Offseason Swerve Design Documentation

2020-2021 hardware team

I. Why Swerve?

A Swerve drive is a type of drivetrain that has gained much popularity amongst FRC teams and is a characteristic of many winning robots. Swerve drives are 4 wheel steering robots that have a motor designated to each module for rotating the direction of the wheel and another motor for turning the wheel in order to move the robot. They have many benefits in comparison to other strafing methods like H-frames or mecanum drivetrains, such as easy navigation around defense and high traction. Because of the replay of the 2020 FRC game in the 2021 season, we decided to invest our offseason/preseason time in designing a swerve drive for the upcoming and future seasons. Additionally, we aimed to train and encourage participation from newer, younger members in the design and assembly process. This documentation is for unfamiliar members to understand our procedures and rationale for design requirements, as well as our mechanical design and manufacturing process.

II. Design Requirements

A. Wheel Size

Wheel size in terms of diameter is a large factor in determining the mechanical design of a swerve model. The most common wheel sizes range from 3 to 6 inches, with the 4inch diameter wheel being the one that our club has used on two of our past 3 robots. On our 2020 robot, we used 6-inch wheels to cross the truss in the center, and in 2016 we used large pneumatic wheels because of the barriers. Most games where a swerve drive is viable have little to no restriction on ground clearance. In the 2020 game, there is a short truss in the middle which is about 0.875 inches tall, which does not require any additional design when using a 4-inch wheel.

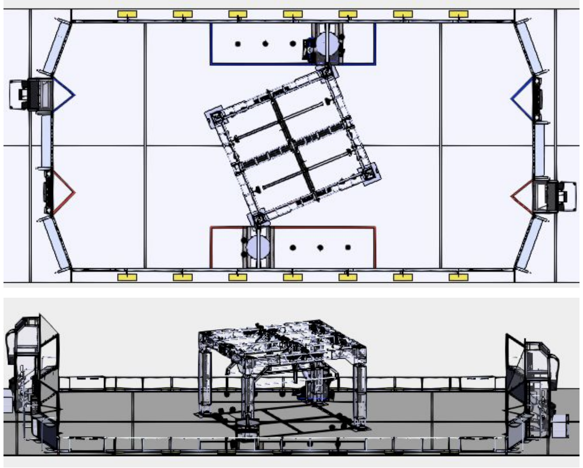
Having a lower center of gravity makes control easier for software and gives the robot other beneficial characteristics. A low center of gravity and our experience with this common wheel are the main reasons we chose a 4-inch wheel.

B. Wheel/Tread Type

Many different types of wheels are offered by different companies, but one of the most common ones our club uses is the AndyMark performance hub with the Blue Nitrile tread. This wheel is machinable and comes with a hole pattern that is used by many gears, meaning that extra machining may not be required for attaching a bevel gear, and machining a bearing hole may be easier in comparison to other wheels. The Blue Nitrile tread is one of many options, but it stands out because it provides lots of grip for the FRC standard field mats. The AndyMark performance wheel hub supports the use of many treads, so if we would like to switch to say a red nitrile, we could easily do so.

C. Top Speed

The gearbox setup of our swerve is largely dependent on the desired top speed of our robot. A combination of factors like openness and motor capability helps us determine our top speed. For challenges such as the 2020/2021 Infinite Recharge game and 2019 Deep Space game, the field features a good amount of open space where it is crucial for robots to quickly navigate through.



2020 Infinite Recharge Field

Considering our robot will experience lots of long straight runs in areas protected against defense, we need to make sure our gearbox optimizes acceleration and top speed to quickly travel across a straight run but also be able to push against defense. Assuming a long run where our robot behind at rest, the distance it covers is characterized as

$$\Delta x = \frac{1}{2}at^2$$

where a is the acceleration of the robot, which is directly related to the gearbox and output torque.

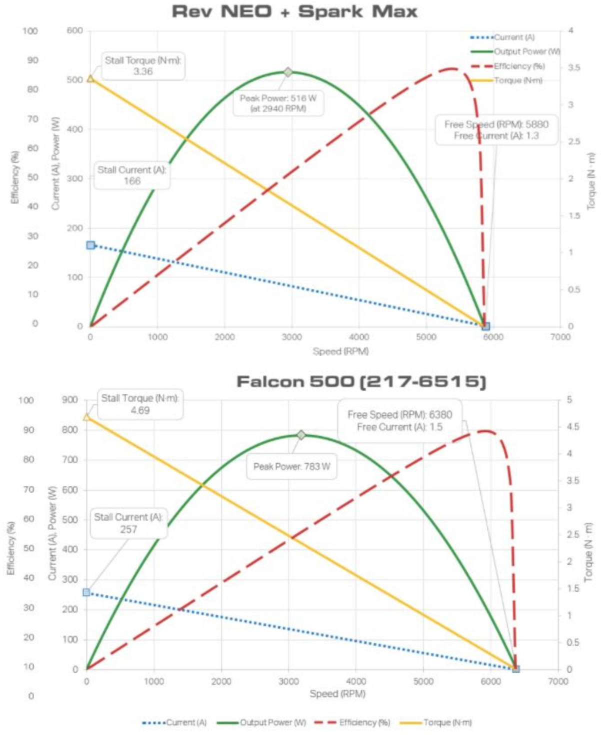
$$v_{max} = k\omega r = at_{max}$$

The robot also reaches a maximum velocity where k is the ratio of the gearbox, ω is the maximum angular velocity of the motor, and r is the radius of the wheel. t_{max} is the amount of time the robot will accelerate before reaching its maximum velocity.

Based on these factors, we determined that a top speed of **16.5 m/s** will allow us to navigate the field quickly, push against other robots, maintain wheel traction, and accelerate through long straight runs.

D. Drive Motor

The major FRC drivetrain motors used in the past 5 years have been the CIM, mini CIM, Neo, and now the new Falcon 500. The Neo and Falcon 500 are brushless DC motors, while the CIM motors are brushed. Both brushless motors are far more powerful and efficient than the brushed motors and do not require waiting for cooling. Additionally, they both have built-in encoders. While the Neo encoder is rather inaccurate and not reliable enough to use for a drivetrain, where-as the Falcon 500 encoder has been used as a drivetrain encoder by other teams and is far better. The Neo runs on a Spark Max motor controller which has been found to be unreliable and has caused many problems for our team in the 2020 season, while the Falcon 500 has a built-in Talon FX, a motor controller which our team has much experience and success with. Based on the motor curves, the Falcon 500 has a much higher stall torque and higher free speed, as well as peak power. However when operating between 20 and 40 amps, the Falcon 500 only slightly outperforms the Neo.



Neo (top) motor data including power, torque, efficiency, and rpm in comparison with Falcon 500 (bottom) motor data.

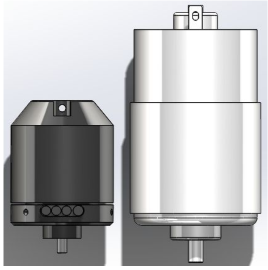
Because of the reliability and added benefits of a built-in motor controller and position encoder, we decided to use the Falcon 500 as our drive motor.

E. Module Motor

One of the biggest debates in the design of the module was what motor to use for the wheel rotation. The module rotation is a low torque task that requires high accuracy. All four modules on a drivetrain must be synchronized in order to have proper control, which also means that the change in the angle of the module should be smooth and highly consistent. Through visualization software, our team estimated that a rotational speed of 130-180rpm would be ideal. Because of the low torque requirement, many FRC motors are considered to be used as the module motor. FRC permitted motors can be classified into two major categories: large and small.

Large motors include the Falcon 500, Neo, CIM, and mini CIM, which are much heavier and output more power than small motors, which are the bag motor, 775pro, and neo 550 motors. Small motors are usually coupled with planetary gearboxes such as the Vexpro Versaplanetary or the Rev Ultraplanetary.

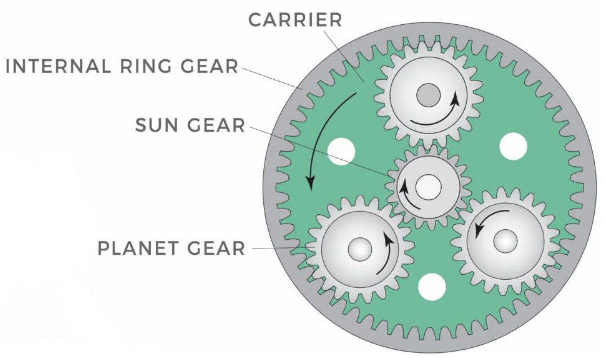
In their respective categories, the Falcon 500 and neo 550 outperform their counterparts for varying reasons. The Falcon 500 has a built-in encoder and motor controller, higher power output, and does not require cooling. The neo 550 is significantly smaller and lighter than the 775pro or bag motor, has a shaft and backplate output, and has a lower free speed, meaning lower gear reduction.



Neo 550 (left) size comparison with 775pro (right)

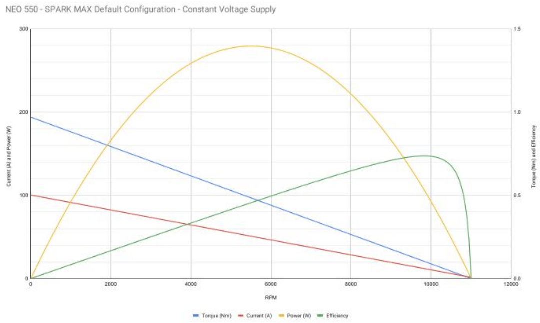
Although the obvious choice appears to be the neo 550, we must consider what is required for it to be used as a module motor. In order to achieve 150rpm module speed from the 10,000rpm brushless motor, a gear reduction of about 66:1 is required, meaning that a planetary system is required. In a two-stage

Versaplanetary gearbox, the weight of the planetary system itself is 0.74lbs, meaning the combined weight of the motor and planetary gearbox is about 1.05lbs, not to mention the extra weight of the spark max motor controller. When using an Ultraplanetary gearbox, the additional weight is reduced to only 0.273lbs. However, at the cost of this reduced weight is the use of a nylon planet ring, meaning that when the steel pinions are accelerated they could wear and tear at the outer nylon ring. Excluding the weight of the gears, the neo 550 and planetary system totals to a weight of about **0.84lbs** including the spark max motor controller (which we wanted to mount onto the swerve module itself to prevent long wire runs).



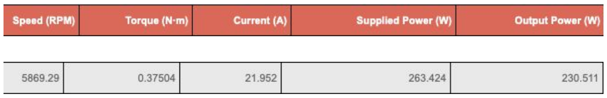
Labeled diagram of a planetary gearbox

Considering that a neo 550 would also require an external encoder for the module rotation shaft and that it is a less reliable system when paired with the spark max because of the increased number of wire runs and our lack of experience with it, the Falcon 500 rose as a major opponent. The Falcon 500 outputs more power than the neo 550 when pulling the same amps and also turns at a lower rpm meaning that less of a gear reduction is required. We see from the motor charts that when operating at 100% duty and pulling a maximum of 20amps, the neo 550 has an rpm of ~9000, torque of ~0.2Nm, and ~170W of output power.



Neo 550 motor curve

Meanwhile, @20amps the Falcon 500 outputs according to the values below, which are far more desirable in comparison to the neo 550.

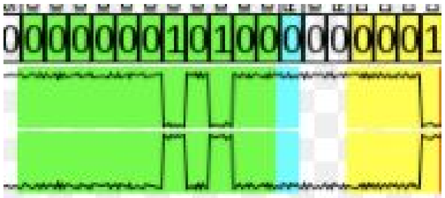


Speed (RPM)	Torque (N·m)	Current (A)	Supplied Power (W)	Output Power (W)
5869.29	0.37504	21.952	263.424	230.511

The Falcon 500 also has a reliable built-in position encoder and can allow the swerve drive to look symmetrical to an extent because of the use of two of the same motors, which potentially prevents the work of CAMming and manufacturing mirrored parts. Although it is 0.3lbs heavier per module, we ultimately decided the benefits outweigh and that the Falcon 500 is our best option for a module motor. Because an absolute encoder is required, we still plan to use an external encoder for measuring the module rotation.

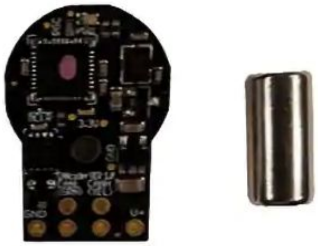
F. Encoders

In order to measure the position of our rotating module, we need an absolute encoder to measure position. Past encoders that we have used are the MA3 encoder, the MAG encoder, and the CANcoder. The CANcoder is similar to the MAG encoder but it wires through CAN protocol, which our robot uses in order to mitigate noise.



CAN signal

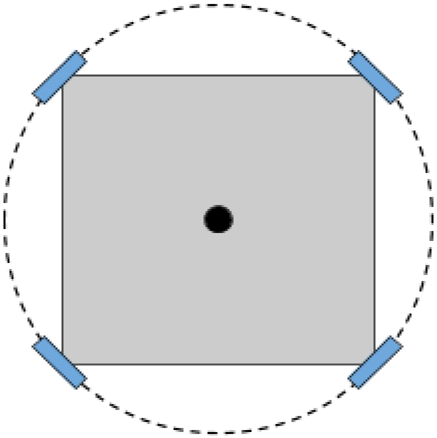
CAN uses a high and low signal and measures the difference between those values to determine bits. This is useful as any outside disturbances will affect each signal the same amount, meaning the difference between them will be fairly similar. The CANcoder from CTRE (shown below) uses this protocol and makes wiring around the robot much easier, which is why we chose it as our module rotation encoder.

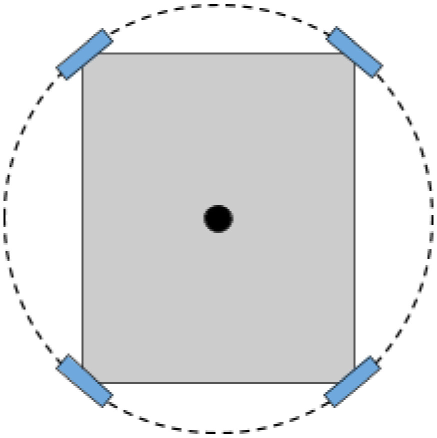


CTRE CANcoder

G. DriveFrame

Oftentimes Swerve drivetrains are configured as squares for symmetry, but this is not actually necessary to get full functionality from a swerve drive. Besides strafing, one other function of a swerve is a turn-in-place that has no friction. When a tank-style or a west-coast drivetrain turns about its center, the wheels experience lots of friction as they slide. However, a swerve drive allows the robot to angle its wheels to the tangent lines at the points where the wheels are fixed to create perfect rotation about the robot's center. This doesn't require a square frame, as seen below.



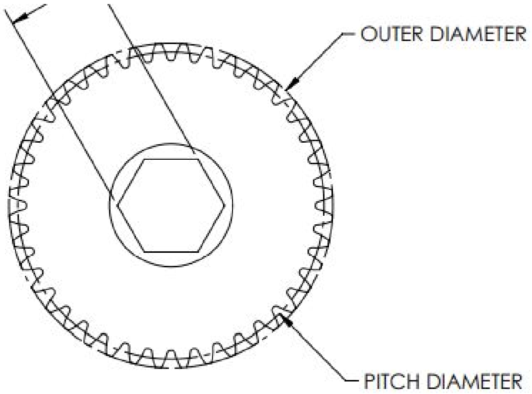


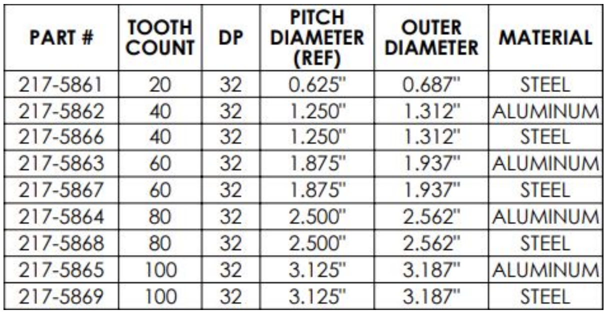
A rectangular frame will allow us to have the same functionality as a square, except for the fact that we can travel sideways through any gap that we can travel forward through. This may help us navigate through the trench run in the 2020 season, but it is early to determine the exact shape of our drivetrain considering that we do not know the exact location of the subsystems that may be on the robot. Our drivetrains are usually made of 2x1 box tubing with a mounting pattern that will work with a standard swerve design, allowing the swerve plate to also act as a gusset.

III. Gearbox Calculations

A. Drive

As we identified earlier, we wanted to use a single Falcon motor and a 4 inch wheel for our drive, as well as achieve a top speed of ~16.5 ft/s. With that, we used some basic motor data to calculate the overall gear ratio we would need. The Falcon 500 motor operates at about 6380rpm at free speed, meaning no load. Theoretically, this value should not necessarily decrease when a load is attached as the work done should come from the current pull of the motor, but tests from past years reveal that this is not true, and motors often run at only 70-90% of their free speed. Given that this motor is more efficient than its past counterparts, we used the mid-range value of 80% to calculate what maximum rpm the Falcon 500 will actually operate at when under the forces of the drivetrain. Using this value, we calculated that to achieve a top speed of ~16.5 ft/s, we would need a gear ratio in the range of 6.8-6.9:1. The determining factor at this stage is the gears we use, because we cannot manufacture gears ourselves without dedicating much labor and time. We order gears from WCP and Vexpro, which come in two major profiles, 32 and 20DP. The DP number is a ratio between the pitch diameter of the gear and the number of teeth, as seen in the chart below. Multiplying the pitch diameter, which is the length from the center to the midpoint of the tooth, by the DP gives the tooth count.





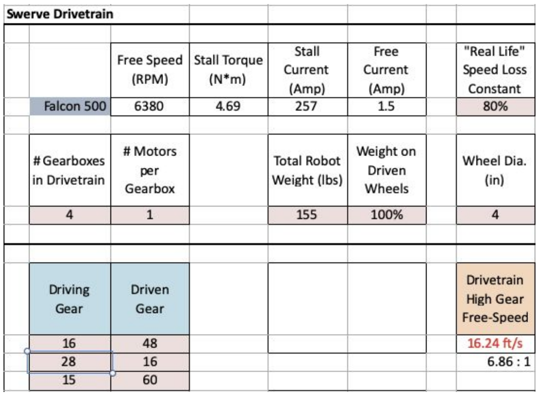
PART #	TOOTH COUNT	DP	PITCH DIAMETER (REF)	OUTER DIAMETER	MATERIAL
217-5861	20	32	0.625"	0.687"	STEEL
217-5862	40	32	1.250"	1.312"	ALUMINUM
217-5866	40	32	1.250"	1.312"	STEEL
217-5863	60	32	1.875"	1.937"	ALUMINUM
217-5867	60	32	1.875"	1.937"	STEEL
217-5864	80	32	2.500"	2.562"	ALUMINUM
217-5868	80	32	2.500"	2.562"	STEEL
217-5865	100	32	3.125"	3.187"	ALUMINUM
217-5869	100	32	3.125"	3.187"	STEEL

Images from Vexpro

When selecting gears, we first identified the gears that we must use first, and then used the options from our gear suppliers to determine what our final ratio will be. The motor pinion has only a few options, a 14t and 16t gear, and since they have a similar pitch diameter, they are essentially interchangeable, meaning we can easily switch them out to adjust our ratio. A limiting component of the gear train in a swerve drive is the bevel gear, as the transmission must be transferred perpendicularly from the motor to wheel.

SDS Bevel Assembly

Based on past designs and what is available for us to purchase, the bevel gear set we settled upon is a 15 tooth-60 tooth assembly, meaning that the final stage of the gearbox must be this 4:1 ratio. A new type of double-gear had been made available for purchase by SDS, a company making swerve drives, which allows for a central dead-axle for the drive, reducing the need for extra parts to be made for the encoder (discussed more later). Using this 48 tooth to 28 tooth gear, the other choices fell into place to create a 3 stage gearbox that achieves a 6.86:1 gear ratio.



Swerve Drivetrain						
	Free Speed (RPM)	Stall Torque (N*m)	Stall Current (Amp)	Free Current (Amp)		"Real Life" Speed Loss Constant
Falcon 500	6380	4.69	257	1.5		80%
# Gearboxes in Drivetrain	# Motors per Gearbox		Total Robot Weight (lbs)	Weight on Driven Wheels		Wheel Dia. (in)
4	1		155	100%		4
Driving Gear	Driven Gear					Drivetrain High Gear Free-Speed
16	48					16.24 ft/s
28	16					6.86 : 1
15	60					

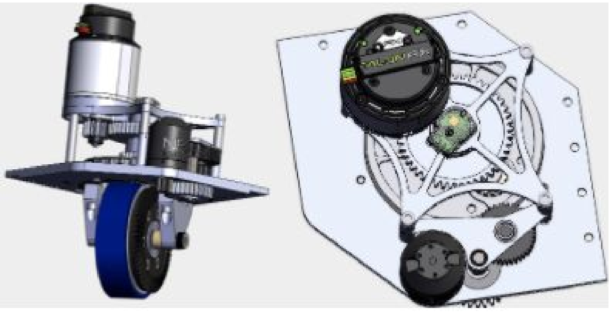
SDS 48-28t Double Gear (top) and JVN Calculator (bottom)

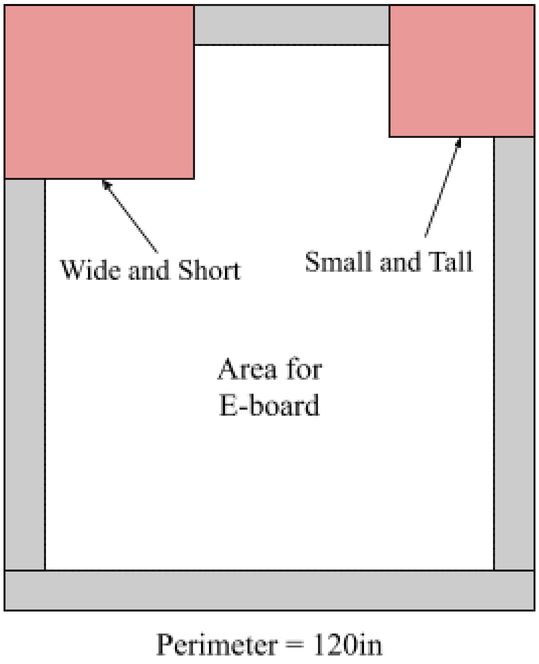
B. Module Gear Train

Based on our idea of what the design may look like, the module rotation will likely be controlled by a large timing pulley which is attached to a small timing pulley. Because of the low torque requirements when using a Falcon 500, the only specific reason we need a gear train is for control on the software side. Using a rpm visualizer, we calculated our max rpm should be ~150rpm and determined our reduction using that value

IV. Layout

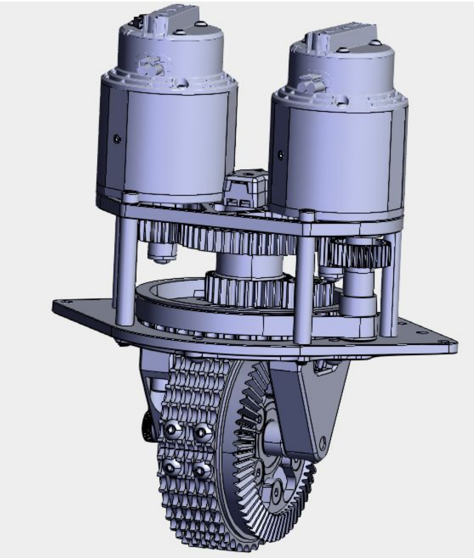
One major discussion we had was the layout of the swerve design. In some initial designs, we had two different layouts, one featuring a wide footprint of motors and gear layouts that is short, and another featuring a small footprint with a taller height. Ultimately, we decided that a "small and tall" design would be best as we don't have to worry about obstruction under the baseplate, and so we can save footprint space for electronics, which is often cramped on the drivetrain.



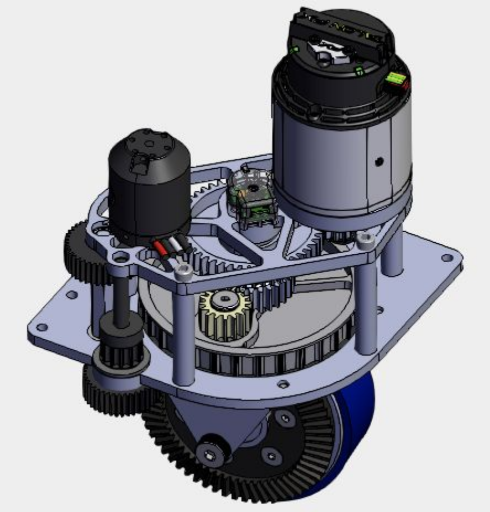


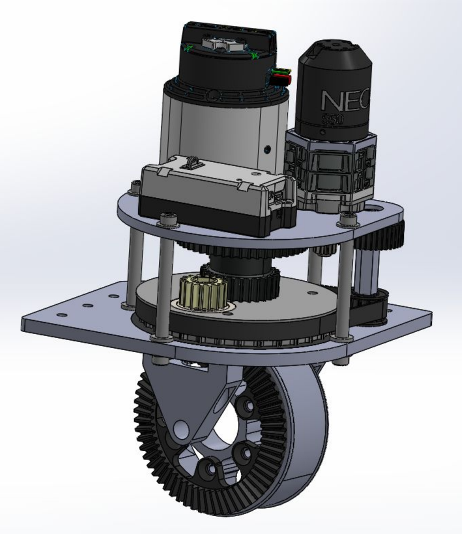
V. Part Design, CAD

A. Initial/Past Designs



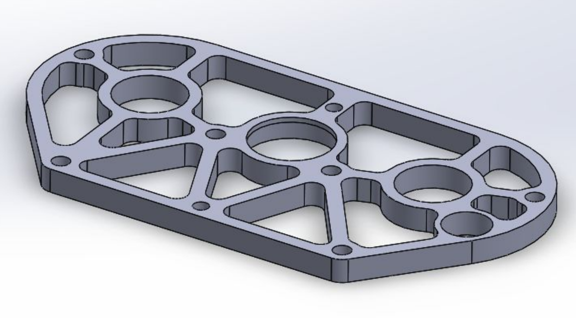
SDS Design





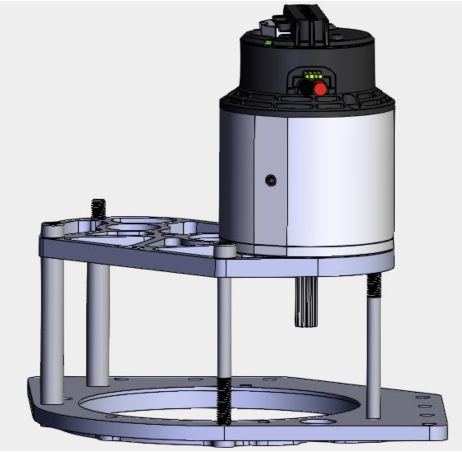
B. Motor Mount Plate

To eliminate the need for a mirrored version of the design, we made the motor mount plate symmetrical. Symmetry not only reduces the room for error in assembly, but also means fewer machining processes and CAM. Based on our layout decisions, we wanted to mount our motors upright and have the motor plate held away from the main base plate by standoffs. Because of the orientation, we realized we can utilize the standoff screws to also mount the motor. The faceplate of the Falcon 500 has a hexagonal hole pattern, meaning that just two bolts across from each other are needed to hold the motor down. Using separate bolts on the inner edge and standoff bolts on the outer edge, we pocketed the plate to have ribs from each connection point to the outer contour.



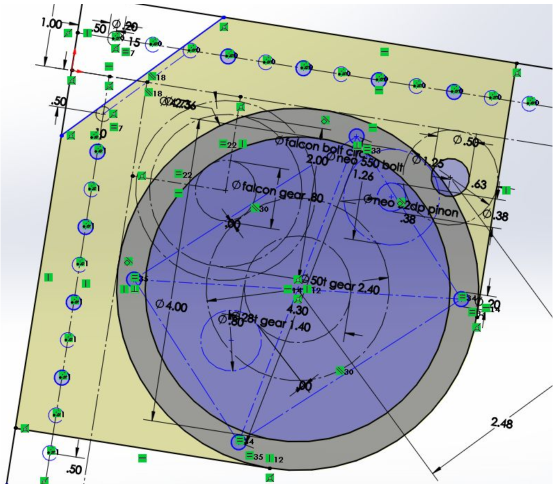
C. Standoffs

Based on the motor-mount plate design, we also needed standoff mounts on places that did not bolt into the motors, so we added two more along the edge. We used partially threaded bolts that go through the entire standoff, essentially making it a long spacer that the bolt-head and nut will press the plates into, instead of a threaded standoff which would press the plate against the standoff itself. The image below shows the location of the bolts and standoffs, with one pair removed to show the directions of the partial threads.



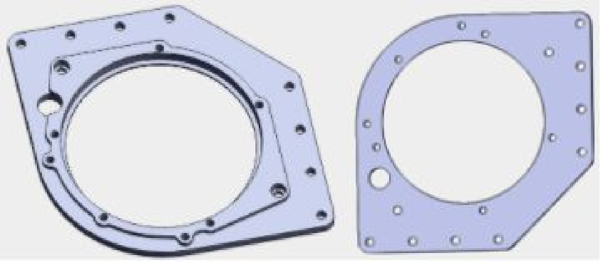
D. Base-Plate

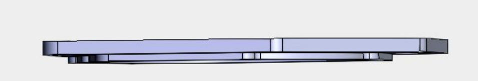
The base plate holds the entire module together and also mounts the module to the drivetrain, making it the most important part of the swerve. The design for this component is largely driven by the gear layout, so we did a geometry sketch in SOLIDWORKS to determine where to locate parts so that the baseplate has the smallest footprint, but ensures for no collisions in parts.



Although this looks like a mess of circles, the geometry here carefully displays the locations of things like our motors based on the tangency points of gears and the location of the module along our drivetrain. Using this geometry, the baseplate was then designed around it to extrude the main contour of the base plate.

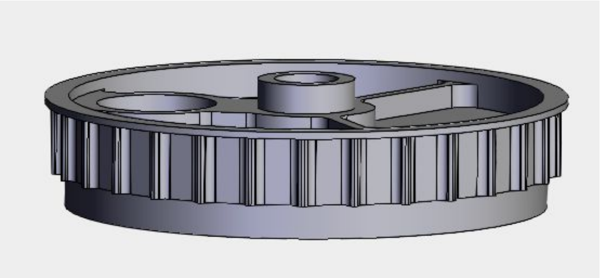
The module needs to be accurately manufactured and strong, which means a couple things for our design. As seen from the images in the next column, one side is completely flat, meaning that we can do a standard CNC operation with a flat bottom to get accurate holes. There are also two thicknesses to the part, as we need to cover the entire thickness of the large bearing that fits inside the large hole, but also need to save weight. The holes close the hole were carefully placed so there is enough material to be strong, but also a small enough gap that a bolt-head can creep over into the hole space to act as a flange for the bearing that we need to retain in the hole. From the image on the left, you can also see a flange inside the hole that is used to keep the bearing and entire wheel assembly from pushing up into the drive module due to the weight of the robot. Additionally, we added tapped holes and counterbores for the standoff bolts to sit in so we would not have any protrusions, and so that we would not need to use nuts. We added holes along the edges to mount onto the drivetrain rails, which lineup with our standard 0.5" hole pattern. Lastly, we added a hole (the one slightly larger than the drivetrain mount holes) that fits a bearing that will host the axle of the small pulley.



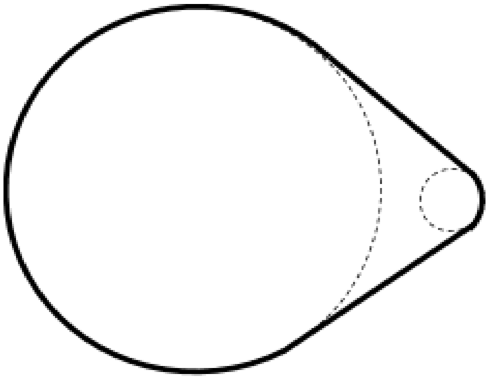


E. TurnTable Pulley

The middle turntable pulley has multiple purposes as it also hosts the wheel assembly and a few stages of the gear train. It's main design is it's outer profile, which is a timing belt profile for a 5m HTD belt that will attach to a small pulley, which attaches to the Falcon 500.

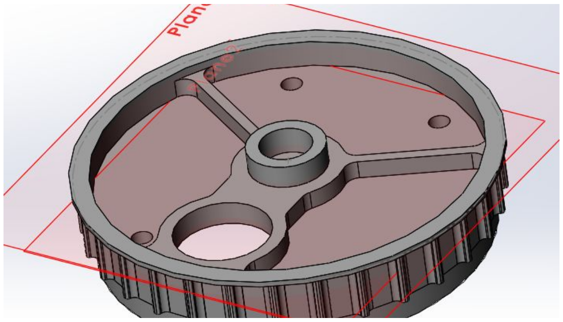


From this side view, we see that only about half of the teeth are designed into the pulley. This decision was made as having all teeth increases machine time by a large amount and simply isn't necessary considering the belt will be wrapped around a large portion of the pulley during operation.



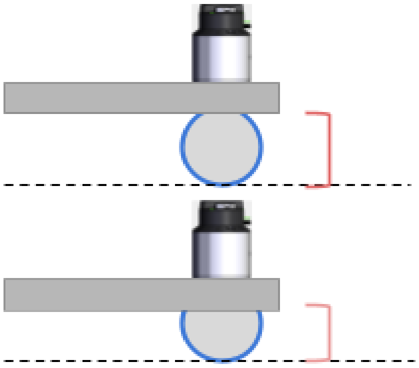
Belt Coverage Around Large Pulley

Inside the pulley, an entire gear train resides, including a point along the edge where the bevel gear pokes through the pulley onto the underside in order to make contact with the large bevel gear, which is attached to the wheel.



From the top view, we see the connection point between a gear in the middle to a gear on the edge. The ribs on the top face are for strength, and much material on the inside is removed to save weight, The four holes are tapped and pass through the bottom for the wheel mounts to bolt into.

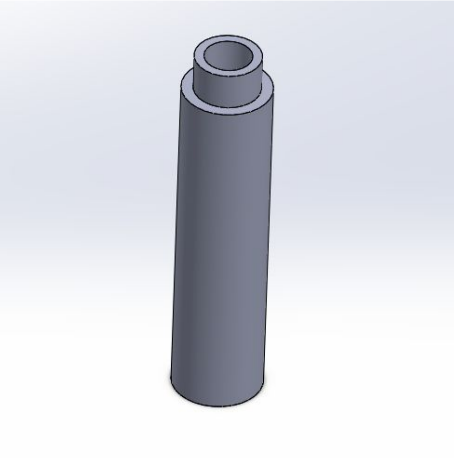
On the bottom, we cut out a large cavity for the wheel to sit inside to reduce the ride height of the drivetrain, and also added a countersink in the middle for a bolt that can attach to a central dead axle, on which the encoder magnet and some gears will sit.



A lower ride height means the weight of the robot rides closer to the ground, lowering the center of mass and giving our robot more predictable and favorable driving characteristics.

F. Central Axle

The central axle is mounted to the turntable pulley and sits in a bearing that is on the top plate. The double gear spins about this axle and at the top, there is a hole in which the magnet for the CANcoder to sit inside. Originally, the axle was far more complex with many different "steps" or radii, but because of the manufacturing complexity, we reduced it to a 12mm shaft with just a few step downs and holes.

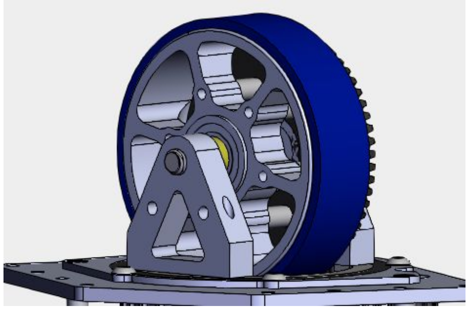


Refined Central Axle

The magnet hole depth was dimensioned using the guidelines from CTRE on how far the magnet should be from the encoder, and we sized the inner diameter using tolerances listed on their website. In the bottom of the axle we added a tapped hole in which the countersunk bolt in the bottom of the large pulley will thread into.

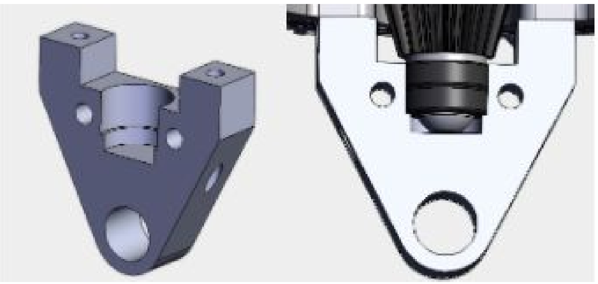
G. Wheel Mounts

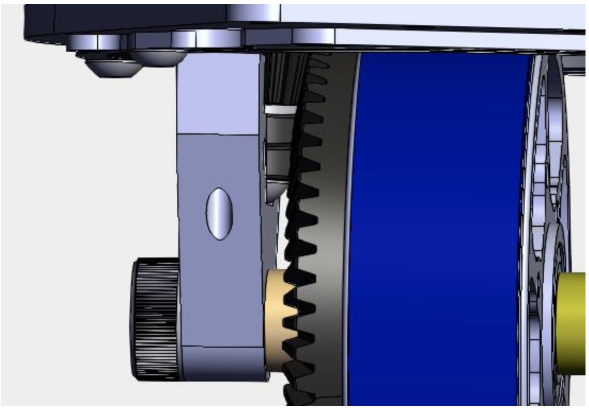
There are two wheel mounts, and one is very different from the other. The simple wheel mount is a thick aluminum piece that mounts perpendicular to the turntable pulley using two bolts, then has a hole for the wheel shaft.



The hole on this wheel mount is tapped to mount the shaft, which is a shoulder bolt. A shoulder bolt is a bolt that has a long "shoulder", which is essentially a shaft, and then threads at the end. The benefit of using a shoulder bolt is that it is easy to fasten, and does not require retaining rings or glue to hold it in place. It also doesn't need to be custom manufactured as we can buy parts to size. The shaft is toleranced to a size that fits bearings, so we can fix the shaft in place and put bearings into the wheel.

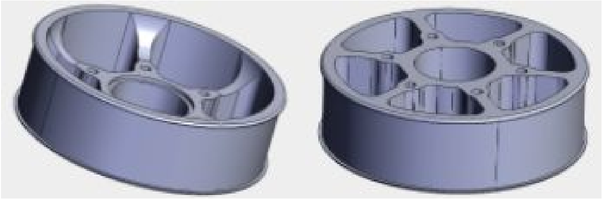
The second wheel mount is far more complex in terms of design and manufacturing as it also needs to hold the bearings for the axle on which the small bevel gear rides. Because of the geometry, the part cannot be wide enough to host a hole large enough for the bearing to fit into, and therefore just over half the bearing will sit inside the part. There are multiple lips so that the bolt under the bearings and the bearings themselves can fit inside the part. Gears naturally want to push away from each other, so it is not a problem that half the bearing is not supported, because the half that is is the direction in which most forces will be applied.



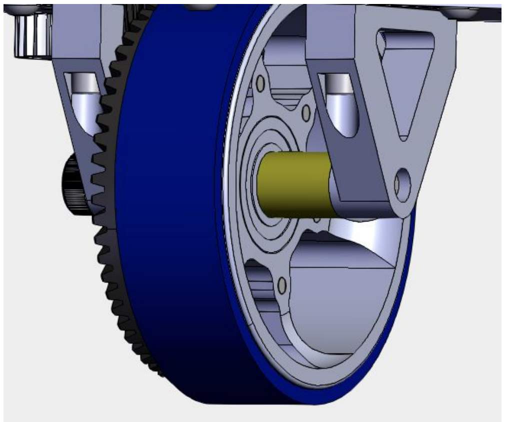


H. Bevel Gear Mount

One major change we made toward the end of our design was the location of the large bevel gear on the wheel. The 4 inch wheel that we are using is the andymark performance wheel, which has a plate with six holes on one face that is thinner than the entire wheel, so on the other face there are curved ribs that meet the outer ring of the wheel.



We originally had the bevel gear mounted as shown below, but we realized that the wheel would be facing heavy torque from the force of the ground caused by the robot's weight, which could lead to the bearing hole wearing down or the wheel bending.



To counter this, we moved the bevel gear to the other side and mounted it onto the shaft using its own bearing and used basic spacers and bolts to mount the bevel gear to the wheel. This means that the torque on the wheel is minimized as the force goes through the spacers and into the bevel gear bearing hole.