Differential Housing 2022-2023

Gnubs (2023) / Andy Zhang, Yoon Sung Kim

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Introduction

This year was the first year we created a custom differential for our vehicle. This project was a collaboration between myself (Andy Zhang ‘25) and Yoon Sung Kim ‘23. The purpose of this document is to provide the most extensive documentation of the design, manufacturing, and testing of the differential housing.

System Overview

The differential housing is made up of 4 sections. We have unofficially called them the Housing Body, Housing Lid, Input, and Endcap. Note that this document only covers the housing itself, not the internals of the differential. I am not at all knowledgeable about gears, so refer to Dash’s design doc for that information.[1]

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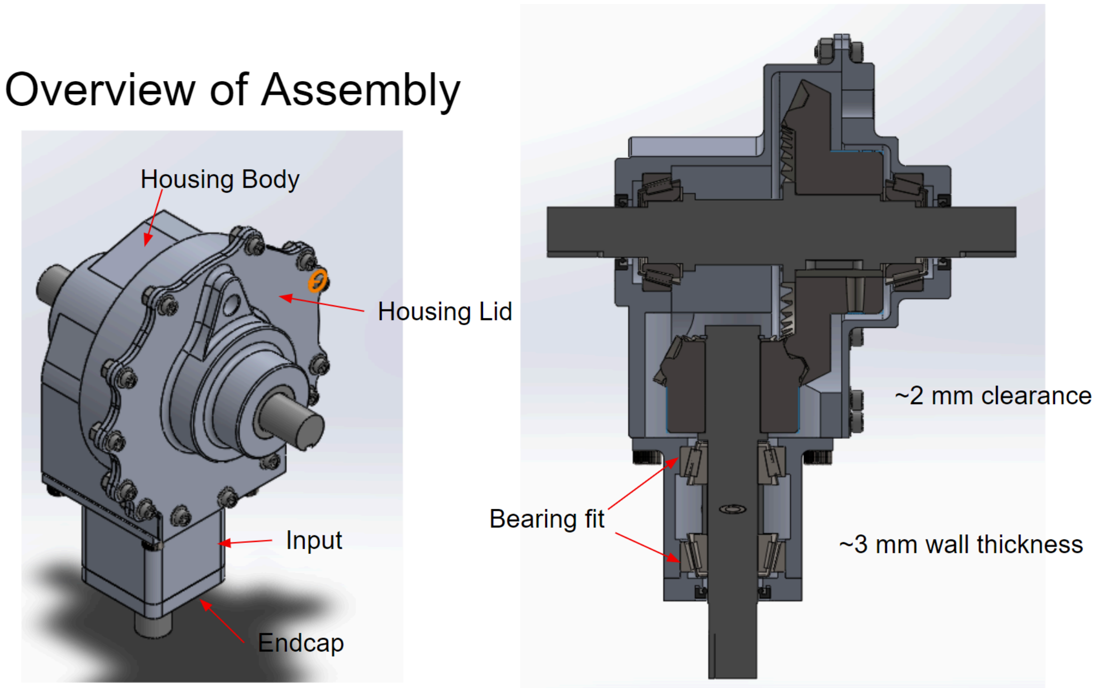
[1] Although we call our system a “differential” it is really just a right angle gearbox. Technically, if you counted the one-way bearings in the hubs, you might make the argument that our gearbox functions similar to an open-differential, but I personally don’t agree with this. In my opinion, it is a mistake to call this anything other than a right-angle gearbox, as a real open differential is more complicated (spider gears) and well beyond our capability to custom design. Most teams you see at comp (who claim to have made their own differential) are running a right-angle gearbox, rather than a real differential. If you see any real custom-made open or limited slip style differentials, take notes.



Timeline

If you are reading this, it probably means that you are tasked with creating a future differential housing! I will say that this was quite a challenging and time consuming process. Some of this is due to the fact we had little documentation or previous experience, but a significant amount of time was spent simply manufacturing all the components. It is important that you stay to a timeline and allow plenty of time for manufacturing, especially since the powertrain subsystem is the first to go onto the car during assembly. Our timeline was roughly as follows:

Early September - Gathering background information, consulting with subteam lead on goals, challenges, things to improve on

September to mid October - Design part on Solidworks. Consult in meetings frequently with subteam lead and gather feedback.

Late October - Design Review. Chief Engineer formally reviews the part and offers feedback.

Early November - Part is formally “locked” on Sharepoint, no modifications can be made. Order blanks for manufacturing.

Mid November to Winter Break - Begin to write CAM. If you have never CNC’d before, I recommend learning over Thanksgiving break. Ideally, aim to complete all CAM programs by the end of winter break.

Winter Quarter - Manufacturing season. I tried to get as much CNC done in the first few weeks when my course load was a bit lighter. I found this to work out well.

Late Winter Quarter - All manufacturing should be done. Try to assemble with shafts/gears to determine if there are any issues with fit.

Spring Quarter - Testing

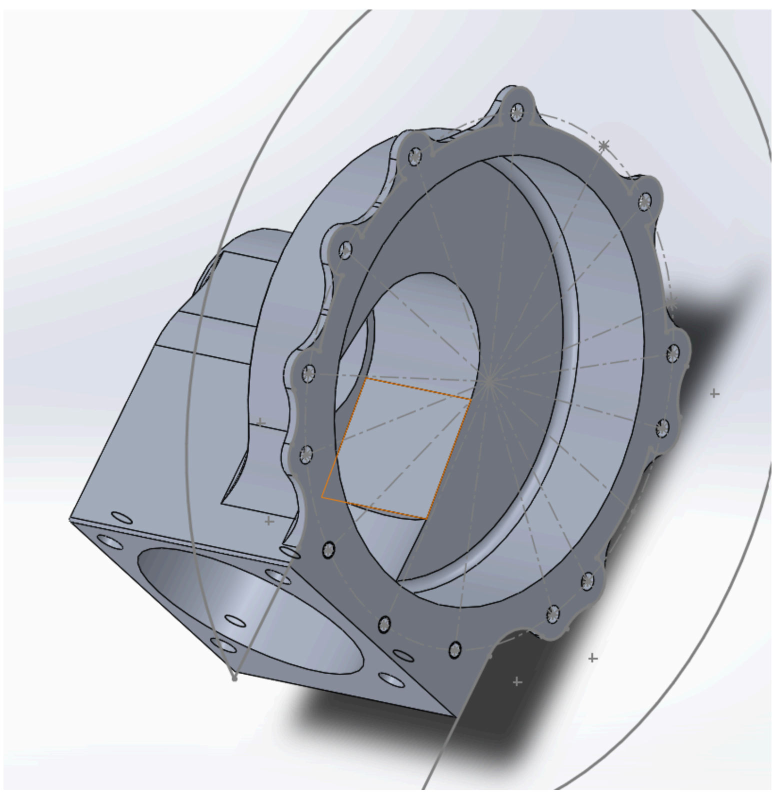
Design

Since this was our first time creating a differential housing, even thinking of a design was quite challenging. Hopefully, you will have lots of documentation and team wisdom of how to design a differential housing. The best first step may be to go see the most recent differential and understand how each component was created. Because there are many considerations in the design process, I have chosen to split this section into several subsections. The subsections are generally in the order that we designed the part.

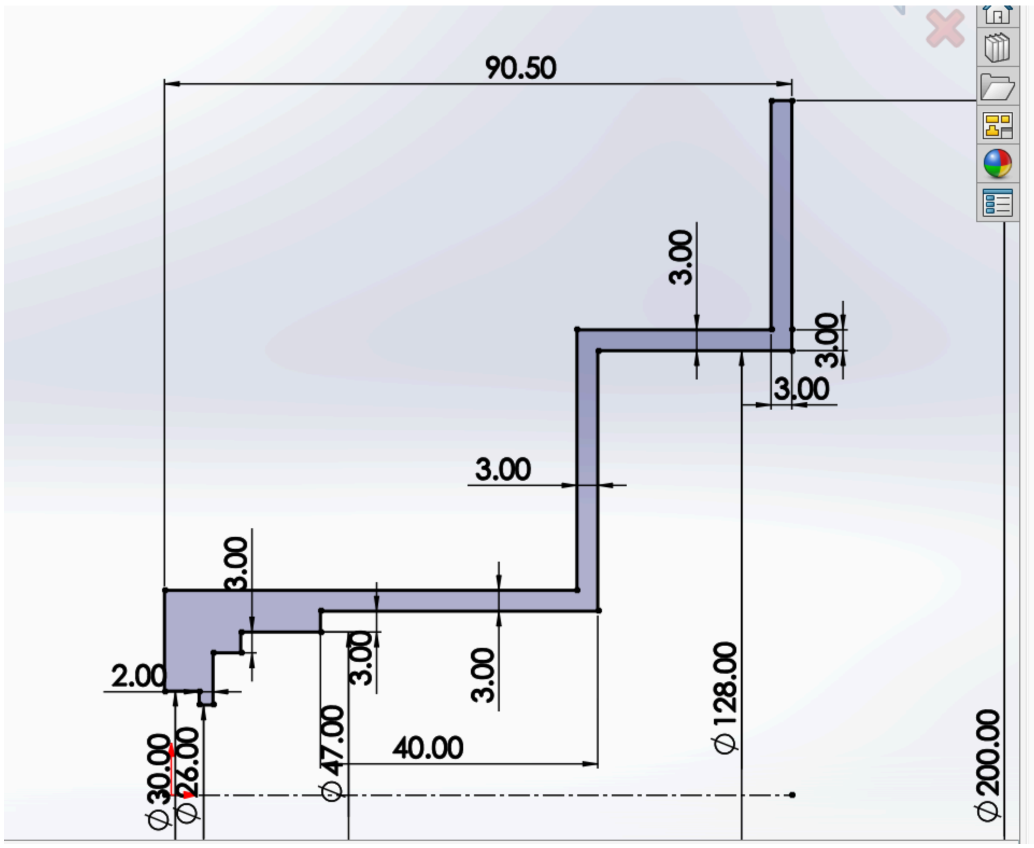
Design Subsection 1: Using Revolve in Solidworks

For our part, we heavily relied on the Revolve feature in Solidworks to create the circular shapes.

To give an idea of our thinking process, let's take, for example, the main body of the differential housing, shown below.



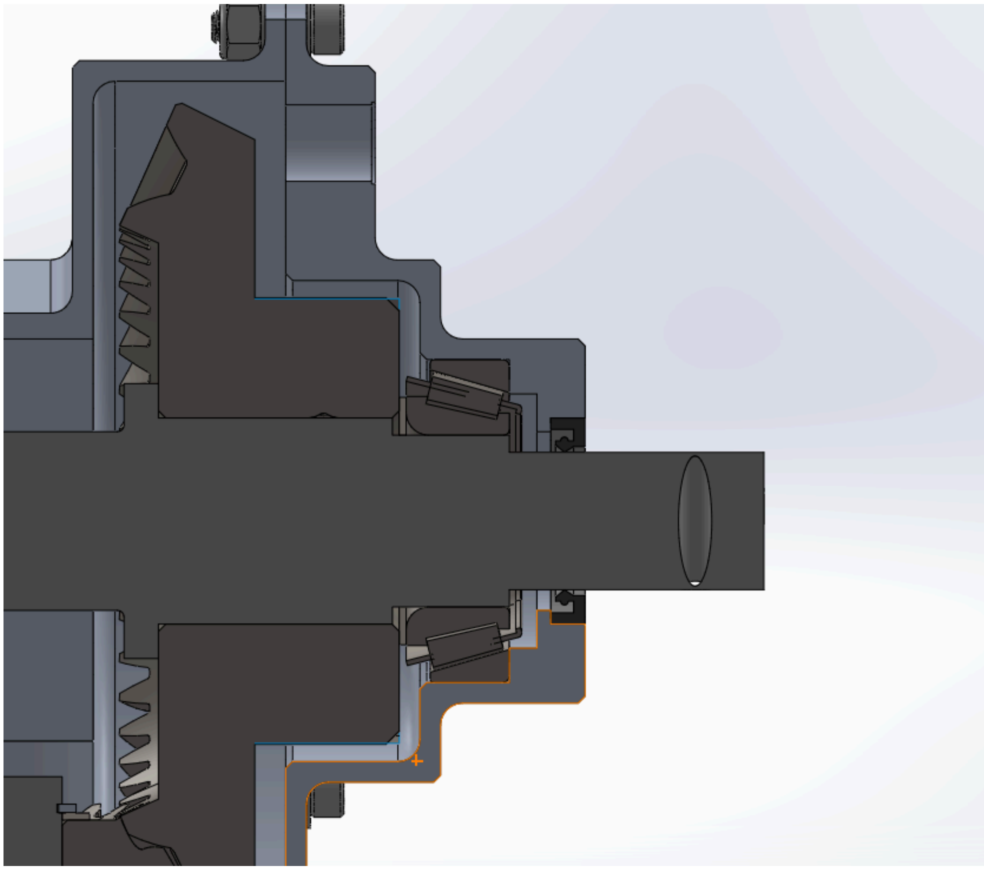
You may notice that we have flanges for the bolt holes, as well as external mounting features. Don’t worry about that for now - you should make these features at the end. What you need to focus on first is making this basic circular shape. To do this, you will create a sketch, as such:



Notice how this sketch mimics the general profile of the housing itself?

Remember when creating a sketch, you must dimension your distances wisely. Don’t just randomly smart dimension things until it says “Fully Defined”. Think more about what makes the most sense. This was a mistake I made early on - I did not think about if I needed to make a sudden change to the shape and just randomly dimensioned things, which made it very difficult to edit later on.

Again, I would suggest that you focus on making a simple cylindrical shape first. Then, as you become more comfortable with creating these sketches, work up to creating this profile. Generally, work from the inside out. Consider your initial attempt to be a very rough draft. You will likely have to go back to make changes as you create flanges, mounting, etc. I will touch on this later.



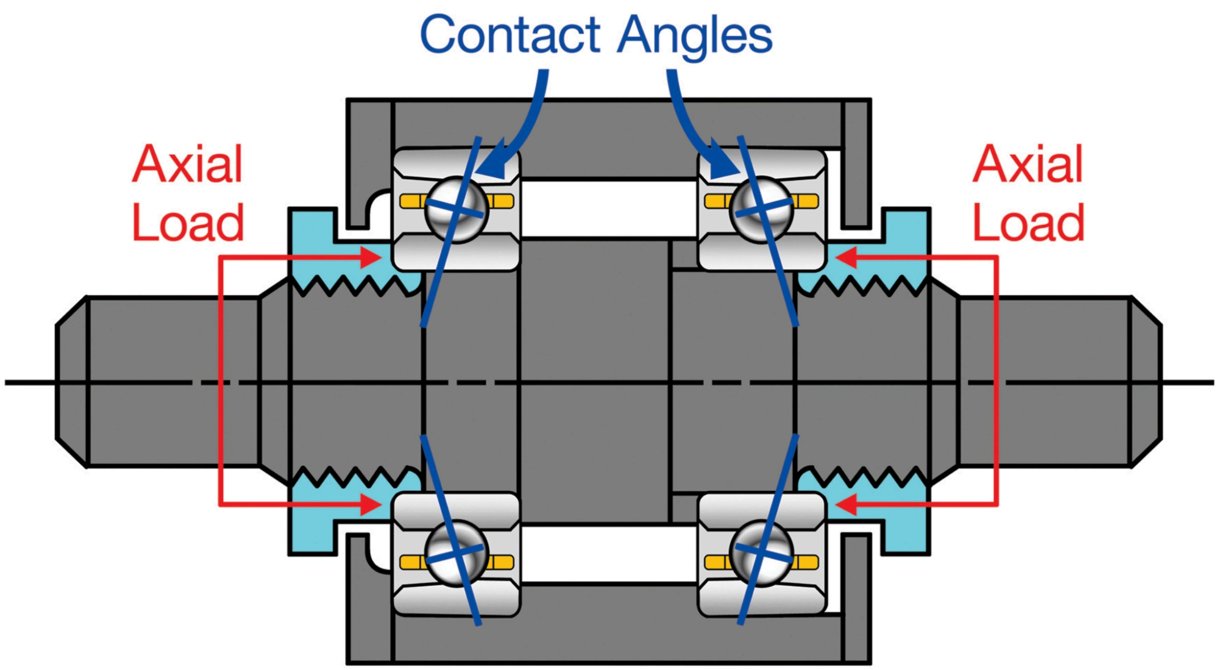
Another thing to keep in mind is what components of the differential internals should come directly into contact with the housing, and what should have a clearance. We designed the gears to have around 2 to 3 mm of clearance between the walls. The areas for the bearings should be designed exactly on-size with the bearing itself. The furthest right after the bearing is a seal - this should also be designed on-size in the model (though should also be firmly pressed in when manufacturing).

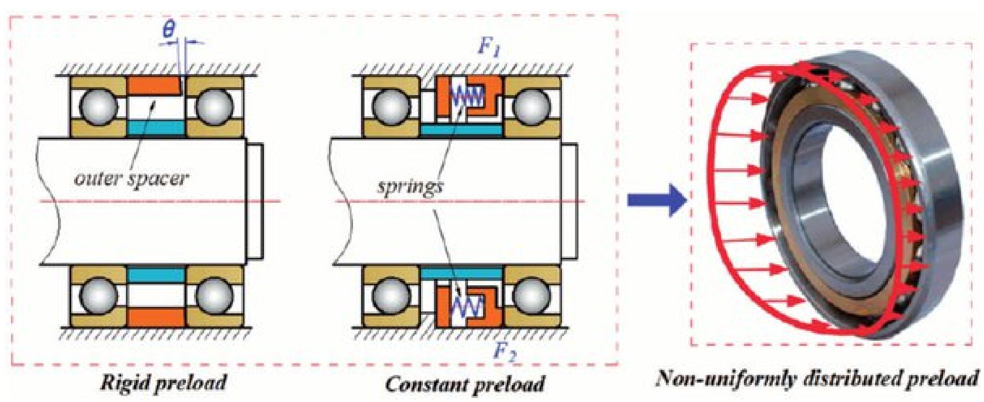
The walls of the differential housing are 3 mm all around, the minimum thickness allowed by SAE rules. I would not recommend going below 3 mm thickness.

In general, you should always be asking yourself - is this geometry machinable? Remember that we are rather limited in what we can do with a 3-axis CNC. Throughout the design process, Yoon Sung and myself prioritized DFM (Design for Manufacturability). One important aspect of DFM is identifying locating features and fixturing points that will be used during the manufacturing process - more on that in the Manufacturing section.

Design Subsection 2: Preloading

To reduce wear and tear on the bearings, we must create preload using shims and shoulder features. Unlike radial ball bearings, tapered-roller bearings come with two pieces: the outer race and the inner race with the rollers. A correct amount of preload must be applied to these bearings to provide optimal reaction loading and bearing life.

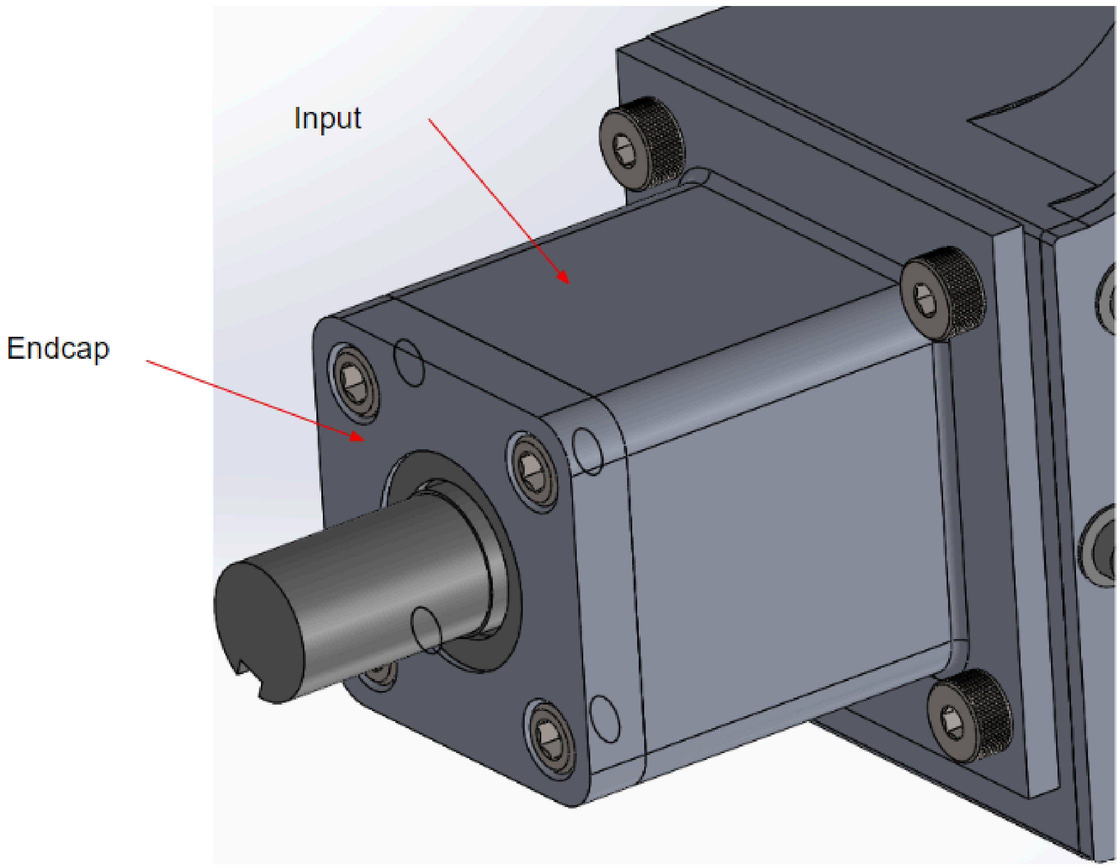




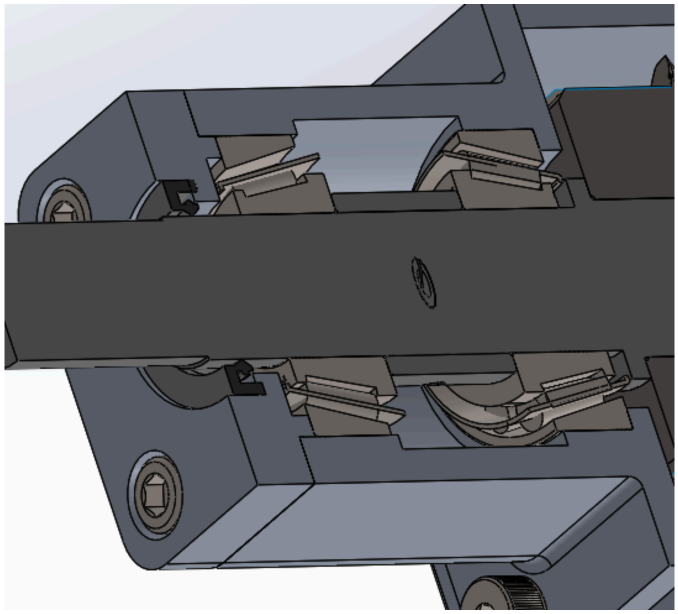
We used 32005 Tape Roller bearings for each half shaft-facing side and a pair of 32004 Taper Roller bearings for the propshat-facing side. Our preloading system was achieved using a single 1mm thick steel shim and a shoulder on the housing body. When designing the shoulder, be careful to cover most of the length of the bearing, but not the roller sections of the bearing itself. Notice in the image below how far up the shoulder comes - it should not go any further than this. Second, always use steel shims. During Blizzard ‘23, I (shockingly) found a member from the Michigan Baja that gave some details on their first differential. Apparently, they had used shims that were too weak (we are guessing Aluminum shims) which immediately blew up the differential. During assembly, you should test for the correct preload carefully. If, after assembling, you can shake the differential and hear rattling, then there is not enough preload - that rattling sound is coming from the bearing moving around. On the other hand, if, after assembling, you attempt to turn the shaft and find it very tight, this is a sign that the preload is too high. Ideally, there should be no rattling and the shaft should turn rather easily.

Design Subsection 3: Endcap and Input Section

We have colloquially referred to the two smaller sections facing the input shaft as the endcap and input section.

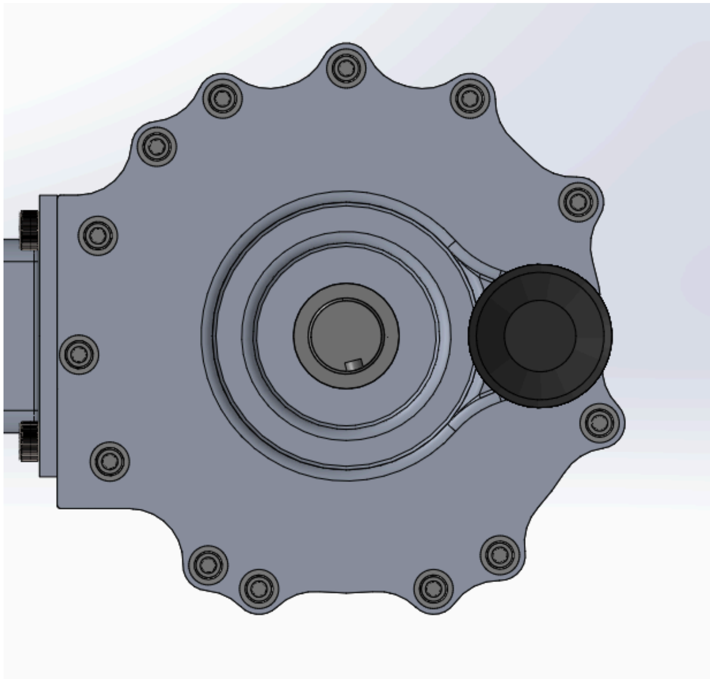


To be clear, these are two separate sections. They were designed and manufactured as two separate sections. Contained within the “Input” section are two SKF 32004 Taper Roller Bearings.

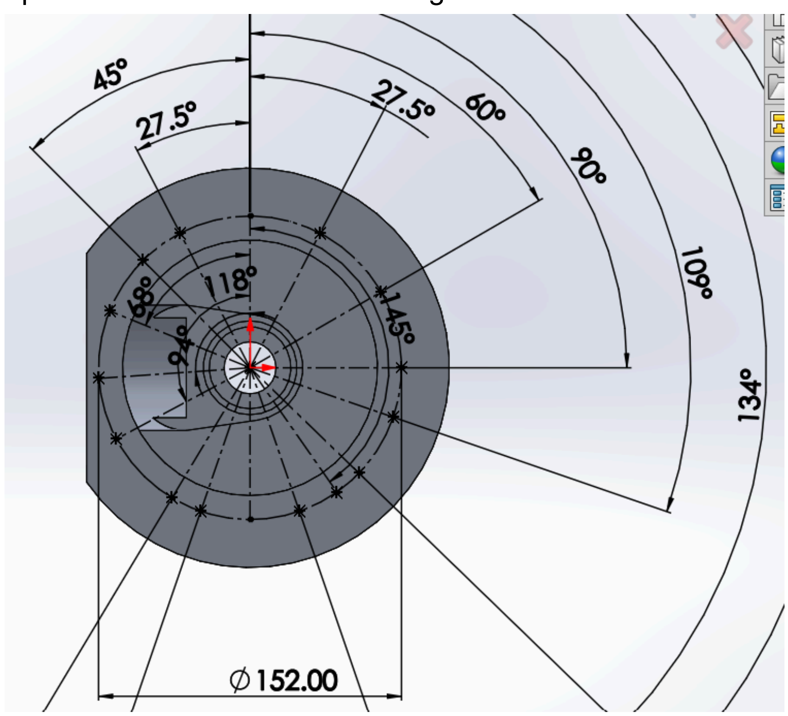


Important item to note: You may see between the two bearings a wider circle that appears to be nonmachinable. The purpose of this wider area was to theoretically make bearing fits easier since we have two bearings in this one space. Specifically, you would not need to do a bearing fit on the entire length of the internal area, just on the two surfaces the bearings would be fit on. While such a shape is apparently possible to create using a T-Slot cutter (?? not too confident on this), we chose not to do this when we actually manufactured the part. We found that using the Alumaster 20mm tool produced an impressive surface finish that did not pose any issues when doing bearing fits.

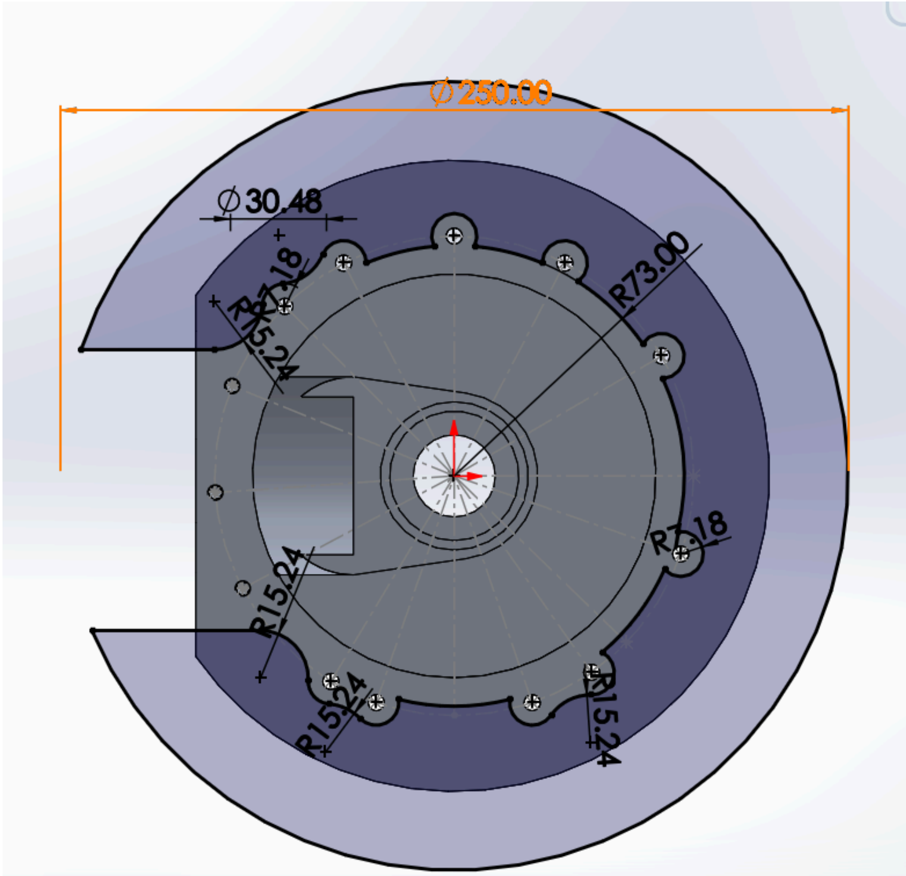
Design Subsection 4: Flanges



We created flanges for the bolting holes. This process is pretty straightforward and should be done after you complete the internals of the housing.



First, we created the positions for the bolt holes. You can see this for yourself in the Housing_Body_v2 file. After this is done, then you can create the flanges

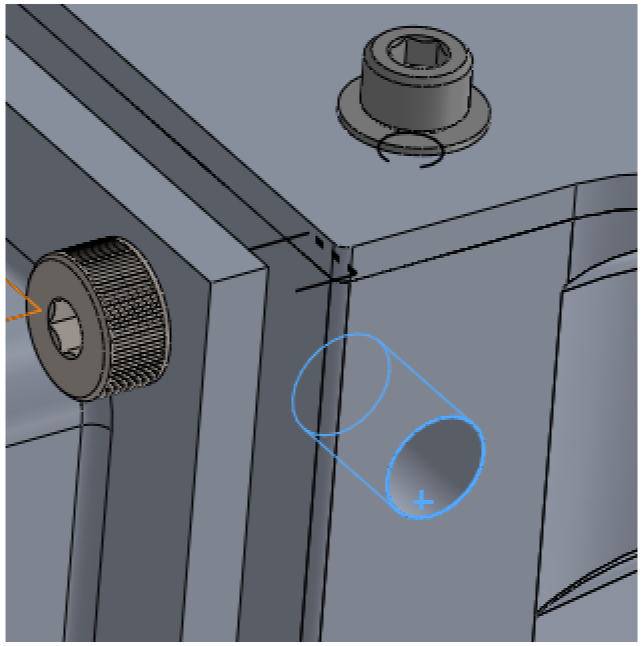


Simply sketch the profile of the flanges and then use the Flange Trim feature to create a flange. You may notice that this sketch is missing the fillets on the model. This was done later on with the fillet feature. After this is done, use the Trim Entities feature to apply this flange to the secondary side of the housing.

Be aware if the flanges may interfere with other components of the car, such as the steering rack or a frame member. To be sure of this, make sure you check the all-car model and communicate with Ergo and Chassis leads.

Design Subsection 5: Mounting

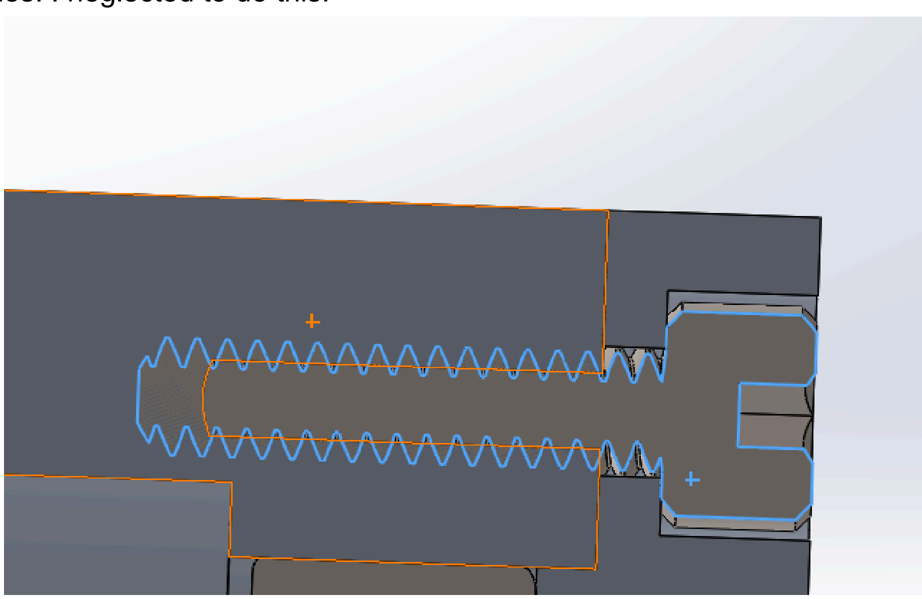
Lastly, you need to consider how you are going to mount your differential. This could be achieved with a tube and a bolt sleeve, a tab welded onto a tube, or any other option that you see fit. You will likely need to create a set of mounting points that come out of the circular revolve area to mount the differential. This process, again, was pretty straightforward. See the Housing_Body_v2 file if you want to see how we achieved this.



The only thing that you need to be really careful about is the positioning of the holes relative to other holes. In this bottom corner, you see there are 3 tapped holes, each coming quite close to intersecting with one another. While we didn't have any issues with this, I can see how a small oversight could lead to many problems down the line.

Design Subsection 6: Miscellaneous items

Finally, you need to consider fastening hardware, filets, and expansion bellows. For hardware, we used 10-32 socket head screws, nuts, and washers around the flanges, shoulder screws to fasten the input to the main housing body, and socket head screws to fasten the endcap to the input section. When choosing fastening hardware, be sure that the fasteners actually fit into the modeled holes. I neglected to do this:



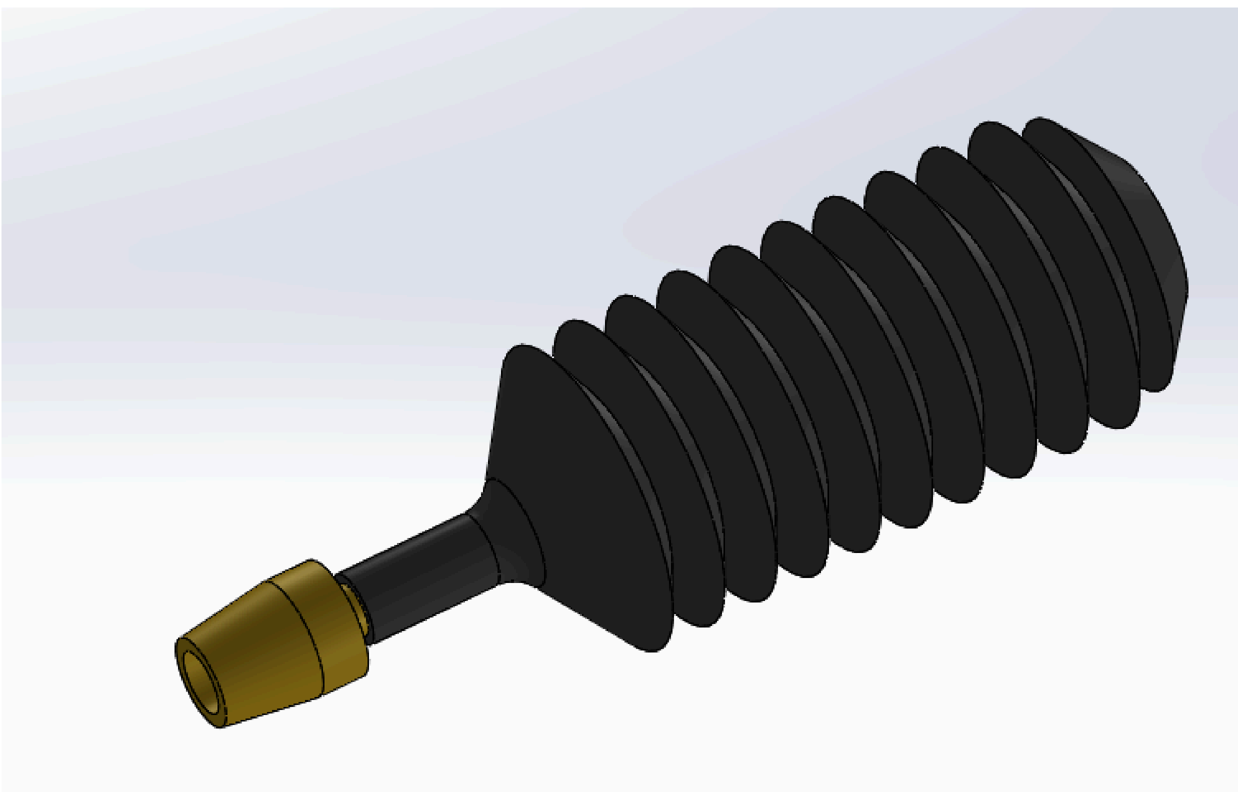
In hindsight, it's quite obvious that this screw is too long for the tapped hole. Unfortunately, I did not realize until late in the Winter Quarter. Instead, I had to cut down the screws using a dremel so that they would fit.

To comply with SAE rules, all gearboxes must have a ventilation system to capture expanding gasses.

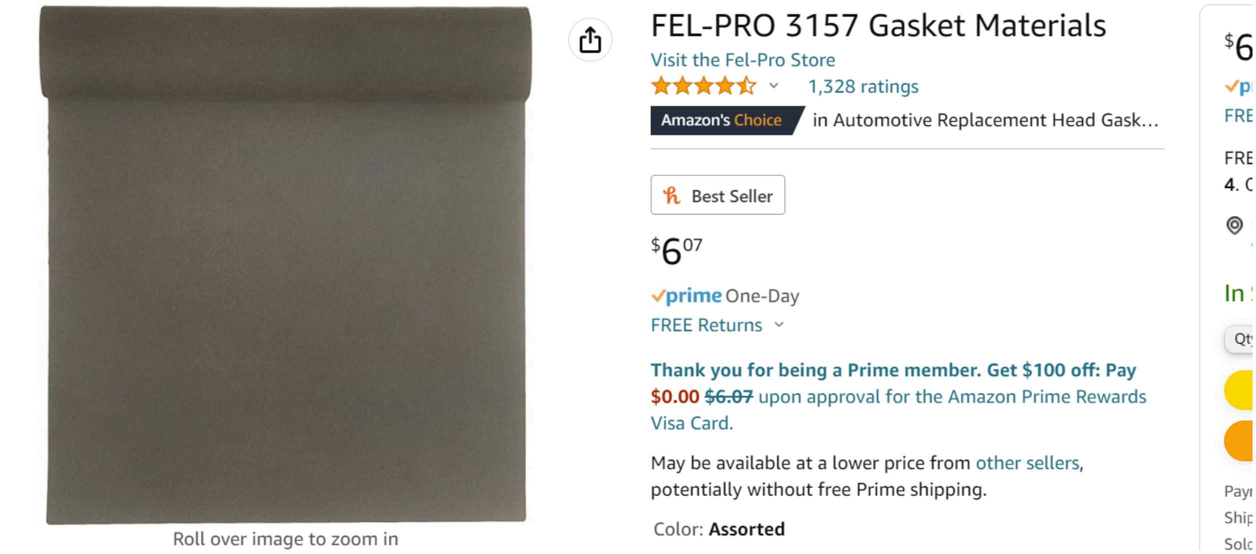
B.9.4 - Drivetrain Breather / Vent System

Gearboxes and transmissions using lubricants such as gear oil, automatic transmission fluid, or similar mineral oils shall be equipped with a vent system that shall minimize loss of fluid by way of a rollover and by thermal expansion. This shall be accomplished either with a closed system expansion chamber or an air trap vent system. Portal hubs are exempt from the requirements of this rule.

The rubber vent bellow is used to capture these expanding hot gasses. We have not had any issues with this bellow so far. This style bellow is used on many Baja cars. We created a ¼" NPT Threaded hole approximately halfway up the section of the housing. While the differential should only be 1/3 full of oil for maximum performance, we chose to place the fill hole halfway up and fill halfway up to account for leakage over time.



Fel-Pro 3157 Gasket Material was cut by hand to create gasket material. Do **NOT** use the laser cutter, you will fry a lens.This was an improvement over using silicone seals, which requires creating an indentation in the profile of the gearbox, as well as RTV, which, while it does the job, is a mess to apply and remove.



We found Fel-Pro 3157 to do the job well. It is available at a reasonable price and you do not need too much - two sheets was enough to create all the gasket materials for both differentials and the gearbox.

Full BOM

Part Description	MTS/OTS	Supplier	Supplier P/N	Qty (EA)
Main Body (6061)	MTS	Midwest Metals	N/A	2
Housing Lid (6061)	MTS	Midwest Metals	N/A	2
Input Body (6061)	MTS	Midwest Metals	N/A	2
End Cap (6061), ½" Thickness Sheet	MTS	Laura's Uncle	N/A	2
SHCS#10-32x.3125	OTS	McMaster	91251A337	6
SHCS#10-32x.5625	OTS	McMaster	91251A356	20
#10-32 Hex Lock Nuts	OTS	McMaster	95856A235	20
#10-32 Washers	OTS	McMaster	90107A011	20
SHS.3125x.375	OTS	McMaster	91259A576	8
SHC.25x.875	OTS	McMaster	91251A541	8
Vent Bellow Kit, ¼" NPT	OTS	TMR Customs	N/A	2
Fel-Pro 3157 Gasket	OTS	Summit	N/A	2

Manufacturing

This section is not meant to be a comprehensive guide on running a CNC, but rather a rundown of specific challenges and problems we faced. In my opinion, manufacturing was far more challenging than designing the differential itself. As a warning, this process was quite time consuming. Even though I felt like I prepared extensively over Winter Break, it still at times consumed my life during WQ.

The schedule we followed was:
Early November - DR complete, order blanks

Mid November - Refresh CAM skills. Write CAM for Input Section over Thanksgiving Break.

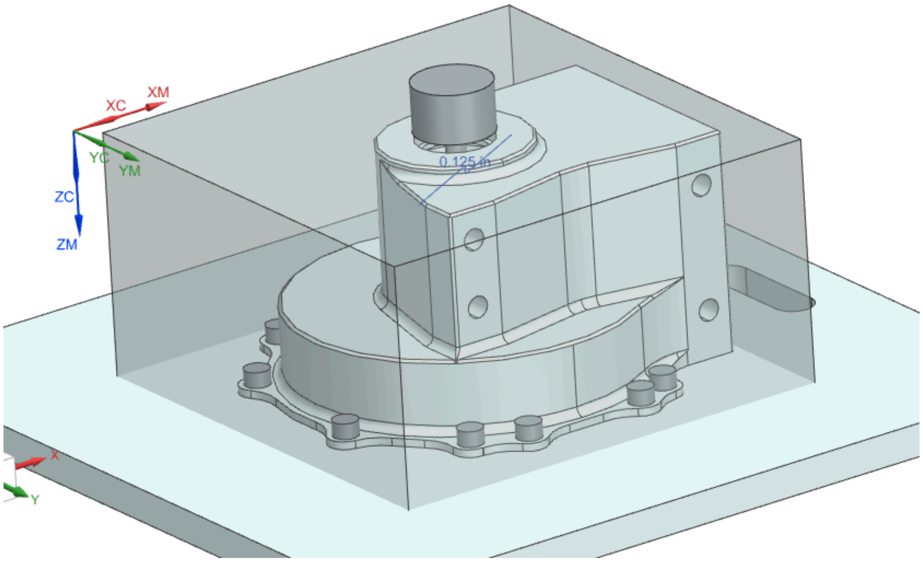
Early December - Manufacture Input Section. This should be considered a warm up for what's to come.

Winter Break - Write CAM program for all parts.

January - March - Manufacture

Manufacturing Subsection 1: Fixturing & Locating Features

Before you write CAM for any part, think about how you will fixture the part. For the two large housing sections, we used a fixture plate and secured the part down using a large ½" bolt (the kind in the green bolt holder thing at the bottom of the red tool cart). We then used 10-32 Socket Head Screws to further secure the part down, as well as to serve as a locating feature for the 2nd op.



When writing CAM, make sure that you program a clearance over fixturing bolts. Additionally, check the clearance plane after adding in the clearance for the top bolt. We nearly had a collision because the clearance plane was set in reference to the top of the blank, rather than the top of the fixturing bolt. **NX will not warn you of an intersection between your clearance plane and a part in the model.**

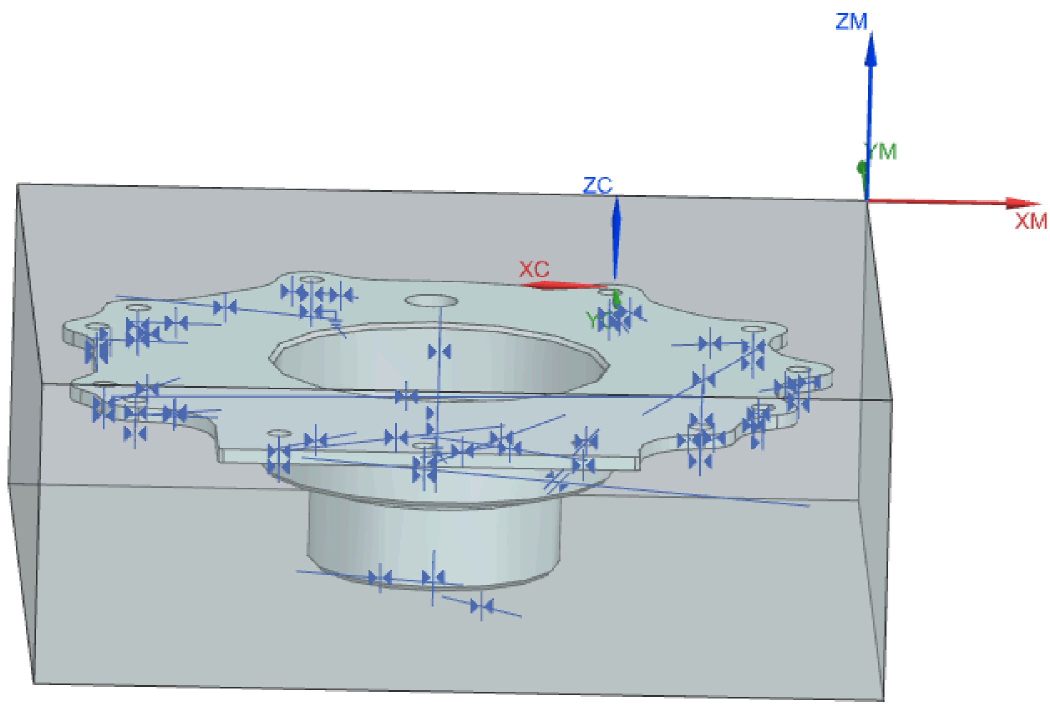
As previously mentioned, having a locating feature is a necessity. Our locating feature was the central bore. Basically, in the first op, we used a ½” drill to drill a hole through the entire blank. Then, when doing op2, this drilled thru hole became the locating feature. For the best accuracy, stick a dowel pin through this clearance hole when setting your zero with the dial indicator - you will get far better accuracy versus just indicating off the drilled section.

Although not completely necessary, I highly recommend designing the fixture plate and throwing it into the manufacturing program before writing any programs. I felt this helped me visualize things a little better.

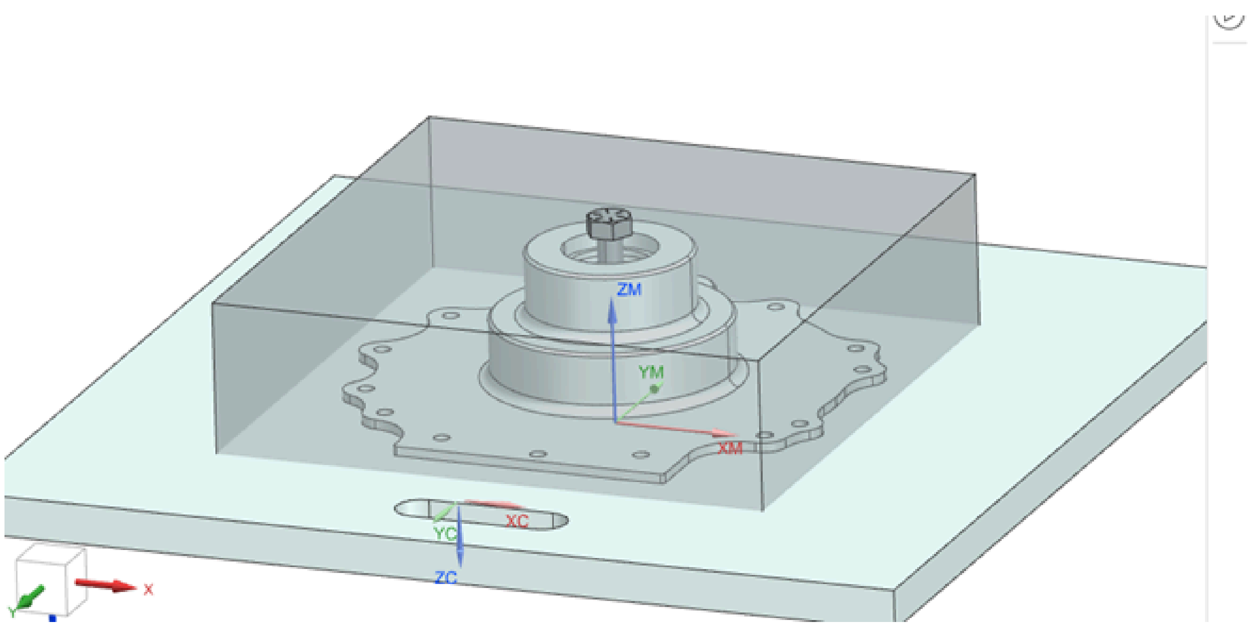
Manufacturing Subsection 2: Fixturing and MCS

Probably the most important part, deciding how to fixture your part and placing the MCS. I am going to list out our fixturing and MCS locations. We did not have any issues with the fixturing as it was, though it’s not to say that this was the only way to do it.

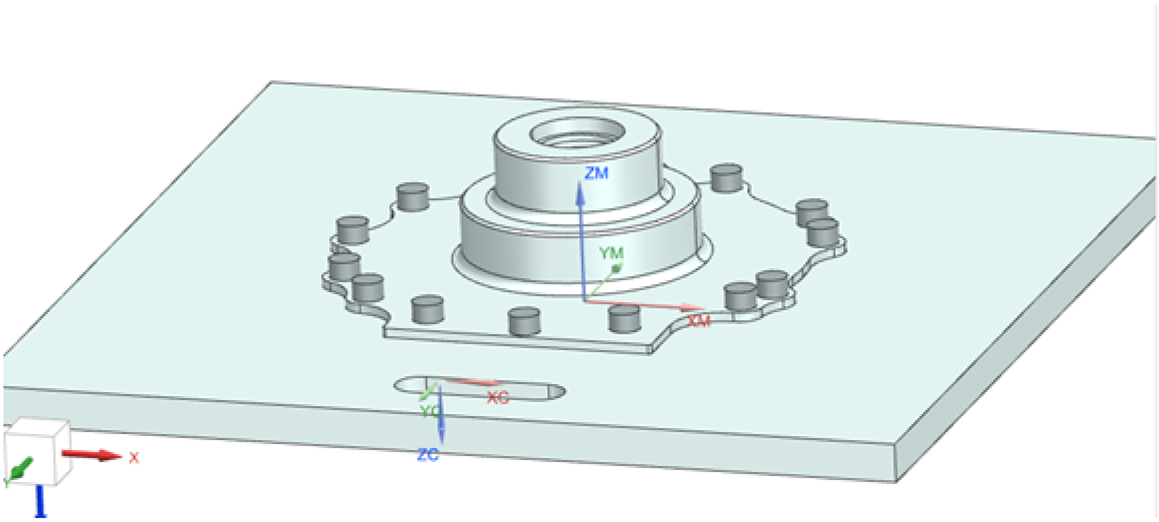
Secondary Housing Setup:



OP1: Mill out internals and bearing fit. Start with solid block in vise. We set MCS to far right top corner

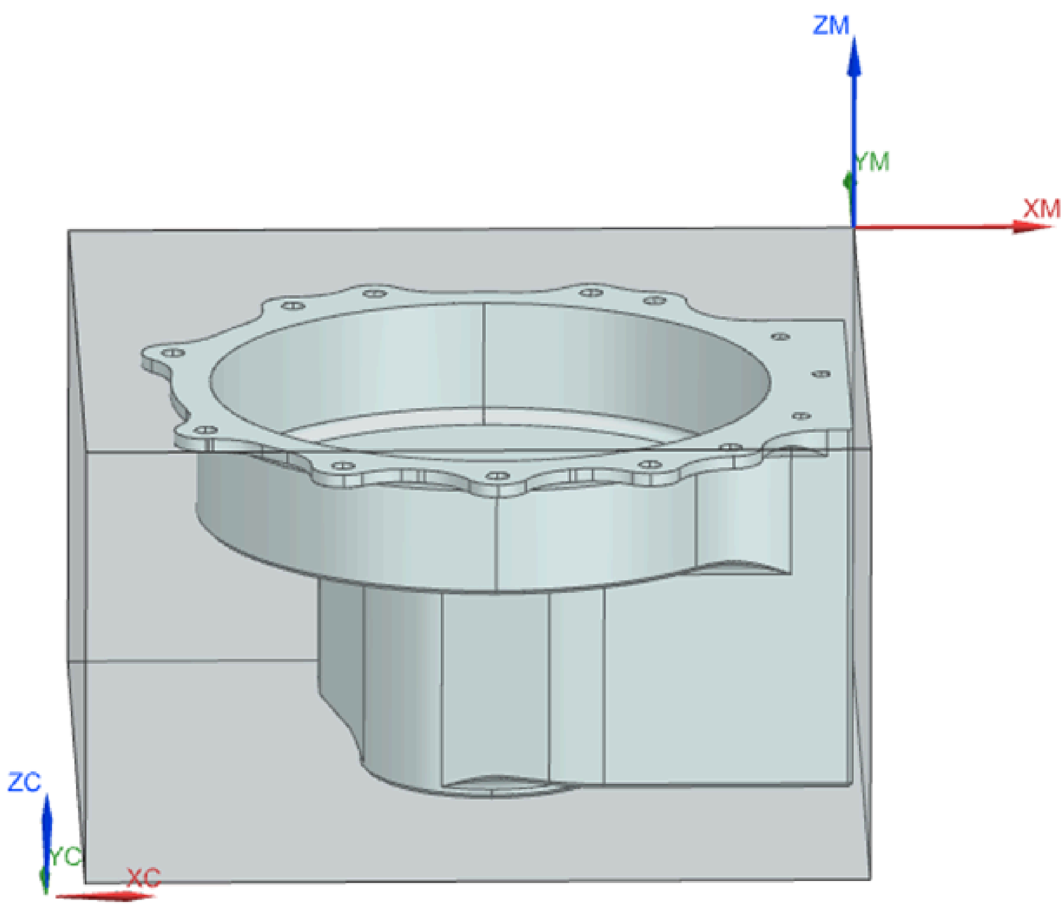


OP2: Rough out external. Use single bolt (the kind in the red tool cart in office) and set MCS to bottom of drilled hole in fixture plate.

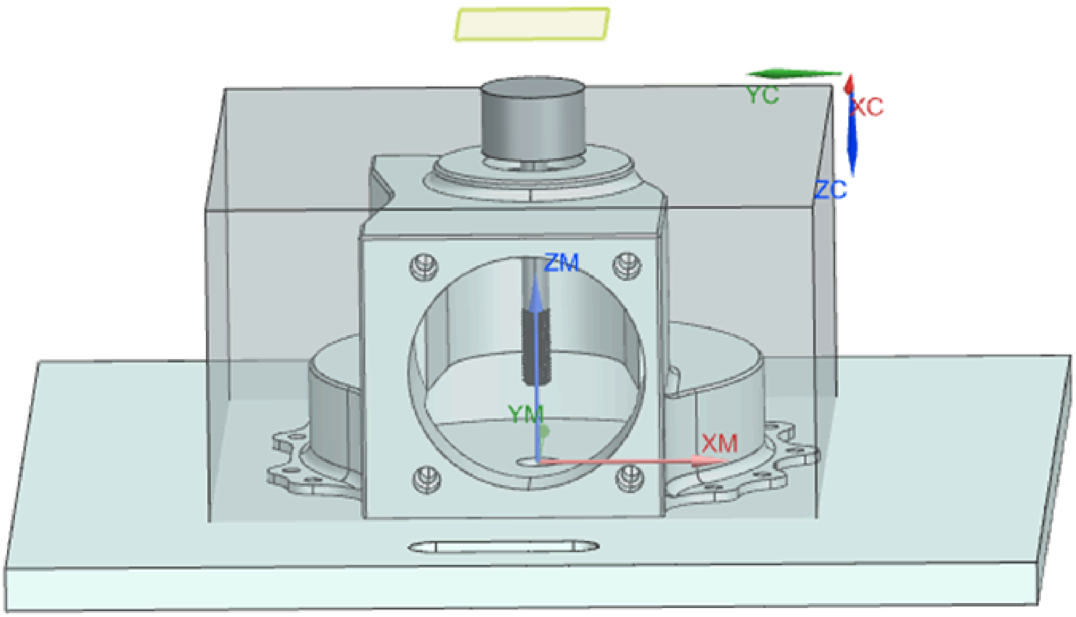


OP3: Finish external. Same MCS as last OP.

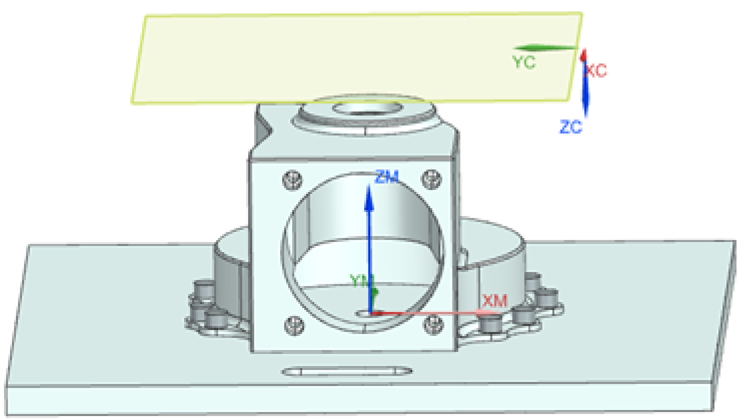
Main Housing Setup:



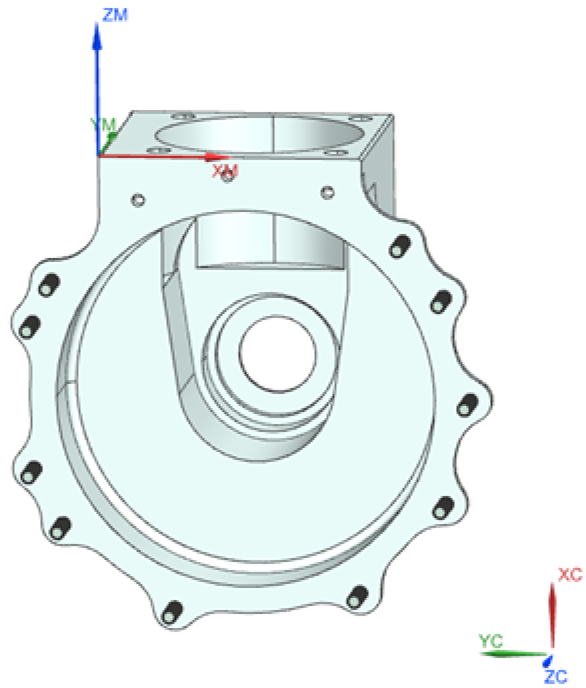
OP1: Mill out most internals. Start with solid block. Set MCS to top right far corner.



OP2: External roughing. Use long bolt to fixture. MCS using bottom of hole in fixture plate.



OP3: External finishing. Fixture with 10-32 screws. Same MCS as before.



OP4: Finish internals. Fixture part in the same fashion as OP3, rotate part 90°, and place onto vise. Make sure part is flat. Finish off edges of the fixture plate to ensure a flat surface. Not pictured is fixture plate, which should go in front of this part.

While this certainly is quite a bit of CNC'ing, it is far from the most complex operations that we have done. The main recommendation I would make is, when starting out, to set the MCS to the bottom right corner instead of the top right. This is a bit more work when edge finding, but makes it almost a non-issue should you have to stop half-way through due to some issue. Also, although the final operation of the main housing went fine, it did not sound very good. I might suggest moving this operation to the first op.

Manufacturing Subsection 3: Fuckup & Failure Log

I would like to preface that the manufacturing season was quite rough. There were a handful of mistakes, which, while not catastrophic, could have been easily avoided. In addition, we had a handful of near-catastrophes, which we luckily avoided. Most of these mistakes were due to my own inexperience - I will describe these failures below so that you may be aware of them.

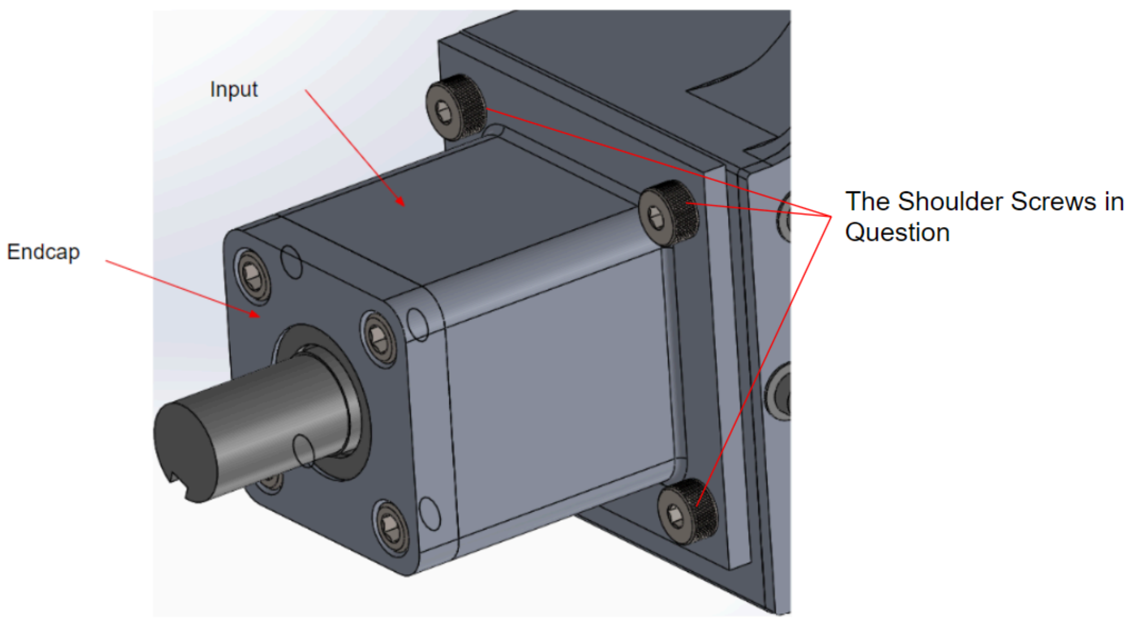
1. Version control issues caused the flanges holes to be mismatched: This small error almost ruined two parts. It all started sometime in Early November. After the part was officially approved, I thought to be proactive and import that part into NX. Well, during a meeting, we decided to change the angle of two flanges by 1° each. This was supposed to help with feature finding in the future. Well, what had happened was that I forgot that changes to the Solidworks model were not reflected to the NX model. On the other hand, our fixture plate had holes pointed to the new bolt holes were. Over winter break, I noticed that the holes appeared to be misaligned - this should have been an early

warning to me. But, I had ignored this unfortunately. Well, what had turned out was that everything was shifted slightly to the left. Luckily, this issue was fixed in the end, but it was indeed very concerning.

2. Check your tool insert radius! When I was preparing the Mitsubishi Indexable, I did not carefully check the tool insert and used a 1/32” radius tool when I programmed a ⅛” tool. In this case, there was no real issue, as this only caused an external fillet to be at a right angle, but important to keep this in mind
3. Surprisingly, the most problematic step of this entire manufacturing process was actually the endcaps. We decided to manufacture on the conversational mill. However, due to a series of missteps and mistakes, we actually had to throw out 3 parts before we made 2 successful parts. So maybe familiarize yourself with the conversational mill.
4. Cut the gaskets by hand instead of the laser cutter. We fried at least 2 lenses!

Testing

This year, we were fortunate enough to conduct two Squires testing trips in addition to comp. This proved to be incredibly important. Remember a few pages ago when I said that the shoulder screws had to be cut down? Well, this led to the rear differential housing being torn apart at the input section. In my opinion, this was partially due to the taps not being as deep as they could have been (**always use a bottoming tap for a blind hole**) and the tapped holes themselves probably not being designed to be deep enough. This issue was resolved by re-tapping the holes into the housing body and replacing the ¼” thread Shoulder Screws with 5/16” Shoulder Screws. We did not have any further issues after this.



The differential system experienced no issues during squires 2. Now off to comp!

Grubs at Oshkosh 2023

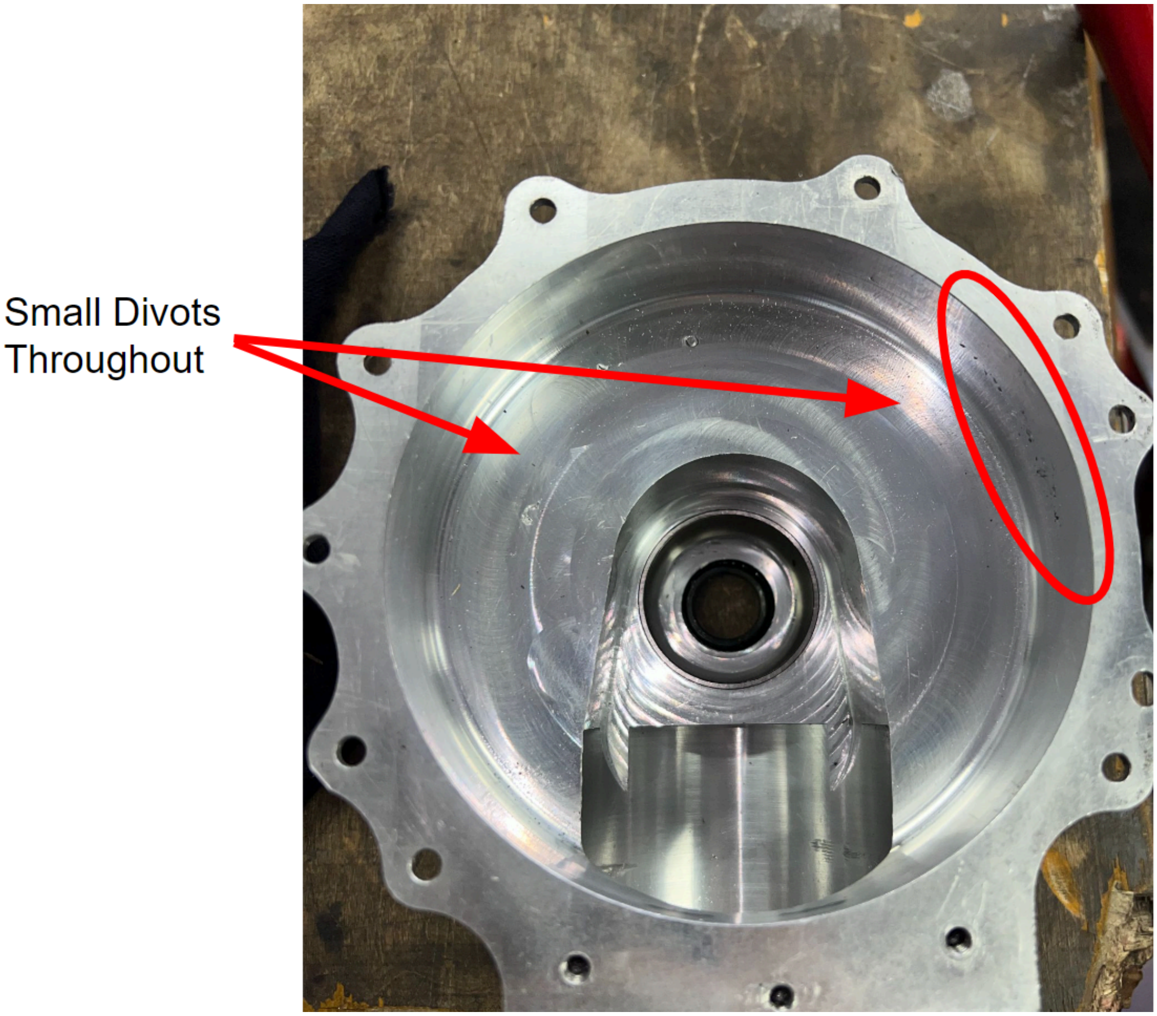
Oshkosh ‘23 was quite a hectic comp. Throughout the 4-hour endurance race, Gnubs did impressively well, holding T10 throughout the race and even T3 at one point. Gnubs did experience one major failure, which was related to the rear differential housing having exactly **0** mounting bolts. This meant, as you were driving down the track, the housing (and all its internals) would move completely unconstrained. This then caused an axial load on the input-facing gear and its shaft. In the below photo, you can see how the section of the housing has completely bowed out. This was directly caused by a tensile force on the housing, essentially ripping it apart.

Oil loss caused a small fire

When we got back, we had the chance to disassemble the housing and its internals…

It’s not supposed to look like this!

Small gouge ~0.5mm deep



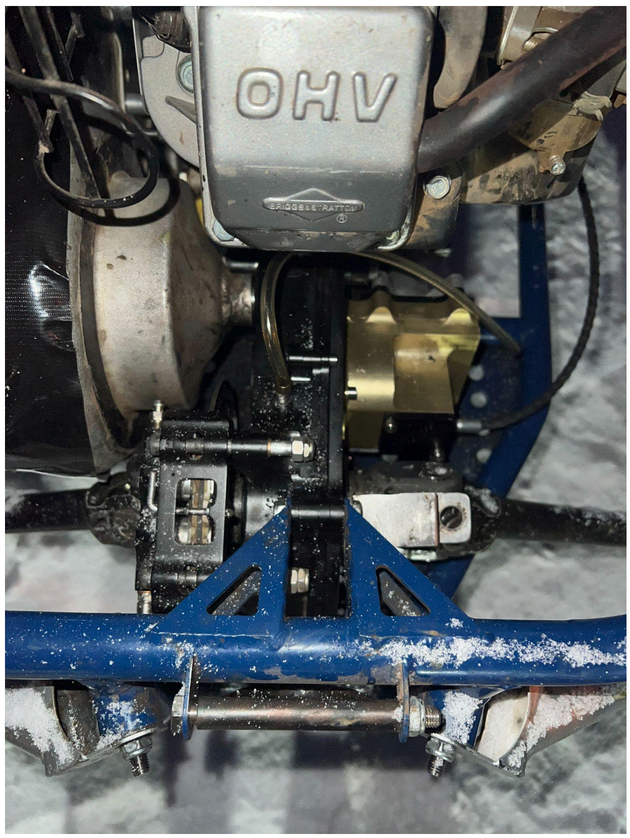
Metal flakes from rubbing of gears caused many small divots on walls

Overall, the damage to the housing was minimal. Besides the input section, everything else remained usable. Moral of the story - always do a bolt check! Thinking back on it, I know exactly when this happened. During the last hour of tech inspections, when everyone was racing to put a new belt on the CVT, someone had unbolted the diff to put on the belt. Then, whoever was in charge of those 4 bolts never put them back. I am almost certain this happened because someone still managed to bolt on the rear skid plate. Had the bolts simply pulled themselves loose, those bolts would still be pressed in by the skid plate. Instead all 4 were missing.

Reflections and Closing Thoughts

For next year's differential housing, there are a few improvements I would recommend:

1. Design and tap longer holes. Clearly, there are forces being placed on the housing (which we had not accounted for)

2. Start doing FEA on the housing? We should at least start thinking about what kinds of forces are being exerted on the housing
3. Consider moving to 7075. 7075 has much better tensile strength and shear strength than 6061, which might be important based on what you find in (2). But, then again, it is also more expensive. There is also the argument that all our failures were due to user error, rather than a failure of the design itself, which is true in some ways.
4. Powertrain packaging needs to improve. We should not be putting the differential inside of the CVT. Unplugging the coupling from the input shaft and the half shaft from output shafts were also a pain, and required using a crowbar. This caused lots of dents and divots on the soft aluminum housing. Again, 7075 would be more resistant to deformations. Although really, pulling out half shafts or couplings should not require the leverage of a crowbar.
5. **Most of all**, physically smaller gears will lead to a smaller differential housing. Look at this picture of Michigan's diff housing:
6. 

Felt like I was risking my life taking this picture. They were NOT happy about this :)

Speaking of other teams' 4WD systems, I am confident that we have one of the most effective full-time 4WD systems out of any team. During comp, one section of the track required cars to drive through deep mud. While many teams had their cars get stuck and required pushing, our vehicle easily went through the mud with hardly any wheelspin at all. To me, this is clear evidence that we are doing something right here. Now, the next step (which all the most competitive T10 teams are all doing) is to develop a system which can somehow switch between 2WD and 4WD. Whether this comes in the form of a mechanical disconnect, a transfer case, or something else, that is something that we need to look into to be truly competitive in the dynamic events (maneuverability, sled pull come to mind).

All in all, this was a very enjoyable, yet challenging project. I know that this document was a bit long, but there was just so much that we learned and so much knowledge that I deemed necessary to pass down. Of course, this document shouldn't be used as a step-by-step guide for how to build a differential housing (I am far from being right 100% of the time), but it should be a good starting point for your housing. Good luck!