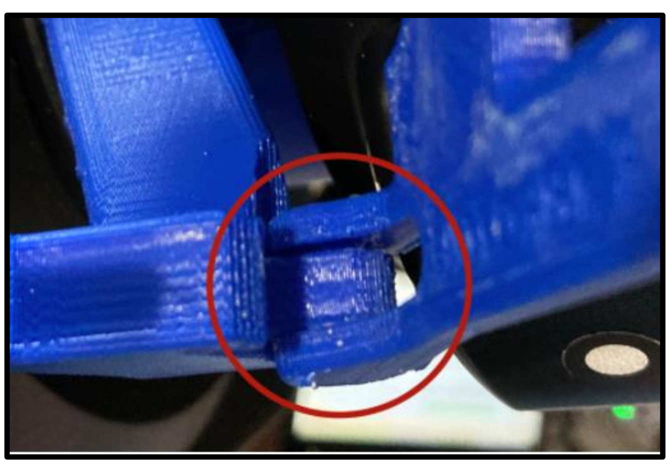






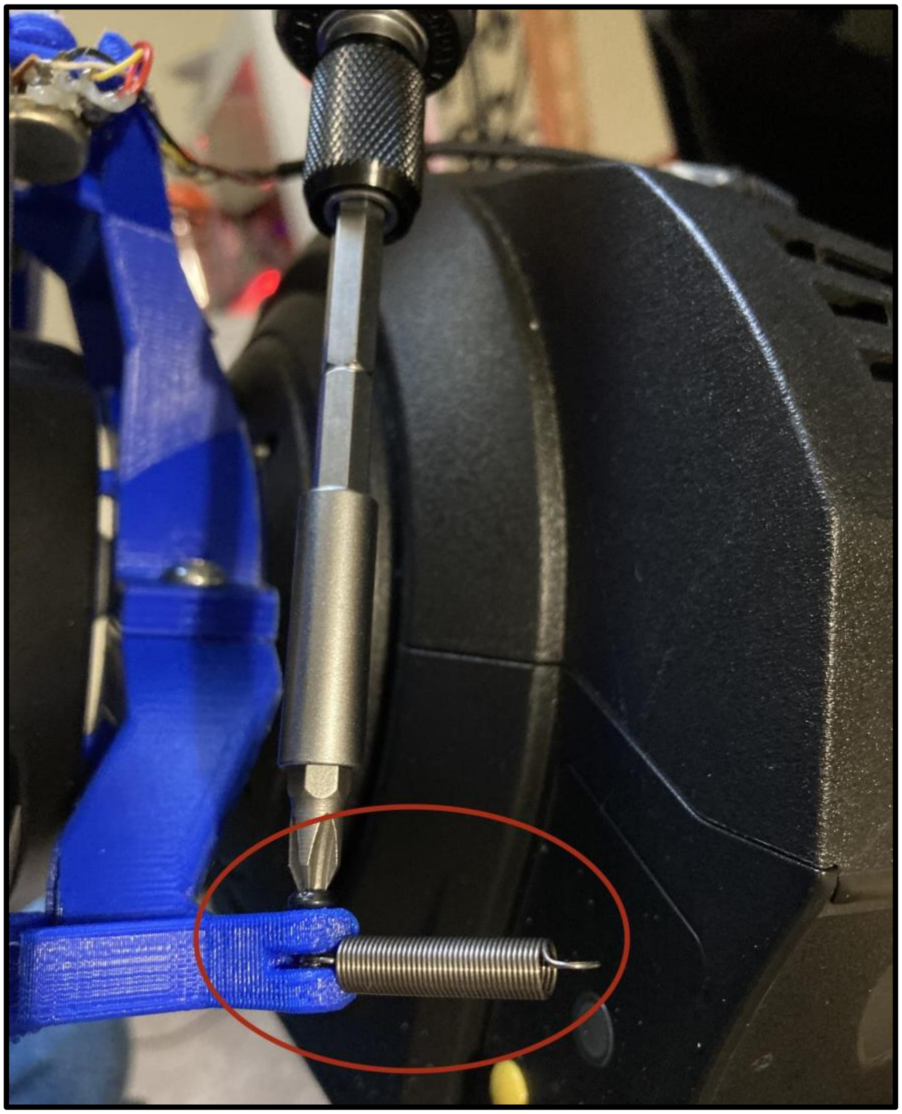
10. Repeat steps 8 and 9 for the left side paddle.



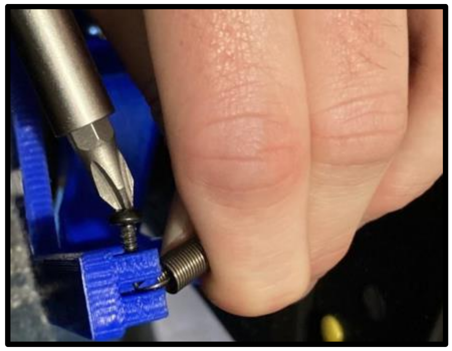


11. Starting with the right side, place the 5108N212 spring loop between the bottom bracket nubs. Tighten the screw to ensure the spring loop is fully encapsulated by the black phillips head screw.

- Tug on the spring to ensure it is secured.



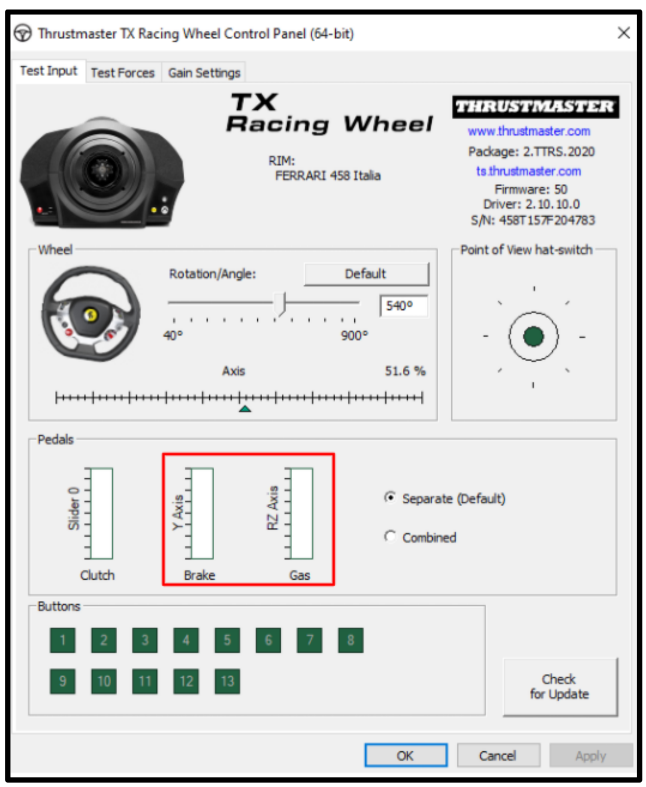
12. Still on the right side, connect the spring loop to the paddle attachment point in the same manner as with the bottom bracket.



13. Repeat steps 11 and 12 for the left side.

14. Now plug the wiring harness into the wheelbase

- It is advisable to plug the wheelbase into your PC/Console so the wheel enters its calibration phase before plugging in the harness
- By entering the control panel, you can confirm proper potentiometer calibration once the wire harness is plugged in.



15. Now you are ready to race!