# Design Description of FRC 2767 Stryke Force "Third Coast" Swerve Drive Units

Introduction and History (up to 2019)

Stryke Force's motivation to convert to Swerve Drive came from watching and being pushed around by another west Michigan team, FRC Team 141 "Wobots." (Imitation is the highest form of flattery.) We started in the 2011 off season with the commercially available "Revolution Swerve," developed by 221 Robotic Systems. We used it to learn about incorporating Swerve into a robot, and how to program and drive it. We borrowed freely from the wealth of public information on swerve drive programming and (eventually) field-oriented control available on Chief Delphi. Special thanks are due to the user "Ether," who has provided a wealth of very cogent information.

We did not compete with the Revolution units due to high BOM cost and a strong desire to incorporate more mechanical learning into our program. Stryke Force developed its first custom swerve drive unit as shown below for the 2012 game, Rebound Rumble.
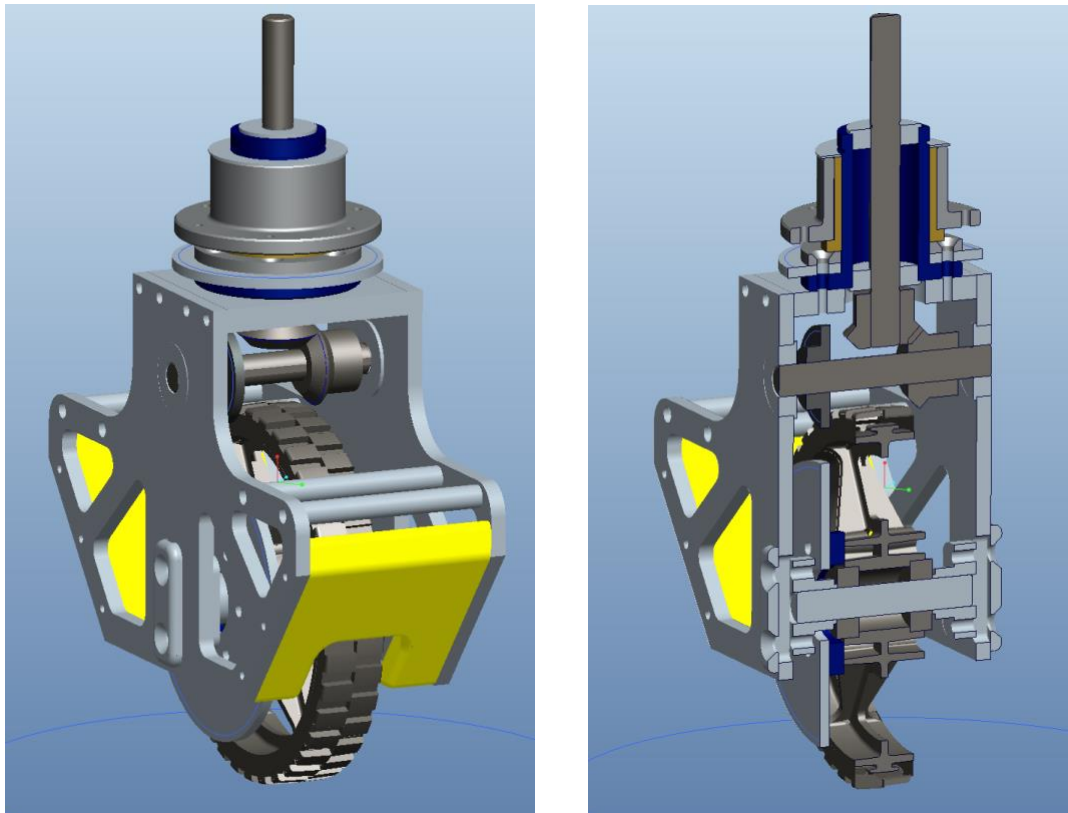

This was essentially a scaled-up version of the Revolution, with "wheel pant" skid plates so that it could jump over the mid field barrier. It had 6" diameter wheels. Although we had success and were hooked on Swerve, there were several serious shortcomings with our first custom design:

- Robot center of gravity far too high—causing us to limit acceleration and forcing our driver to be careful to avoid tipping over. This obviated much of the intended advantage of swerve.
- Overall space claim on the robot and weight were too high.

- Too much weight on the perimeter of the robot—limiting rotational acceleration/maneuverability.
- Difficulty driving straight in autonomous and dealing with obstacles.

Our design for Ultimate Ascent in 2013 attempted to address some of these shortfalls by reducing wheel size to 4", removing discrete bushings for the azimuth rotation (employing the housings themselves), and adding posi-traction (described more completely later in this document). We also added a servo-actuated, dog clutch two-speed transmission. We also 3D printed timing belt pulleys to facilitate the design of the two-speed transmission.
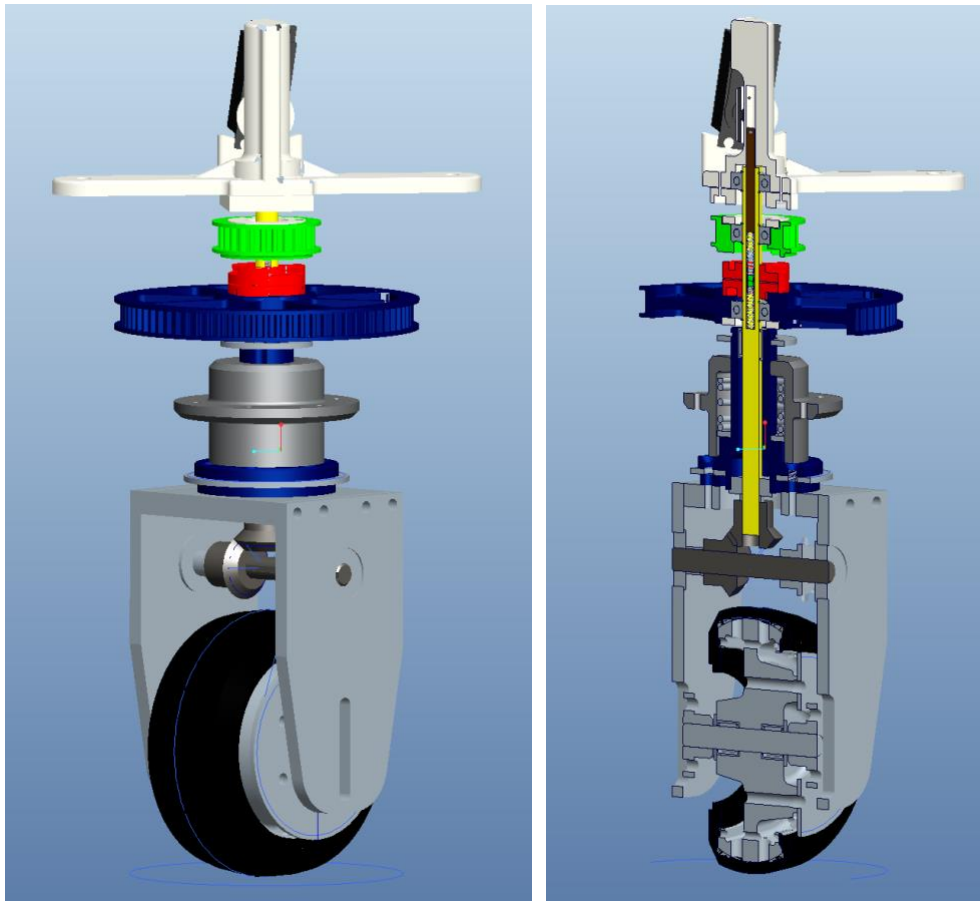

This swerve design was a large improvement. The ¼" throw posi-traction was helpful in improving the control of the robot, but also made it sway during hard maneuvering and the recoil of the Frisbee shooter was visible in the mechanism. There were some other, more significant, shortfalls:

- COG still too high
- Space claim and weight higher than desired.
- Shifting time limited the utility of the transmission.
- High maintenance
  - Custom wheels/tread
  - Multiple chains, which are pinch hazards, potential failure points, and need to be adjusted periodically.
  - Multiple light duty belts, which were prone to wear & failure

- o Insufficient thickness in mounting plate on robot (not shown), leading to bending/alignment issues.
- o Motor mounting issues leading to belt walk.

Our next iteration, developed for 2014's Aerial Assist game, began an emphasis on simplification. The most significant and visible change was the elimination of the horizontal drive shaft and its sprockets/chain by direct driving the axle, and the corresponding move to "dually" wheel sets. The wheels were 4" VEX Versawheels/Versahubs with some secondary machining ops to accommodate the bevel gear set. The top driveshaft bearing was changed from a ball bearing to a needle bearing. Overall height and complexity were reduced relative to previous iterations. We found reliability was improved, and the maintenance load on the pit crew was dramatically reduced. We also started to notice improved handling. It was visibly unique, and our team started to identify with it. Playing off the "West Coast Drive" name, we've taken to calling our dual wheel posi-traction swerve a "Third Coast Drive," in reference to the Great Lakes region.
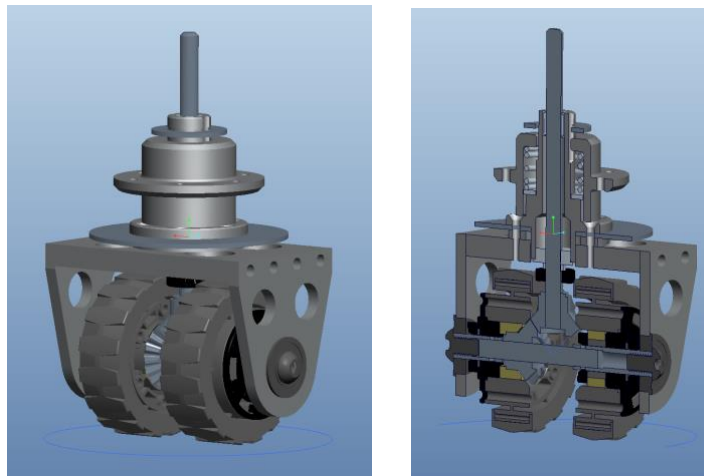

Items targeted for improvement after competing with this first generation Third Coast Drive:

- Weight
- Vertical drive shaft cantilevered off lower bearing too far—led to occasional bent drive shafts. This was in part due to some shafts with improper heat treatment.
- Conversion of azimuth chain to belt
- Method of setting bevel gear mesh

2015's game, Recycle Rush, really didn't emphasize the traditional capabilities of Swerve. However, since we had a lot of comfort and experience with it, we did it simply for the advantages of maneuverability in tight quarters. The main differences between this design and the former were that we changed how the axle was constructed and the bevel gear adjusted, and we converted the azimuth from chain to belt drive. We also eliminated the bolted connection between the side plates and the top plate. In this version, this last change meant that we bolted a retainer for the axle bearings in from the bottom (not easily seen below). At the time, we thought this was necessary for maintenace on the wheels. As in 2014, the design required secondary machining ops on the wheels to accommodate the bevel gears. The whole axle assembly also had quite a few spacers.
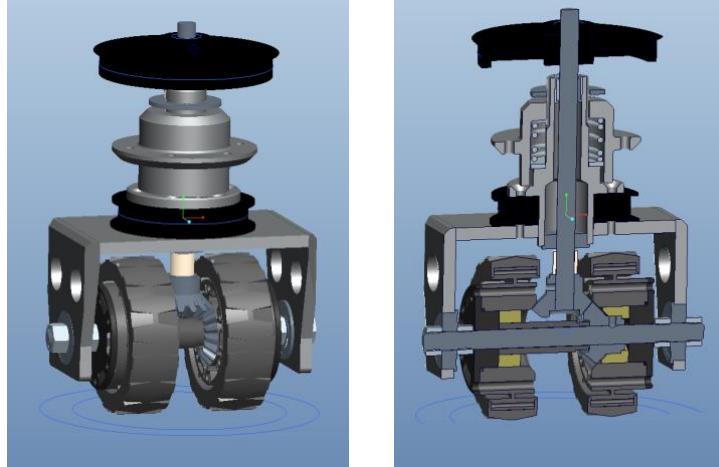
In the off season between 2015 and 2016, we created a Third Coast Drive T-Shirt Cannon Robot. For the drive units in this design, we hoped to get rid of the hassles and time penalties of azimuth zeroing by shifting to absolute encoders. We developed an in-house method of mounting an optical encoder on a Vex Planetary Gearbox output—only to find out that Vex simultaneously released a similar product with a more robust magnetic-based encoder. We happily adapted to using theirs. Other refinements included using a composite saddle (wet layup over printed ABS core), exploring using a gear set rather than pulleys and belts for azimuth control, moving to Colson wheels to improve wear, elimination of several axle spacers, smaller wheel size to reduce the overall gear reduction needed for a target speed, elimination of secondary machining on the wheels, and the axle bearing retainers. Overall, this module, which never saw FIRST competition, was very light and a nice upgrade but the fabrication of the composite saddles was time intensive and we didn't have faith in them or the azimuth gear set given the posi-traction axial motion.
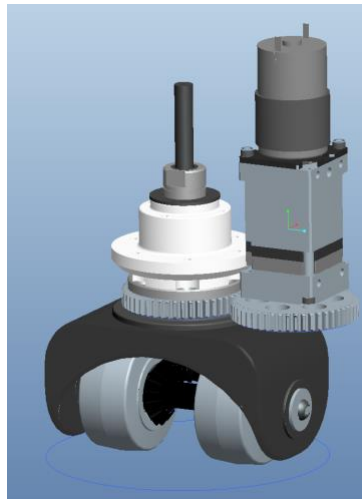

In our initial estimation, 2016's game, FIRST Stronghold, did not lend itself to Swerve Drive. The amount of physical abuse we expected the robots to take gave us pause, and the wide variety of orientation in obstacles made us worry about swerve's appropriateness. For example, if the dual wheels were not aligned with an obstacle when they hit it, the impact with the leading wheel would create a torque-shocking the azimuth belt, potentially skipping teeth or breaking it. Thus, we went to an eight wheel

tank drive with the outer wheels raised slightly for maneuverability. Each set of four wheels were mounted in suspended "skis" intended to smooth out impacts going over obstacles. In hind sight, FRC 16 "Bomb Squad's" robot for that game proved that Swerve could still be used to very good effect. Hat's off to their team's insights on how to make that all work out.

With the wide-open field of 2017's game, FIRST Steamworks, we went back to swerve. The 2017 generation of Third Coast Drive started with what we learned from the T-Shirt Cannon Robot and put a lot of emphasis on simplicity, ease of manufacturing, and weight reduction. Key design elements were shifting to a Nylon mounting "bonnet" vs. the traditional aluminum (weight savings), moving to 775Pro drive motors, a 2:1 bevel gear set, and reduction of posi-traction throw to facilitate a stable shooting platform. This design is described in detail below:

**2017 Stryke Force Third Coast Drive Detailed Description**
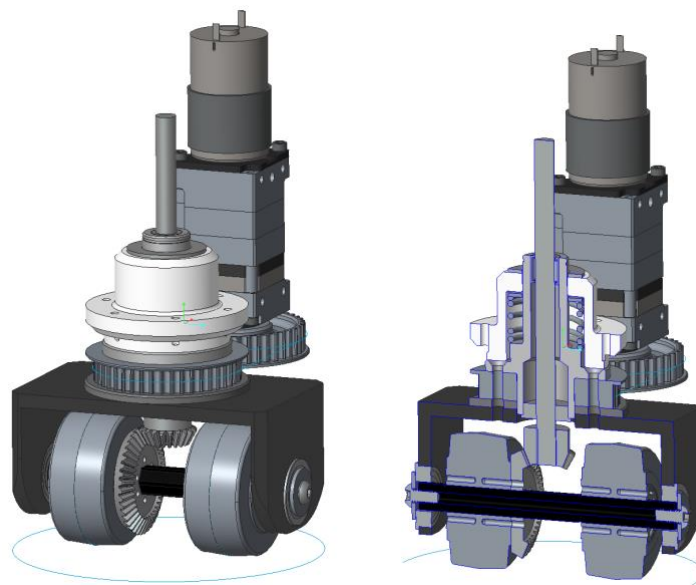
Wheel/Axle Assembly: Use of durable 2.5" Vex Colson wheels with ½" hex bores and Andy Mark's 2:1 bevel gear set along with AndyMark CIMiles allowed us to move to lighter high speed motors while keeping things simple and the drive pulley ratios reasonable. Earlier Third Coast Drive designs used lower speed CIM or mini-CIM motors. To use the Andy Mark gears on axles made from Vex ½" Thunderhex, we removed the flange on the large gear's back side, opened the 3/8" hex to ½" hex (drilling and broaching) and drilled a hole pattern in its face matching the one in the Colson wheels. All torque was transmitted through the hex flats; the screws going through the hole pattern were simply to keep the face of the gear flush against the wheel face, counteracting the moment created by the bevel gear mesh forces. Note that the opening of the 3/8" hex bore to the ½" hex bore had to be done very carefully. We used a mill and a dial indicator to set up the job. The concentricity of the bore to the gear tooth pattern is critical to properly setting backlash. Lack of concentricity will force unnecessary backlash. Unnecessary backlash will lead to premature gear wear, noise and poor control. Similarly, care must be used in the broaching operation.
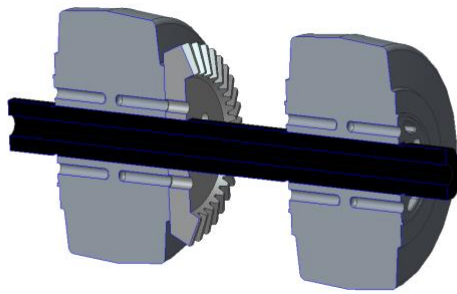
The wheels were axially held in place on the axle with three snap rings (not shown); one for the geared wheel (opposite side from the gear to take the mesh thrust), and one on each side of the non-geared wheel.   The location of the snap ring grooves in the axle was determined by the location to hold the geared wheel in the nominal mesh location relative to the mating gear on the vertical drive shaft. The non-geared wheel was located symmetrically about the vertical drive shaft relative to the geared wheel. This was done so that scrubbing torques are equalized and the robot can stay stationary when azimuthing a swerve unit. One way to think about it is that essentially a virtual wheel is created on the vertical axis. The axle length was set carefully so that it could just be rocked in position in the saddle when the bearings were not in place. This elimated the need for a complicated saddle with bearing retainer plates.

Saddle: The incremental design goal for the Saddle in 2017 was for it to be one piece and machinable by build team students using basic skills. The Saddle started life as a ¼" wall 5"x5" 6061-T6 Aluminum extrusion. The extrusion was cut to length on a horizontal bandsaw and then cut in half using a vertical bandsaw. The width was determined by what was necessary to provide complete support for the azimuth pulley diameter and the height was what is left after cleaning up the bandsaw cuts. The next step was to mill the saw-cut faces in order to square them up. After the faces of the horseshoe were squared up, the axle shaft holes were carefully drilled and reamed to fit 1-1/8" OD Thunderhex flanged bearings. The top hole was then drilled out to intersect the axle shaft axis at right angles. This hole must intersect the axle shaft hole for proper gear mesh. The bolt pattern at the top was also done on the mill at this time and the holes were subsequently tapped. In order to minimize weight and swept diameter, the edges were chamfered and the bottom corners cut off around the axle bearings. Note that in CAD, these corners are radiused, but on the actual robot, they were cut off at 45 degrees—simply easier for fabrication. On our prototypes we didn't even bother with these cuts at all. Note that minimization of swept diameter is important because we set up the wheels so that the swept path is almost tangent to the frame—wheelbase reduces as swept diameter increases, and wheelbase is important for stability/handling.
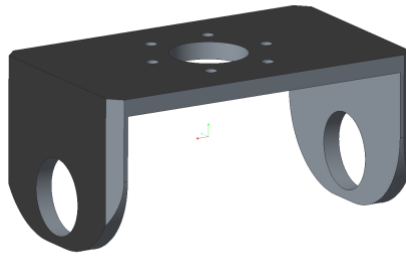
Azimuth Pulleys: The azimuth pulleys were 3D printed by our sponsor in polycarbonate using a commercial FDM type printer (Fortus400MC). A flange for the swerve unit side was also printed (visible in assembly views, but not shown below). We have found that the teeth profiles need to be tweaked a bit (opened ~0.002") to get the timing belt to settle into them fully. This is important because if the teeth don't settle in fully, the belt teeth will jump under load and you'll lose wheel alignment.

Note that to be able to take advantage of the absolute encoder on the output of the azimuth gearbox, these two pulleys must be the same number of teeth. We used 44T in 2017. Also note that we now use HTD, 5mm pitch, 9mm wide belts. To minimize "backlash" due to belt stretch during direction reversals and possible slipping of teeth, these belts need to be fairly tight. Earlier versions used XL type belts which weren't quite as smooth or robust to the loads. The pulleys were a little wider than the belts in order to accommodate the posi-traction motion. One thing we struggled with in this design was durabiltiy of the hex driven azimuth pulley. We prevented outright failure by JB Welding an SAE aluminum washer in around the boss surrounding the hex. This washer took the hoop stress and prevented the cracks we were seeing at the hex vertices. The hex fit could still loosen a bit due to wear over the course of a tournament, leading to some backlash in the system. We inspected for this closely and changed them out as soon as we saw one with some relative motion. The hex shaft-mounted azimuth pulley was retained on its shaft with a washer and button head screw. An off the shelf aluminum ½" hex pulley could be used, but we were looking to save weight and eliminate the backlash associated with the typical clearance fit.   Note that in order to keep the overall packaging as tight/low as possible, we cut down the stock Versaplanetary hex shafts to custom length and re-drilled/tapped the ends. Off the shelf shafts could be used if the azimuth actuator axis is moved further away from the Swerve Drive. The larger clearance pulley could also likely be an off the shelf pulley with a large bore. The Swerve Pivot Hub would just need slight re-design to accommodate it.
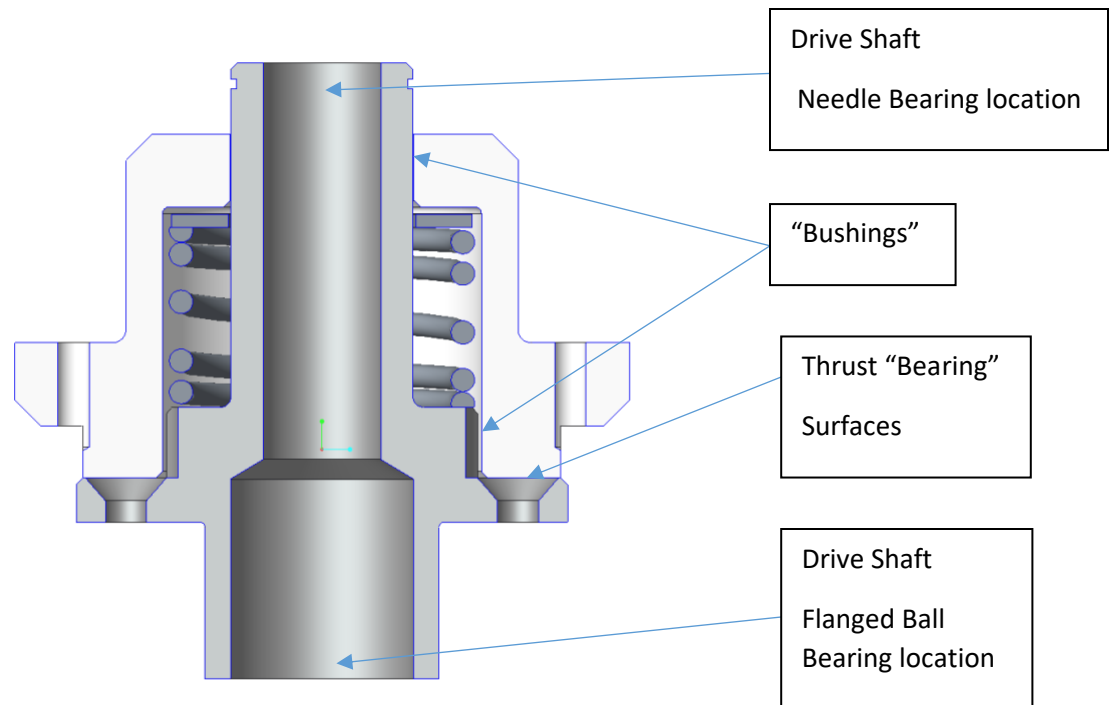
Swerve Pivot Hub and Mounting Hub:

These were the two "complicated" parts in the system which were done on a sponsor's CNC lathe with secondary ops on a mill.
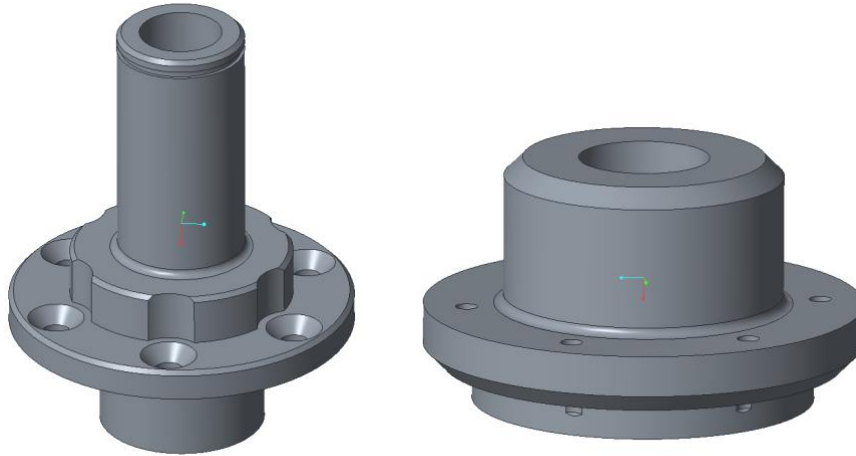
The Pivot Hub (left) was aluminum and supported an off the shelf 6" long Ø3/8" case hardened steel vertical drive shaft (McMaster-Carr). This support was accomplished with a 7/8" OD flanged bearing (AndyMark) at the bottom, and a 7/16"OD needle bearing at the top (McMaster-Carr), both of which were pressed in. The separation of the two bearings nicely supported the vertical drive shaft. One key to success was to get the lower bearing close to the bevel gear. If this distance was too long, the 3/8" diameter drive shaft could bend under the combined loading of the bevel gear thrust and wheel side loading. The Pivot Hub was bolted into the top of the saddle using flat head screws. It sandwiched the printed azimuth pulley and a spacer such that those printed plastic parts were vey well supported. The heads of the flat head screws were slightly recessed below the face they went into. This was because that face served as a thrust bearing for the underside of the Mounting Hub. Essentially, ¼ of the robot weight less the posi-traction force (described below) acted on this thrust bearing. The hole pattern was originally determined by our use of off the shelf sprockets for our chain driven azimuth. In this iteration, it was vestigial, and since it drove us to make the milled "scallops" to clear the heads it was redesigned for 2018 as will be seen below. The moment was transferred through the assembly to the robot frame by two separated cylindrical faces. The first was the scalloped face and the second was the area immediately below the snap ring groove. The two faces and the thrust face were all carefully deburred and lubricated (we used "Super lube"). The Mounting Hub interfaced with these faces as described next.

The Mounting Hub (right) was made from cast nylon (McMaster Carr), which made a nice bushing material and was still strong. Delrin would also likely work well. The robot frame sat on the flange with the bolt pattern. The holes making up the bolt pattern in the flange were tapped and this was how the Swerve Drive unit attached to the robot.

Drive Shaft
Needle Bearing location

"Bushings"

Thrust "Bearing"
Surfaces

Drive Shaft
Flanged Ball
Bearing location

Positraction Description:

For a robot to efficiently drive straight, the following must be satisfied:

1. All wheels have same surface velocity. Usually:
    a. Same diameter
    b. Same rotational speed
2. Same traction. A result of:
    a. Evenly distributed power.
    b. Evenly distributed traction.
3. All wheels pointed in the same direction (aligned)

Pos-itraction helps with item 2b. Three points define a plane. More points are odd men out—in engineering speak, the plane is "overconstrained." In practical terms, when four rigid swerve units are put on the ground, manufacturing tolerance stackup or post manufacture movement (such as from a damaging collision, or drop) cause one of the points to come off the ground. The robot will then be less stable than it would otherwise be, possibly rocking (depending on frame stiffness), or will at least have less traction on the higher wheel. Even aligned, if the traction isn't similar between wheels, the robot will not drive straight without some other correction. The posi-traction spring is sized to push the Swerve Pivot Hub and Mounting Hubs apart with a force roughly 20% of the fully weighted robot. Thus, the robot normally rides with its "suspension" bottomed out on the thrust "bearing." However, when one wheel starts to become unweighted or even comes off the carpet, the spring will push back down and keep the wheel in contact with the ground. We know from practical experience that the posi-traction works and will make up for significant frame bending. It also helps control when accellerating hard, driving onto a shallow ramp or over minor obstacles. Unfortunately, the amount of travel must be limited to fairly small amounts, or the robot is not a stable shooting platform. We limited travel to

approximately 3/32" for the 2017 robot because of the recoil from the Shooter. The inside surface of the Mounting Hub Nylon was protected from the end of the steel spring by a washer.

Unit Assembly:

The unit, less the Mounting Hub, Washers, and Spring were assembled (as shown below) off the robot.

Mesh Adjustment Screw
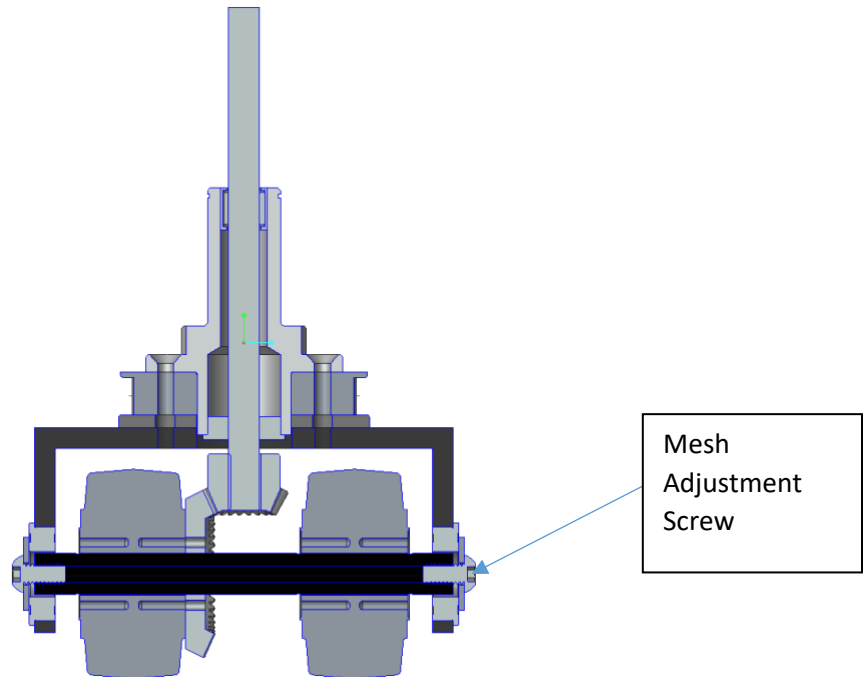
Shimming of the bevel gear set was either done now or after mounting on the robot and is described next.

Once assembled into the saddles, the horizontal component of the mesh was adjusted by jacking the axle back and forth several thousandths from the nominal location. This jacking was accomplished using the ¼-20 button head screw threaded into the Thunderhex bore (tapped) on the non-geared wheel side. Mesh was adjusted vertically with shims (not shown) between the back of the vertical shaft bevel gear and the support bearing inner race. Mesh is proper when the gears line up as shown (maximizing facewidth engagement), have minimal backlash, and move freely through full rotation. Once set, the opposing ¼-20 button head screw was tightened to lock the shaft in position. Both axle screws were doped with Blue Loctite to prevent loosening. This process was checked again after operation under load. Once re-adjusted after "burn in" we did not have to revisit the mesh during a season.

Final Assembly:

The Mounting Hubs were bolted into the robot frame. The posi-traction spring was set on the Pivot Hub with a washer on top and then pushed into the Mounting Hubs from the bottom. The spring was compressed until the snap ring groove at the top of the Pivot Hub came through the top of the Mounting Hub. A second washer was placed on top of the Mounting Hub and a 7/8" snap ring was put in place to hold the whole thing together. The top washer protected the nylon of the Mounting Hub from the steel snap ring as it rotated with the Pivot Hub. Posi-traction motion could be reduced by

adding washers between the Mounting Hub and snap ring if necessary. Posi-traction force could be adjusted by adding washers inside the Monting Hub or grinding down the spring as needed.

Drive Pulley Location
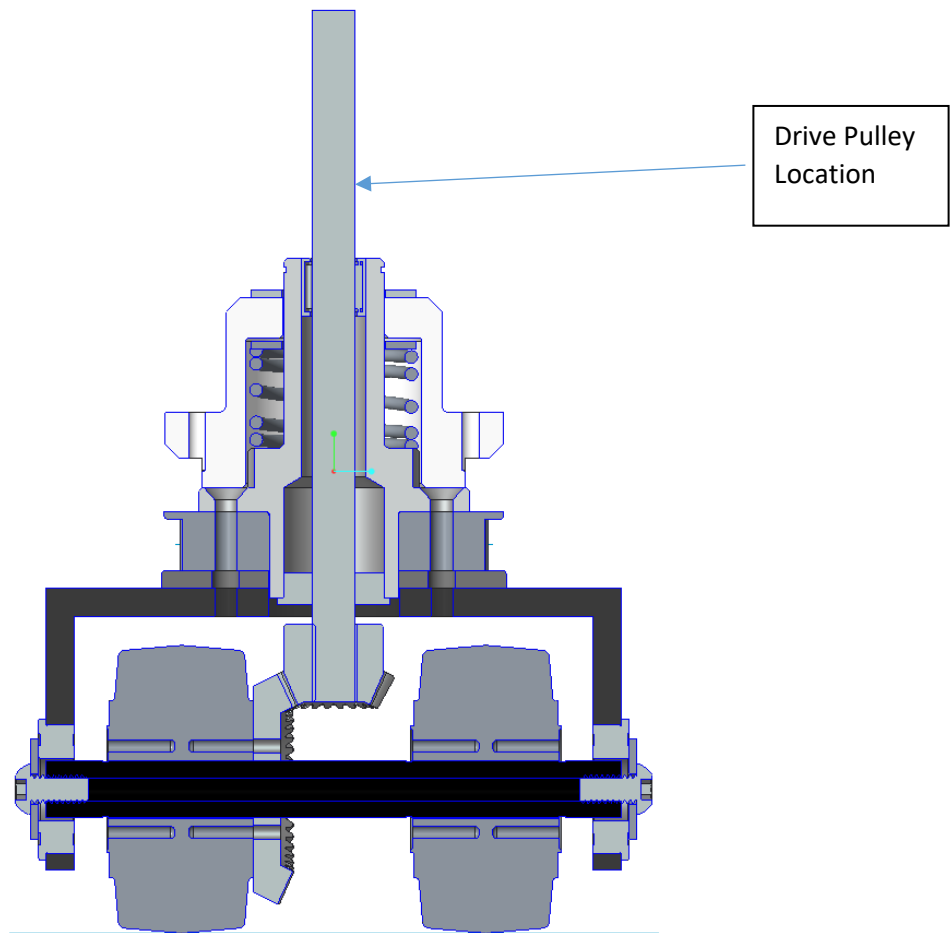
Other Notes:

- In 2017, we opened the bore of the vertical drive shaft bevel gear (it comes 8mm) and welded it to the 3/8" drive shaft. We have also succesfully cross-drilled and pinned them, and used keyed connections in the past.
- It is good practice to try to get the Drive Pulley down close to the needle bearing in order to minimize that cantilever and the resultant moment loads on the shaft. However, we have not had an issue with the upper portion of the shaft bending with the gear ratios we're using.
- It's important to give careful thought to how motors and gearboxes are mounted. Belt loadings can be significant and if the shafts are not parallel to the swerve drive unit axis, belts will walk and slip off pulleys. Also, note that our azimuth pulleys are significantly larger than the belt widths in order to provide for posi-traction travel.
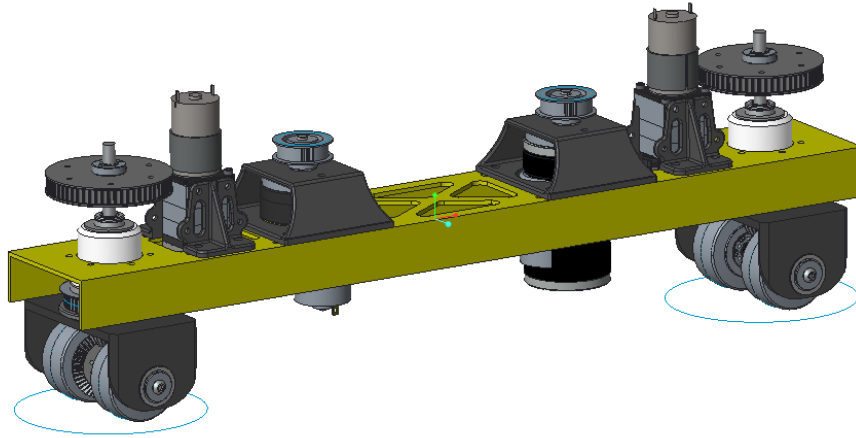
- We designed in features to adjust belt tension for both drive and azimuth belts. We mounted the motors/gearboxes/encoders in either sections of tube, or printed structures as shown above and then bolted those down to the yellow Swerve Drive Rails using slots. The Swerve Drive Rails were welded or bolted into the robot frame. Note that the 2017 design accommodated either 775Pros with Cimiles or CIMs. The higher unit in the picture above shows both in this screen shot. Note that we have also mounted swerve units individually rather than in pairs. This was done using sheet metal with edges braked for stiffness. We like the rails because they help keep the units planar, which should reduce the need for posi-traction travel.
- We set our azimuth motor pointing down (the belt is under the C-Channel in the above screen shot) and our drive motor pointing up (belt over the C-Channel above). The components nested within the belt paths to minimize overall footprint. One or the other of these could be rotated and the drive motor brought in towards the Swerve Drive if that form factor is advantageous.
- In addition to the azimuth pulleys discussed above, we 3D print our drive pulleys to save weight and cost. We make our hubs out of ¾" aluminum hex to reduce the stress on the plastic. We turn down the ends of the hex to ½" round, slit them and then clamp onto the shaft through the slit round section using two piece heavy duty aluminum clamping collars. When tightened down, they don't slip.
- Closed loop tuning will likely be necessary to get the whole package working nicely. Without it, larger motors, and/or gear ratios may be required. Tuning is discussed briefly below, but a detailed description is another subject…..Stryke Force teaches a course on tuning in the off season. A recording of the most recent one is available on Youtube. There are links on our website. A lot of information we go over is provided in CTRE's Talon SRX user manual/materials.
  - In 2017, we used a BaneBot RS550 for the azimuth motor since it had plenty of power and was very light weight. At various times we have geared it from 64:1 to 100:1 using Vex planetary gearboxes with ½" hex output shaft and encoder stage. In the past we also successfully used BaneBots's planetary gearboxes. The azimuth pulleys were 1:1, and we used 2.5" Colson wheels set apart approximately 2-5/8." Under position control, with the Talson SRX PID loop properly tuned, that range of ratios easily turned those wheels on carpet and did so very quickly. The tuning was hot enough that the azimuth control loop was marginally stable with the wheels in the air, but good on carpet.

o In 2017, we used a Vex 775Pro drive motor with a CIMile and CIMcoder. The drive pulley ratio was adjusted to balance acceleration and top speed based on wheel size, the game and driver preference. In 2017 the drive pulley ratio was approximately 2.4:1. Since the Cimile has a ratio of 29:12 (~2.42:1) and the AndyMark bevel gear set is 2:1, the total ratio used was ~11.6:1 (2.42x2.4x2). Larger wheels would need more gear ratio for similar performance. Note that if you use 775Pros, the motors need to be current limited or you will burn them up. The current limit necessary for robustness will depend on how you gear and drive your robot. We also use several driver techniques to help with this issue. We used a CIMcoder to enable closed loop speed and position control.

2018 Stryke Force Third Coast Drive Detailed Description

The goals for 2018 were to improve our ablity to manufacture parts using in-house (non-CNC) resources and further reduce weight, and swept volume.
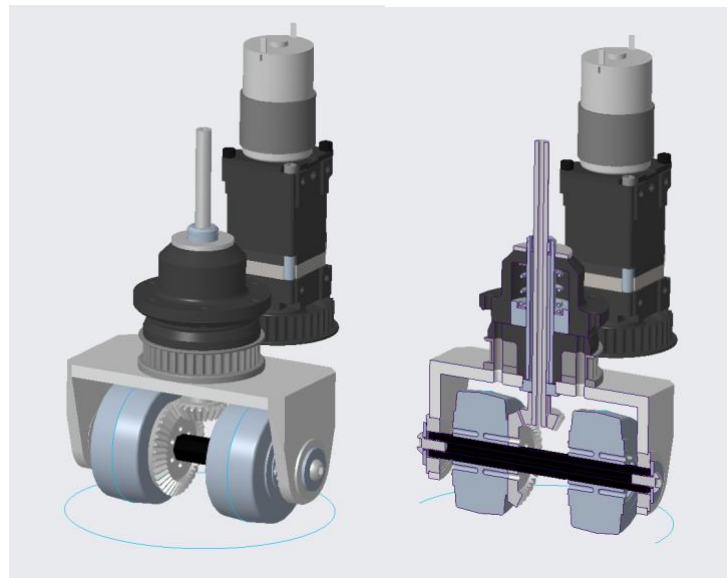

Wheel/Axle Assembly: This was essentially unchanged from 2017 other than a minor chamfer on the ends of the Thunderhex to make putting the axle in the saddles easier. One note: It makes sense to check the straightness of the hex stock before manufacturing the axles. In 2017 we saw some bent axle shafts which caused difficulties in setting the mesh, similar to a non-concentric opening of the bore in the bevel gear.

Vertical Drive Shaft: The 2018 vertical drive shaft was changed from 3/8" to 8mm. The primary reason was to avoid the necessity of re-boring the AndyMark bevel gear. However, once changed, a beneficial cascade resulted. We were able to use smaller bearings which drove smaller housings. These size reductions, along with closer attention to detail in all of the other components allowed us to realize a weight savings approximately 20%, or 1 pound per swerve corner—an overall robot weight savings of 4 pounds! We tested key elements of the changes in the offseason and were convinced we didn't loose any significant durability and this was borne out during the season. One other note: We used hollow 8mm shafts in 2018 (SDP/SI "pipe shafts"). This was done not so much for weight savings, but to enable

a potential shifting swerve design (ultimately not needed/used). Also new this year, after it was welded to the shaft, we turned down the hub on the bevel gear to save some weight.

Saddle: The incremental design goals for the Saddle in 2018 were weight reduction, improved load paths and development of a couple of fixtures to ease manufacturing. The weight reduction was accomplished by starting with a smaller 4" x 4" extrusion, reducing width and extending the sidewall tapers. The main fixture developed was a block to ensure the saddle side walls are supported while drilling/reaming the axle bearing openings. This improved our ability to make sure the vertical drive shaft axis and axle axis are perpendicular and in the proper locations. The vertical drive shaft hole was sized to press fit the lower shaft support bearing. This put shaft thrust and much of the radial load directly into the saddle instead of the Swerve Pivot Hub. We also opened the bolt holes to clearance holes and moved the tapped holes to the Swerve Pivot Hub. This was done primarily to improve the manufacturability of the Swerve Pivot Hub as will be seen below.
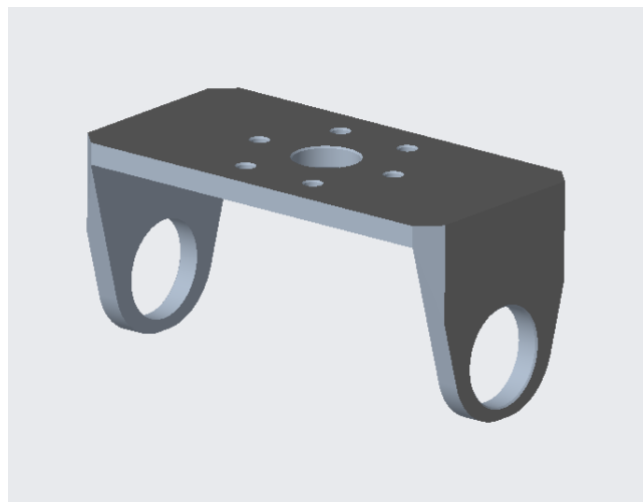

Azimuth Pulleys: The azimuth pulleys were reduced from 44T to 38T to enable the width reduction in the saddles. This potentially could have led to tooth slippage issues, but we upgraded our Azimuth drive mounts so that they are more robust (shorter load path) and convinced ourselves with testing that we were still OK. As in 2017, the pulley was printed without the flange to maximize the tooth profile accuracy. At this point, we believe this is not necessary. The pulley with the hex hole was printed in Nylon with short carbon fiber (Onyx) on a MarkForged printer with continuous strand carbon fiber around the hex hole to take the hoop stress, avoiding the epoxied SAE washer from 2017. The hex interface was a press fit and we thereby eliminated the wear issues we saw in 2017. We printed three ¼-20 holes in this pulley and later tapped them so that we could tie into them if it was ever necessary to pull the pulley off the shaft. We printed a "spider" pulley puller to work with them. The puller had a tapped central hole that we could use as a means to jack the pulley up off the shaft by turning a bolt against the ½" hex shaft end. It worked very well, but we never had to use them at a competition.
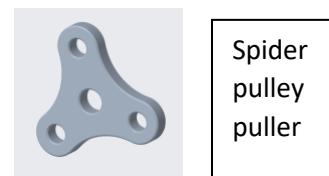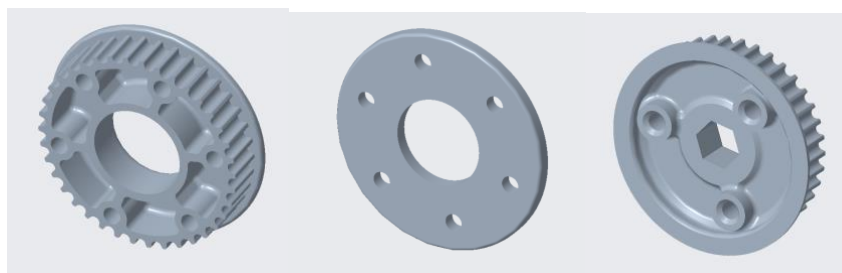
Spider pulley puller

Swerve Pivot Hub and Mounting Hub:

The two "complicated" parts in the system were converted for in-house fabrication.
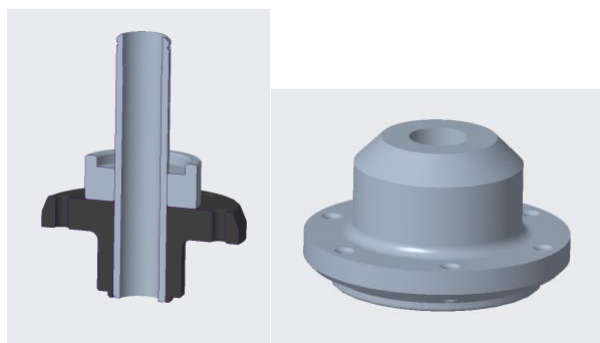
The Pivot Hub (left) was converted to a three piece hybrid aluminum and printed plastic assembly. The printed plastic was MarkForged Onyx and had continuous strand Kevlar reinforcement in a few areas. A 5/8" OD 2024 aluminum tube (McMaster-Carr) was pressed into it. This assembly supported the vertical drive shaft (SDP/SI). Shaft support was accomplished with a 19mm OD flanged bearing (AndyMark) at the bottom pressed into the saddle, and a 12mmOD needle bearing at the top (McMaster-Carr) which was pressed into the Aluminum tube. One end of the tube was reamed for the 12mm needle bearing and grooved for the snap ring. The Pivot Hub was bolted through the saddle and Azimuth Pulley into tapped holes in the Pivot Hub. This change avoided the conterboring/countersinking operation (and scalloping of the lower bushing) on the 2017 design. We also replaced the lower bushing area with an aluminum tube/sleeve to reduce the likelihood of wear/galling due to plastics of the same type running on each other. This short tube was trepanned at one end to keep the posi-traction spring centered. A thin steel shim washer prevented the spring from digging into the aluminum. All interfacing surfaces were lubricated with Super lube. The step down in diameter at the bottom of the printed part was used to interface with the bearing bore in the Saddle so as to drive concentricity of the assembly. Note that the printed part of this assembly could easily be machined from either Aluminum or cast Nylon.

The Mounting Hub (right) was Onyx reinforced with continuous strand Kevlar in select areas. The Mounting hub bushing surfaces (IDs) were printed for slight interference. These surfaces were subsequently cleaned up with a boring bar to ensure a smooth, print artifact-free surface finish so as to avoid interference with the positraction axial travel. This part could easily be turned from cast nylon.
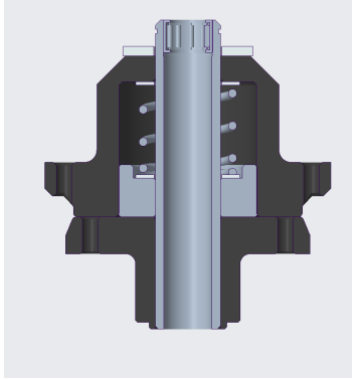
For 2018 we limited positraction travel to to approximately 1/8". The printed Nylon was protected from the end of the steel spring by another thin steel shim washer.

Unit Assembly:

The unit, less the Mounting Hub, Washers, and Spring was assembled (as shown below), off the robot. Socket Head Cap Screws (not shown) came up from the bottom and the heads cleared the wheels easily. However, it was easier to do this part of the assembly before the axle and wheels were put in place.
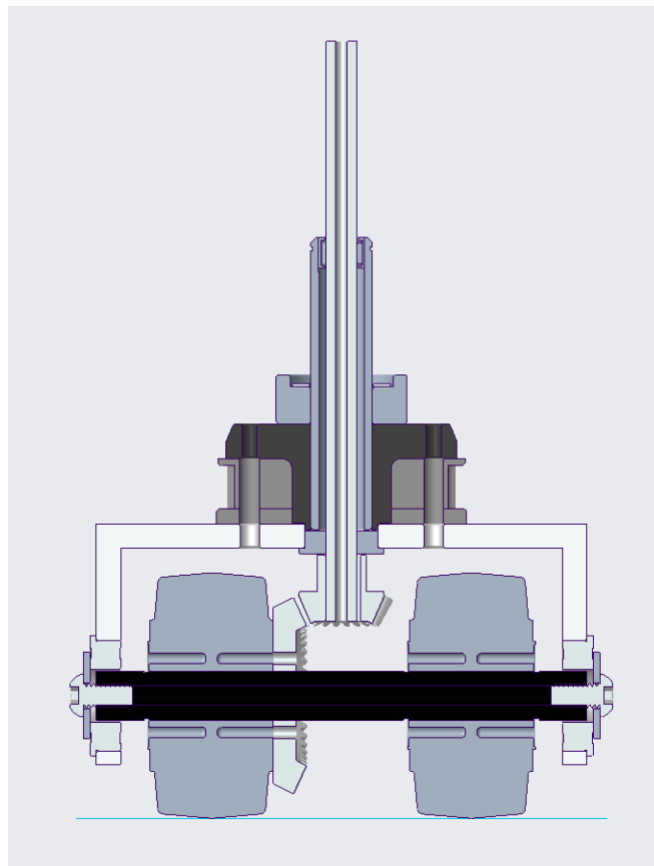
Shimming of the bevel gear set was done as in 2017.

Final Assembly:

The Mounting Hubs were bolted into the robot frame. Mating parts were test fit, ensuring the bushing surfaces had smooth operation rotationally and axially. Bushing surfaces were then lubed. The posi-traction spring was set on the Pivot Hub with a washer on top and then pushed into the Mounting Hubs from the bottom. The spring was compressed until the snap ring groove at the top of the Pivot Hub came through the top of the Mounting Hub. A second washer was placed on top of the Mounting Hub and a 5/8" snap ring was put in place to hold the whole thing together. The top washer protected the nylon of the Mounting Hub from the steel snap ring as it rotated. As in 2017, posi-traction motion could be reduced by adding shim washers below the snap ring. Posi-traction force could be adjusted by adding washers inside the Monting Hub and/or grinding down the spring.
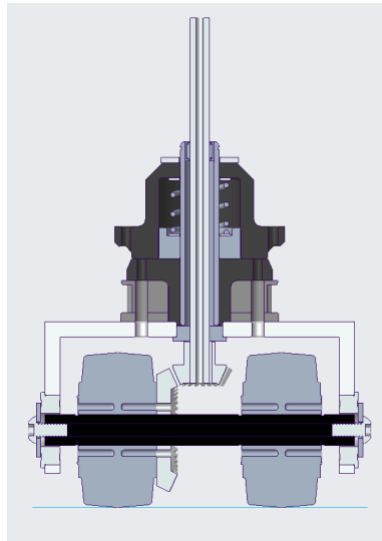

Other Notes:

- Overall weight reduction vs. 2017 was approximately a pound per unit and all manufacturing was done in house, without CNC.
- We improved our azimuth and drive gearbox mounting to add stiffness, reduce weight and ease access for belt tension adjustment.

Azimuth Assembly

Drive Assembly
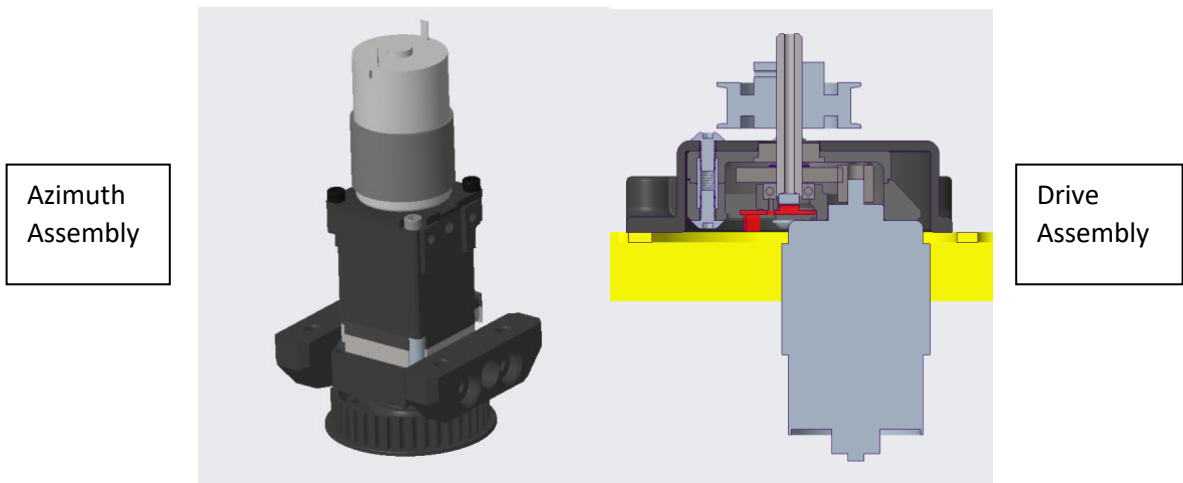
- Due to the cascade of size reductions driven by the shift to an 8mm shaft, we were able to use a 3-1/2" channel for mounting instead of the previous 4", further saving weight and footprint associated with the drive system.
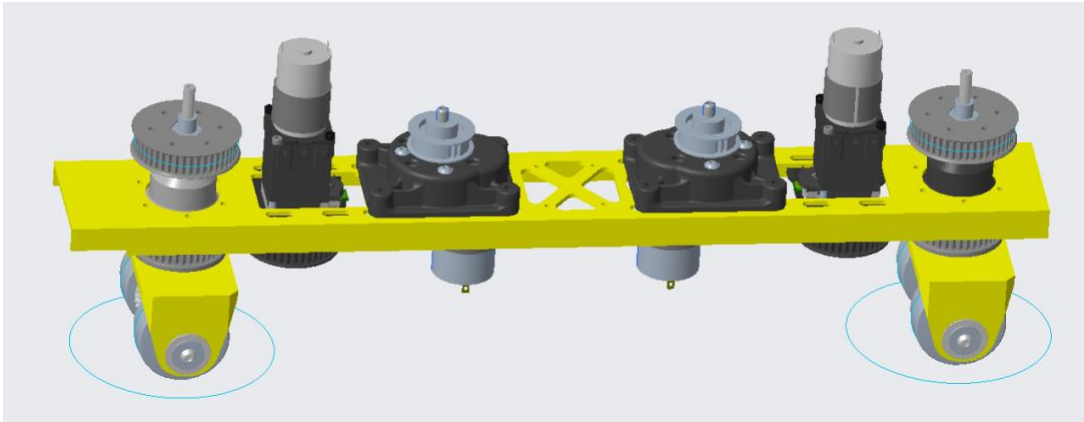
- We used an AndyMark 9015 for the azimuth motor since it had plenty of power and was very lightweight. We geared it 100:1 using Vex planetary gearboxes with ½" hex output shaft and an encoder stage. The pulleys were 1:1, and we used 2.5" Colson wheels set apart approximately 2-5/8." Using CTRE's Motion Magic, with the Talon SRX PID loop properly tuned, that ratio easily turned those wheels on carpet and did so very quickly. The tuning was hot enough that the azimuth control loop was marginally stable with the wheels in the air, but good on carpet.
- In 2018, we again used a Vex 775Pro drive motor, but with a custom 3D printed (Onyx) gearbox with steel gears and a built in CTRE mag encoder. To save cost, we used stick form gears, cut them to length, bored them, and then case hardened them. The case hardening process was necessary because the stick form gears do not have sufficient carbon for a standard hardening process. The gearbox is shown mounted in the drive assembly picture above and by iteslf below. To change out a motor/gearbox assembly, the belt is rolled off the pulley, the pulley is removed, three screws were removed on the top and the unit drops out from the bottom. In this fashion, a new unit can be put in without need to readjust belt tension.
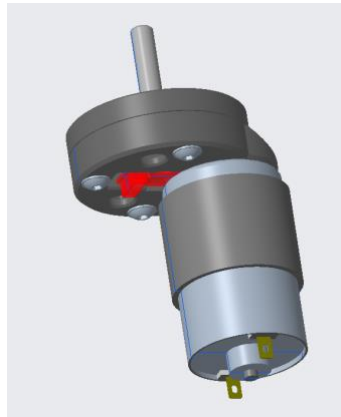

- In 2018 year the drive pulley ratio was approximately 2.29:1. The custom gearbox had a ratio of 40:12 (~3.33:1) and the AndyMark bevel gear set is 2:1, so the total ratio used was ~15.3:1 (2.29x3.33x2). Larger wheels would need more gear ratio for similar performance. Note that <u>if you use 775Pros, the motors need to be current limited or you will burn them up. The current limit necessary for robustness will depend on how you gear and drive your robot. We use 40A</u>.

We also use several driver techniques to help manage the issue. We are under closed loop velocity control during Auton and open loop voltage control during Teleop.

2019 Stryke Force Third Coast Drive Detailed Description

In PowerUp, we struggled with our longer autonomous routines largely due to variable carpet slip. Variations in the way the carpet was worn and oriented caused us difficulties the entire season.

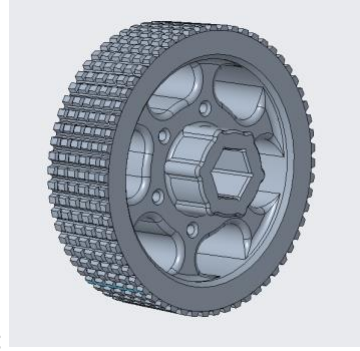 The goals for 2019 were to improve traction on carpet, and further reduce weight and swept volume.
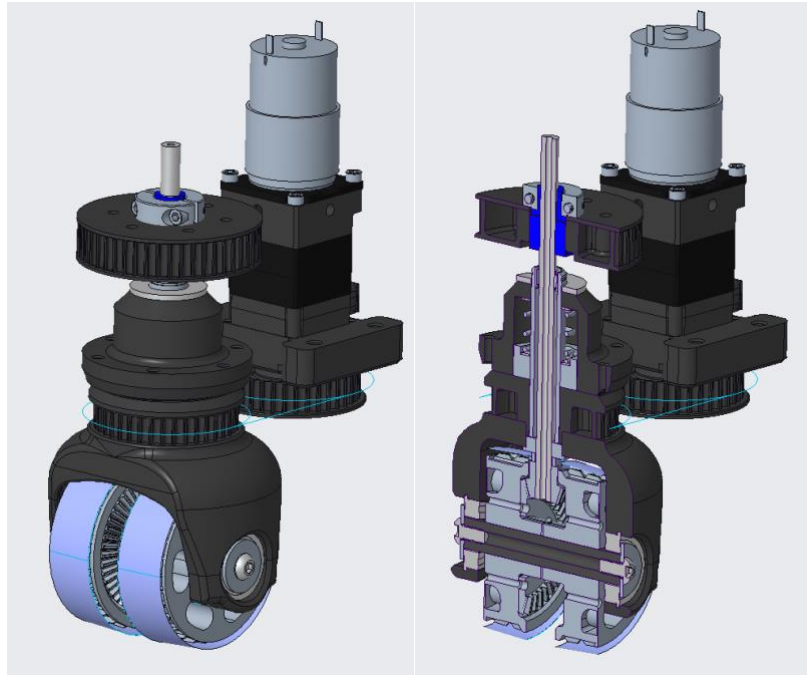
Wheels:

We considered two potential design paths to reduce wheel slip: Custom hubs with rough top Nitrile and custom hubs with knobby tread designed to interdigitate with the carpet. In 2013 Stryke Force had used silicone rubber R/C car tires on CNC machined custom hubs and had significant issues with tread wear and roll off. Thus, Nitrile was shelved due to concerns they would be similar. Instead, we focused on developing a printed hub over molded with urethane treads. The tread wasn't printed directly due to the "no hard plastic" rules regarding tires and we don't have access to a printer with capability to print TPE or TPU. Our hubs are printed in MarkForged Onyx and have continuous strand CF reinforcing the area around the ½" hex axle.

Two part casting urethanes are widely available in several durometers, generally have good wear characteristics and can be molded relatively easily. Our hubs were designed with features intended to mechanically interlock with the treads since urethane won't chemically bond to Nylon, our intended hub material.
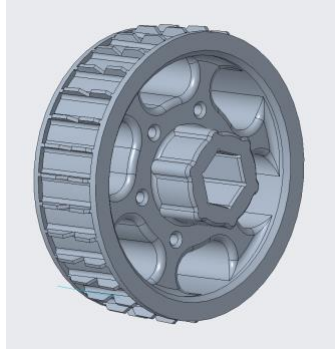
Before Overmolding: After:

After conferring with a local urethane supplier (Alumilite), we printed 3" OD master wheels from which we made silicone molds. These molds were carefully constructed to keep the hub and tread concentric. Molds were filled and then placed under vacuum to draw bubbles out. We made our own vacuum chambers with PVC pipe sections and polycarbonate endplates with rubber gaskets. Shortly before the chemistry kicked over to harden, the vacuum was removed and replaced with approximately 30psi pressure to drive down the size of any remaining bubbles. Once stripped from the mold a few hours later, the hub/wheel assembly was further cured in an oven. Overall, this process was an excellent case study in process development for our students.

Several tread patterns were evaluated for slippage and wear. One (slightly different from the above picture) was ultimately selected for evaluation at an off season invitational and proved very successful—solving our problems from the previous season. However, traction was poor on HDPE surfaces when materials hard enough to have good wear characteristics were used. Thus, when Deep Space was revealed with slippery HAB surfaces and no true auton period we went back to lower durometer slicks. In retrospect, we intend to keep looking for an optimal balance of traction and wear since we could have used better dead reckoning capability to enable fast multi-hatch autons during the Sandstorm period.

The use of custom hubs facilitated three other changes from previous years. First, we nested 3:1 KHK bevel gears into the hubs, allowing closer spacing of the wheels. The bevel gears screw into the 6 hole pattern seen in the images above. Second, we designed our 3" OD wheels to have a slight (~2degree) taper to the tread with the larger diameter to the inside. This was done to mimic the wear we have seen naturally develop on Colson slicks in the past. The theory was that it would slow the overall wear rate down by reducing scrub. Third, we optimized our wheel thickness to better balance wear with swept volume/weight of the module.

Saddle: The incremental design goals for the Saddle in 2019 were weight reduction, improved load paths and reduction of swept volume. The weight reduction was accomplished by conversion to printed plastic (MarkForged Onyx), and reducing width. To compensate for the loss of stiffness due to the material change, we made a design change so that the lateral loading on the wheels was shared by the two sides of the saddle. This was accomplished by capturing the flanges of the axle bearings in slots capped with retainers coming up from the bottom as shown below:
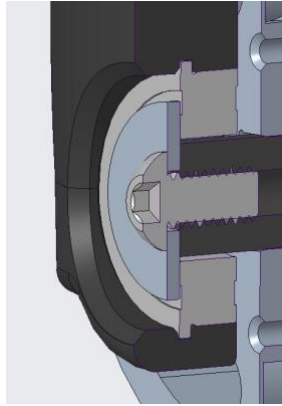
The retainers were affixed with # 6 screws tapped into the Saddle. The axle thus became essentially the fourth side of a box beam. Moment loading was reduced by narrowing the overall module width via nesting the bevel gears and minimizing clearances. The Saddles were further reinforced with several strategically placed ribs and layers of continuous strand Kevlar to increase their rigidity. This rigidity was critical to maintain proper mesh of the bevel gear set. Finally, the top of the Saddle incorporated the bottom flange for the azimuth pulley, which was bolted on from the inside bottom surface of the Saddle with six button heads.
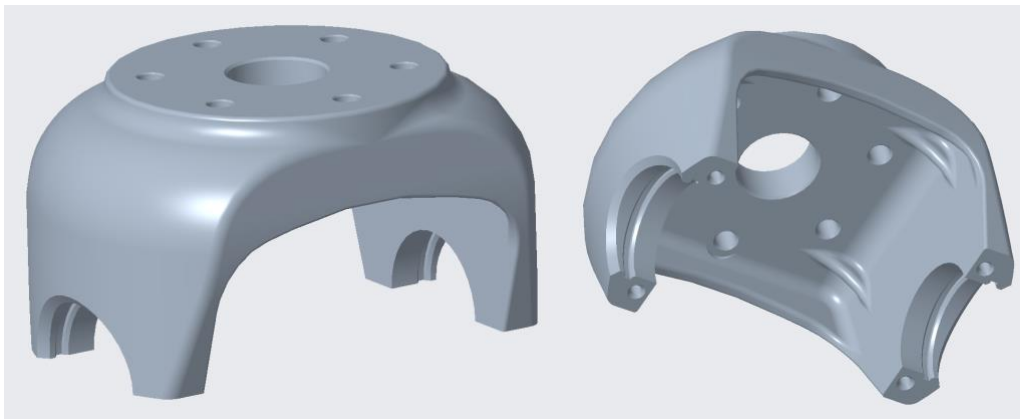

Azimuth Gearbox:

For 2019, we designed our own 3D printed (MarkForged Onyx) input and output housings for the Vex Planetary gearbox and went to a lightweight plastic ring gear on the high speed side. These changes allowed us to incorporate optimized mounting features, reduce part count and save weight. A side-effect was that each printed part was less than $5 which allowed us to save cost on the BOM compared to the off the shelf kit.
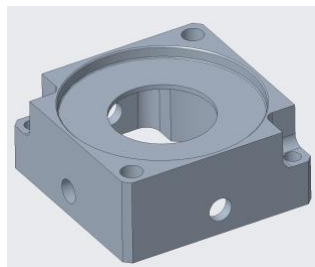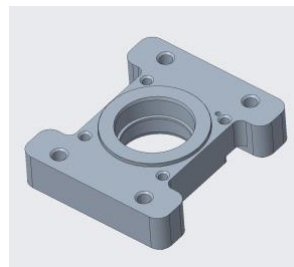

Input Housing: Output Housing:

Swerve Pivot Hub and Mounting Hub:

The Mounting Hub was unchanged from 2018. The Swerve Pivot Hub was very similar to 2018, except we reduced part count by incorporating the Azimuth Pulley. Incorporation of the pulley also allowed a slight reduction in stack height while giving a longer thread engagement for the screws coming up from the Saddle.
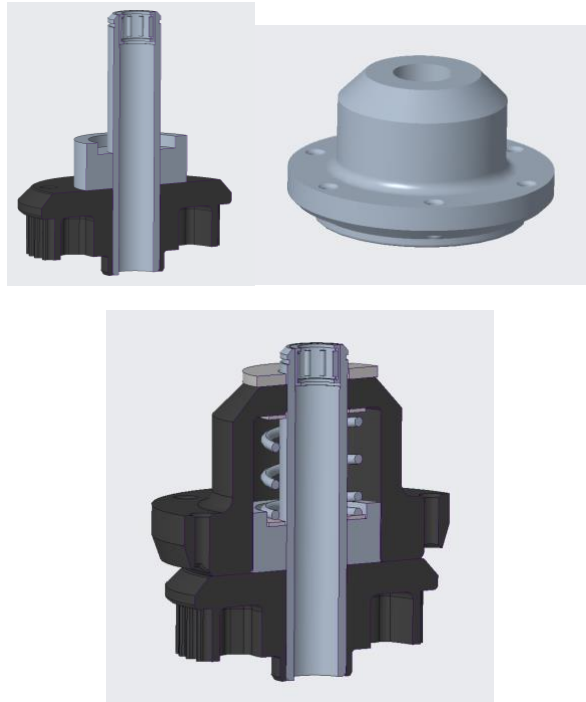
For 2019 we again limited positraction travel to to approximately 1/8".

Unit Assembly:

The unit was assembled (as shown below), off the robot. As in 2018, Socket Head Cap Screws came up from the bottom. These were put in before the axle and wheels were put in place.
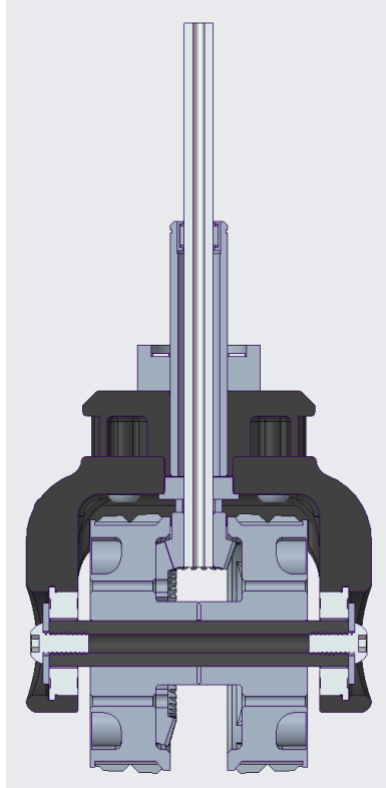
Shimming of the bevel gear was done as described for 2017 and 2018. Mesh is proper when the gears line up as shown (maximizing facewidth engagement), have minimal backlash, and move freely through full rotation.

Final Assembly:

The Mounting Hubs were bolted into the robot frame. Mating parts were test fit, ensuring the bushing surfaces had smooth operation rotationally and axially. Bushing surfaces and posi-traction washers were lubed and some lightweight oil was applied to the needle bearings. The posi-traction spring was set on the Pivot Hub with a washer on top and then pushed into the Mounting Hubs from the bottom. The spring was compressed until the snap ring groove at the top of the Pivot Hub came through the top of the Mounting Hub. A second washer was placed on top of the Mounting Hub and a 5/8" snap ring was put in place to hold the whole thing together. The top washer protected the nylon of the Mounting Hub from the steel snap ring as it rotated.
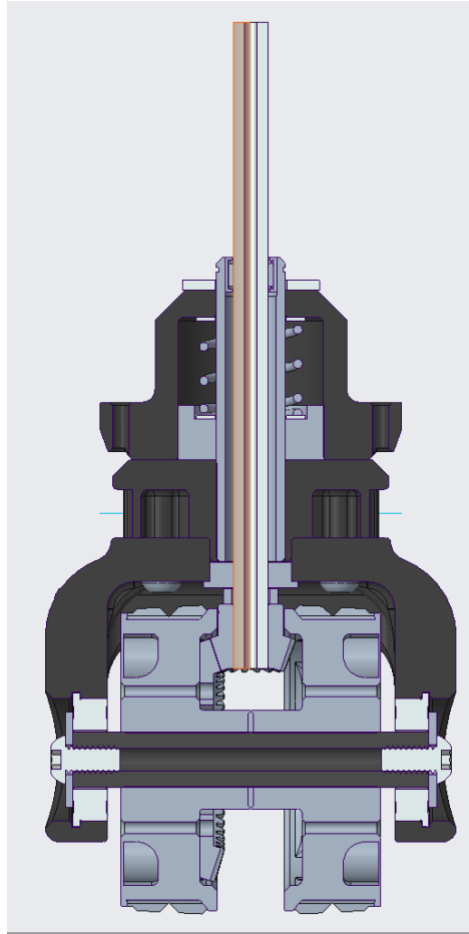
Other Notes:

- Overall weight reduction vs. 2018 was approximately 1/4 pound per unit and all manufacturing was done in house, without CNC. Each corner weighs less than 4.5#, including the motor controllers, but not the mounting rails (yellow in the above illustrations).
- We used an AndyMark 9015 for the azimuth motor since it had plenty of power and was very lightweight. We geared it 100:1 using Vex planetary gearboxes with ½" hex output shaft and an encoder stage. The pulleys were 1:1. Using CTRE's Motion Magic, with the Talon SRX PID loop properly tuned, that ratio easily turned the custom wheels on carpet and did so very quickly. The tuning was hot enough that the azimuth control loop was marginally stable with the wheels in the air, but good on carpet.
- We dropped the assemblies out of their mounting hubs, inspected, cleaned and re-lubricated them at the end of each event. Without this routine maintenance they sometimes squeeked.
- This year, we again used a Vex 775Pro drive motor with our 2018 custom gearbox. We made a spacer to raise the gearboxes ~1/2" off the drive rails in order to increase ground clearance under the 775Pro power terminals.
- This year the drive pulley ratio was approximately 1.76:1. The custom gearbox had a ratio of 40:12 (~3.33:1) and the KHK bevel gear set was 3:1, so the total ratio used was ~17.6:1 (1.76x3.33x3). Larger wheels would need more gear ratio for similar performance.

- We have helped several teams successfully get started with swerve drives based on the Third Coast design. One of the stumbling blocks is availability of 3D printing for the azimuth pulley. Several teams have done a conversion to (modified?) off the shelf pulleys and that may be worth exploring if robust printing isn't available to you. Gears may also be an option. Note that this year's Saddle could have easily been made from aluminum extrusion as in years past.
- We used the NavX gyro/accellerometer board to provide the field orientation signal.
- We used USB connected flight controllers for the driver. The sticks then function similarly to flying a drone, but without the need to keep track of which way the drone is pointed: The left stick is pushed forward to go down the field, left/right to move cross-wise, and pulled back to come back. The right stick spun the robot clockwise or counter clockwise. This scheme allowed drivers to easily drive in a straight line and spin while doing so if they desired. Without field orientation controls, this can be done, but requires difficult mental gymnastics by the driver. Even with this aid, there is no substitute for lots of driving practice on a playing field.
- Chief Delphi has a wealth of information archived on its site. We'd like to thank its site manager and contributors, in particular "Ether" for publicly sharing and clearly communicating the critical analysis and algorythms necessary for Swerve and Field Orientated Controls implementation. An excellent place to start is his paper available on Chief Delphi.   Our swerve code is very accuractly described by this document and we would recommend it as a starting point independent of what coding language you are using.   We've now done it sucessfully in Labview, C++ and Java (current). Our current Java implementation can be found at: https://github.com/strykeforce/thirdcoast
- Thank you to everyone who has helped us get where we are. In particular, this swerve drive journey started with inspiration from Wobots which led us to 221's Revolution Swerve Drive. We're grateful that they were there for us.

Final Comments:

Stryke Force didn't arrive at this Third Coast Drive design on its own or overnight. It wasn't dropped out of the sky or bought with bags of money. It was bought by a continuous team effort in a focused evolutionary process combining inspiration, analysis, drive team input/ feedback, and experimentation. We believe it's pretty darn good, but we're not done and probably never will be. One of our chief tenets is "never fall in love with your design"--be open to different ideas and judge them soley on their merits. Not all FRC games have been or will be swerve-appropriate. Further, it's entirely possible that a different and better way of "swerving" will come about and, if so, we'll happily adopt it and work on making it our own. This requirements-driven continuous improvement process is how great things and performances are made possible, and one of the biggest lessons we hope to convey to our students.

Hopefully, this paper and the accompanying links to CAD and code help inspire your own swerve drive development efforts. If they do, it is highly recommended you make it an off-season project which can be wrung out well before kickoff. We believe making the jump to a swerve drive system is worth it (why wouldn't you want to be able to drive sideways while spinning?), but don't forget it comes at a cost and the drive team needs plenty of time to learn how to make the most of it.