CONSTANT VELOCITY JOINTS FOR THE 2023 UNION COLLEGE BAJA RACING TEAM

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ABSTRACT

Constant velocity (CV) joints have a long history of development. They are designed to transmit angular velocity from one axle shaft to another when they are not collinear. The Union College Baja racing team decided to use CV joint axles as outboard drive shafts (half shafts), which deliver the power from the engine to the wheels, in the 2023 car. Due to the geometries of the joints' components, they are difficult to manufacture without specialized equipment. Therefore an axle assembly was ordered. However, it was very difficult to find a CV axle to purchase and without a car it is near impossible to test. Dynamic analysis is a useful tool which could be used to study potential selections and whether they would fail.

INTRODUCTION

Constant velocity (CV) joints have a long history of development. They are designed to transmit angular velocity from one axle shaft to another when they are not collinear. There are many different types with different design features that specialize them, making them useful for different circumstances. Some examples include the cross-groove joint, double offset joint, and the s-plan tri-pot joint used by Buick in the 20th century[1]. The two most common are the Rzeppa joint (ball joint) and the tripod joint[2]. Rzeppa joints work by attaching an inner race with grooves for ball bearings, which are then put in these grooves and held in place by a cage. The bearings then interface with an outer race which is connected to the other axle (Figure 1).

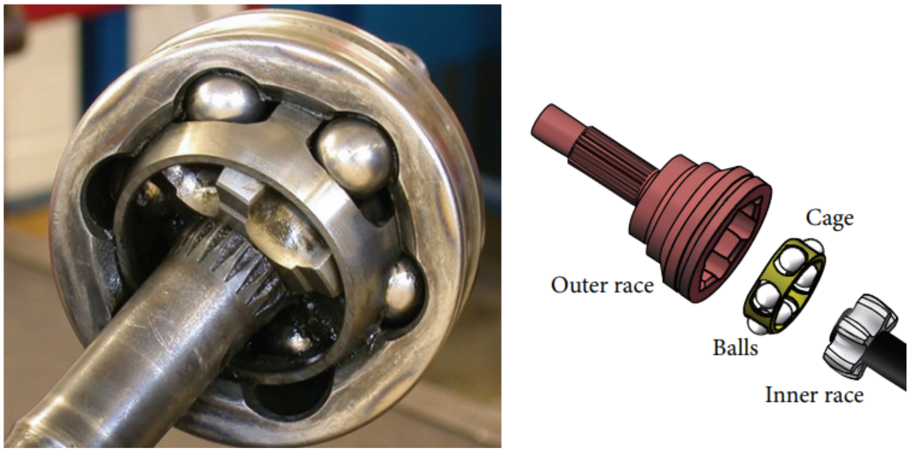

Figure 1; (Left) - Assembled view of the Rzeppa joint. (Right) - Exploded view of a Rzeppa joint. The inner race houses the ball bearings in grooves and the bearings are held in place by the cage[2].

Tripod joints have one axle connected to a spider, which has three roller bearings. The spider is then placed inside an outer race with room for the spider to move in and out. This plunging motion is why they can be referred to as plunge joints. The outer race connects to the other axle (Figure 2).

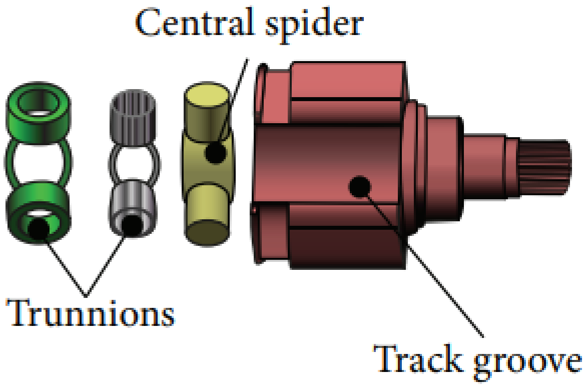

Figure 2: View of a Tripod CV joint. The axle on the right connects to the spider, the part that has the three roller bearings. This subassembly then is placed inside the outer race or housing which is connected to the other axle[2].

When a tripod joint is placed as the inner (upstream of power transmission) CV joint and a Rzeppa joint is used as the outer (downstream of power transmission) in a half shaft assembly, these joints create an axle that can operate at a wide range of angles and at different distances from each other (Figure 3).

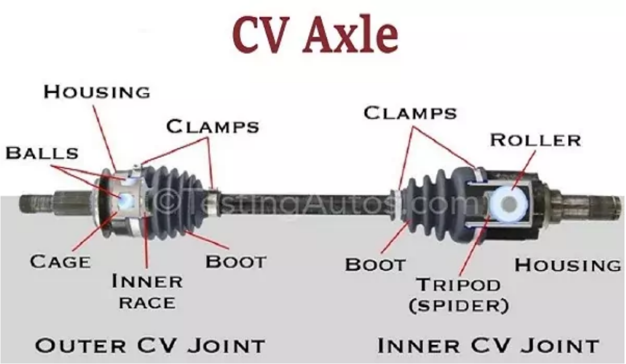

Figure 3:. A CV axle assembly using a Rzeppa joint (Left) and a tripod joint (right). The axial motion of the tripod joint allows the axle to work at different lengths[3].

The primary purpose of all CV joints is to transmit angular velocity from one axle to another across a range of angles. More specifically, they are designed to spin the output shaft at the same angular velocity as the input shaft, without variation. The reason for the constant velocity property is the bearings or rollers on the interior of CV joints make contact with the inner and outer races (one connected to each shaft) in the plane of constant velocity, which is the plane that bisects the angle between the shafts[4].

CV joints are not without risk. All CV joints are enclosed in a boot, which holds in grease that prevents the interior components from overheating, reduces friction and keeps out unwanted contaminants. If the boot is compromised and the grease escapes or contaminants get in, the CV joint can fail prematurely due to high friction and heat or the contaminants wearing down the interior components to the point where they no longer operate as they should. Therefore it is important that the boots are checked regularly for tears or leaks and if one is found, they should be repaired as soon as possible[5].

We in the Union College Baja Racing Team used this knowledge to design and eventually select CV axles for the 2023 car. The axles would have to connect to the jack shafts, which transmit the power from the chained drive train, and deliver energy to the portals (Figure 4), which are gearboxes connected to the wheels in order to raise the vehicle and increase the gear ratio to the wheels.

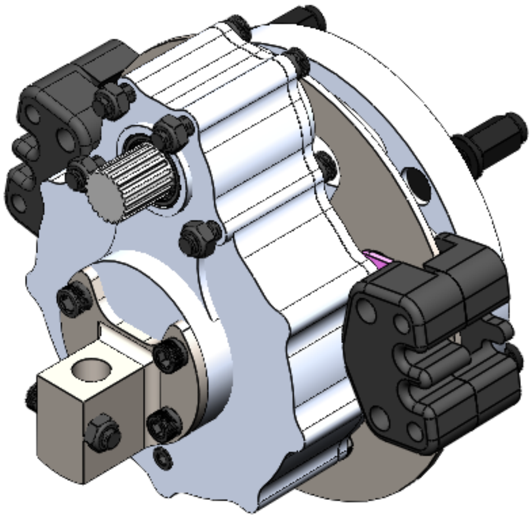

Figure 4: Portal gearbox for the 2023 Union College BAJA racing team car. The half shaft supplies power to the splined shaft at the top of the gearbox. That shaft spins a gear inside the portal which is connected to a larger gear. This larger gear is connected to the hub (circular flywheel at the back of the portal) which in turn connects to and moves the wheels.

At the start of the 2023 season, the Baja team planned to design and manufacture the CV joints and the corresponding axles in the college's machine shop. However, the research showed the complicated geometries required for the joints to work, which would be too difficult to manufacture without specialized equipment. Therefore, paying attention to the design requirements, an axle was selected from the online shop Sixity, the Sixity XT Front Right Axle for 1998-2001 Arctic Cat 400 4X4 - M/T (Figure 5), and modifications were developed to fit the 2023 car.

Figure 5: Sixity XT Front Right Axle for 1998-2001 Arctic Cat 400 4X4 - M/T[6].

Selecting a CV axle is difficult and without rapid testing it is difficult to ensure the given part will work. It would be useful in the future if there is a tool or modeling method to predict whether failure will occur in the interior of the joints, potentially making it easier to evaluate potential half shaft selections. Research has been done and simulations have been performed, such as the dynamics performance performed by Mao et al[2]. The Racing Team could use this model to further evaluate potential CV joints.

PROBLEM DEFINITION AND DESIGN REQUIREMENTS

This year's Baja car required four-wheel drive, meaning there needs to be four half shafts. The half shafts will transfer power to the portals, which have the same basic design, from the jack shafts, which all have the same design. Therefore the same CV axle could be used for all wheels, different from some offroading 4x4's.

The design and selection of the CV axles had to comply with multiple constraints. When searching for an appropriate axle, one of the CV joints needed to have a female ended spline to correctly adapt to the portal's input shaft as it is shown in Figure 4. The connection between the half shaft and the portal was arguably the most important requirement of the CV axle selection. By the time CV axles were searched for, the portals were mostly designed, and there wasn't room for change with the portal input shaft as it was held in place inside the portal, and any redesign would require the portal to be redesigned. Thus it was the only constraint that could be evaluated when reviewing CV axles before purchase. Other considerations had to be made when the axle arrived. For example, the assembly had to withstand an expected torque load of 144.3 ft·lb from the jackshafts, which leads to another requirement; the inner joint (the one upstream the flow of power to the wheel) needs to connect to the jackshafts in order to successfully transmit energy to the portals (Figure 6).

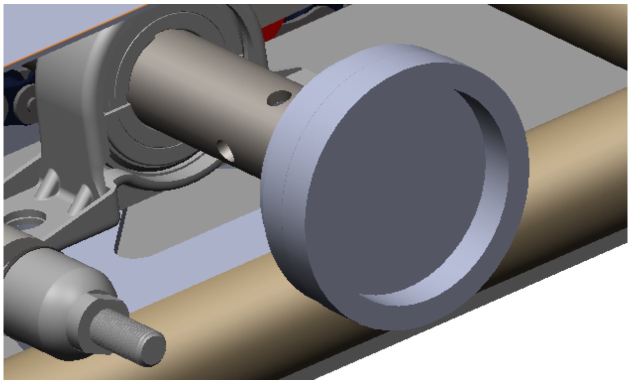

Figure 6: CV joint outer race connected to the jackshaft in the model for the 2023 car.

It also needed to be an appropriate size. The CV joint that interfaced with the portal could not exceed three inches in diameter, otherwise it would conflict with other structures in that area, such as the connection for the suspension, which sits atop the portal, shown in Figure 7.

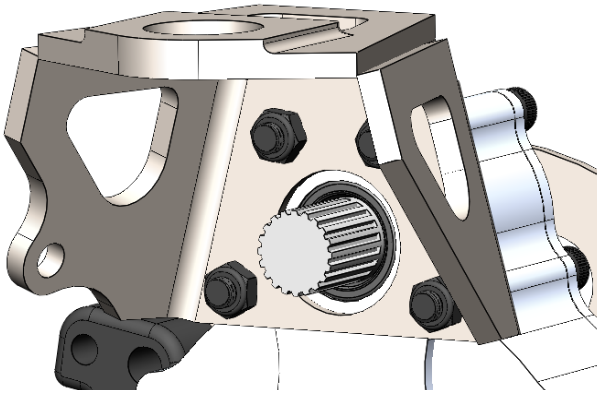

Figure 7: Portal gearbox with the connections for suspension components. The CV joint connected to the portal needs to fit within those pieces to interface with the portal input shaft.

Another critical requirement was for the assembly to be able to withstand six inches of vertical travel from the suspension, requiring the axle length to change. When the portal input was level with the jack shaft, the assembly would be at its shortest, and when the suspension compressed or extended three inches, the axle would be at its longest. The outer CV joint would also need to accommodate 22° of steering as well as the angle induced by the suspension travel.

LITERATURE REVIEW

Multiple research teams have developed models that perform dynamics analysis on the interior of CV joints to predict failure and study wear. For example, Mao and Luo[2] used MATLAB and Simulink to model a standard CV half shaft to study predicted wear and evaluate the results compared to reality. Their paper focuses on the whole drive shaft, building off of previous works to gather necessary equations and models to analytically analyze the interior and exterior components of the half shaft.

INTRODUCTION TO RESEARCH

The experiment done by Mao and Luo[2] builds upon previous works concerning the analysis of constant velocity joints. For example, they referenced the work done by Kimata et al[4]. Mao and Luo use the referenced works to develop their MATLAB and Simulink code to analyze not only individual CV joints, but also a complete CV half shaft assembly. The research upon which their work is based is concerned with individual joints[2].

Before the experiment began, Mao and Luo derived the necessary equations to establish the relationships found in both the fixed ball and plunging joints[2]. The analysis of the ball joint yielded an equation of:

$$\theta_2 = \theta_1 \pm C_1 \tag{01}$$

where θ_1 is the angular position of the input shaft, which connects to the outer race of the ball joint, θ_1 is the angular position of the output shaft which is the axle between the two joints, and C_1 is the angular clearance inside the joint between the outer race and the inner race. An equation for the tripod joint was also derived and found to be:

$$\varphi = \theta + \frac{r_1}{2L} tg\delta tg^2 \frac{\delta}{2} \cos 3\theta \pm C_2 \tag{02}$$

which is derived from Figure 8. φ and θ represent the axle angle and the tripod outer race angle respectively. C_2 is the clearance of the tripod joint[2].

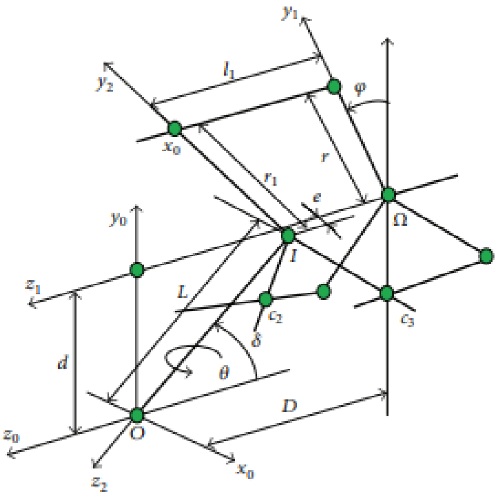

Figure 8: Illustration of a Tripod joint[2].

With the analysis of both joints complete, Mao and Luo derived the dynamic equations for the entire half shaft assembly. They started with a dynamics model of the half shaft (Figure 9[2]). From this model the derived the following equations:

$$\begin{gathered} J_1\ddot{\theta}_1 + D_1\dot{\theta}_1 - K_1(\theta_1 - \theta_2) + M_i = 0 \\ J_2\ddot{\theta}_2 + D_2\dot{\theta}_2 + K_1(\theta_1 - \theta_2) + K_2(\theta_2 - \theta_3) = 0 \\ J_3\ddot{\theta}_3 + D_3\dot{\theta}_3 + K_2(\theta_2 - \theta_3) - F_f R = 0 \end{gathered} \tag{03}$$

where K_1 and K_2 are the effective stiffness of the drive shaft, D_1, D_2 and D_3 are the damping coefficients of the gearbox, the axle and the wheel, M_i is the torque generated by the engine, R is the radius of the wheel, F_f is the friction force of the wheel and J_1, J_2 and J_3 are the inertias of the gearbox, the axle and the wheel respectively[2]. Since K_1 and K_2 are the effective stiffness of the same drive shaft, they should be equal and could be replaced by a single variable K.

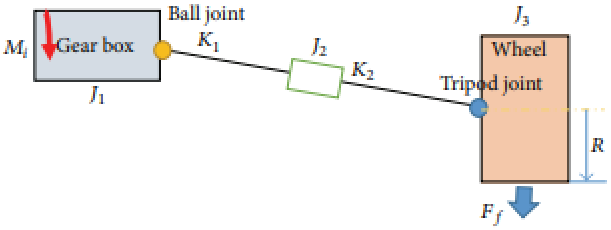

Figure 9: Simplified dynamics model of a half-shaft[2].

EXPERIMENT

With the relations and system of equations from Equations 1, 2 and 3, Mao and Luo modeled the drive shaft and performed the experiment. The model they developed in Simulink is shown in Figure 10.

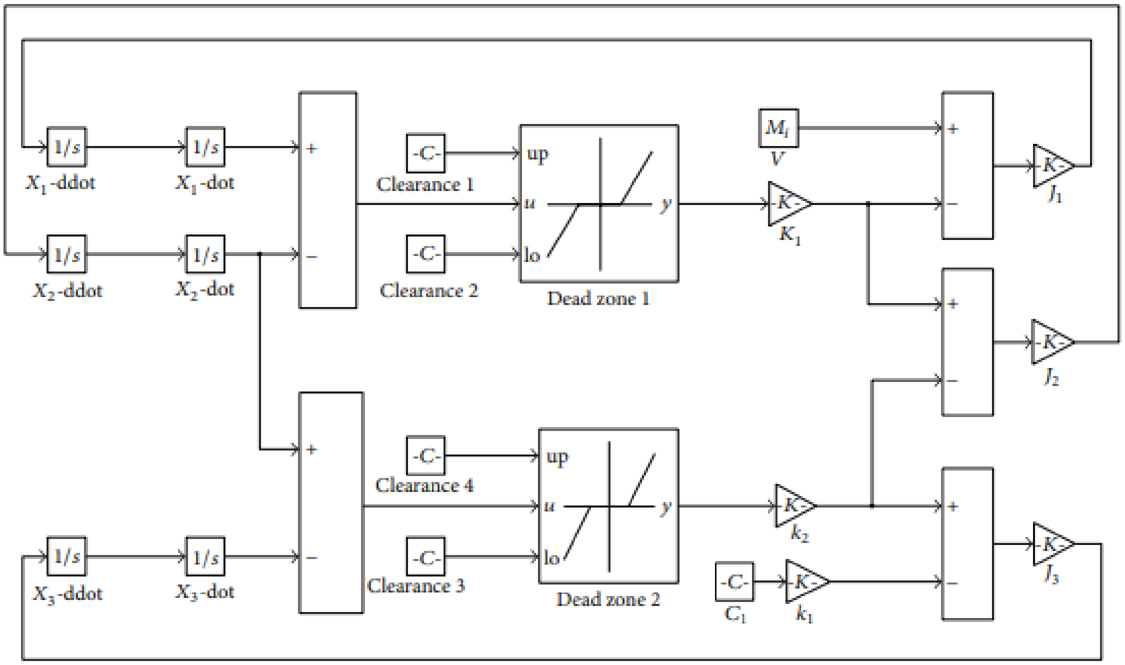

Figure 10: Simulink numerical model of the half shaft[2].

As well as this numerical study, Mao and Luo performed physical analysis with the half shafts. They put the half shafts in a testing apparatus and recorded the clearance, wear and torque loadings of the various components.

RESULTS

Mao and Luo came to multiple conclusions through their experiment. For example, they found the clearances of the joints should be considered in the dynamics study, as it affects the performance of the half shaft. They also concluded that the presented dynamics model can be used for quick analysis of the half shaft, but the accuracy of the model can and should be improved. Furthermore, the abrasive wear of the Rzeppa joint is dependent on the relative velocity between the ball and the races with a constant loading. They suggest improving the surface hardness of said components to reduce wear. Also, as the wear of the joints increases, so does the magnitude of the clearances, which further affects the performance of the overall assembly. Lastly, they state that experiments with various relative velocities between the components should be performed to verify that the theoretical model works in future research[2].

APPLICATION TO UNION COLLEGE BAJA

Knowing that a MATLAB and Simulink code can be accurate when it comes to analyzing wear and possible failure, the Union College Baja Racing Team could use this code to test CV axles without ever putting them in a car.

DETAILED DESIGN

The CV axles went through multiple design iterations. At the beginning of the 2022-2023 academic year, the joints and axles were being designed. Once the Baja team realized it would be too difficult to manufacture the needed components, we began searching for manufactured joints to be adapted to the Baja car. However, most CV joints come in half shaft assemblies which specify the vehicle they are designed for, but not the actual size and shape of the assembly or its components. For this reason, the initial search focused on joints or axles with the dimensions given. Eventually one Rzeppa joint was found, but there was difficulty finding a plunging joint. Therefore one design involved using two of these Rzeppa joints with a slip joint in the axle between them. This idea was also thrown out because the Rzeppa joints did not have a female spline to adapt to the portal. Thus the renewed search was modified to include joints and axles of unknown dimensions, and potential components would be ordered and measured to evaluate whether or not they could work. If not, they would either be returned or placed in storage for future use. As a result of this method, the Baja team ordered a Sixity XT Front Right Axle for 1998-2001 Arctic Cat 400 4X4 - M/T deemed it appropriate for the Baja car once some modifications were made. However, it would be placed in the car in the reverse of its designed orientation, meaning the plunging joint would connect to the portal and the Rzeppa joint would operate as the upper CV joint.

The first design of the CV half shaft was of a tripod joint and a Rzeppa joint designed and manufactured in house. The tripod joint would connect to the interior drivetrain components of the car, meaning it was the upper CV joint. This joint would transfer power to an axle through a splined connection. The axle would carry this rotational motion to the Rzeppa joint through another splined connection. This joint would be connected to the portal, meaning it was the lower CV joint, and it would deliver the power to the portal gearbox. However, after multiple different models were developed in SOLIDWORKS, the Baja team realized it would be extremely difficult to manufacture in house without special equipment. The curved grooves on the interior of the Rzeppa joint's outer race (Figure 11) would be extremely difficult to manufacture as they need to be a semicircle path following the interior of the race. A standard milling machine would not be able to create such geometry and a lathe would not be able to cut the grooves individually.

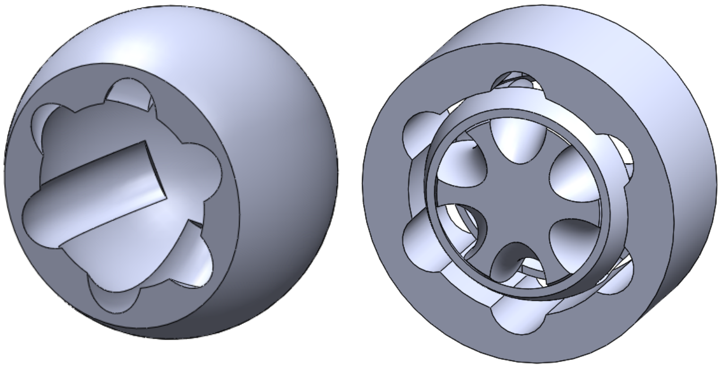

Figure 11: (Left) Rendering of a Rzeppa joint outer race, done in SOLIDWORKS. (Right) Partial assembly view of a Rzeppa joint, done in SOLIDWORKS.

Since the parts could not be made, we began shopping for CV joints or CV joint half shafts which would work in the designed car. CV joints and half shafts are designed and built to fit within specific vehicles, so most companies do not list the dimensions of the joints. To make shopping less of a guessing game, the search for the CV components was limited to components with given dimensions.

The initial CV joint search yielded the Polaris Rzeppa joint shown in Figure 12. The inclusion of the ruler allows shoppers to get a rough estimate of the size of the part using the ruler as a reference.

Figure 12: Initial choice for Rzeppa Joint from Partzilla, the Polaris 2203334 CV JOINT[7].

With a potential Rzeppa joint found, the search began for an appropriately sized plunging joint. Unfortunately, most of the ones found were already in assemblies or did not have attributes listed. The descriptions of the joints did not list how much plunging motion the joints could withstand or their overall size. This led to the idea to use two of the Rzeppa joints and a slip joint in the axle in between to accommodate the axial motion (Figure 13). The inspiration for this design came from the previous Union College Baja Racing car, which used two universal joints and a splined slip joint in the half shafts (Figure 14).

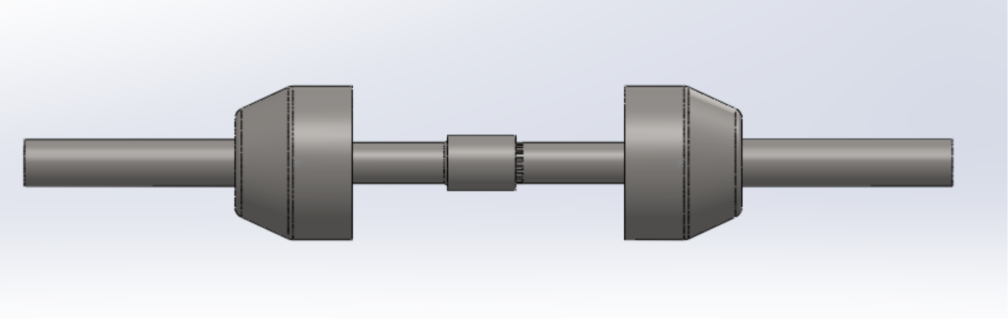

Figure 13: SOLIDWORKS model of two of the Polaris CV joints with a mock slip joint connection between them. The slip joint connection is made through the use of two axles, one to each CV joint. One has a male ended spline and the other has a female ended spline, that way they can interface, with one spinning the other, but they are still able to telescope past each other.

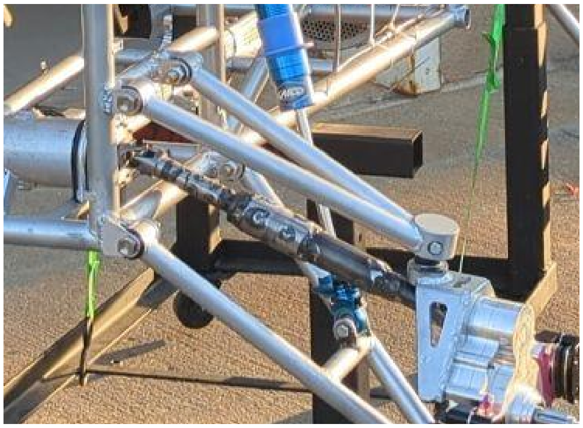

Figure 14: Half shafts for the 2021-2022 Racing Vehicle. Consists of two universal joints with a splined slip joint in the middle. Served as the inspiration for one of the designs for the 2022-2023 Racing Vehicle.

However, this design was incompatible with the given design constraints, as the Rzeppa joint did not have a female output spline to connect to the portal. If these joints were used, they would serve as the portal input shaft, but the portal was designed to be its own system, so it could be quickly disconnected from the car and replaced if need be. The input shafts were a part of that system. They were designed to fully integrate into the interior components of the portal gearbox, and to take them out, the whole portal would need to be disassembled. If the Rzeppa joint was the input shaft, the whole half shaft would have to be removed with the portal. Therefore, the idea of using the two Polaris Rzeppa joints was deemed infeasible and abandoned.

At this point, the search resumed for CV joints or half shafts, this time the search included joints and assemblies without given dimensions. Once a potential part or parts was identified, the Baja team would order them to study them when they arrived to determine whether they would work in the car.

After some searching, we discovered the Sixity XT Front Right Axle for 1998-2001 Arctic Cat 400 4X4 -MT (Figure 5) assembly. We deemed it a viable option because it had a female spline for the portal input shaft to connect to. Therefore one of the axles was ordered for study.

When the axle arrived, we made multiple different measurements and observations. The first thing the team noticed was the female spline which would connect to the portal was on the plunging joint, meaning that for this assembly to work in the Baja vehicle, it needed to be connected to the car in reverse orientation. Therefore, the plunging joint would have to be the outer CV joint and the Rzeppa would be the inner CV joint. We looked for assemblies that had a female spline on the Rzeppa joint, but if the assemblies had them, were on the plunging joint. With this information, the Baja team began taking further measurements to identify whether the Sixity axle would work in this configuration.

The process of measurement involved deconstructing the ordered axle and studying the interior components and their properties (Figure 15). One of the first measurements taken was the plunging distance, or how much the assembly could grow or shrink. The Union College machinists, Paul Tomkins and Rob Harlan, measured this change in length to be approximately 1.25”. Using geometry and the 3” of compression and extension designed for the suspension, this slip distance would compensate for any configuration where the distance between the two CV joints was greater than 3”. Moving along, the Baja team needed to know if the plunge joint, which was identified as a double offset joint (Figure 16), could withstand the angle deflection caused by the suspension travel and steering, which was calculated to be 22°. When the assembly was fully compressed, the plunge joint was able to reach an angle of 27°, and the only time the axle would be fully compressed would be when the two CV joints were level. Due to the geometry of double offset joints, the less compressed they become the greater the angle they can achieve, so as the suspension travels, the extra angle induced by the suspension would be compensated for by the axle assembly decompressing.

Figure 15: The axle on the top is the Sixity axle that was ordered to verify it would work in the Baja vehicle. It was deconstructed and taken apart to get a better understanding of its working components. Once it was deemed it could work, five more were ordered for the car (one extra is case of issues), one of which is the axle on the bottom.

Figure 16: These images represent the two joints from the Sixity axle. The image on the left shows the internal components of the Rzeppa joint, while the image on the right shows the internal components of the plunging joint, which is a double offset joint.

Other considerations were also made relevant to the design requirements, such as the axle withstanding the estimated torque load and the joints fitting their respective regions in the vehicle. The axle is made from 5140 Chromoly steel and is 0.85” in diameter. Using SOLIDWORKS Finite Element Analysis tool and the properties of 5140 steel from Matweb[8], a shaft with the appropriate diameter and a net torque of 144.3 ft-lbs applied has a minimum factor of safety of 16 (Figure 17). Lastly, the joints had to have an outer diameter less than 3” to fit in the vehicle. Both joints were sufficiently sized with diameters of 2.71” and 2.72” for the Rzeppa and double offset joints respectively. At this point,the Baja team deemed these axles would work in the car, so further measurements needed to be taken to adapt the assembly to meet the rest of the design requirements.

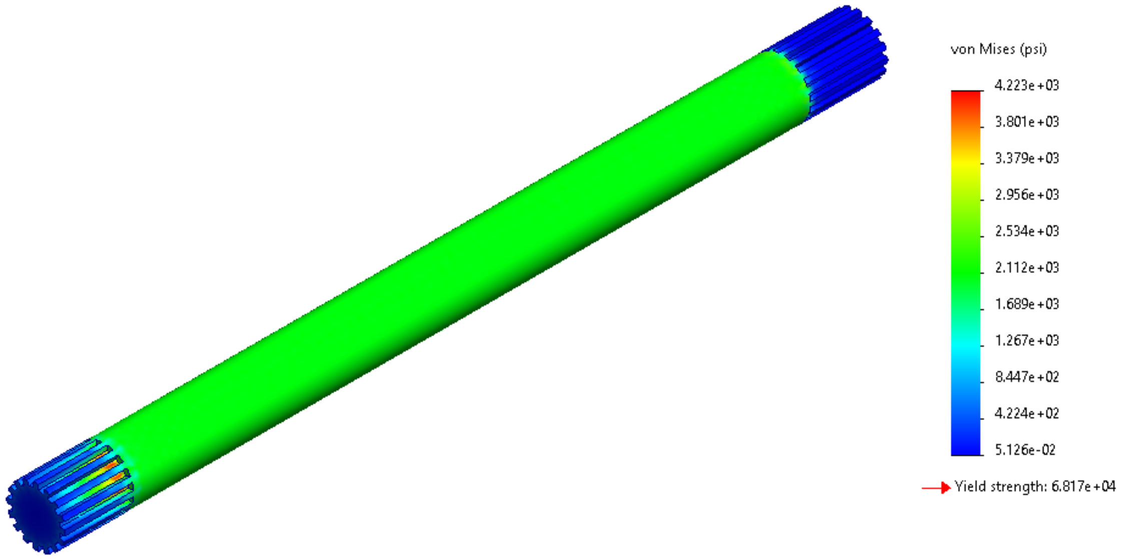

Figure 17: FEA of a mock 5140 chromoly steel axle with a diameter of 0.85”.

With the Sixity axle assembly selected as the CV half shaft for the Baja car, the focus shifted to making it so it would correctly interface and work in the vehicle. At the beginning of this process, the Machine Shop cut a small segment of the female spline off and measured the profile using the optical comparator. The shop shared this spline with the team and then it was used to develop the spline pattern on the portal input shaft so the joint would slip on the input shaft and transfer rotational energy. The next task was devising a way for the Rzeppa joints to connect to the jack shafts. The student who designed the jackshafts and the student responsible for the half shafts discussed this issue and arrived at making the Rzeppa joint slot into the jackshafts and have two through bolts at 90°. To accomplish this, the Machine Shop would turn down the splined shaft on the Rzeppa joint, shorten it to 1.25”, and add two cross holes at 0.50” from each other shown by the drawing in Figure 18.

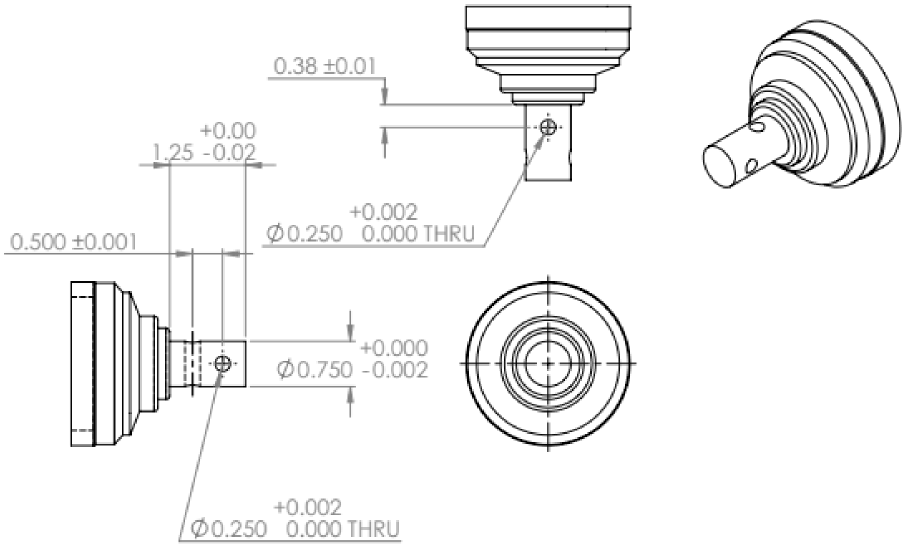

Figure 18: Drawings of necessary modifications to the Rzeppa joint.With these dimensions the joint would slide into and connect to the jack shafts with two cross bolts.

The last measurement to consider was the length of the axle in the half shafts. To make these measurements, the distance between the two joints was measured in SOLIDWORKS after they were mated to their respective parts. We compared this distance to the same measurement from the actual part. For the front of the vehicle, the measurement was too long, meaning the axle had to be lengthened either by replacing the axle or designing an appropriate adaptor. The half shafts in the back however fit perfectly. Instead of machining the half shafts, the student responsible for the jackshafts lengthen the front shaft to be the same length as the one in the back of the car so the half shafts for the front and back were the same and their lengths required no adjustment.

The final design of the CV half shafts is shown via a SOLIDWORKS rendering in Figure 19 and is shown in the car in Figure 20.

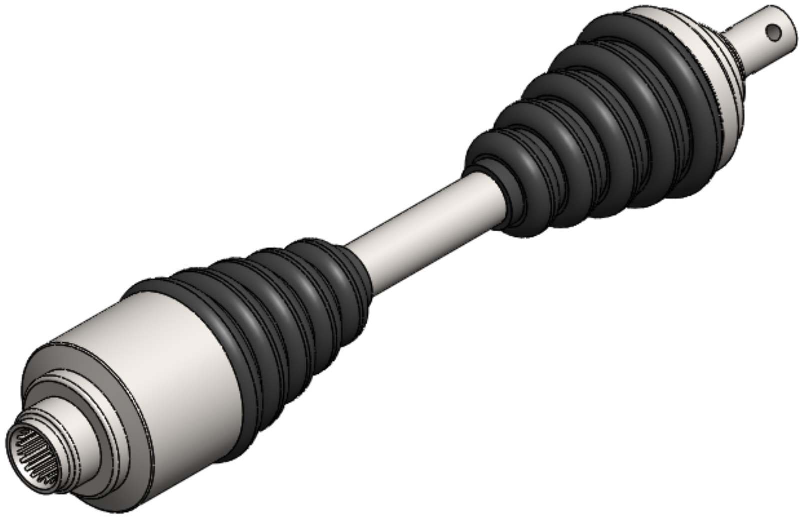

Figure 19: SOLIDWORKS rendering of the final CV outboard drive shaft design.

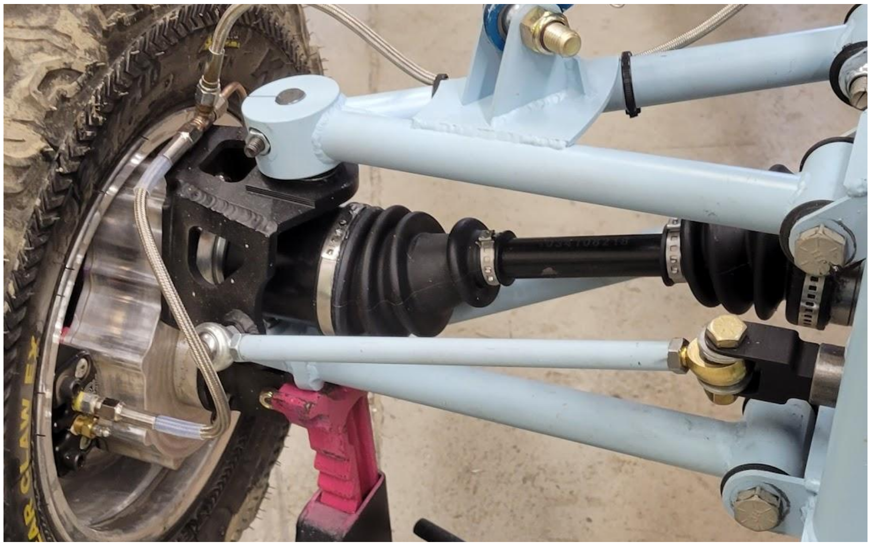

Figure 20: CV outboard drive shafts in the 2023 Union College Baja Racing Team vehicle.

EVALUATIONS

After the team assembled the vehicle, it was ready for testing which led to the identification of some issues with the CV half shafts. The construction of the car was done with less than a week before the competition in Oshkosh, Wisconsin. Even with the lack of time, the Baja team did a test drive on the Union College Baja test track. During the test, the CV boot connected to the front left double offset joint came off the joint causing CV grease to spill out

(Figure 21). Since boot failures lead to failure of the joint[4], this issue needed to be addressed before the car was driven again, so the joint was cleaned and a new boot clip was installed to hold the boot in place. At this point there was no time left for testing as other aspects of the vehicle required attention before it was driven to Oshkosh by Paul Tompkins. We made sure the CV joints were all secured within their boots and sent along heavy gauge zip ties for rudimentary repairs in case the boots disengaged during the competition.

Figure 21: The outer CV joints boot disconnected from the joint causing grease to escape and dirt and mud to get it. The joint required immediate attention to reattach the boot.

During the competition, the half shafts performed decently until the last event. The Oshkosh competition had a sled pull, an acceleration test, a mobility test, a hill climb test, a braking test and a four hour endurance race. The Union team had some issues with a large turning radius due to the limits of the double offset joints, but the half shafts were sufficient at transferring power to the portals. During the endurance race, the suspension components of the car failed causing the chamfering of the wheels which pulled the double offset joints away from the axles and caused the boots to slip off the joints.

CONCLUSIONS

Much was learned from this project. For example, the Union College Baja Racing Team gained experience with purchasing and using CV joint half shafts. However, due to the limits placed on the steering due to the plunging joints being used as the outer CV joint, it would be wise in the future to design the CV outboard drive shaft or the components it interfaces with to allow the outer CV joint to be the Rzeppa joint, as that is how the half shafts were designed to work. Another solution would be to do deeper research into various CV drive shafts on the market and find one that meets the design requirements of the vehicle question better than the Sixity axle used this year. On the downside, it is very difficult to find pre-built parts to fit into parts designed personally. So either design the parts to work with the half shaft selected or figure out how to make CV joints in house. This could work as a senior project. However, this would take years and could just be a waste of time. Therefore another solution would be to use universal joints instead of CV joints. They are cheaper and easier to purchase and replace (why they are generally preferred for serious offroading). The joints could be purchased and then an axle could be designed to connect with them to make a half shaft. The downside of using the universal joints is they have no slip, and since the half shaft length in the Baja car changes with suspension travel, a slip joint would have to be engineered into the axle to accommodate the required axial motion. Ultimately it is up to future generations of the Baja team to identify the best course of action using this paper, their knowledge and past experiences to guide them.

ACKNOWLEDGEMENTS

This project was possible due to the outside help given in all stages. Brian Gardner, a manufacturing engineer and toolmaker at General Electric Global Research Center provided knowledge about automobiles, physics, machining and tooling assistance wherever it was needed or asked for. Caleb Rondeau and Devin Rochelle both provided guidance on how to undertake this project and information about past experiences. Rob Harlan and Paul Tomkins were kind and gentle when discussing the abilities of the machine shop and taking time to discuss the engineering drawings required for this project and actually making the parts from the said drawings. Last but not least, Professor William Keat helped keep the project on course and provided information about how to proceed with engineering processes and analytics.

REFERENCES

[1] https://youtu.be/SqhjGs2zFLo

[2] Mao J, Luo Y. Dynamics Performance and Abrasive Wear of the Automotive Drive Shaft. *Advances in Mechanical Engineering* 2014;2014:1-9.

[3] https://www.testingautos.com/car_care/when-replace-cv-axle.html

[4] Kimata K, Nagatani H, Imoto M. Analysis of ball-type constant-velocity joints based on dynamics. *JSME International Journal C: Mechanical Systems, Machine Elements and Manufacturing* 2004;47:736-745.

[5] Miller J. Neglected CV Joints – Why Replacing Torn CV Boots Matters. *Fifth Gear Automotive*. 2016 from https://fifthgear.biz/fifthgear-blog/neglected-cv-joints-why-replacing-torn-cv-boots-matters/

[6] https://www.sixity.com/1998-2001-arctic-cat-400-4x4-front-right-atv-axles-xt-passenger-m-t-complete-side-2034200033.html

[7] https://www.partzilla.com/product/polaris/2203334?gclid=Cj0KCQjwy5maBhDdARIsA

Mxrkw2qOVBABZZ1JKUtpvcA-OcRlkyDqZSZ6PQ2lTAPKqVs-eGNTjjn_BwaAh2UEALw_wcB

[8] https://www.matweb.com/search/datasheet.aspx?matguid=e7e6da5526874df5b8e1aaec7995150f

ATTACHMENTS

Figure 22: The 2023 Union College Baja Racing Team car.