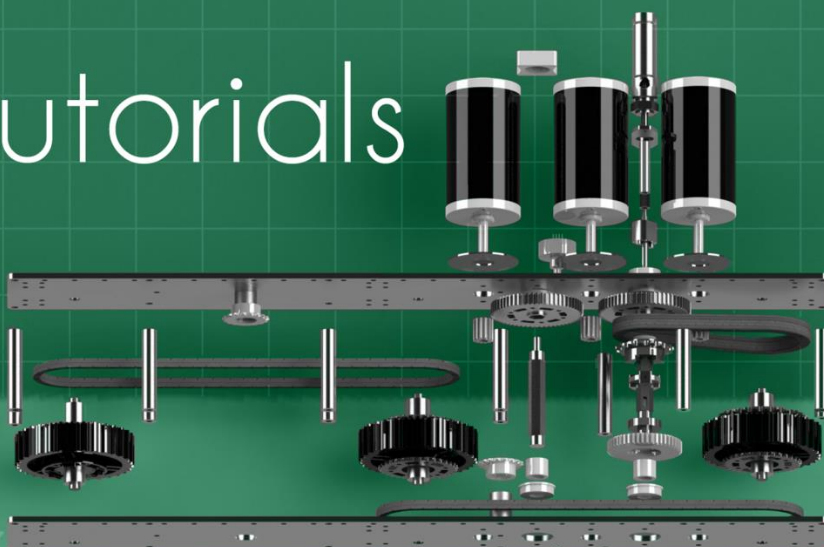
Design Tutorials



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Class of 2013-2014

Rev9

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INTRODUCTION

Engineering is, quite simply, problem solving. It is the process of designing solutions to problems and then executing those solutions. There is never one correct way to do something, rather, each solution is unique and holds its own value. Design can't be taught from a book, but is rather learned from experience and failure. This set of tutorials merely serves as a guideline for designing your own solutions. It is not a recipe for designs but teaches the essential techniques for everything from building gearboxes to lifts. Take great pride in what you build but always be open to critique.

These tutorials assume a reasonable understanding of SolidWorks and a working knowledge of some basic physics concepts (torque, gear ratios, etc.). Also, keep in mind that ideas are cultivated on pen and paper and in CAD, and not with a sledgehammer and drill. Work through these tutorials, and by the end hopefully you will have the tools to tackle any challenge the GDC throws at you.

Important tips before you get started:

1. Use the Design Library. It has everything from sprockets to motors and will save you lots of time looking for off-the-shelf parts.
2. Use off-the-shelf parts when convenient. For example, order spacers when possible – machining a dozen spacers takes time, resources, and is no fun.
3. Make things generic lengths and use standard parts. Make parts to fractions of an inch (e.g. 1/8" = .125; 3/8"= .375) so they are easier to machine, and you will be more likely to find an off-the-shelf part. Also, don't use weird stock sizes or rare/special parts as they will be hard to find.
4. NAME YOUR FILES PROPERLY! REMEMBER TO SAVE! DON'T FORGET WHERE YOU SAVED IT!
5. Always ask for help if you need it.
6. As cliché as this is: never give up.

On the cover of this document is an exploded view of the 2013 drive system. Hopefully by the end of this you will be able to design something just like it.

FASTENERS

This basically covers all of the screw sizes you will ever use:

4-40

- Essentially the smallest screw we use
- Low stress applications (e.g. panels, covers, trays, sensor mounts)
- Rarely use this size

6-32

- Most commonly used on VEX Motors
- Usually only used when an 8-32 is too big
- Not bad for tapping

8-32

- Most common screw in VEX – used to attach essentially everything
- Fairly common for assembling smaller FRC components (e.g. pneumatic tank mounts, electrical boards)
- Not bad for tapping

10-24

- Most common screw used
- Used for assembling the shooter, battery mounts, intakes, etc.
- Too big to tap the sides of thinner sheet metal/plastic but can still be tapped on thicker material

10-32

- Used almost exclusively to mount the CIM motors

¼-20

- Used when a 10-24 is too small and/or for higher load applications (e.g. while assembling the drive frame)

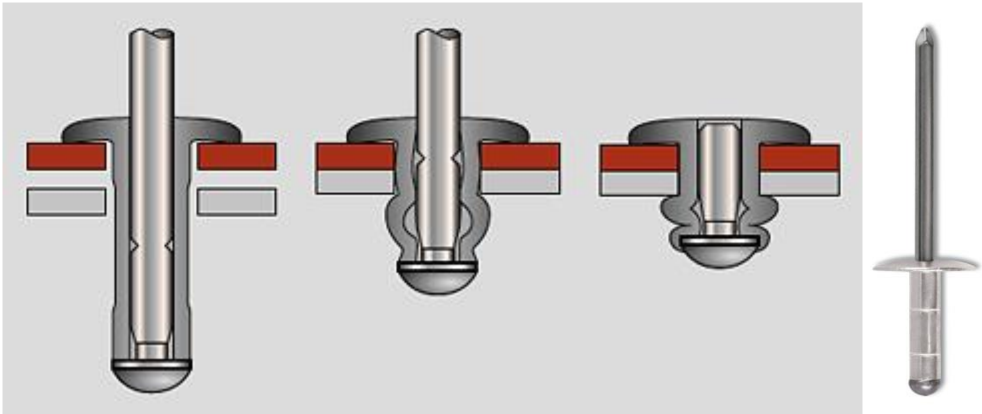
Larger sizes do exist but we don't use them very often. Sometimes, a larger screw like a 3/8 may be used as an axle. Most screws and nuts are steel, although they do come in other materials such as nylon and aluminum. For what size hole to use for a given screw go to Appendix A.

Some Special Nut Types:

Keps Nut		These nuts have a special face that grips the material that it is holding to prevent it from coming loose.
Lock Nut		They have a nylon insert that doesn't allow the nut to loosen or to come off. Must be used when a screw is being used as a pivot; if not, the nut will just undo itself. They are also commonly used in places where the nut will vibrate or shake off.
Pem Nut		A nut with a special face that you press into the part so that the nut stays attached to the part. Commonly pressed into a part before the part is assembled because without the nut already in the part, it would be difficult to put in once assembled. Must be pressed into the part ahead of time.

The above comprises >90% of the ways you will hold things together.

Rivets function like screws but work in a different fashion.



They are extremely convenient because you don't need to have a nut (nuts can be problematic when access to the other side is limited). Rivets are also much lighter than screws because they are aluminum. While the weight of one screw may not seem like much, a whole robot's worth of screws can add up. The disadvantage of rivets is that unlike a screw, they can't be undone and put back together as easily. Removing a rivet involves drilling it out. The majority of our robots are held together with screws, but a fair amount of rivets can be found too, they come in sizes such as 1/8', 3/16', and ¼'.

STOCKS AND RAW MATERIALS

The two main materials we use are plastics and metal. Of the metal, most of it is aluminum (6061 or 6063 and 7075), and most of our parts are machined from aluminum. Some steel is used, mainly in the form of shafts. We barely ever use steel, as it is harder to machine and much heavier than aluminum. Steel is stronger, but for most purposes aluminum will do. You will see some instances where aluminum would wear down too easily, such as in a dog gear. For plastics, we generally use either Lexan brand polycarbonate (a transparent plastic material that does not crack and is incredibly strong), or Delrin (a low friction plastic). Some occasional Teflon, nylon, ABS, and acrylic end up in the shop for special applications.

Metals and plastics come in the forms of sheet, an extrusion, or, rarely, in a block, and the stock is machined down to size.

Always check shop for stock availability. Go to "www.mcmaster.com" to search McMaster-Carr for full stock options. These are just general guidelines.

1) Metal (Aluminum only unless specified)
    a) Sheet or a rectangular Bar
        i) 1/16" Thick (.0625)
        ii) 1/8" Thick (.125)
        iii) 3/16" Thick (.1875)

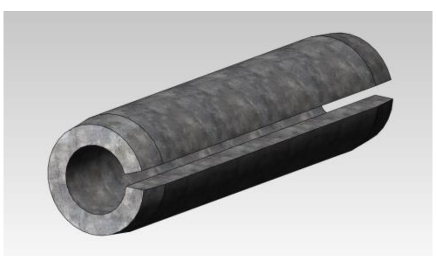
        - iv) ¼” Thick (.25)
    - b) Extrusions
        - i) Shafts [aluminum and steel] (OD = Outer Diameter)
            - (1) 3/16” OD (.1875) –round only
            - (2) ¼” OD (.25) –round only
            - (3) 3/8” OD (.375) –hex and round
            - (4) 1/2” OD (.5) –hex and round
        - ii) Tubes
            - (1) Essentially any OD of generic size (1/2”, 1”, 2” etc.) with either 1/8” or 1/16” walls.
        - iii) Box, C and L Channel
            - (1) Essentially any combination of .5”x .5” up to 4”x 4” OD. Either 1/8" or 1/16” walls.
        - iv) Blocks
            - (1) Check shop
- 2) Plastics
    - a) Sheet
        - i) 1/16” Thick (.0625)
        - ii) 1/8” Thick (.125)
        - iii) 3/16” Thick (.1875)
        - iv) ¼” Thick (.25)
        - v) 5/8 Thick (.625) Delrin
    - b) Other
        - i) Check shop stock

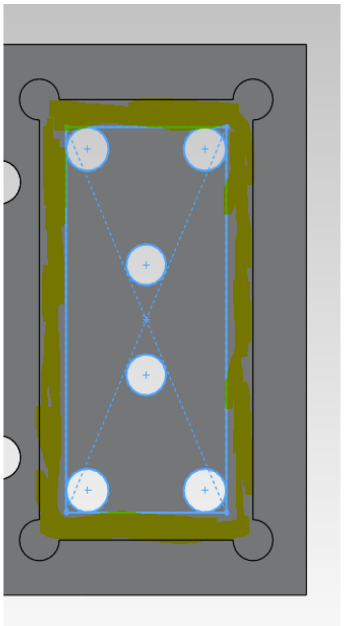
Always check to see if your stock size is available. If it is not, try to see if you can use something else. If not, order it. Stick to the generic stock sizes.

ROLL PINS

These are metal pins that are pressed into part.

Here is what it looks like. This one is designed to fit into a 3/16’ hole, but is actually slightly larger than that. These pins are pushed into the metal and stay in because it is a tight fit.

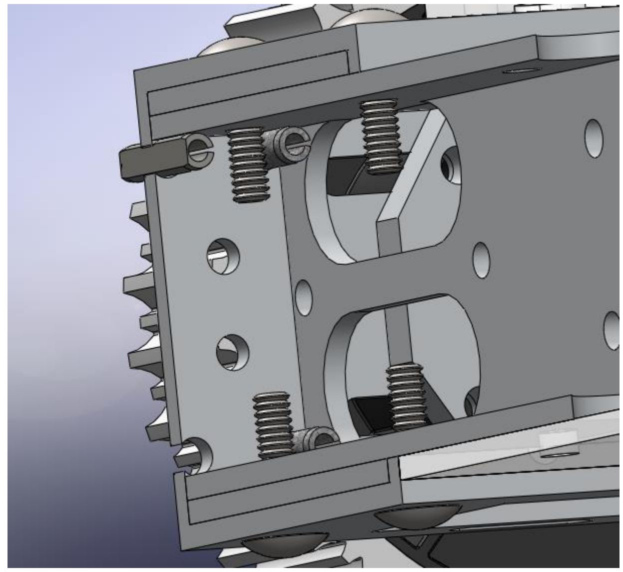




The pins can be used in many ways, but one of the ways we use them is to join a square tube perpendicular to a flat surface.

Here we have a cross bar for a drive train being joined with the drive train.

Looking head-on, the yellow region is the space occupied by the perpendicular tube.

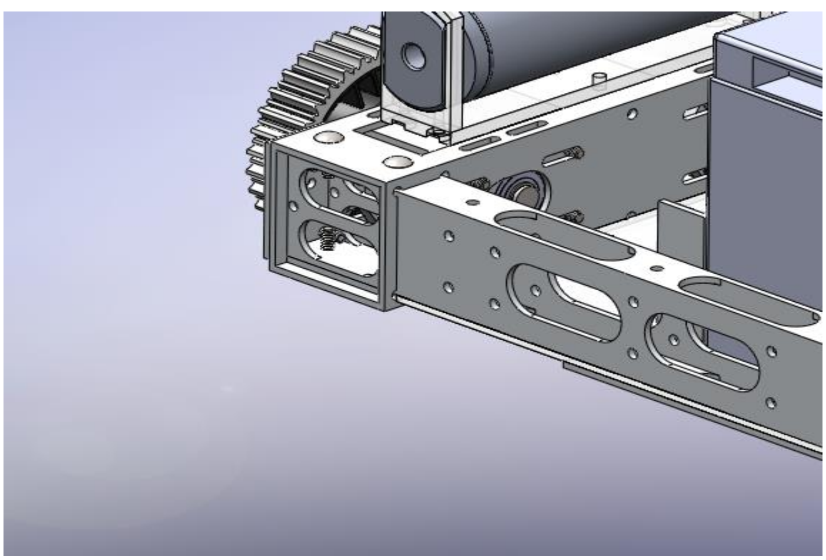


Tangent to the tube are 3 roll pins. (Note: the centre two holes are irrelevant)

In the 4th (empty) hole, a piece of threaded rod runs from one end to the other. Nuts on both sides keep the tube from sliding out, while the pins keep it from rotating or moving.

In this particular case there are also 4 screws that secure it from top and bottom. Notice the insert sandwiched between the 2 tubes. That piece is there to prevent the tube from caving in when the screw is being tightened. Over-tightening the screw can cause the screw to vice and warp the metal.

Also, notice how on the side that the perpendicular tube runs through, the rectangle has its four corners drilled out. This is because we can't cut perfect 90° inside corners. The 4 corners are drilled out so that the part fits in smoothly. The alternative is an army of grade 9s with files – but that's no fun.



Screws are also shown in this case. In general, you don't need to put those into your CAD unless you have too much time or the amount of available space is in question. Screws take up space too! It might be very little, but if you can't get them in, it's no good.

TAPS

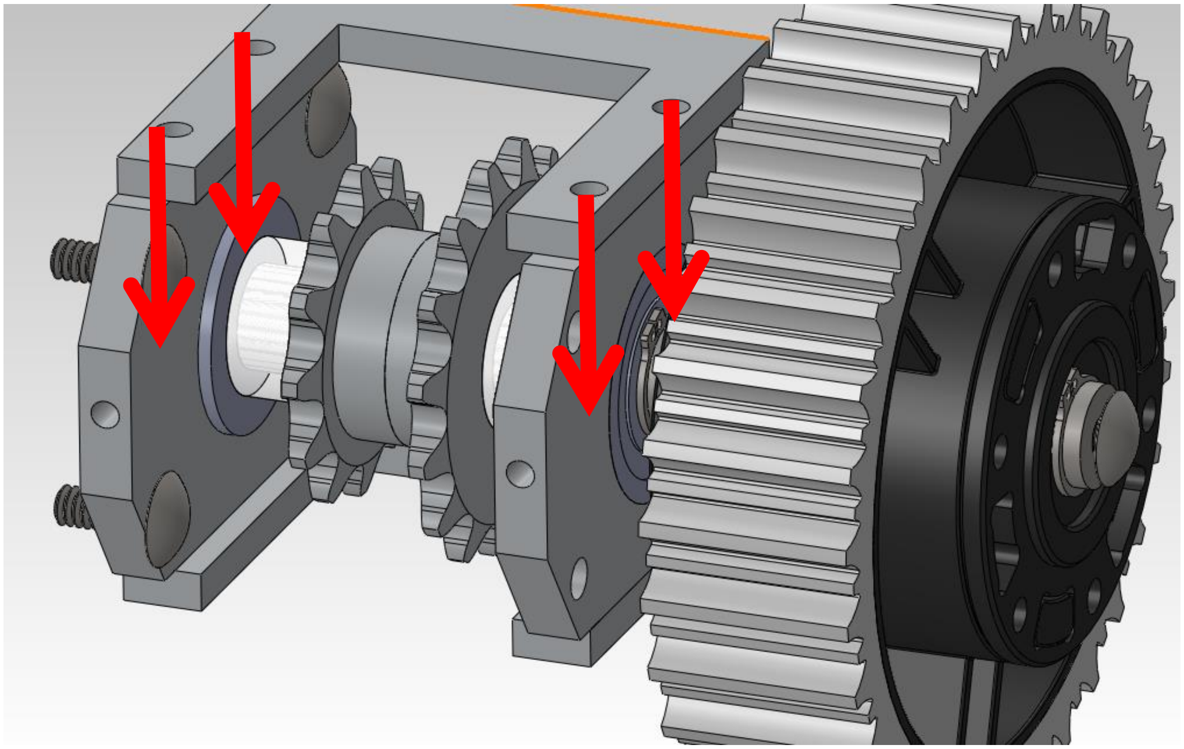
In places where you need to join 2 pieces of metal together but a nut will not fit or a rivet will not do, there is the tap. Tapping essentially involves giving a hole in a part threads such that the part itself acts like a nut and keeps the screw in.

This is what a tap looks like. It basically cuts a thread into a hole.

To tap a hole; first drill a hole slightly smaller into the part, then turn the tap into the part as if you were screwing it in.

Taps are delicate (the tool and the threads) and break easily. When they break, you need a new part. Tapping is also very laborious and time consuming.

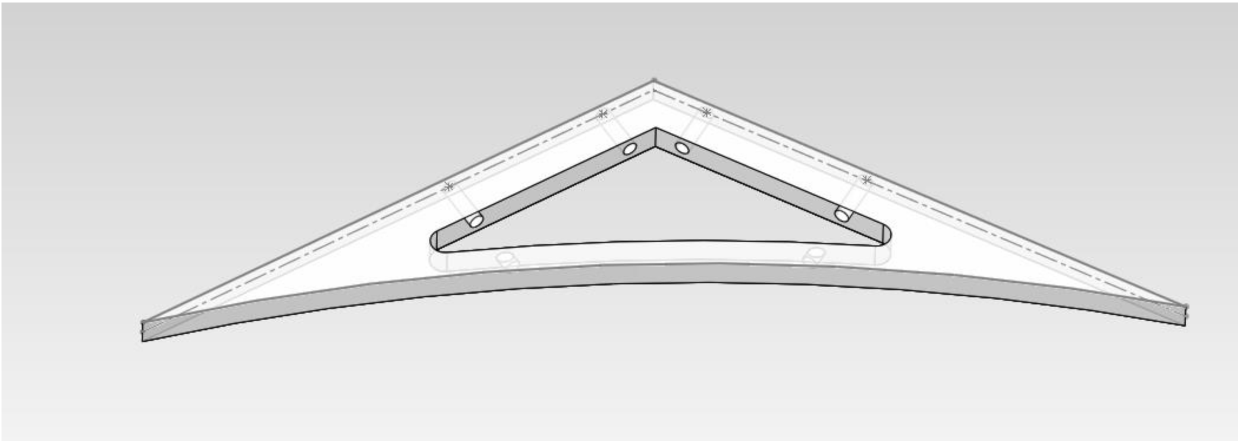
This bearing block (we will talk about these later) has a roof piece that needs to attach to the side piece. In this particular piece, a section of L channel will not do because the assembly needs to be small enough to fit into the drive tube. Typically, taps are used to connect something to the side of a sheet of material, where you can't put a nut or fit a gusset.



Refer to Appendix C for tap drill sizes

Taps can be annoying to make, and are not as strong as using a conventional nut. Where possible, avoid taping.

This part is designed to hold two plates perpendicular to it at an angle. To avoid tapping, a slot was cut into the middle so that a nut could be placed there instead.



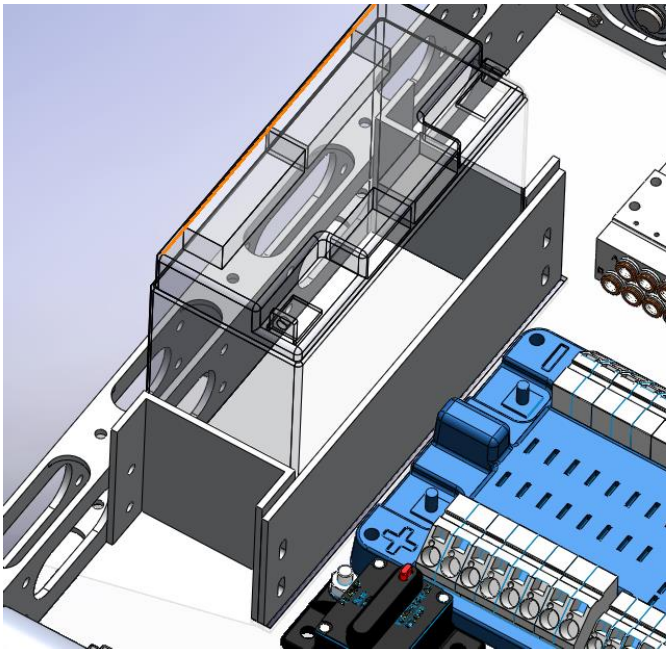
THREADED INSERTS

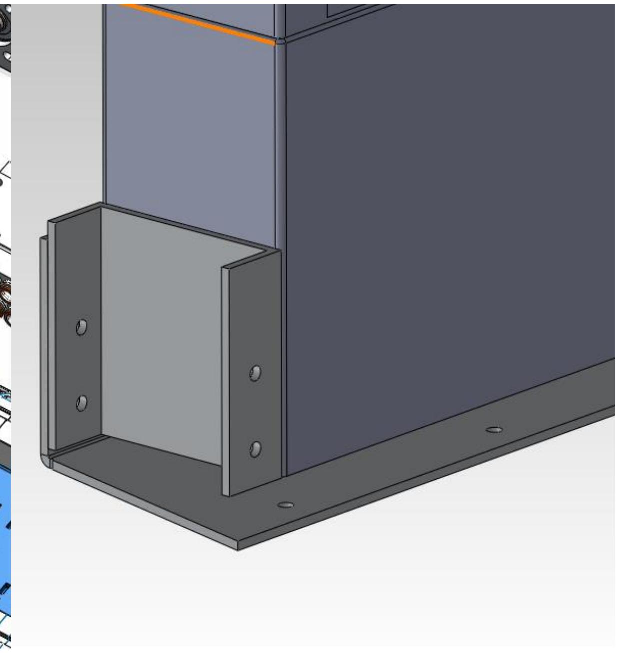
Quite simply, these are shoved into the ends of round tubes. To connect the end of the tube perpendicular to something, pound the insert into the end of the tube, and secure a perpendicular plate to the end by putting a screw through it. (This works similarly to how a base flange works for a pipe.)

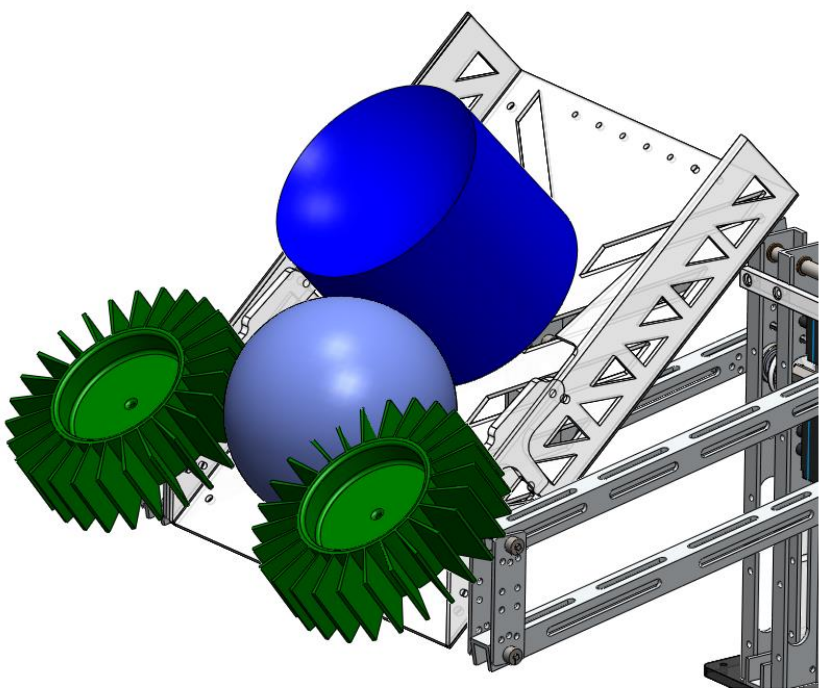
They come in sizes such as a 10-24 thread for a 1" pipe.

SHEET METAL

Instead of cutting two separate sheets and connecting them with a third piece, sometimes it is easier to make one part and bend it.







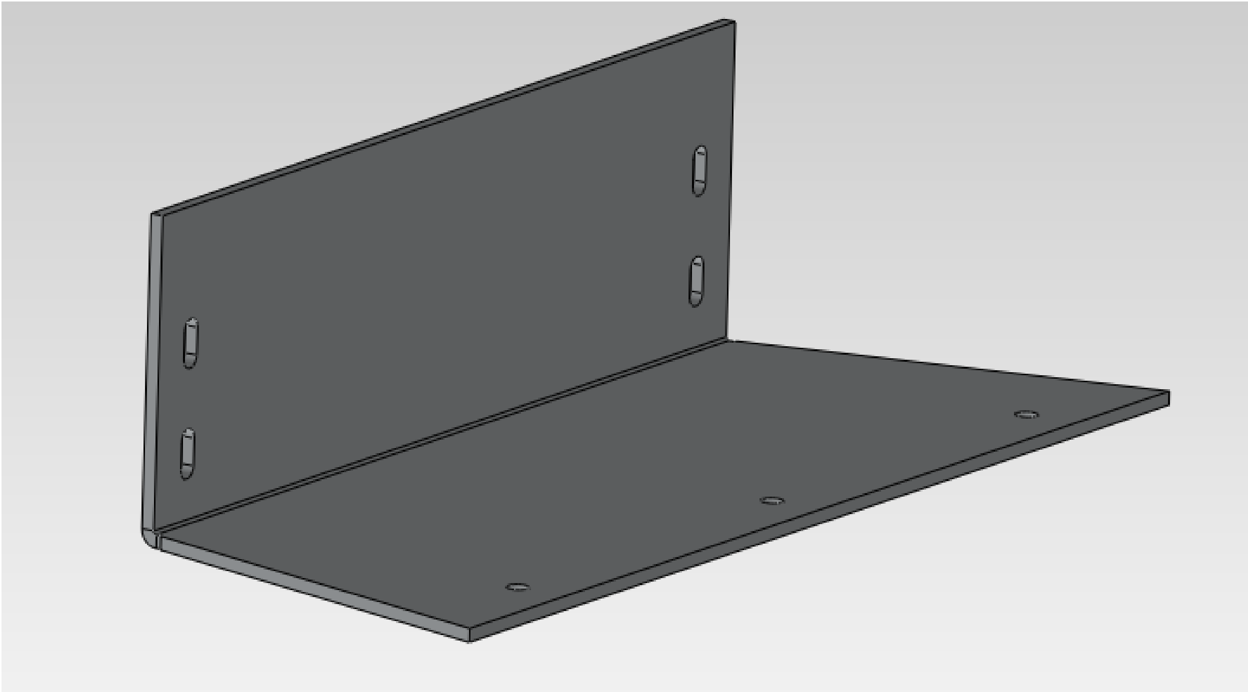
A single continuous plate holds the battery from underneath and in the front.

Giving parts a flange (bending the sides) can also increase its strength (think of C and L channels, and I beams)

Take this tray for example; (made from 1/8" polycarbonate) without the side flanges (ignoring the fact that the pieces would fall out), it would flex and bend back a lot.

In general, things are much more rigid when they have a bend in them.

A problem with sheet metal however, is that we cannot accurately place bends with our bender.

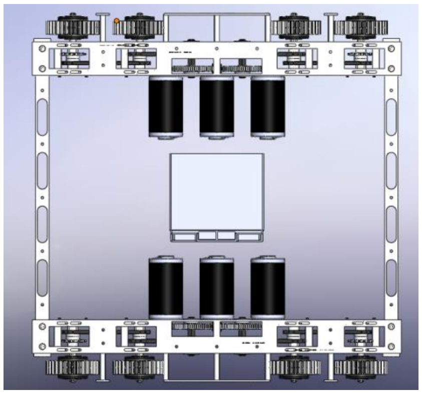


Take this part, for example. Since we cannot precisely control the position of the bend, the height of the flange could be too low or too high, causing the holes to not line up (hence the slots you see there). For parts like this where accuracy is a non-issue, we just put slots in. However, anything that needs to be precise can only be so on one side of the bend. Keep this in mind when designing with sheet metal!

DESIGN CHALLENGE

This is a basic revision of how to assemble things. Find the folder called: "Drive Base Battery Assignment". Open the Assembly called: "Drive Base".

Your Task:



1. The battery MUST go there and cannot be moved (don't ask why it is in the middle of nowhere – that's the challenge)
2. Build a mount that will secure the battery (remember it weighs ~15lbs.)
3. Assume the drive train has already been built and assembled (why it would be built without a battery mount is irrelevant) and you may not modify any components, you may only add.
4. Common sense applies. Remember to try to keep it as light, simple, and easy to machine as possible.

POWER TRANSMISSION (ROTARY)

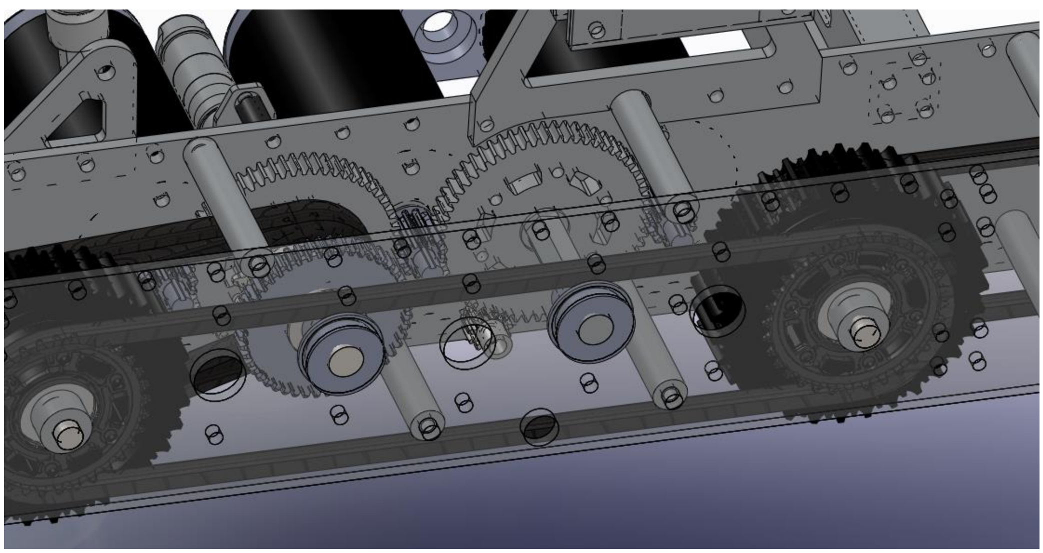
Batteries provide all the power for the robot. In general, everything on the robot is powered by motors (rotary motion) or pistons (linear motion) which run off of compressed air. Here, we will be dealing strictly with motors and getting power from the motors to a winch, arm, roller, or whatever you want to power.

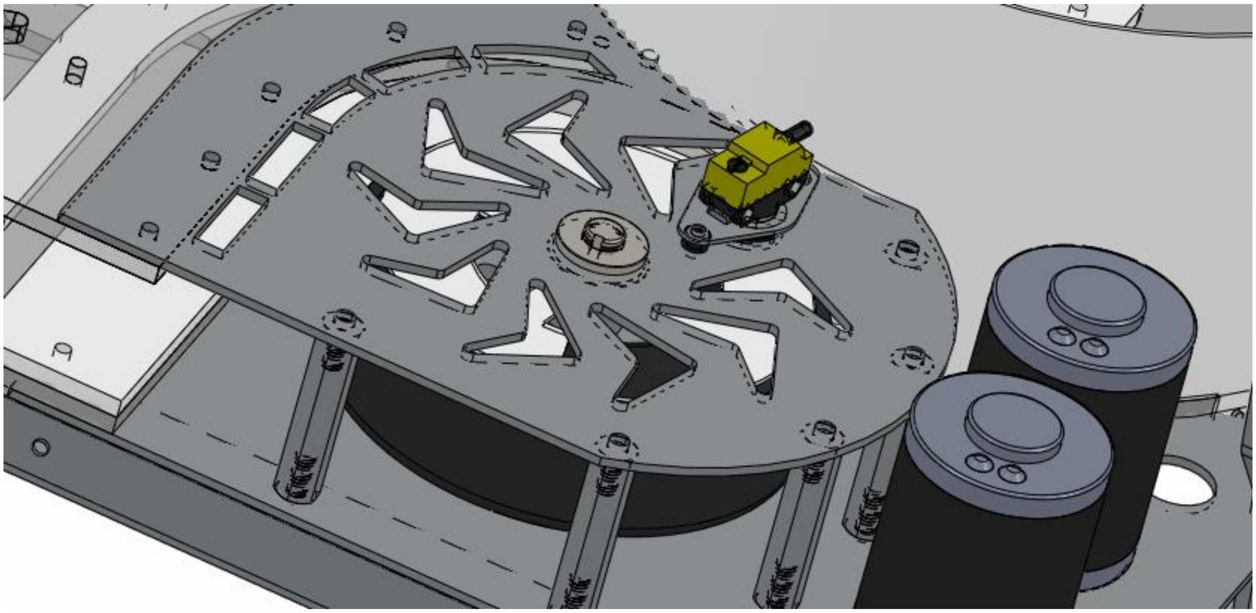
BEARINGS

This is a bearing. Essentially, bearings hold shafts in place and allow the shaft to spin freely with low friction. Anywhere that you have a spinning shaft you will need to put a bearing to hold it in place.

Most bearings that we use are for a ½ inch or ⅜ inch shaft, although we occasionally do use some other sizes such as ¼ inch or 3/16 for smaller applications. There other types known as sleeve bearings which are bearings without balls. They are just made of out a material that allows the shaft to spin with little friction. They don't allow the shaft to spin as well, but the advantage is that sleeve bearings are much smaller and can take much higher loads (not that we will ever come close to needing that).

Here we see two bearings in the side plate, holding shafts in place for the gear box. The bearings keep the shaft in place, but allow it to spin smoothly.

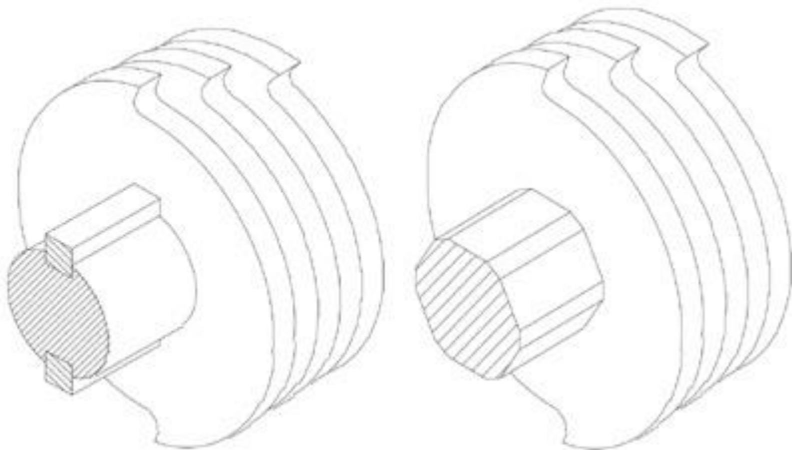




Here on the shooter wheel, it is the same story. The shaft on which wheel spins is held in place with a bearing. Typically, to put bearings in, we just press them into the stock.

SHAFTS

Shafts are used to transmit power. They are considered either live or dead axle. Live axle means that power is being transmitted through the axle, whereas dead axle means that the shaft is not transmitting the power; they are just there to hold the gear. An easy way to tell if an axle is dead or live is to ask this: If an axle were perfectly round and not spinning, would power still be transmitted to an appendage on the end? If the answer is yes, then it is a dead axle. If it is no, then it is a live axle. Also, a live axle will always have to have one of; a keyway, hex, or set screw to transmit the power.



We would normally only put one key/keyway in an axle (not two as shown in the picture).

MOTORS

Here are the motors we typically use:

Name	Primary Application	Picture
CIM	The drive train is the main application for these (allowed up to six). Most robust motor. Used for the most strenuous tasks. Many teams will run four of these on the drive. You also find them on mechanisms that require lots of torque, such as hangers.	
Mini CIM	Smaller CIM motor that is usually used for medium sized tasks such as shooters and arms, even though they are said to be “drop-in replacements” for the larger CIMs.	
Bag Motor	Even smaller CIM motor that is often used to power rollers, feeders and smaller arms. Also known as a “baby CIM”. A combination of up to four of these and Mini CIMs is allowed.	
BaneBot RS550	Comparable power output to some of the larger motors. However, its' smaller and more compact design means it is worse at thermal distribution (i.e. it overheats more easily). They are also not as reliable or as robust as CIMs. You will often find these on lifts, rollers, and feeders.	
Bane Bot RS775	Slightly more powerful than the RS550 but significantly less reliable.	

There are many more, but these are probably the five that you want to stick to make your life easy. Other motors include the “window motor” which has a built in worm gear so it is not back drivable, the AndyMark 9015, and the Fisher Price Motor. Reminder: models of all of these motors are in the design library and they have their weight already set. Use them!

Know that these motors spin at incredibly high RPM so quite often large reductions are needed. We could build large gearboxes for these motor but often we buy planetary gear boxes that fit right onto the face of the motor. VEX Pro VersaPlanetary gear boxes can fit on any motor (changeable face plate on the gear box) and can be configured up to 100:1.

GEARS & CHAIN

I don’t think I will have to explain what gears and chain are. In FRC, the gears we use are 20DP with a 14.5 degree pressure angle. You can’t mix gears with different DPs or pressure angles, but everything we use is the same. 20DP means that the number of teeth on the gear is 20 times the pitch diameter. In other words, if I have 20 teeth on the sprocket, the pitch diameter is 1 inch. The pitch diameter is the distance at which you want to mount the gear to other gears. If I have a 20 tooth and a 60 tooth, their pitch diameters are 1 and 3 inches, so their centres should be 2 inches apart (add their pitch radii). The chain we use in

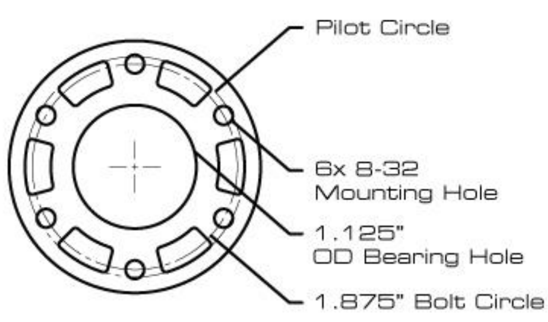
FRC is either #25 chain (also known as ¼ pitch chain because each link is .25 inches) or #35 chain (3/8 pitch or .375" long). #25 chain is sufficient in most cases, including drive trains, which usually take the highest load. Sometimes the drive train will be designed with #35 chain. #25 chain has never broken on us but does rarely derail (rarely is about once in a season or not even once in a season; it derails in the off season). #35 is fatter and wider so it is much harder to derail; the disadvantage is that it weighs much more. In 2011 we used a #35 chain drive, but in both 2012 and 2013 we used #25. You will also find #35 chain on the 30pt. hanger gearbox for our 2013 robot. To get the size of a pitch diameter, you are probably better off looking it up than calculating it. Andy Mark has a list of their sprockets and their respective pitch diameters. To calculate the sprocket distance and the number of links you will have to do something different.

For sprockets of the same size, the centre distances should be a multiple of the chain's pitch. The number of links equals the number of teeth in contact with the chain on both of the sprockets (the two halves of the two sprockets) plus the distance between the 2 sprockets' centres times two. For sprockets of different sizes don't bother with the math. Use this: http://www.islandpondrailroad.com/chain.htm

We usually get all of our sprockets and gears from VEX Pro and AndyMark. VEX Pro generally has better ones, and the gears from VEX Pro are also aluminum, and thus lighter.

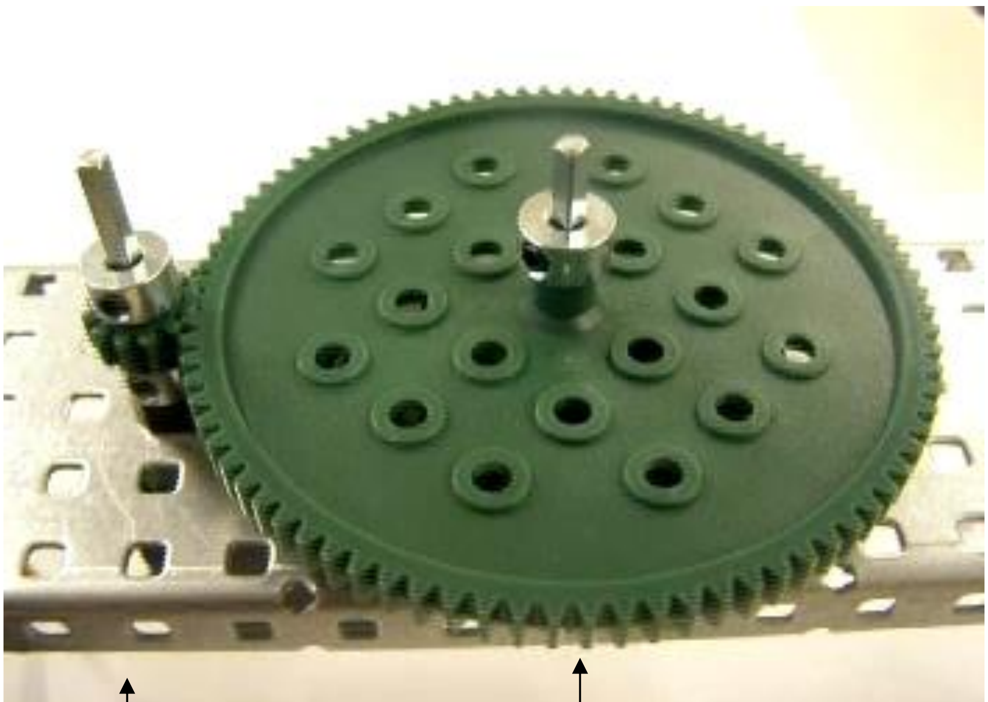
Unlike gears, sprocket pitch diameters are not as easy. Refer to Appendix D for sprocket pitch diameters.

Further, there are hub sprockets and plate sprockets. Hub sprockets are designed to be put on shafts (they are either hex or keyed). Plate sprockets are dead axle and have a hole pattern that allows them to be easily bolted to a wheel or an arm.



GEAR AND SPROCKET RATIOS

Due to the nature of motors, they typically spin at high speeds and low torque. For most applications, we want high torque (i.e. lots of force) and will sacrifice speed.



Driven (Follower) Gear

Driving Gear

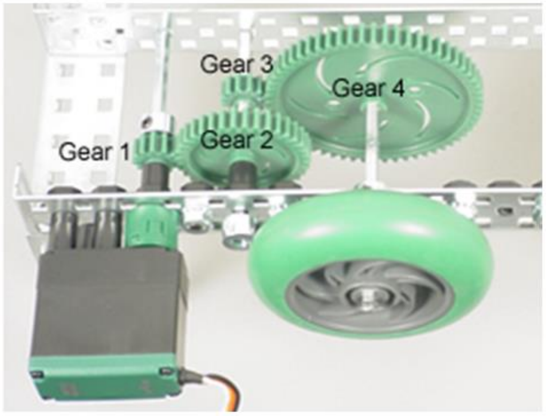
The driving gear is the gear that is being directly powered, and the follower gear is powered by the driven gear.

In this picture, the driven gear, which is attached to the motor behind, is a 12 tooth gear, and the follower is an 84 tooth gear.

For every 1 rotation of the driving gear, the follower will also rotate 12 teeth. Only, on the follower, 12 teeth is a fraction of its total, so the 12 teeth on the follower translate to only 1/7 of a rotation.

In other words, the driving gear must rotate seven times before the large gear rotates once. The gear ratio would be called a 7:1 gear ratio because for every seven rotations you put in, you get one out. In this way, a motor with a free speed (the speed that the motor runs at with no load) of 100 rpm geared down 7:1 will have an output rotation speed 14.3 rotations per minute, or rpm (100/7).

Let's say we were using an RS550 whose free speed is about 19000rpm. Now we would use a VersaPlanetary Gearbox with a 100:1 gear ratio and that would bring it down to 190 rpm. Now, let's say we weren't using a planetary gearbox and wanted a 100:1 reduction. We can't easily find a 100 tooth gear and a 1 tooth gear, and a 10 tooth gear paired with a 1000 tooth gear sounds equally as obscure. In order to achieve higher gear ratios, we compound them together as follows.



Gear 1 = 12 teeth   Gear 2 = 36 teeth

Gear 3 = 12 teeth   Gear 4 = 60 teeth

Gear 1 & Gear 2:

$$\frac{\text{follower}}{\text{driver}} = \frac{36}{12} = \frac{3}{1}$$

Gear 3 & Gear 4:

$$\frac{\text{follower}}{\text{driver}} = \frac{60}{12} = \frac{5}{1}$$

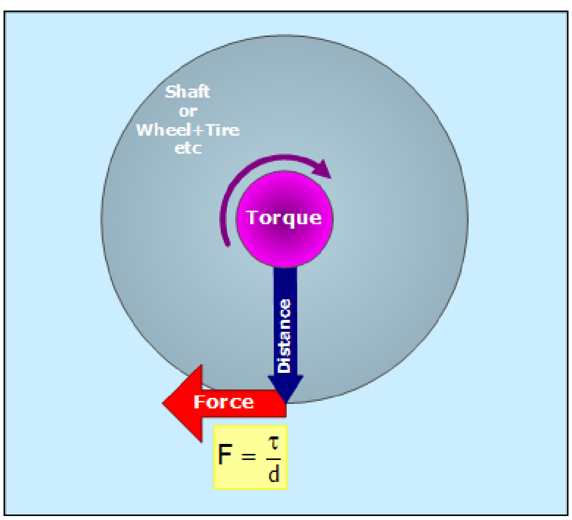
Multiply the gear ratios:

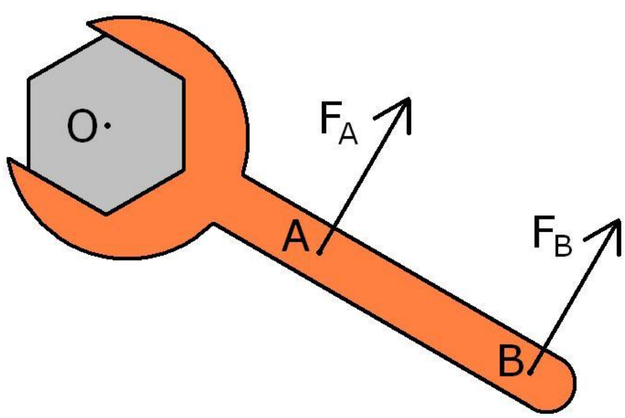
$$\frac{3}{1} \times \frac{5}{1} = \frac{15}{1} \longrightarrow 15:1$$

This way, if we use a 10:1 ratio and another 10:1 ratio, we can get a 100:1 gear ratio.

The advantage of gearing is that you can either speed things up or slow things down. When you speed things up, you trade torque (the amount of rotary force) for speed, and when you gear down, you essentially trade speed for torque.

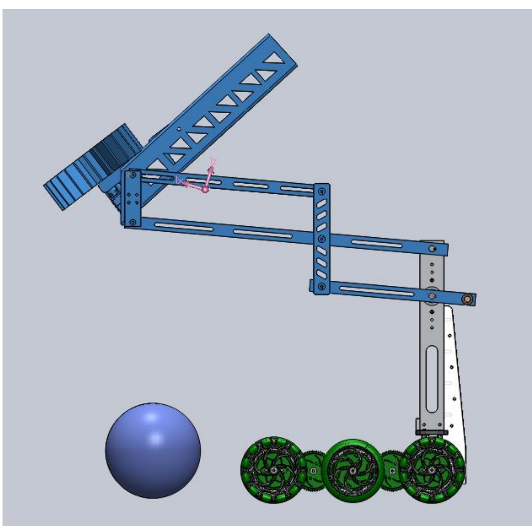
Torque is measured in inches*pounds, or inch-pounds. There are other units for torque too, such as Newton-metres, but we mostly use inches and pounds, so inch-pounds makes sense. Torque is basically a measure of how much rotary force or twisting force there is. As the units suggest, torque is dependent on how much force you push with and the length of the distance the force acts on.





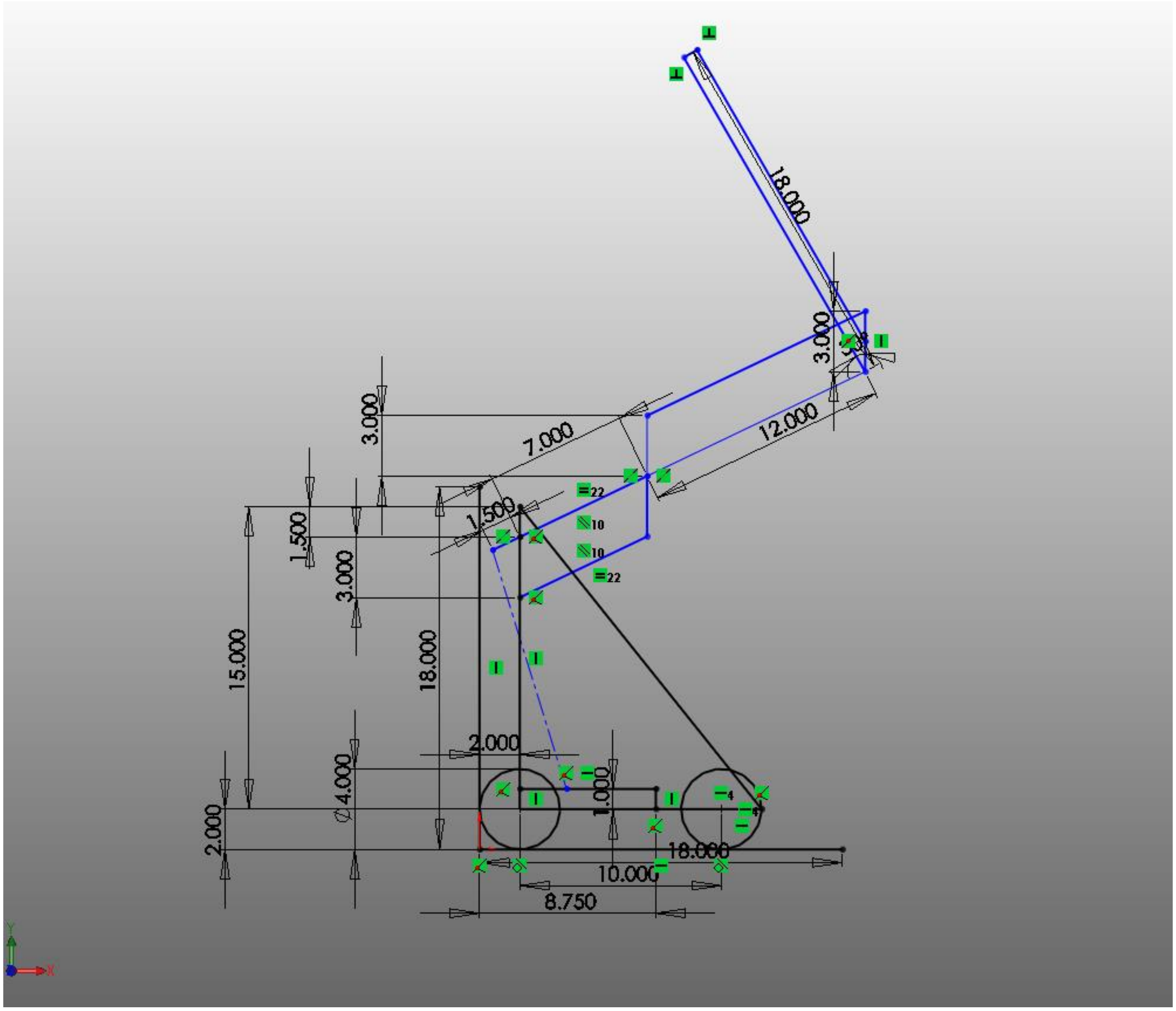
Similar to the idea of a lever arm, pulley, etc., if you push from point B and point A with the same amount of force, pushing from point B is going to yield a higher amount of torque on point O. This concept is very useful when we talk about how much force we need to rotate something with and how much of a gear reduction we need from the motor to get the desired amount of force.

A CIM, for example, has a free speed of 5000 rpm, but a stall torque (the amount of torque required to stop the motor from spinning or the maximum amount of torque the motor can deliver) of only about 20 inch-pounds. In other words, if you were to put 4 CIMs on the drive train geared 1:1 with 6 inch wheels (3 inch radii), you won't have much force available for moving the robot. The maximum pushing force of four CIMs is just four times the stall torque of one, which is 80 inch-pounds. The wheels will try to spin at 5000 rpm but will only have 80 inch-pounds of torque. On the surface of the wheel 3 inches away, it will only have about 25 lb. of force (1/3 of 80: Remember that 80 inch-pounds means with a 1 inch radius drum winding in a rope, 80 lb. is the max weight you can lift. With a drum that is 3 times as big, the lever arm is 3 times a big and is working against you, so you can only use 1/3 of what you could originally). A robot with a weight of 120 lb. that can only push forwards with 20 lb. of force presents a problem. Gearing down gives us more torque. While it seems like we are getting something for nothing, it is similar in concept to how a pulley works. You arrange the pulleys such that you have to pull in twice the amount of string but only have to pull half as hard. In the case of gear reductions, you have to spin the shaft twice as many times but you only need half the torque.



Here is a VEX robot made out of custom parts. Its lift uses a 6-bar linkage. Basically, it is a clever series of joints that keeps the end (the tray) parallel to the ground as the tray moves up and down. If it were just a single pivot and the tray was fixed to the arm, the tray would change angle relative to the ground as the arm moves up and down.

Below is a 2D sketch of the robot. Often, this is the first thing we do before designing anything. The 2D allows us to easily play with the geometry of the robot and tells us how big or small we need to make everything.



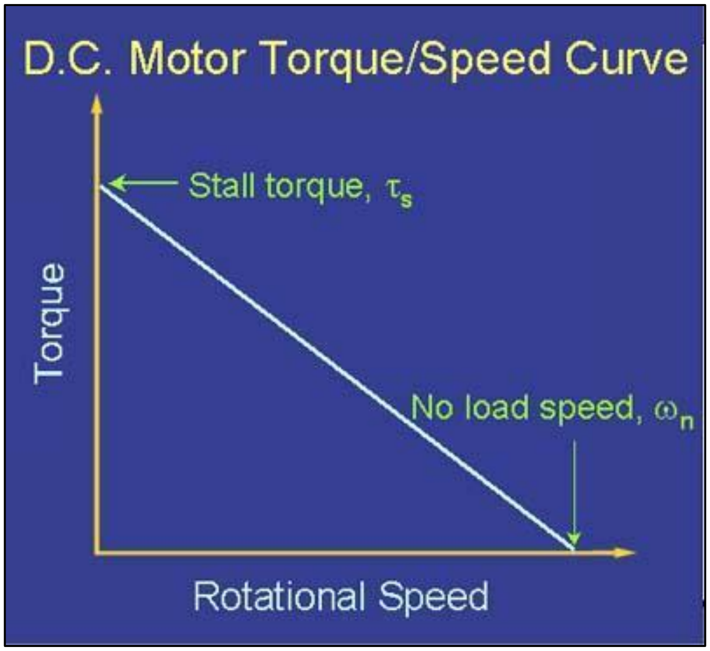
We know the total length of the arm is going to be around 19 in from the sketch above. We also know that the weight of each ball/barrel from VEX Gateway is about .5 lb., so in total the robot must lift 1.5lb (the tray can only hold 3 pieces).

Given this:

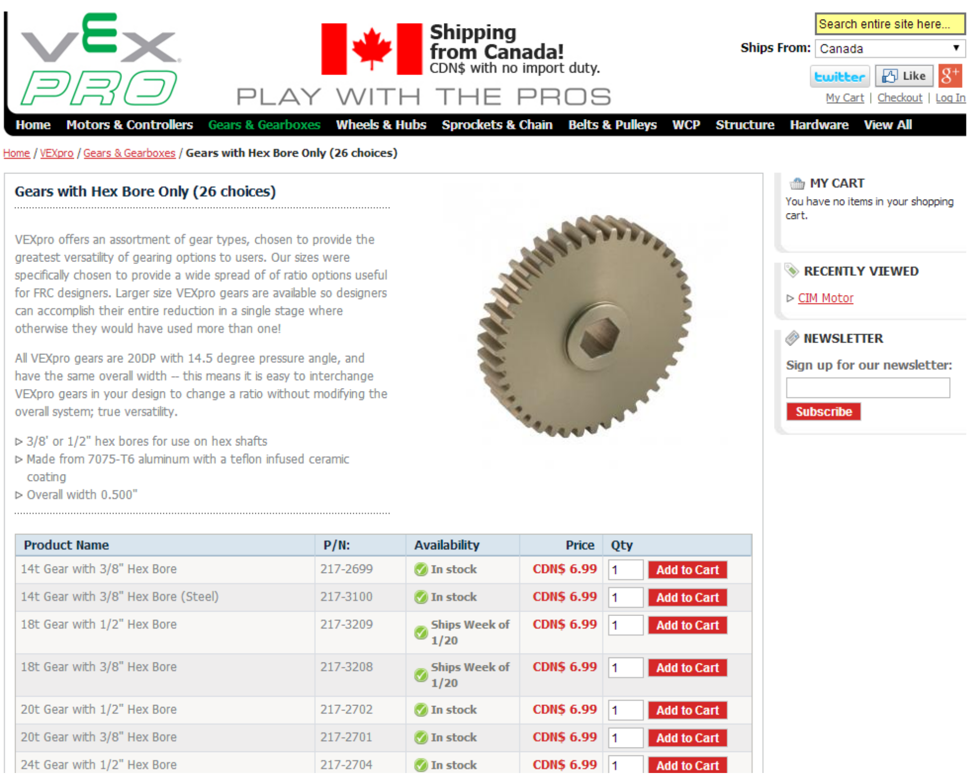
$$Torque = inch \; X \; pounds$$

$$T = 19in \; X \; 1.5 \; lb$$

$$T = 28.5in * lb$$



For now, we will assume the weight of the lift itself is negligible. If we dedicate 2 VEX 393 motors to the lift, each motor has a stall torque of about 13in-lb and a free speed of 100 rpm. Remember that stall torque is how much torque will cause the motor to seize up or stop spinning. A general rule of thumb, you want to run your motors at about 50% of stall torque, which is about 50% of speed. Speed and torque are not exactly linearly related but it is a good approximation. If you are running at about 75% of stall torque, you will be at about 25% of the free speed of the motor. Thus, if we have two motors and want to run both motors at about 50%, we have a total of 13in-lb coming out of the motors. However, we need about 30 in.-lb. to get the lift to move the game objects up. With a gear ratio of about 3:1, it will have about 39 in-lb. of torque (13*3). The speed of the lift will be about 50% of the motor's speed divided by 3 because we have geared it down 3:1. Assuming the lift must lift 90 degrees, that takes about half a second to one second (100rpm / 3 / (60 seconds / minute)), which is pretty good in this scenario.



This is a VEX robot, so we would have simply used a 12 tooth gear and a 36 tooth gear to create a 3:1 gear ratio.

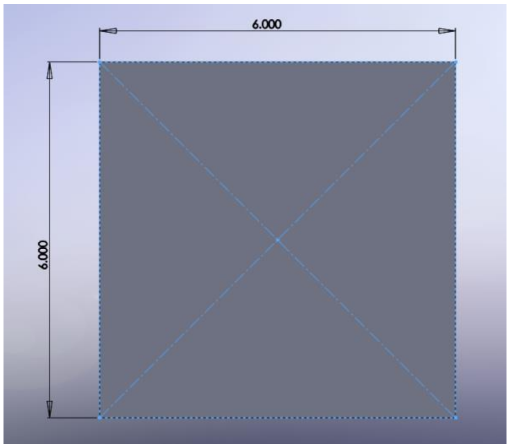
When we design mechanisms in FRC, we usually go to VEX Pro to get our gears, as they have a lot of options.

GEARBOXES & INTRODUCTION TO 2D SKETCHES

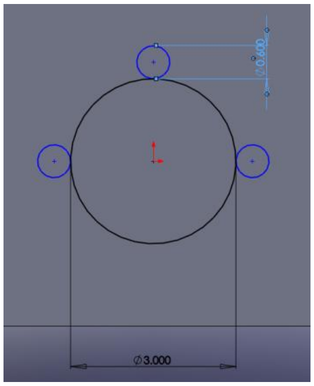
While you can often just buy a gearbox, sometimes a custom one better suits your needs. In this part of the tutorial it is recommended that you follow along with the instructions to create a gearbox for a drivetrain. Here we are going to use 6 CIMs (3 per gearbox).

An overall reduction of around 10:1 is a good amount for a drivetrain gearbox. You can go to: G:\Upper School\Robotics\Design and find the document called Drive Train Calculations and there are some parameters that you can play with, but for now we will assume approximately a 10:1 ratio. Go to the VEX Pro website (or the design library and find a matchup of gears that will get you around 10:1. In this example, we will use a 12:60 ratio followed by a 24:50 ratio to give an overall reduction of 10.4:1. The gears you choose don't really matter, however depending on what type of space you have to work with, you may have to use bigger or smaller gears and fewer or more stages.

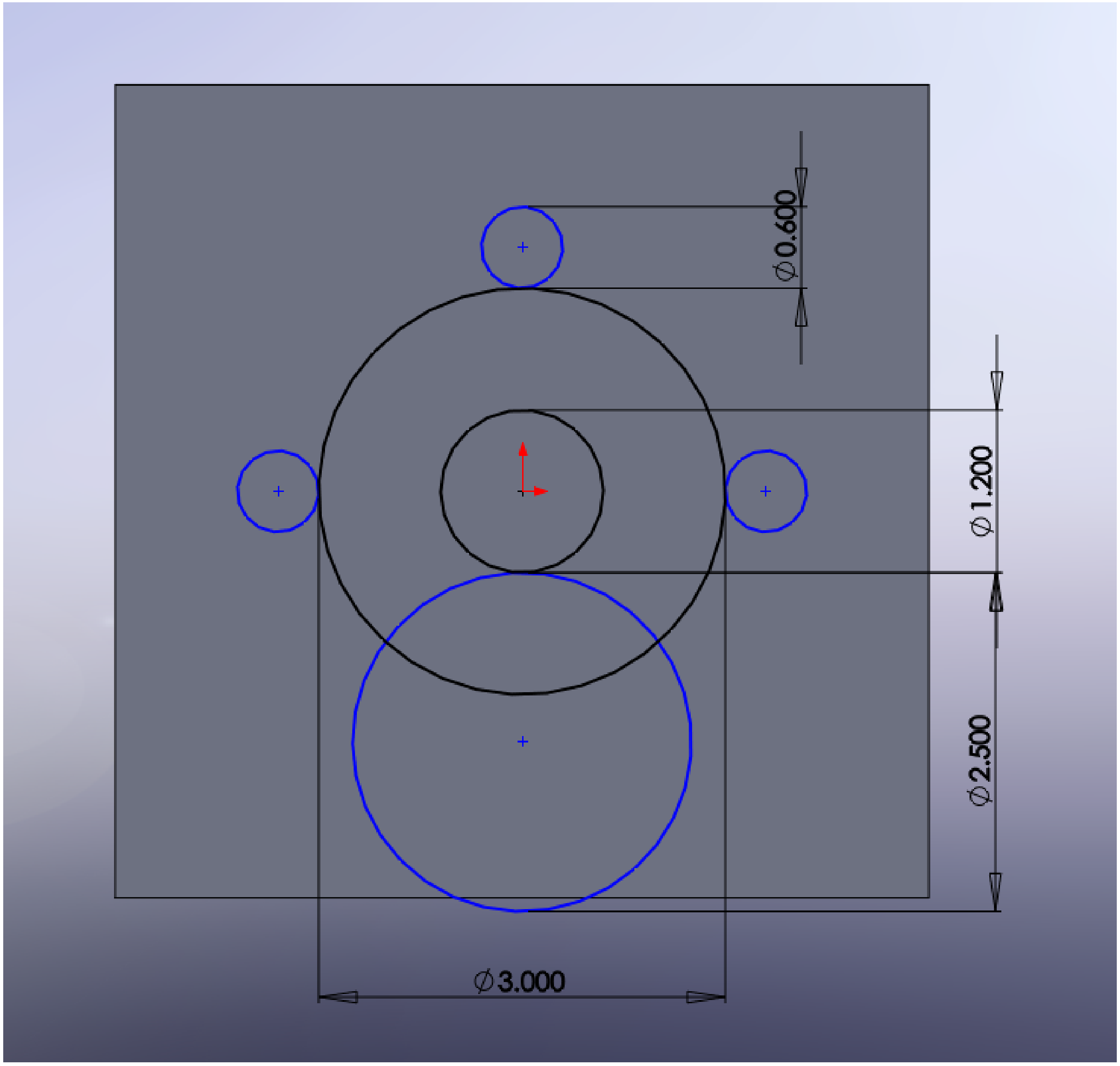
Start by drawing the side plate. You can start with an arbitrary size. It is a good idea to start with the origin in the centre.



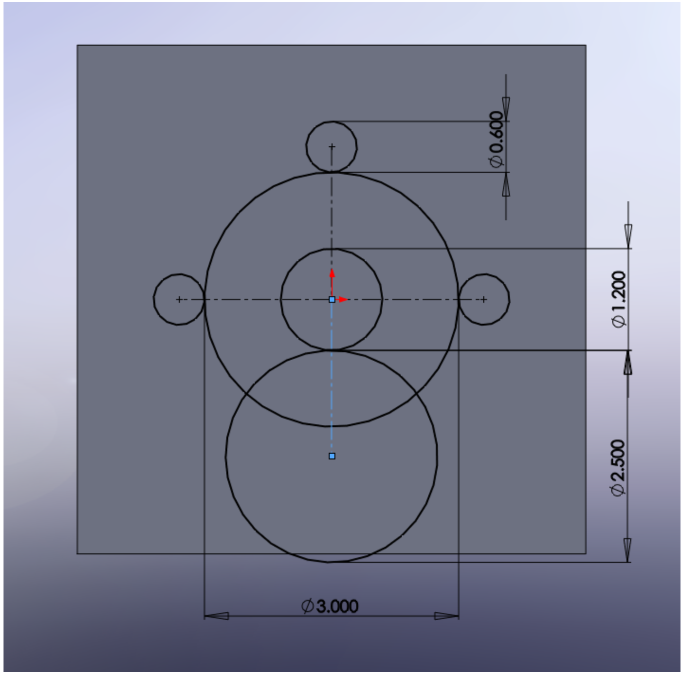
Before we start making the gearbox itself we are going to make a 2D sketch of the layout of the gearbox. This will come in handy later. Make a new sketch on the face of the part.



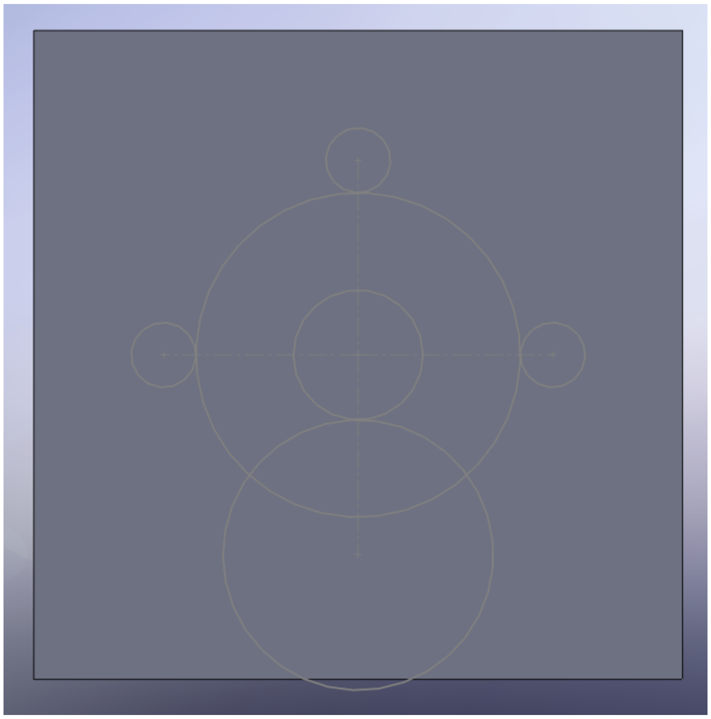
Represent each gear by its pitch diameter. The middle circle represents the 60 tooth gear and the 3 outer circles are the 12 tooth gears to which the CIMs are attached. Make the 12 tooth gears tangent to the centre 60 tooth gear. Ignore for now the fact that the gear is off the plate.



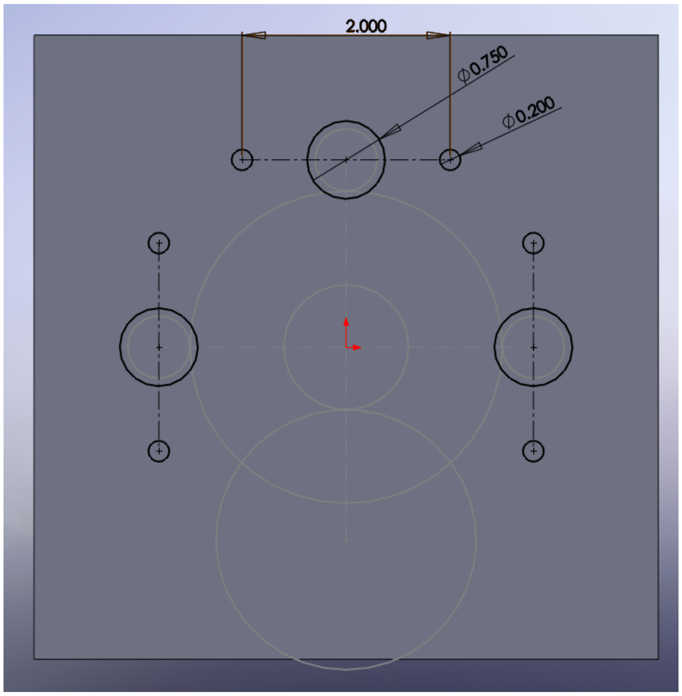
Next add the 24 tooth gear and make it concentric with the 60 tooth gear (concentric because they share the same shaft) and the 50 tooth gear tangent to the 24 tooth. Now you have added the second stage of the gearbox.



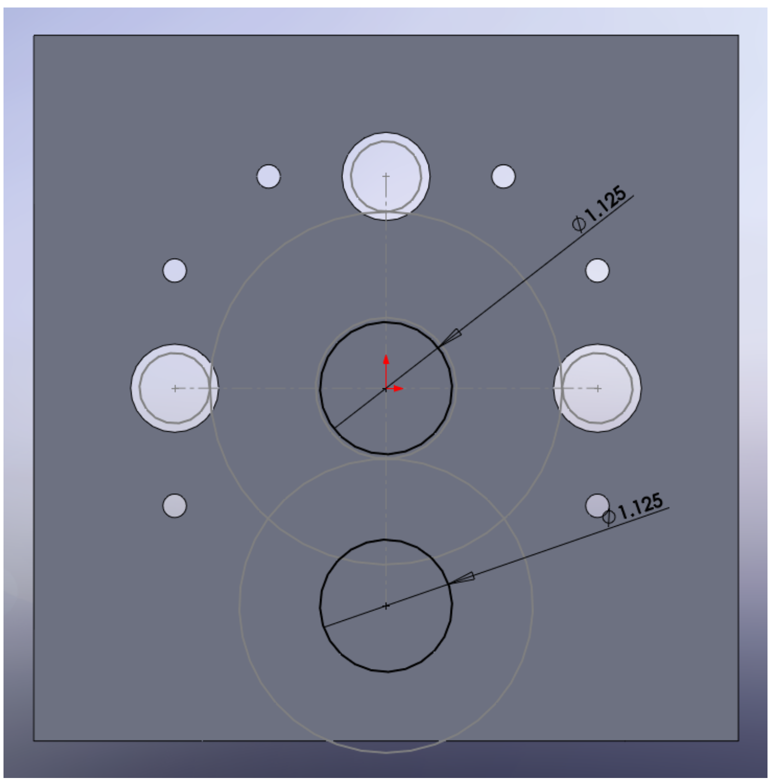
Fix the location of the gears and then close the sketch.



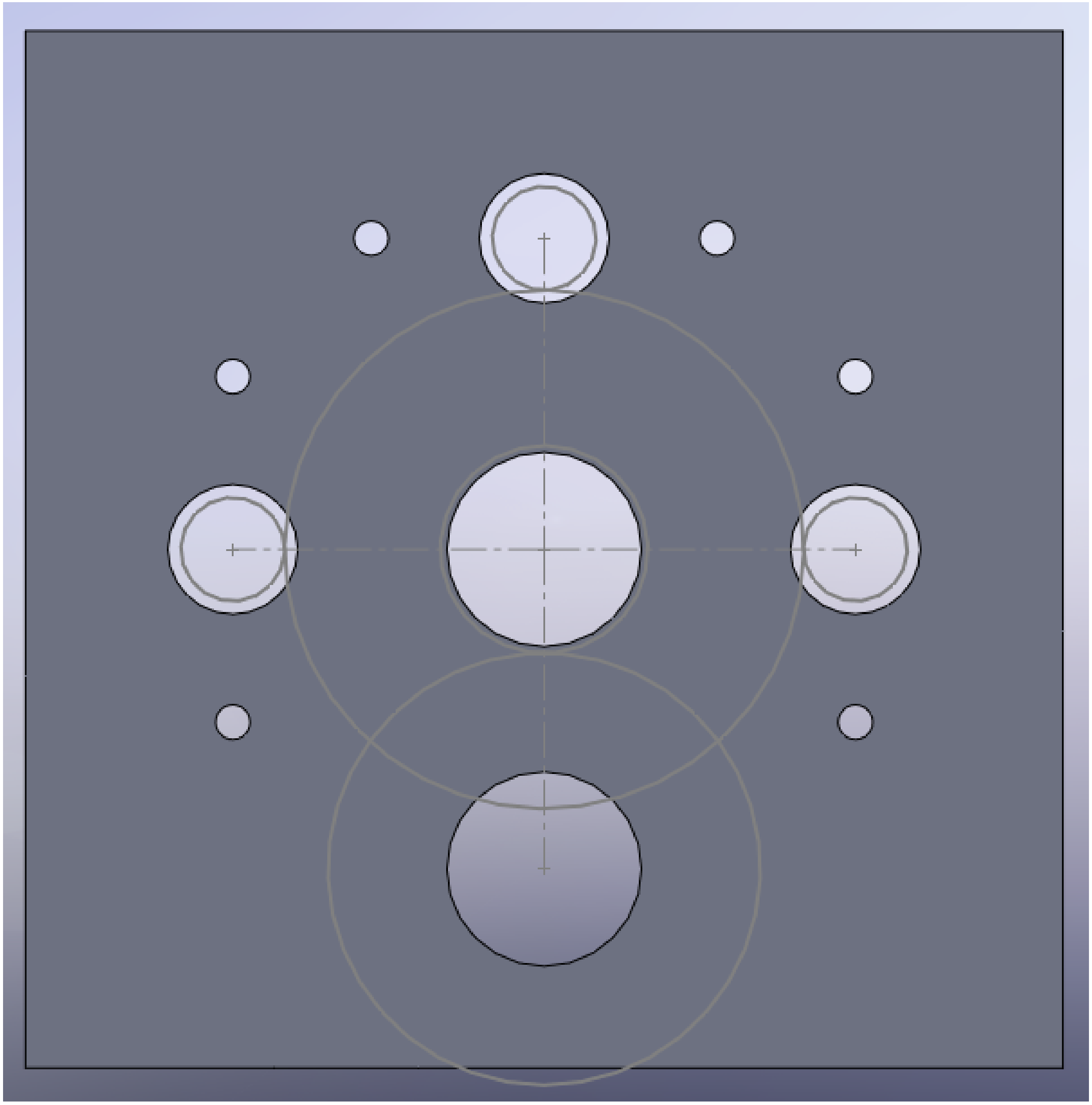
Now you have the layout of the gearbox drawn onto the face of the plate. Now, when you want to make holes for the bearings, you can reference this sketch. If you shift anything around, edit the layout and everything else will change with it.



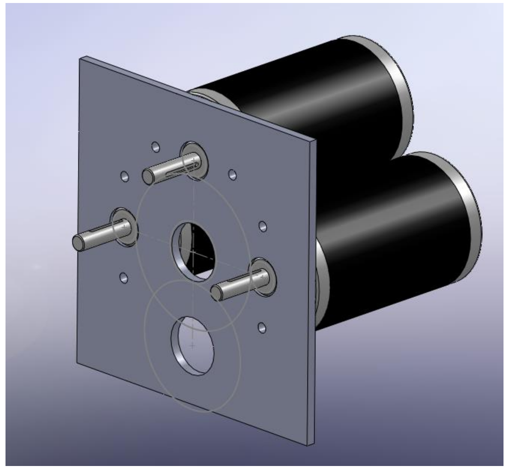
Make a new sketch on top and add a mounting feature for the CIM. Do not dimension the location of the holes. Reference the hole position to the location of the original sketch. Cut these holes out.



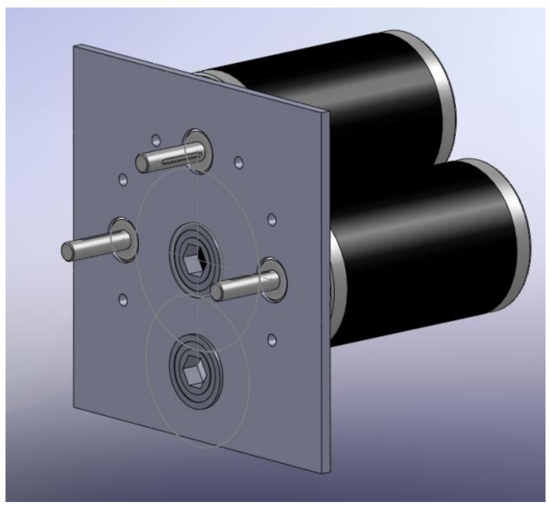
Make another sketch on top and make holes for the bearings. Cut these holes out too.



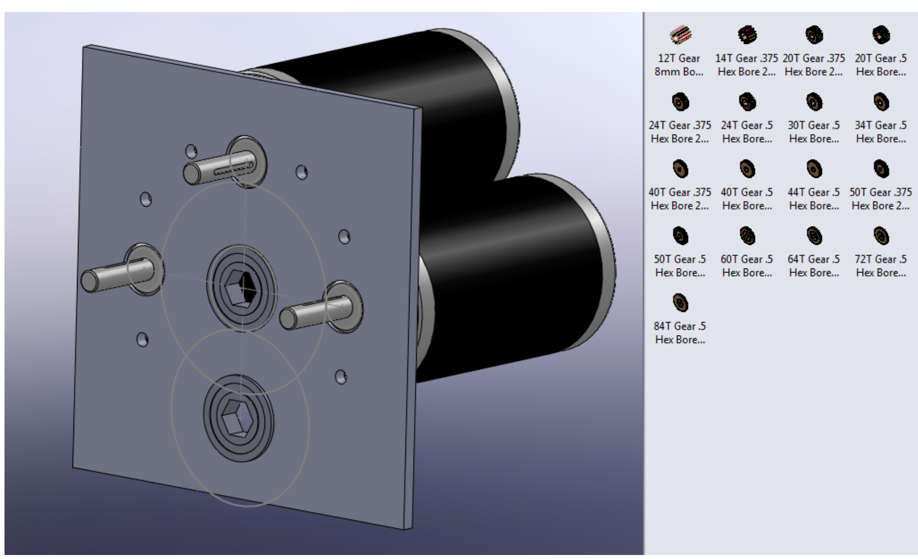
The part should look like this now. Save it and make a new assembly with it.



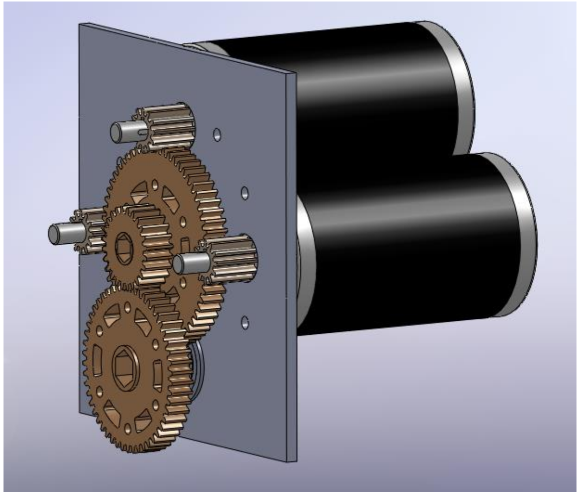
Mate the CIMs onto the plate. It should look like this.



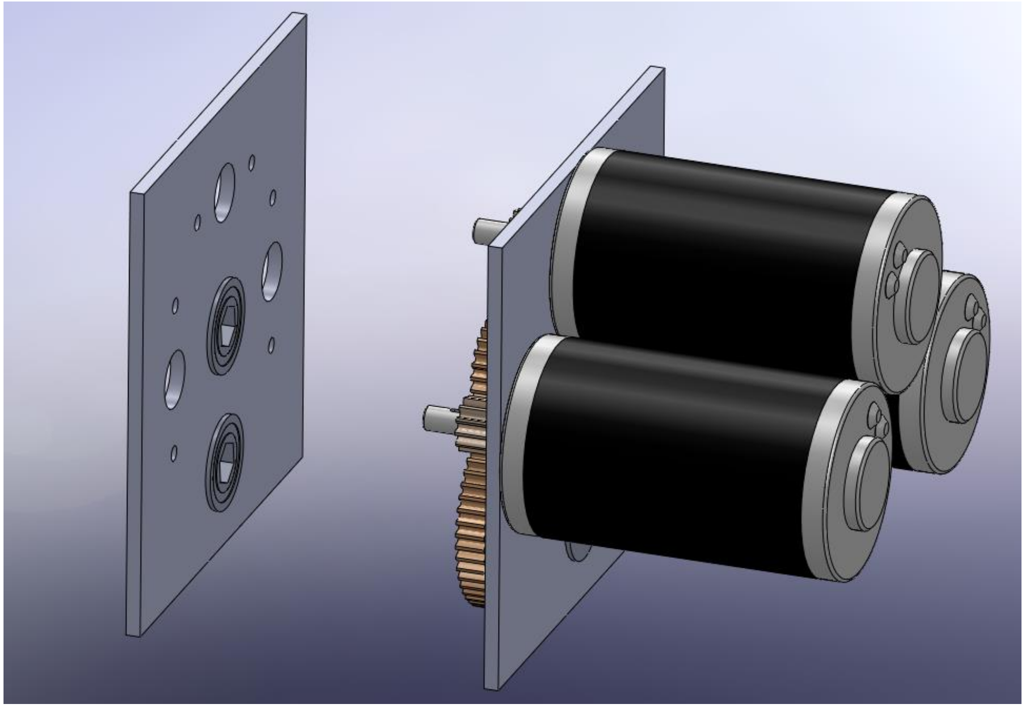
Put in two .5 hex bearings into the plate. Put the flanges on the inside; you will see why later.



Open up the design library and find the 12 tooth CIM gear. Put 3 of them on the 3 CIMs and add in all the gears such that it looks like this.

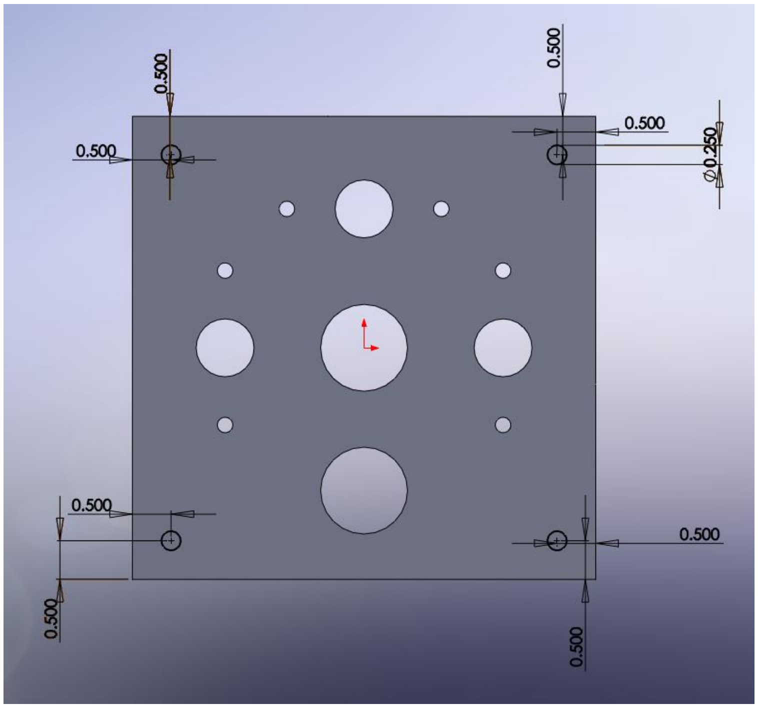


Don't worry about the spacing and fact that half of the stuff is free floating; we will deal with that later.

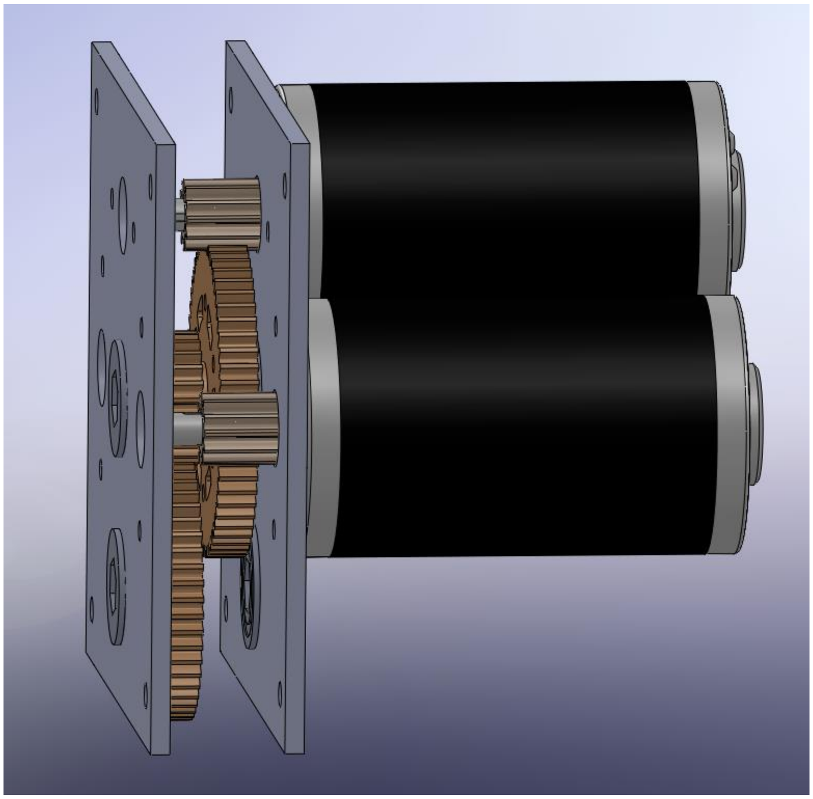


Put a second plate in (the same one). Sometimes you will have to make a different part, but in this example we will be using the same plate. Put bearings in the plate. Place the flanges facing the inside.

Go back to the original part and add 4 holes in the corners for standoffs.

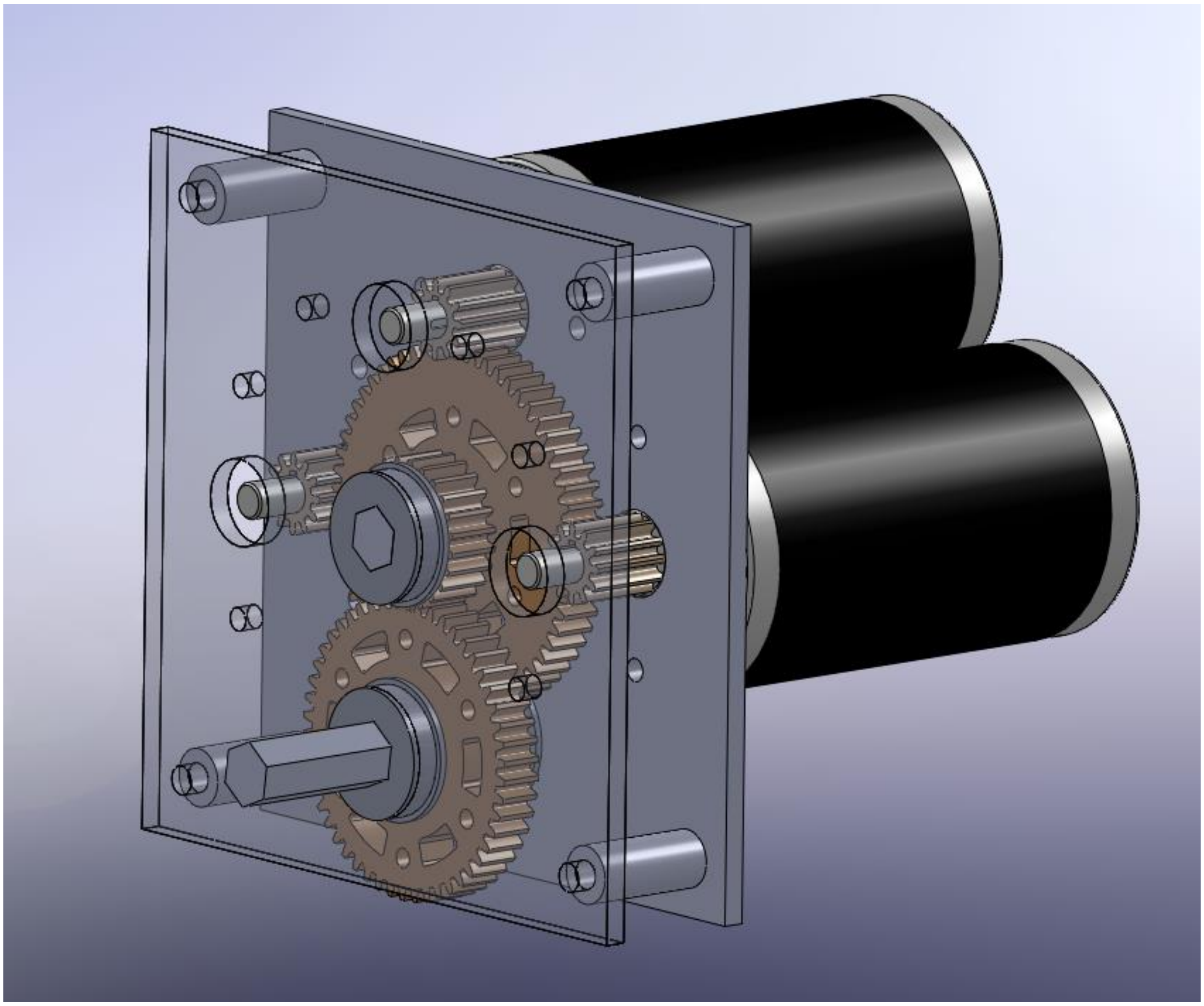


Mate the plate in so there is no space left over.



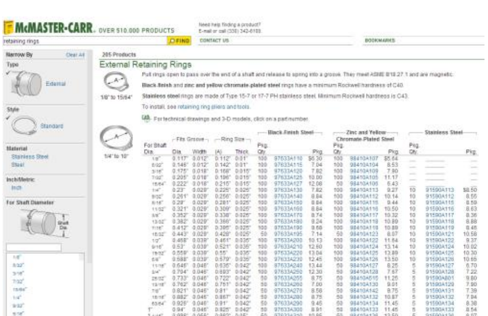
Now you have essentially all of the parts of the gearbox. Now add in some shafts and spacers and you are done…

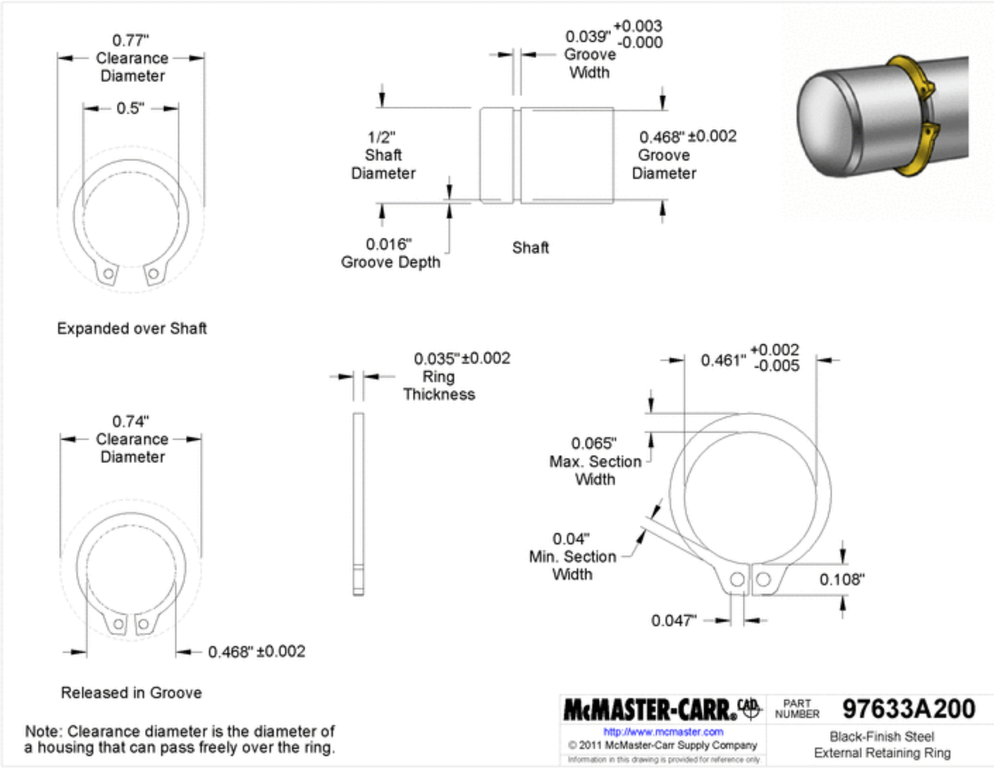
At this point you may think you are done, but you may have forgotten that your shaft can fall out and there is nothing keeping it in place.

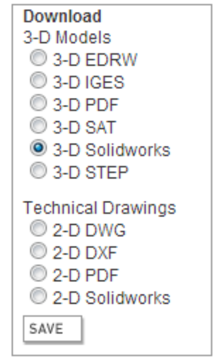


One of the ways we can solve this is by extending the length of the shaft slightly and adding retaining rings to the shaft. Basically, a retaining ring is a ring that fits into a groove that you machine into the shaft that prevents the shaft from moving.

You can find them on McMaster-Carr.



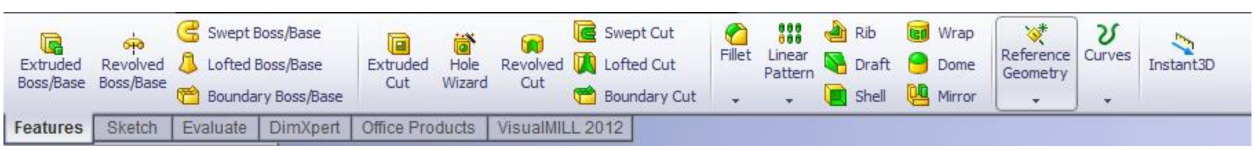




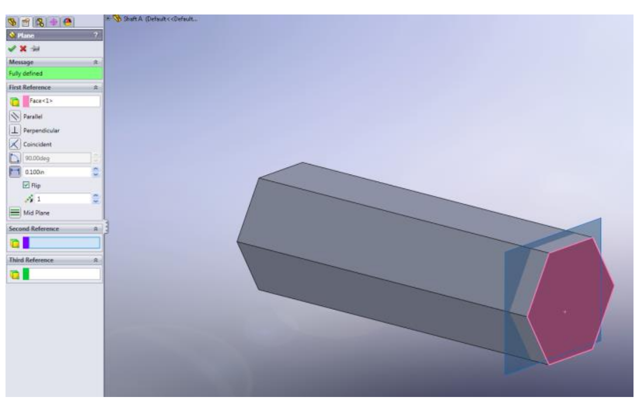
Click on the part number for the retaining ring size you would like. Then click on "CAD". It will bring you to this drawing. Here it specifies the size of groove that you should make on the shaft. You can also download a CAD model for it.

There are multiple ways to make a retaining ring groove; this is one way.

Go to reference geometry and insert a plane.



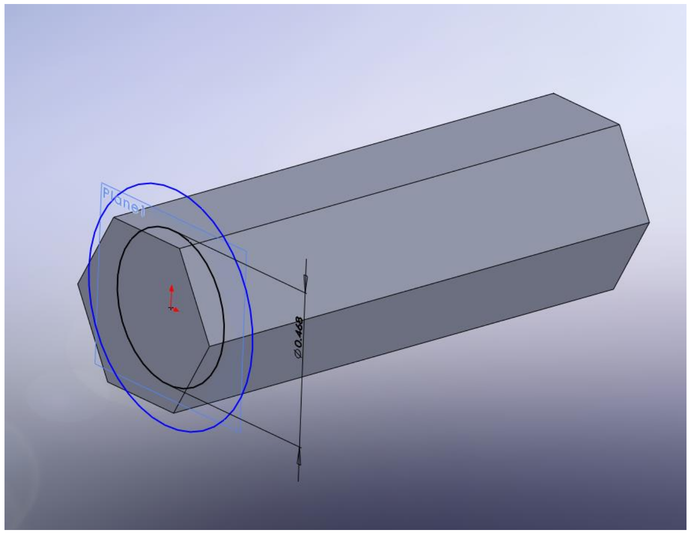
Click on plane. We are going to make a plane and cut the groove on that plane.



Set the distance away from the end of the shaft on which you want to place the retaining ring. You should probably leave at least 1/16 of an inch off the end of the shaft.

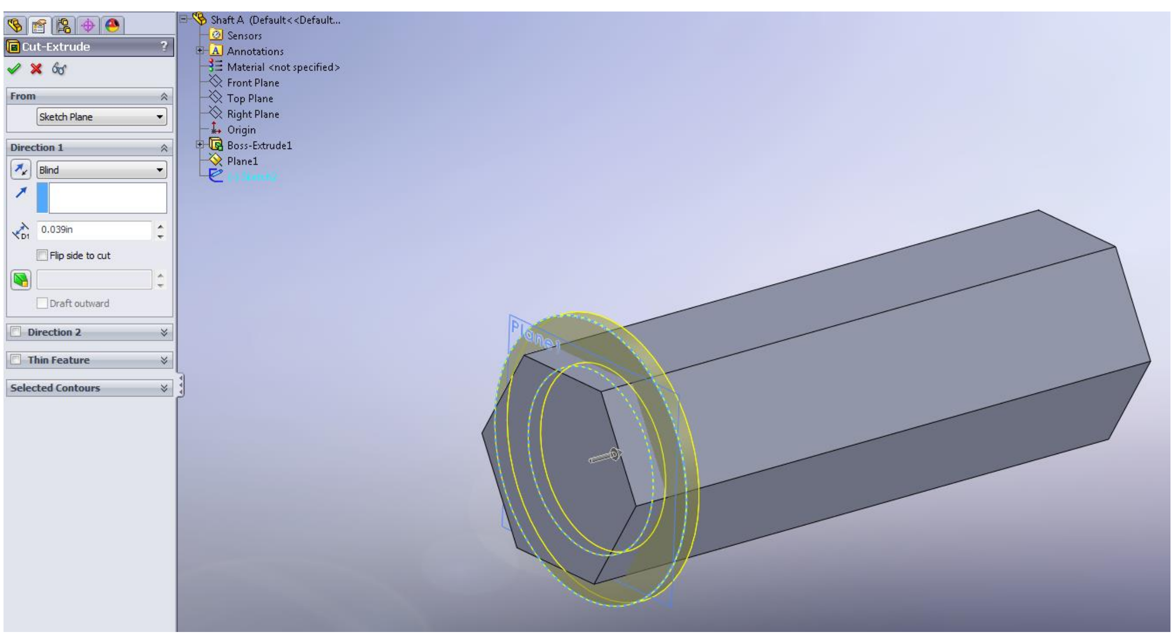
Click ok to make the plane.

Right click on the plane to make a sketch.

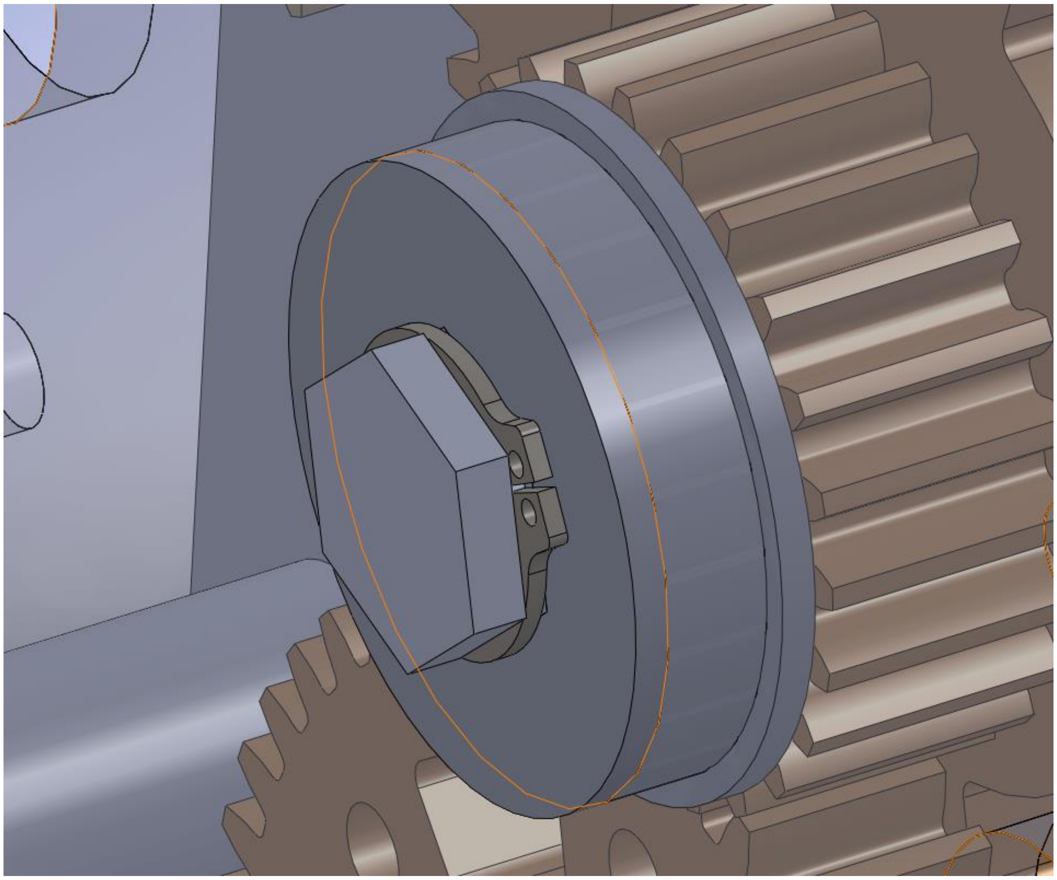


Sketch on the plane the inner groove diameter and a circle that is larger than the diameter of the shaft. The outer circle does not matter as long as it is bigger than the shaft.

Cut extrude the sketch.



Now you have a retaining ring groove.



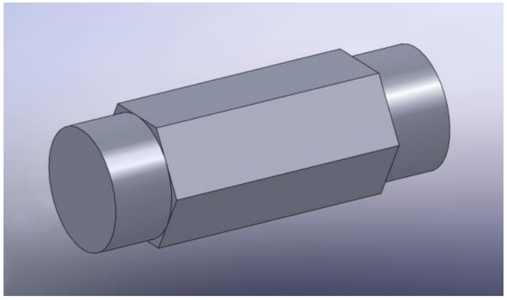
The end result will look like this.

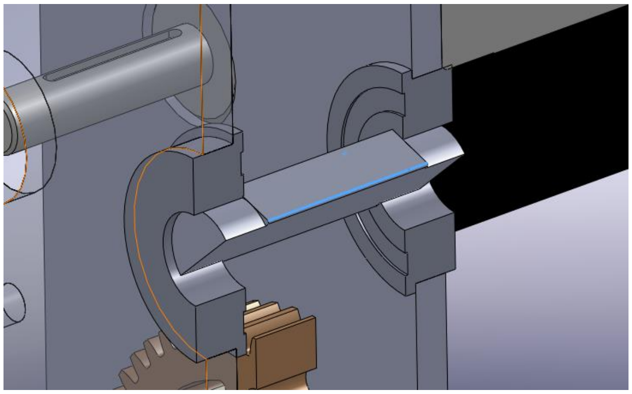
There is, however, an easier way to hold the shaft in.

Remember how you put the flanges in the inside. This is where it comes into play. Currently, you have "hex bearings" inside. These are bearings with a hexagon shape inside. Replace all of those bearings with round bearings for a 0.5 inch shaft.

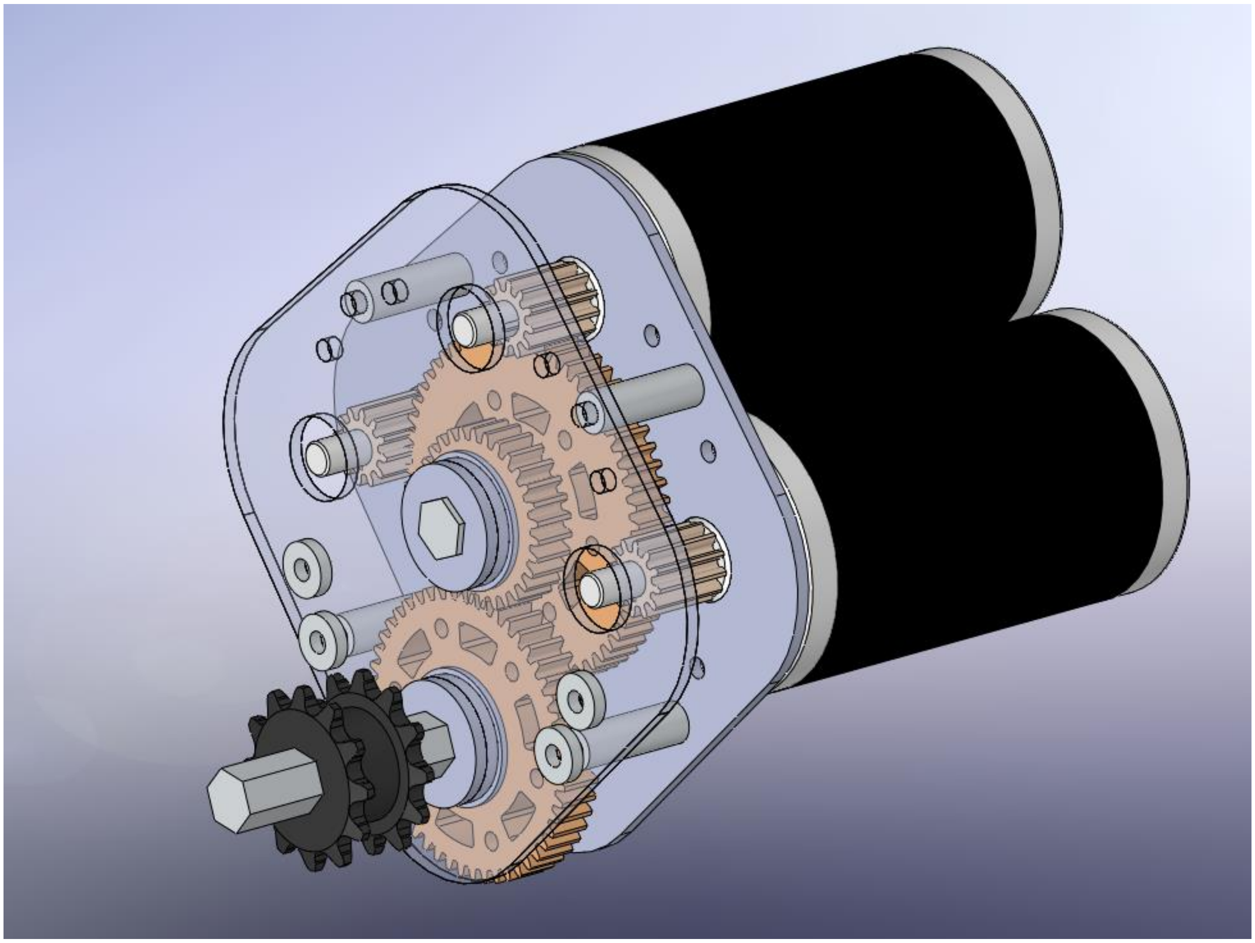
Instead of using a retaining ring, we are going to round off the ends of the hex shaft and use round bearings to keep the shaft from falling out.

Change the shafts so that they look like this:





Notice now how the “hexagon” part butts up against the round bearing keeping it from falling out. This method is often preferred as it doesn’t require additional parts (the retaining rings) and is easier to machine. Either way is fine though. Add some mounting holes and now you are done.



You can round off the corners to save some weight and make it look nice. Whatever you end up powering (in this case, a double sprocket) goes on the output shaft. You have now just made a gearbox.

DESIGN CHALLENGE (ROTARY)

A 10 pound linear lift needs to lift a 5 pound game piece. The lift is driven up on a belt run. Given 2 Mini CIMs, build a gearbox that will get the 60 inch lift up to the top as quickly as possible and calculate how long it will take to reach the top.

<u>Mini CIM Specs:</u>

Free Speed: 6,200 rpm (+/- 10%)

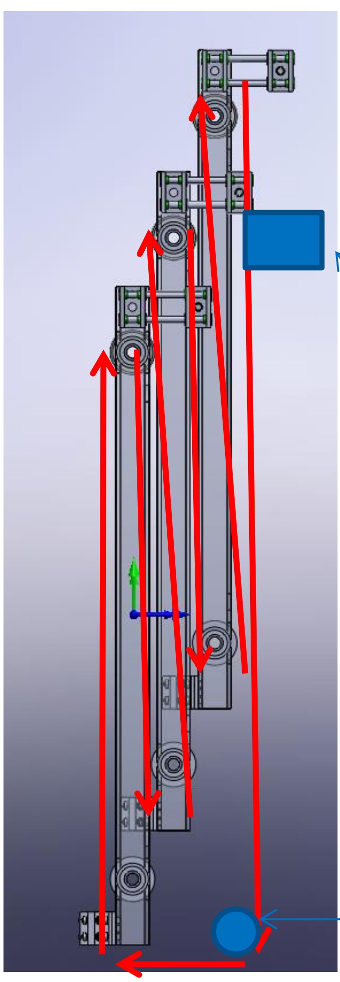
Free Current: 1.5A

Maximum Power: 230 W

Stall Torque: 12.4 in-lbs. [1.4 N-m]

Stall Current: 86A

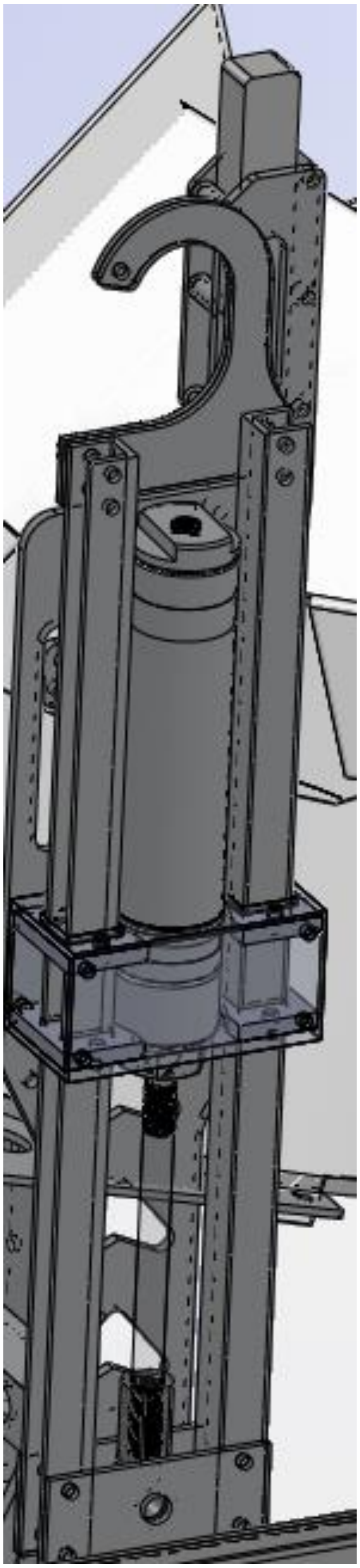
Mounting Holes: (4) #10-32 tapped holes on a 2" bolt circle



The type of belt that would be used would be 5mm (GT2). You can find timing belt pulleys: https://sdp-si.com/eStore/Catalog/Group/217

Note that they keep changing their website so this link probably won't work for long. The company is called Stock Drive Products.

LINEAR MOTION



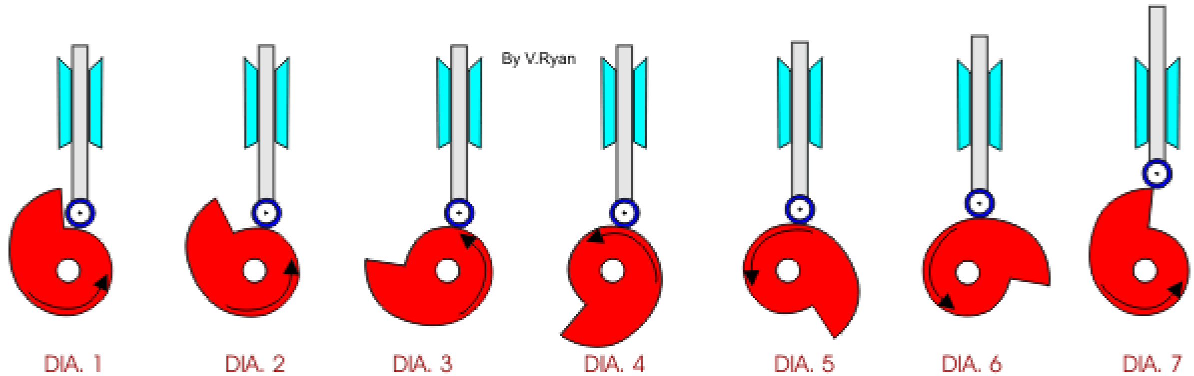
Motors deal with rotary motion: pivoting arms, spinning wheels, etc. While it is possible to go between linear and rotary motion, it is often messy and inefficient. Linear motion in general is usually harder to design with but sometimes comes with benefits. Most linear motion is generated by pistons, but mechanisms such as "snail cams" and racks and pinions can be used to take a motor's "rotary" force and convert it to a linear movement. Typically, you will need some sort of a "linear bearing" to guide the thing in place. This can range from anything from an Igus rail (http://www.igus.com/), to a drawer slider, to little plastic rollers. We usually don't deal with linear motion that much, but the telescoping arm we used for LogoMotion (2011) and the 10 point hanger from Taz, (2013) are good examples of linear movement. The general rule is plastic on metal, metal on plastic. You don't want metal rubbing against metal. We typically use Delrin, a low friction plastic. VEX bearings are made of this and it is a relatively cheap and durable plastic. Teflon is nice but expensive. ABS isn't bad and Lexan isn't too good but will do for cases where you don't really care how smooth it is. Of course, you can use perpendicular ball bearings but that often magnifies the size and complexity.

The 4 light grey blocks are Delrin pads cut from a 5/8" sheet and allow the c-channel to slide up and down freely. You can see how it would have been much more difficult to fit a bunch of ball bearings into this housing. Also, when the two pistons put out a combined force of 200lb, the friction of the Delrin pads is negligible. That being said, you still want the mechanism to move smoothly up and down. Keep in mind that when designing, you should add a few thousandths of an inch tolerance so that it is not super tight. In this case, we added .010 of an inch to the C channel profile to give the c-channel so wiggle room.

Most of the time, linear motion will be powered by pneumatics. However, cams and racks and pinions are also fairly common.

SNAIL CAMS

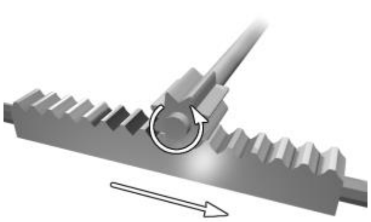
Below is a diagram of a snail cam.



As you rotate the red piece counterclockwise, the follower arm is pushed up until it hits the highest point at which point it drops back down to the starting point. This mechanism is particularly used full for reloading and is often used in kickers, catapults, shooters, etc. The "winding" of the cam effectively "cocks the shooter" (e.g. pulling back on some spring or elastic) and the "drop off" allows the mechanism to fire (e.g. letting go of the sling shot). This is very useful because now only one mechanism is needed to cock and release the mechanism and it is continuous, with no "rest period" of any sort.

VEX has one for the VRC and you can probably buy one somewhere, but you could also machine your own out of a thick sheet of plastic or metal.

RACK AND PINION

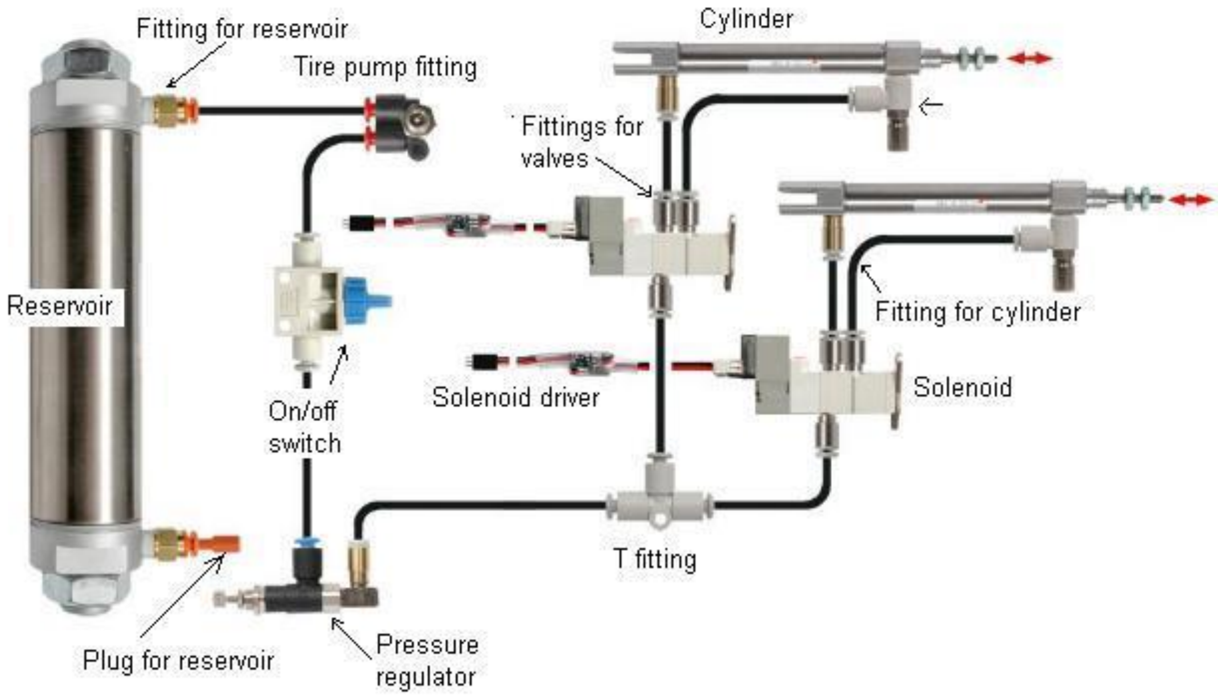


Think of a rack like a linear gear. Quite simply, rotating the pinion moves the rack up and down. Calculating the amount of force you get pushing from the rack is just the inch pounds of torque/radius of the gear. (Think back to the definition of an inch pound). Again, VEX has some rack and pinion kits. As for FRC we've never used one. They're usually not the most convenient option. A piston will usually suffice.

PNEUMATICS

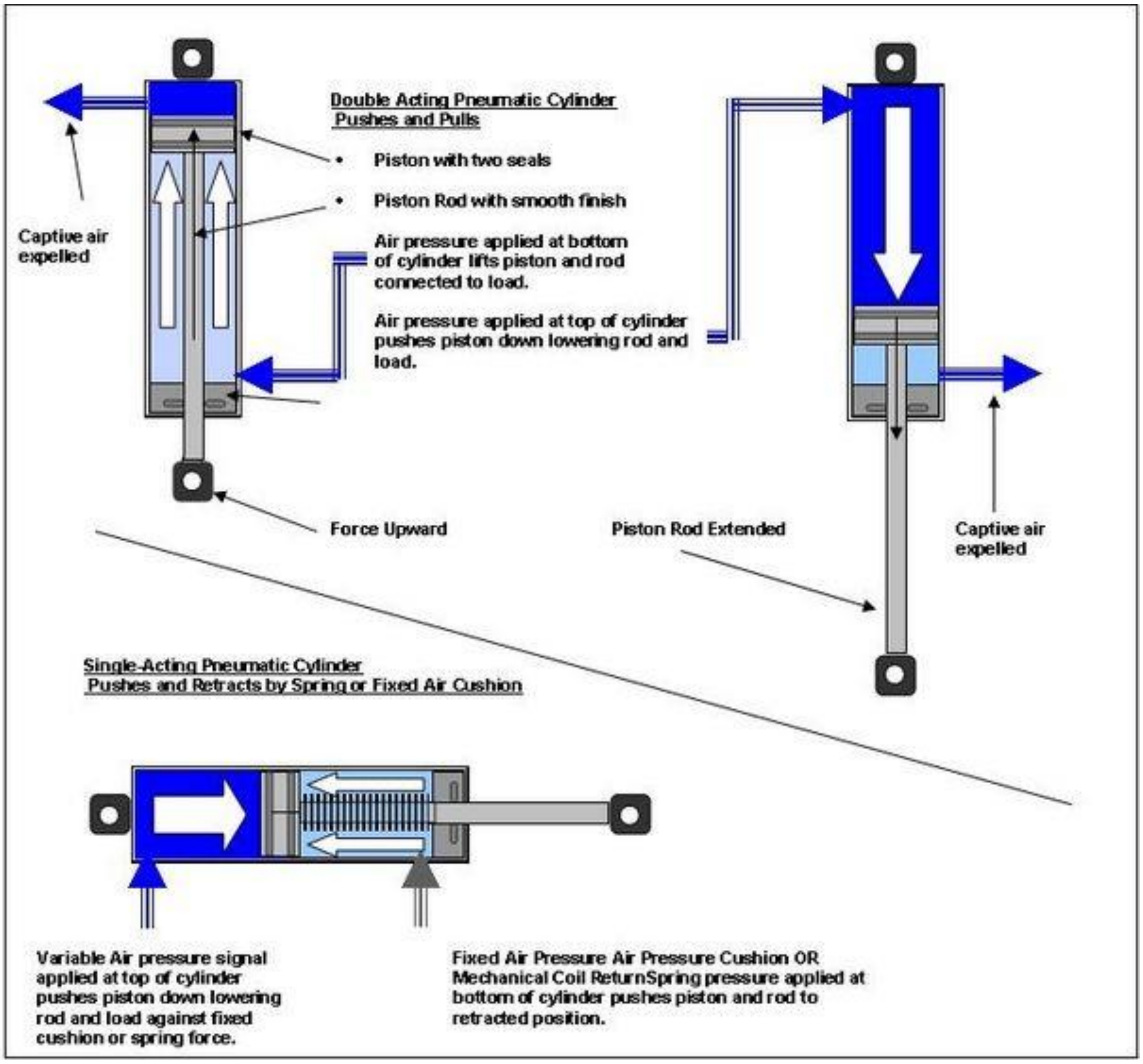
Pneumatics are basically the method of using pressurized gas to power a mechanism. We usually deal with it in the form of cylinders (often called pistons).

This convenient and over-simplified diagram helps give a basic understanding of how it works:



Compressed air is stored in the air tank (reservoir). We won't worry about the tire pump fitting. That is basically where the bike pump connects to so you can pump it up with air; in FRC we use a compressor. The on/off switch is self-explanatory. As for the regulator, (this one is a bad example) they usually have a gauge that you set to a certain pressure and it only allows through the set amount of pressure. You might store you air at 120 psi but regulate it down to 30 so only 30 PSI passes through to the cylinders. This both saves you air (as you are letting less air out) and is also a safety feature as sometimes you don't want too much force coming out of the cylinders. The solenoid is a basically the "on/off" switch of the cylinder. Basically, it controls the flow of air to either the top portion or bottom portion of the cylinder which determines whether it is retracted or extended.

This diagram shows double acting pistons (i.e. pistons that pull and push). There are also single acting pistons (pistons that only push and rely on a small spring to retract it). Double acting pistons obviously require more air (because they need air to pull the rod back in as well as push out), but as you will see later, they have certain advantages.

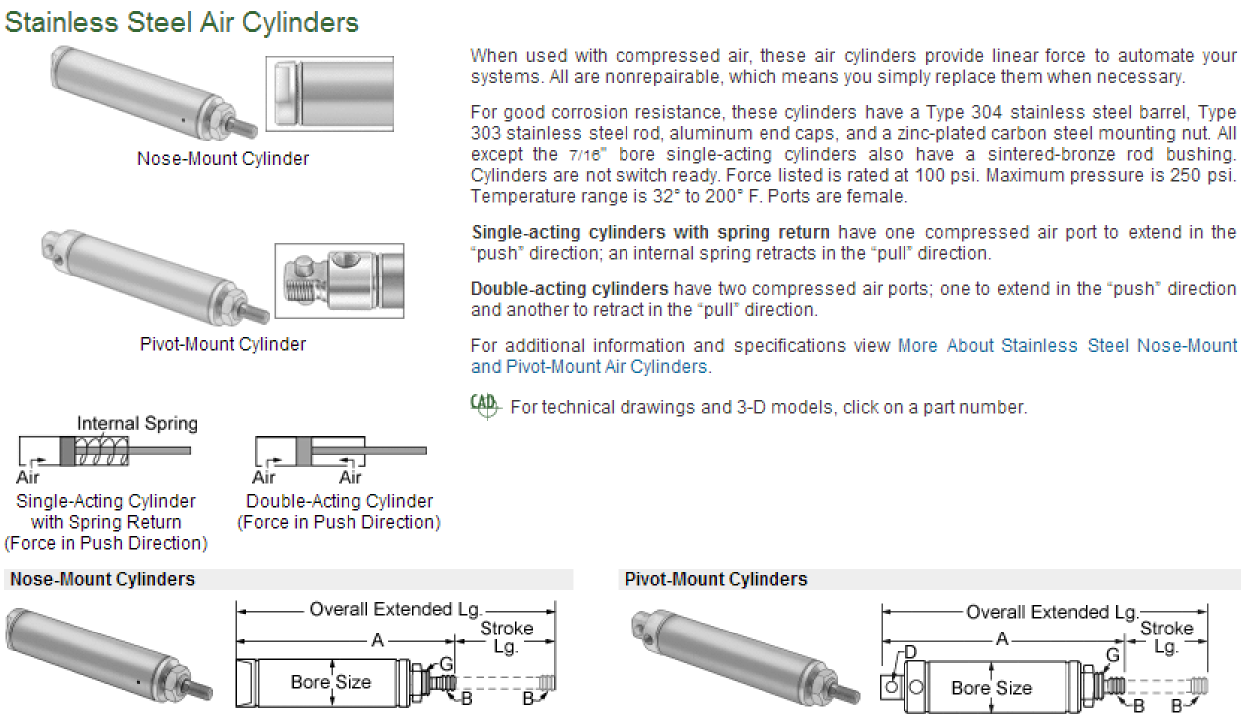


The term "psi" refers to "pounds per square inch". 1 psi means that for every square inch of surface area, the air is pushing back with 1 pound of force. In FRC we are allowed a maximum of 60 working psi. The air can be stored at up to 120 psi. Let us say we want to calculate the force of a piston with a 1 inch bore and ¼ rod that has a 5 inch stroke @60 psi.

Bore: Refers to the internal diameter of the piston which will be used to calculate force of the piston

Rod: The part that moves out; you will see later how this comes into effect.

Stroke: How far the piston extends.



Stainless Steel Air Cylinders

Nose-Mount Cylinder

Pivot-Mount Cylinder

When used with compressed air, these air cylinders provide linear force to automate your systems. All are nonrepairable, which means you simply replace them when necessary.

For good corrosion resistance, these cylinders have a Type 304 stainless steel barrel, Type 303 stainless steel rod, aluminum end caps, and a zinc-plated carbon steel mounting nut. All except the 7/16" bore single-acting cylinders also have a sintered-bronze rod bushing. Cylinders are not switch ready. Force listed is rated at 100 psi. Maximum pressure is 250 psi. Temperature range is 32° to 200° F. Ports are female.

Single-acting cylinders with spring return have one compressed air port to extend in the "push" direction; an internal spring retracts in the "pull" direction.

Double-acting cylinders have two compressed air ports; one to extend in the "push" direction and another to retract in the "pull" direction.

For additional information and specifications view More About Stainless Steel Nose-Mount and Pivot-Mount Air Cylinders.

CAD For technical drawings and 3-D models, click on a part number.

Single-Acting Cylinder with Spring Return (Force in Push Direction)

Double-Acting Cylinder (Force in Push Direction)

Nose-Mount Cylinders

Pivot-Mount Cylinders

With a 1 inch bore, the surface area of the plate (on the inside of the piston connected to the rod, i.e. the part that the air is pushing on so it can expand):

$$SA = \pi r^2$$

$$SA = \pi (1in)^2$$

$$SA \cong 3.14in^2$$

So we know the plate has an area of 3.14 square inches and we know there are 60 psi or pounds per 1 square inch. Given that:

$$F = Area \ \times Pressure$$

$$F = 3.14in^2 \ \times 60lb/in^2$$

$$F \cong 188.4lb$$

Let's say this was a single acting piston: would the force of the single acting piston also be 188lb?

Will the return force (the retracting force of the piston) be the same 188lb?

Yes/No?

The answer is on the next page.

The answer is, in fact, no. Why? The return spring (the spring build into the single acting piston to pull the rod back) offers resistance. When dealing with tiny pistons the force is negligible, but when dealing with larger pistons sometimes the return spring can be quite significant so you should factor it in. Single acting pistons will save you air but will have less force for the same size bore as its double acting counterpart.

As for the return force question, the answer is also no.

Remember that we are only concerned with the area of the plate (the highlighted yellow region) because that is the part the compressed part tries to push out to give the air more volume.

When the pistons extends, it has the entire surface to push up against, however when it returns it has less room because some is being taken up by the rod. We must factor this into our calculations.

Thus, the surface area is the area of the plate minus the profile of the rod:

$$SA = \pi {r_1}^2 - \pi {r_2}^2$$

$$SA = \pi(1in)^2 - \pi(.125in)^2$$

$$SA \cong 3.09in^2$$

Force is the same:

$$F = Area \times Pressure$$

$$F = 3.09in^2 \times 60lb/in^2$$

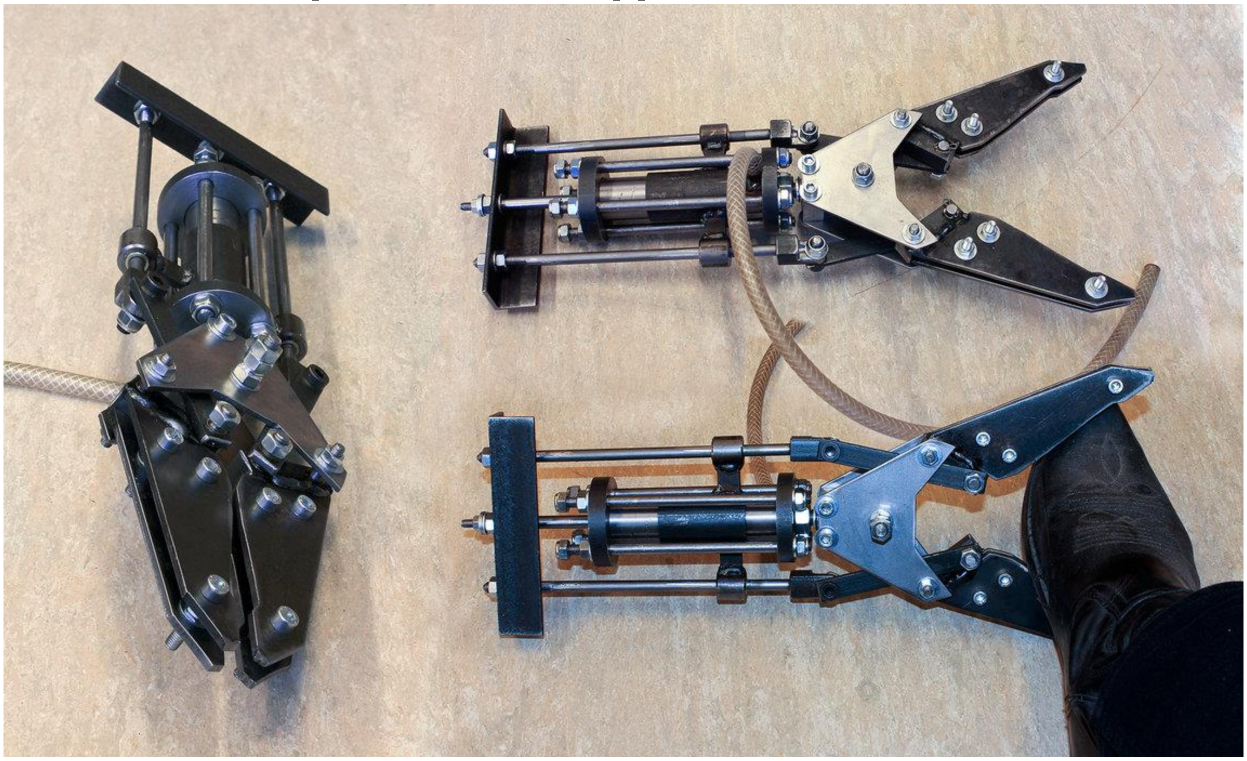
$$F \cong 185lb$$

In this case it was only a loss of about 3 lb, but when the size of the rod increases, the difference can be significant. Ever wonder why on the 2013 world champion robot the hanger pistons seem to be pointed downwards? This is so that the retracting of the piston actually brings the hooks up and the expansion, which has more force, lifts the robot. It is also why the piston is a double and not a single, even though it required very little force to bring the piston up and we only need force pulling down. This is because the force of the return spring is too large and we would not get enough force pulling the robot up.

DESIGN CHALLENGE (LINEAR)

In physics, you were probably told about something called mechanical advantage. The farther you apply a force from a fulcrum, the easier it will be to push, and the closer the load is the fulcrum the easier it will be to lift. So why exactly do excavators, dump trucks, bobcats etc. often look like they are doing the opposite? While heavy machinery runs off hydraulics (pressurised liquid) as opposed to pneumatics (what we use in FRC and sometimes in VEX; pressurised air) pistons can deliver massive amounts of force. Take the 2013 10 point hanger. Those two pistons combined have a total output of about 200 pounds whereas if we geared a CIM 100:1 we would get about 88.5 ft-lbs. of torque. While this isn't the best comparison, pistons can deliver a large force over a small distance while motors can deliver comparatively less force but for a much larger distance. Thus when it comes to heavy machinery, the pistons can deliver more than sufficient force to do the job, but the stroke of the piston is not nearly long enough to provide the desired reach, thus the pivot is placed such that you effectively get more stroke of the arm and less force. In general, we don't really care that we are losing some force because of the immense force we are going to get. With motors we "gear down" to provide more force but go slower. With pistons we go farther but get less force, effectively the same as if we were to "*gear up*". Pistons are nice when you want something to be binary (on/off and only two positions), and when you want a lot of force; which is sometimes helpful. Motors on the other hand can vary their speed and position, and while you could gear them down, to have the same great amount of torque it would probably end up being too slow. While motors might be better for an arm or intake roller, pistons might be preferred for an indexer or a gate.

For this design challenge you are going to build a pneumatic claw. How you do it doesn't matter, but the claw should clamp shut on a 1 inch steel pipe with about 100lb of force.



DESIGNING A DRIVE SYSTEM

When asked, "What is the single most important aspect of the robot?" naturally people gravitate to saying: shooter, intake, or some sort of game piece manipulation, often neglecting the single most important aspect of the robot: being able to drive. With the exception of some very special cases (such as if you were only going to try to hang in Ultimate Accent) without a good drive base, you can't score. Thus the drive system in almost all cases is not only the physical backbone of the robot, but all scoring is dependent on it working. Because of this, much care, and thought should be put in when designing the drive. Obviously you want it to be robust and reliable but at the same time you want to cut down on weight and space. There are also many options when designing the drive such as wheel choice and gearing to name a few. Designing one encompasses a broad range of skill and for 610 it often marks the transition from CADer to Designer. The following is a step by step tutorial for designing the drive for Taz.

This drive system performed exceptionally for us, literally carrying the robot onto Einstein (not to mention performing at two regionals flawlessly). It also had a power take off that we never got a chance to use, but it was "fun" to design and fit in. Again this is not the only way to this, it is just one instance of how we did it and it turned out well. You are encouraged to try out different designs.

The first thing we are going to do is decide on a few things. In the case 610's 2013 season we optimized for the distance between the feeder slots and the back of the pyramid where we planned to shoot. The numbers we came up with were a max speed of around 10ft/s and a time of about 4.5 seconds to get from the feeder station to the pyramid. The (relatively) low top speed (and 6 CIM drive) meant that we had a higher acceleration. This became a very big advantage as the majority of the time we were stopping and going short distances, not driving over large distances. It also came into play when we encountered defence. Pushing (and sometimes dragging) defence became a non-issue. The magic gear ratio that turned out so well for us was an 8:1 with a 4 inch wheel. We like it a lot and will probably stick with it.

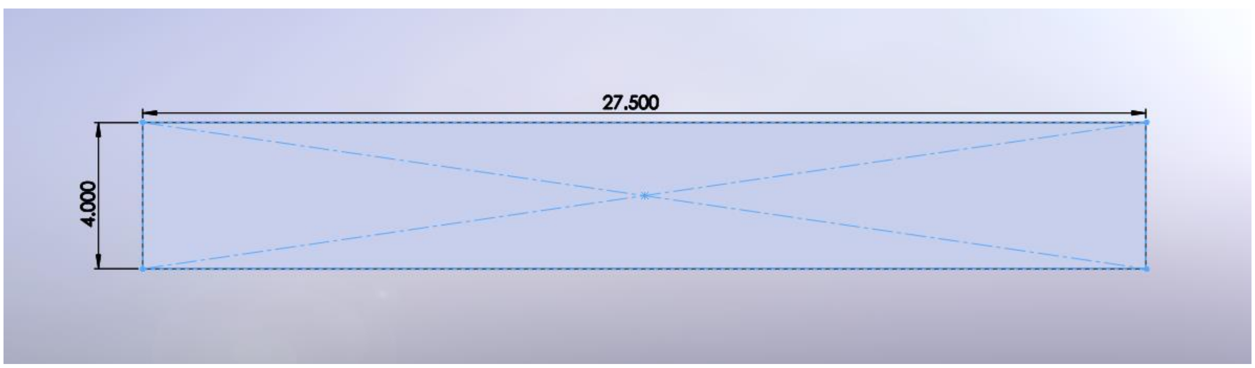
For the choice of wheels, we went with 4 inch AndyMark HiGrip wheels (the 4 inch version of the 6 inch KOP wheels from 2013 and 2014) as they proved to be fairly durable (we changed them once per competition). The reason for going with a 4 inch wheel was that smaller wheels require less reduction thus smaller gears and fewer stages. 6 vs. 8 wheeled drive prove to be a factor as usually it doesn't have much of an effect on performance, but we choose to embed the gear box into the drive rail (i.e. no separate gear box) and thus we only had room for 6 wheels.

The type of construction we decided to go with was a 3/16 aluminum plate sandwich for each drive rail with standoff s in-between. It is simple to assemble and has been very reliable for us through several years. The main reason for using 3/16 plate instead of sheet metal or using square tube was really dependant on the types of tools and machines we had/have. Sheet metal is no good for us because we can't bend anything accurately. We had a manual mill and a CNC router so it made a lot of sense to cut plates on the router. Since then, we have acquired a CNC Mill and as a result, some of our construction techniques have changed. In 2013 we also decided to go with a square frame as it provided us with the maximum internal area to work with. We also choose to go with deal axle and chain because it we have used it for several years and it has worked well, especially in combination with two side plates. The goal was to machine as little parts as possible. These are all things to consider and decide before you even think about getting to the real design. Similarly to writing an essay, if you don't have an outline you'll just be writing incoherent words.

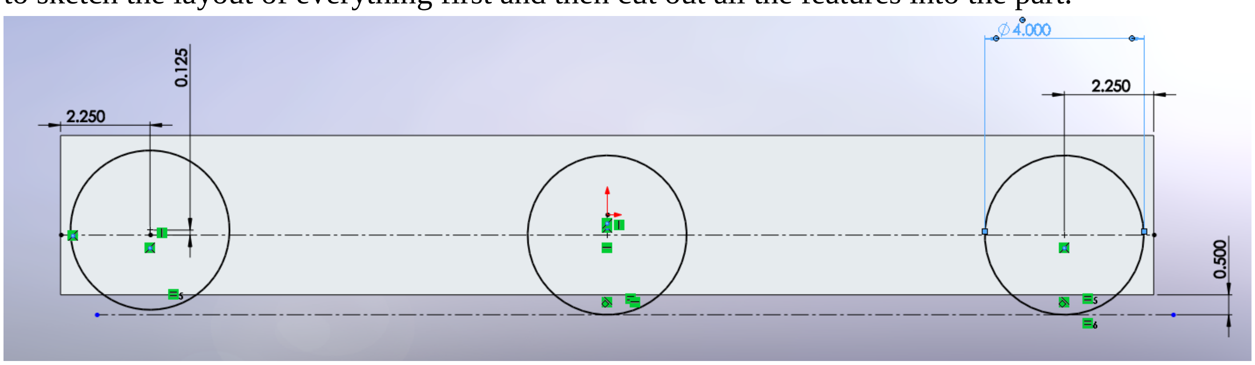
For this example we are going to build a drive system similar to the 2013 robot. By the end of this you should be able to design the picture on the cover page of the tutorial.

Now that we've decide on what we are going to use let's begin.

We'll start with a 4" bar x 3/16" thick x 27.5" long (just under the size of a maxed out square frame perimetre).

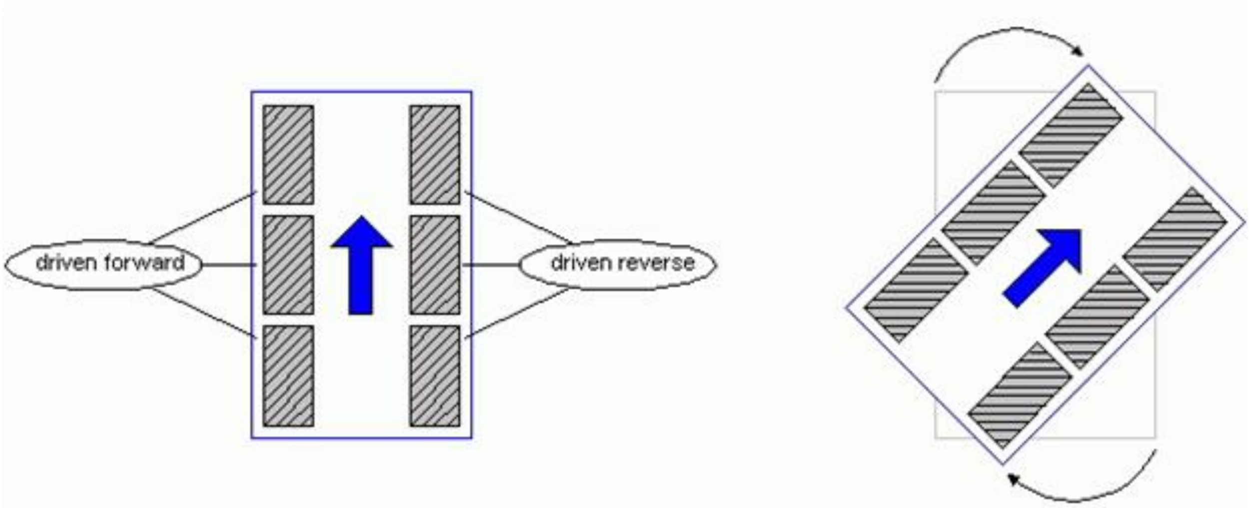


Make a new sketch on face of the part. Similarly to what we did with the gear box, we are going to sketch the layout of everything first and then cut out all the features into the part.



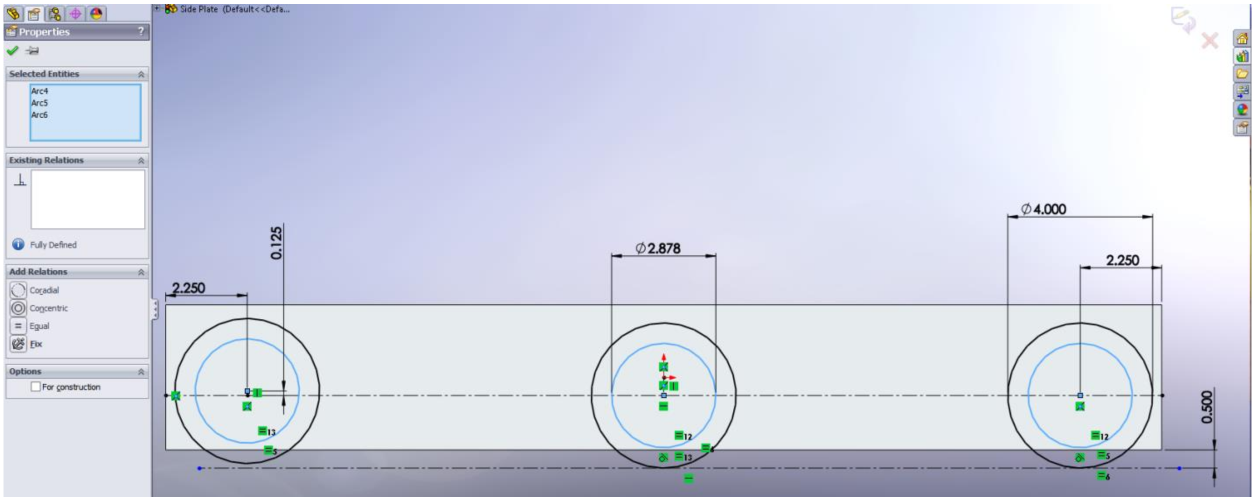
Starting with the wheel placement, the larger 4 inch circle represents the wheel. The line on the bottom represents the ground and the amount of "ground clearance" you have. On a flat field (no obstacles) you don't need much clearance because there is nothing to go over; you just want to make sure that you're not rubbing the bottom of the robot on the ground.

We are actually going to raise the front wheel 1/8” higher than the other two wheels. This is what is known as a rocker. The reason we do this is because if we had all 6 wheels on the ground and tried to turn, the centre 2 wheels would travel in a circle but the outer 4 wheel would have to skid sideways on a large arc. It required a noticeable amount of force to push the 4 outer wheels sideways and does result in a larger current draw from motors as they have to work much harder.



To make this less of problem what we do is raise or lower one of the wheels such that at any given time only 4 wheels are touching the ground. This makes it so the four wheels on the ground are much closer together and don’t have to skid as much. This begs the question “Why not just have a 4 wheel drive?” If we had a 4 wheel drive and the wheels were close together then the turning would be fine but the robot would be prone to tipping. If we just had the 4 wheels in the corner of the frame then we aren’t doing much better than the 6 wheel drive as the 4 wheels will still be forced to skid a lot. 1/8” is a good number to start with. It’s small enough to keep the robot from rocking significantly on the front to wheels and then back, but large enough that when we turn we aren’t tripping breakers.

Next we are going to add sprockets to the wheel. This is how power will be transmitted from wheel to wheel.

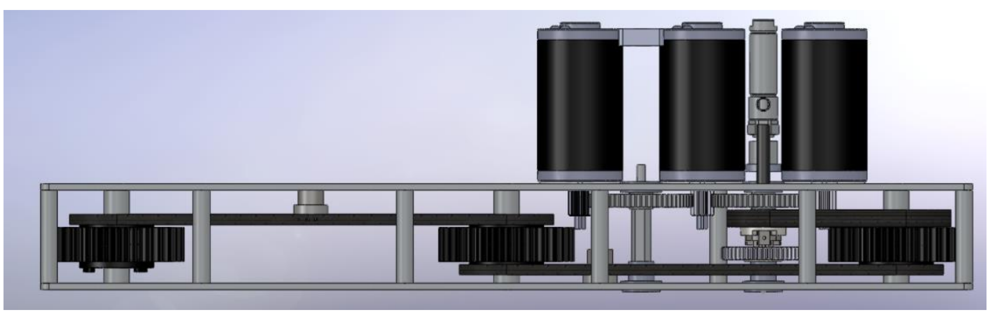


We are going to use a 24 tooth sprocket. Unlike gears, there isn't an easy way to get the pitch diameter and they are ugly numbers so just look them up. Go to Appendix D for the values.

Tip: instead of dimensioning all of the circles, select them all and set them equal so changing the dimension of one changes them all. This saves time and also cleans things up.

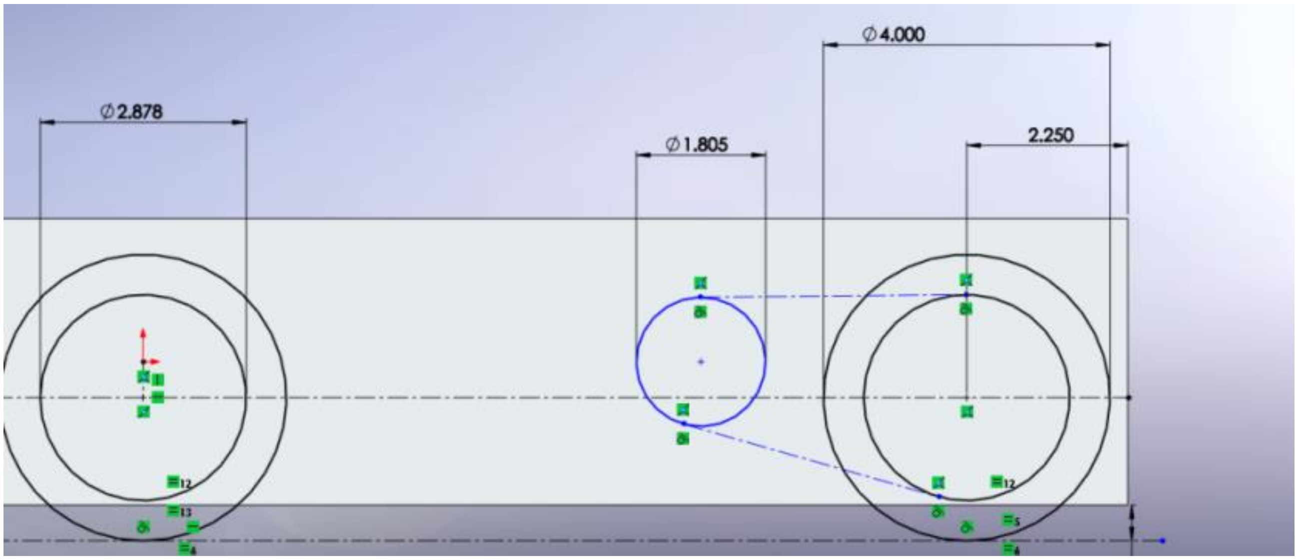
Side note: wherever possible uses larger sprockets. They have more teeth in contact with the chain, making it harder for them to skip/derail. With larger sprockets the chain also takes less force.

Now we are going to try to put the gear box in the drive rail. To try to understand what we are trying to do let's look at Taz.

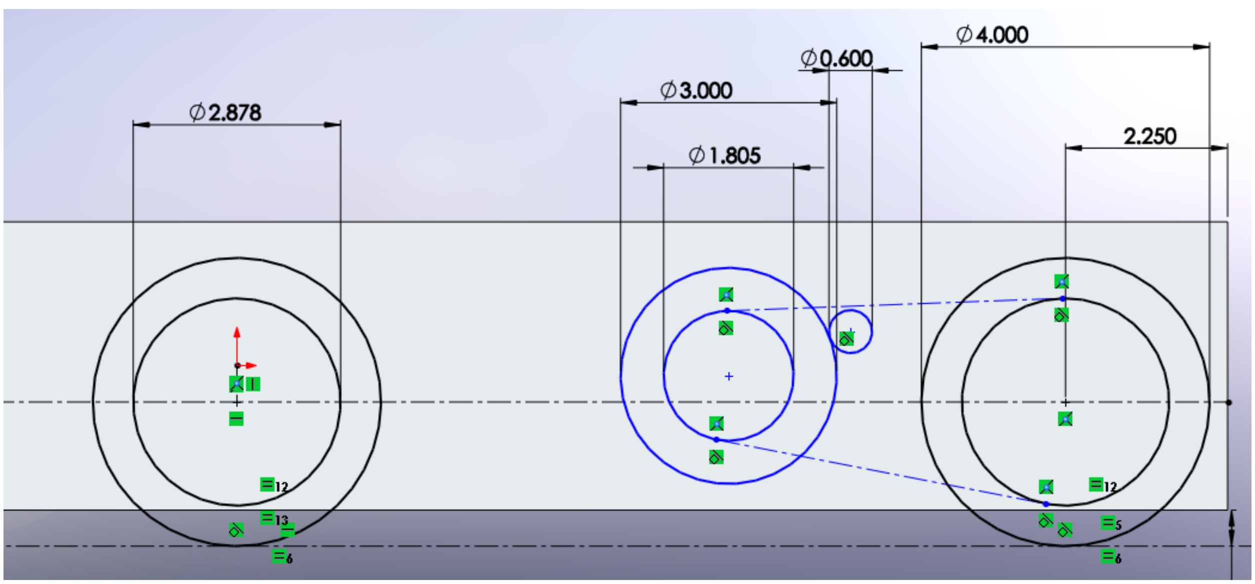


To do this and be able to power all the wheels, we are going to have to power the rear wheel, and have that power the centre wheel, and have that power the front one. Typically it is advantageous to power the centre wheel so that if a chain fails, you still have your centre wheel powered (in the case of rocker, the centre wheel will always touch the ground). In this case if we snap the chain going from the gearbox to the rear wheel we are going to have no wheels powered (hence that one linkage is made from #35 chain instead of #25). To simplify things a bit we aren't going to have a power take off in the gear box and we're going to use #35 chain for everything. The reason that this robot has 2 links of #25 is that it is thinner and weighs less. For this drive and your first crack at it we'll keep things simple.

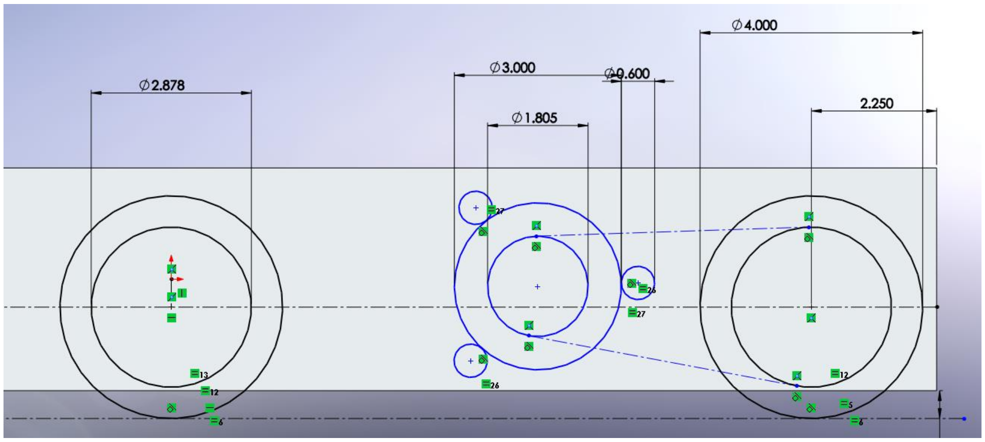
To achieve 10ft/s with a 4 inch wheel (remember bigger wheels travel further with one rotation thus need higher reductions to keep the same top speed) an 8:1 reduction is required. In order to save space and be able to fit everything into the drive rail, we are going to do a 12T to 60T gear reduction and 15T to 24T sprocket reduction from the gear box to the wheel. Go back to the section on gear ratios and reductions for a refresher on how we come up with these numbers. The two dotted lines represent the chain runs.



For now, we have arbitrarily placed the 15T sprocket. The 15T sprocket will be on the same shaft as a 60T gear. The 60T gear is driven by a 12T coming off the CIM.

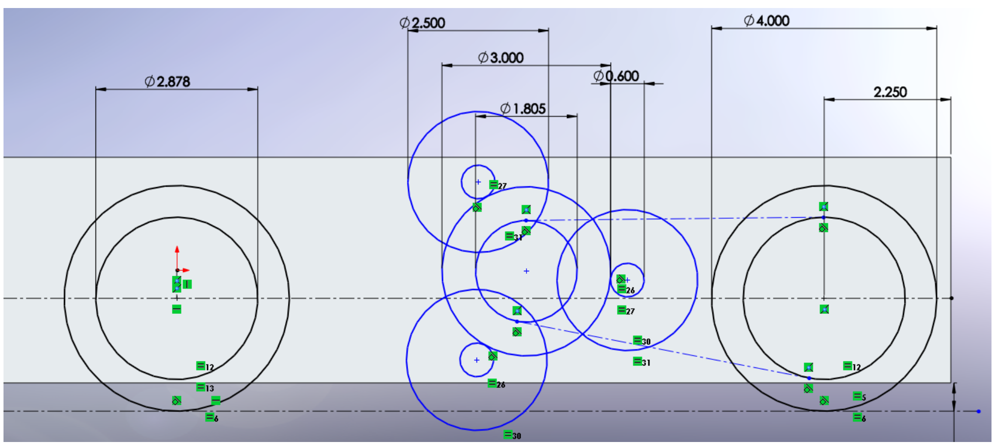


We want a 6 CIM drive so we need to find a way to attach 2 more CIMs.

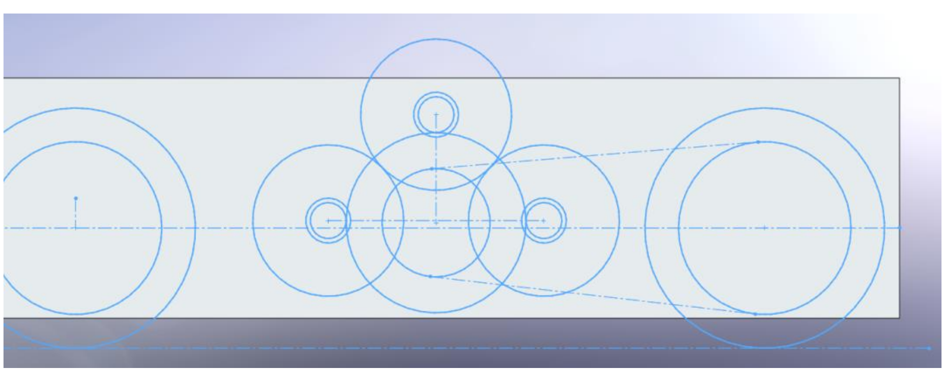


Mounting the two other CIMs to that same 60T gear seems like a good idea until we remember that the motors have to fit together and that they need to be mounted to a plate.

When we draw the CIMs in one is in the ground.

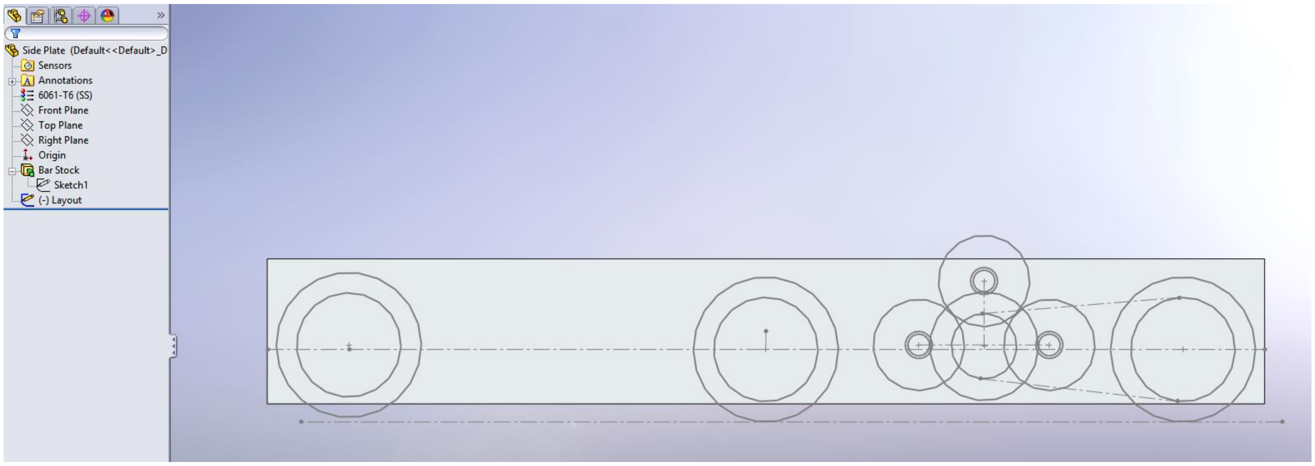


Obviously this isn't going to work but we look at this and say we might just be able to put them all on the plate. Remember we don't want to make the plate any larger than it has to be in order save weight. As well as that we don't want anything sticking out of the plate because we want to cut it from a 4 inch bar. So let's see if we can't move things around until it fits.



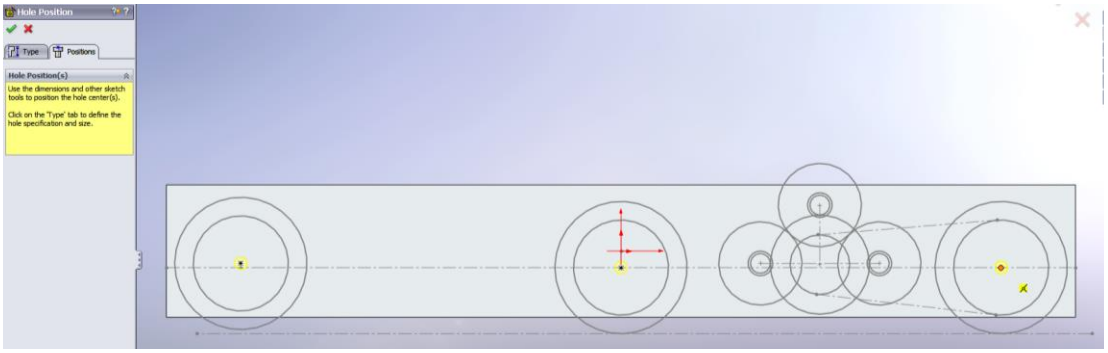
With some moving around see if you can't get it to fit like this.

Now that we have everything in place it's just a matter of cutting the holes for everything. Remember to base everything off the layout sketch as if we want to move anything later it's just a simple matter of moving it in the layout sketch.

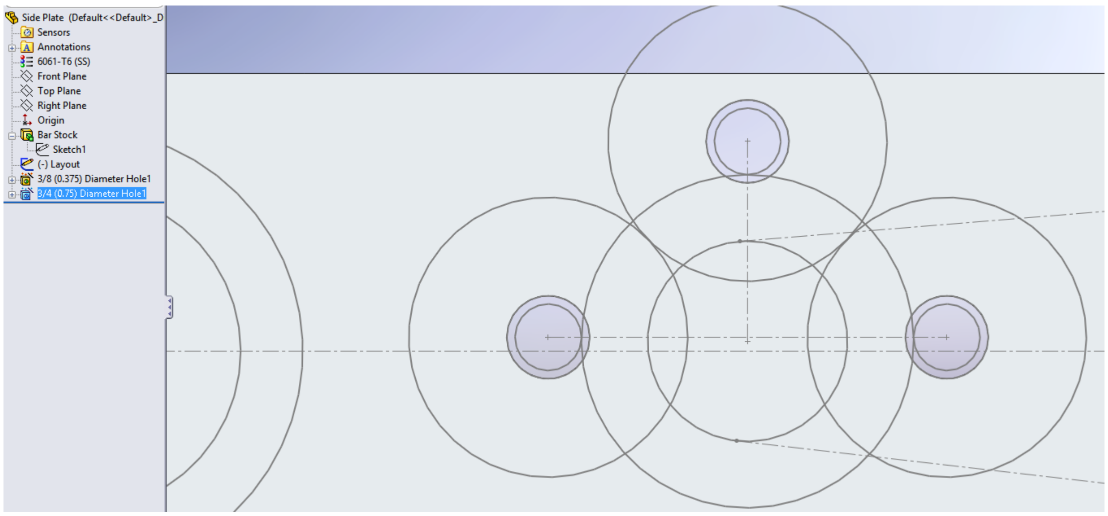


Next we are going to make holes for the wheels shafts. Remember we are going to go with a dead axle design. The bearings we will put on the wheels and the shaft will remain stationary. If you don't understand this now it will become much more obvious later but for now just put in a 3/8 hole for a 3/8 shaft.

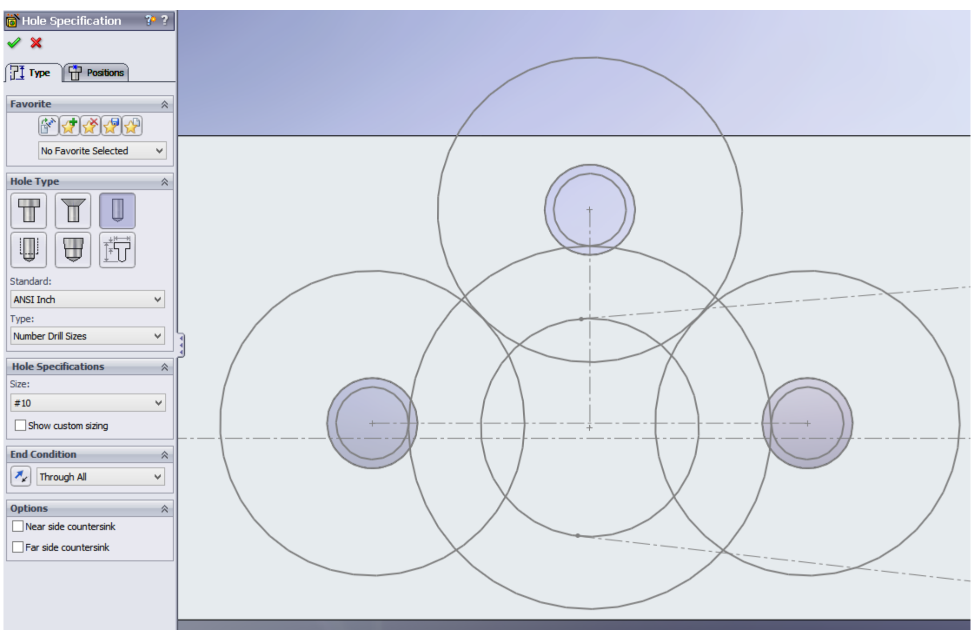
Simply select hole wizard and choose a 3/8 hole and click on the point you want a hole on.



Do the same for the ¾ recess for the CIMS

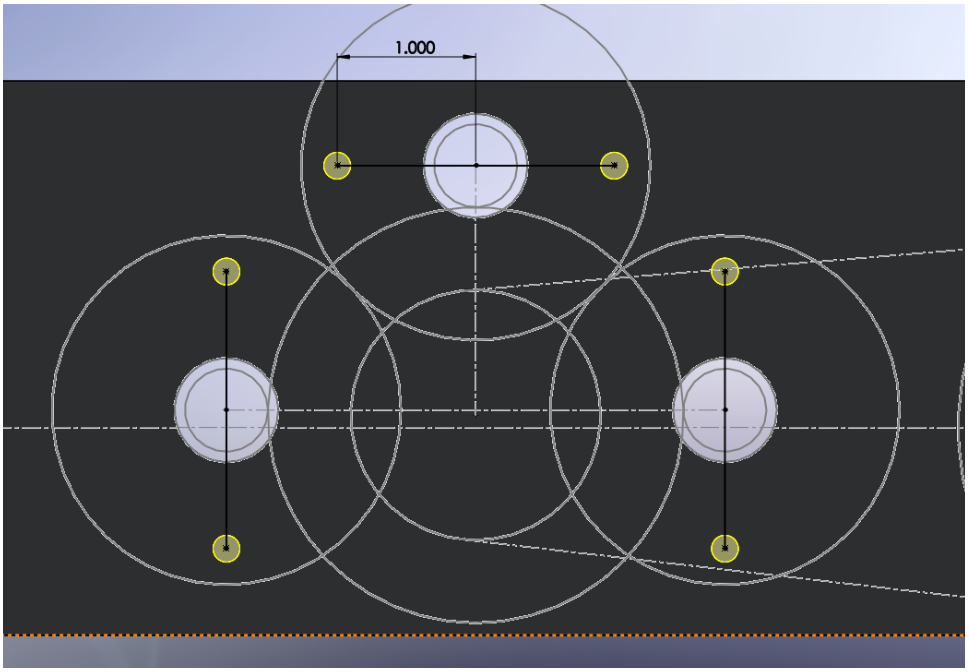


Now we are going to put in some mounting holes for the CIM. Instead of drawing a new sketch we are going to do it within the hole wizard to clean things up.

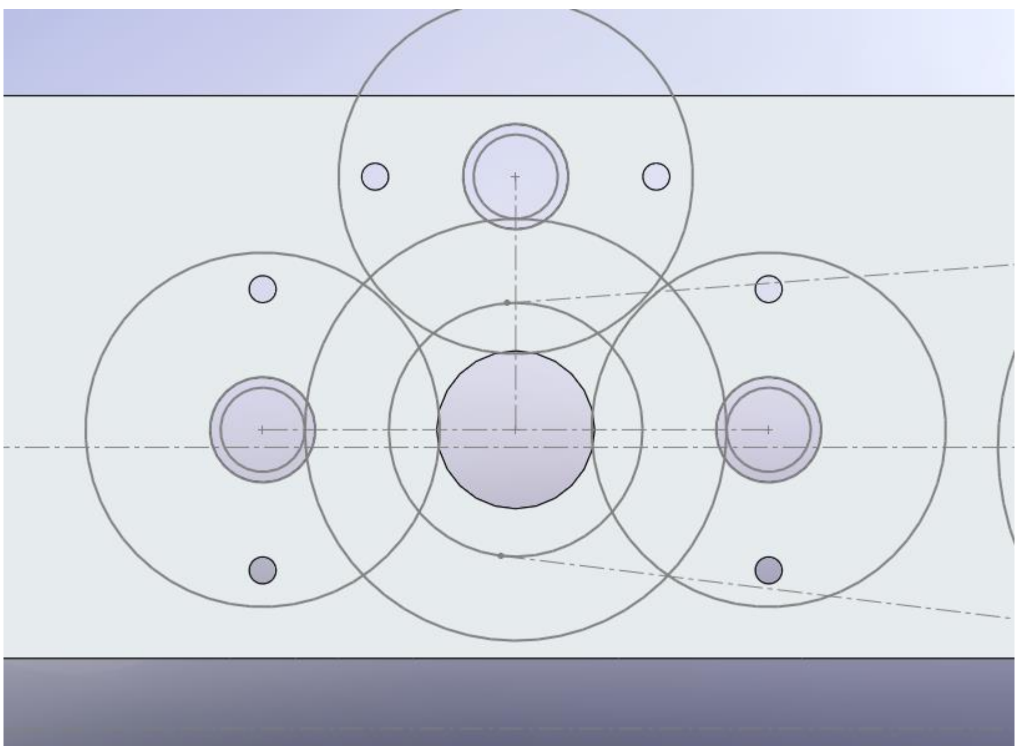


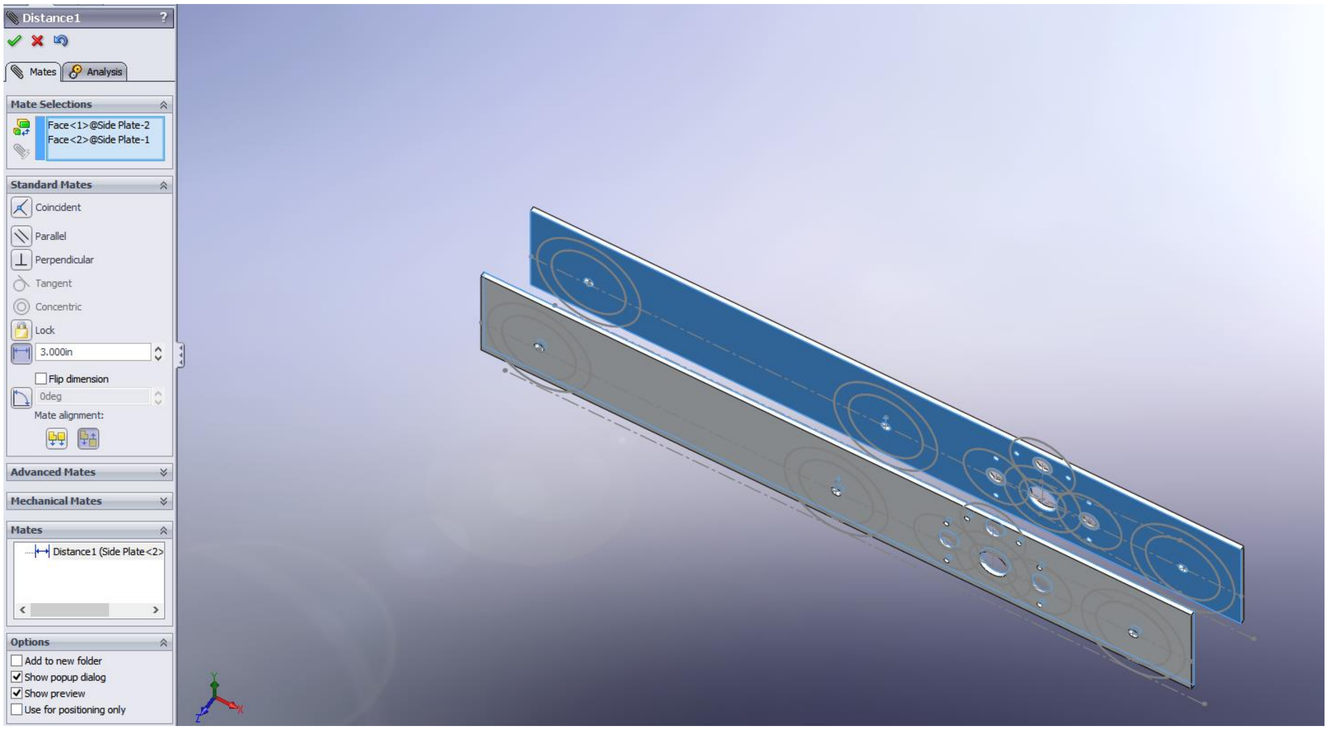
Select a #10 hole.

When you select the position for the holes you'll have to draw some extra lines.



Now just cut a hole for the bearing.

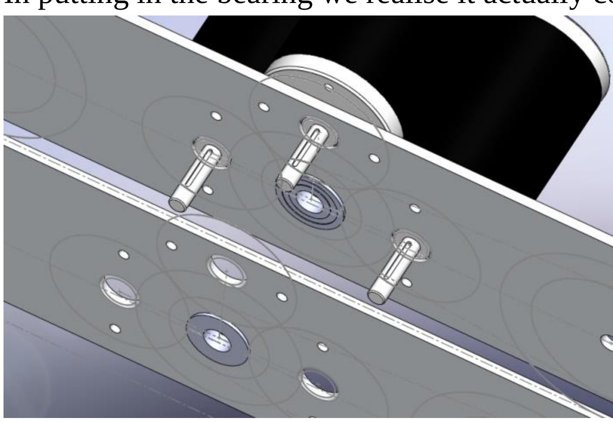


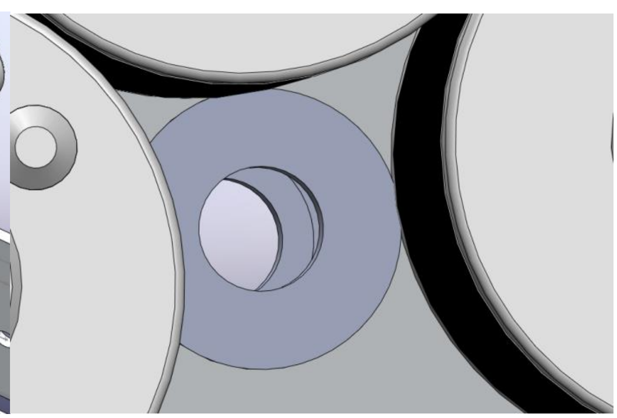


Put the two plates in an assembly and make it so they both line up. Separate them by 3 inches. We're not quite sure how wide to make it just yet so for now we'll just make it something reasonable.

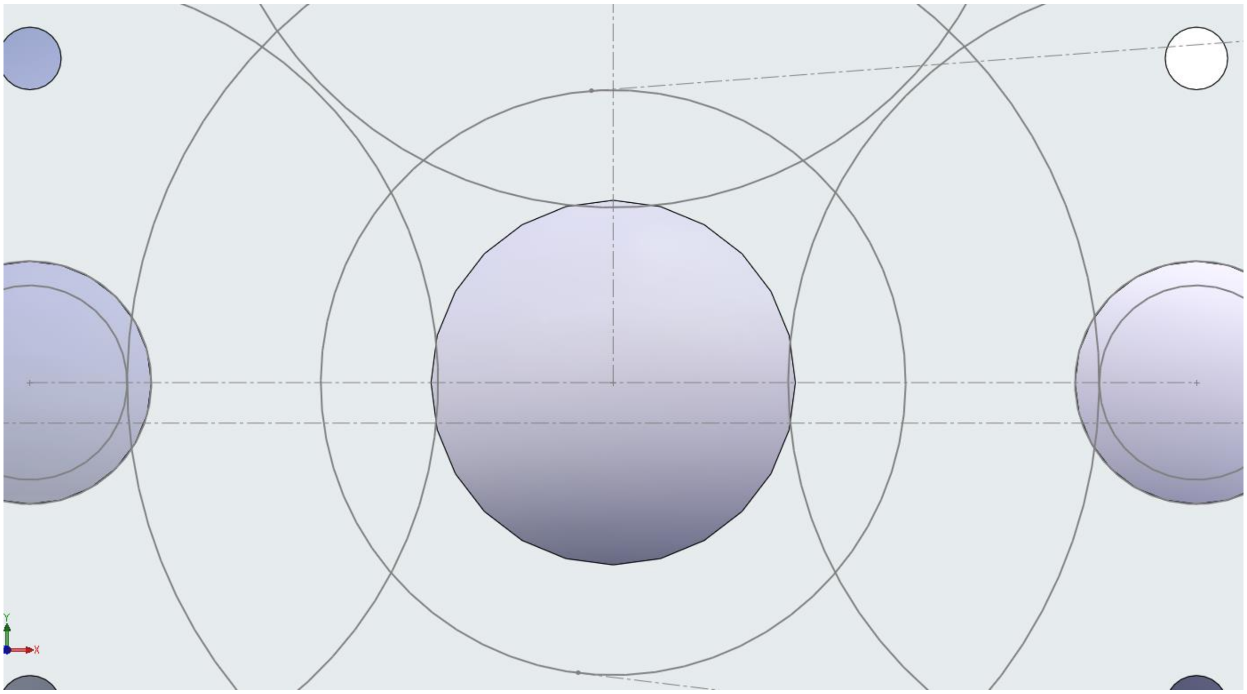
Add in all the parts we have accounted for so far.

In putting in the bearing we realise it actually collides with the CIM.



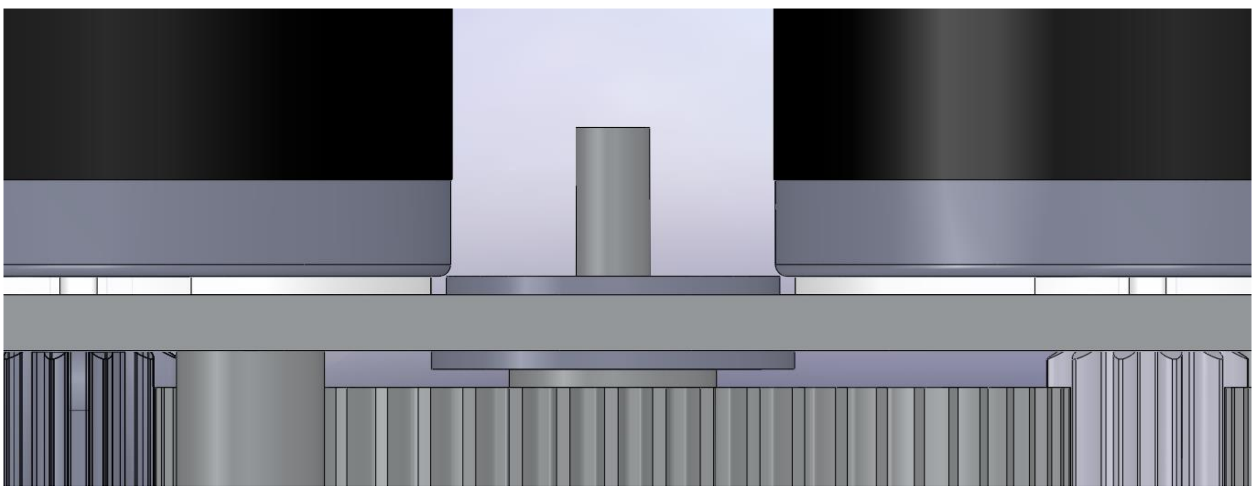


Upon checking our 2D, we realize we made a boo-boo.



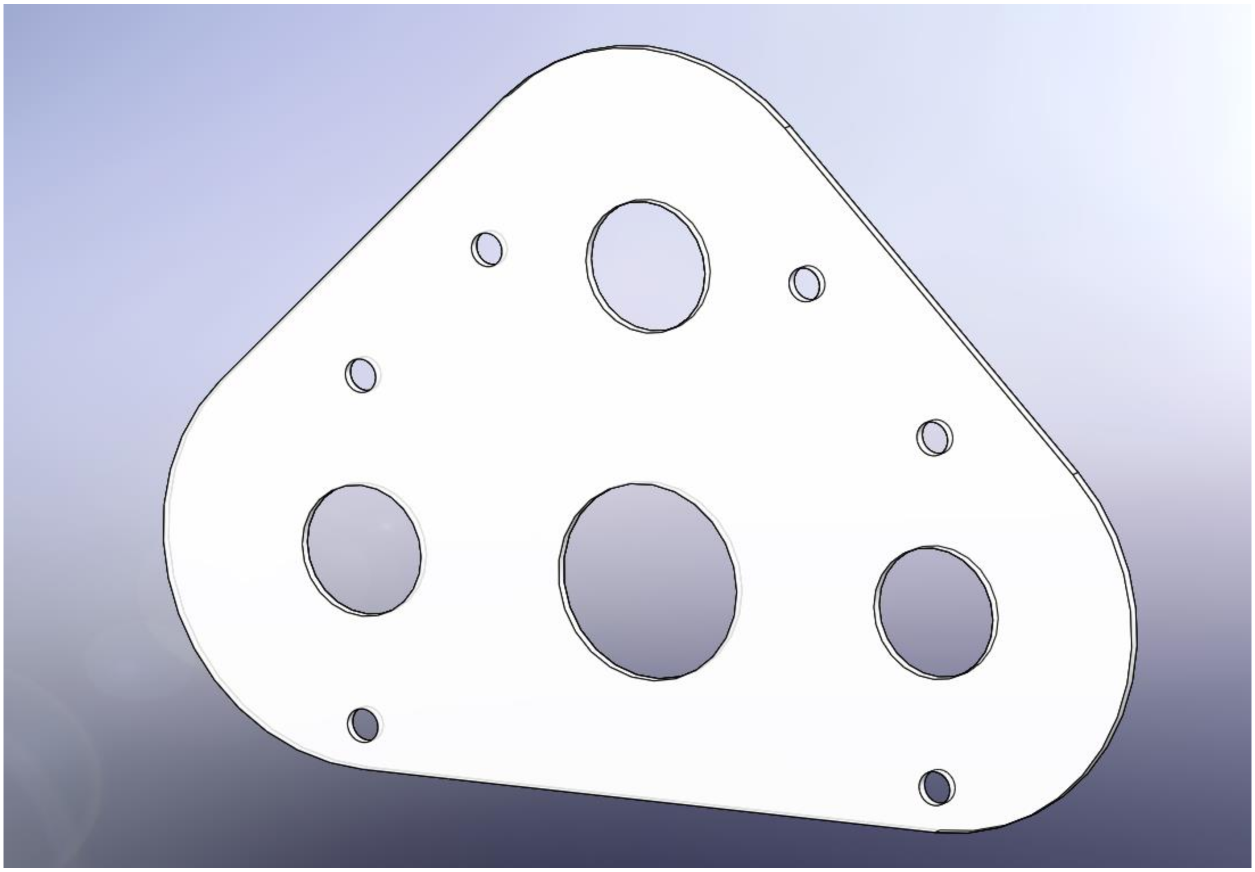
The bearing hole interferes with the CIMs.

There are several ways we could fix this issue. We could use a smaller bearing or use a bigger gear. However, the bearing only sticks out a tiny bit. So what we are going to do is something like this:

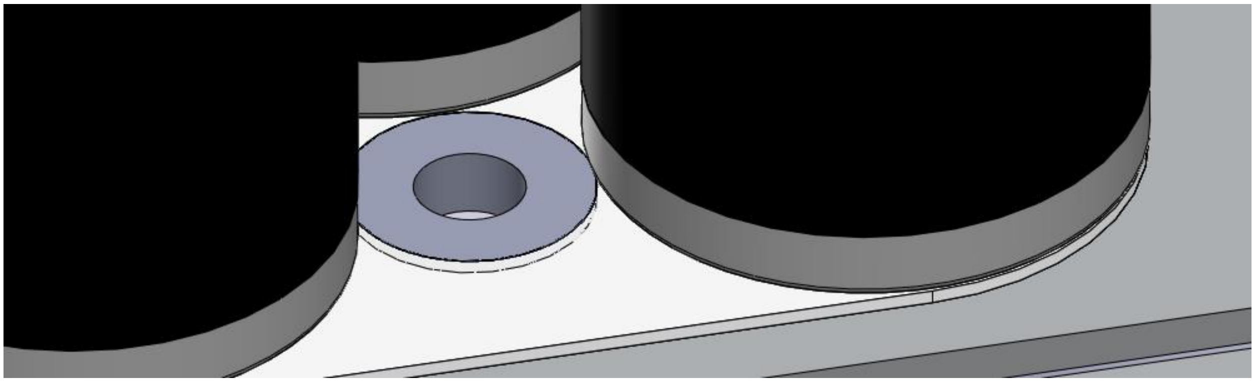


Put a spacer between the CIM and the plate that is slightly smaller and allows for the bearing to clear the CIM.

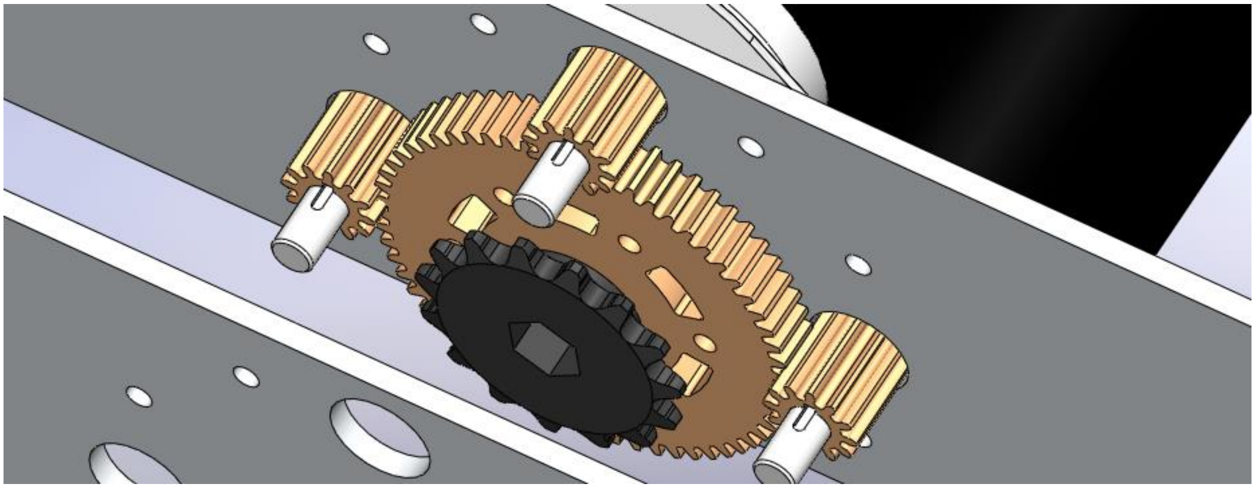
Since our CIMs are together we're going to make one part that spaces them all out



Make the outside match the profile of the CIMs and cut out all the necessary holes.

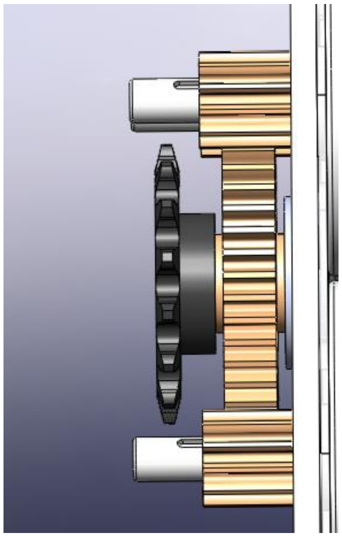


With the spacer plate the CIMs no longer collide with the bearing.

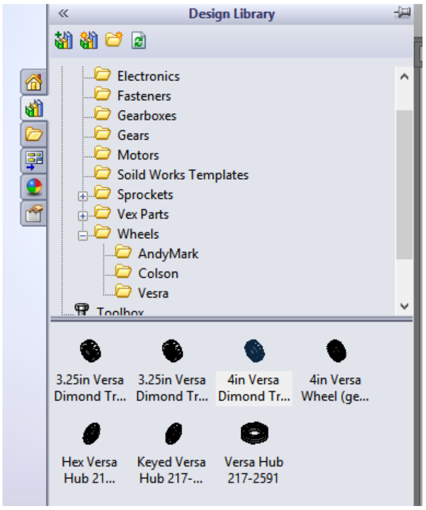


After adding in the gears and sprockets, the next step is to put the wheel assembly in.

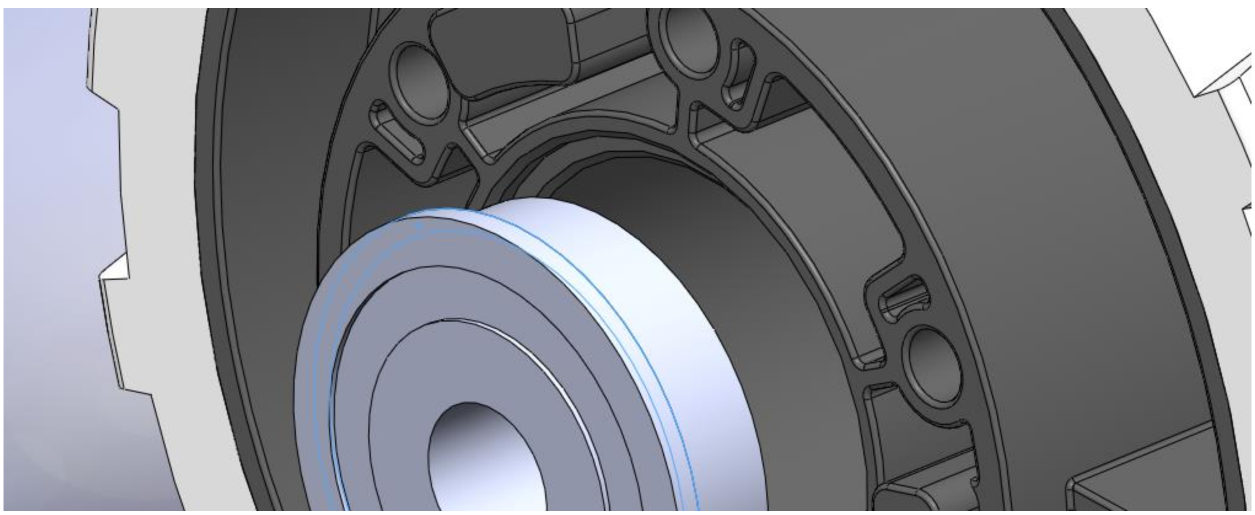
One detail to note: Mate the sprocket hub against the gear. We don’t want the chains to rub against the gear.



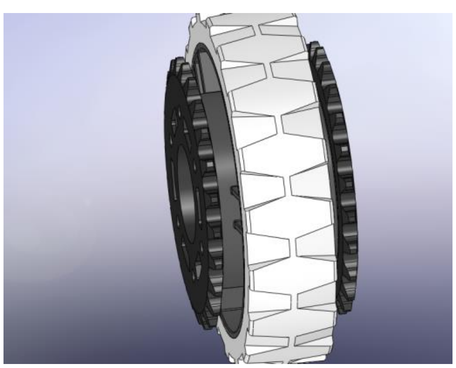
The type of wheel we are going to use is the VEX Pro Versa Diamond Tread for the simple reason that it is really easy to attach sprockets to them and they come together nicely. Start by making a new assembly and adding the wheel into it.



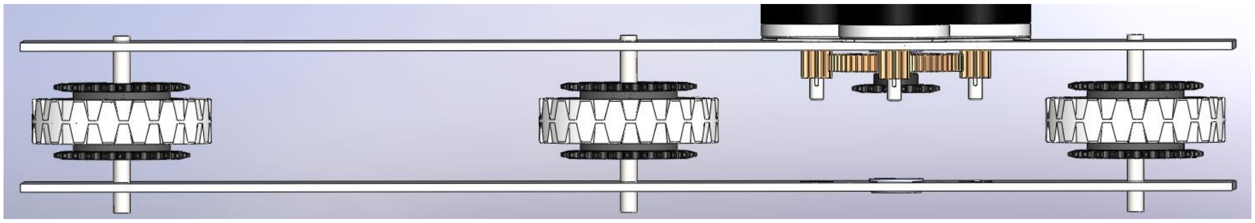
Put 3/8th bearings into the wheel. Note that there is a recess for the flange of the bearing.



Add in two 24T sprockets (one on each side). Make sure they are for #35 Chain.



Make a 3/8 shaft of arbitrary length and add it into the main assembly. We will figure out the exact length later.

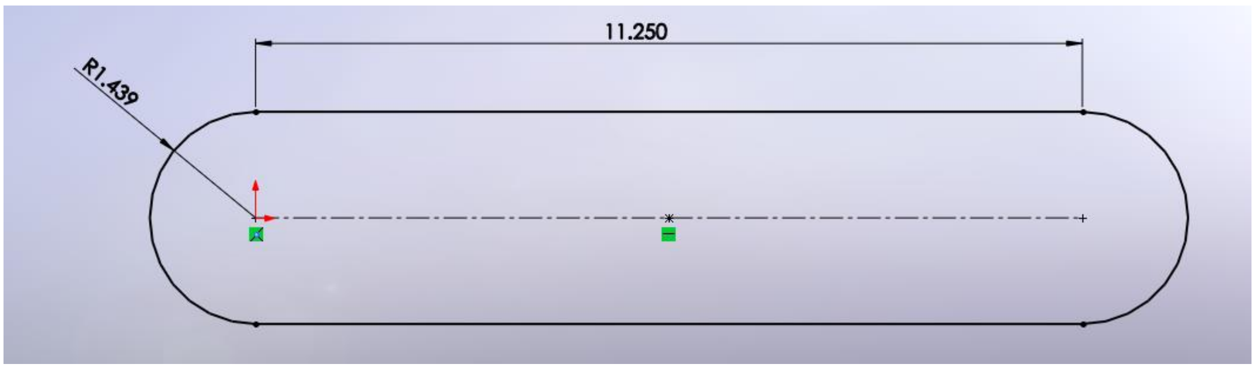


Add the wheel assembly in the main assembly and line up the wheels with their respective holes.

Again don’t worry about their exact placement.

Next we are going to put in a chain.

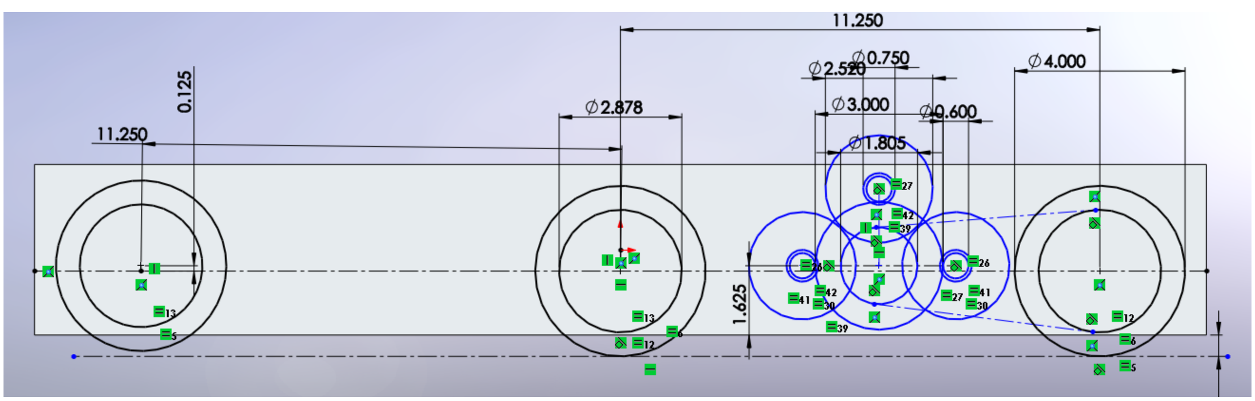
Make a loop that represents the chain path.



Have you spotted the problem yet?

Chain runs between two equal sized sprockets should have a distace that is a multiple of the chain pitch.In this case, #35 chain has pitch of .375 and the centre distace should be a multipe of that which it isn’t.

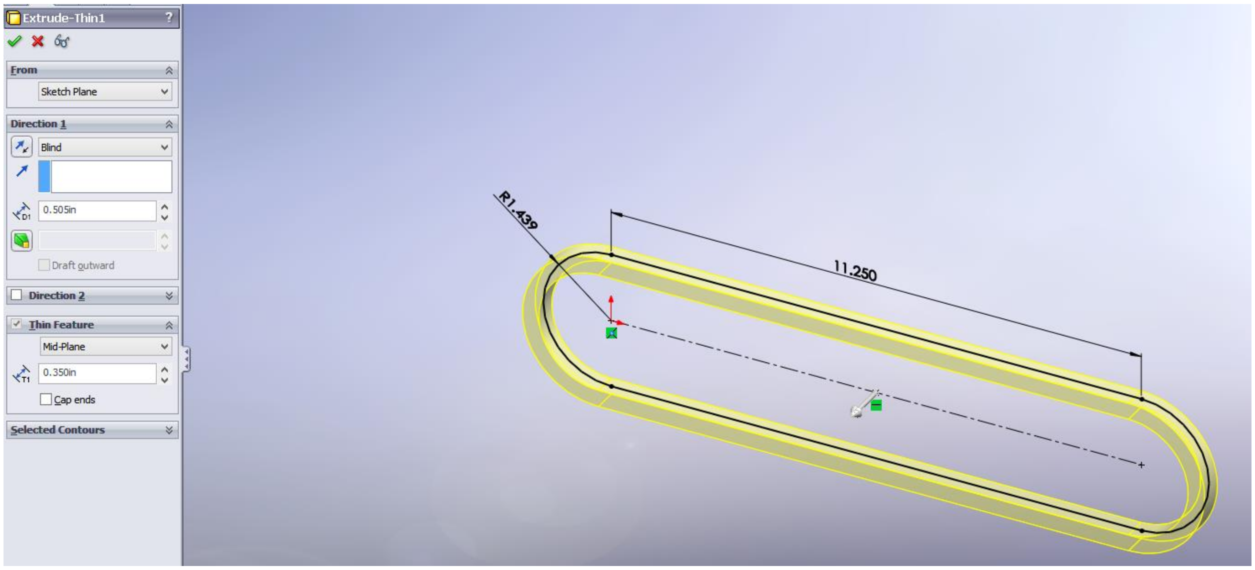
Go back to the orrignal layout sketch and change the centre distance betwee the wheels to 11.25 which is divisible by .375



Remember with the 1/8” rocker; be sure the **centre distance** between the front and middle wheels is 11.25 **not the horizontal distance** between them.

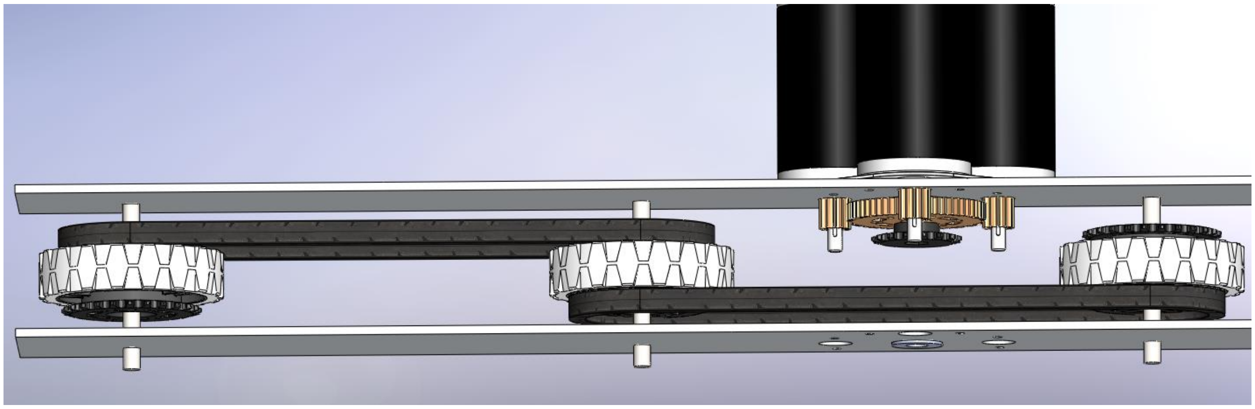
Go back to the chain loop and change it to the correct dimension. Now extrude the loop.

Make the chain height .225 and the width .305 for #25 chain and for #35 .505 width and .35 height.



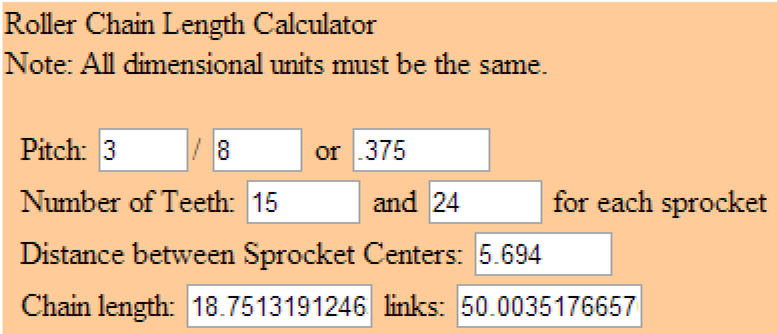
Use the thin feature. That will turn it into a loop instead of a block. Size it accordingly. Make sure you select mid plane. Remember the loop you sketched repents the centre.

Now it is possible to put in a "real chain" but for our purposes we just want to ensure that our chain does not intersect with anything so this mock-up will do.



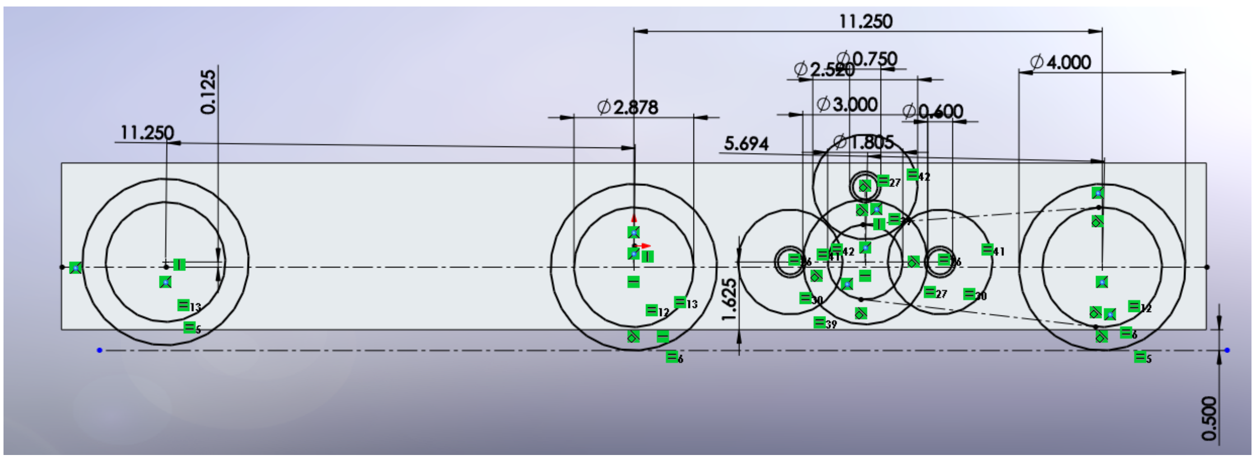
A tip for putting the chain in: make the ends of the chain loop concentric with the shaft and use a width mate to centre the chain and the sprocket. All we are really concerned about is making sure it is not going to hit anything like a standoff.

Now for the more difficult chain run, refer back to the gear and chain section on how to find a centre distance for two different sized sprockets.

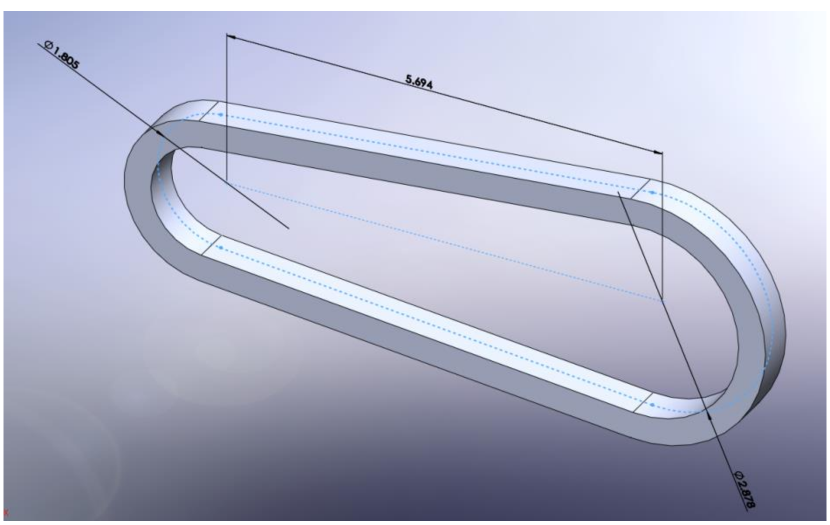


Putting in the correct parameters with a centre distance of 5.694 we get slightly more than 50 links. Also note that even amounts of link are preferred as having an odd amount will require the use of a master link (not a huge deal but will save some time).

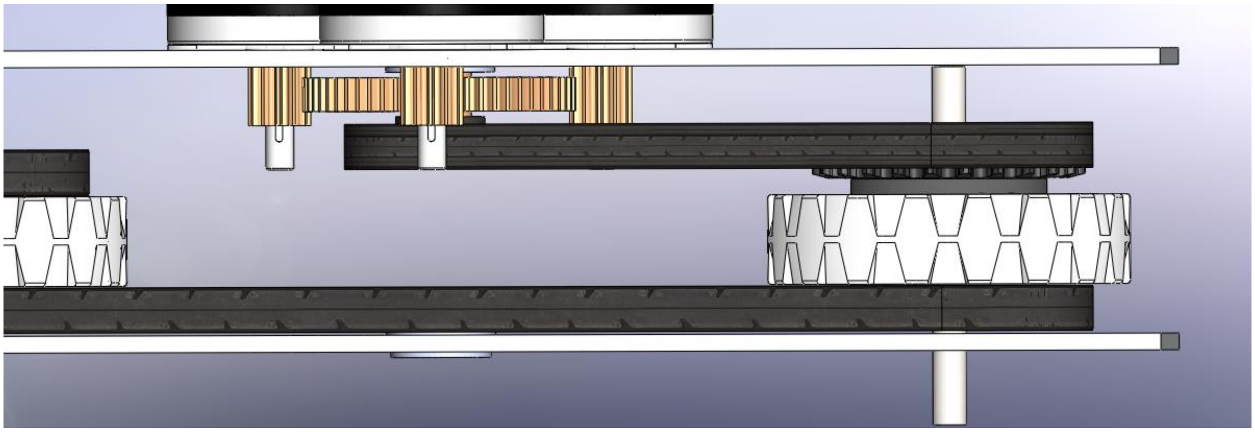
Change the layout sketch so that the sprockets are the correct distance apart.



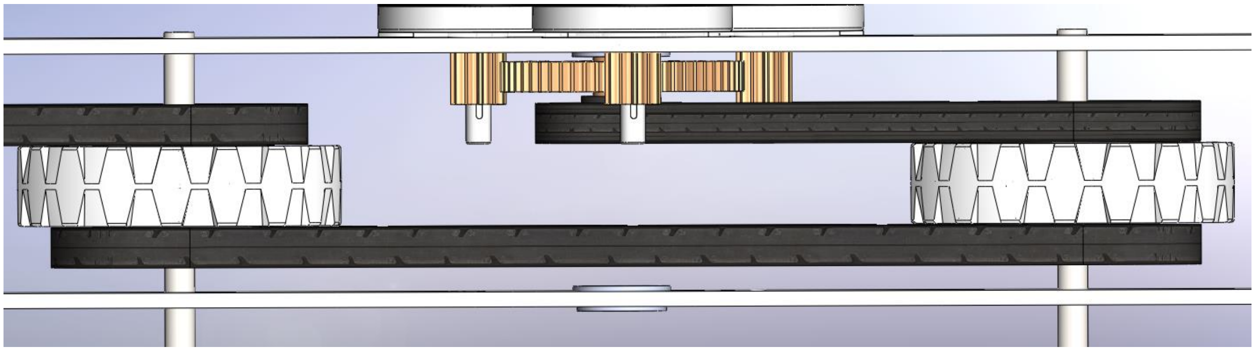
As you will notice everything is now black and thus it is all fully defined.



Make a chain run and add it into the full assembly and line it up with the gear box.



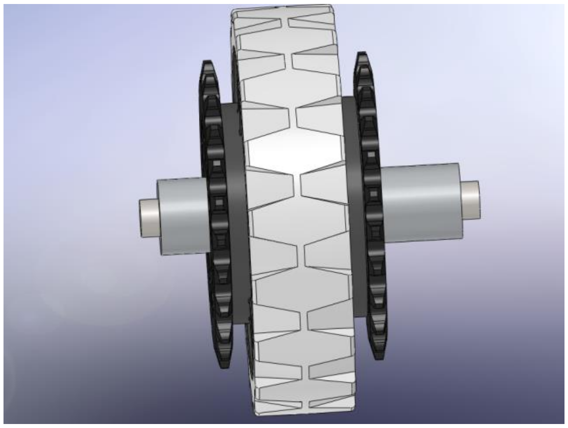
Now line it up with the rear wheel.



Now that everything is lined up we can see 3 inches in between the plates is a pretty good number. However if we wanted adjust it we could simply change the distance mate.

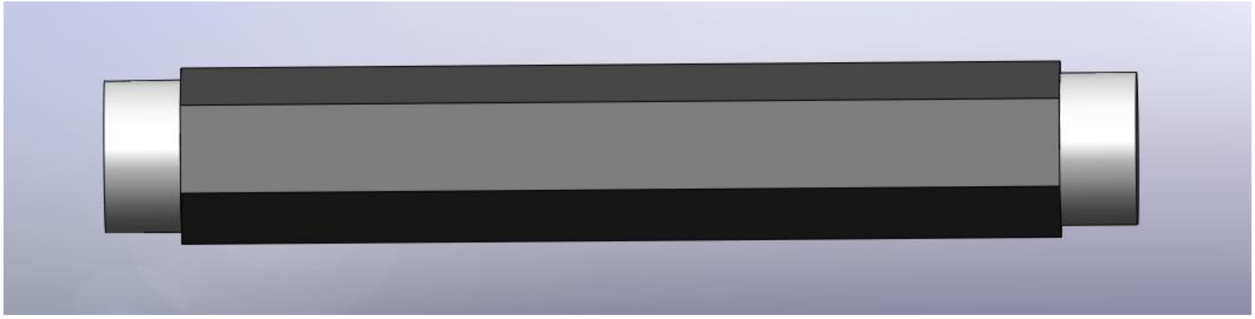
Now that all the important components are in now it's just matter of putting the spacers, shafts, and stand offs in.

Let's start with the wheel assembly. Measure the distance from the bearings in the wheels to the sides of the plate. Make some spacers and put them onto the wheel assembly.

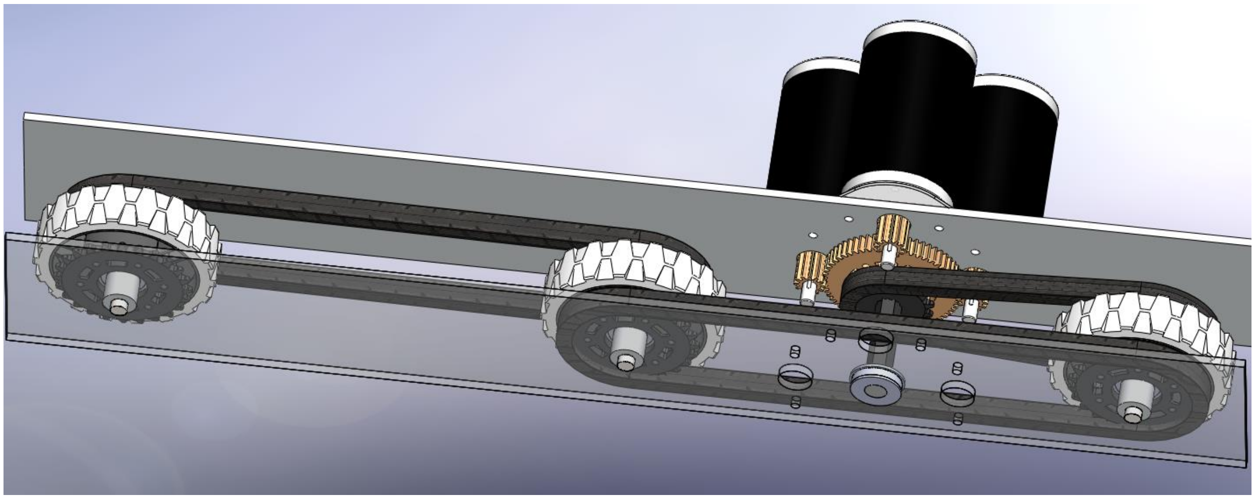


Also cut down the length of the shaft so that it fits into both plates.

Next on the list: let's put a shaft in the gear box. A simple hex shaft with the ends rounded out will do. Remember we put the flanges of round bearings on the inside. Also note that the length of the hex part of the shaft is slightly less than 3" as there is the width of 2 flanges to account for.



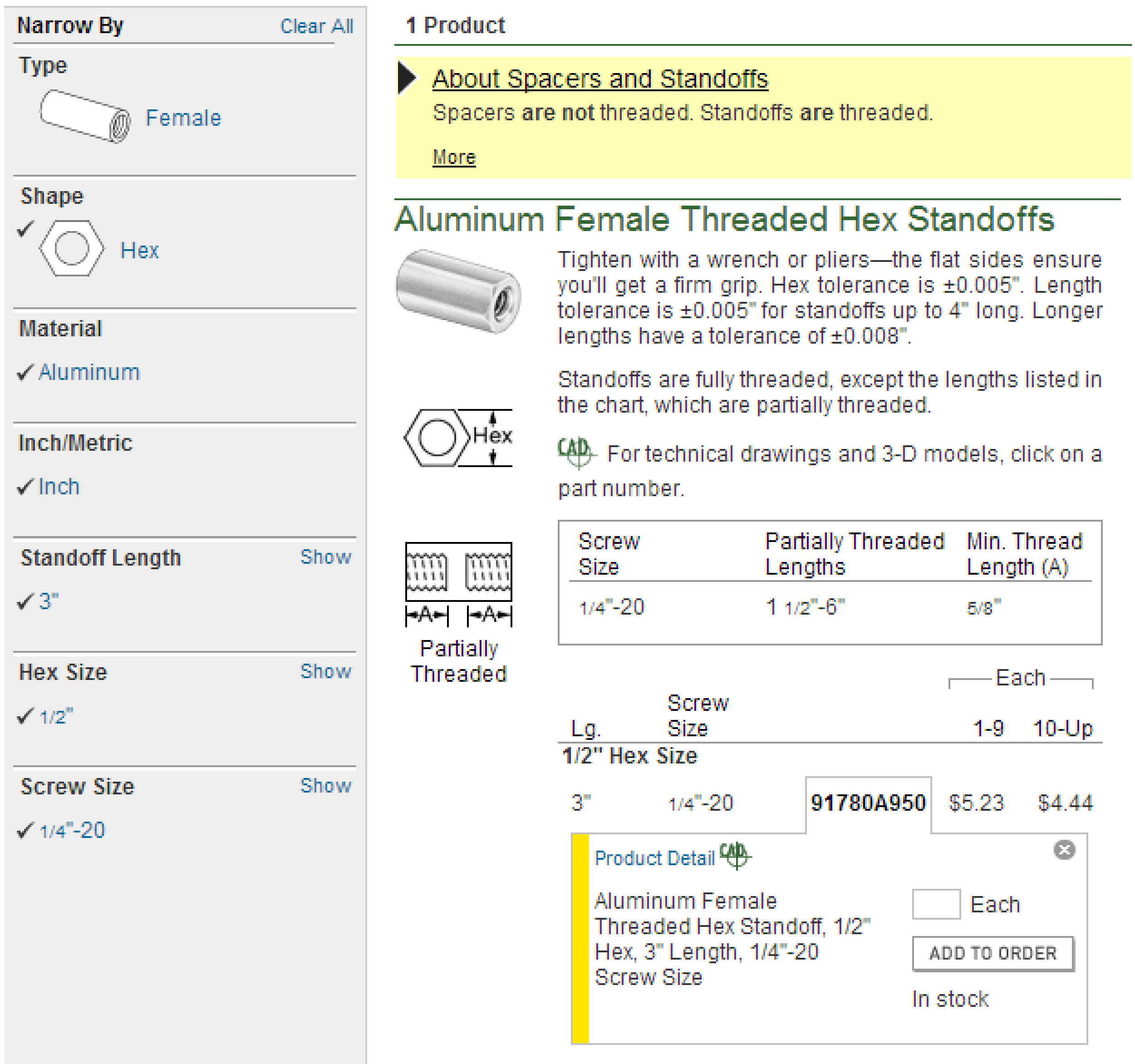
Put the shaft into the main assembly.



Now all the power transmission components are in place. Next we'll attach the two plates.

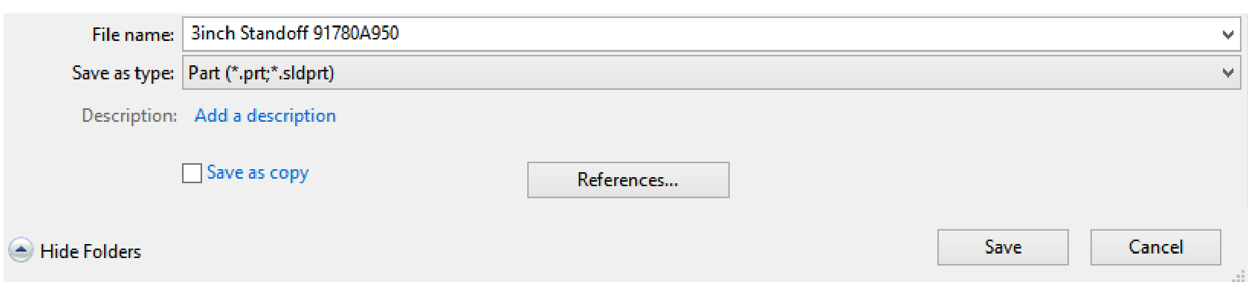
To attach the two plates together, one of the easiest ways is standoffs.

Go to McMaster Carr and punch in the parameters of the part we want.



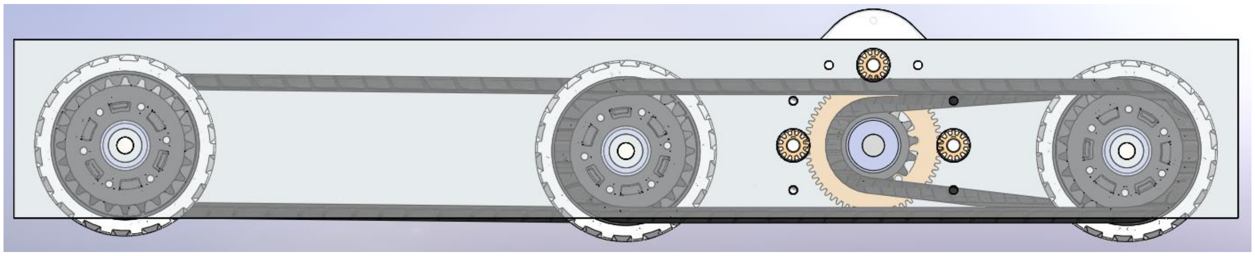
We end up getting this. Beside product details click on the CAD icon. Some McMaster Car parts come with cad files/drawings/spec sheets such as this one. In this case this part only comes with some drawings and we are going to make our own standoff.

It’s a very easy part but make sure when you name you add the part number after it.



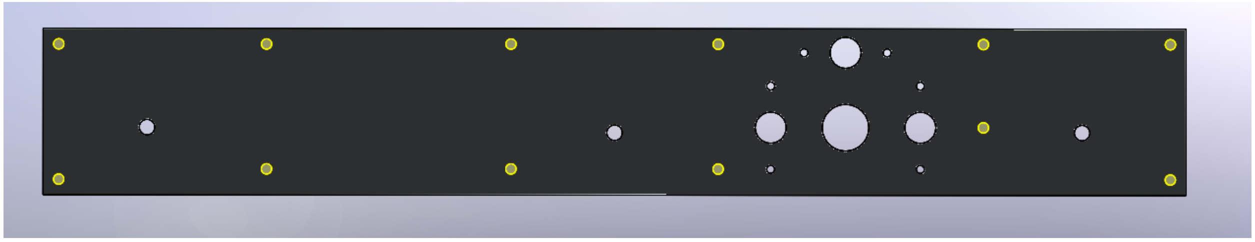
This helps a lot when you want to go actually make the make the thing.

Go back to the side profile and look at places where we can put standoffs.

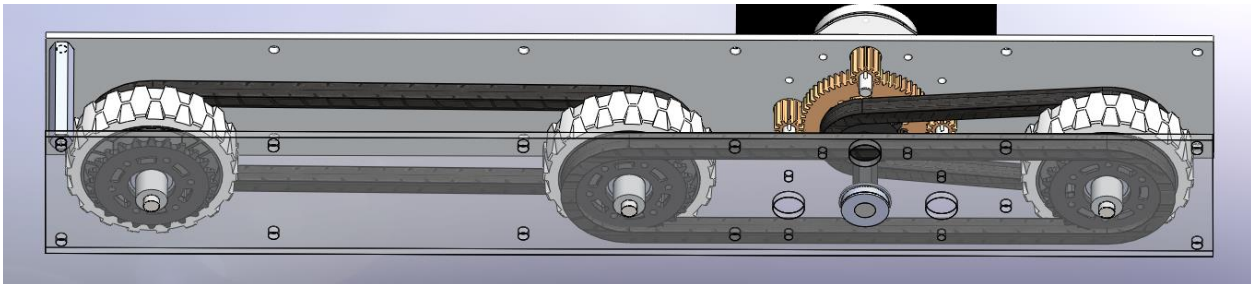


We know we definitely want to put one in each of the 4 corners and a few around the gearbox in-between he chain runs.

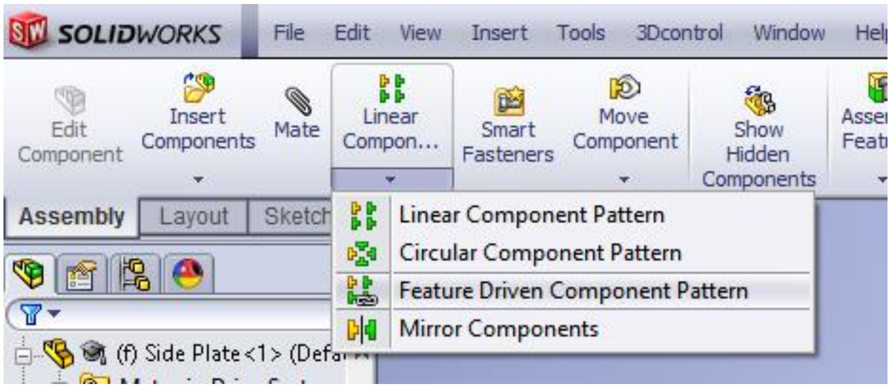
Go back to the side plate and punch in some holes for the standoffs.

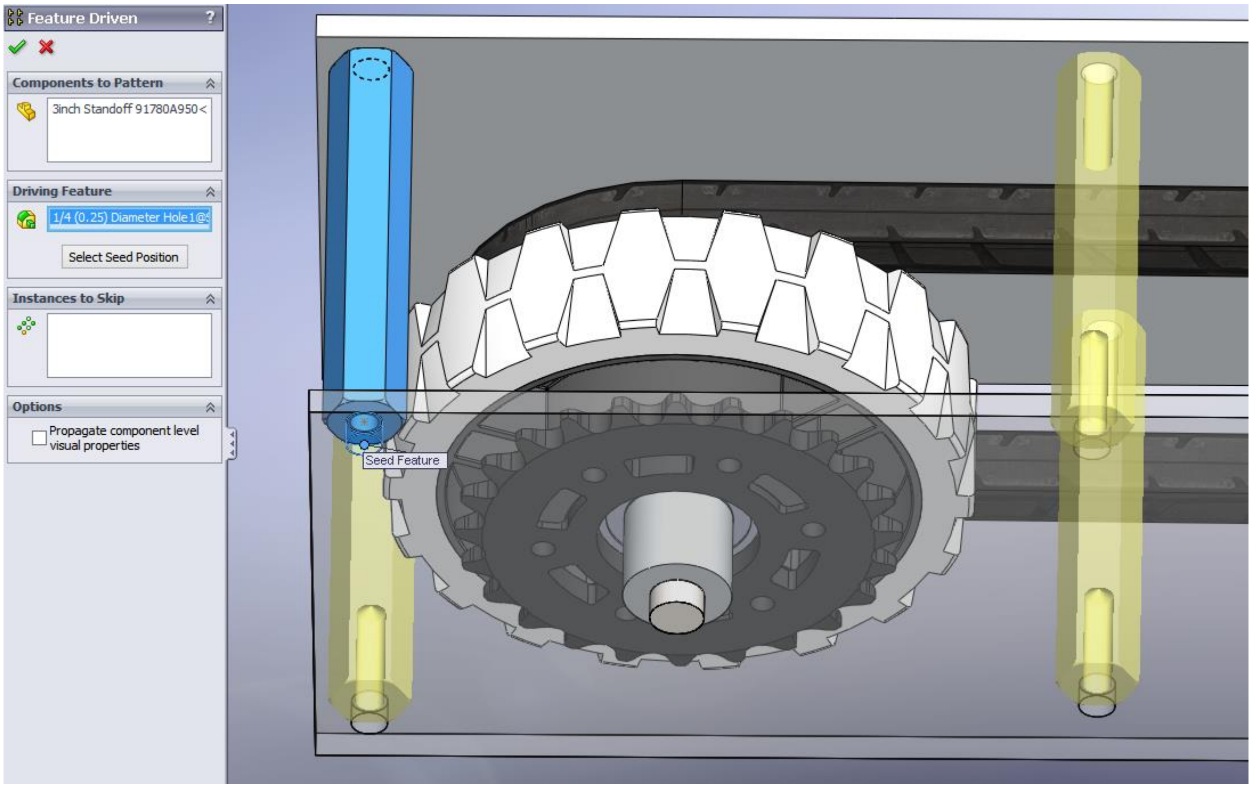


Go back to the assembly and mate one standoff in the upper left hole.

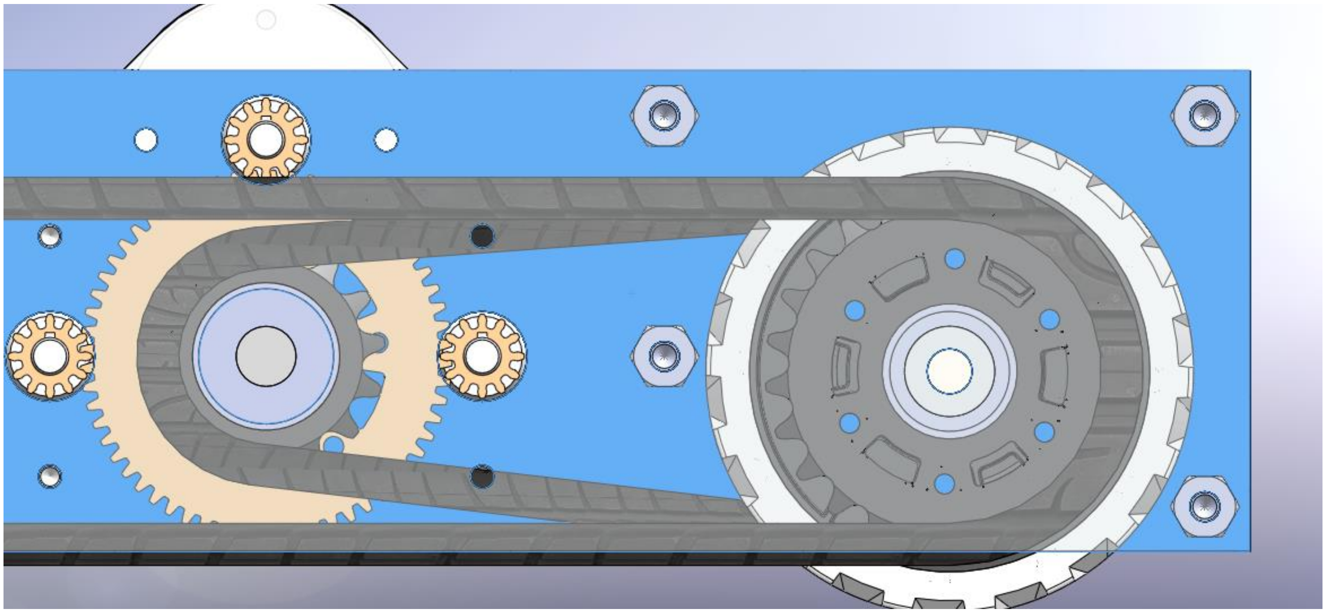


Next we are going to use “Feature Driven Component Pattern” to put the rest of them in.





Select the standoff that you want to pattern. For driving feature select the hole that the standoff was put in. SolidWorks will put in a standoff everywhere else hole wizard put a hole.



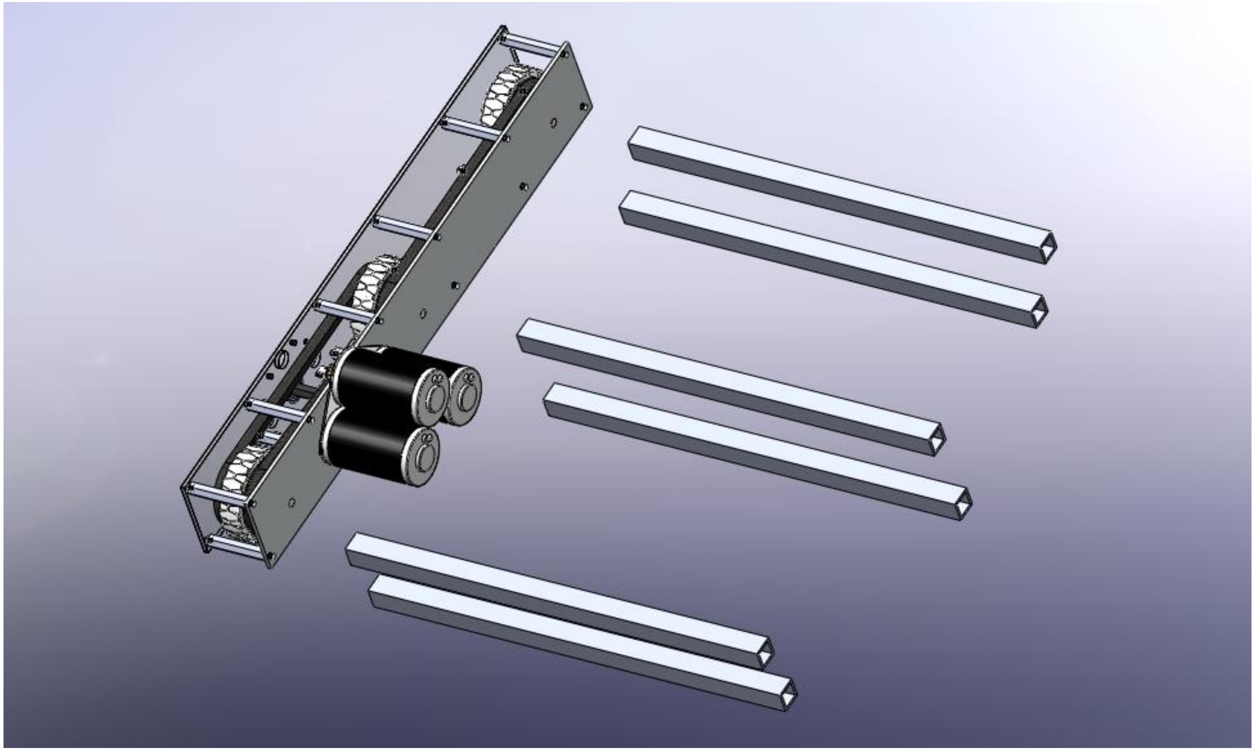
Here we see a standoff is a bit close to the wheel. While it would have been fine we'll shift it over just a bit.

After changing the location of the hole, the assembly should update itself.

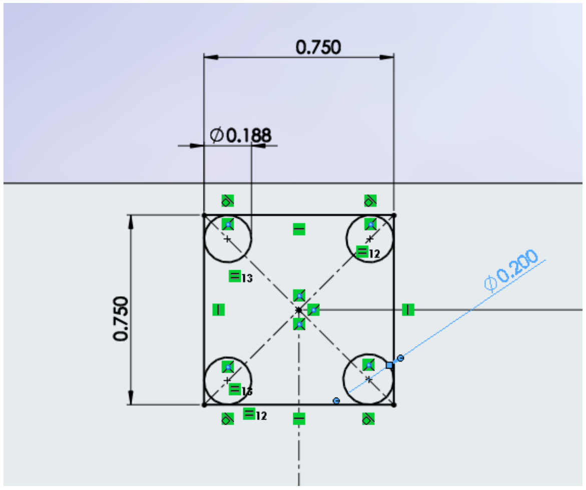
This half of the drive rail is now essentially done. Now we are going to work on putting a frame together.

Make a new assembly and add the drive rail assembly into it.

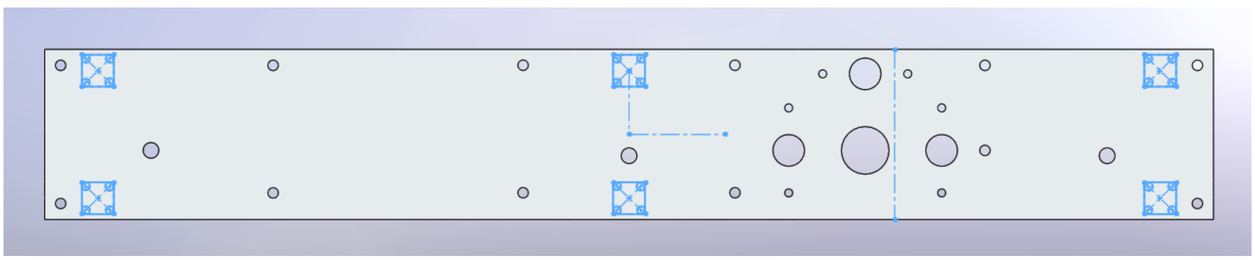
To attach the two sides we are going to us a 1x1 square 1/8” thick tube.



Six tubes is probably too many, but we are going to put 6 in so if you want to have an open front or back (for an intake or other mechanism) you can simply remove the front two. If you don’t need an open front, remove the middle two. We are going to fasten the tube perpendicular to the plate with roll pins and threaded rod. If you don’t remember how to do this you can go back to section one.

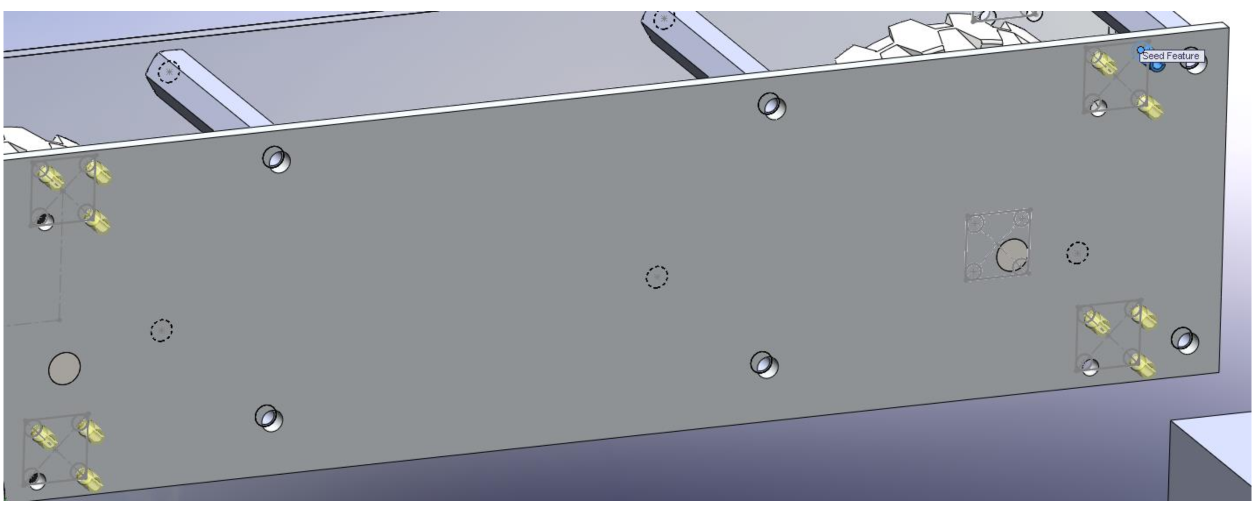


Sketch the pin/threaded rod layout then pattern the layout for the 6 different cross bars.

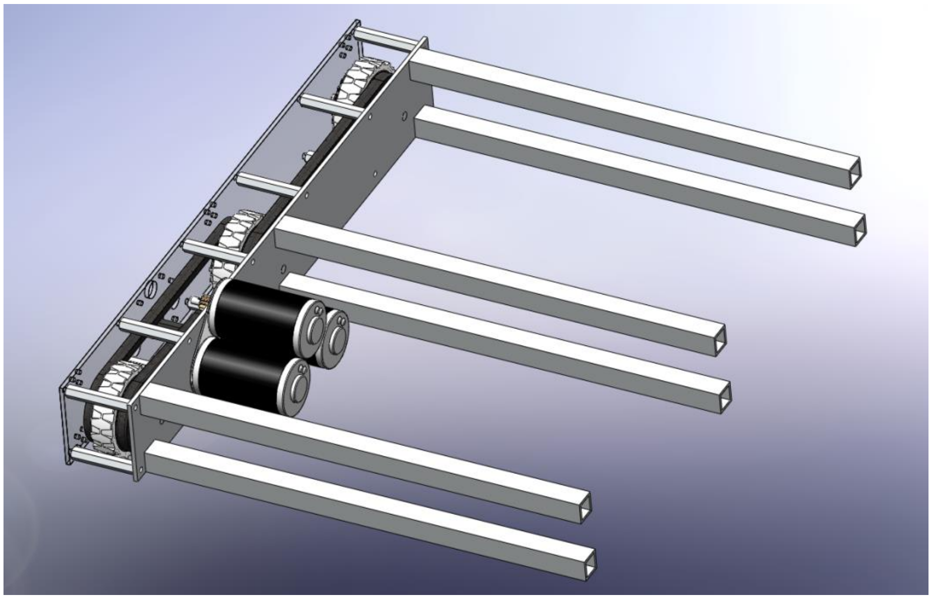


Use hole wizard to punch out the 3/16 holes and the #10 holes based off of the sketch you just made.

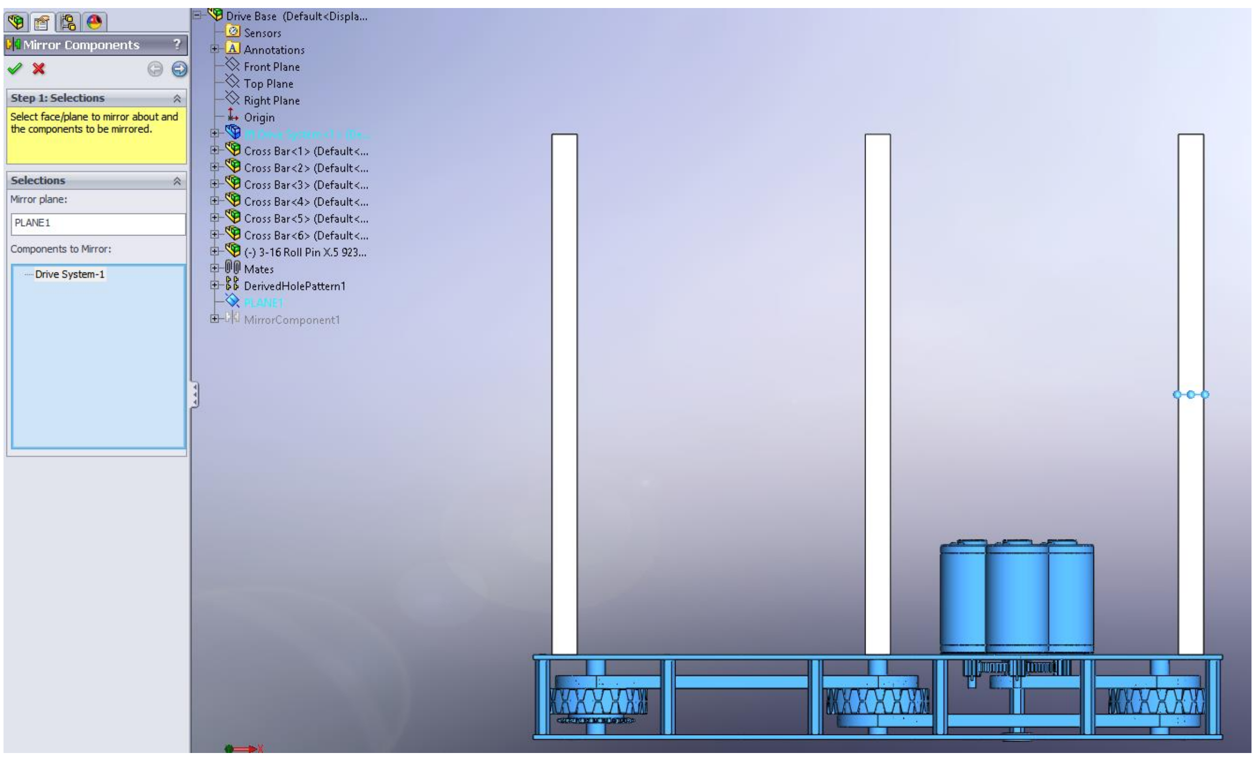
Use the same feature driven component patterning to put pins in each of the 3/16 holes



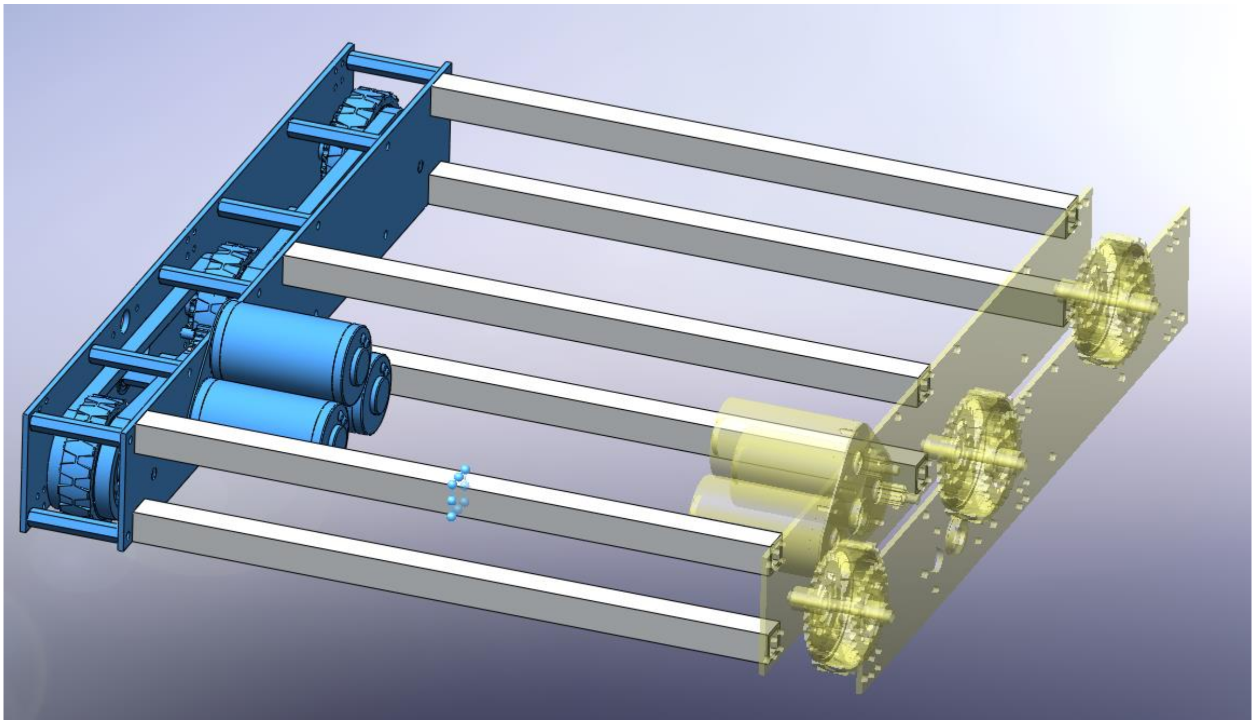
Now put the cross bars on.



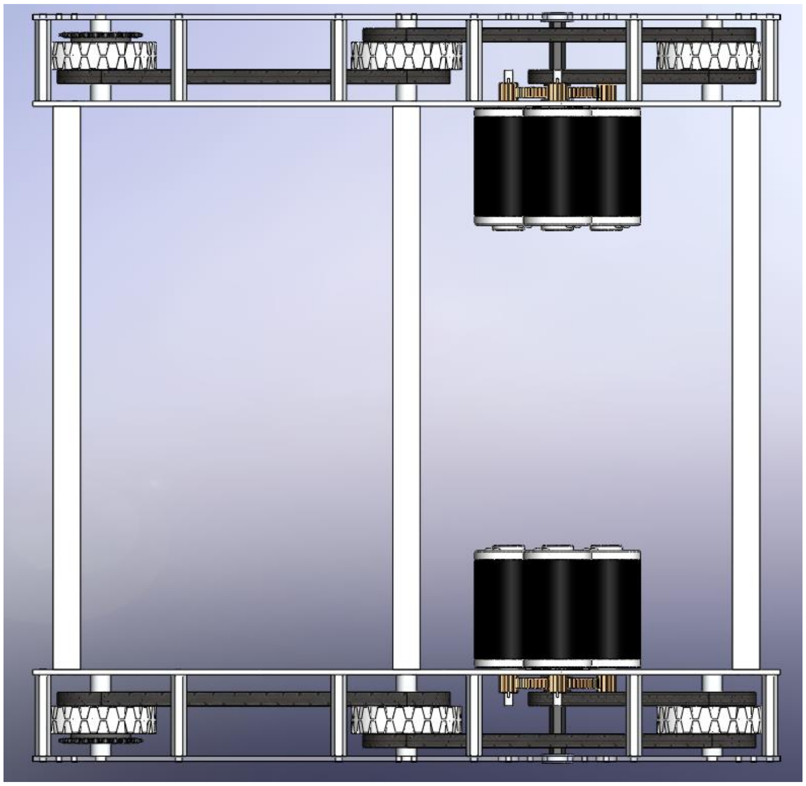
Now we are going to mirror the drive rail. Keep in mind depending on the part the mirrored version may be different from the original. In this case we don't need to worry as everything will be the same on both sides.



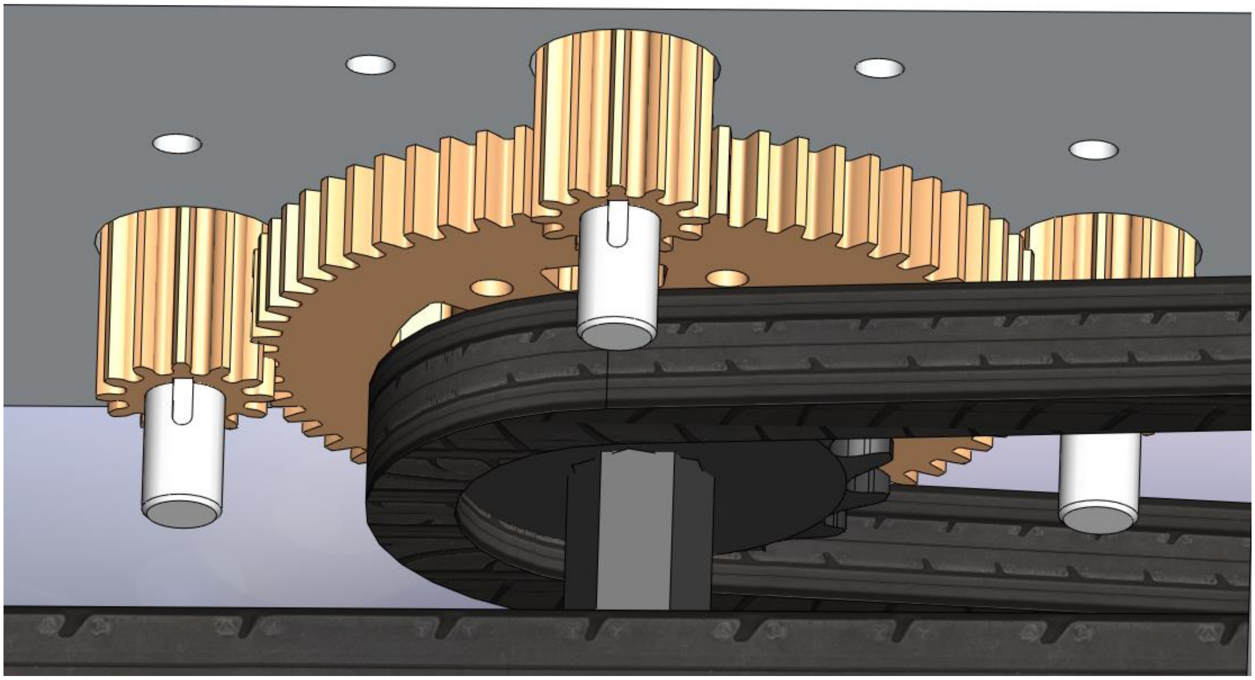
Create a plane to mirror the drive rail from.



If necessary, create mirrored versions of the part and then add them to the assembly. In this case it shouldn't be and you should just flip it into the correct orientation. Note that if you do have to create mirrored versions of the part select "Mirror Derived Configuration" instead of "Create New Part".

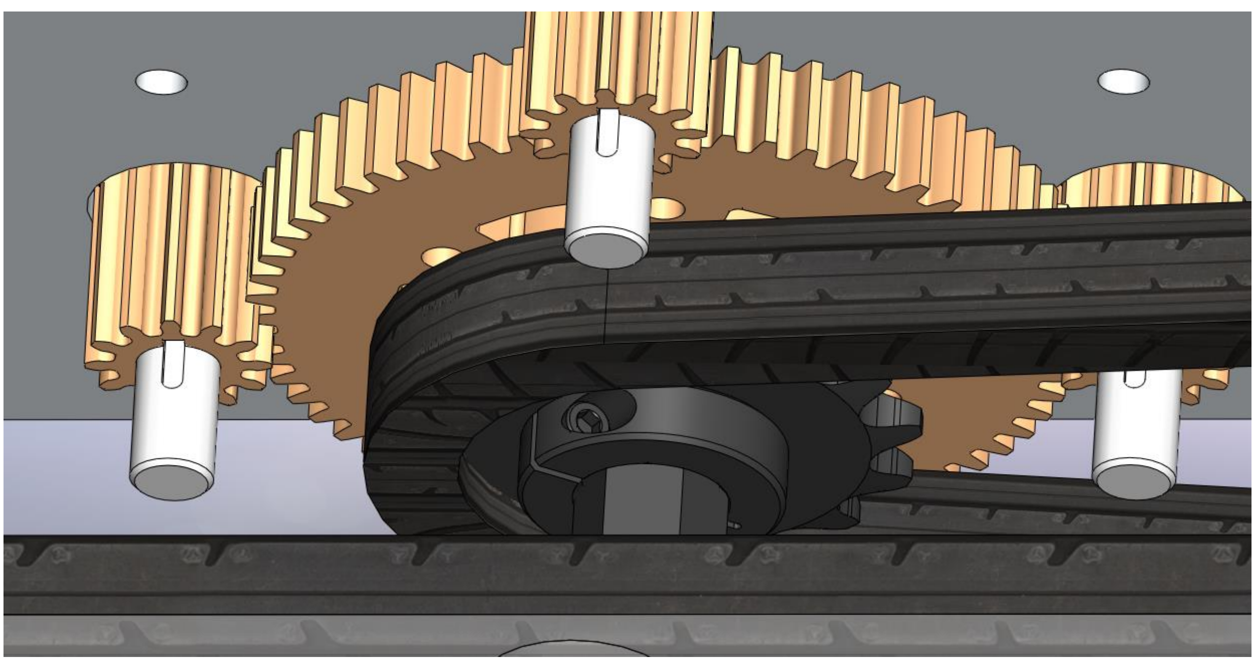


After mirroring the drive we are basically done. There are just some last things to cover. Go back to the drive rail see if you can spot any problems like anything that isn't held in place etc.

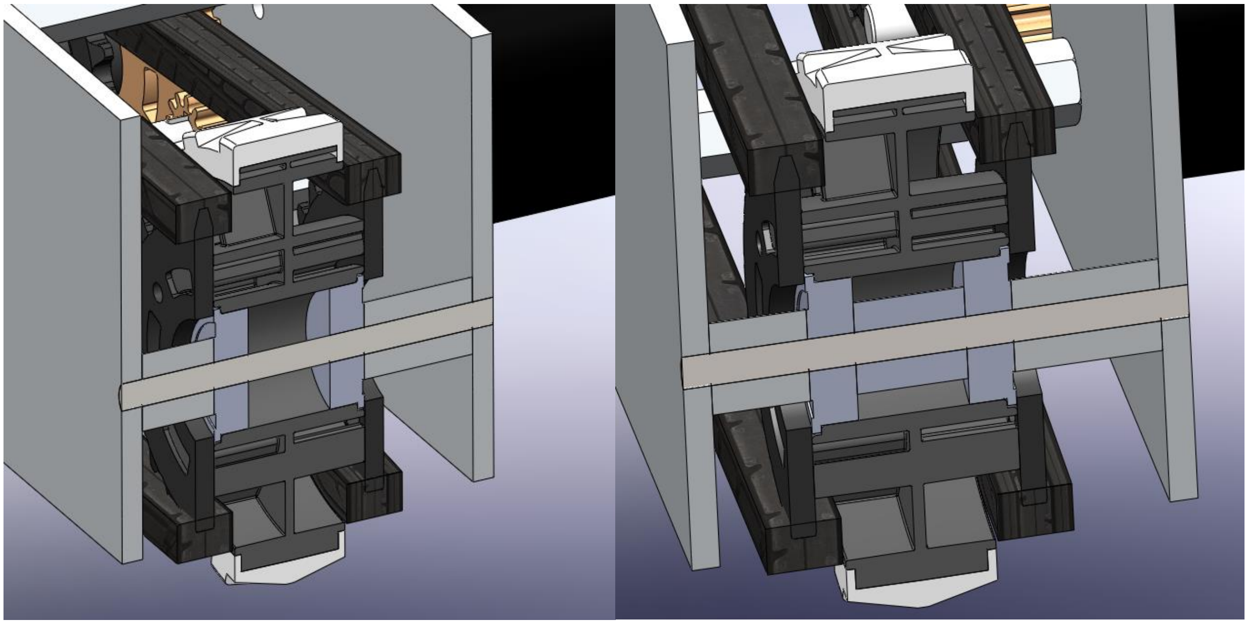


The CIM gears will have retaining rings to keep them from falling off but the 15T sprocket needs to be held in place.

Pop a shaft collar on it.

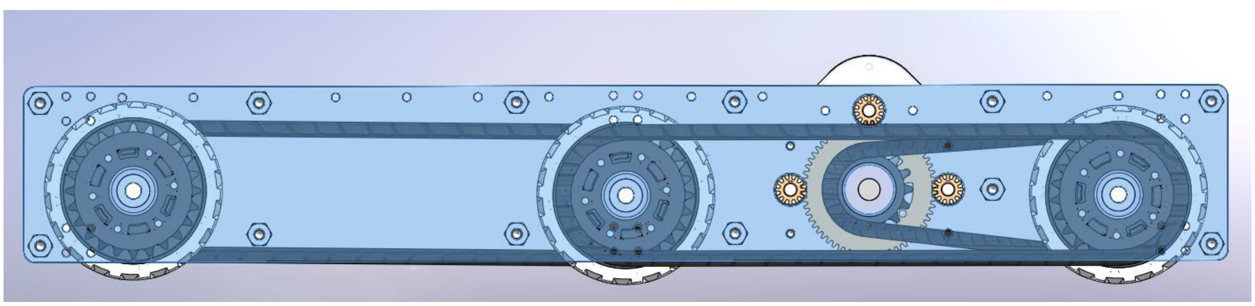


Also, instead of using a 3/8 shaft for the wheel what we are going to do instead is use a 3/8 bolt. It will be fewer parts to make and also more simple to assemble. The shaft will also act like an extra standoff. However, to prevent the bolt from caving in the bearings what we are going to do is add a spacer inside the wheel assembly in-between the bearings.

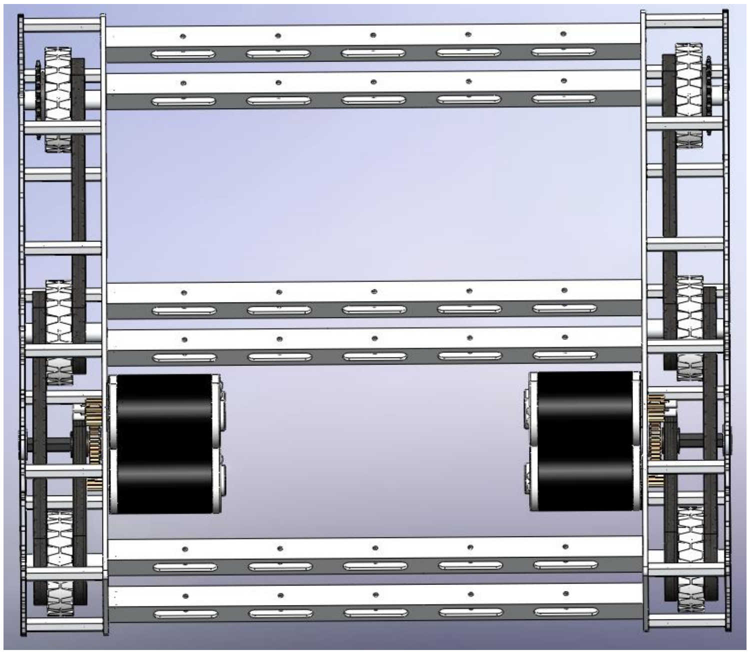


We should also add some mounting holes for adding anything on top of the robot. Open the side plate and add some holes along the top of the rail. Make them for a #10-24.

Why not round off the ends of the plate with the fillet feature?

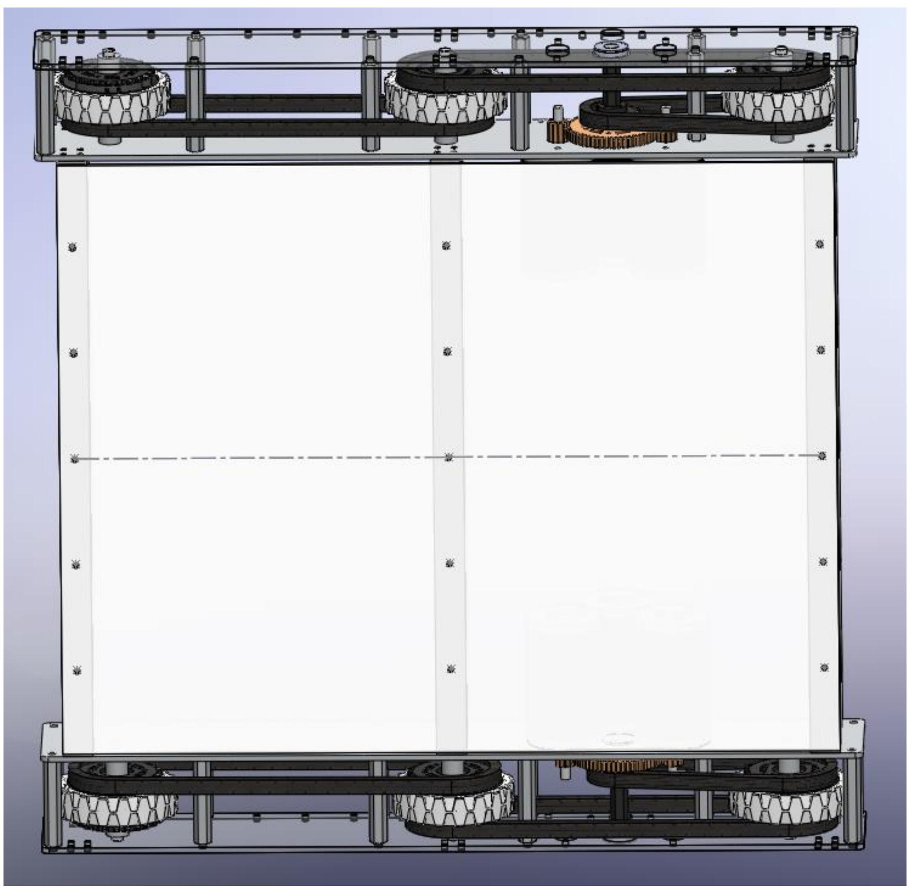


The drive rail should look like this now. Add some slots and mounting holes to the cross bars.



The slots will reduce weight and act as access holes for putting nuts on the inside of the tubes.

Now put in a belly pan of some sort for electrical mounting.

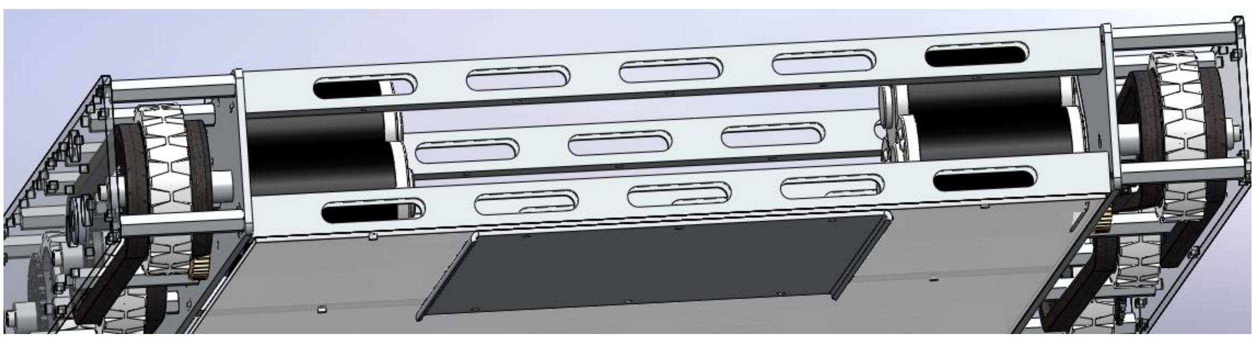


Next we are going to need a place to put a battery.

For simplicity's sake we are just going to lay it on its side and just use an off the shelf part to keep it from sliding. Typically whenever possible we try to find an existing part or modify an existing part instead of making one from scratch, as it saves time and effort.

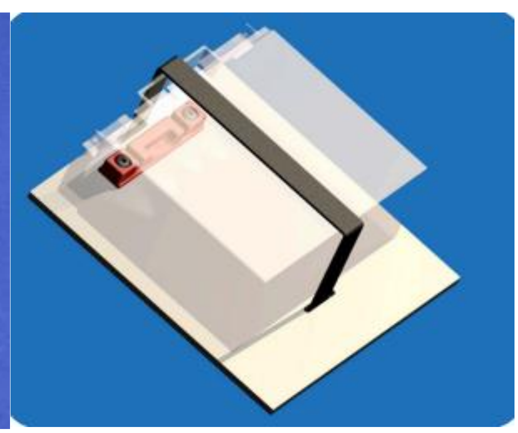
We are going to put the battery in the back along with the gearbox and CIMs. At first this seems counter intuitive as we have all our weight in the back. Depending on whatever else goes on the robot you might want to balance out the robot weight by shifting the battery around. For us we want to put all out weight in the back. Think back to the beginning; we raised the front wheels 1/8 of an inch. Now we could centre our weight distribution but that would mean we flop between the back to wheel and front two wheels often. If we can keep all the weight in the back we will stay on our back two wheels most of the time.

We're going to lay the battery in-between the CIMs. The battery does weigh a good 15lb so we are going to need a bit more than just the Lexan belly pan to support it. Add a 1/8 sheet of aluminum underneath the Lexan spanning from the middle cross bar to the back one. Add two small flanges to the sides of the sheet as they will add a lot more rigidity to the part.



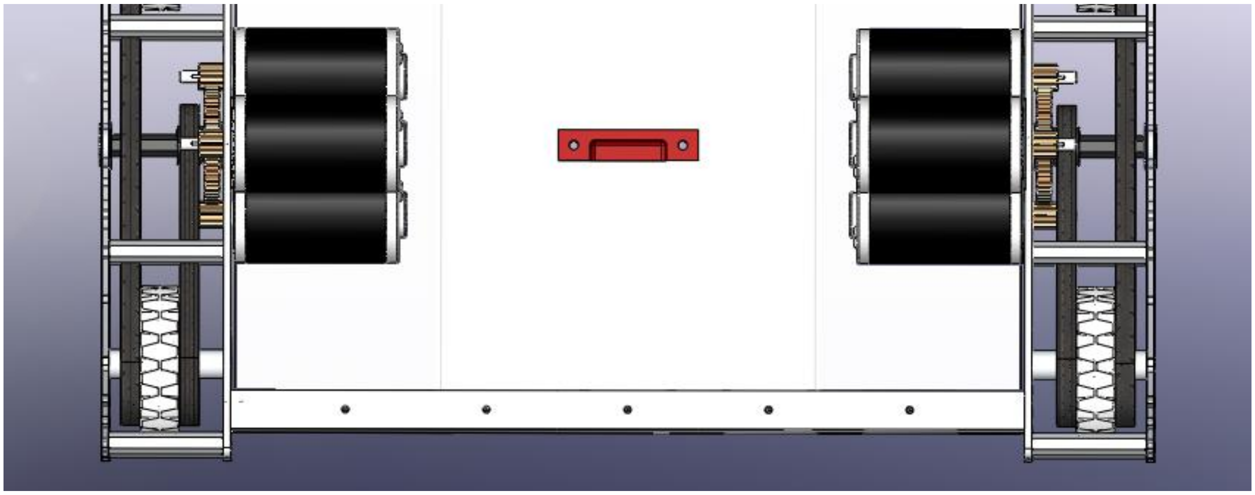
You should end up with something like this.

To secure the battery we are going to use this part:

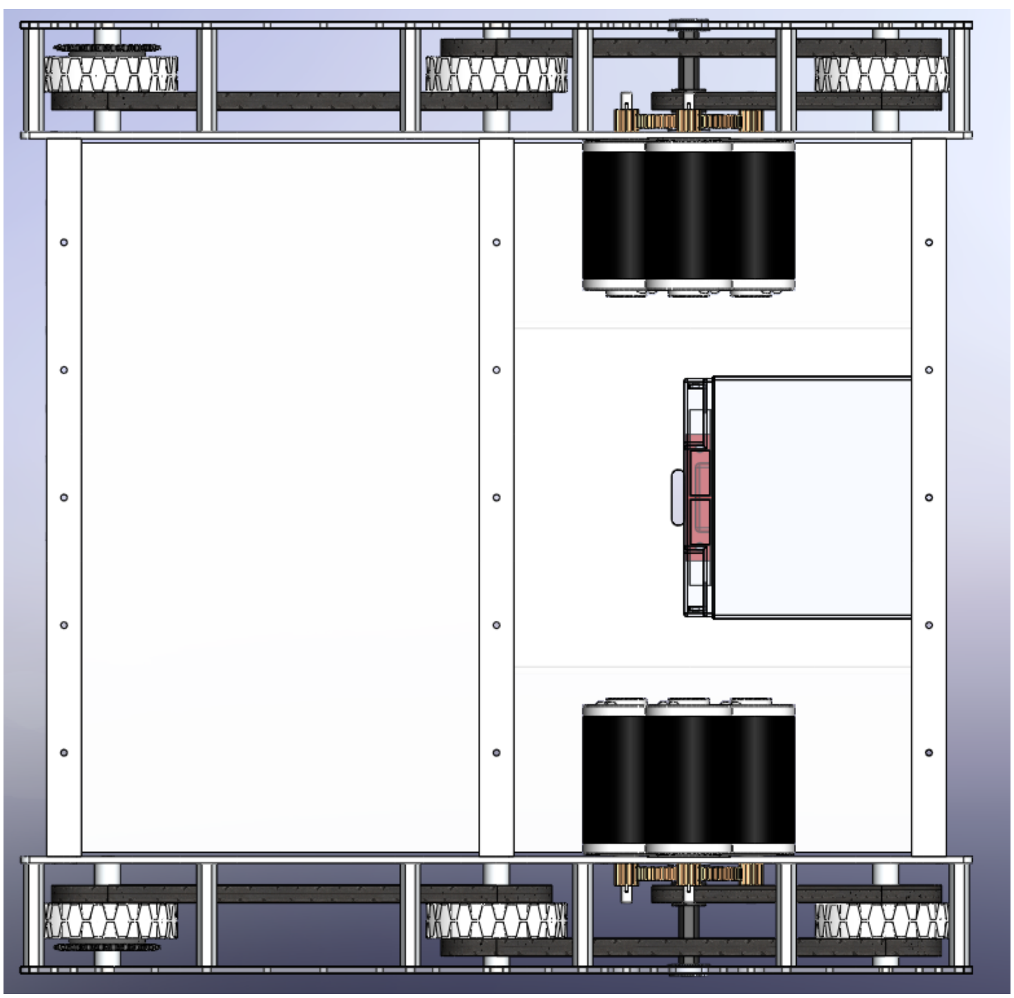


And here is the hole layout.

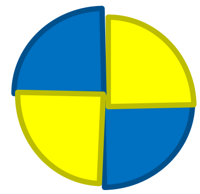
Put in the holes and in the part.



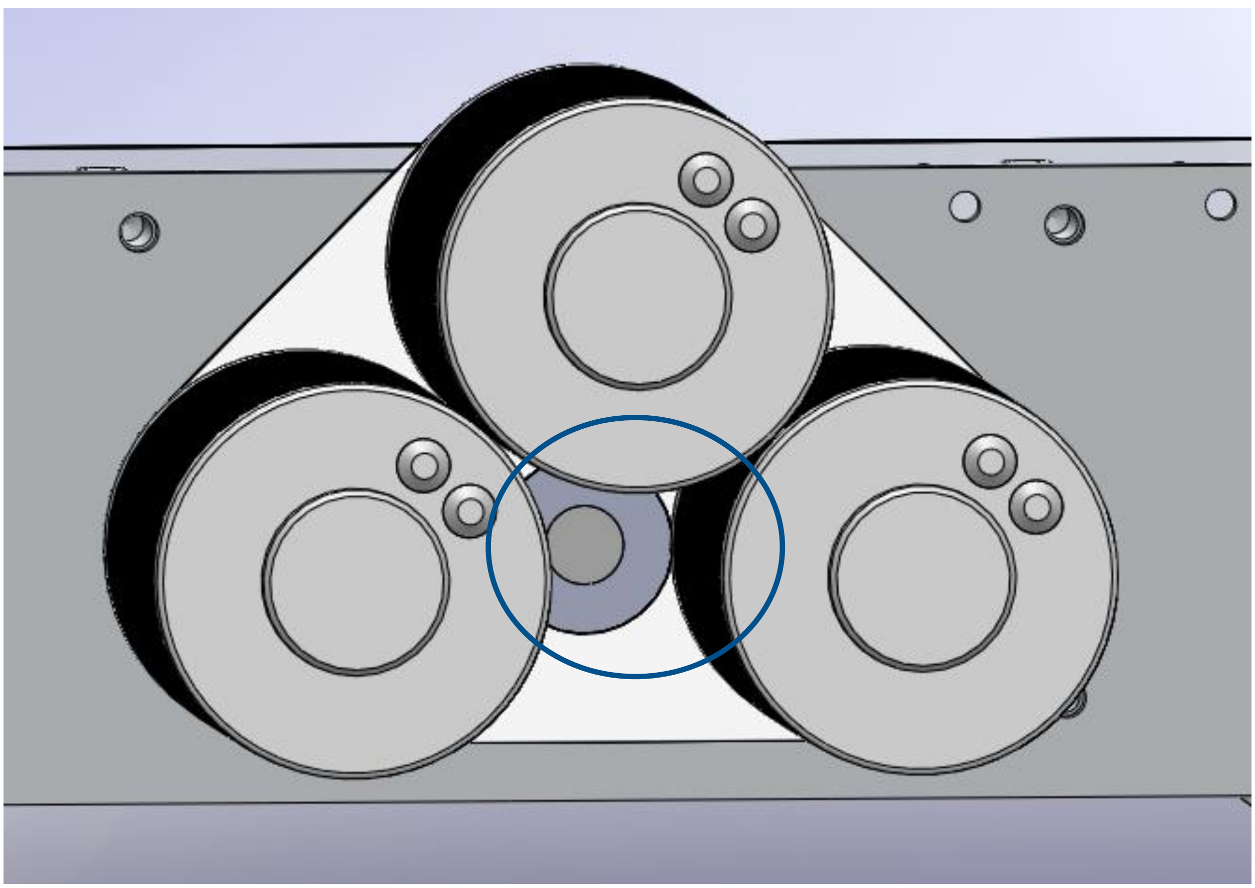
Place the battery in then add a slot for the Velcro in the front. We’ll have the battery butt up right against the back bar so don’t worry about putting a slot for Velcro there.



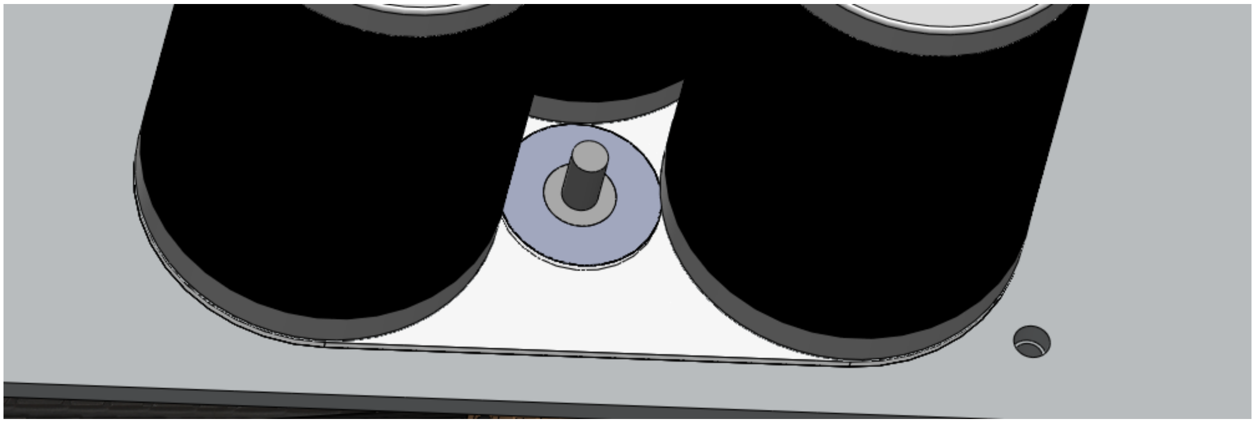
That basically sums up all the major features, now for some of the smaller things that we want to add on. An encoder for those who don't know is basically a rotation sensor. It counts the number of rotations a shaft makes. Without getting into too much detail, basically how it works is there is an encoder disk made up of a light and dark region. As the disk spins an optical sensor records the amount of times it changes from dark to light. One thing to note about encoders is that they are kind of sensitive. Which is also one of the reasons we use a piece surgical tubing almost as a "universal joint" so that we don't break the encoder with any slight misalignment of the shafts. This will make more sense later.



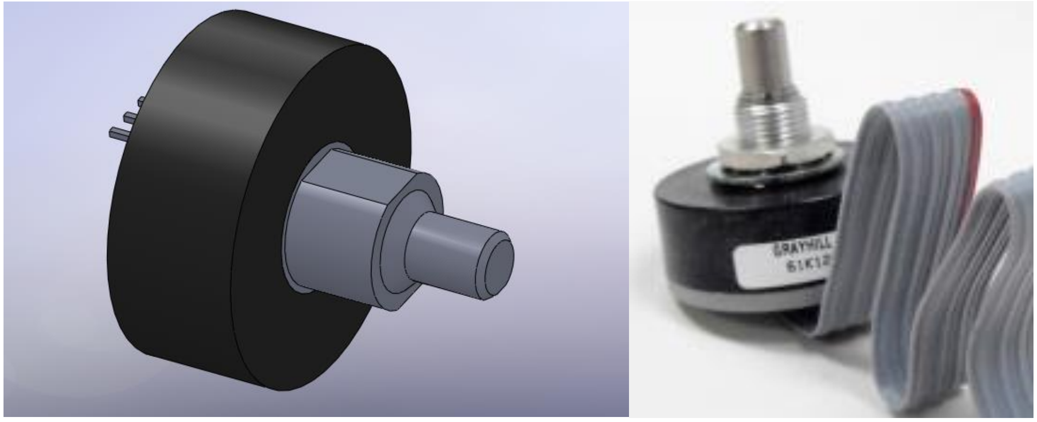
There is only one shaft that actually spins on this robot so we're going to have to use that one or we're going to have to put in a new gear.



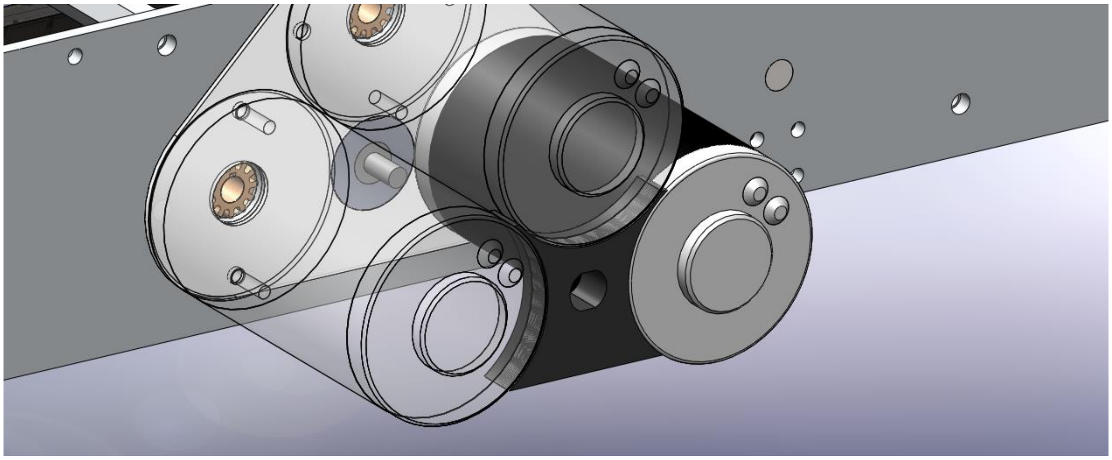
Here's where the encoder will end up. Take the gear box shaft and make a small extension of diameter .25 about .5 inches long coming off the end of the shaft.



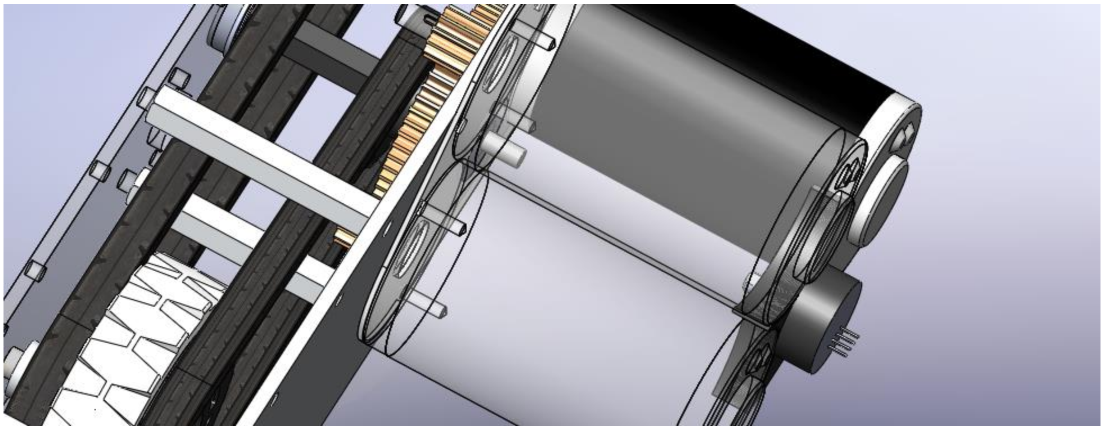
Next, open up the GreyHill encoder and take a look at it.



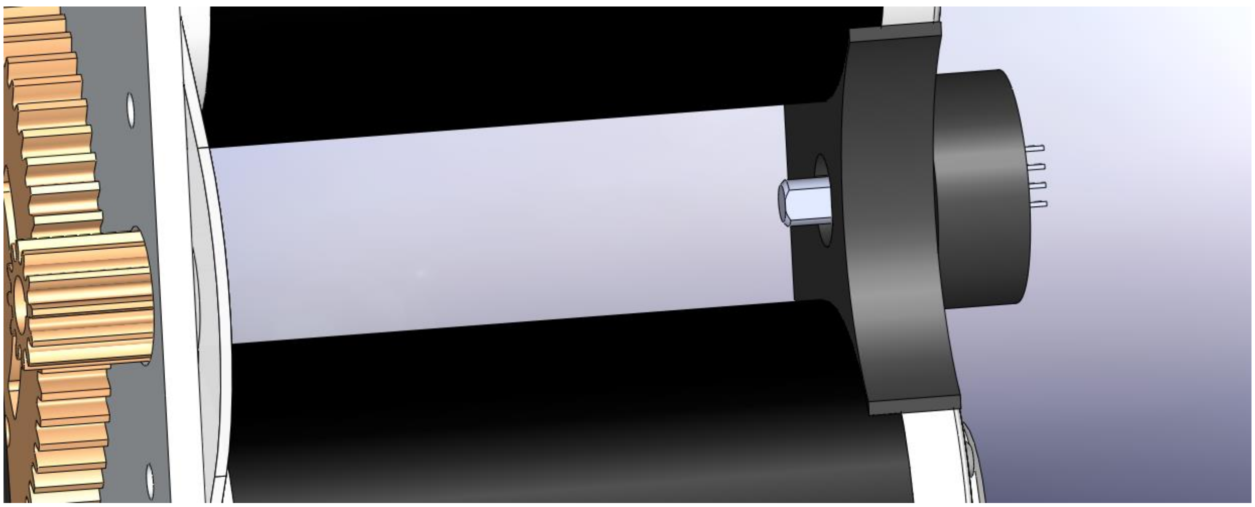
The black part is the encoder itself. The middle larger round part is threaded (not shown in the CAD) and the thin outer part is the part of the shaft that spins. A nut goes over the treaded part to face mount the encoder. We're going to make a plastic part that this encoder rests on that sits in-between the CIMs.



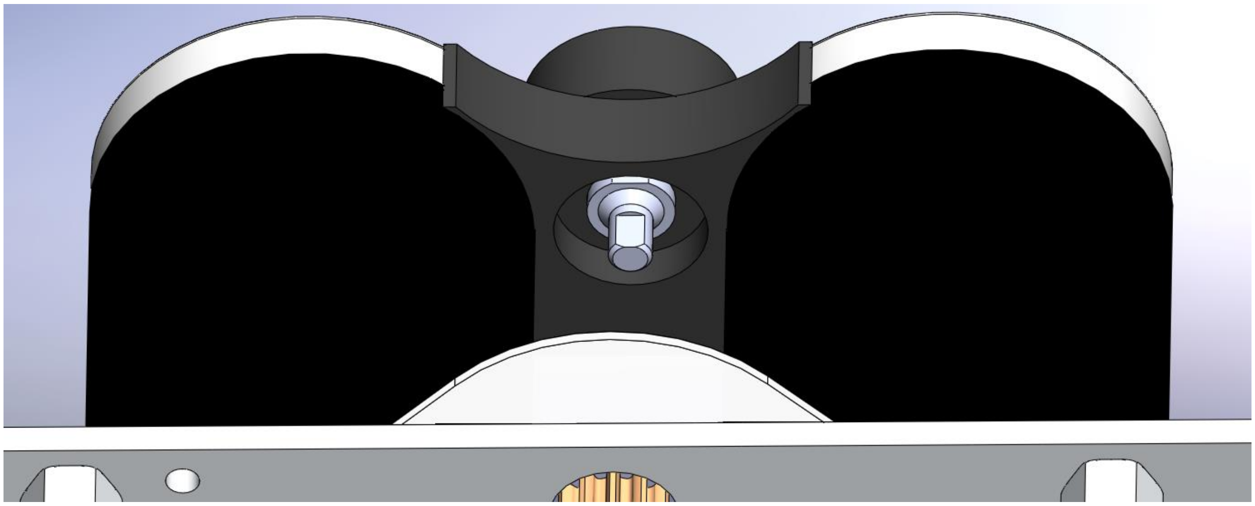
Put the encoder on the part. Notice the hole with the 2 flat parts.



A piece of surgical tubing wrapped around both shafts will connect the encoder to the gearbox shaft. There isn't must resistance/force on the encoder so "floating" it there (i.e. not holding it in place with anything really) has worked just fine for us for many years.



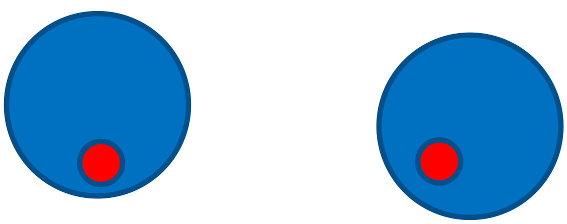
Here's a problem. The threads aren't long enough and don't go through the plastic. We can make the plastic thinner or cut a recess in the part for a nut.



Now the nut will go on!

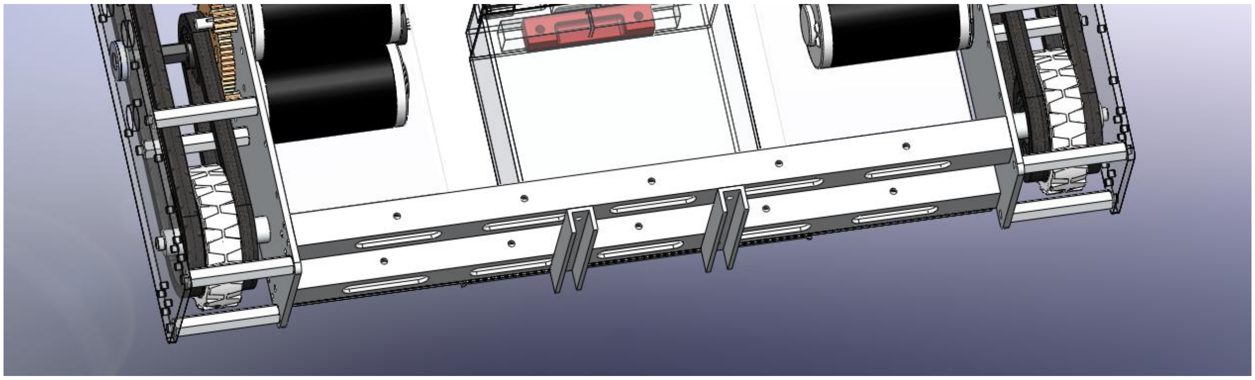
One brutal omission to this tutorial has been chain tensioners. Not only is it hard to get the chain spacing just right, but chain also stretches over time and as it stretches, slop builds up in the chain.

How we will work it is there will be a small sprocket on a shaft that is attached to the frame on an eccentric hole (the red dot). As you rotate the shaft, the height of the sprocket changes as well, allowing you to tighten the chain run. The only problem with this is that we can very quickly max out the chain tensioner. In 2013 even with the chain tensioner maxed out and a massive amount of slack on the chain run, we never had any skipping or derailing problems with the chain.



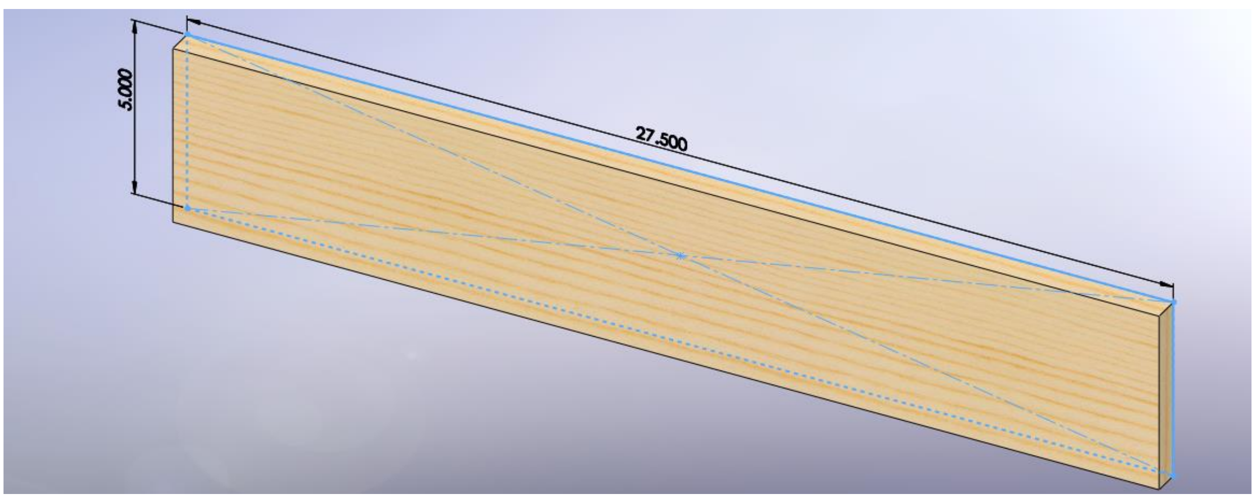
So for this drive train in an effort to keep thing simple, we're just going to skip the whole chain tensioning business and use #35 chain (stretches less) and the largest sprockets possible (less prone to skipping). If you find out you need a tensioner you can always add something.

The drive is essentially done now. The next step is bumpers. One of the things you may have noticed is that the front and rear cross bars are set back from the front of the robot. Bumper rules say that the bumper can't be unsupported for more than 8 inches. So here we have added pieces to the front and back of the robot to fill in the gap.

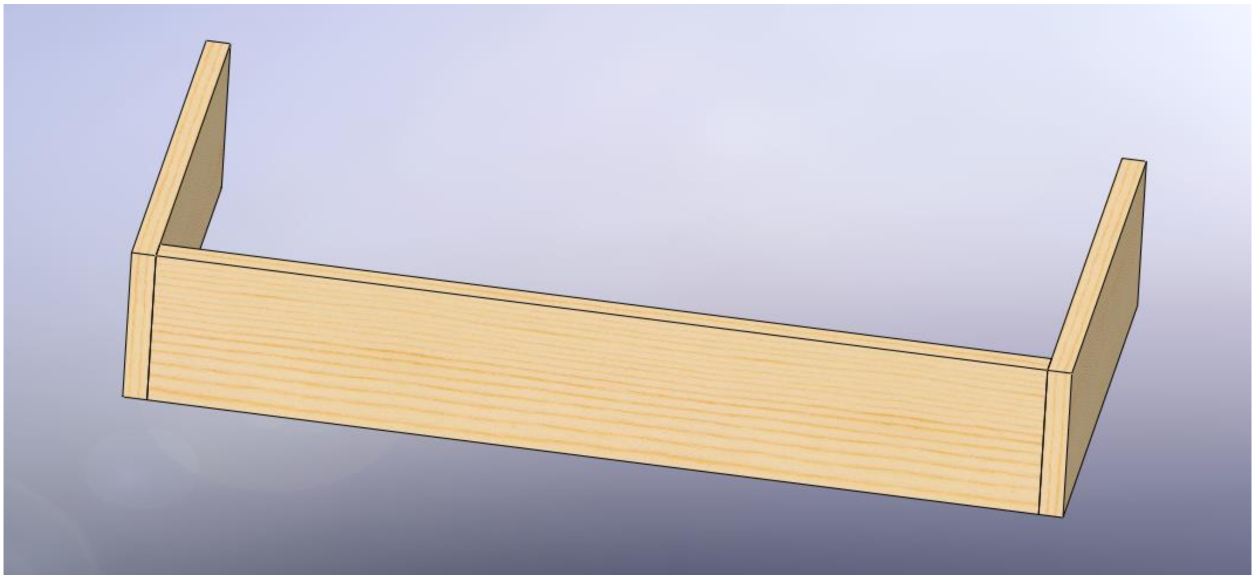


If you are wondering why we didn't push the bar all the way up to the edge of the robot, here are the reasons: You want the wheels as far up forward as possible to prevent the robot from tipping. You also need a standoff in front of the wheel or else the plates will just split when you hit something. Thus the standoffs must be pushed up as far as possible and the cross bar can't go there. Now one could say that if we moved them closer together we could push them all the way to the front and fit them in between the standoffs, however the further the cross bars are apart, the more rigid the frame. The difference is probably negligible, but these bars will come in handy when we try to attach the bumpers, so, like most things, it evens out.

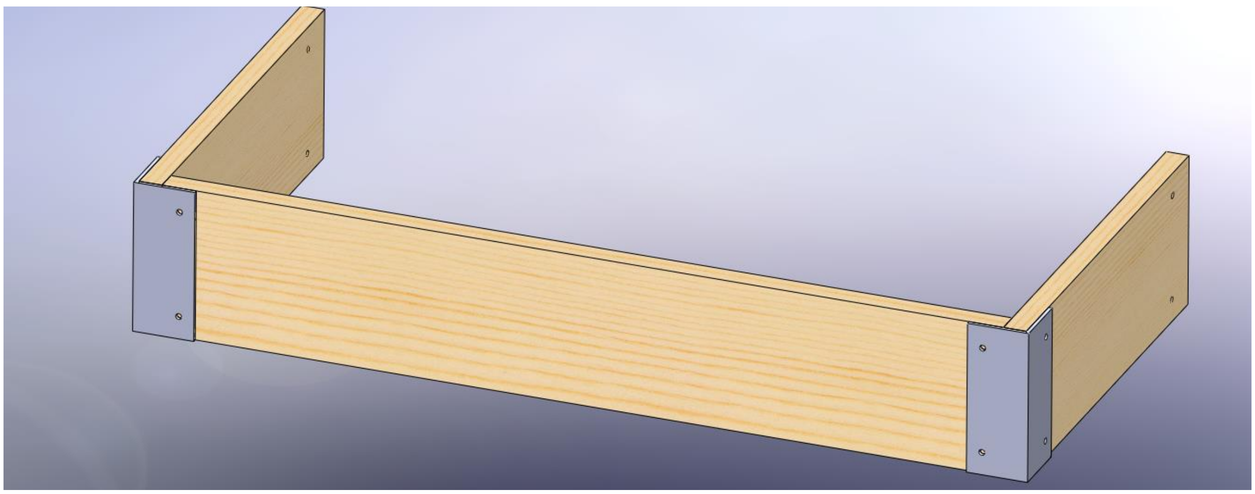
Now we are going to tackle bumpers. We'll start with a piece of wood 5inches tall by 27.5 (length of drive) and ¾ thick as per the rules.



Make another piece that is half that length and put them into an assembly. We are going to make the bumpers in two halves, two "C"s that go on either side.

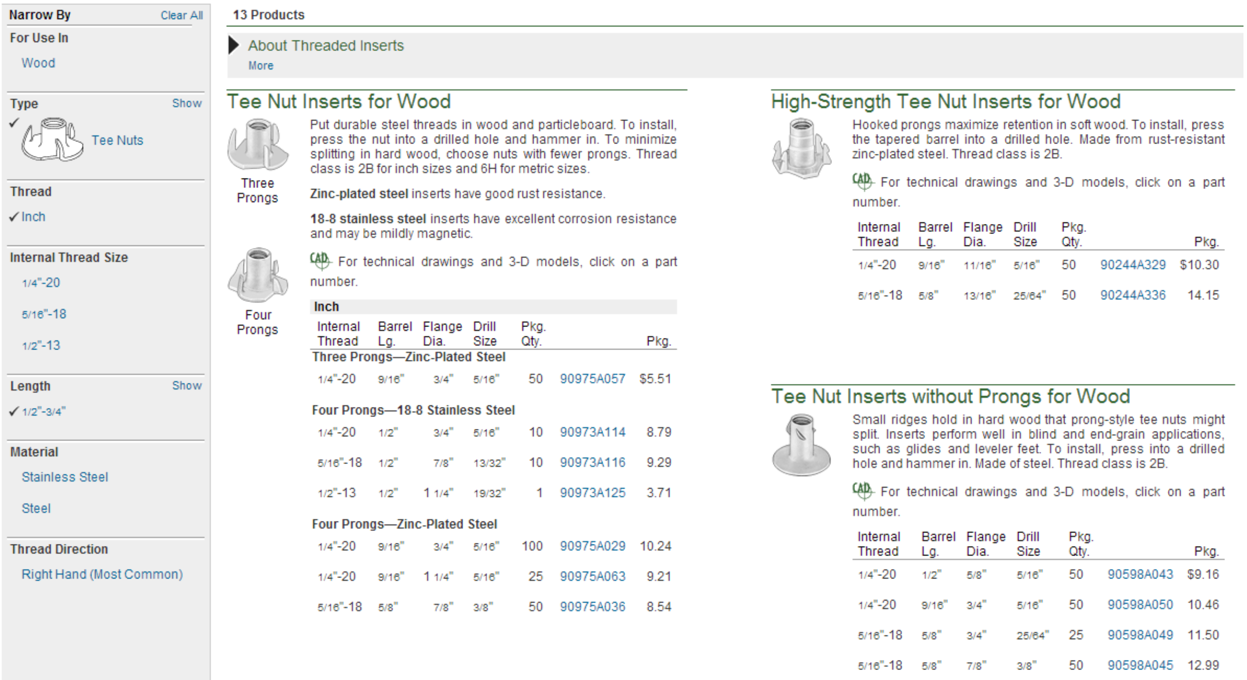


Here is one half of the bumpers. Next we are going to make some aluminum brackets to hold it in place out of a piece of 2 x 2 x 1/8 thick L channel. Use a #10 screw.



If you look carefully, you will notice on the two short pieces of wood, holes were added on both sides. This is a pretty simple part but this is done keep all the parts the same and symmetrical so we don't have to keep track of left hand and right hand parts. Here, putting the extra hole in isn't going to take much more effort, especially if we are going to CNC router it. In general it just helps to keep parts the same. The brackets are actually also the same on both sides so we don't have to keep track of which side is which and the holes on the plywood are made to compensate for that.

Now we realise that there is a small problem. If we assemble this with screws and nuts, the nut or screw head will be sticking out and collide with the drive. Because of this, we've got to find a way to fasten it such that a nut doesn't stick out, we could counter bore the wood but that would require more machining. Instead we are going to use a threaded insert. Let go see what our options are.



Narrow By — Clear All

For Use In: Wood

Type (Show): ✓ Tee Nuts

Thread: ✓ Inch

Internal Thread Size: 1/4"-20; 5/16"-18; 1/2"-13

Length (Show): ✓ 1/2"-3/4"

Material: Stainless Steel; Steel

Thread Direction: Right Hand (Most Common)

13 Products

About Threaded Inserts
More

Tee Nut Inserts for Wood

Three Prongs / Four Prongs

Put durable steel threads in wood and particleboard. To install, press the nut into a drilled hole and hammer in. To minimize splitting in hard wood, choose nuts with fewer prongs. Thread class is 2B for inch sizes and 6H for metric sizes.

Zinc-plated steel inserts have good rust resistance.

18-8 stainless steel inserts have excellent corrosion resistance and may be mildly magnetic.

CAD For technical drawings and 3-D models, click on a part number.

Inch

Internal Thread	Barrel Lg.	Flange Dia.	Drill Size	Pkg. Qty.		Pkg.
Three Prongs—Zinc-Plated Steel						
1/4"-20	9/16"	3/4"	5/16"	50	90975A057	$5.51
Four Prongs—18-8 Stainless Steel						
1/4"-20	1/2"	3/4"	5/16"	10	90973A114	8.79
5/16"-18	1/2"	7/8"	13/32"	10	90973A116	9.29
1/2"-13	1/2"	1 1/4"	19/32"	1	90973A125	3.71
Four Prongs—Zinc-Plated Steel						
1/4"-20	9/16"	3/4"	5/16"	100	90975A029	10.24
1/4"-20	9/16"	1 1/4"	5/16"	25	90975A063	9.21
5/16"-18	5/8"	7/8"	3/8"	50	90975A036	8.54

High-Strength Tee Nut Inserts for Wood

Hooked prongs maximize retention in soft wood. To install, press the tapered barrel into a drilled hole. Made from rust-resistant zinc-plated steel. Thread class is 2B.

CAD For technical drawings and 3-D models, click on a part number.

Internal Thread	Barrel Lg.	Flange Dia.	Drill Size	Pkg. Qty.		Pkg.
1/4"-20	9/16"	11/16"	5/16"	50	90244A329	$10.30
5/16"-18	5/8"	13/16"	25/64"	50	90244A336	14.15

Tee Nut Inserts without Prongs for Wood

Small ridges hold in hard wood that prong-style tee nuts might split. Inserts perform well in blind and end-grain applications, such as glides and leveler feet. To install, press into a drilled hole and hammer in. Made of steel. Thread class is 2B.

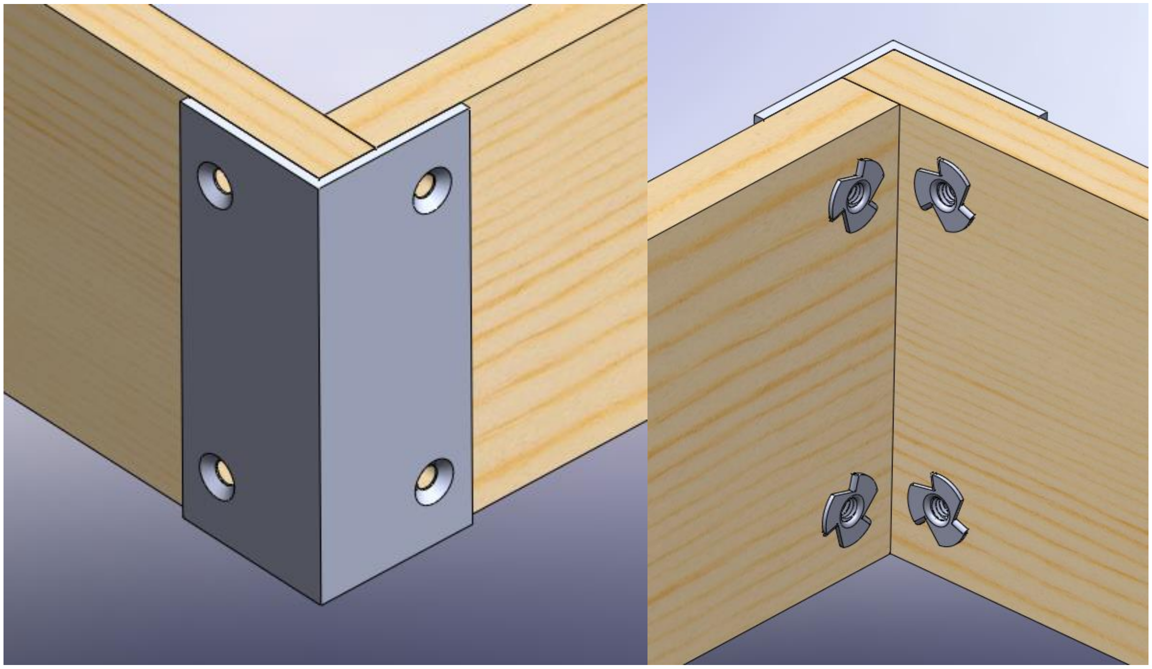
CAD For technical drawings and 3-D models, click on a part number.

Internal Thread	Barrel Lg.	Flange Dia.	Drill Size	Pkg. Qty.		Pkg.
1/4"-20	1/2"	5/8"	5/16"	50	90598A043	$9.16
1/4"-20	9/16"	3/4"	5/16"	50	90598A050	10.46
5/16"-18	5/8"	3/4"	25/64"	25	90598A049	11.50
5/16"-18	5/8"	7/8"	3/8"	50	90598A045	12.99

These “Tee Nut” insets basically push into the side of the wood and act as a nut while remaining flush with the wood. To help make our decision, we don’t want anything longer than the thickness of the wood, we don’t really care about the strength, and let’s stick with a 1/4-20 screw because that what we are used to.

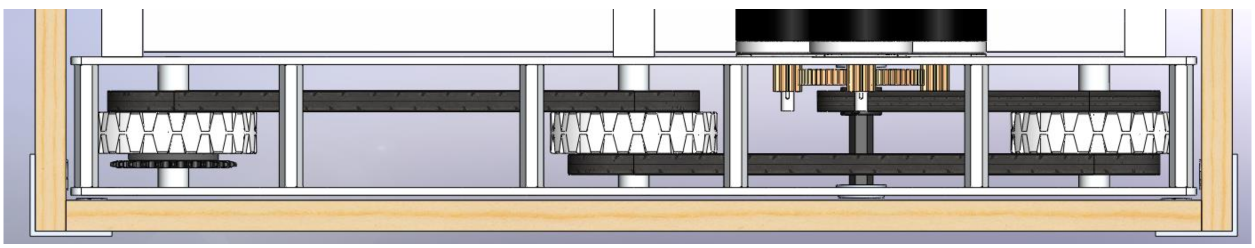
While we are at it, we might as well counter-sink the bracket so the screw head sits flush. In the holes wizard, there is a counter sink option and it will automatically put it in for you.

Choose an insert and you will see that you will need to drill the hole a bit bigger. CADs and drawing also exist for these so you might want to download a CAD file.

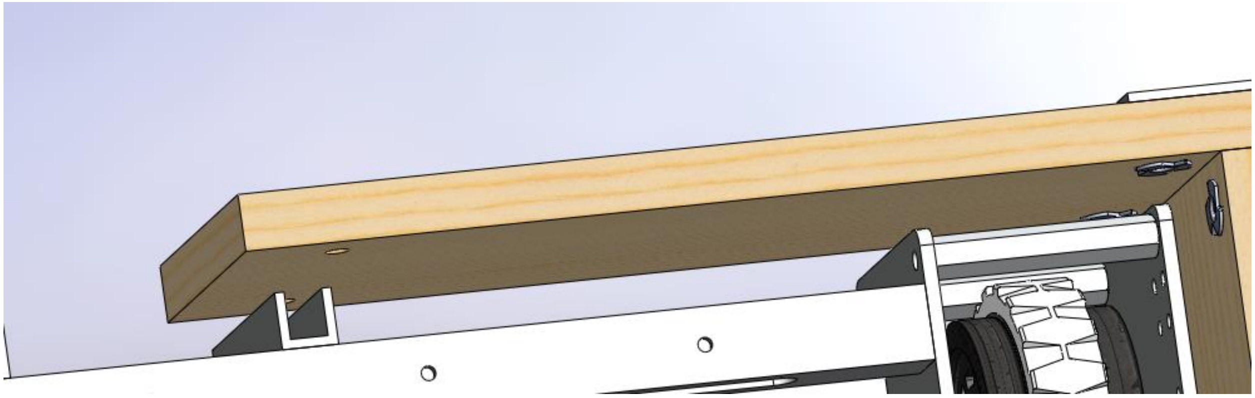


As you can see the heads sit flush but still pop out a tiny bit so well make the board slightly longer than 27.5" so that it fits on nicely. Change the length to 27.75 (that gives us 1/8" of tolerance on each side). Now let's look at how we'll mount this to the frame. Save the bumper assembly and this assembly into the drive assembly. Whenever possible you want to work with sub-assemblies, it keeps everything much cleaner.

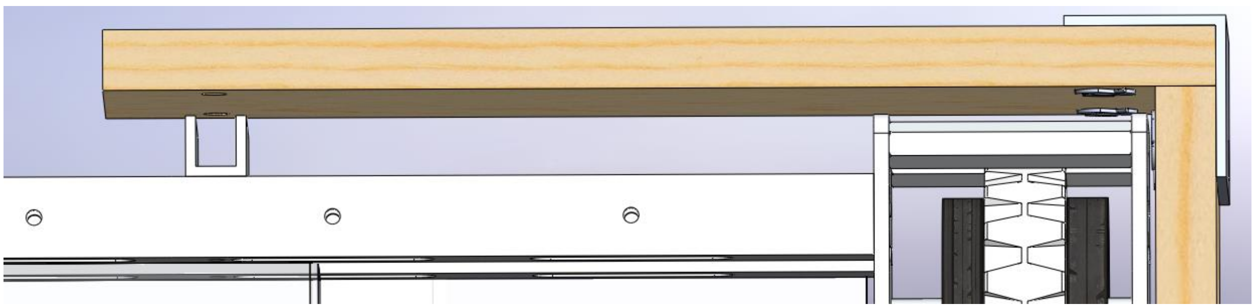
Put the bumper frame in place. You should have an 1/8" on all sides to account for the fabric, staples, screw heads from the drive frame etc.



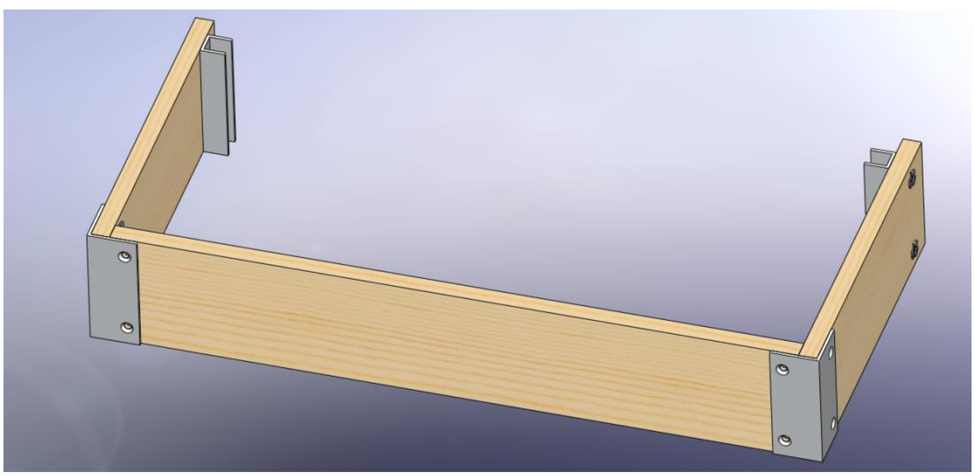
Thinking about how we are going to mount the bumper in such a fashion that they can be easily attached and detached, we notice that the C channels that we put in earlier would be a convenient place to slide the bumpers on. If we mount some sort of piece to the bumper such that it slides over or onto the C channel vertically we could lock it into place there.

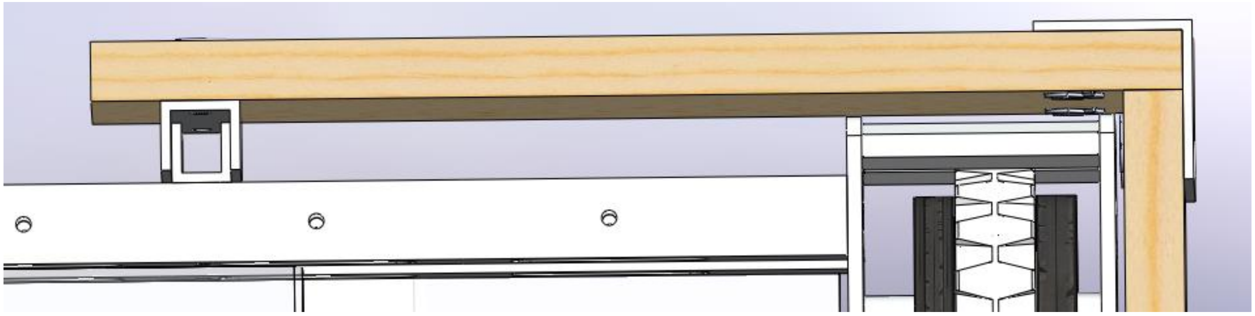


The mirrored holes that we put into the short piece of the bumper almost perfectly line up with the C channel. We don't want to change the hole on the plywood piece because that would change the bumper bracket and we don't want to make it asymmetrical but it's a pretty easy change to move the C channel over a tad, seeing as it is arbitrarily placed anyways.

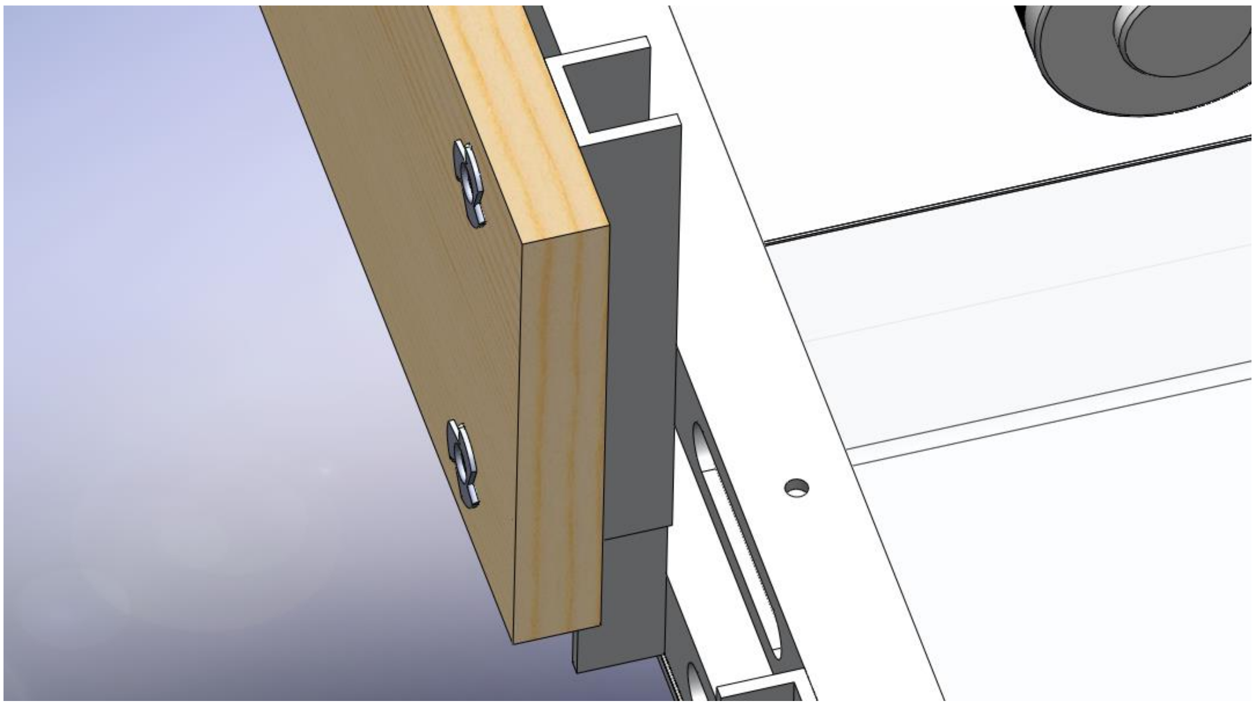


Now make a part that is attached to the bumper using those pre-existing holes that interfaces with that c channel.



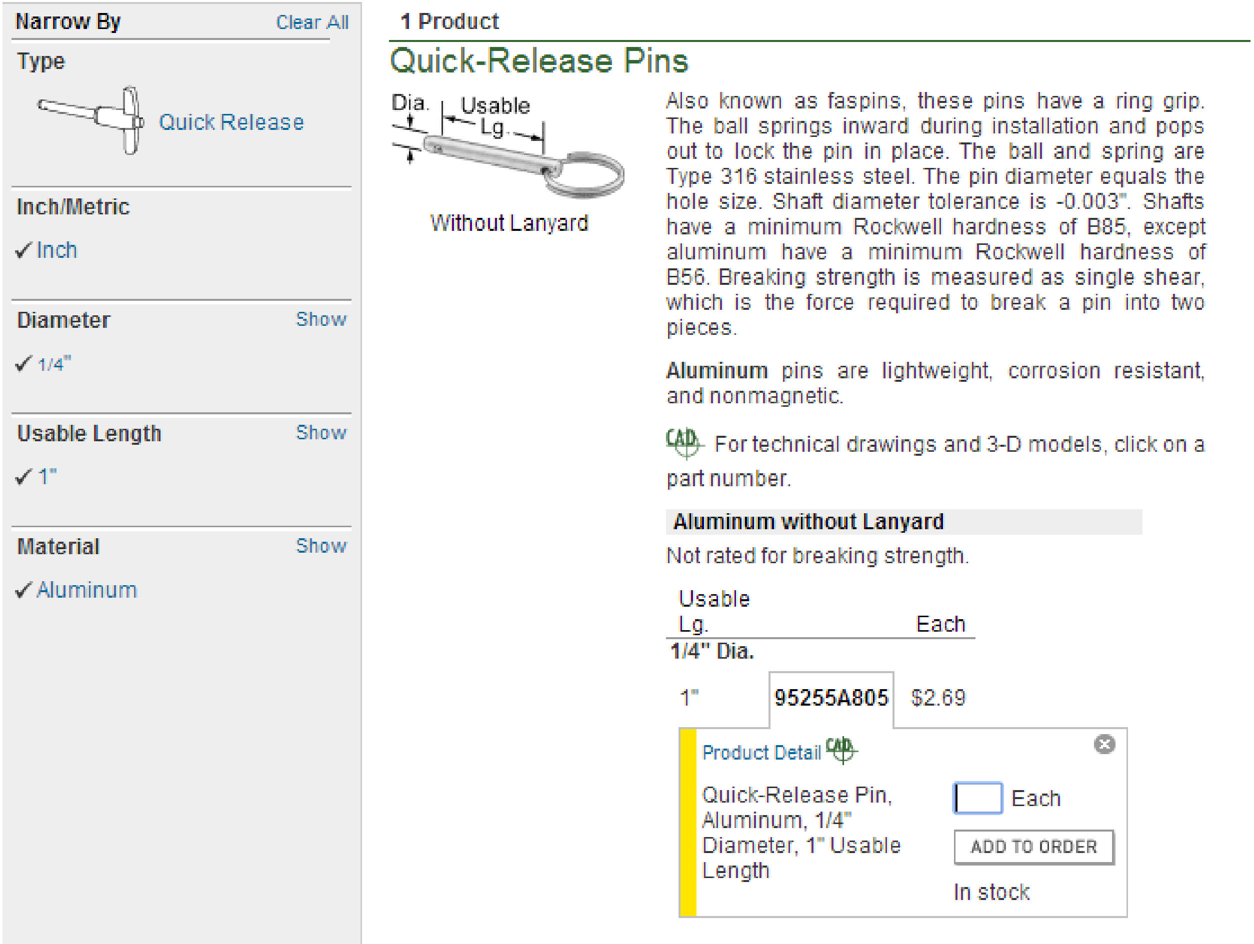


Some filling might be required to make it a smooth fit but it looks like it will work quite well. Note that the C channel is a 1 x .875 which probably doesn't exist but remember we can always take a 1X1 C and take it down an 1/8 of an inch.

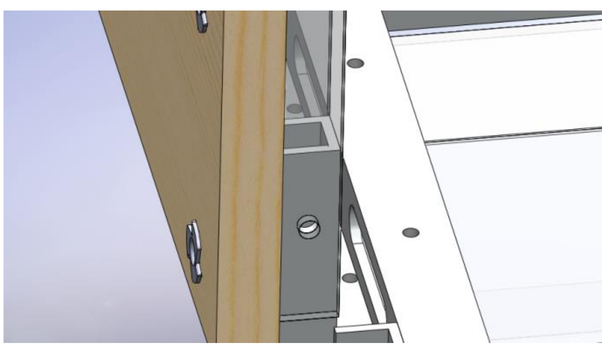


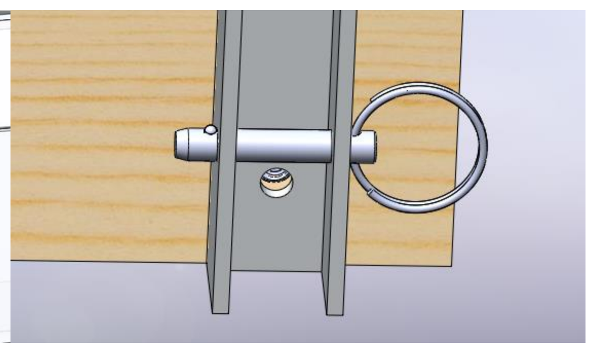
Next let's look at putting a pin though the side of both c channels. The channel will keep the bumper from sliding left right and front back but nothing is preventing it from sliding up.

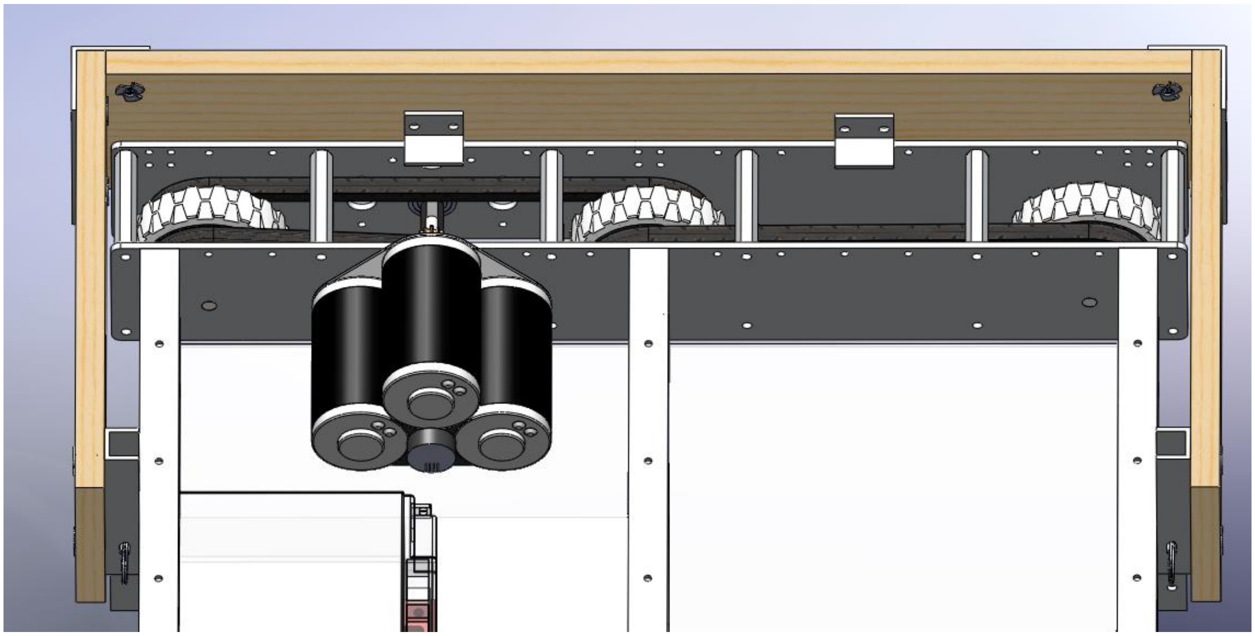
A quick search on McMaster Carr reveals a perfect part for the job



We'll download the part file while we are at it.



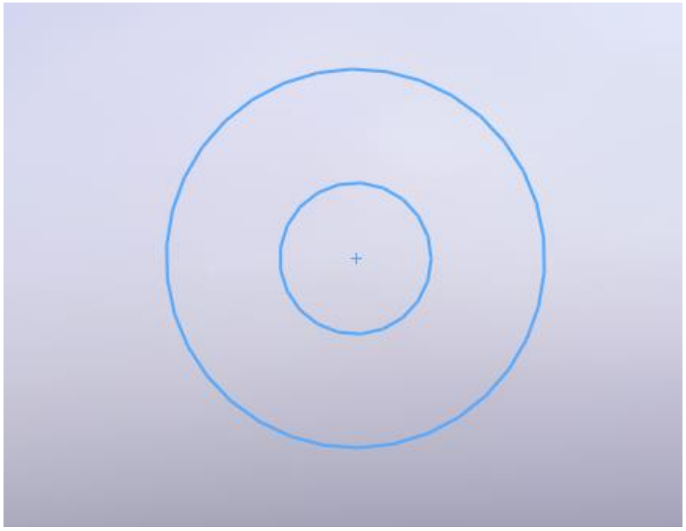




Add two small brackets to help support the bumpers. Have the brackets just rest on the drive rail. The bumpers (and all the parts for the bumpers) are essentially done. While we don't have "machine the pool noodle" it would be nice to see them in the design so that lets say we had an intake which extended outside the frame perimeter it would be good to know where exactly the intake goes to be able to better compensate for it.

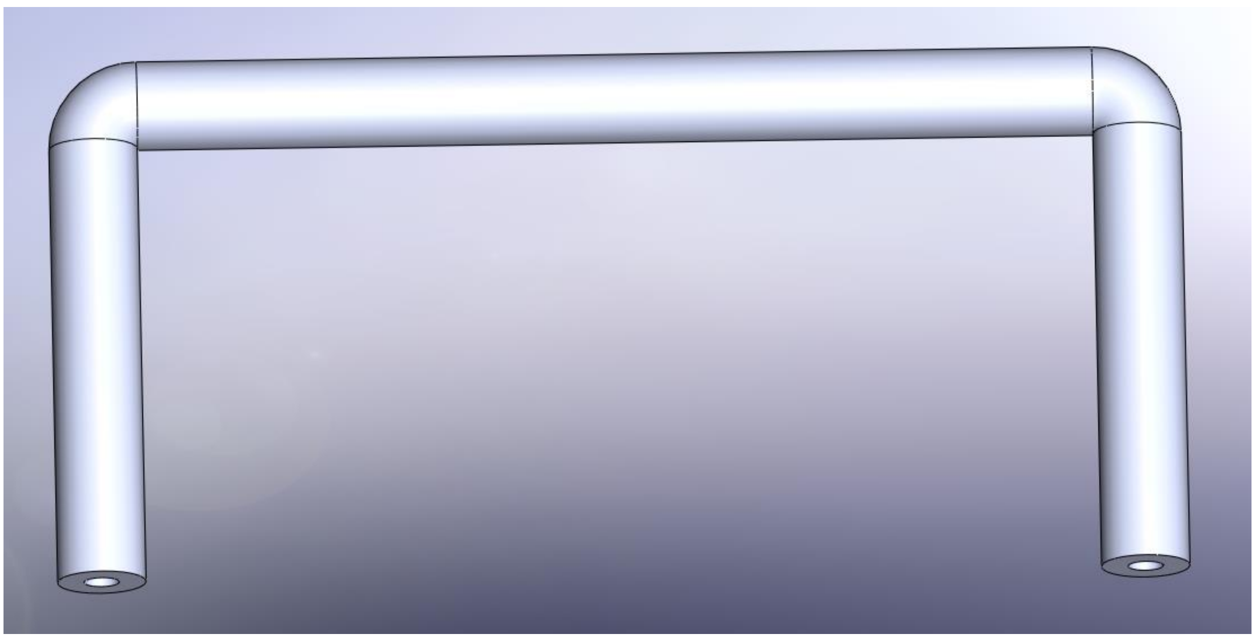
The pool noodle is a bit of an awkward part to CAD as it bends around the frame. Now we could just make it in a few several parts but we could also use the swept feature.

First draw a stack of pool noodles together.



Then draw a wire frame of where you want the pool noodle to go.

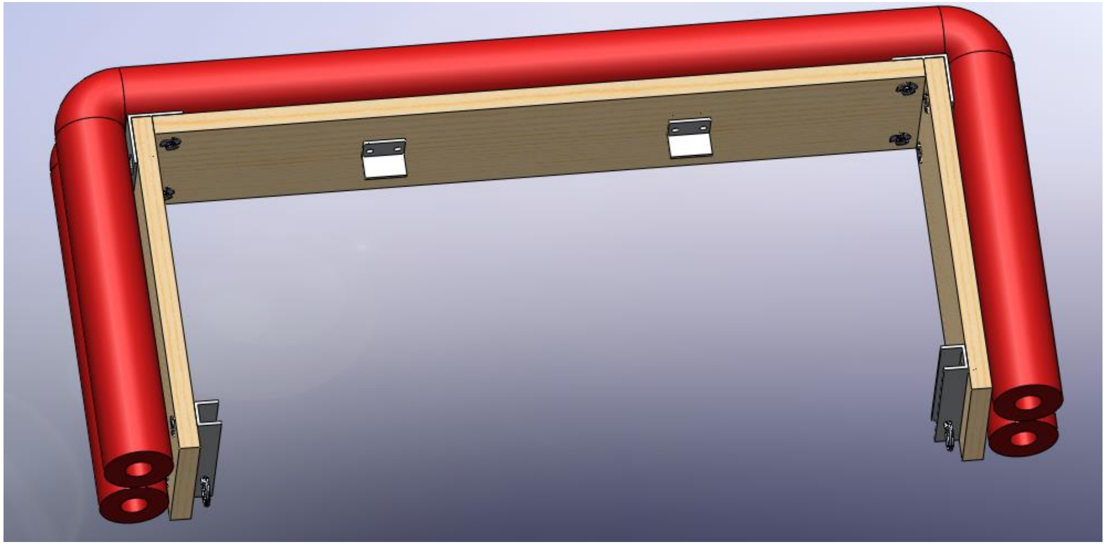
Make sure they start in the same place. Find the Swept Boss/Base Feature.



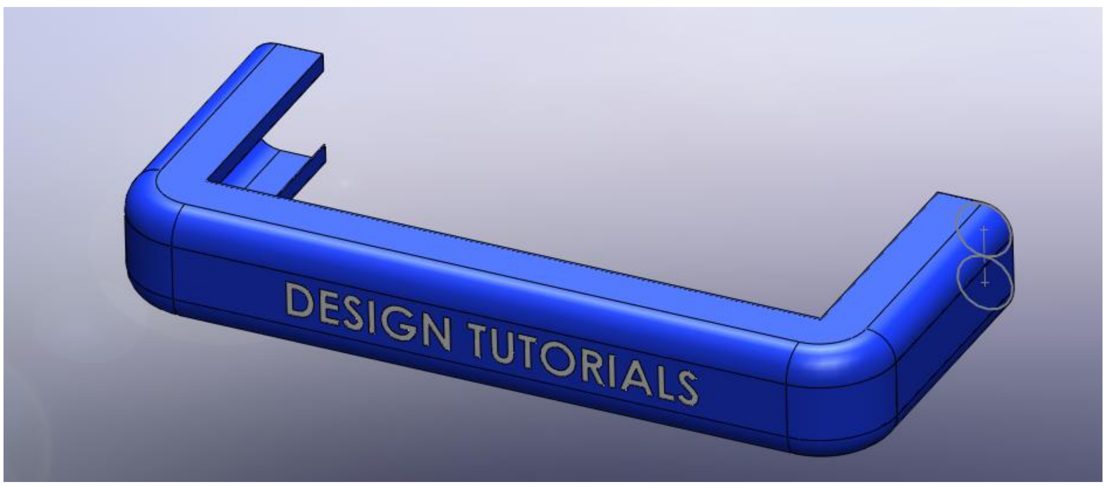
Give the wire frame a rounded corner if you want the noodle to have a nice rounded corner.

Set the colour and material of the bumper.

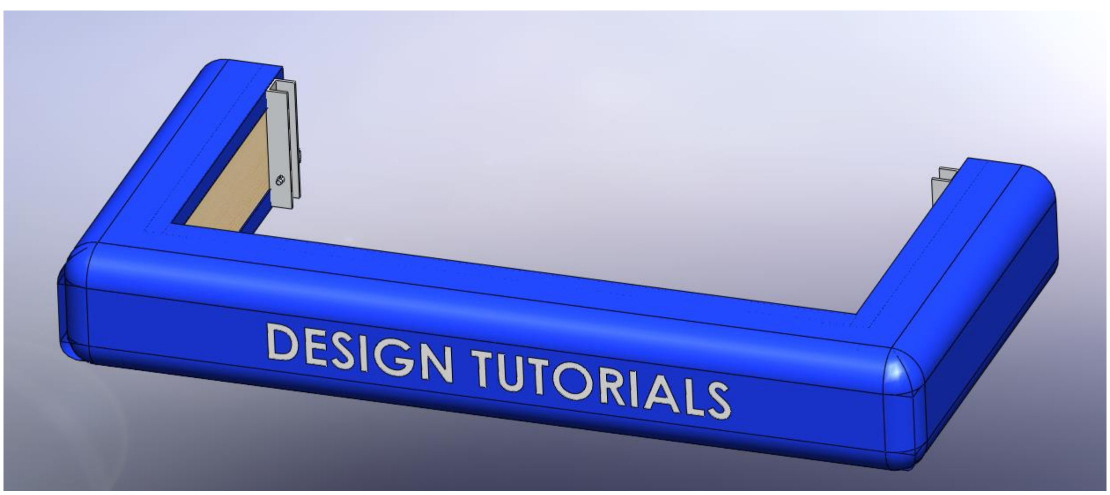
Set the noodles onto the frame.



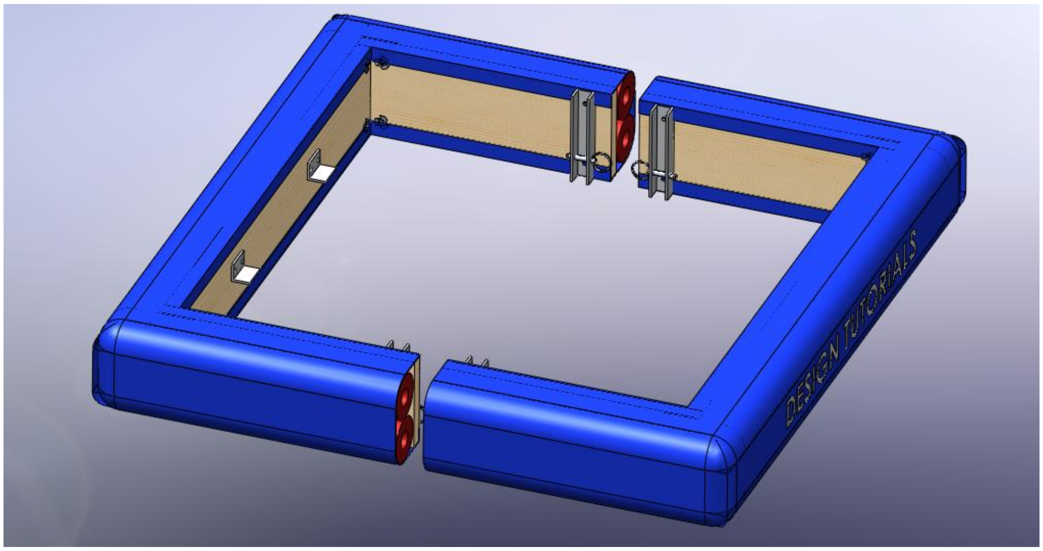
We'll make a fabric cover using the same technique.

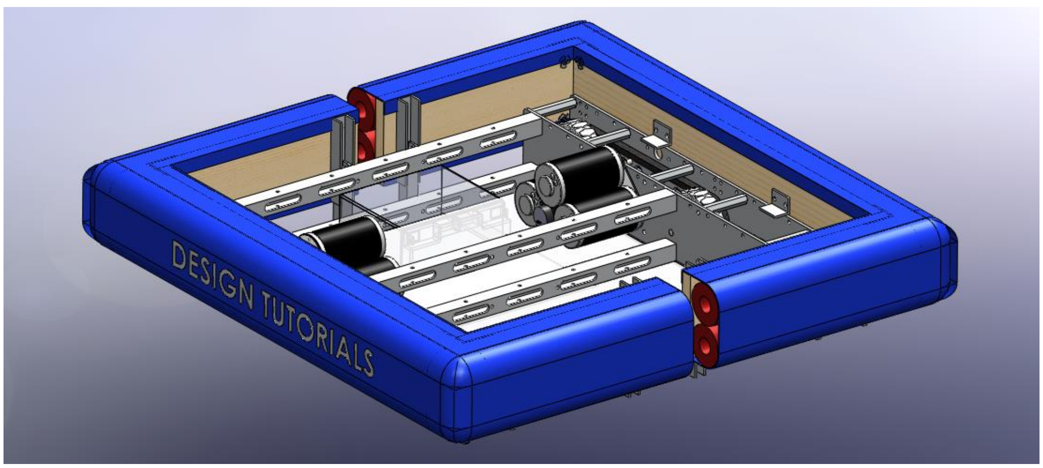


Add the cover into the bumper assembly.

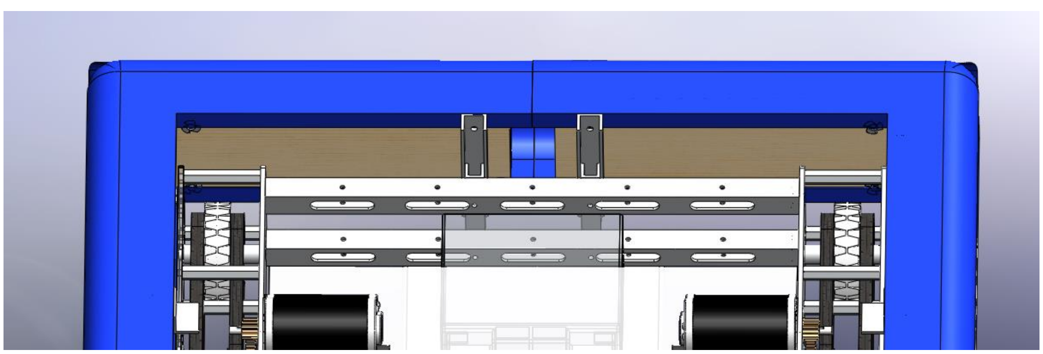


Mirror the assembly.

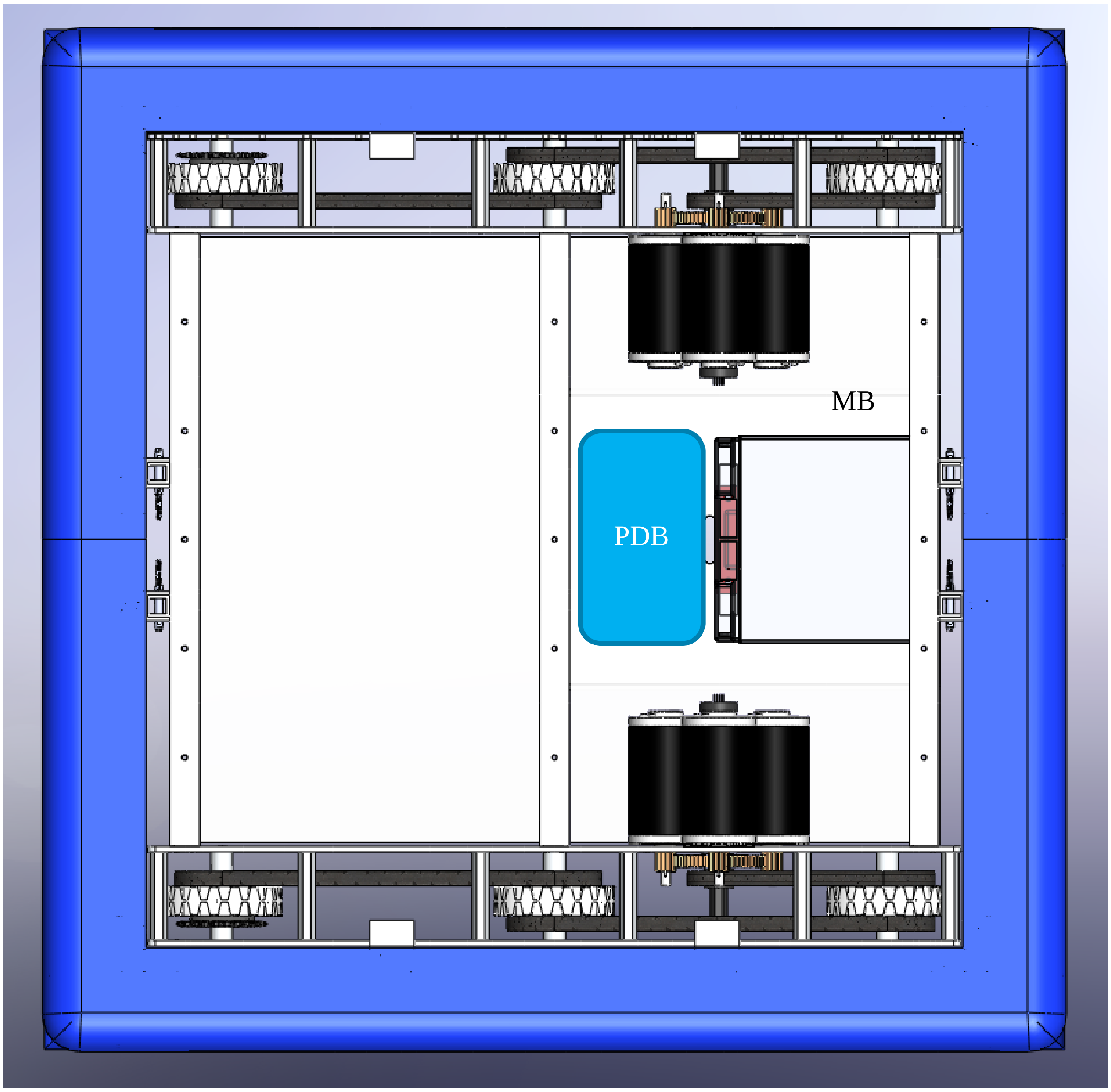




The crack in the bumpers is so that there's some room for the fabric to warp around the ends. For now its looks really awkward so we can just extend the fabric to close up the gap.

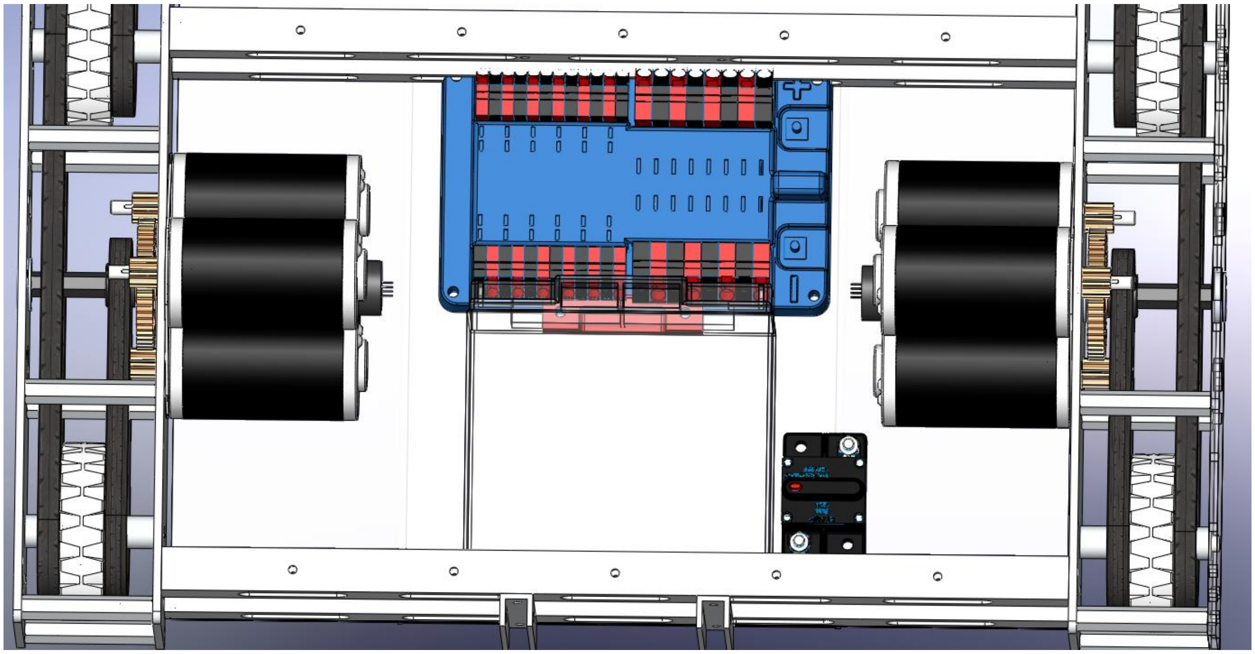


Now that the bumpers are done there isn't much left to do; time to put the electronics onto the board!



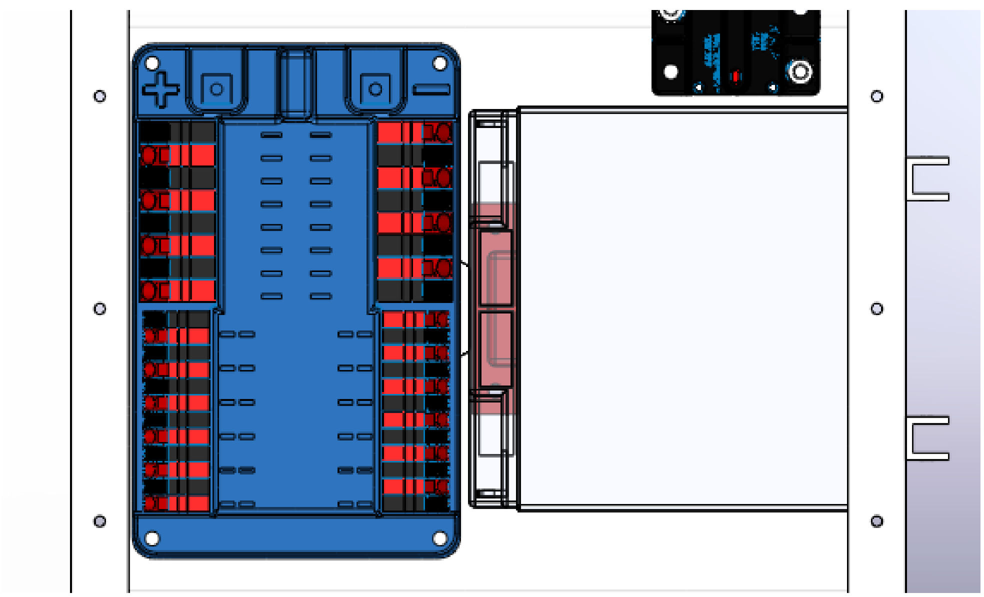
The battery we have already decided we want in the back with the CIMs to keep all the weight in the back (front wheels are raised). The PDB or power distribution board takes power from the battery and distributes it to everything on the robot, so we want to keep this close to the battery. MB represents the main breaker; it's the robots on/off switch and basically disconnects the PDB from the battery, so we want to keep that close by as well.

All of the electrical parts are in the design library so just drag the parts into the assembly. Mate the parts to the belly pan. Now you can slide the components around feely to figure out where they should go. After we are satisfied with the general layout of everything we'll make the mounting holes.



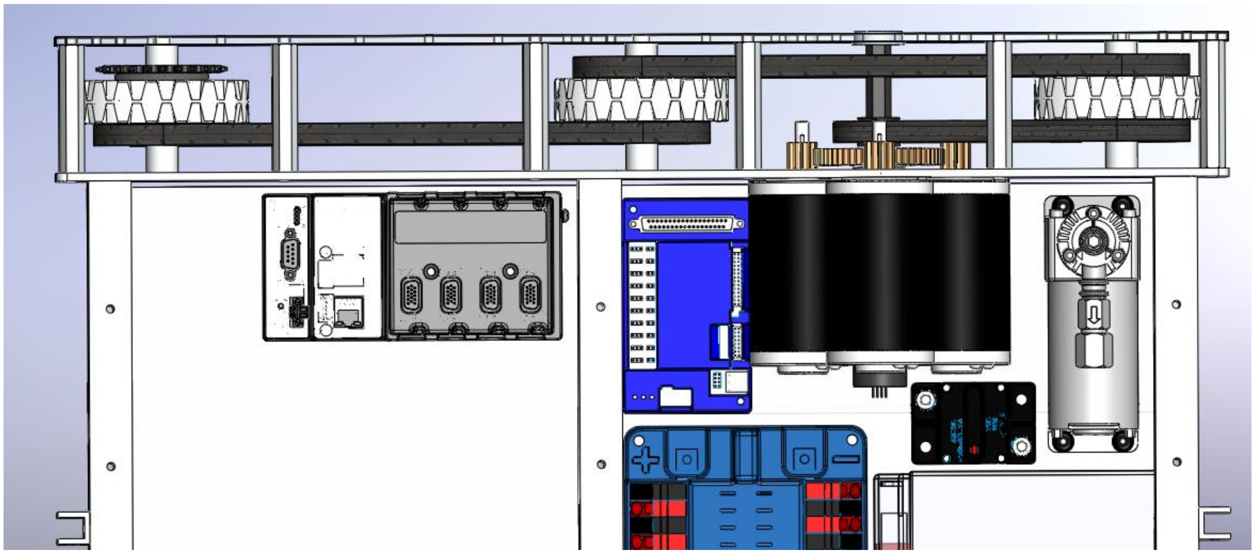
Immediately we realise there is a problem. It doesn't fit! Now we could put it on the other side of the cross bar but that would make the connections to the battery really long (typically you want the connection to be as short as possible as short wires are more efficient). We could put the PDB on the other side of the cross bar and move the battery forward and butt it up against the centre cross bar, however that would make changing the battery a pain and we want to keep as much of the weight as possible in the back. The next best solutions are to make the battery vertical, or we could move the cross bar forward. Moving the cross bar forward might be preferred as making a vertical battery holder would result in more parts to make.

Shift the centre cross bar up 1 inch. Make sure to also shift the holes for the belly ban up too.



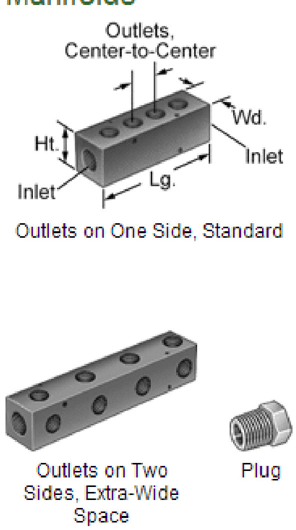
Small side note: since we are no longer working on the bumpers, and what we are doing is not affected by them, you can supress the bumper assembly so that it doesn't obstruct your view.

Fitting the larger and most important components first usually helps. Sliding the breaker over gives us just enough room for the compressor. The cRIO should also be close to the digital side car which we have shoved in a gap between the CIMs and cross bar.



For the pneumatics we'll need to get tubing manifold.

Manifolds



Aluminum Manifolds

No. of Outlets	Pipe Size Inlet	Pipe Size Outlet	Overall Size Lg.	Overall Size Wd.	Overall Size Ht.	Outlets, Ctr.-to-Ctr.	Mount. Hole Size		Each
Standard									
2	1/4	1/8	1 3/4"	1"	1"	3/4"	0.17"	5469K101	$13.68
2	3/8	1/4	2 1/8"	1 1/4"	1 1/4"	7/8"	0.20"	5469K103	15.62
2	1/2	3/8	2 3/4"	1 1/2"	1 1/2"	1"	0.20"	5469K105	18.18
3	1/4	1/8	2 1/2"	1"	1"	3/4"	0.17"	5469K111	14.89
3	3/8	1/4	3"	1 1/4"	1 1/4"	7/8"	0.20"	5469K113	18.15
3	1/2	3/8	3 3/4"	1 1/2"	1 1/2"	1"	0.20"	5469K115	19.21
4	1/4	1/8	3 1/4"	1"	1"	3/4"	0.17"	5469K121	17.08
4	3/8	1/4	3 7/8"	1 1/4"	1 1/4"	7/8"	0.20"	**5469K123**	18.36

Product Detail CAD

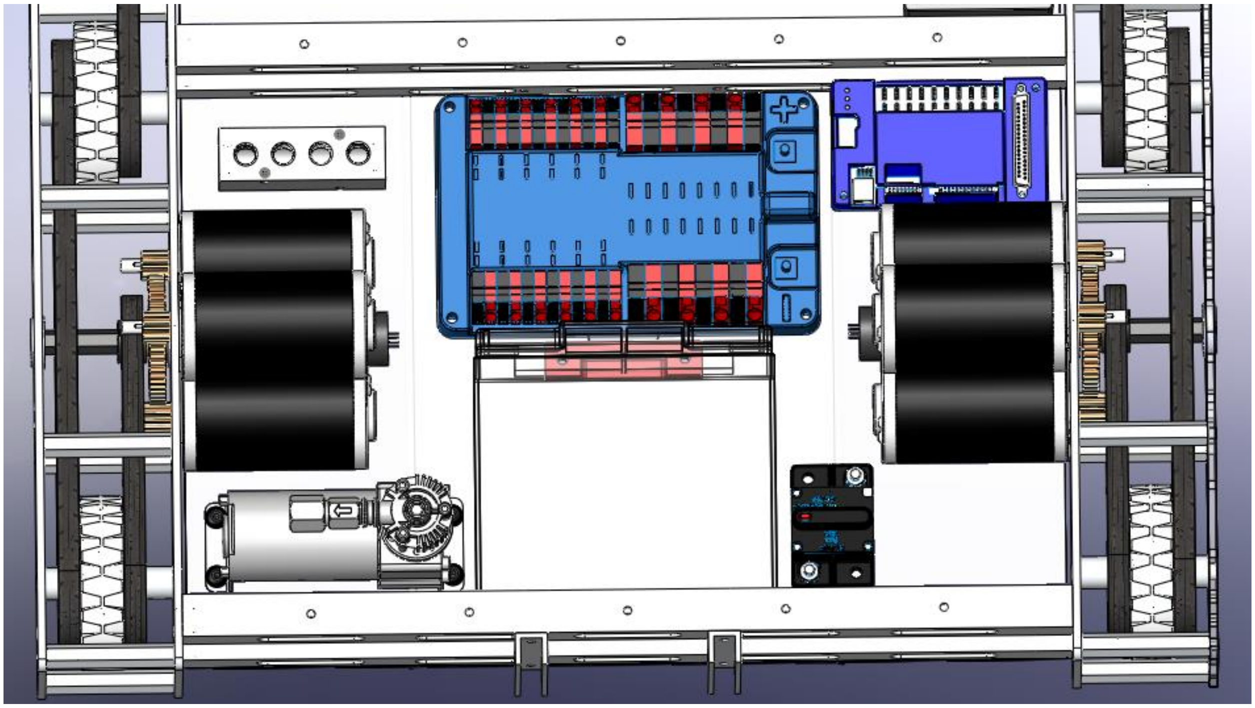
Aluminum Manifold, 4 Outlets, 3/8" NPT Inlet x 1/4" NPT Outlet

Each

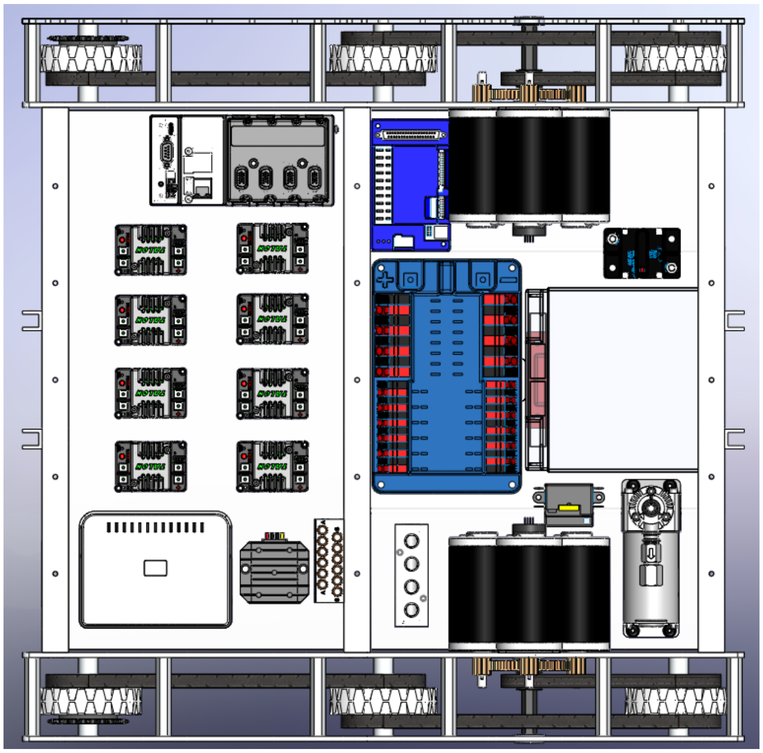
ADD TO ORDER

In stock

McMaster-Carr comes in handy again. Download the model.



On second thought, it makes sense to put the compressor on the side with the manifold seeing as the compressor will feed into it.



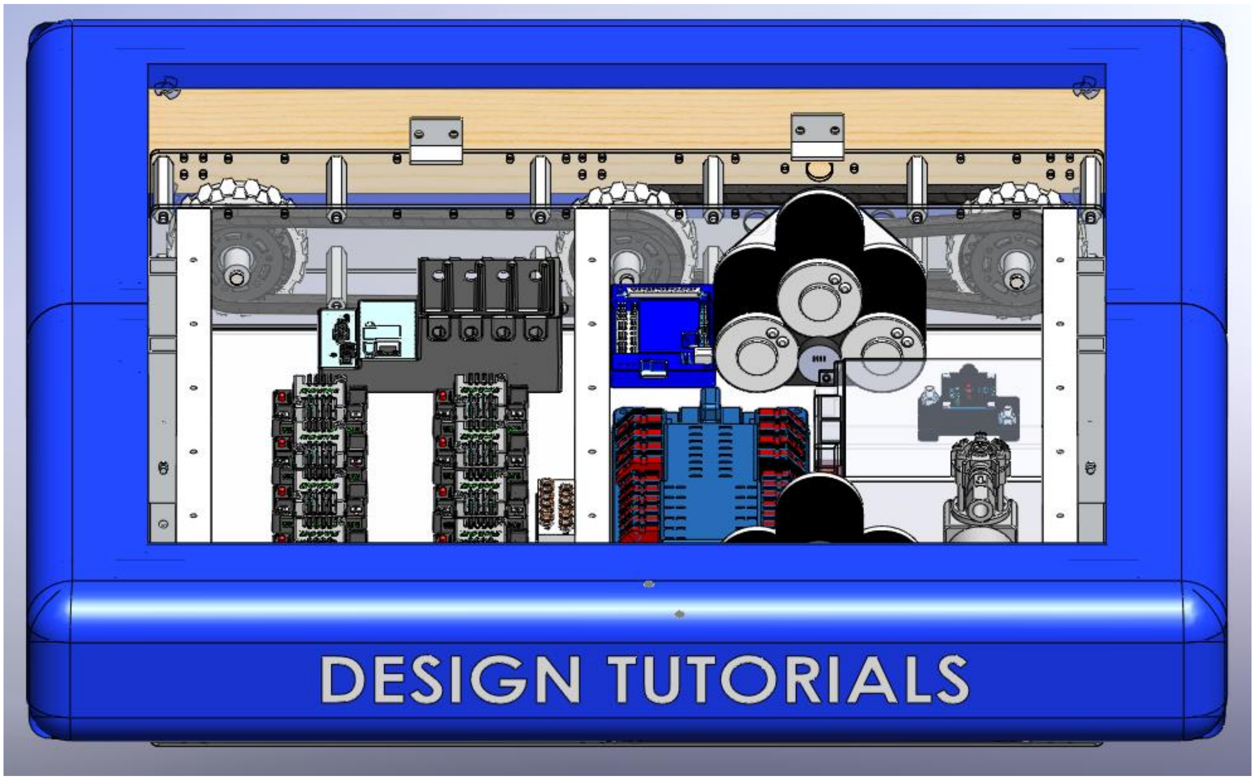
Next to the compressor behind the CIMs is a spike. It is a motor controller but it cannot give variable power, only full forward, reverse, and off. We use this to turn the compressor on and off.

To the left of the manifold is the solenoid manifold. It houses all the solenoids and all the air that goes to the cylinders come out of there. It is vertically mounted for ease of getting tubes out.

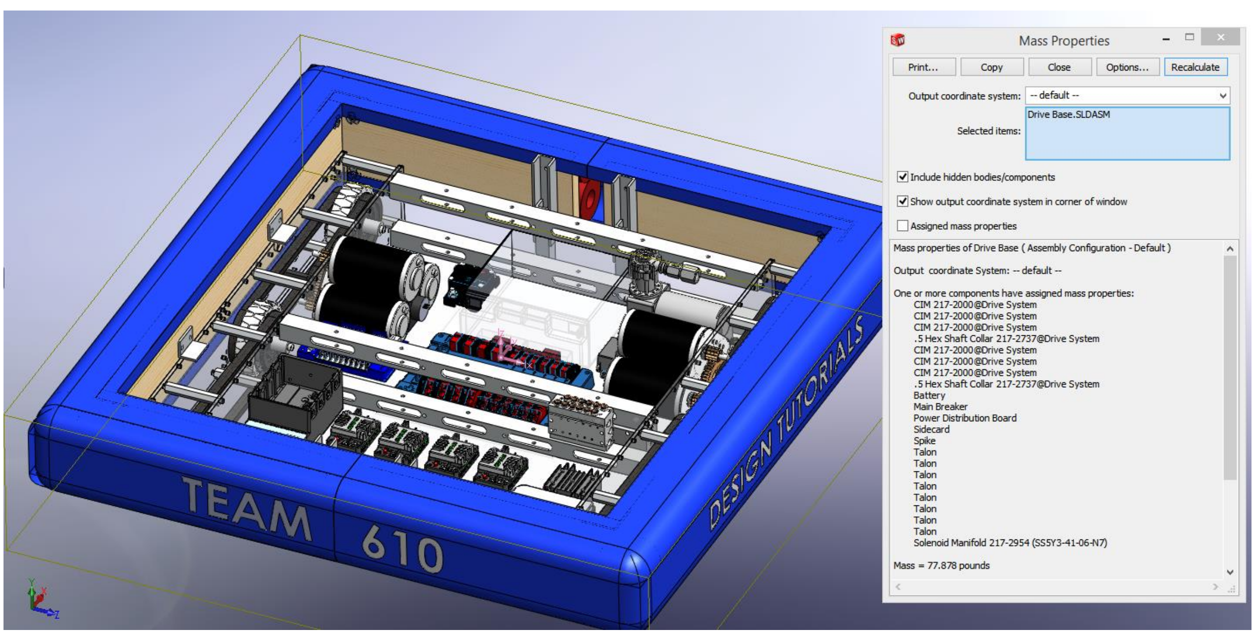
Next to that is the power converter for the radio and the radio. Typically one would mount the radio higher up on the robot and away from anything that could create interference. Seeing as we don't have anything else to put it on, we'll live with this.

Lastly is the Talon array. Six talons service the drive motors and two others will be used as spares or for other devices.

Drill out all the holes for the electronics into the belly pan (use the electronics as a reference).



And you're done!



Some final things to consider are making sure you have all your mass properties set. For electronics and off the shelf parts, make sure they have set weights. As for custom parts, set the materials and Solid Works will calculate their weight. 80lb for a drive including the battery (about 15lbs.) and electronics and bumpers isn't bad. If you do find yourself low on weight, take off 2 CIMs and their respective motor controllers.

CLOSING

Many thanks to the mentors on team 610 who have taught me everything I know, and without whom I would not be the same. Many thanks to Rob Stehlik who has taught me everything I know about mechanical design, Shawn Lim for sharing his computer science and electronics know how, Don Morrison for running the entire robotics program, Marcella Fioroni for getting s to competition as well as making sure we are always having a good time and last but not least, David Grant who started the program so many years ago. Also, a big thank you to Jeff Adams and Ian Fisher for mentoring my FIRST Lego Team and getting me involved in robotics nearly a decade ago. Credit also goes to Matthew Lang '14 and Jamie Rose '14 for helping edit the whole thing and Matthew Riley '15 and Jonathan Pearce '15 for giving me the idea for all this.

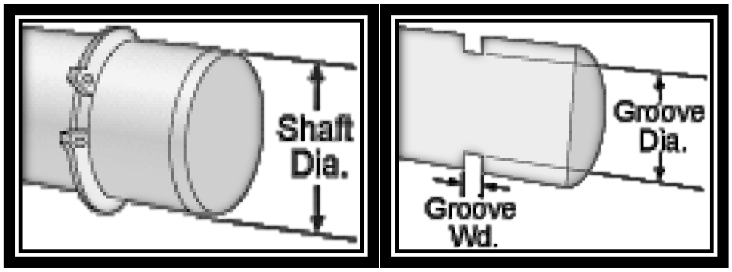
This book is dedicated to all the future members of 610 in the hope that they will learn something from it and carry the team on for many years to come.

APPENDIX A

Screw Size	Recommended Clearance Hole Size	Closest Fractional Drill Size
#4-40	0.125”	1/8
#6-32	0.156”	5/32
#8-32	0.172”	11/64
#10-24	0.203”	13/64
¼-20	0.266”	17/64

Screw Size	Recommended Clearance Hole Size	Closest Fractional Drill Size
M3	0.141”	9/64
M4	0.188”	3/16
M5	0.219”	7/32
M6	0.266”	17/64
M8	0.390”	25/64
M10	0.453”	29/64

APPENDIX B



Shaft Diameter	Groove Diameter	Groove Width
¼”	0.23”	0.029”
3/8”	0.352”	0.029”
½”	0.468”	0.039”
5/8”	0.588”	0.039”
¾”	0.704”	0.046”
1”	0.94”	0.046”

APPENDIX C

Screw	Holes Size (Fractional Approximation)	Tap Drill
4-40	5/64”	#43
6-32	3/32”	#36
8-32	1/8”	#29
10-24	9/64”	#25
¼-20	3/16”	#7

APPENDIX D

#25			#35		
Teeth	Pitch Diameter	OD	Teeth	Pitch Diameter	OD
16	1.282	1.407	12	1.449	1.625
22	1.757	1.889	15	1.804	1.989
32	2.55	2.6881	22	2.635	2.833
34	2.717	2.848	24	2.873	3.073
36	2.868	3.008	26	3.111	3.313
38	3.030	3.167	28	3.349	3.553
40	3.186	3.327	30	3.588	3.793
42	3.341	3.486	32	3.826	4.032
44	3.505	3.646	33	3.945	4.152
48	3.822	3.964	36	4.303	4.511
54	4.300	4.442	42	5.018	5.229
58	4.618	4.761	44	5.257	5.468
60	4.777	4.920	48	5.723	5.946
64	5.095	5.239	54	6.449	6.664
66	5.267	5.398			
72	5.731	5.876			

“Sir, I’m done”

-Every 610er who ever existed

DESIGN TUTORIALS