DLos Altos Academy of Engineering

Drive Train & Steering Technical Report

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Introduction

2020 will be Los Altos Academy of Engineering's third consecutive invitation to the Solar Cup Challenge. Solar Cup has become our engineering program's favorite competition in our most recent school years because it grants us an opportunity to work together as a team and use our engineering shop to its maximum capabilities.

Now that several of our members are veterans of Solar Cup, we have placed our sights on a higher ranking, which we hope to reach by improving various parts of our boat. With a fully equipped machine shop and design software, we believe that we have the ability to create a boat that is superior to our prior entries.

The central change to our boat for Solar Cup 2020 is using a variable chain-and-sprocket transmission in favor of the direct drive transmission which we have used in past competitions. A variable transmission is needed because our boat was not competitive in Sprint, where variable gear ratios would simply blow our direct drive's speed out of the water. We have long been accustomed to under-performing in Sprint, but compensating for our lower score in Sprint through the Endurance race. We seek to completely shift this dynamic. We are cognizant of the many challenges posed by radically changing our transmission system, such as matching the gear ratio to the propeller's ideal revolutions per minute; but we realize that in order to continue our goal of improving our boat's construction, and its competition placement, redesigning our transmission is a necessary risk which we are ready to take.

After a spell of bad luck in Solar Cup 2019, complete with a snapped battery terminal, faulty solar mounts, and a broken steering system defining our weekend, our program's now experienced base of students has learned from last year to expect the worst, and a brand new transmission system which will have us hoping for the best, we believe that Solar Cup 2020 will be our best year of Solar Cup yet.

Buoyancy and Center of Gravity Calculations

Because of the extensive amount of non-buoyant weight in our boat, we will need to create a buoyancy ballast to keep our boat afloat and to make sure that our boat does not sink. We expect to need a ballast of 3.04 cubic feet. Excluding the batteries, the drive train and solar mounts will add the most weight to our boat, (see Table below and Figure 1). The additional weight from the transmission will move our center of gravity further back than our previous boat. Along with the added weight of the transmission, our sturdier solar mounts this year will cause more weight to be distributed towards the rear of the boat due to the rear mount weighing heavier than the front. We expect to have a boat with a center of gravity which will allow us to ride nearly parallel to the water, which is beneficial because according to the Technical Manual, "if the cg does not remain relatively fixed, the plane of the driveshaft will change and performance will change as well" (Technical Manual, 2018, p. 53).

Category	Weight (lbs)
Batteries	54.2
Solar Mounts + Solar Panels	37.0
Drive Train	25.5
Motor	24.0
Electrical Systems	10.0
Steering System + Rudder Stem + Rudder	6.5
Miscellaneous Fasteners + Clamps	2.4
Fire Extinguisher	4.0
Dashboard	2.3
Total non-buoyant weight	167.5 lbs.
Displacement with a safety factor of 20%	201 lbs.
Displacement needed / 62 lbs per foot	**3.24 cf**

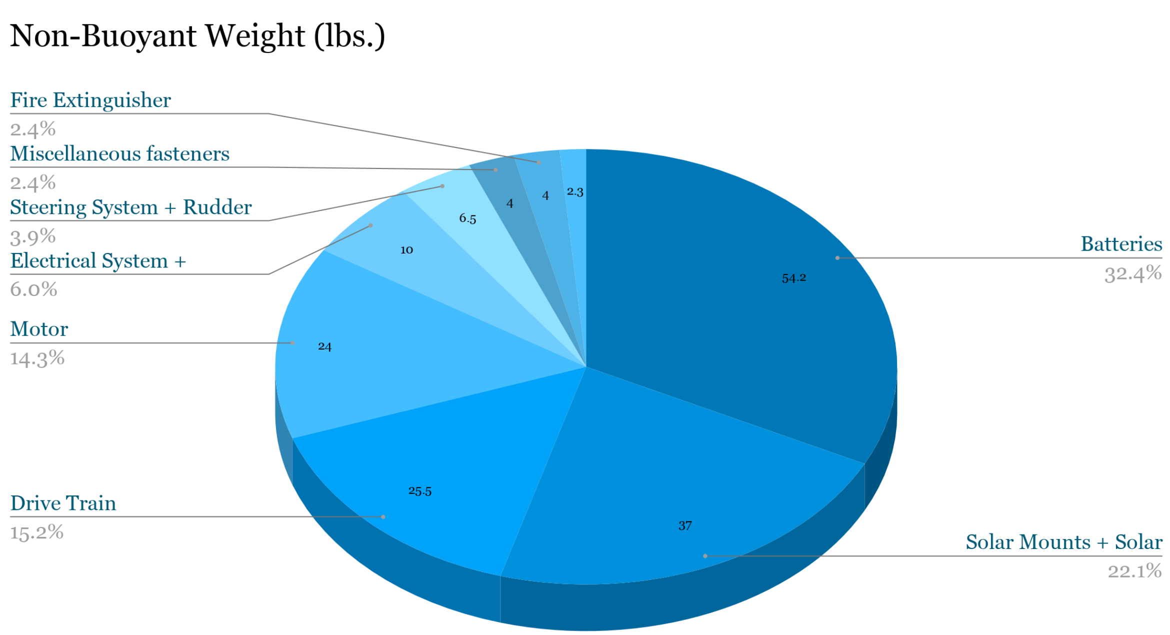

Figure #1: Distribution of non-buoyant weight (lbs).

Motor Mount

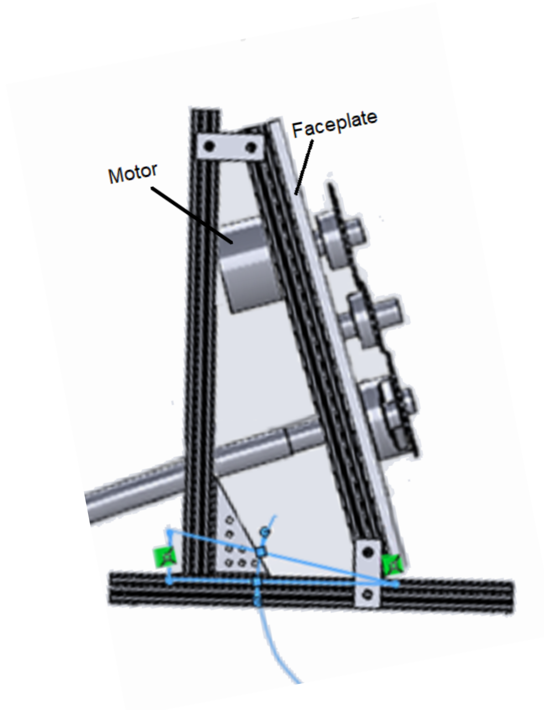

Figure #2: Labeled diagram of motor mount build

This year we contemplated using 3/4" steel tubing, 1" hollow aluminum tubing, and 1" T-Slotted aluminum for constructing the frame of our motor mount however, we chose to have the motor be mounted to an aluminum plate, connected to a truss base made from 80/20 T-Slotted aluminum.Steel tubing was advantageous because of its strength and the fact that we have plenty of it to work within our shop. However, we did not choose it as the strength which it offers is not needed, and not worth the increased weight. We have other materials like aluminum in house as well, so abundance is not unique to steel.

We also thought about using 1" hollow aluminum tubing for our motor mount, which is also very common around our shop. Aluminum is also strong enough to hold up our motor and sprockets, so strength would not be an issue. However, constructing a motor mount with aluminum is going to be a difficult task. Welding will be the most feasible way to join together the aluminum tubing, but we currently lack the correct gases and experience needed to weld the aluminum in our shop. We could ask local companies to weld the aluminum for us, but this will increase the cost of the motor mount. For this reason, we did not choose hollow aluminum tubing to make our motor mount.

Figure #3: A close-up of T-Slotted aluminum extrusions. Fasteners which hold two extrusions together mount into the channels above, making construction far easier than welding.

T-Slotted aluminum extrusions are lighter than steel tubing while maintaining the strength we require for holding the motor and our aluminum plate. Another benefit of using the T-slotted aluminum is that we do not have to weld the pieces together because we can put aluminum fasteners in them (see Figure 3). Without the need to weld, we will save lots of time and money. Time has consistently been a challenge for us, so the time gained from using T-Slotted aluminum extrusions and fasteners will be beneficial to us.

Our motor and transmission system will be mounted onto a ¼” thick aluminum panel, making up the face of the motor mount. We will drill large holes throughout the aluminum panel to cut down its weight. The weight loss is much more valuable than the minimal strength we would lose. The base of the motor mount will be 14 x 12 and 16 inches tall.

The mount’s aluminum panel will include an idler sprocket and a two-bolt flange bearing. The idler sprocket and the flange bearing will be explained in further detail in the following sections such as Transmission and Thrust Bearing sections.

Transmission

In a complete departure from last year’s direct drive transmission, this year, our transmission will be a chain-and-sprocket variable transmission.

The reason we moved away from direct drive is that although this system had its benefits, it simply did not suit our goal to perform better in the sprint portion. The propellor requires more power from the motor and simply attaching the propeller via driveshaft does not sufficiently meet the power needs to become competitive in the sprint heat.

In terms of efficiency, a key factor in the Endurance race, the direct drive configuration was perfect. However, in the Sprint race, where efficiency goes out the window in favor of sheer speed, we have significant problems. The propeller RPM in a direct drive setup is far too low to work our propeller and motor configuration, as according to Solar Cup veteran Jim Donovan's propeller slip chart (Donovan, 2019, slide 5). It should be noted that although slip, which is the percentage of water not able to be 'gripped' by the propeller, is not the only measure that affects propeller performance, it is a vital measure that we must take into account when judging if a propeller will be efficient and effective.

Propeller Handbook: Propeller Diameters For Minimal Slip								
RPM	hp	diameter	RPM	hp	diameter	RPM	hp	diameter
100	0.5	34.75	100	1	39.921	100	9.3	62.358
200	0.5	22.93	200	1	26.338	200	9.3	41.141
300	0.5	17.98	300	1	20.65	300	9.3	32.257
400	0.5	15.13	400	1	17.376	400	9.3	27.143
500	0.5	13.23	500	1	15.199	500	9.3	23.742
600	0.5	11.86	600	1	13.624	600	9.3	21.282
700	0.5	10.81	700	1	12.42	700	9.3	19.402
800	0.5	9.98	800	1	11.464	800	9.3	17.908
900	0.5	9.299	900	1	10.682	900	9.3	16.686
1000	0.5	8.73	1000	1	10.028	1000	9.3	15.664
1100	0.5	8.244	1100	1	9.4703	1100	9.3	14.793
1200	0.5	7.825	1200	1	8.9885	1250	10	13.901
1300	0.5	7.458	1300	1	8.5671	1300	10	13.578
1400	0.5	7.134	1400	1	8.1945	1400	9.3	12.8
1500	0.5	6.844	1500	1	7.8622	1800	9.3	11.009

Figure #4: Jim Donovan's Propeller RPM Chart, slide 5.

Our propeller has an ideal RPM of about 1250 according to the 1 hp chart (Donovan, 2019, slide 5). However, this cannot be achieved with a direct drive. Our motor's optimum RPM, is roughly 2170 RPM. According to Figure #4, if we divide motor RPM by 2.5 to 3, we are left with our direct drive's propeller RPM, which is about 800. 800 is far less than 1250, so our goal is to match these two RPMs (Donovan, 2019, slide 5). To increase our RPM to 1250, we will need a variable speed transmission, in the hopes of being competitive in Sprint for Solar Cup 2020.

We considered a variable speed pulley transmission. This system uses a rubber belt rather than a chain belt. We decided not to use this system because the distance between the pulleys must be exactly precise for the belt, meaning that we had to place the pulley at very specific locations in order for the belt to fit correctly. For this reason, we decided not to use this system because it was too difficult of a task to make an effective system out of. Therefore, we decided to stay with the chain-and-sprocket variable transmission instead.

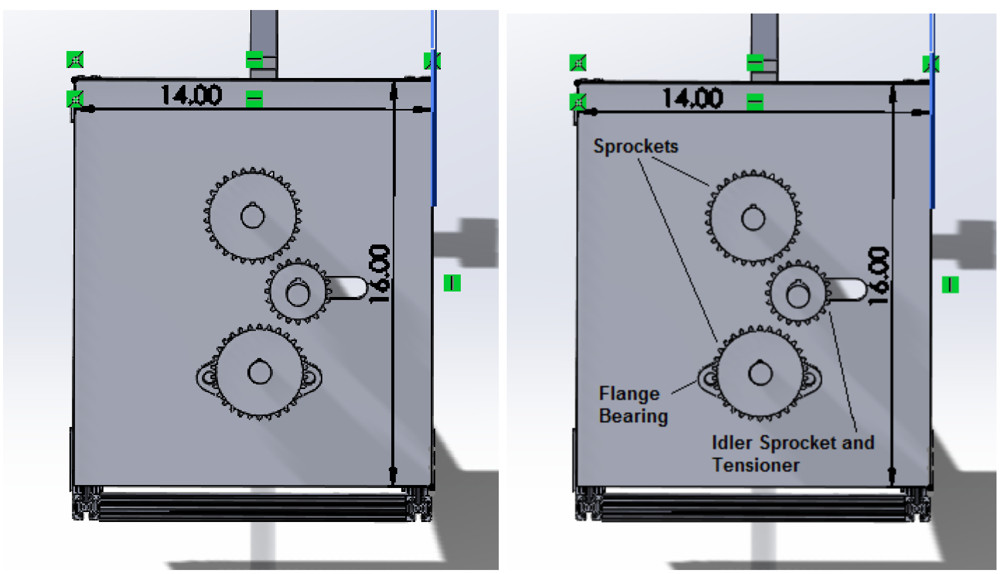

Figure #5: Sprocket layout of the transmission. Weight-reduction holes not pictured.

This chain-and-sprocket transmission consists of four essential parts. These parts are the sprockets, idler sprocket, the thrust bearing, and the transmission chain. All of these parts are going to be mounted onto the motor mount faceplate.

The idler sprocket is one of the main parts of the transmission. According to Ryle Manufacturing, “Steel idler sprockets maintain proper chain tension, and guide the chain around obstacles and prevent excessive chain wear and vibration”, where proper chain tension prevents the chain from coming off of the driver sprockets (Ryle Manufacturing, n.d.).

The sprockets and chain serve the vital role of transferring power from the motor to the propeller through the driveshaft. One sprocket will mount onto the motor shaft and one will mount to the driveshaft, on a welded ⅞” cap which will have a milled keyway. This milled key locks the driveshaft and sprocket spinning the same rate at the same time, rather than the two slipping out of sync and spinning independently of one another.

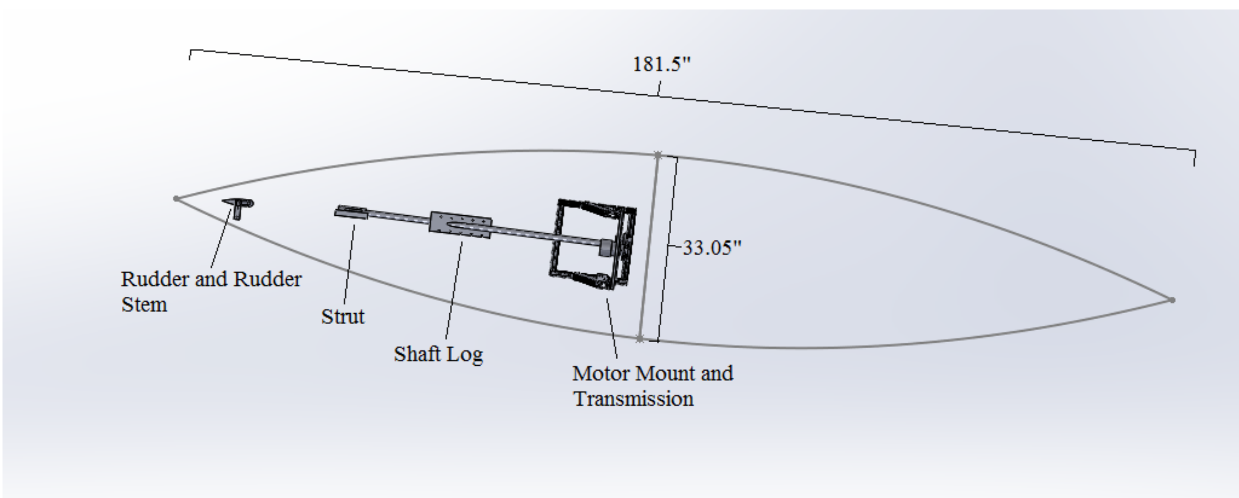

Figure #6: Top view of drive train

Despite the gear-based system being much more complicated than the direct drive system, its pros outweigh its cons. The first benefit that will come from this system is that we will be able to adjust our gear ratios based on which event we are doing. During endurance, we can configure our gear ratio in a way with will allow us to have the maximum efficiency possible, while in sprint, we are able to configure our gear ratio in order to maximize speed.

Thrust Bearing

We will use a flange bearing, mounting between the motor mount faceplate and the driveshaft. This thrust bearing will protect our transmission system from the immense amount of torque and rotational energy produced from the propeller by absorbing it into the faceplate (Gill, 2019). This torque will spin parallel to chain and sprockets through the flange bearing, rather than straight down the shaft and disrupting the delicate sprocket arrangement.

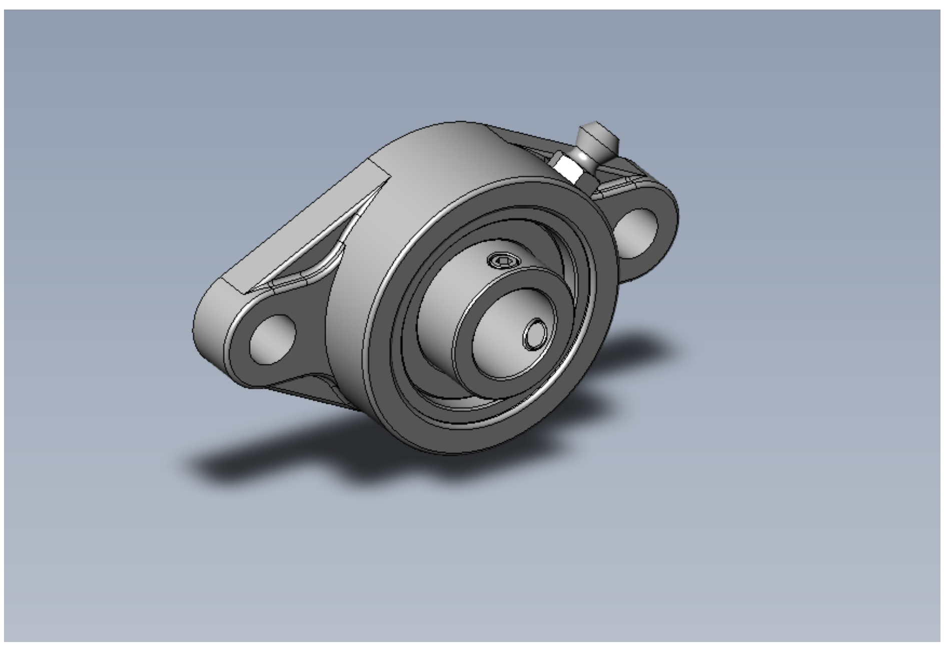

Figure #7: Angled view of thrust bearing

Driveshaft

The main goal for the driveshaft for this year is to optimize the strength of our materials with more precision along with mounting it in a way that will effectively take advantage of our new transmission and motor mount.

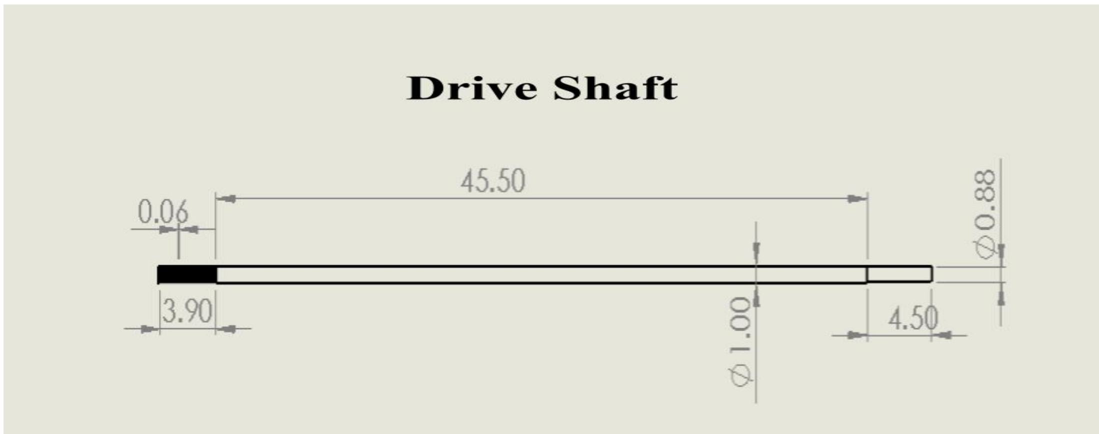

Figure #8: Driveshaft dimensions

This year's driveshaft will be 54" long, made from a 1" OD stainless steel rod. We chose to go with a stainless steel shaft because it offers good durability, corrosion resistance, and is available at an affordable price. Our team also knows how to effectively work with steel allowing for more efficient use of materials and a less likely chance to make mistakes. While an aluminum shaft was also an option due to its lower weight than steel, it was simply outclassed by the aforementioned factors but also steel is welded easier than aluminum. According to EVSmetal, a metal solutions company, states that "aluminum also has a layer of oxide that allows it to resist corrosion, which is helpful in many applications but has an extremely high melting point. A very clear understanding of how temperature affects aluminum is essential for skilled welders" (EVSmetal, 2019). While we have the capability to weld aluminum in our shop we chose not to due to its difficulty and inexperience we have welding with the material, especially due to this high melting point. This was one of the deciding factors when deciding between steel or aluminum.

Solid carbon steel was also another option that we considered, but "the corrosion resistance of carbon steels is poor", steering us away from using it (Pearlite Steel, 2015). Another material we considered was titanium. Titanium offers many more benefits than stainless steel, such as having a "high tensile strength-to-density ratio" (Comparing Titanium, 2017). Also, when comparing two tubes of the same dimensions, the titanium tube costs $271.03 (Buy Specialty, n.d.), while the stainless steel tube costs $46.13 from our main supplier, McMaster Carr. Due to these circumstances, we decided that stainless steel was our best option for the driveshaft.

The driveshaft will also have its mounting position changed this year due to our new transmission system. The new system required us to mount the driveshaft differently and the decision was to mount it to the thrust bearing on the motor mount. This decision was made to capitalize on the efficiency and power of the new transmission system. The direct drive mounting position worked but was not effective and lacked power but the new system will have the ability to sustain our new transmission system. The new motor mount will effectively support the driveshaft and with the changes of base materials, while being heavier, it will undoubtedly be stronger and provides many more upsides to the previous shaft. The improvements to the driveshaft allow for the absolute best transfer of power from the motor to the propeller.

Strut and Shaft Angle

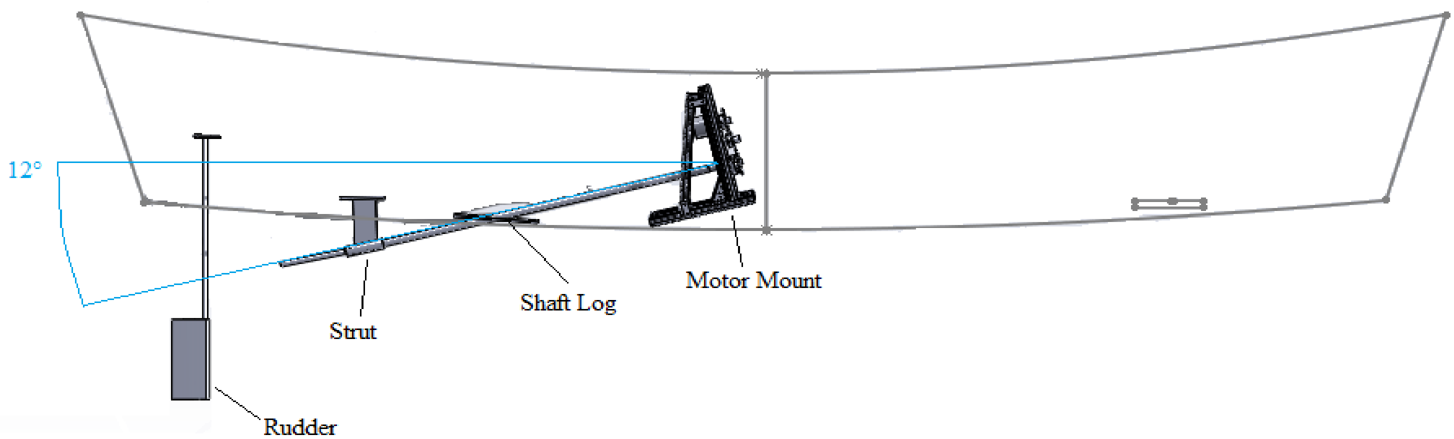

Figure #9: Side view of the drive train

The strut will still provide additional support for the driveshaft under the boat and help maintain position from the driveshaft to the motor. We will purchase our strut this year from Glen-El Marine Supply. The materials for the strut will be brass due to its strength and anti-rust properties. The angle will be twelve degrees because it is an excellent compromise between underwater clearance and propeller efficiency, shallow enough to prevent cavitation (Rice, n.d.).

Shaft Log and Stuffing Box

This year, we will build our own shaft log rather than purchasing a prefabricated one. We decided to build our own last year because of two major factors, which were price and weight. Purchasing a shaft log from marine supplies proves to be a difficult task. It is hard to find a mass-produced general shaft log that fits within the specifications that we need. We would need to create a custom order for a manufacturer to produce a shaft log that fits within our specifications. In addition, these manufactured shaft logs are typically made from solid bronze and brass, making them extremely heavy. We have come to the conclusion that a shaft log that we manufacture in-shop will be far cheaper, lighter, and just as effective as a custom purchased one.

Our shaft log will be made out of PVC pipe and a plank of marine plywood, which will make up the base. We will use marine adhesive sealant and epoxy to attach the two pieces together and make them waterproof. In addition, we will add a rubber gasket between the shaft log and the boat in order to ensure that water does not enter the boat through the shaft log. As the strut will be at an angle of 12 degrees, the consequential We had a flawless experience with these same shaft log materials in Solar Cup 2019, so we are confident that this shaft log will carry out its duties effectively.

Propeller

Our plan this year is to purchase a propeller from a marine vendor called Hill Marine. The propellers are being purchased as the accuracy and precision for making an effective propeller are tight and the equipment within our shop only adds unnecessary difficulty. The purchase of a propeller simply saves our team, time, resources, and effort that would be better utilized on other aspects of the boat.

(Propeller section continues below)

Figure #10: View of the two-bladed propeller

The propeller is made from stainless steel and will have a diameter of 8.75” and a pitch of 13”. Purchasing a stainless steel propeller is advantageous due to the much better durability and performance of it when compared to an aluminum propeller. Crowley Marine, a boat propeller provider states “Stainless steel is five times stronger than aluminum, dramatically improving performance and durability. Stainless steel propellers offer better acceleration and are less likely to be damaged from striking objects in the water” (Crowley Marine, 2019). The all-around strength and performance increase was the deciding factor in the propeller we chose.

The propeller that we will be utilizing is two-bladed because the lower amount of blades decreases the amount of drag created by the propeller, increasing our overall top speed (Props, n.d.). This would help us achieve our goal of performing better during the sprint event. Switching the blade count does not come without its drawbacks meaning we must make adjustments according to the propeller’s new build. Switching from a three-bladed propeller to a two-bladed propeller would require a higher pitch to provide the long enough for the propeller to reach maximum efficiency. According to boating company Evinrude, “A high pitch puts more load on the engine, which reduces low speed pulling power and acceleration, but usually provides more top speed” (Evinrude, 2011, p. 3). This will result in an overall higher top speed that will increase our placement in the sprint heat with a differently placed propeller. However, a drawback of the new propeller is the boat’s lower acceleration. We believe that the higher top-end speed is much more beneficial than the lower acceleration in the sprint and we are already offsetting a portion of our acceleration issues by having a stainless steel propeller. Our team's main goal is to increase our competitiveness within the sprint heat and to commit to that goal, we are ready to sacrifice our acceleration in order to reach higher top speeds. Purchasing the two-bladed propeller is more in line with our goals of placing higher in the Solar Cup rankings.

The propeller will be connected to a ¾” shaft from the end of our driveshaft and will be held in with a pin and bolt and will also have a key. A pin will prevent the prop from coming off of our driveshaft. The key would make the prop move dependently of the driveshaft. We could mount the propeller differently, such as welding it to the driveshaft, but we quickly realized that this was not a favorable solution. This would make a permanent and extremely strong fix, however, we would be unable to remove the propeller, and excess heat could warp its blades. For this reason, we ruled out welding the propeller to the shaft. With these new changes, we hope to become a top competitor with a newly improved sprint propeller.

Steering System

In Solar Cup 2018, we decided to change our steering system from a steering wheel drum-and-pulley system to a push-pull lever system. We solved the clunky, heavy, and unresponsive nature of the drum-and-pulley system in our change to a push-pull steering system. For this reason, we decided to stay with the push-pull lever system.

A benefit is that the push-pull cable-based steering system is much lighter than a drum-and-pulley system. When we used the drum and pulley system, it was heavy in comparison to the push-pull lever system. The weight of our current system is about 2.45 pounds. The weight of the drum and pulley system is estimated at around 5.5 pounds. Less weight translates to lighter boat and potentially higher speeds and ranking in Sprint, the goal for our boat this year.

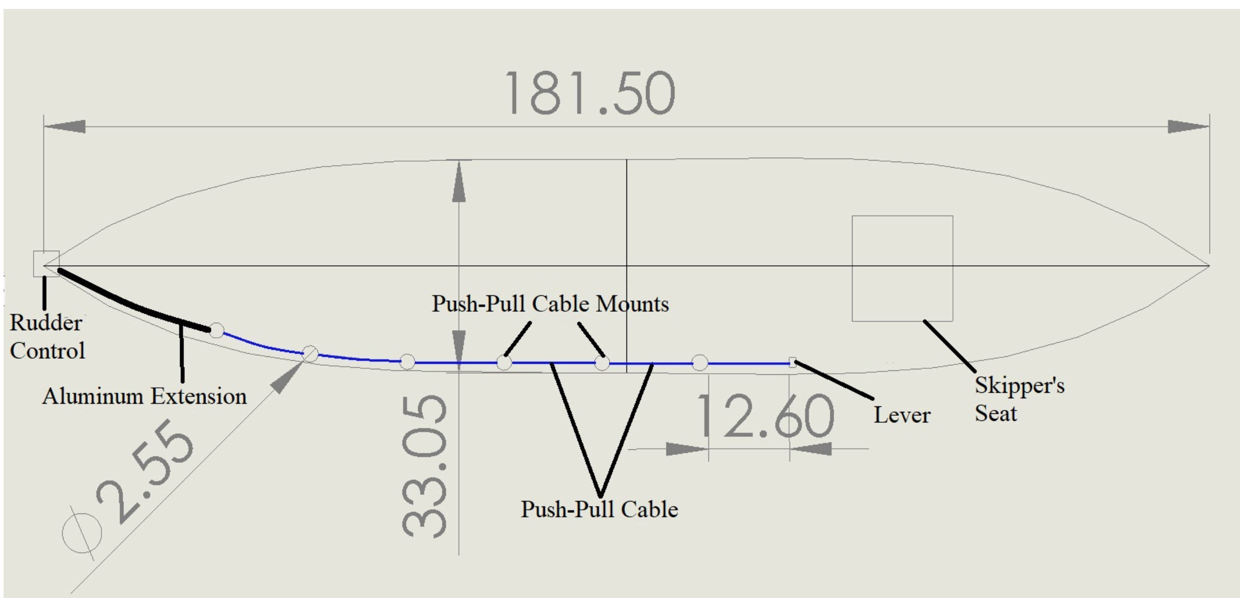

Figure #11: Top view of the steering system inside the boat with dimensions (in inches).

The push-pull steering system consists of three major components: the lever, the push-pull cable, and the rudder arm. With only three items, the steering system is extremely light and extremely simple.

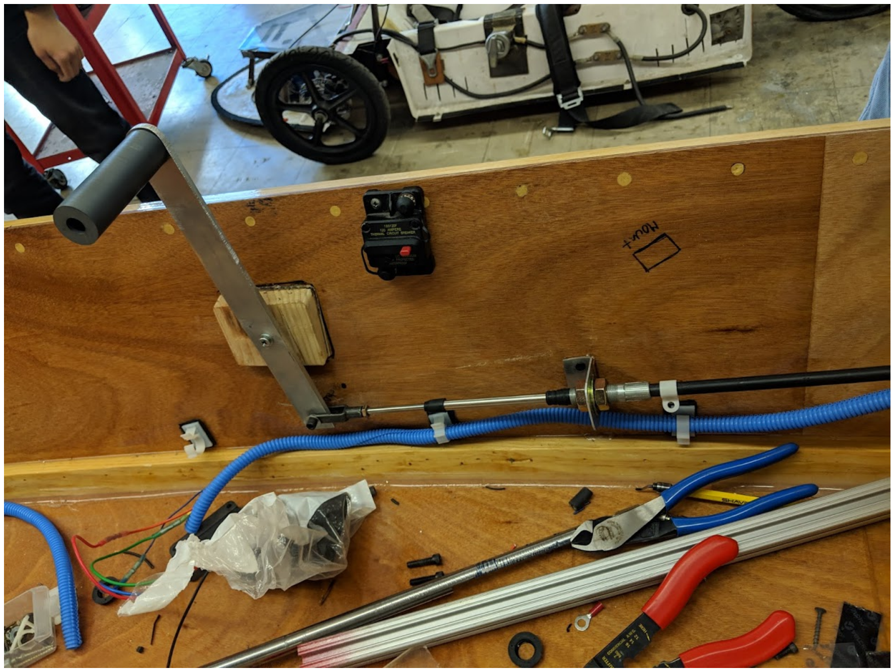

Figure #12: Picture of our past lever. We are keeping the design the same.

The lever will be located to the right of the skipper for easy control (see Figure 12). Mounted centrally onto a pivot, the lever will only have one axis of rotation. We decided to mount the lever this way because of the simplicity of its installation. Along with being mechanically simpler than mounting the lever on its bottom, it allows for the lever to rotate freely. The lever will move forward and backward. The bottom of the lever is where the main connection between the push-pull cable and the lever itself will be. The top end of the lever will have a handle where our skipper will steer from.

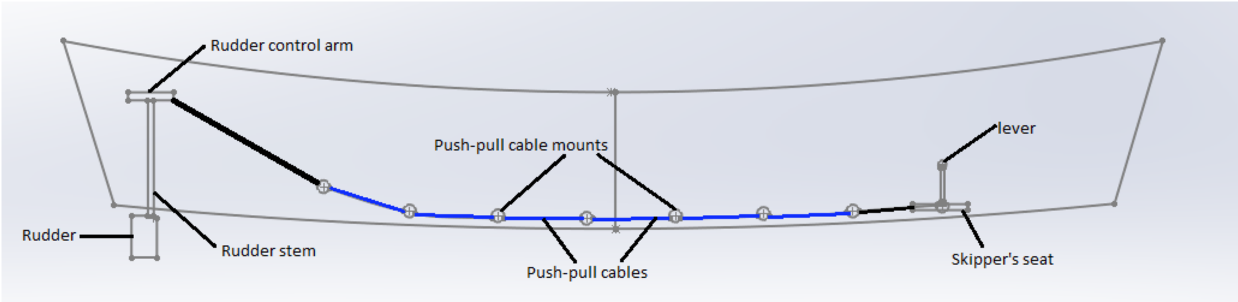

Figure #13: Side view of the steering system

The push-pull cable will be connected to the bottom of the lever and the rudder arm. It will be our means of transferring the movement of the lever to the rudder. The cable we are using is a 6-foot long cable from McMaster-Carr and will be connected to the lever via a clevis rod end. The clevis rod end is a U-shaped piece that has a hole at the end of each prong. These holes allow a pin to pass through, where it interlocks with the lever. The other end of the cable will have an aluminum extension with a ball joint linkage at the end of it (see Figure 14). The ball joint linkage will be the connection between the push-pull cable and the rudder arm. The ball joint linkage allows the rudder to rotate without stalling the push-pull cable. It also allows us to easily disconnect the rudder shaft from the push-pull cable.

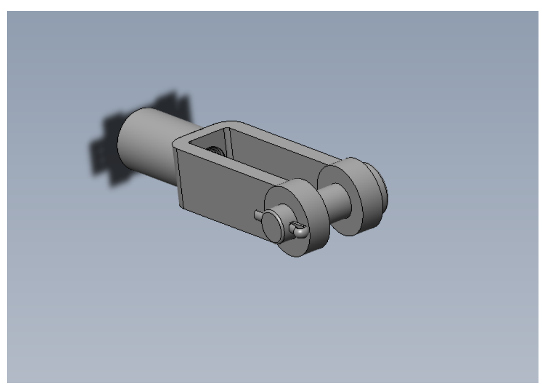

Figure #14: Ball joint linkage (left) and clevis rod end (right).

The final part of the steering assembly is the rudder arm, which connects the push-pull cable to the rudder shaft (see Figure 15). This link is where the movement of the push-pull cable is transferred into the rotation of the rudder. This year, we are planning on changing the way we are making the rudder arm.

In the previous year, this arm was made from a 3” long L-shaped steel bracket that was attached to the rudder shaft with a screw and thread locker. We applied a small amount of epoxy to the connection for some extra reinforcement. When we were out on the lake, a technical issue occurred that broke this connection between the arm and shaft, resulting in us being unable to steer. Our assembly also prevented us from being able to fix the boat quickly.

For this reason, we plan on building a much more structurally sound arm. This arm will consist of a shaft collar that wraps around the top of the rudder shaft. The steel shaft collar will have a piece of quarter-inch steel welded to it. In order to attach the sleeve to the shaft, we are planning on drilling and threading a hole through both the shaft and the sleeve. We will be putting a bolt through to hold the two parts together. This connection is much better than the epoxy and screw connection because the bolt goes through the sleeve and shaft. This connection means that each part cannot rotate independently of each other. Due to the bolt’s strength, the chance of the parts disconnecting from each other is very low, unlike the more fragile screw-and-threadlocker connection.

Rudder

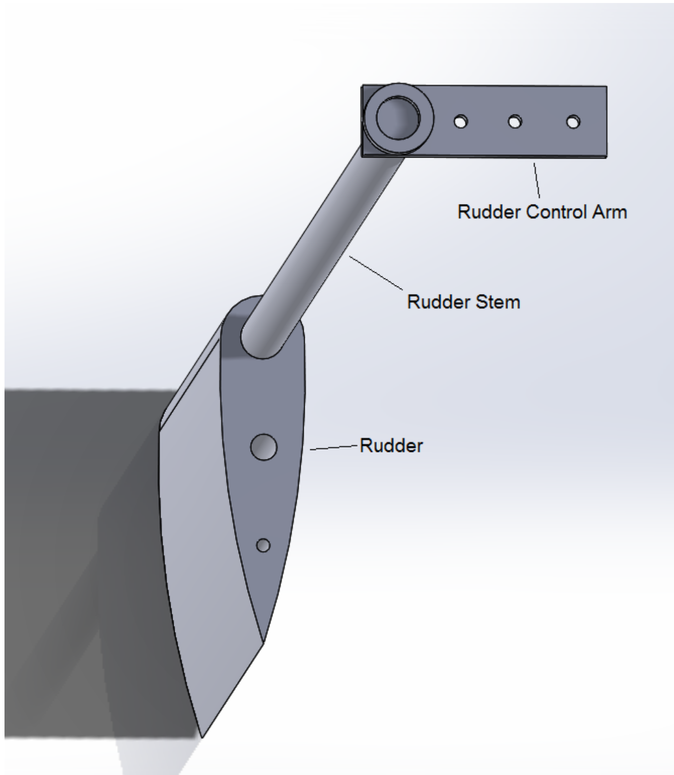

Figure #15: Top down view of whole rudder part with labels

This year, our rudder is changing in material, shape, and position, in order to lower our amount of drag underwater. Our previous rudder was very blocky and wide, creating a problematic amount of drag.

The rudder itself will be composed of common redwood construction lumber as opposed to carbon fiber and fiberglass used previously. Despite a composite rudder being very lightweight, we decided to build this year's rudder out of construction common redwood lumber because this type of wood is extremely sturdy and is able to take pressure from multiple angles without adding too much weight. Although there were many other kinds of wood we could have chosen to create the rudder from, we decided on redwood because of its excellent resistance to the elements and relatively affordable price. “Redwood is a premium building wood. It has a chemical inside the pores that makes it weather-, insect- and rot-resistant”, qualities which are highly desirable for a rudder (Shaddy, n.d.).

We are making the rudder from several small sections of redwood instead of being one complete piece. We are making these sections with the help of an X-Carve, a CNC-like machine that uses files uploaded by the user from a separate computer to carve into wood or other materials. The use of files lets us make each section of the rudder identical, virtually eliminating any possible error in the rudder creation. It is also much easier to make a rudder this way and will only get easier as our team learns the machine and other CNC machines. Since we are using an X-Carve to make the sections, all we needed to do is design a 3D model of the rudder section and have the machine create it for us. To complete the rudder, we will stack the identical redwood sections using two wooden dowels as guides then hold them together using wood glue. We will sand any excess material to get our shape then coat the rudder in epoxy for more strength and additional protection to potentially harmful elements as well as water.

The rudder stem will be placed into a hole drilled into the boat and be supported by a piece of PVC that will create a tight fit, similar to a shaft log. The rudder will be bolted to the rudder stem, which will be a ⅝” anodized aluminum rod compared to just an aluminum rod that we used previously. This anodized aluminum was chosen due to its corrosion resistance and its durability when exposed to the elements. Anodized aluminum is covered in a durable, corrosion resistant coating, making it resist rust which is common out on the water.. The two pieces will be connected through a hole located in the front of the rudder. The rudder is connected to the rudder stem with bolts running along the threaded holes on the sides of the rudder. In order to keep the teardrop shape of the rudder and reduce drag, we plan on countersinking the holes made on the rudder in order to conceal the bolts inside instead of them protruding out.

Before we had decided on making the rudder out of several sections of construction common redwood lumber, we originally thought of making a rudder out of an aluminum shell with a foam center. Along with having strength from having an aluminum shell, it would have also been light due to not being completely made out of aluminum. We moved away from this idea because we discovered that turning a sheet of aluminum into a teardrop shape would have taken much of our time and would require a large amount of precision to get the perfect shape. For this reason, we decided that wood was a much easier material to work with and would be much more effective.

Another consideration we had was similar to our current plan for the rudder, except it would be made out of steel. Despite being a very strong material, we figured that it would become way too heavy for the boat and would ruin our center of gravity. Another idea we had for the rudder was using a 3-D printed rudder to make one. We quickly abandoned this idea because a 3-D printed rudder would break easily and would be a waste of time.

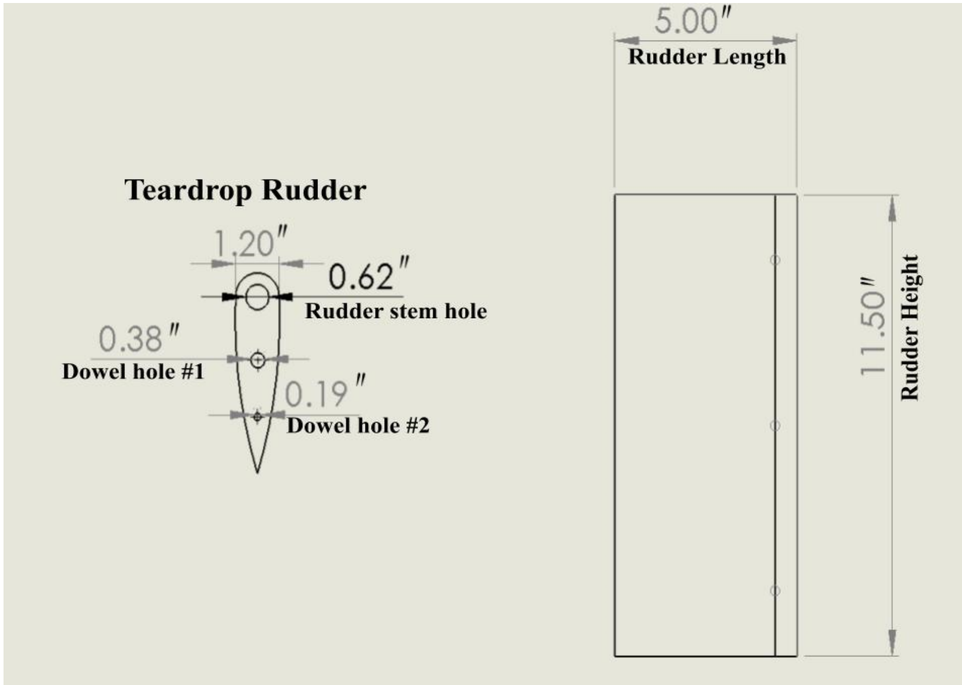

Figure #16: Top down and side view of the rudder with dimensions

The next major issue that we plan on addressing is the shape of the rudder. The previous year, our rudder was a flat plate without any indication of curvature. Its lack of surface area caused the rudder to not be able to catch much water creating issues at the expense of the boats handling. This year, our plan is to make the rudder teardrop-shaped due to its hydrodynamic nature. While designing the new shape of the rudder we considered the coefficient of drag and how it would affect the performance of the rudder. A teardrop shape also enables the rudder to have a very low coefficient of drag (Cd) when compared to other shapes, as proven by NASA's Glenn Research Center (see Figure 17). In a research journal analyzing rudder design, Professors Liu and Hekkenberg of Delft University of Technology mention that "In general, NACA profiles can generate sufficient maneuvering force with a high efficiency". This NACA shape, extremely similar to the teardrop shape we are using for the rudder has also been proven to provide an ample amount of surface area for handling.(Liu and Hekkenberg 2015). A change we made about the size of the rudder was making the rudder around 50% of our propeller disk area because this will make our rudder not oversized or undersized. If our rudder was oversized it will slow the boat down and if it was undersized our steering capabilities would decrease. Our challenge was to find our perfect ratio in which the rudder does not demerit the boat's performance. With our new design, we hope to have less drag and have a more efficient boat allowing for peak performance.

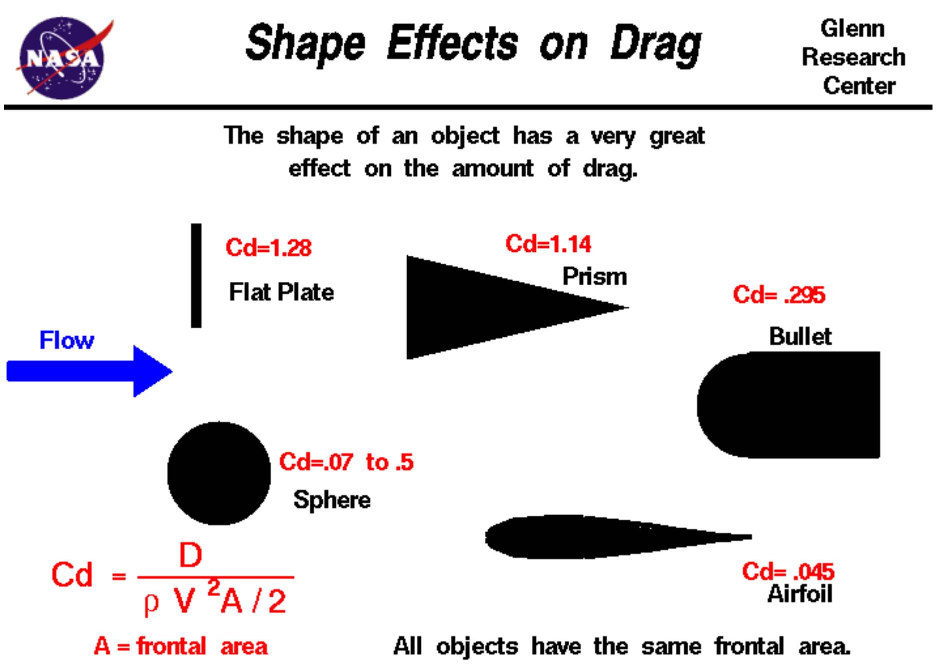

Figure #17: Coefficient of drag values of various shapes. The airfoil shape, which nearly matches our rudder's shape, has the lowest Cd of all the shapes provided.

Conclusion

With all these major changes and improvements coming to our boat, such as a focus on a completely new transmission system and an improved rudder, we hope to rank much more favorably in Solar Cup 2020. With much of our program experienced with Solar Cup now, we are confident that the lessons we have learned in the past years will guide us through our boat design and construction, and steer us into the direction of success. This year, our third year consecutive year of competing in Solar Cup, we are determined to make the best boat we have made to date; and our chances are better than ever.

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