Developing a Fully 3D Printed Vehicle for Autonomous Delivery

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A *Major Qualifying Project*

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Abstract

Autonomous technology is becoming a safe and convenient method of transportation. Our project goal was to design and create a fully 3D printed vehicle fit for an autonomous driving software package to aid in the delivery of consumer payloads. We began this project by test driving and dissecting RC cars from previous student projects to identify areas for improvement. From these tests, we evaluated subassemblies that were composed of outsourced materials, such as the gearbox, differentials, and wheels, and designed 3D printable adaptations. Furthermore, we designed, printed, and validated various snap and slide fits to reduce the fasteners used. The 30% reduction in outsourced parts and fasteners alleviated assembly issues and improved the modularity of the vehicle. After assembly of the vehicle, we tested drive quality and individual subassembly performance. Finally, through the evaluation of printed subassemblies, we identified challenges with our 3D printing methods and made recommendations for future teams.

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1. Introduction

Autonomous technology, defined as any technology that can execute tasks without human control, is taking the world by storm. With the current state of this technology, engineers are developing a plethora of ways to make the average consumer's day a little bit easier. Today, a vacuum will independently clean the first floor of a home, or someone's favorite groceries will automatically be placed in a digital shopping cart for their next purchase. However, this phenomenon is not just rooted in convenience, but also in safety.

Autonomous or robotic vehicles make it possible to remove human presence from potentially dangerous or harmful scenarios. For example, bomb squads use disposal robots to safely remove a bomb from an area without putting the human operators' indirect harm. On a larger scale, the Mars rovers' Curiosity and Perseverance are able to be operated from 225 million miles away to collect samples from the red planet.

On a scale a bit closer to Earth, autonomous delivery vehicles combine both safety and convenience to provide the best services for their operators or consumers. Autonomous delivery achieves the convenience factor by eliminating the consumer's need to leave their home and improves safety by removing the need to operate their own vehicle or interact with other consumers. During the time of this pandemic, human-to-human contact can be daunting for people as well as potentially dangerous, and autonomous delivery can accommodate this. Furthermore, autonomous technology presents an opportunity to assist elderly or disabled individuals with the delivery of medicine or household items.

While autonomous delivery is actively satisfying improved comfort and convenience, there still exists a large stigma against autonomous technology. According to a AAA survey conducted in 2019, only 44 percent of respondents claimed they had trust in self-driving food delivery vehicles (Edmonds, 2019). This number dropped as low as 19 percent when respondents were asked if they trusted autonomous vehicles to drive their children. Autonomous delivery has faced numerous setbacks, including the fatal incident involving a self-driving Uber in 2018, proving that this technology has a ways to go before it is widely adopted by the public.

As autonomous technology continues to make strides, additive manufacturing techniques, such as 3D printing, are progressing concurrently. With 3D printing, more innovative ways are being explored to produce designs in a variety of applications including the aerospace, medical, and automotive industries. With lasting supply chain issues in 2022, 3D printing boasts a clear advantage in facilitating the manufacturing of components at the point of assembly (Petch, 2022). As the scope of 3D printing applications grows, so do the materials involved. Different settings warrant different material properties, and a range of filament or resin types have been developed to accommodate them. In the context of autonomous delivery, 3D printing provides an opportunity to rapidly-produce small-scale mechanical subassemblies.

1.1 Project Statement

To destigmatize autonomous vehicles in the public eye, it is essential for this technology to prove efficacious at the consumer level. Our project is focused on researching, designing, manufacturing, and testing a fully 3D printed autonomous vehicle that can accommodate a variety of delivery and retrieval tasks as a result of its modular subassemblies. The implementation of print farms in businesses and universities as well as the growing market for consumer printers are making 3D printing an increasingly available manufacturing process. While the actual production of parts is enabled by 3D printers, online platforms such as CADENAS and GrabCAD promote a community where designs and models can be shared and accessed in the public domain. The combination of readily-available printers and downloadable models makes 3D printing one of the most rapid and cost-effective manufacturing mediums. Because autonomous technology is expensive at this relatively early stage of its life, 3D printing the main components of an autonomous vehicle can help prove this technology remains in reach for the average consumer. Our aim is to democratize consumer access to autonomous vehicles in their everyday lives. In achieving such an aim, we are creating a cheap, easily recreatable, and adaptive vehicle that can retrieve and deliver payloads. This 1/8th scale car incorporates a 3D printed four-wheel drive (4WD) system, a limited-slip differential system (LSD), and a planetary gearbox transmission. In addition, the car can be remolded to fit various subsystems to improve ergonomics for consumers.

1.2 Report Organization

Our report has been organized into various chapters to offer readers specific breakdowns of our progress and project development on various components of our car. The report starts with Chapter 1 which introduces our project and what we hope to accomplish; Chapter 2 focuses on an in-depth analysis of last year's team and its specifications. Chapter 3, which serves as our methodology, goes over our various project goals and a detailed breakdown of what will be focused on and accomplished for the car. This chapter also dives into 3D printing, trailer design, steering, as well as suspension goals and challenges. Chapter 4 encompasses our experience working with other RC cars to better our understanding of their function and expose us to concepts such as steering, suspension, 3D printing, designing, and trailers. Chapter 5 explores areas of improvement with last year's car and changes we are making to ours based on that. Chapter 6 offers a deeper analysis of trailer mechanisms and the concept of modularity. The final chapters (7,8,9 and 10) of this report include the results obtained as we designed, manufactured, and tested our car. It also provides reports on the presentation of our project at different events. We also provide a discussion of our methodology and important learning outcomes. We conclude this report with recommendations for future projects as well as personal reflections on our work.

2. An In-Depth Analysis of the Previous Design Iteration

This chapter will analyze the design decisions of Boggess et al., 2020 and Czuba et. al, 2021 teams and their creations of Printed Autonomous Robotic Vehicle, or PARV, and its predecessor, PrePARV respectively. The purpose of this analysis is to understand the reasoning behind key design decisions made by the past two teams and to help build upon the foundations they provided. In addition to analyzing the performance of each subassembly, our team tested drive PARV's drive quality and This analysis expedites the early design process and allows us more time to implement new features.

2.1 PARV Analysis

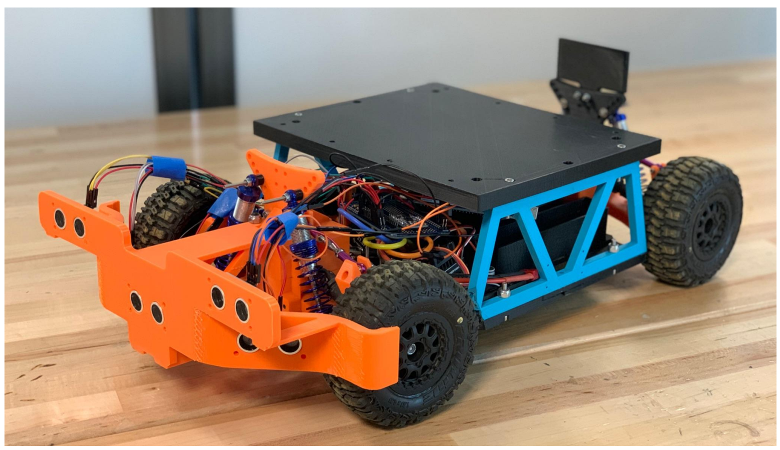

Figure 2-1: Final PARV Model (as reproduced from Czuba et al. 2021)

Last year's team by Czuba et. al, 2021 created a 3D Printed Autonomous Robotic Vehicle (PARV) intended to deliver payloads. Unique to this vehicle in comparison to PrePARV was the incorporation of a four-wheel drive (4WD) system and a limited-slip differential (LSD), as well as smaller improvements to holistic structure (i.e. steering, suspension, and drivetrain elements). Due to its modular design, PARV incorporated further system additions, such as trailer iterations, and autonomous driving packages. These next sections will further detail the design of the various mechanical and electrical components last year's team incorporated into their final product. Refer to Appendix G for a comprehensive list of PARV specifications gathered during this analysis.

2.1.1 Drivetrain

PARV's drive train begins with a brushless DC motor that transfers power to a VEX planetary gearbox transmission. After the gearbox, power is distributed between the front and rear of the vehicle from the transfer case. The transfer case can swap between 2-wheel drive and 4-wheel drive. Finally, in 2 wheel drive, power is transferred to the rear wheels via a direct drive differential. If the 4-wheel drive is engaged, power is distributed once again to the rear wheels as well as the front wheels through an open differential. Figure 2-2 shows the location of each of the aforementioned features of the drive. Additionally, steering is powered by a servo through a 3D printed steering subassembly that connects each front wheel as seen in Figures 2-3. Finally, included in the drivetrain is a 3D printed suspension assembly that mounts to each differential shown in Figures 2-4. The suspension system consisted of 4 Hotracing shocks for each wheel on PARV.

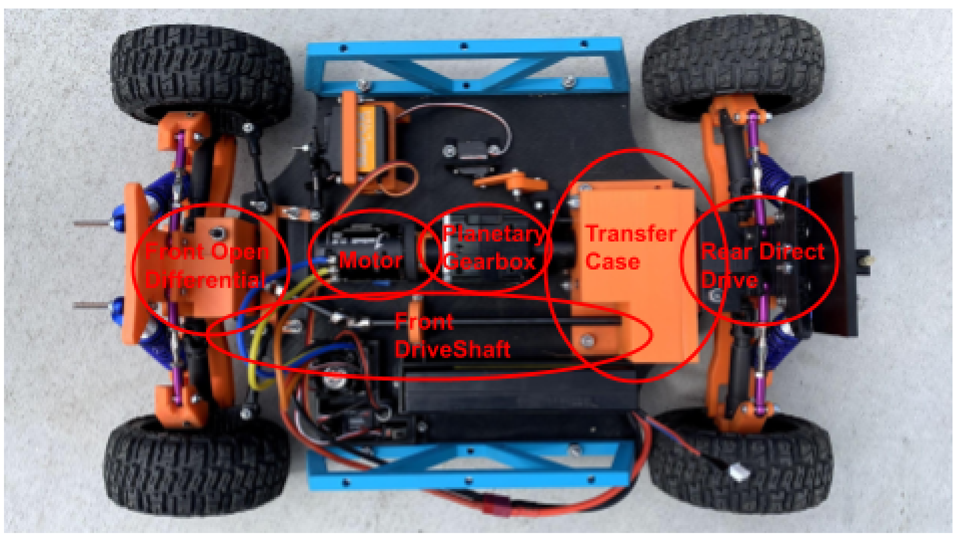

Figure 2-2: PARV Drivetrain on Final Assembly

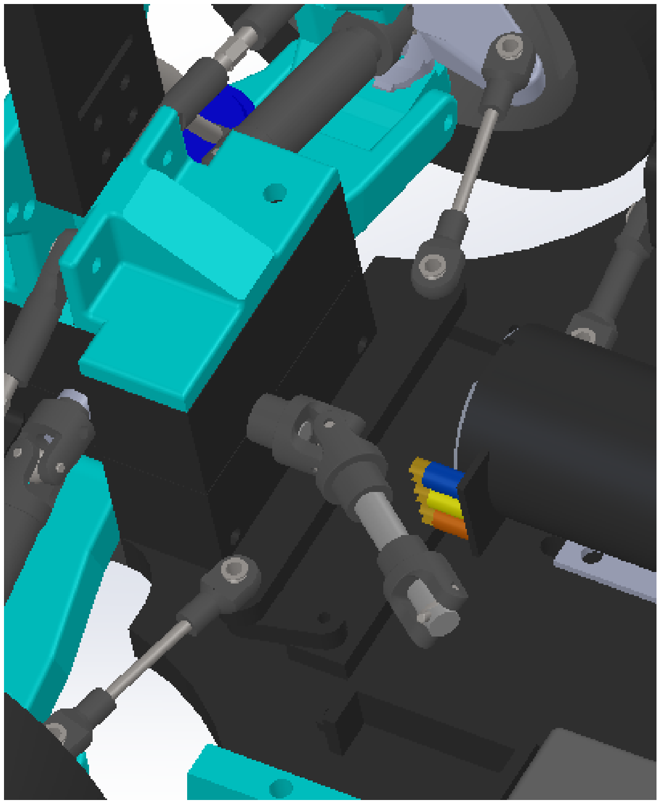

Figure 2-3: Overhead View of PARV Steering

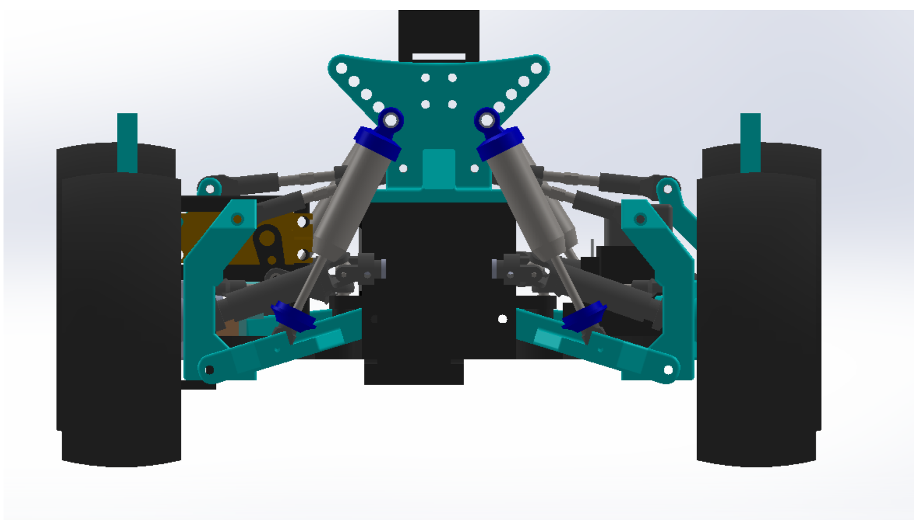

Figure 2-4: Front View of PARV to Show Suspension

In PARV's final iteration, the gearbox, motor, and differentials were purchased while the transfer case and couplers were 3D printed.

One of the key features implemented by last year's MQP team was a four-wheel-drive system. To accomplish this, the team designed and printed a custom transfer case that allows torque to be transferred between the front and rear wheels equally. The vehicle switches freely between two-wheel drive and four-wheel drive using this transfer case.

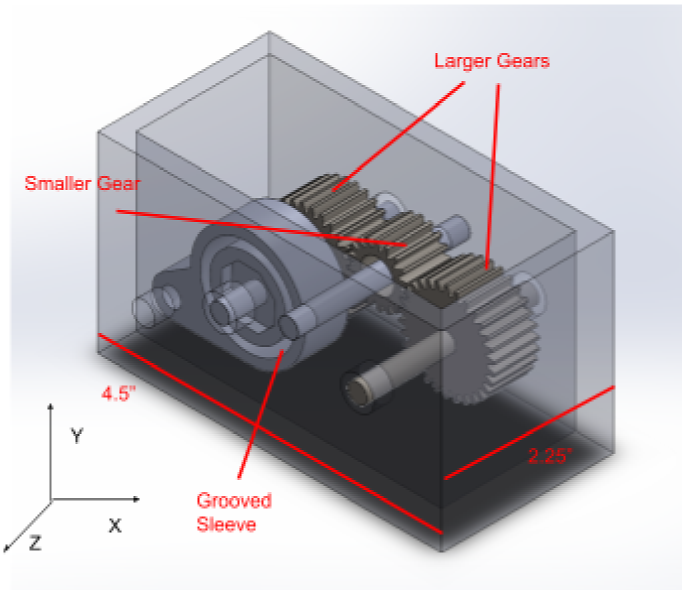

Figure 2-5: Model of Final Transfer Case Assembly (Czuba et al., 2021).

The motor selected by the past two iterations of this MQP was the Hobbywing XR10 Justock Sensored 10.5 turn motor. This motor is brushless and it comes with an electronic speed controller (ESC) and power switch. The servo motor selected to power the steering was the Savox 1256TG High torque servo which produces 17.4 lb-in of torque (Amain Hobbies, 2022). The motor and steering servo is powered by a 7.4 V 5200 mAh Lipo battery.

Figure 2-6: Hobbywing XR10 Justock Sensored Brushless Motor (left) and Savox 1256TG High Torque Servo Motor (right)

The transmission was also selected by the past two iterations of this MQP was the VEX planetary gearbox. This transmission was chosen due to its compact durable design. This gearbox consists of three 31 tooth planet gears, a nine tooth sun gear, and a ring gear, which come together to create a 9:1 gear reduction. The hex-shaped output shaft connects to the transfer case.

Figure 2-7: VEX Planetary Gearbox

2.1.2 Chassis

Last year's team modeled their chassis similar to the 2019-2020 team pictured in Figures 2-8 below.

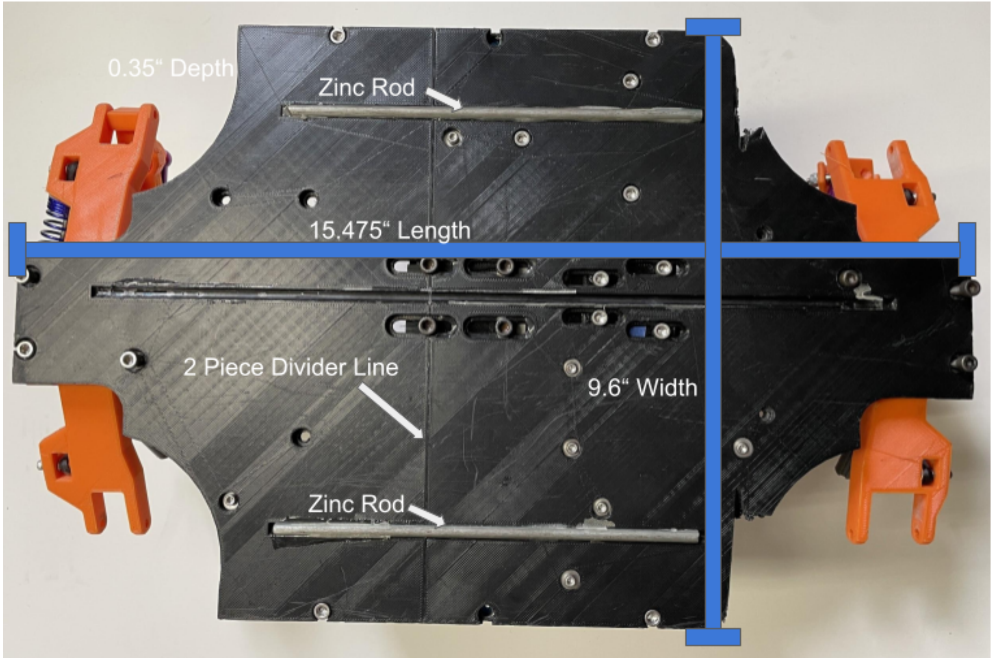

Figure 2-8: PARV Chassis Dimensions

Although a 1/8th scale car, the chassis was quite large and could not be printed on a standard 3D printer bed. Measuring 15.475" by 9.6" by 0.35" (L x W x D), the overall size exceeded the dimensions of the printer beds available and required two pieces to be secured together. Last year's team modeled a two-piece 3D print that was adhered with epoxy. The baseplate had slots for 3/16" zinc rods to increase strength and resistance to bending. The team designed this component last as it needed to accommodate the other car's parts.

2.1.3 Differential

Last year MQP (Czuba et. al) began with a 3D printable differential, but due to failures in the print and testing the team shifted to a purchased open and direct drive differential system. They purchased a 1/10 scale Traxxas Sealed Differential system This purchased differential system still uses 3D printed housings and spacers. The previous team's 3D printed requirements consisted of a limited-slip differential (LSD) system that can be used for both front and rear axles. The system was designed so that both the front and rear differentials would reliably transfer power and torque between the wheels in normal and slippery conditions as shown in Figure 2-9 below.

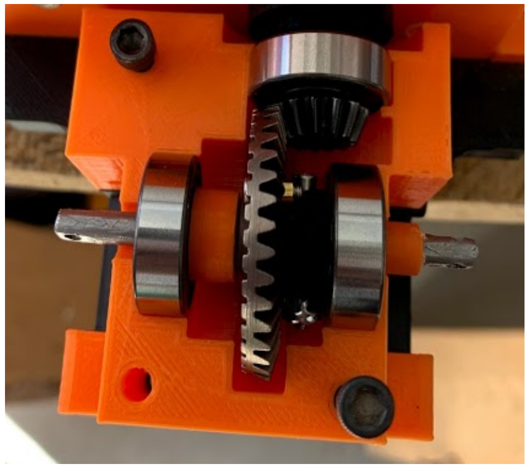

Figure 2-9: Metal Direct Drive Differential System

Some 3D printing problem last year's team was facing was that the new direct-drive gears that were printed using PLA materials were breaking under regular load. This may have occurred since the team was restricted by dimensions and shape which would reduce the load that the PLA gears would handle. They determined 3D printed shafts were not a feasible option due to the amount of torque those shafts experienced during driving.

To fix the failure of 3D printed gears, last year's teams tested PLA, Tough Resin, and Nylon X. These various parts kept failing; however, the Nylon X gears were not as precise as needed which prevented the necessary meshing between the gears. Due to all these failures, last year's team abandoned 3D printed differentials systems. Another important factor was plastic on plastic contact which causes a buildup of heat and a fusion of parts locking up the differential system.

2.1.4 Transfer Case

Czuba et. al designed a transfer case with the capability to switch between a 4WD and a 2WD drive system when needed. To design a feature like this, it was important there was enough torque to split between the four wheels of the car. A 4WD drive system provided the car with better power and frictional contact with the ground and the ability to overcome slippery or rocky terrains. The 3D-printed gears used in the transfer case had a 1:1 ratio to prevent any rotational speed loss. The overall case had a sleeve attached to a four-bar linkage system to help engage the 4WD or 2WD systems if needed. To activate the 4WD system, the sleeve is mocked to lock onto the gear mesh to split power between both front and rear wheels. And when removed from the lock position switch to a 2WD system where the power is sent to the rear wheels.

2.1.5 Trailer

Czuba et al, 2021 spent the final segment of their project producing a trailer fit for payloads. Some features of the trailer include a VEX planetary gearbox and Hobbywing XR10 justock sensored brushless ESC/SD G2.1 Motor drivetrain fit for RWD capability. Rather than using the Pro-Line Trencher X SC wheels that were used on PARV, the team printed joint TPE and PLA wheels, which mimicked rubber-like properties. The trailer was a two piece chassis print and used 56 fasteners. Figure 2-10 below presents the trailer.

Figure 2-10: Previous Team's Trailer Assembly

2.2 PARV Testing

Initial testing of PARV included testing the car while unloaded, with a 12 lb_f load, over bumps, and at full power via the throttle trim on the remote both loaded with a 12 lbf load and unloaded. During these tests, multiple issues with PARV were documented. There is a tendency for the left front wheel to either lock up, or for the wheel itself to fall off during testing. Figure 2-11 shows the lock nut that is responsible for this.

Figure 2-11: Left Front Wheel and Locking Nut

Another major issue was the bottom pin holding the right front spindle to the hub constantly falling out. This was remedied using epoxy to seal the pin in the hole.

Figure 2-12: Lower Right Front Pin

While carrying the 12 lbf load, PARV nearly fully bottomed out, meaning that the chassis was starting to drag the ground. PARV was intended to be able to carry a load of 25 lb_f without bottoming out. This suggests that PARV needs stiffer suspension springs, which was documented by last year's team. PARV was tested driving up an incline to test how well the car could accelerate and was then tested for lateral grip on the incline using a tilt test to see at what angle the car would laterally slide down the incline. The tilt test is designed to test how well the suspension functions to keep the car from losing grip or potentially rolling over. The track width of the car, combined with the droop of the un-loaded side of the car during this test helped balance the car on the tilt and keep it from sliding or rolling over. PARV was able to drive up the 32.3° incline, but the tires began slipping while trying to climb the 34.2° incline. On the tilt test, PARV's suspension was able to maintain grip at the 32.3° incline and the 34.2° incline but began to lose grip and slide at a 37.9° incline.

Figure 2-13: Incline Test

Figure 2-14: Tilt Test

Finally, PARV's average speed was tested by marking out the distance and then timing how long it took for PARV to travel this distance. This test was done 5 times and an average time was used in the distance overtime calculation. This test did not account for the time it took PARV to accelerate to top speed, so it is not the most accurate way to measure average speed. The average time it took PARV to travel 10 ft was 1.692 s. The average speed calculated for PARV was 5.91 ft/s or 4.03 MPH. Another part of testing PARV was seeing how well it does in the natural environment. It involved running PARV outside on the natural pavement and a little on grass as well. It performed as expected just with some slight wheel locks that could be fixed. The main recommended improvement would be a higher wheelbase or chassis since at some point the bottom chassis was scratching the pavement and was right on the grass as well. If the aim is to have the car adapt to various terrains a higher chassis from the ground would be something to analyze and hopefully implement.

A detailed breakdown of the specification and data of this version car can be found in the PARV Specifications section of the Appendix.

3. Project Goals and Methodology

With PARV providing a platform for our project, we wanted to use principles and testing from PARV as a foundation for our project. Launching into our project we named our project FETCH, which stands for Fully Extruded Transport Consumer Hardware. Our goal is to create a fully 3D printed vehicle with autonomous features that can complete various tasks as a result of its modular and customizable design. The autonomous features will be installed on top of the car using a 3D printed plate, as this year's autonomous driving team plans to use Lidar technology that can be easily mounted. We plan on providing ample space on the top plate to mount the Arduino and batteries needed to power the cars' autonomous package.

Transitioning to a mechanical design focus, it was important for us as a team to understand the modular breakdown of the vehicle (i.e drivetrain, steering, differential, trailer, gearbox, chassis) and produce innovative means to ensure these 3D printed parts handle the strong forces and stress it will face when running. To increase 3D printing components and reduce fastener reduction, we plan on having a fully 3D printed gearbox and a limited-slip differential. We are also planning on incorporating snap and slide fit technology to reduce the number of fasteners used on the car. These new additions separate our project from previous years' and introduce new concepts such as snap and slide fit and a fully 3D printed gearbox. Overall, this chapter provides a detailed breakdown of our objective and what we hope to accomplish at the end of this project.

3.1 Suspension System Requirements and Goals

1. The suspension system, including the upper and lower control arms, the upper suspension mount, and the wheel hubs will be 3D printed mostly out of PLA, which is a common 3D printing filament
2. The rear suspension system will be able to keep the car from bottoming out while hauling a maximum load of 15 lbf
3. Both the front and rear suspension systems will allow the driveshafts to pass through to each wheel hub so they can transmit the motion from the limited-slip differentials to the wheels and move the car
4. Remain fully functional at least a 1-mile journey to simulate a potential delivery

5. The front suspension must be able to prevent the front end from bottoming out during travel over rough surfaces
6. Reduce the number of outsourced parts and replace them with 3D printed components

3.2 Steering System Requirements and Goals

1. The steering system will turn each wheel a minimum of 30° and will have an equal turning radius for each wheel
2. The steering system will be easily installed and removed from the chassis and suspension system, potentially utilizing snap fits or slide fits
3. The steering linkages will fit together in a compact manner minimizing the space taken up on the chassis
4. The steering system will be made of 3D printed linkages using PLA or ABS
5. The steering system will not interfere with the drivetrain or the suspension system

3.3 3D Printed Gears

1. The limited-slip differential for the car will be 3D printed, reducing the need for expensive metal gears.
2. The gearbox and transfer case will be fully 3D printed to aid with easy switching between rear and 4WD.
3. Gears and casings will be 3D printed using PLA materials
4. Gears are going to be scaled up for better print quality and functionality
5. The casing will incorporate snap or slide fit parts for easy access when needed

3.4 Trailer

As our team is concerned with a scale vehicle, the actual payload volume on the vehicle is limited. To fully address the delivery need, a trailer is warranted. The trailer accomplishes additional real estate and payload volume, as well as provides a platform for additional modules. Our team's trailer components must accomplish the following project goals:

Trailer Chassis Requirements and Goals

1. Contain no more than 2 3D printed base components

2. Operate in tandem with driving vehicle
3. Support attachment of payload modules (i.e. large storage container, compartmentalized container) as well as other instruments (i.e. robotic arm, lift)
4. Accommodate wide wheel-base and 3D printed or pneumatic wheels
5. House drivetrain, including motor and transmission

Trailer Lift Requirements and Goals

1. Comprise of 90% 3D printed snap-fit components to accomplish interchangeability
2. Ascend and descend the top plate while the vehicle is stationary
3. Achieve 2 feet of vertical translation
4. Support loads of 5 pounds at top position
5. Maintain a balance of trailer chassis

3.5 Design for Assembly Requirements

1. Reduce the number of fasteners by 30%
2. Introduce 3D printed snap and slide fits to drivetrain subassemblies
3. Publish downloadable models to an open-source platform

When the production of FETCH began, we conducted initial design meetings to brainstorm ideas and discuss the basic functionality of our design. Notably, we used a Pugh Matrix to provide a scaling system for the different design components we were interested in. Pugh Matrices are a standard of the Six Sigma methodology and use criteria-based decisions to evaluate alternative designs against a "baseline" option (Adams, n.d.). By assessing each alternative and summing the totals for each design consideration, the Pugh matrix helped our team clarify which tasks would be most actionable at an early stage.

Table 3-1: Pugh Matrix used to prioritize FETCH Design components

New Car Features	Going up Stairs	Food/Drink Delivery	Picking up Trash	Driving on the Beach	Modular Trailers
Feasibility	1	5	4	2	3
Contribution	4	3	3	3	5
Modularity	1	4	4	3	5
Novelty	3	3	3	2	5
Total	**9**	**15**	**14**	**10**	**18**

Our team categorized columns by first considering the demographic we were trying to appeal to and the needs warranted by it. With an average consumer classified as the customer, we found ourselves giving more weight to design parameters that would achieve a range of simple daily tasks. The totals at the base of the table aided the team in deciding which tasks to prioritize. As seen from the table 3-1, “Modular Trailers” and “Food/Drink Delivery” accumulated the most points so we began to discuss these two items in more detail. Our conversation helped us conclude that interchangeable trailers would prove to be a constant in a variety of vehicle capabilities. As different payloads would be accommodated, there could exist a modular trailer fitted for the specific need. To isolate the first task, we decided to create a scissor lift for a coffee delivery trailer. These initial ideas were then turned into drawings using Solidworks 2021. When necessary, free body diagrams were created to show the forces exerted on the designs. After analysis, drawings were sent to Ultimaker Cura as STL files to be printed. Prototypes of these preliminary drawings were printed using two 3D printers, the Ultimakers in WPI’s Foisie Prototyping Lab and a Creality Ender-3 pro. Early testing using the printed prototypes allowed us to make any necessary changes to the drawings in Solidworks, such as adjusting printing tolerance issues or improving the overall functionality of the produced prototype. This process was repeated until a final iteration that satisfied all requirements was produced. This design process was used for each newly printed item on FETCH.

To achieve our goal of a fully 3D-printed vehicle, our team set out to design connections and joints that snap, push, and slide together. These designs eliminate fasteners in various areas on PARV while still allowing the primary function of the system. Reducing fasteners also has the benefit of reducing costs and complexity since more pieces of the car can be 3D printed. The connections and joints each went through more than four iterations before their final dimensions and tolerances were solidified. Alongside that is the importance of 3D-printed gears. By analyzing last year's team's challenges and other cars we noticed the challenge 3D printed gears bring when it comes to high torque areas such as the gearbox and differential. In understanding these challenges and making some tests, the team will look into scaling up the 3D printed gears and differentials. By increasing the size of the gears and sticking with PLA as our primary material, we believe there will be a better chance for our 3D printed gears to handle the high torque and stresses they might face in various conditions. Part of our design goals is eliminating the need for metal gears, and as a team, we believe that can be achieved with our plans for 3D printed gears

4. Mechanics and Preliminary Testing of Various Cars

While full-scale cars and RC cars share many of the same components, the mechanics of each can present various advantages and disadvantages. It was important to first familiarize ourselves with a sample set of RC models to study these differences. Before delving into the design of our team's own autonomous vehicle, we spent seven weeks analyzing a dozen cars previously designed for autonomous driving. Our team's advisor, Pradeep Radhakrishnan, teaches a course oriented towards the design of a basic RC car. Last year, Czuba et al. aimed for their final product to serve as an example for the course and provide a framework for the fundamental mechanical components. The analysis of these cars taught us not only the basic functionality of the RC cars but helped us understand which design decisions worked well and which did not.

As a result of the seven-week term, the functionality, as well as the quality, of the cars used for testing, varied drastically across the fleet. The variance ultimately allowed us to isolate which components yielded the most consistent results. The basic components of an RC car are a motor, a speed controller, a receiver, a power source, and a circuit board or microcontroller and are visually represented in Figure 4-1 below (Khindkar, 2021).

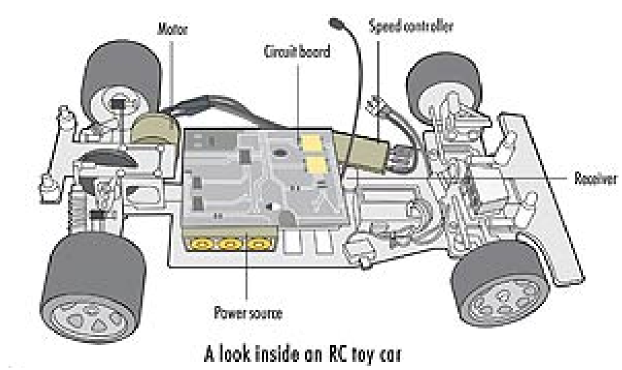

Figure 4-1: Basic Layout of a Typical RC Car as per (Khindkar, 2021).

4.1 Process and Analysis of Cars Worked on

This chapter talks about the different cars worked on during the project to help gain a basic understanding of how RC cars function. Another objective for working on these cars was to provide a platform for the ECE/CS team to test and refine their autonomous driving package. Readers will gain a general understanding of the construction differences of each car.

4.1.1 Rainbow

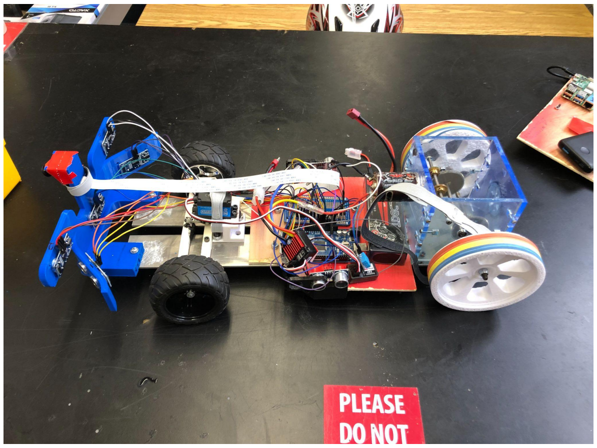

Figure 4-2: RC Car Rainbow

Shown in Figure 4-2, RC Car Rainbow was built using a combination of 3D printed materials, some laser cut acrylic, and outsourced materials such as metal for the base. This car had the incorporation of sensors as shown with the wiring in Figure 4-1. To prevent the chassis from breaking due to poor construction, the team in charge of building the car used some wood as a holder to prevent unnecessary snapping. When testing the rainbow, it ran but due to its length and steering system, it was difficult to turn and maneuver the track.

4.1.2 McQueen

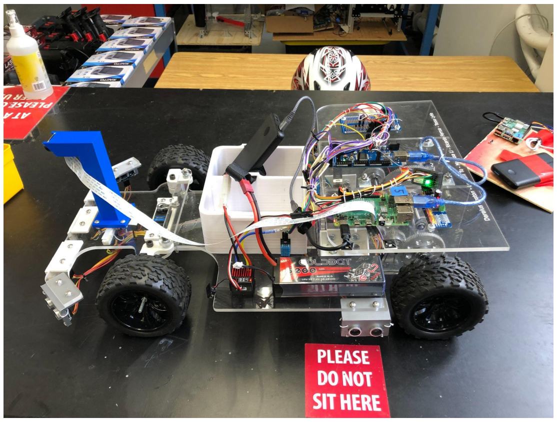

Figure 4-3: RC Car McQueen

Shown in Figure 4-3, RC Car McQueen used a combination of 3D printed parts and acrylic. This car also had the incorporation of sensors such as an ultrasonic sensor and camera. The team in charge of this car outsourced these wheels but 3D printed the battery holders. Metal gears were used in the gearbox of this car making it very efficient but loud when running. In testing this car it performed very well when navigating the track and was immediately transferred to the ECE/CS Team.

4.1.3 Tank

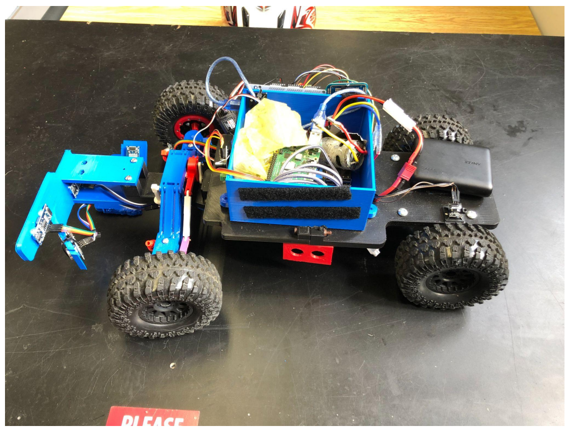

Figure 4-4: RC Car Tank

Shown in Figure 4-4, RC Car Tank mainly relied on 3D printed components. The chassis and sensor holders were all 3D printed. This car came with the incorporation of sensors such as ultrasonics but some parts were broken. The team in charge of constructing Tank used outsourced metal gears for their gearbox. In testing, Tank performed to a satisfactory extent in being able to navigate the track after fixing gear stripping issues.

4.1.4 Cleveland

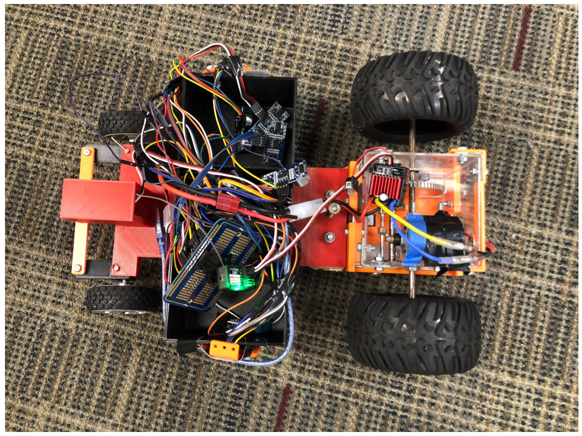

Figure 4-5: RC Car Cleveland

Shown in Figure 4-5, RC Car Cleveland also relied on 3D printed components for the chassis, steering linkage, and sensor holders. Laser-cut acrylic was used to hold the outsourced gearbox which consisted of metal gears. RC Car Cleveland had some sensors but failed to perform as expected. In testing the car failed to move as the metal gearbox faced stripping thus preventing the car from moving. The team also faced challenges with the steering linkage.

4.1.5 Thing 1&2

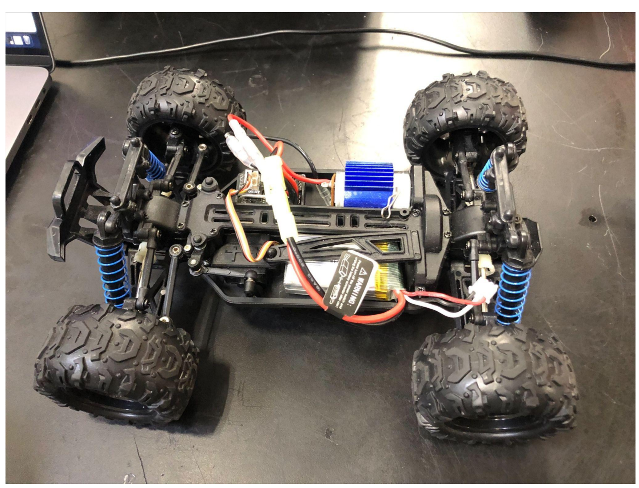

Figure 4-6: RC Car Thing 1&2

Shown in Figure 4-6, RC Car Thing 1&2 was bought online. This car used mainly plastic parts and metal components for the gears. The car performed very well around the track when tested. This car was transferred to the ECE/CS team after testing was complete for their autonomous package.

4.1.6 Car-1 "Carl"

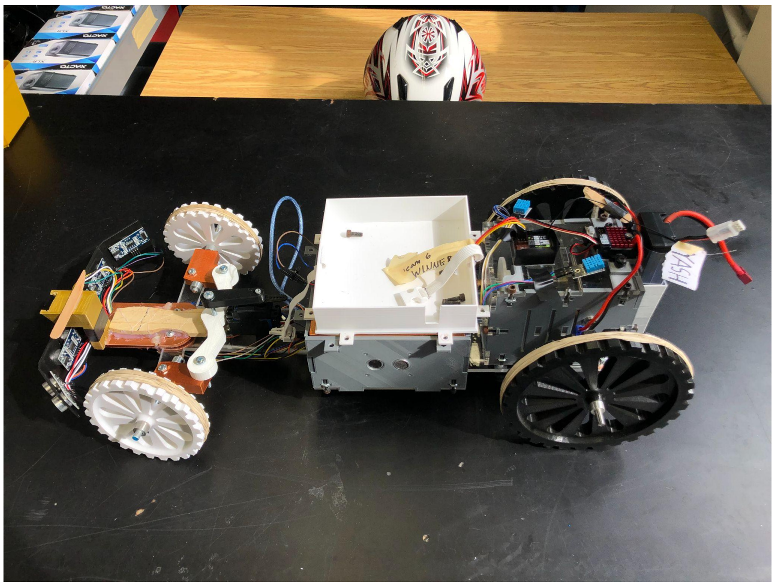

Figure 4-7: RC Car Car-1 "Carl"

Shown in Figure 4-7, RC Car "Carl" used a variety of components from 3D printed components, laser-cut acrylic for the steering linkage, and metal gears for the gearbox. This RC car had the incorporation of ultrasonic sensors for autonomous capabilities. When we tested the car it performed well in driving around the track and steering. Afterward, we transferred the car to the ECE/CS team to test their autonomous driving package.

For all these cars, we focused on the timeline when testing and fixing components. To start, any disassembled car was either put back together or left alone depending on how much work was required to reassemble the car. Since time was limited, it was decided that the cars closest to being fully assembled would be prioritized. Once assembled, each of the cars was tested to see if it was functional and to determine if it performed well enough to be passed on to the ECE/CS team for integration with the modular driving software. To be considered functional, our requirements consisted of being able to respond to all of the remote inputs, such as steering and throttle, and also being able to make a full lap around the track outside of the lab. Once the car was able to make a lap, it would be passed onto the ECE/CS team for use in their own testing. Any time a car was passed on, our team remained on standby to repair any of the cars that may have failed mechanically during the ECE/CS team's testing. This generally meant reprinting broken linkages and replacing them. Once these cars were operational, we shifted our focus to the 2019-2020 car Pre-PARV. Through taking apart and reassembling Pre-PARV the team was able to gain valuable knowledge of how this type of RC car could be designed and assembled. Testing Pre-PARV, shown in Figure 4-8, exposed potential areas of concern that the team would either look to address with this newest iteration or look at the 2020-2021 car PARV to see how last year's team may have addressed some of Pre-PARV's shortcomings and then implement that into this newest iteration.

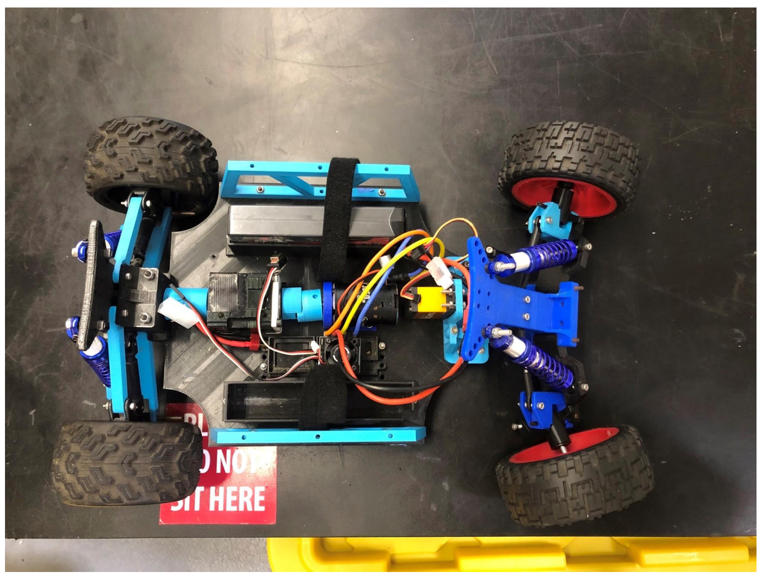

Figure 4-8: Final Iteration of Pre-PARV

Pre-PARV was then passed onto the ECE/CS team once it was made fully operational, and the ME team remained on standby and repaired cars damaged by the ECE/CS team as necessary. Several takeaways can be made for mechanical and electrical components as follows:

4.2 Chassis

The chassis of each vehicle was different but some design components remained consistent. For context, many of the student groups in the class were provided a functional gearbox to build a chassis around and accommodate sensors that would facilitate autonomous control. While most chassis were 3D printed, some included machined aluminum and even wood undercarriages as shown in Figure 4-9.

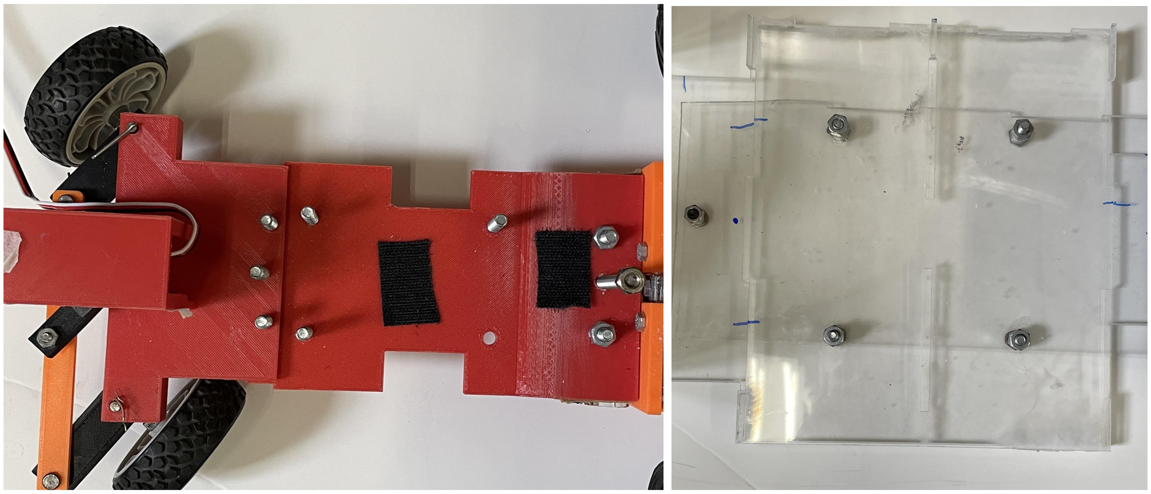

Figure 4-9: Various Chassis of Previous Vehicles

Many of the gearboxes were laser-cut acrylic and a couple of the cars carried this material choice throughout the entirety of the chassis. Some cars could not drive properly as the chassis weighed too much and overbear the gears, causing slipping. The largest problem we discovered with each chassis was the ultimately inadequate consideration of real estate, mainly with sensor and controller placement. A few of those that made space for these sensors did so by printing a rectangular prism to house the electrical components. Because many of the chassis bases were narrow, the printed boxes would sit on top and spill out to either side. Furthermore, the electrical components could not be placed well and secured as the wires interfered and prevented an ordered arrangement. Our team learned that the best chassis layout is a wide and flat design to allow for the proper placement of electrical components. A comparison of an undesirable versus a preferred layout can be seen below.

Figure 4-10: Comparison of Improper vs. Proper Electrical Component Accommodation

4.3 Steering

In our experience with these cars, we found the steering to work well when the servo motor was oriented vertically, and directly actuated a variation of a linkage. Most horizontal orientations did not allow for equal rotation between left and right as the servo could leverage against the frame and linkage and prevent proper motion. The one successful variation of horizontal servo placement included a ball-and-socket joint shown in Figure 4-11 which prevented the leverage problem as there are more degrees of freedom. This can be seen in the figure below:

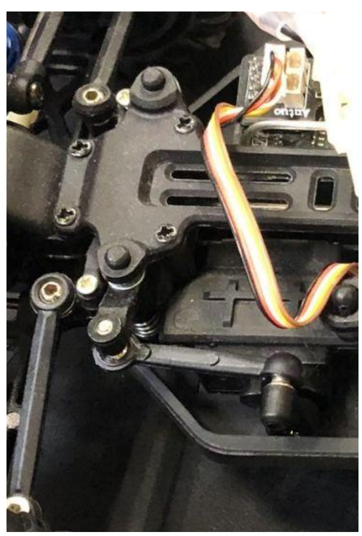

Figure 4-11: Ball-in-Socket Joint Attached to the Servo Arm for Steering Control

4.4 Sensors

With the goal of autonomous driving, sensors are integral for many parts to function properly. Detection of terrain changes, temperature, orientation IMUs, hall effect sensors, and LiPo battery gauges are important for driving capabilities. These sensors can be seen in Figure 4-12 below.

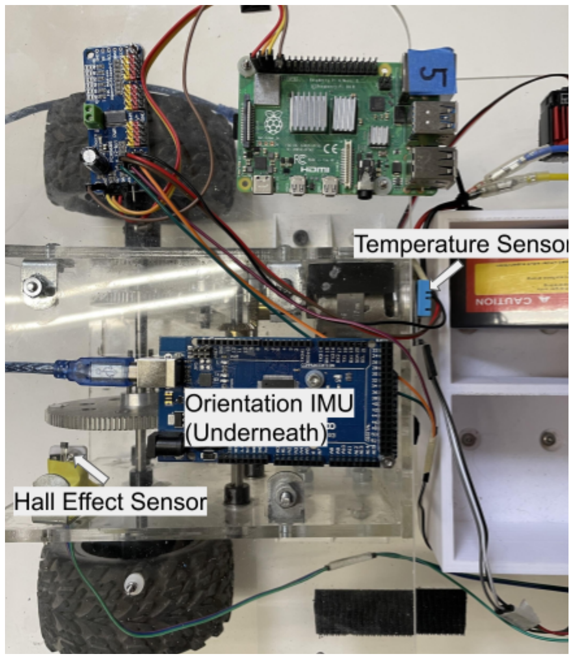

Figure 4-12: Sensors on Previous Vehicles

For autonomous driving, ultrasonic sensors and wide-angle cameras were previously used for the car to understand its surroundings. The temperature sensor is critical to ensure the RC car does not overheat from excessive use. The orientation IMU utilizes accelerometers, gyroscopes, and magnetometers to measure the orientation of the object to which it is attached. Hall effect sensors are used to detect RPM on an axel and utilize magnets to detect the presence of a magnetic field. Ultrasonic sensors function by sending out ultrasonic waves and collecting the bounces off of objects directly in view. The difference in time between the sent wave and the returning wave is translated into a measure of distance. A wide-angle camera measures the light from the driving surface and is used for corrective steering. The output from these sensors is combined and interpreted by a microcontroller, such as an Arduino or a Raspberry Pi. The data received by the microcontroller is used to direct the RC car in all its driving actions.

4.5 3D Printed Parts

3D printed parts present a lot of benefits as they can be readily manufactured and modified. However, some cases of 3D printed parts presented issues during our team's testing of the cars. Mainly, 3D printed wheels presented the most issues. Because of the smooth finish of PLA wheels, little to no traction is provided when the vehicle is under load. This occurred with a few of the PLA-printed wheels we encountered, but we found there are ways to print dependable wheels. For example, last year's team took advantage of TPE filament to produce wheels with pliable centers mimicking traditional rubber tires. Between these two approaches, our team established that TPE should be the material used when printing wheels.

Gears were another component that our team found to be 3D-printed. More often than not, the gears presented issues of slipping as well as drastic wear and tear. The best performing gearboxes were machined metal gears or outsourced gears, such as those from the VEX planetary gearbox. While some 3D-printed gears were operational, the team found that they could easily become dislodged or bent out of alignment. Not only do the gears have to be printed well, but it is important that the tolerances of the fit adequately support the gear meshing.

Our team researched gear printing techniques and found that there are ways to produce reliable gears that are resistant to slipping and overall degradation as a result. Most of the gears we observed were spur gears which are the most commonly used gear. These gears are easier to produce but lack power transmission capabilities and only operate well in low-speed scenarios. A reliable alternative is to use herringbone gears that utilize opposing helix grooves to eliminate axial forces. The elimination of axial forces minimizes wear and tear and preserves the life of the gear (Collins, 2017).

5. Snap/Push Fit and Slide Fit Technology

After the PARV analysis, the team established a list of improvements. To improve the modularity of PARV and reduce the number of fasteners for vehicle assembly, the team focused on incorporating snap, slide, and press fits into existing parts of the vehicle. Overall, 3 designs were developed to reduce various types of fasteners on the vehicle. This chapter focuses on the design and implementation of the snap and slide fit technology. A further breakdown of the implementation of this technology in FETCH is in section 10.5 of the discussion chapter.

5.1 Snap and Push fit

The first design for a fastener reducing connection resembled a snap clip with adaptations to make the clip circular to allow for rotational movement. A joint that can rotate is essential to eliminate fasteners in our trailer scissor lift mechanism. This pin joint was modeled in SolidWorks and modified to allow for slight movement in the pin. Undersizing the pin was crucial to allow for design iterations in each dimension enabling tighter tolerances in the final version of the pin. The first version of the pin joint is shown below in Figure 5-1.

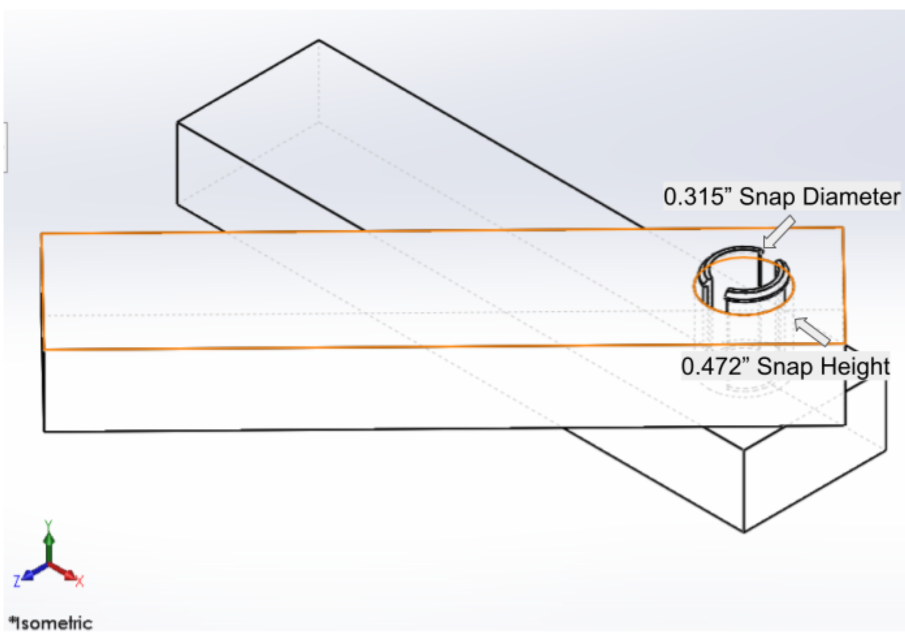

Figure 5-1: CAD of Pin Joint Version 1

Version 1 of the pin joint fell apart after less than 10 snaps together due to the tolerance between the outer diameter of the snap and the inner diameter of the hole being greater than

0.079 inches. This caused drooping in the connection and would result in large amounts of leaning when multiple joints are snapped together. Since the linkages of our trailer scissor lift are longer than this test part, Version 1 of the pin joint would not be feasible for a stable connection. The pin joint was iterated in four areas to improve the design. The areas are shown in Figure 5-2.

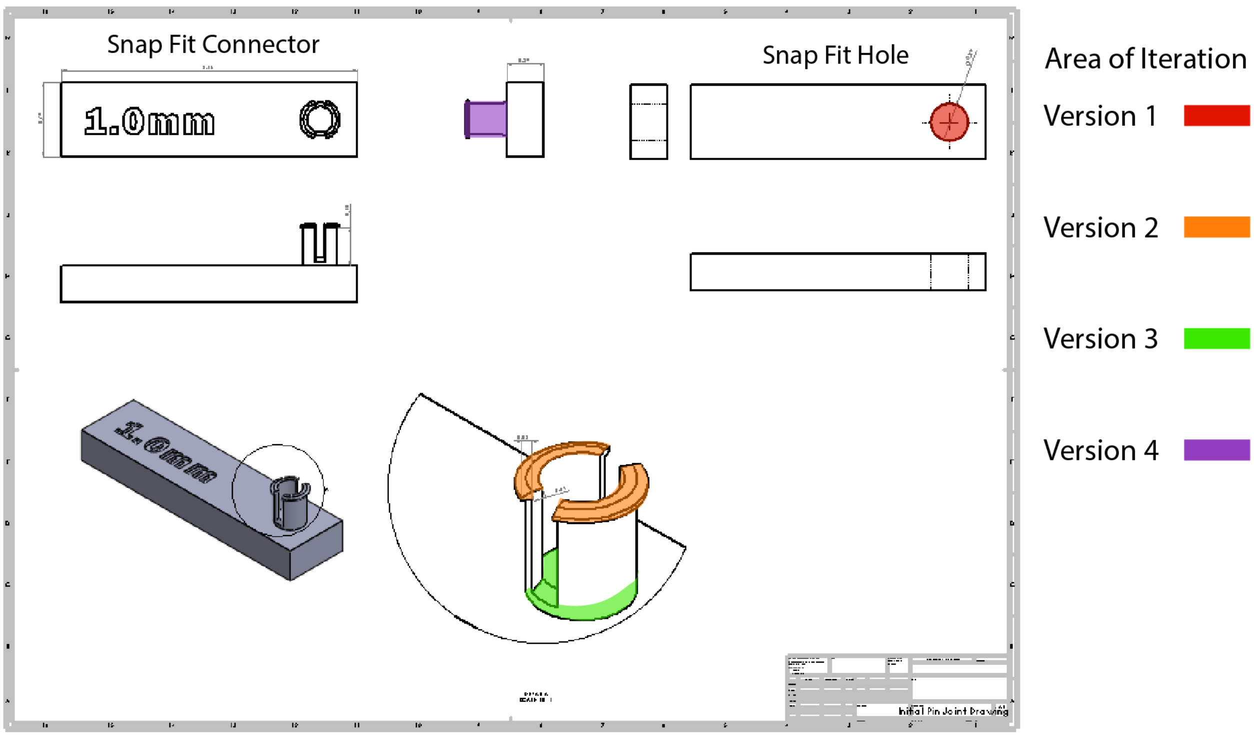

Figure 5-2: Pin Joint Iteration Areas

Version 2 of the snap joint adjusted the overhang distance of the snap. A larger overhang distance results in a snap that is less likely to fall apart after continual use. To find the ideal overhang distance, 4 print variations were made; these overhang variations were 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm. From version 2, the 1.5 mm overhang distance was the best candidate to continue improving the snap joint. Version 3 of the snap joint added material to the base of the snap to provide more strength and resilience when snapping together. The fourth iteration focused on the spacing between the snap overhang and the top of the hole piece. Three variations of 0.5 mm, 1.0 mm, and 1.5 mm from the top of the hole piece were printed to test the fitting in this dimension. All printing was completed at the WPI Prototyping Lab. Based on the fits of these prints, the ideal candidate was selected and continued on to the next design. When version 4 was achieved through testing, the final dimensions of the snap joint satisfied our needs of being strong, rotating 360°, and requiring no additional fasteners. Version 4 of the pin joint connector is shown below in Figure 5-3.

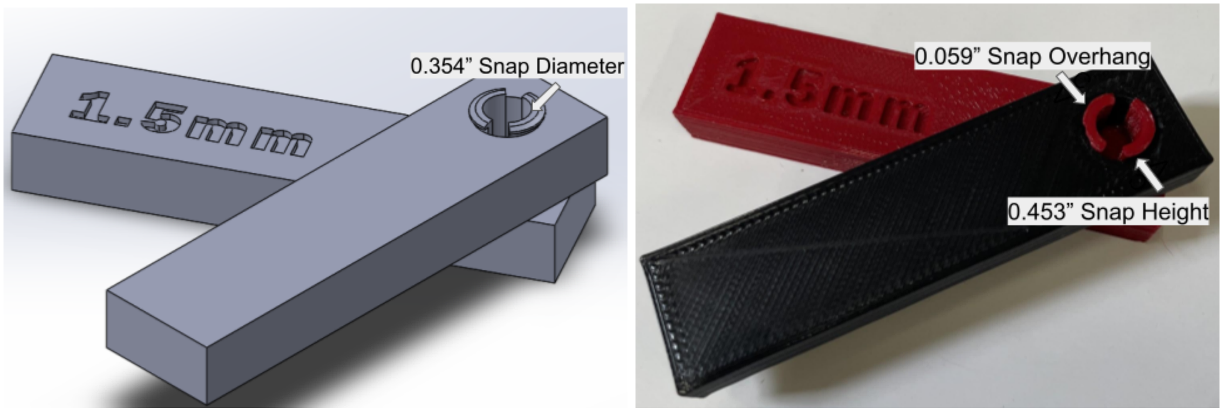

Figure 5-3: Version 4 of Pin Joint

This version of the snap joint allows for easy fastening and removal and can support itself without drooping during use. By using PLA, the main body of the joint remains rigid while the pin body is allowed to flex about a tenth of an inch. The flex of the pin is enough to slide into the connector but not enough to break the PLA. This was verified by fastening and unfastening version 4 of the snap joint more than 30 times to ensure resiliency. The snap joint is the prominent joint used in the trailer scissor lift and helps achieve our project goal of reducing fasteners for car assembly.

Another design to reduce fasteners is a press-fit connector as shown in Figure 5-4 which can be used to secure components to the chassis of the vehicle.

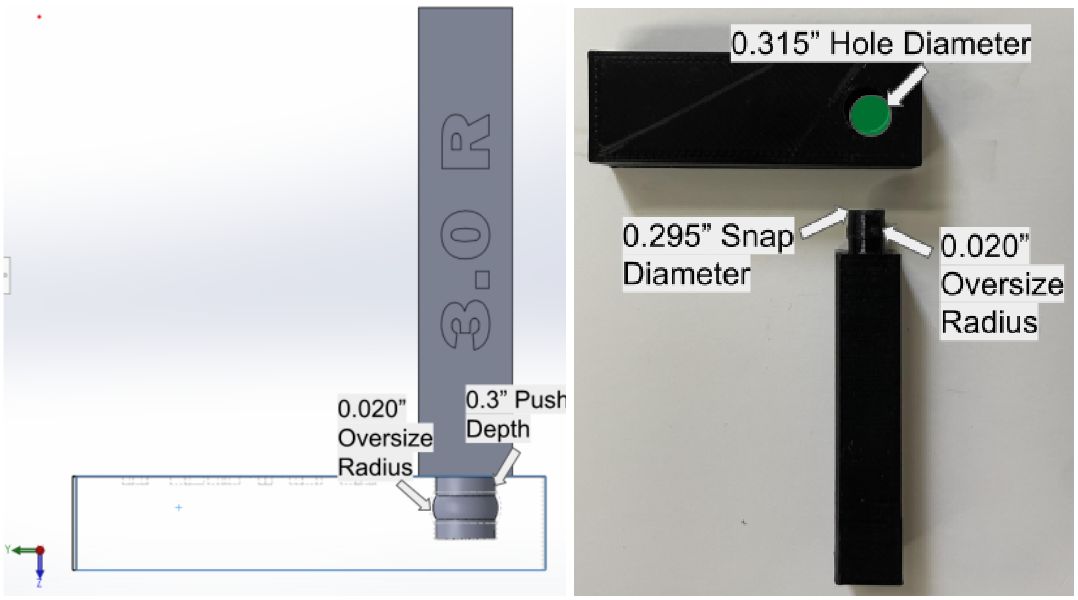

Figure 5-4: Push-Fit Version 4 Test Model

The main diameter of the shaft fits into the hole with a 0.3mm tolerance between the walls of the hole. The snap comes from the oversized diameter in the center of the shaft. When connected, this mate has an equal negative inside of the hole of the connector. By adjusting the size of the largest diameter, the press-fit connector can be modified into two adaptations. First is a press fit that can snap in and out of the hole easily. This is used for parts that do not experience large forces and on covers that need to be taken off to access more intricate areas of the vehicle since these applications allow for the snap to be pressed in and taken out easily. The second adaptation occurs when the largest diameter is 5% larger than the inside diameter of the hole. This connector is a one-time fit and can not come undone after snapping together. A detailed section on where this technology was used is in section 10.5.

5.2 Slide Fit

Like snap and push-fit, the goal of integrating slide fit is to help reduce the total number of fasteners needed. Additionally, slide fit parts are more easily added or removed which makes repairs or changes much quicker and easier.

The results of iterations 1 and 2, as seen in Figures 5-5 and 5-6, were tolerancing the sizing of the lip and groove. Iteration 1 did not slide together properly due to tolerancing issues and the slide portion was much wider than needed. In iteration 2, a .2” tolerance was found to produce the best result, however now the groove was too thin.

Figure 5-5: Slide Fit Iteration 1

Figure 5-6: Slide Fit Iteration 2

Iteration 3 produced the best result. It produced a strong, tight fit that could slide apart easily. Iteration 3’s prototype was used as the proper sizing for the slide fit implementation. The final SOLIDWORKS measurements for the groove can be seen in Figure 5-7.

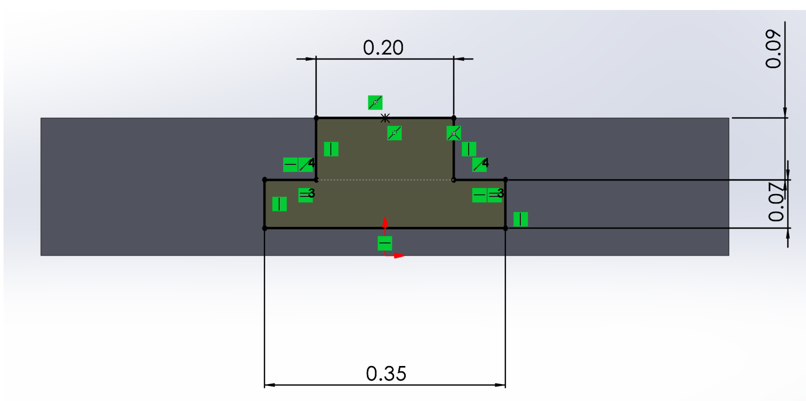

Figure 5-7: Slide Fit Iteration 3, Measurements

Since the slide fit mechanism worked as intended, the next problem to solve was locking the pieces together to ensure they would not slide apart. After printing, the slide fit stuck together extremely well just on the 3D print tolerance alone, however over continued use, or under high stress, the slide fit would come apart easily. Iteration 4 aimed to solve this issue by making a circular space at the end of the groove where a piece of the lip could secure itself inside, as seen in Figure 5-8. This proved to be an ineffective strategy, because if the end was too wide the lip would not fit in the groove. Even if it was not too wide it would undergo the same failure that iteration 3 did under continued use or high stress. The final locking mechanism that we ended up using was a single bolt and nut to prevent the LSD from sliding out of the groove as seen in Figure 5-9.

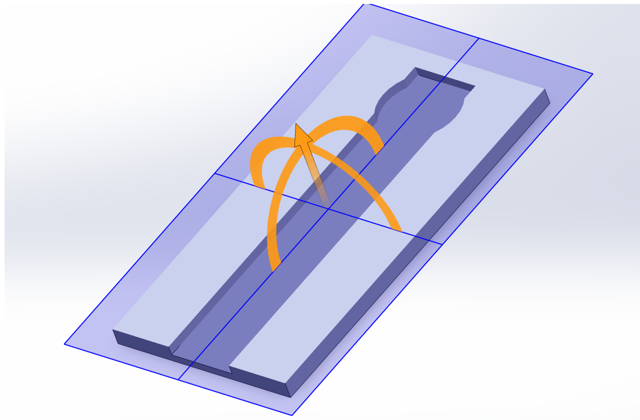

Figure 5-8: Slide Fit Iteration 4, Locking Mechanism

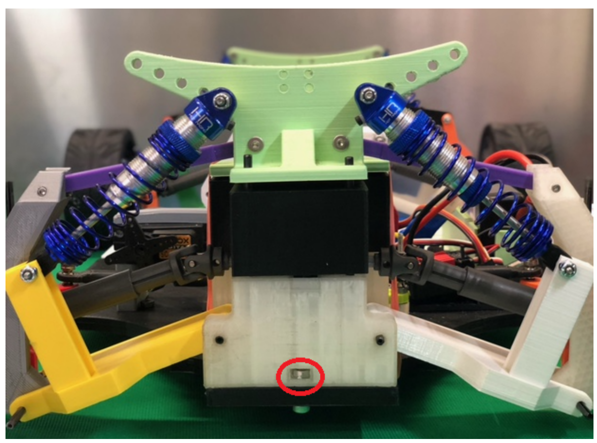

Figure 5-9: Slide Fit final locking Mechanism

Slide fit is used in two areas of FETCH. First to mount each LSD to the front and rear of the chassis as seen in Figure 5-9. Second to mount the transfer case to the chassis as seen in Figure 5-10. A detailed section on where this technology was used is in section 10.5.

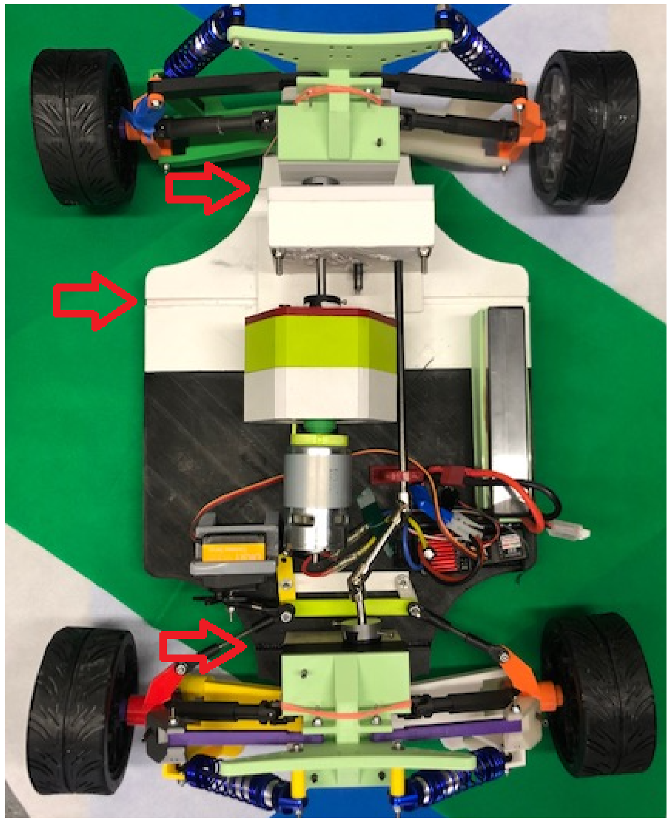

Figure 5-10: Slide Fit Locations on FETCH

6. Trailer Mechanisms and Modularity

This section will provide a detailed breakdown of the trailer system including the scissor lift and gearbox used. It provides a basic understanding of what led to the design parameters used in creating the trailer and scissor lift and the end goal with expectations.

6.1 Scissor Lift

To accomplish a fully autonomous assistive vehicle, the team needed to integrate mechanisms of action that would aid delivery beyond just driving from point A to point B. As Czuba et al. 2021 implemented an outsourced robotic arm in their design, our team decided to focus efforts on aiding consumers in the retrieval and delivery of specific payloads with a printed subassembly. To accommodate consumers, whether they be disabled, elderly, or healthy, we concluded a lifting mechanism that could elevate payloads from drive height to waist height would achieve a large component of the convenience factor we sought after.

As the Pugh Matrix in our initial design meetings exhibited (Section, the team aimed to prioritize trailer modularity and food delivery. As a result, the first task we concerned ourselves with was the shipping and handling of a coffee beverage. We used axiomatic design principles to identify functional requirements and the design parameters that would accomplish each. The decomposition of early ideation can be seen in Table 6-1 below.

Table 6-1: Decomposition of Coffee Delivery Design

Functional Requirements	**Design Parameters**
FR0: Deliver coffee	DP0: coffee delivery trailer
FR1: support cup w/ beverage	DP1: system to hold cup
FR11: support weight of beverage	DP11: hard tough resin concentric cup holder
FR12: Maintain the balance of cup	DP12: suspension system and/or gyroscopic housing
FR2: Raise beverage to waist height	DP2: Scissor lift elevator mechanism

Constraints: weight, the volume of beverage, route surface, number of linkages

We identified a scissor lift/jack as an appropriate device to model our design after. Some of the benefits of a scissor lift include the versatility of power options, cross beam balancing, and snap-fit opportunity. As we isolated design components, we shifted from brainstorming on whiteboards to modeling in Solidworks. An initial model of the scissor lift can be observed as shown in Figure 6-2.

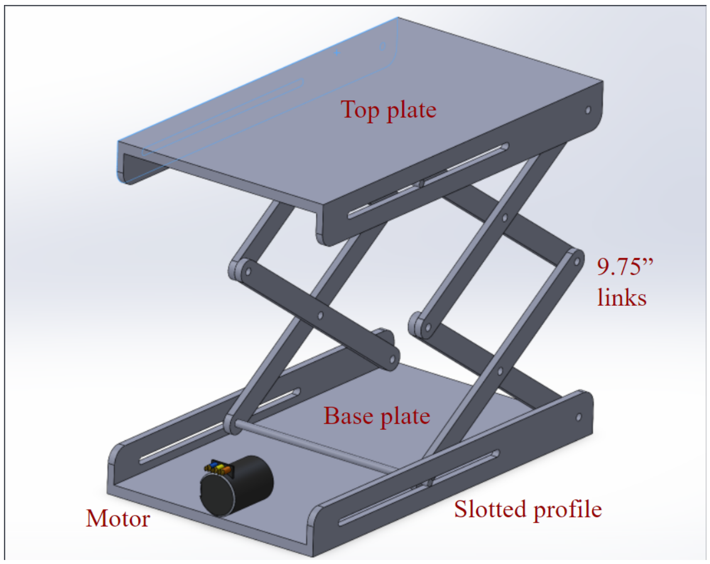

Figure 6-2: Initial CAD of Scissor lift

The initial design included linkages that were fastened with pins. This initial design included two levels of 9.75” cross beam linkages on either side which could accomplish a maximum height of 17.53 in. As one of the fundamental principles of this product concerned the reduction of fasteners, our design shifted to accommodate an assembly fastened primarily by printed snap fits. Where pins were originally intended to fasten linkages, they were eventually replaced by 0.5” male and .48” female snap fits respectively. These snap fits can be observed in the model below in Figure 6-3.

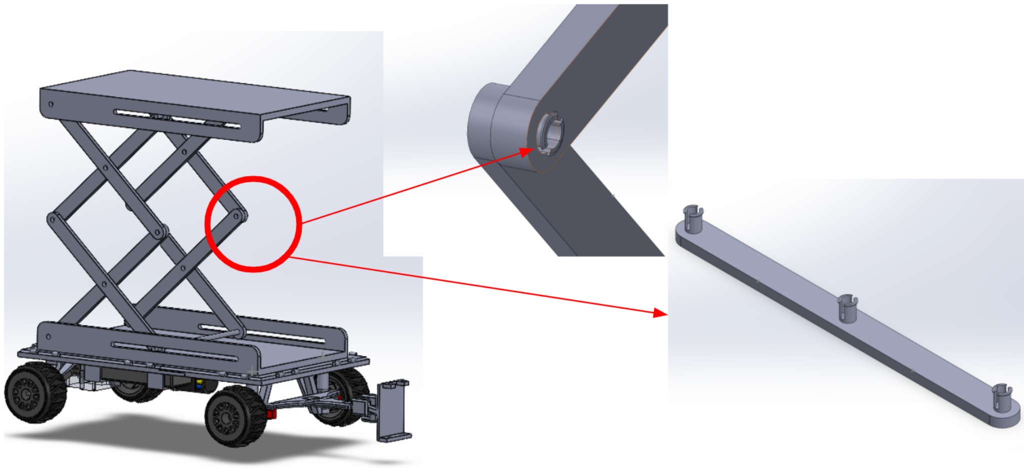

Figure 6-3: Replacement of Linkage Fasteners with Printed Snap Fits

Once attached to the trailer assembly created by Czuba et al 2021, the total achievable height increased to 21.25 inches. To assess how much load the lift could handle as well as the forces at each respective snap-fit, we generated free body diagrams as shown in Figure 6-4 and simulated the static forces in MatLab.

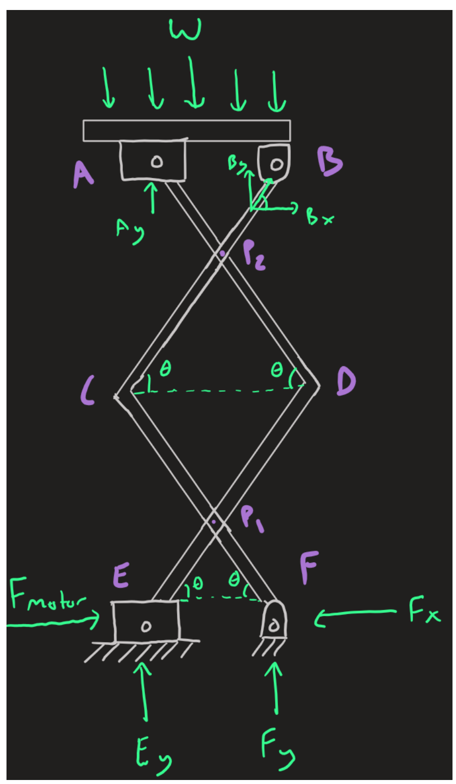

Figure 6-4: Free Body Diagram of Scissor Lift

The final scissor lift model incorporated a top and base plate joined by snap and slide fits and a pair of two-stage linkages with snap-fit fasteners. An additional Hobbywing XR10 justock sensored brushless ESC/SD G2.1 motor was used to power the lift by rotating an 8-inch 1/4th-20 thread lead screw. Rotation of the screw would consequently translate the connecting rod of the slide joint backward and provide vertical lift. This particular subassembly succeeded in achieving our goal of reducing fasteners as the snap-fit and slide fit integration eliminated the need for 24 fasteners.

In comparison to the initial design, the final iteration included 26 printed components and 5 outsourced components. The increase in printed parts was due to size constraints. As the Taz printer available on the print farm could not print an entire base/top plate which exceeded 11.5", the two components were divided into 3 separate components: a slide fit rail, a male fit half-plate, and a female fit half-plate, as seen in Figure 6-5.

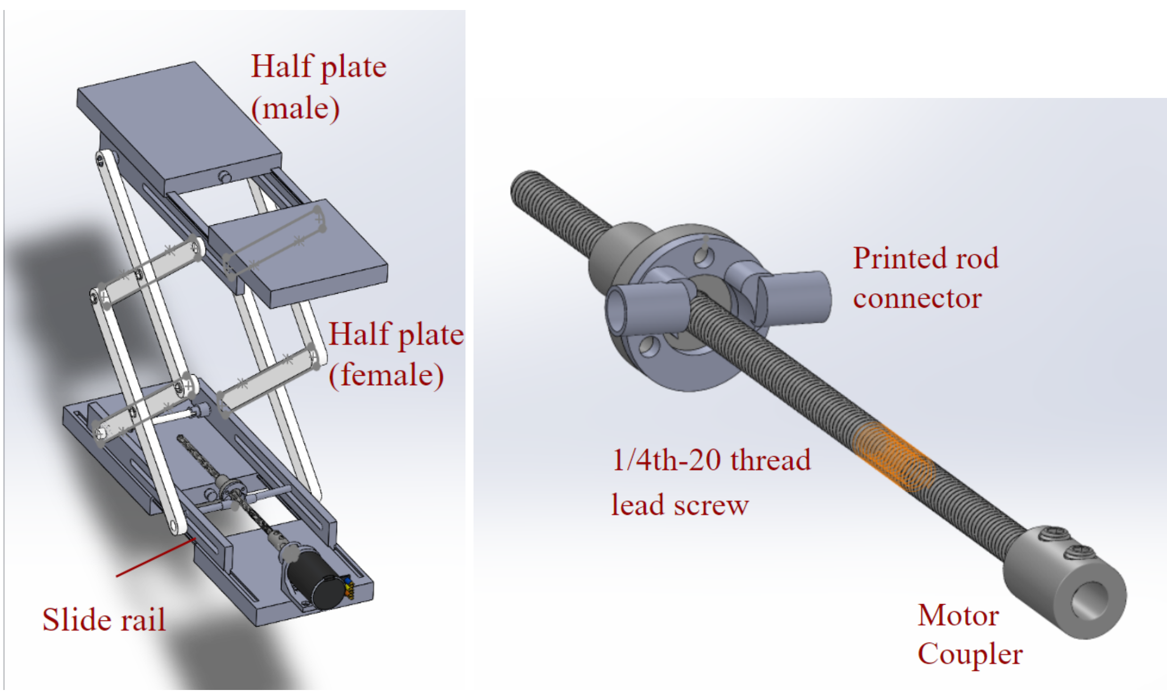

Figure 6-5: Final Scissor Lift Design With Mechanism of Action

7. Project Results

This chapter details the outcomes of the project objectives discussed in the methodology chapter. An analysis of printed subassemblies is explored before drawing conclusions on the feasibility of printed mechanical components and providing recommendations for future designs.

7.1 Gearbox

This year, our team was tasked with creating our own fully 3D-printed Gearbox. To start, we first looked at last year's team gearbox. It is important to note that last year's team outsourced that gearbox. They used a VEX planetary Gearbox with a 9:1 ratio as shown in Figure 7-1 and Figure 7-2. This gearbox was 3.48” long and 1.75” tall.

Figure 7-1: VEX Planetary Gearbox

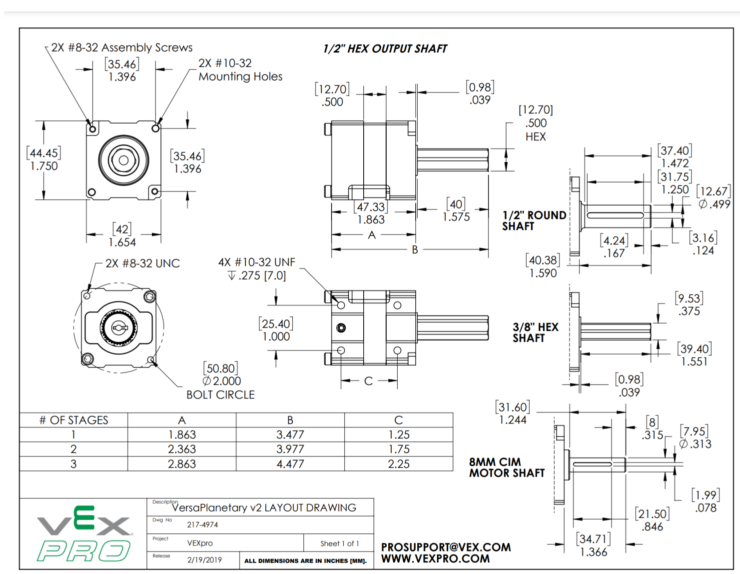

Figure 7-2: VEX Planetary Gearbox Drawing

The VEX gearbox uses metal gears and components. To better understand how we could transition to a fully 3D-printed gearbox, we research breaking down this type of VEX gearbox (Gonzalez et al. 2017). Realizing the complexities of this gearbox, we continued research regarding 3D printed gearboxes, materials to use, and important analysis to design and how to print them. For our 3D print to have an increased chance of success, we decided to increase the size of our gearbox to better accommodate the type of speed and forces it will experience when running. Similar to the VEX planetary gearbox, we knew incorporating a planetary type system would be best for our design as it's easier to design our gearbox to adapt to any needed gear ratio. With modularity as our primary focus, we wanted a gearbox that was easy to upscale or downscale the gear ratio as needed. Through that, we provide consumers the ability to decide if they want more torque or more speed to adapt the gearbox to fit their needs. After research, our gearbox design was finalized and the design is shown in Figure 7-3. The 3D-printed gearbox was 4.82" long and 3.56" tall. Compared to the previous year's outsourced VEX gearbox, we had a 38.5% increase in width and a 103% increase in height to factor in our new 3D printing components. In Figure 7-4 we have our designed stage ratio using SolidWorks. We designed a 24 tooth spur gear and sun gear. We maintained a diametral pitch of .85'' and a pressure angle of 20 degrees. The primary motor designed to run this gearbox was a 6.99 Lb-in (Handson Tech) brushless motor connected to the primary 24-tooth sun gear shown in Figure 7-5.

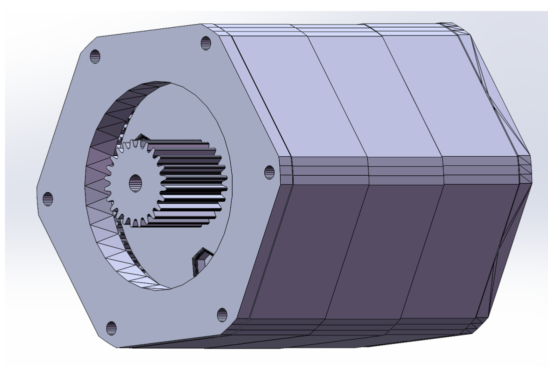

Figure 7-3: Designed Gearbox using SolidWorks

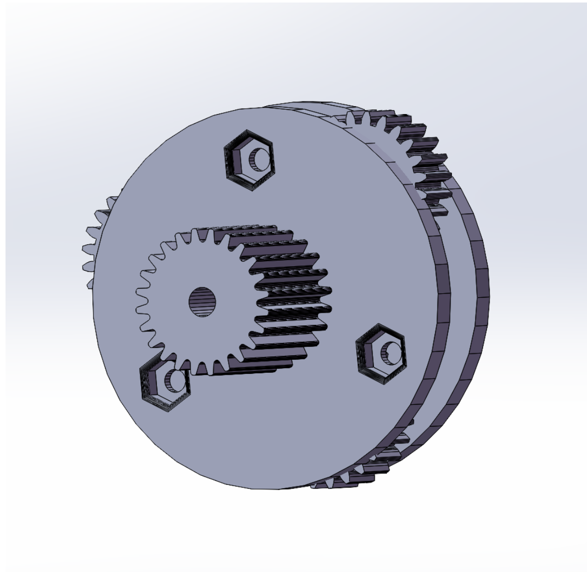

Figure 7-4: Designed Planetary Stage

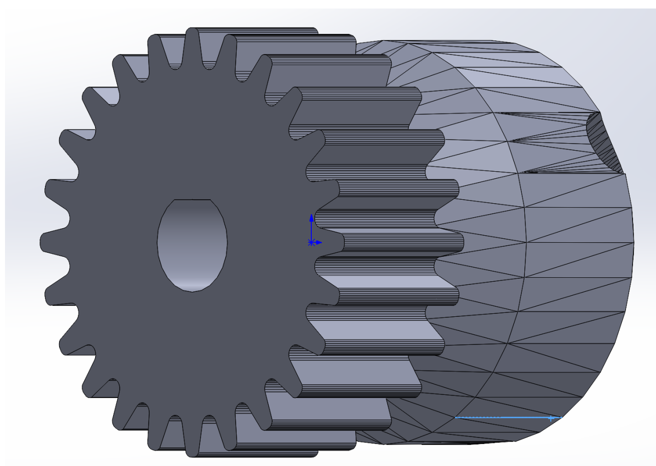

Figure 7-5: Primary Sun-Gear Connected to Motor (Solidworks Model)

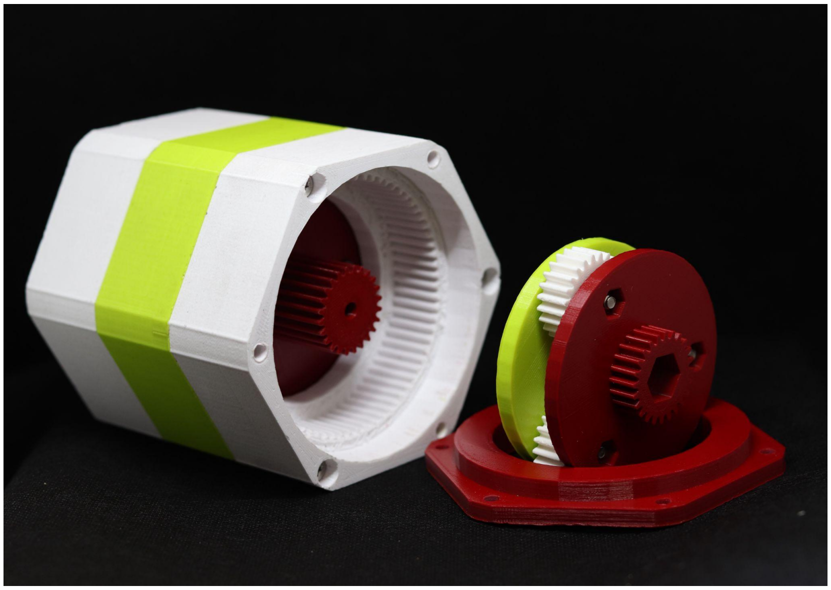

Figure 7-6: 3D Printed Gearbox

Looking at the subassembly of the gearbox our primary focus was on the type of gear to use. We decided to use a 24-tooth spur gear for our planet and a 24-tooth sun gear as shown in Figure 7-4 and Figure 7-5. All stages of the gearbox used the same gear size. Our 3D printed version shown in Figure 7-6 showcases what our final gearbox looks like. The planet carriers were designed to hold the spur gears that will act as planets. The white casing in Figure 7-6, shows how the spur gears sit and stack on top of each other especially with gear groves inside to support the planet spur gears. The motor connects to the primary sun gear that will spin the spur planet gears which will, in turn, spin another set of planetary stages, overall moving the gearbox. In assembling the gearbox we used 624zz bearing for the spur gears, to help with motion, especially at high speeds. We used M4 bolts to hold gears and casings, and M4 lock nuts as well. Figure 7-7 shows the spur planet gear in white with the bearings and the primary sun gear in green which will attach to the motor.

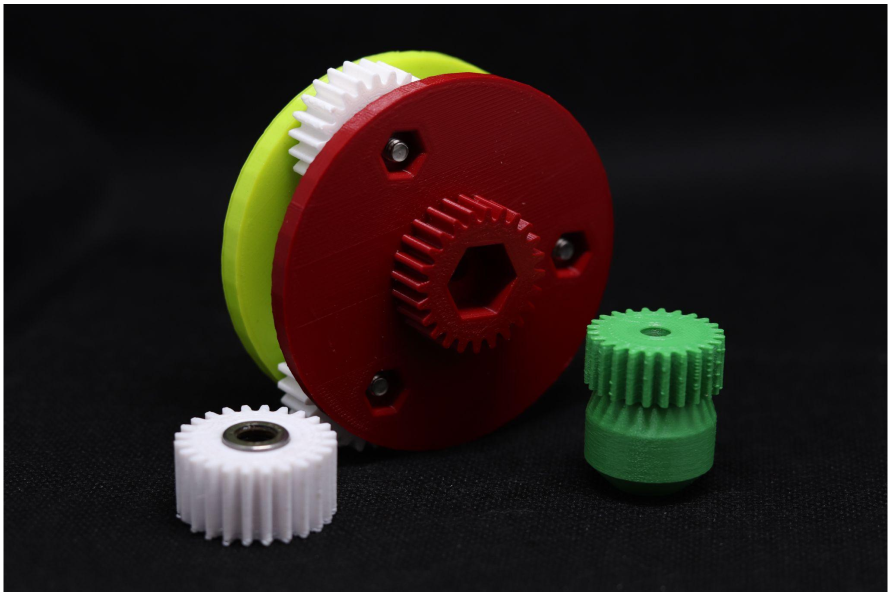

Figure 7-7: Picture of 3D Planetary System with Motor Gear

We wanted to increase the torque with our version so our design was a three-stage 27:1 gear ratio.

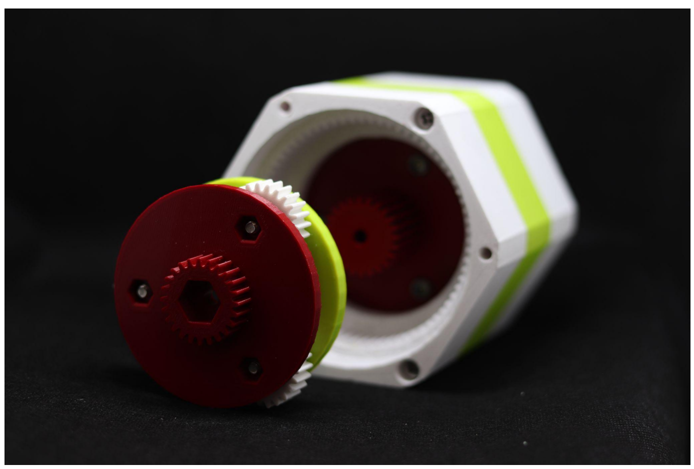

Figure 7-8: Picture of 3D Printed Gearbox

When 3D printing our gearbox as shown in Figure 7-8, we decided to focus on producing high-quality prints by slowing down the speed of our extruder head. We also increased the infill density of our gears to 65% to help produce stronger spur and sun gears that will last longer when running. For the casings, we printed at high quality, at 50% infill density, and a skirt for the base adhesion. The incorporation of bearing and lubrication is another important aspect in preventing our gearbox from stripping and possibly failing when running at high speeds. By making such adjustments, we saw no stripping or failing of our gearbox system and better fit tolerances when making the gears run efficiently in their housing. The gearbox was attached to the chassis with the incorporation of the slide and snap-fit feature shown in Figure 7-9.

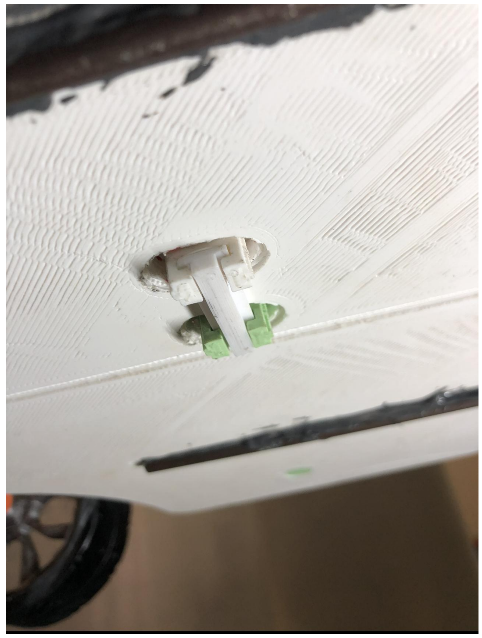

Figure 7-9: Snap and Slide-Fit Feature on Gearbox to Chassis

When incorporating the gearbox into the overall car, Figure 7-9 showcases the connection. The motor is mounted on a circular housing where the sun gear is connected to the output shaft of the motor. Then using our snap and slide fit incorporation shown in Figure 7-9 we connected the main gearbox to the chassis. The gearbox connects to the transfer case using a transfer rod and a hexagonal mechanism. The transfer case then distributes the torque and speed from the transfer rod to the front and rear limited-slip differential.

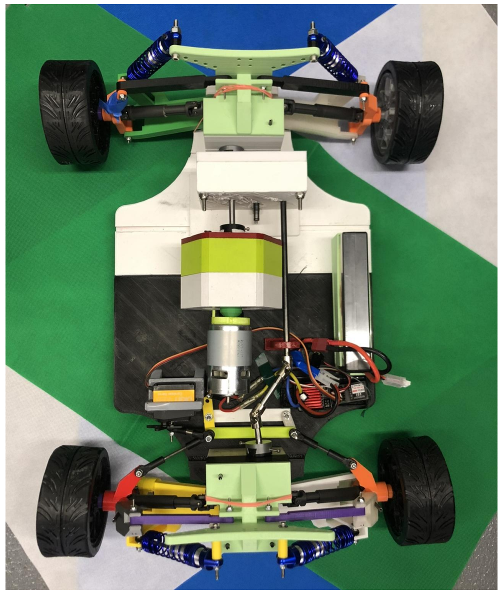

Figure 7-10: 3D printed Gearbox connecting to other Components

7.2 Suspension

This year's suspension system required a number of updates from last year to account for the increase in the size of the car's chassis, as well as our goal to increase the number of 3D printed components. The upper control arms and the lower wishbones on the front and rear suspension systems were increased in length by 34% to accommodate for a 34% increase in the width of the chassis at the front and rear ends. The front and rear suspension assemblies are shown in Figures 7-11 and 7-12.

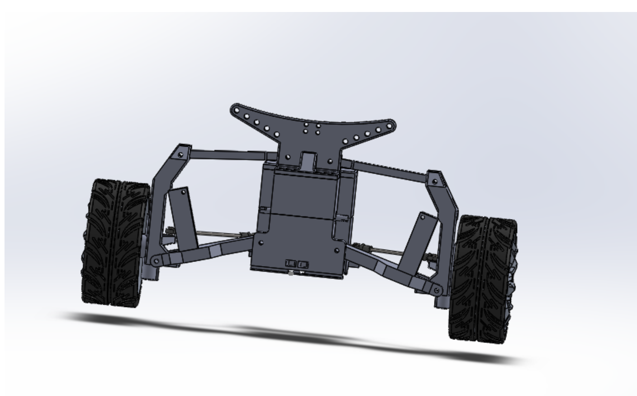

Figure 7-11: Front Suspension Assembly

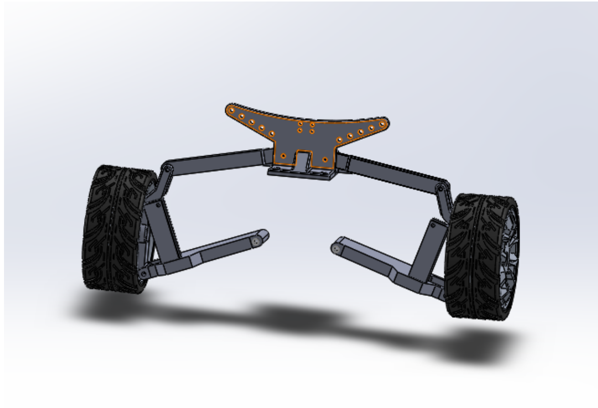

Figure 7-12: Rear Suspension Assembly

The front suspension links were all increased to 3.47 in long from 2.59 in, and the rear suspension links were increased to 3.89 in from 2.9 in, as shown in Figures 7-13 and 7-14. This gave us the narrowest track width we could get, which was 13.72 in as shown in Figure 7-15, without the tires colliding with the chassis during turning. The upper control arms were also tapered at the end where they connect to the upper suspension mount so they could fit into their mounting position more easily here and at the wheel hub. The upper control arms were also 3D printed in PLA this year, unlike last year where turnbuckles were used for the upper links. The reasoning for this change was to better suit our theme this year of reducing outsourced parts in favor of more 3D printed parts.

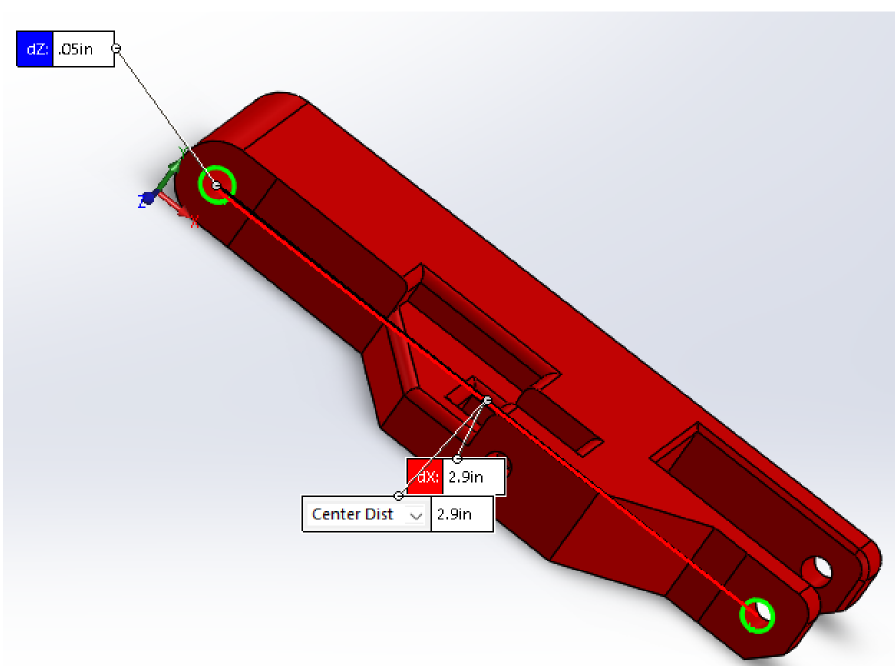

Figure 7-13: Last Year's Rear Lower Control Arm

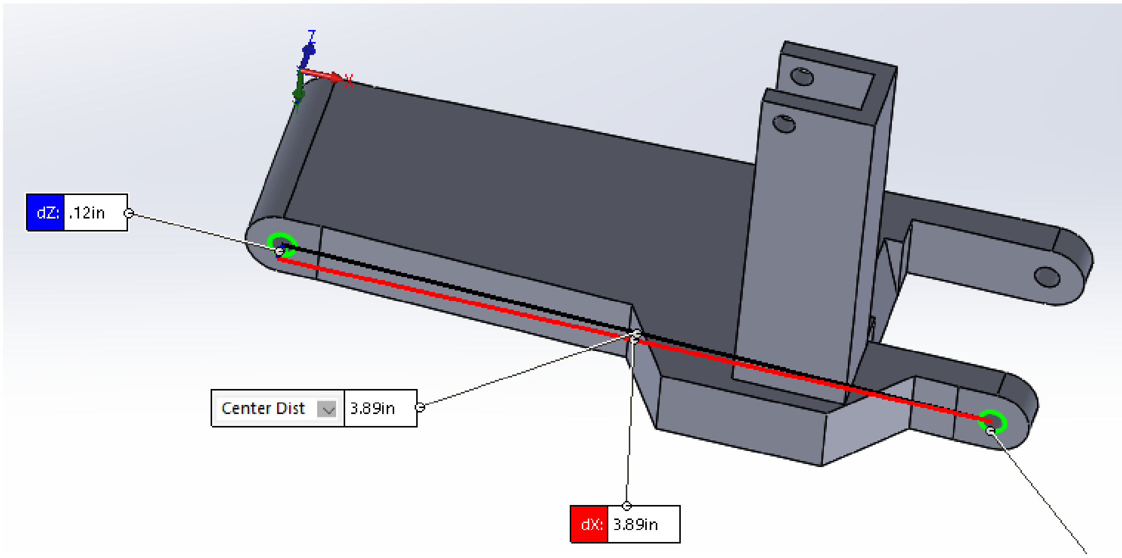

Figure 7-14: Rear Lower Control Arm

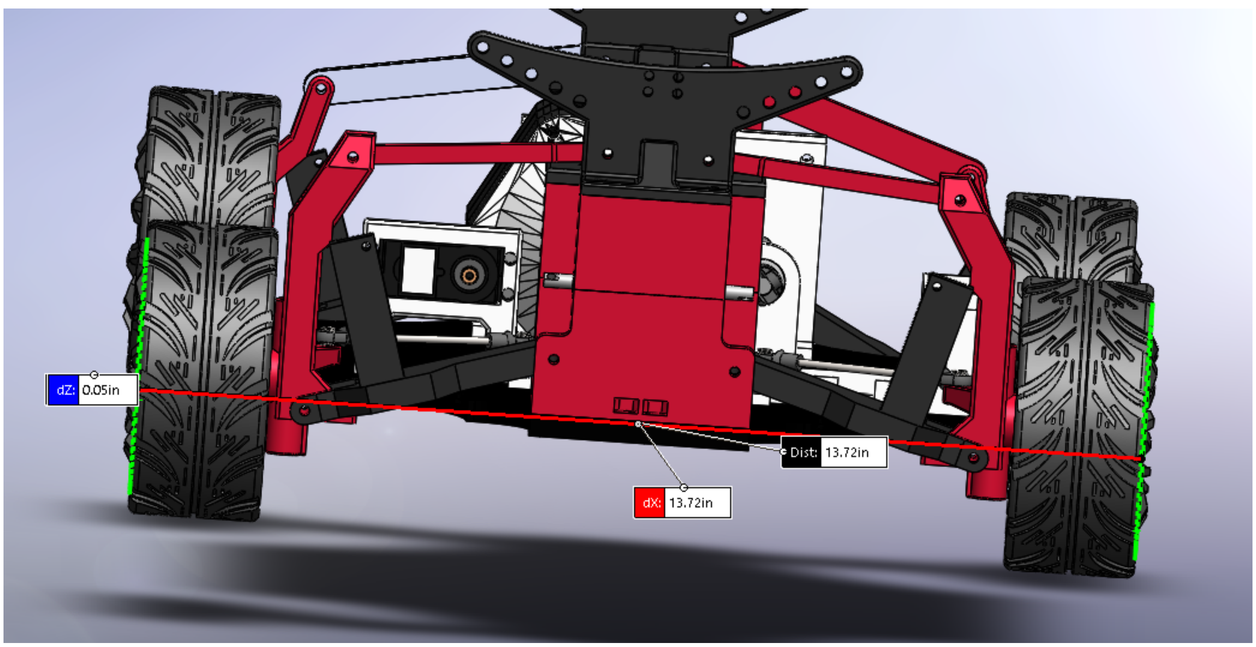

Figure 7-15: Track Width

The lower wishbones and the upper shock mounts had to be further redesigned due to the size of the LSD housing. The LSD housing, where the upper shock mount is located, was 52% taller than the direct drive housing from the previous year's car, meaning the shocks no longer fit their mounting position. After multiple iterations, the upper shock mount was shrunk from 2.01 inches to 1.8 inches and was widened from 3.09 inches to 4.97 inches as seen in Figures 7-16 through 7-18.

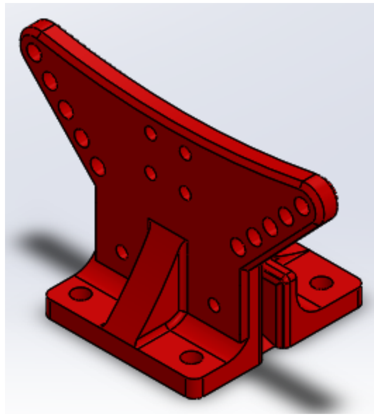

Figure 7-16: Last Year's Upper Suspension Mount

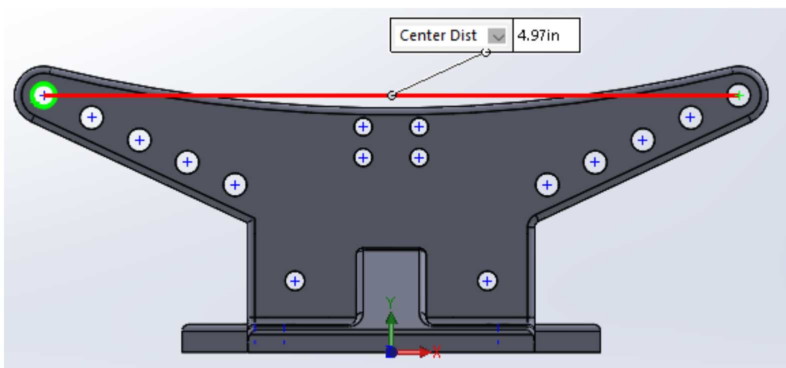

Figure 7-17: Front Upper Suspension Mount

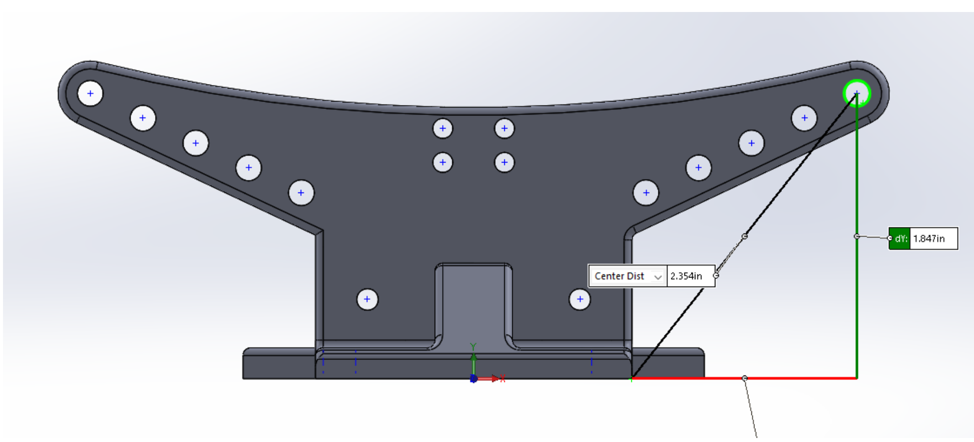

Figure 7-18: Front Upper Suspension Mount (Height)

However we only had enough time to print one of the new upper shock mounts for the front end and not the rear, so the rear upper suspension mount is one of our previous iterations. This required us to mount the shocks on the lowest mounting point rather than the highest mounting point on the upper shock mount to keep the ride height consistent from the front to the rear, as seen in Figures 7-19 and 7-20.

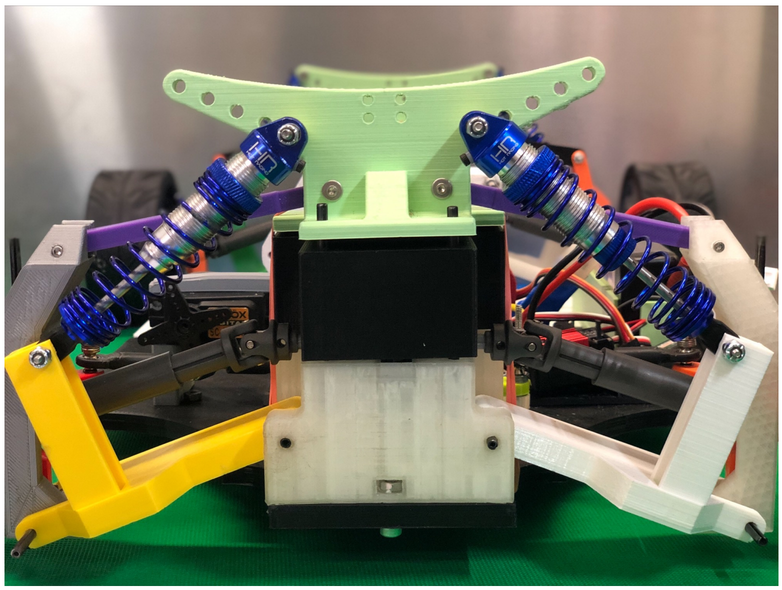

Figure 7-19: Front Shock Mounting Position

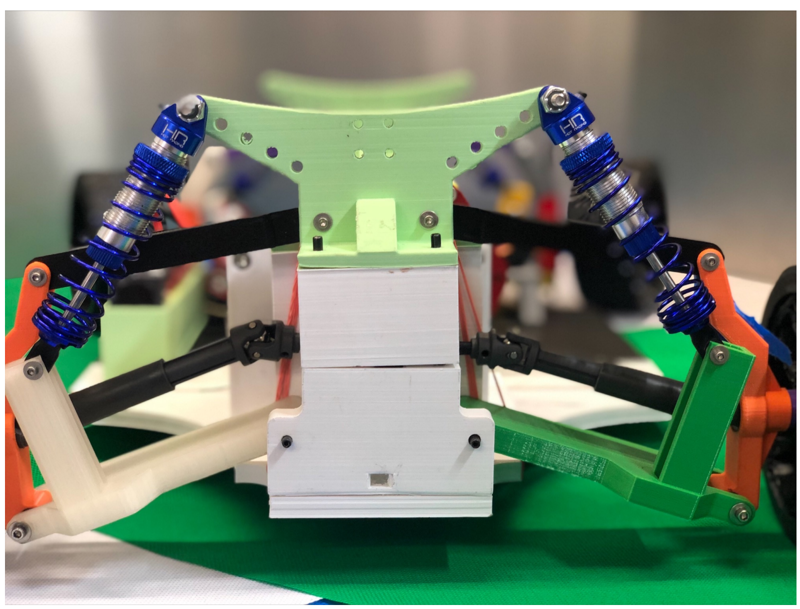

Figure 7-20: Rear Shock Mounting Position

The lower wishbones were redesigned to have a 2-inch tall extrusion to raise the mounting point. Together, this ensured that the shocks would be able to fit in their mounting position while making sure the chassis would not scrape the ground. The front lower wishbones also had their height increased from 1.52 inches to 1.85 inches in order to move the mounting point for the shock outward so the shock would not collide with the front wheel hubs during suspension travel. This year's lower wishbone is shown in Figure 7-21.

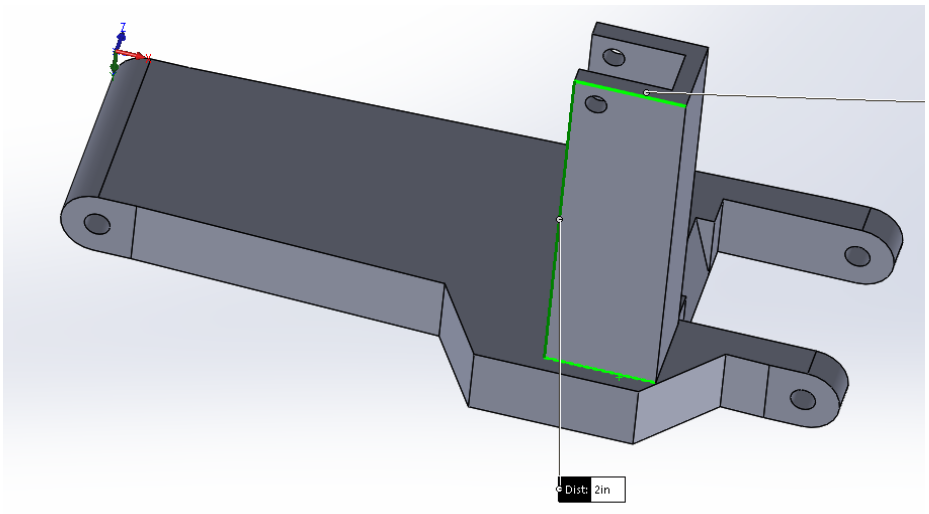

Figure 7-21: This Year's Lower Wishbone

Due to this change, the front shock spacers had to be lengthened to 0.86 in from 0.4125in, as shown in Figures 7-22 and 7-23, in order to make sure the shock would still be mounted vertically.

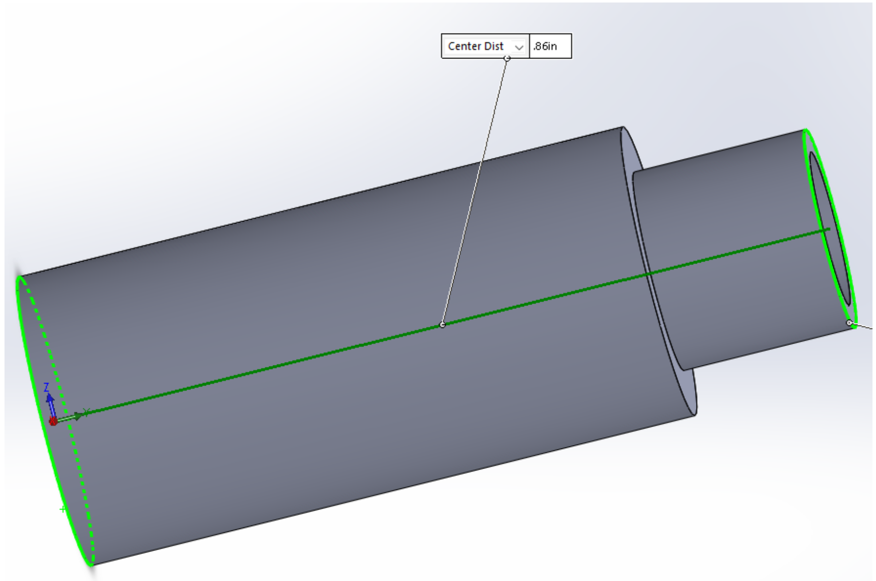

Figure 7-22: Current Front Shock Spacer

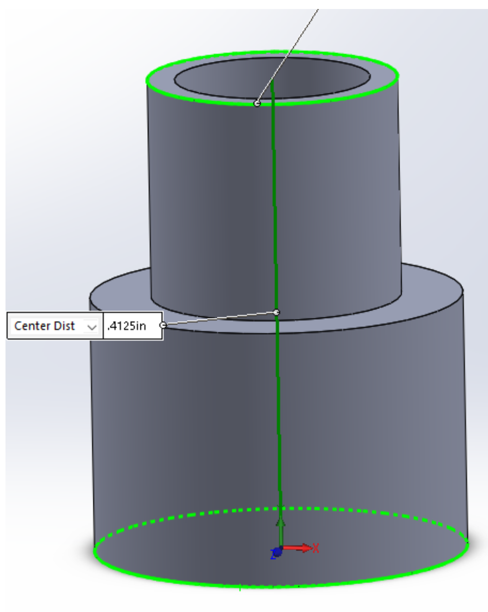

Figure 7-23: Previous Front Shock Spacer

The heights of the front and rear wheel hubs had to be increased to 3.425 respectively, due to the height of the LSD, which is shown in Figure 7-24 through 7-27. This was done to ensure that the upper control arms would be able to move both up and down to allow doop for the inside wheels when going through the corners. This also ensures that the roll centers at the front and rear will not change too drastically from the previous year's car.

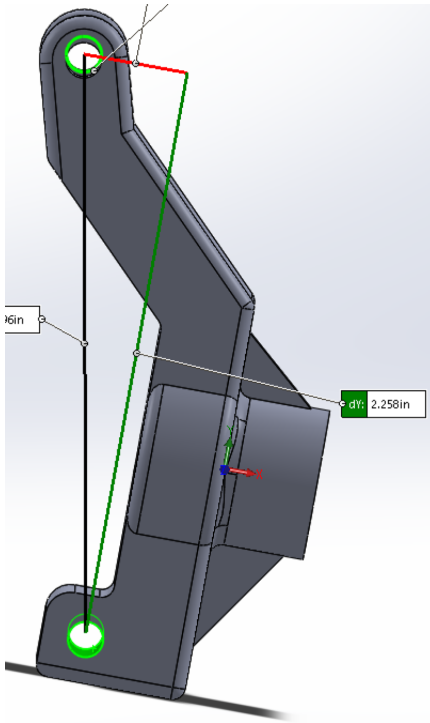

Figure 7-24: Last Year's Rear Wheel Hub

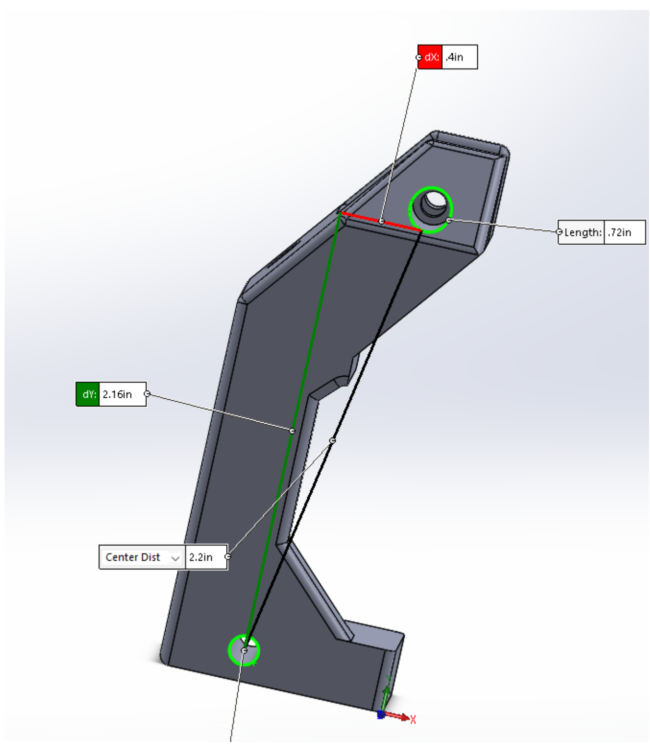

Figure 7-25: Last Year's Front Wheel Hub

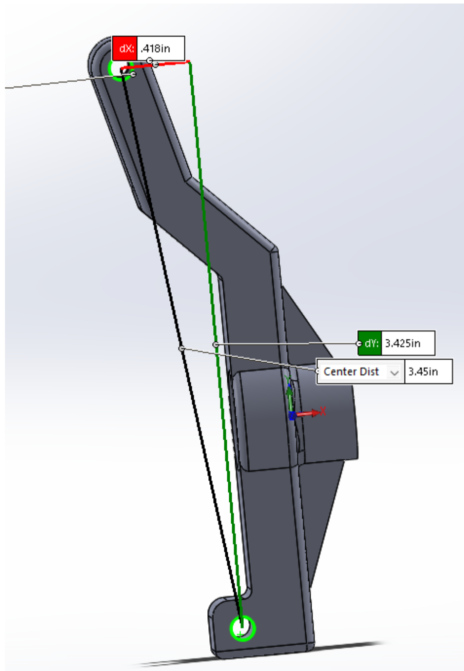

Figure 7-26: Rear Wheel Hub

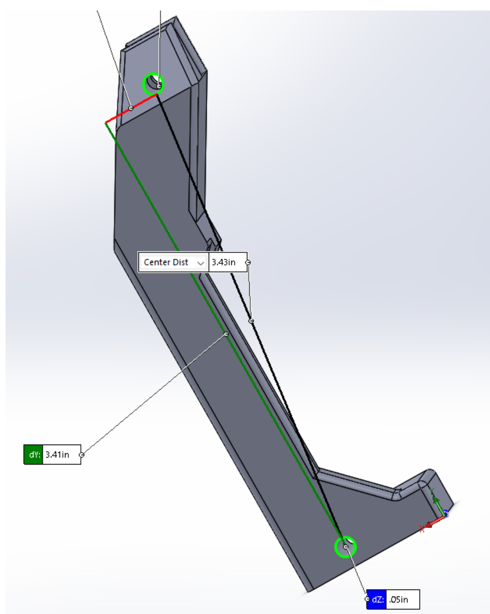

Figure 7-27: Front Wheel Hub

The shocks are the only non-3D printed components in the suspension system, aside from the necessary fasteners. The shocks are Hot Racing 100 mm aluminum coilovers with 30 wt shock oil. Last year's team used 110 mm shocks as opposed to the 100 mm ones. This change was made due to the bleed screw on the 100 mm shocks which made them easier to fill to the right level and provide optimal damping force. This choice was made prior to the finished design of the LSD, and would not have been if the issue of the height of the LSD had been known beforehand.

These changes to the suspension system allowed FETCH to be raised off the ground while maintaining a lower ride height and therefore a low center of gravity for indoor travel.

7.3 Steering

The steering system is the same mechanism used in the previous year's iteration of the car, but with some adjustments to account for the larger chassis and the larger LSD housing. The connecting link of the steering system was increased to 3.3in from 3 inches to accommodate for the increased width of the chassis, as shown in Figure 7-28.

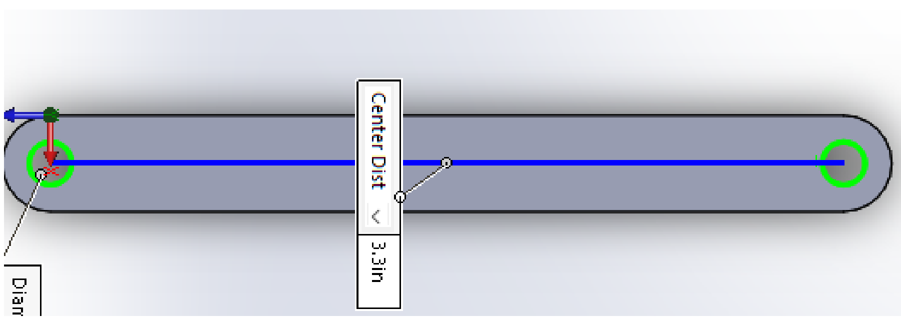

Figure 7-28: Connecting Rod

The entire steering system had to be moved back on FETCH to accommodate the larger LSD housing in order to prevent it from colliding. The steering system was placed 4.65 inches back, as shown in Figure 7-29, from the front of the chassis rather than 4.17 inches, which was approximately 23% of the length of the chassis as it was originally designed to be.

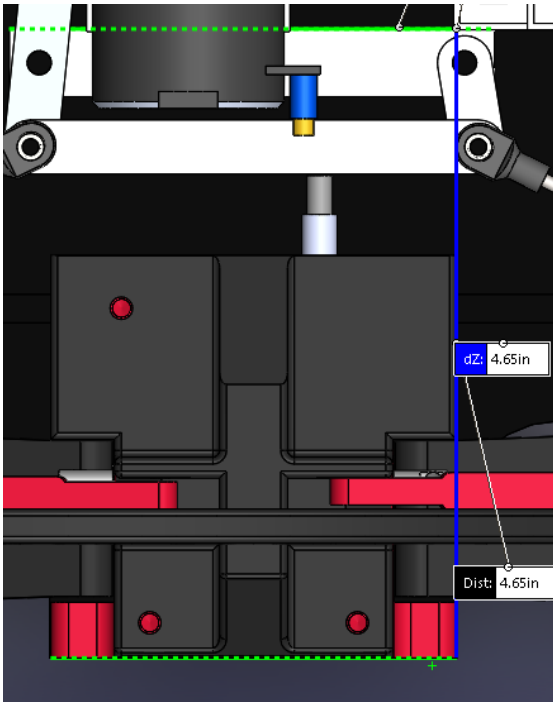

Figure 7-29: Steering System Position

This adjustment meant that the steering servo was now placed too far forward on the chassis and the servo link was no longer able to be connected to the drive link like it was designed to be. This reduced the steering performance of the linkage system. This change also increased the angle between the tie rods and the spindles. This caused the tie rods to rotate at their joints a little bit, instead of pushing the spindles and the wheels, which also hurt the performance of the steering system.

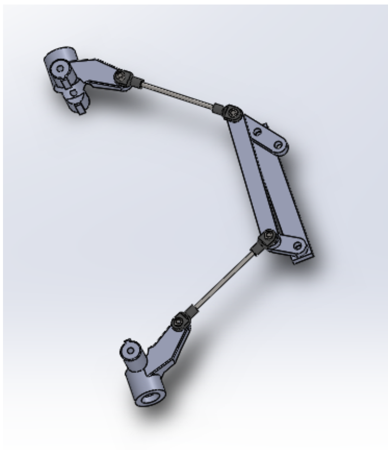

Figure 7-30: Steering Assembly

7.4 Limited Slip Differential

A limited-slip differential (LSD) allows faster cornering by shuffling torque between the driven wheels. This lets the car use its engine's output in the most efficient way possible by preventing wheelspin and maximizing traction. Our task was to see if this subassembly could be 3D printed. After the previous team decided to move away from creating a 3D printed LSDl, our team decided to revisit the design. Because of the previous testing done with the gearbox, we learned that the spurs gears had trouble consistently meshing when the prints were too small. Specifically whenever the pitch diameter was below a threshold of around .85" the gears would tend to fail much more frequently. To combat this we scaled up the size of the chassis, which is explained in further detail in section 7.1. The LSD could now be scaled up since the larger chassis could accommodate the change. Additionally, this would combat the inconsistent meshing problems 3D printed gears have when printed too small.

After considering the new size of the chassis, we decided that the largest we could scale the LSD up without making it too large for the new chassis would be by a factor of 1.3. Table 7-31 shows the new scaled-up sizes of the LSD.

Table 7-31: New Dimensions of Parts in the Scaled up LSD

	Length	Width	Height	Outer Diameter	Inner Diameter	Number of Teeth
LSD Housing	2.98"	3"	2.6"	-	-	-
Pinion Gear	-	-	-	.94"	.74"	12
Ring Gear	-	-	-	2.26"	1.7"	38
Central Gears	-	-	-	1"	.8"	17
Worm Gears	-	-	-	.18"	.09"	4

This system has a gear ratio of 19:6 which is close to 3:1, as the ring gear has 38 teeth on it and the pinion gear has 12 teeth on it. Even on its own, this gear ratio increases the torque being transferred to each wheel, allowing it to have better traction over rough or slippery surfaces.

In the previous iteration of the LSD designed by last year's project team, the shaft and the pinion gear were separated into 2 separate parts, However, we changed this design to reduce the total number of components and non-3D printed components in the design of the LSD. The new pinion design is shown in Figure 7-32.

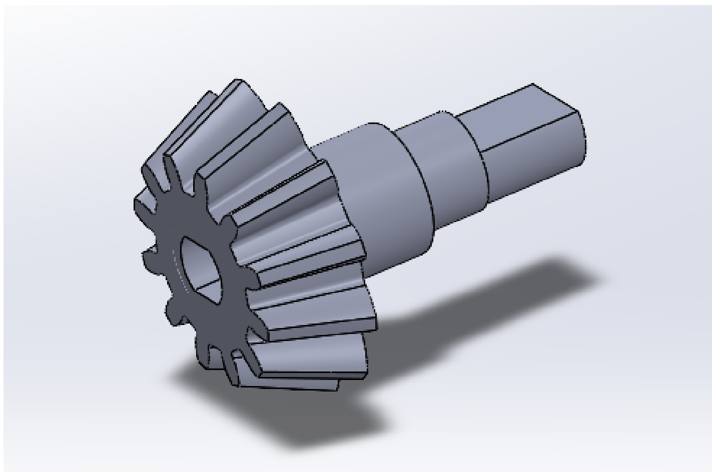

Figure 7-32: New Pinion Design

During the initial assembly and testing of the scaled-up LSD we found that the worm gears would slide along the shaft and would fail to mesh or jam because of this. To help combat this issue and keep the worm gears in place while inside the differential, blocks were added to the shafts to prevent the gears from sliding around on the shaft. To accommodate this change, the worm gears themselves were shortened .1". The updated models for the shaft and worm gear are shown below in Figure 7-33.

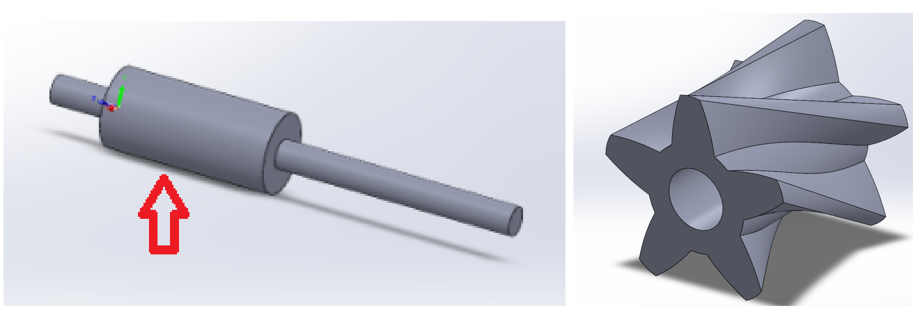

Figure 7-33: Worm Gear and Shaft

Figure 7-34 displays the inside of the LSD before and after assembly. As you can see, the central and reverse central gear rest with the LSD guard, and 2 out of 4 of the worm gears mesh with each central gear. Translation of the worm gears inside the guard is inhibited by the added blockers. Figure 7-35 displays the fully assembled inside portion of the LSD sitting within the bottom differential housing.

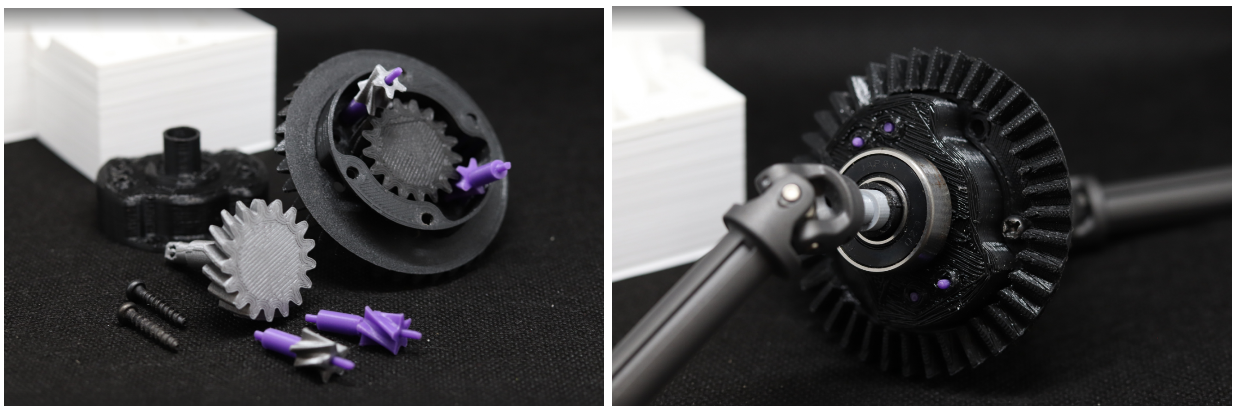

Figure 7-34: LSD printed components Unassembled and Assembled

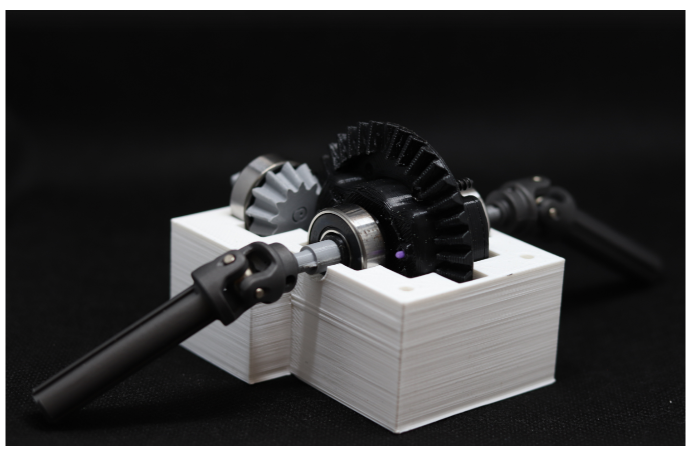

Figure 7-35: LSD Sitting Within the Bottom Housing

Overall, we were able to assemble and test the front and rear LSD which use the same design. The full assembly can be seen in Figure 7-36. During testing, the LSD operated correctly at low speeds when the worm gears would mesh. However, we found even after being scaled up by 1.3 the worm gears would still fail to mesh consistently, leading to jams and blockages in the LSD.

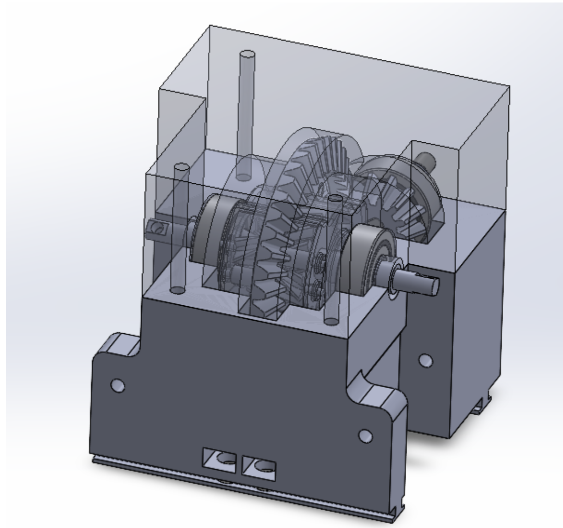

Figure 7-36: Final LSD Design

Overall the LSD has 20 components, all except the 3 bearings are 3D printed using PLA. The LSD consists of the pinion and sun gear connection, the central gear and the reverse central gear, the 4 worm gears and 4 shafts, the 2 guards that hold everything in place, the 3 bearings, and finally the top and bottom housing for the assembly. An exploded view of the LSD is displayed in Figure 7-37 and a table of all list components is shown in Table 7-38.

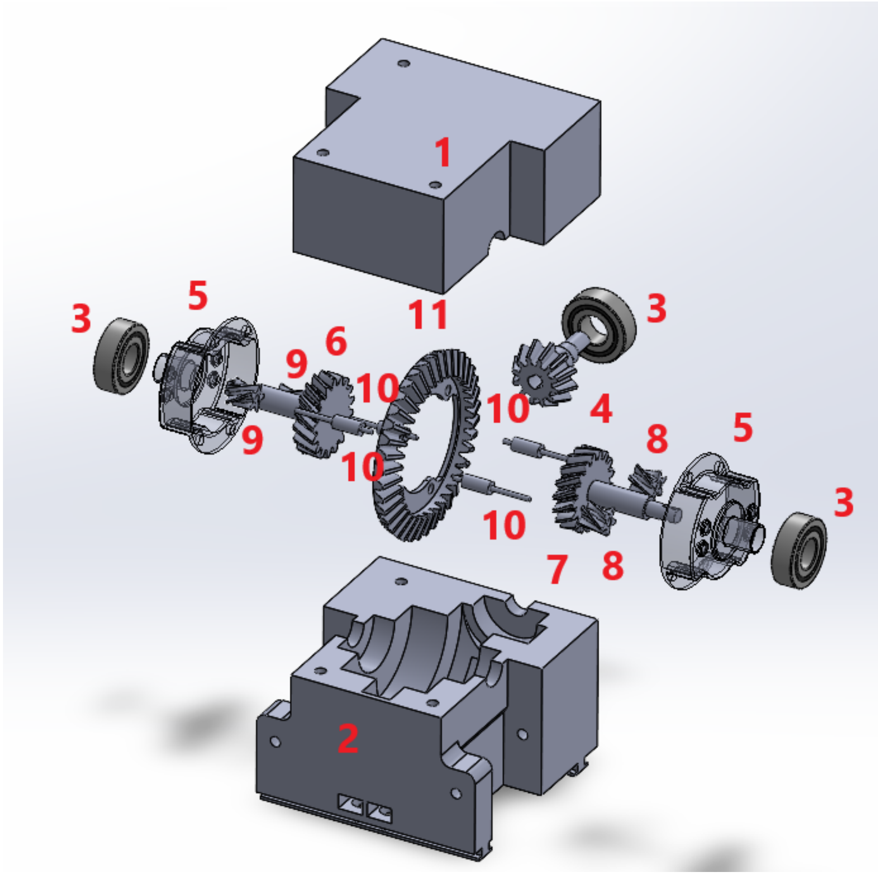

Figure 7-37: Limited Slip Differential Exploded View

Table 7-38: LSD Parts Table

Number	Part	Quantity
1	Top Differential Housing	1
2	Bottom Differential Housing	1
3	Ball Bearing Sealed, Trade Number R6-2RS, for 3/8" Shaft Diameter	3
4	LSD Pinion Gear	1
5	LSD Guard	2
6	Central Gear	1
7	Central Gear Reverse	1
8	Worm Gear Reverse	2

9	Worm Gear	2
10	Worm Bar	4
11	LSD Ring Gear	1

Figure 7-39 shows the fully assembled front and rear assemblies integrated into the FETCH. Overall, the rear LSD performed more consistently than the front LSD. We tested the LSD at different speeds when the 27:1 gearbox was still attached to FETCH. While this gearbox was attached we ran the motor at about 70% capacity and we were able to spin all 4 wheels at once with some jams caused by worm gears not meshing consistently. More on worm gear meshing problems can be found in section 8.2 of the report.

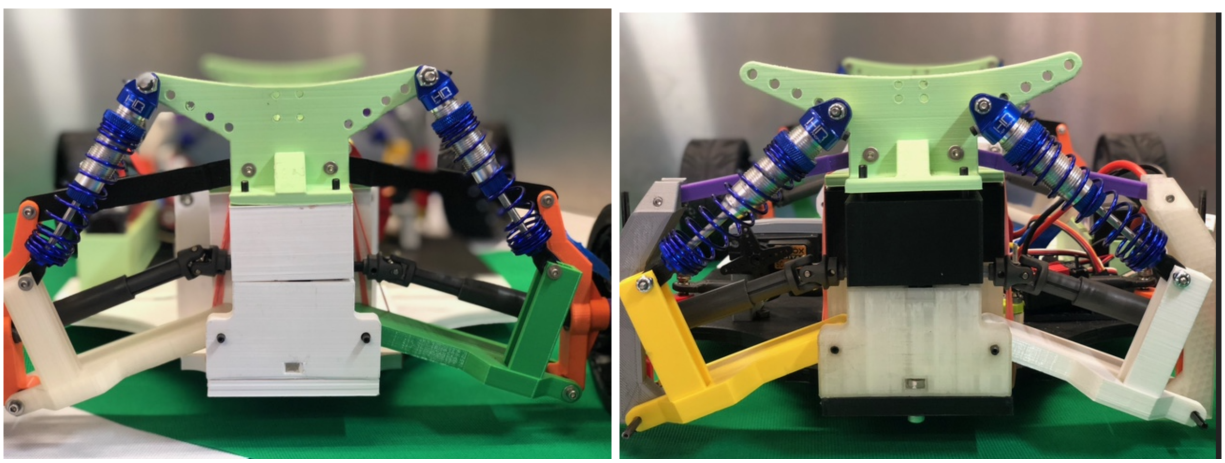

Figure 7-39: Front and Rear LSDs on FETCH

7.5 Transfer Case

The transfer case went through various changes in order to incorporate our modifications to the other subassemblies. To start, the gearbox took up much more room on the chassis. This caused a collision with the links and servo to switch the transfer case between 2-wheel and 4-wheel drive. The solution was to eliminate the ability for the vehicle to drive in 2-wheel drive. Our team felt this elimination was justified when considering the introduction of two limited-slip differentials would ensure there was a minimum of 3 wheels always touching the ground. Additionally, our vehicle could easily convert to a two-wheel-drive if a user disconnected the driveshaft from the front limited-slip differential.

Another change made to the transfer case was also a result of the larger gearbox. Without any modifications to the gear locations, the drive shaft would collide with the side of the gearbox. To solve this problem, the location of spur gears was adjusted to give the maximum distance away from the gearbox. However, this was not enough distance to prevent colliding therefore the center spur gear was increased in diameter to 0.98 inches. With the combination of these two changes, the drive shaft lies 0.05 inches away from the gearbox. Although this is not a large distance away from the gearbox, any increase in separation would result in poorer performance when transferring power to the front limited-slip differential.

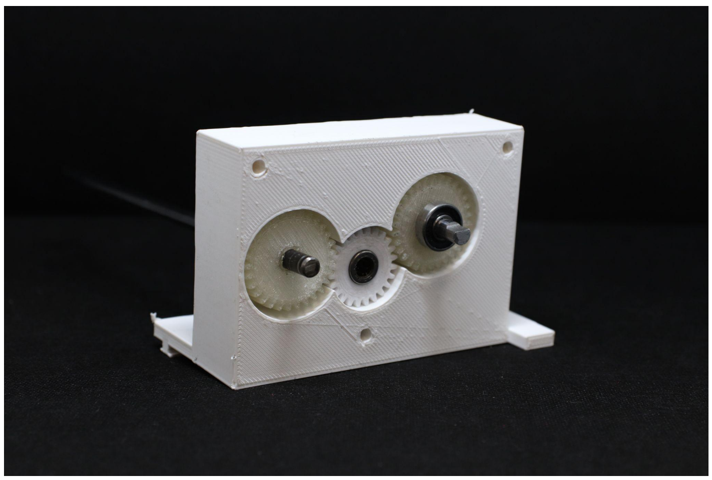

Figure 7-40: Photo of the Assembled Transfer Case

7.6 Wheels

To alleviate material and labor costs as well as facilitate modularity, our team explored the possibility of fully 3D printing wheels for the main drivetrain. Last year's team purchased four Pro-Line Trencher X SC Tires, accounting for about $92 in the bill. Furthermore, the team experimented with TPE wheels on the trailer, which failed to properly support payloads as the flexible material would compress until the wheel hubs were in contact with the ground. Our approach included a PLA printed interior wheel hub and a flexible resin exterior tire.

Our first interior wheel model incorporated a hexagon profile to attach to the axle spacer and then three embossed grooves on the perimeter to slot into the exterior tire. An image of the first design can be seen below in Figure 7-41.

Figure 7-41: Initial Wheel Model

In printing this design, we had difficulty maintaining the circular profile while also producing clean surface finishes where supports were generated. Even with support densities of 3%, the small detailing between spokes was compromised after support removal. Furthermore, print times were increased when we positioned the hollow end downwards as a result of the additional supports.

For the exterior tire portion of the wheel, tread patterns were designed to be mildly aggressive with the intention of driving the vehicle on typical urban terrains such as asphalt roads, cobblestone sidewalks, and indoor flooring (carpet, hardwood, tile). To match the extruded grooves on the interior wheel hub, three slots were cut into the inside of the tire profile. Figure 7-42 presents the final tire model.

Figure 7-42: Final Tire Model

Using an F69 flexible resin on an Elegoo SLA printer, we attempted to print a rubber-like tire. Initial prints failed as a result of inadequate exposure times. F69 is a black resin that exhibits high elongation and tear resistance, and to obtain these properties, higher light exposure times are necessary to maintain adhesion between the build plate and the resin (Resione, 2021). As exposure times were increased from 5-6.5s, we observed a near-successful print. The only issue was that the final layer had not fully cured, resulting in a thin flat spot that eventually ripped when stretched over the PLA interior hub. An image of which can be observed in Figure 7-43 below.

Figure 7-43: Failed Tire Resin Print with a Flat Spot

After increasing the exposure time to 10 seconds and angling the tire 30° from the build plate, we achieved a 4” tire. While the tire did not exhibit as much flexibility as the TPE wheels, it exhibited desirable form-fitting properties while also demonstrating improved levels of print accuracy in the tread details. The final printed wheel assembly can be observed in Figure 7-44 below.

Figure 7-44: Final 3D Printed Wheel Assembly (PLA Interior and Flexible Resin Exterior)

7.7 Chassis

The design of FETCH's chassis follows a similar curvature to the chassis preceding it. The chassis has a 17.5-inch length, 11-inch width, and 0.3-inch depth. This is a 1.5-inch and a 1.4-inch increase in the length and width respectively. The depth of the chassis was reduced by 0.05 inches since 0.3 inches was the snap-fit depth developed prior and changing this dimension would require additional testing. However, there were some key structural changes to accommodate the new sub-assemblies. Due to an increase in the size of the gearbox, the area for fastening subassemblies to the chassis bed was increased by 30 percent; an increase from 65.5 square inches to 93.5 square inches. This area is shown in Figure 7-45.

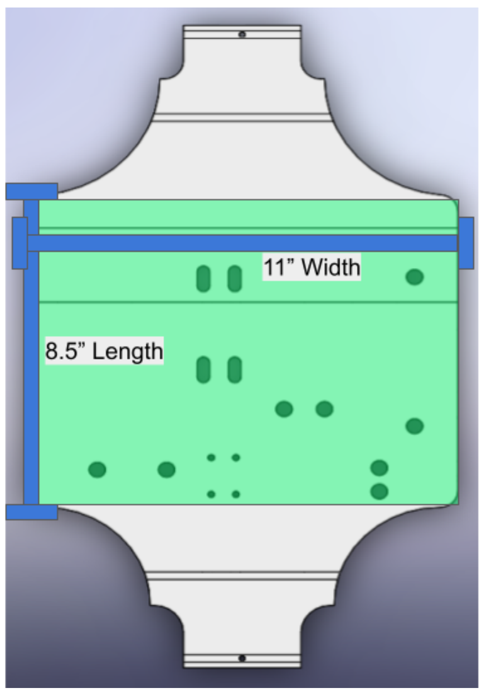

Figure 7-45: Center Area of Chassis

In addition, at the front and back of the chassis, the length of the suspension mounting area was increased by 1 in; an increase from 3.5 inches in length to 4.5 inches. This increase was to accommodate the larger limited-slip differential and ensure the slide fits had enough spacing between the slides. These two areas are highlighted in Figure 7-46.

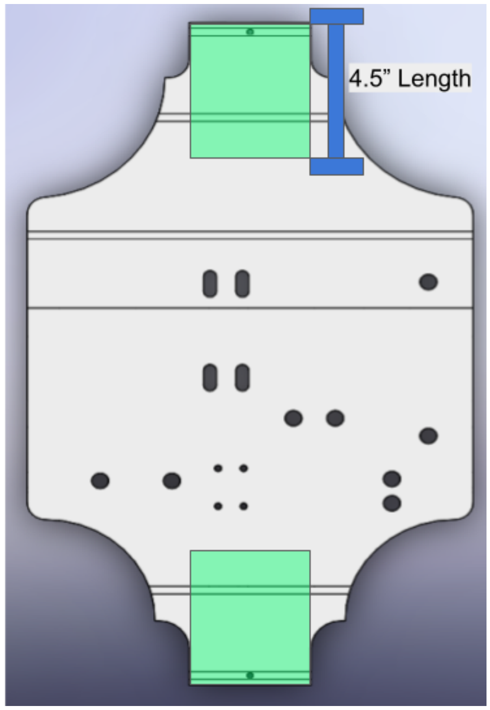

Figure 7-46: Suspension Mounting Area

Another key design decision centered around the final size of the chassis. Due to the 3D printing bed limits of 11 in by 11 in, the chassis needed to be split into two halves. This ensured the required dimensions for our subassemblies could be accommodated as well as adhering to printing bed size limitations.

Additionally, an integral part of our project was incorporating slide and snap fits into the chassis since this was the primary way to reduce fasteners. Snap fits were incorporated into the battery mount, electronic speed controller mount, driveshaft mount, and servo mount. These locations were ideal since they do not experience heavy forces. The snap-fit locations can be seen in Figure 7-47 and the snap-fit components can be seen in Figure 7-48 below.

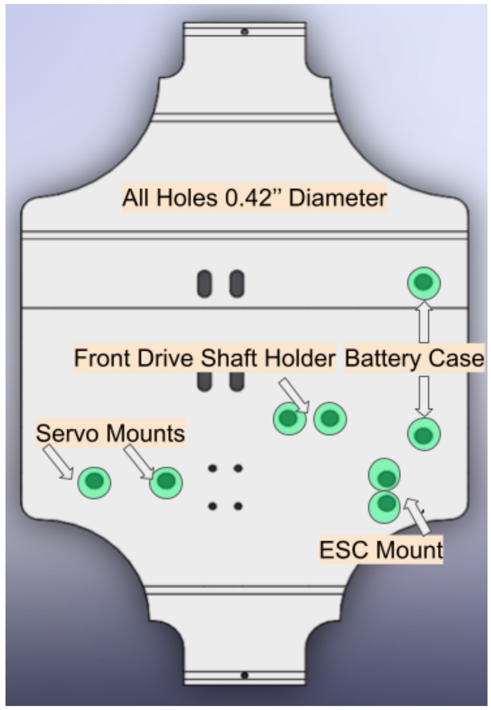

Figure 7-47: Snap Fit Locations on Chassis

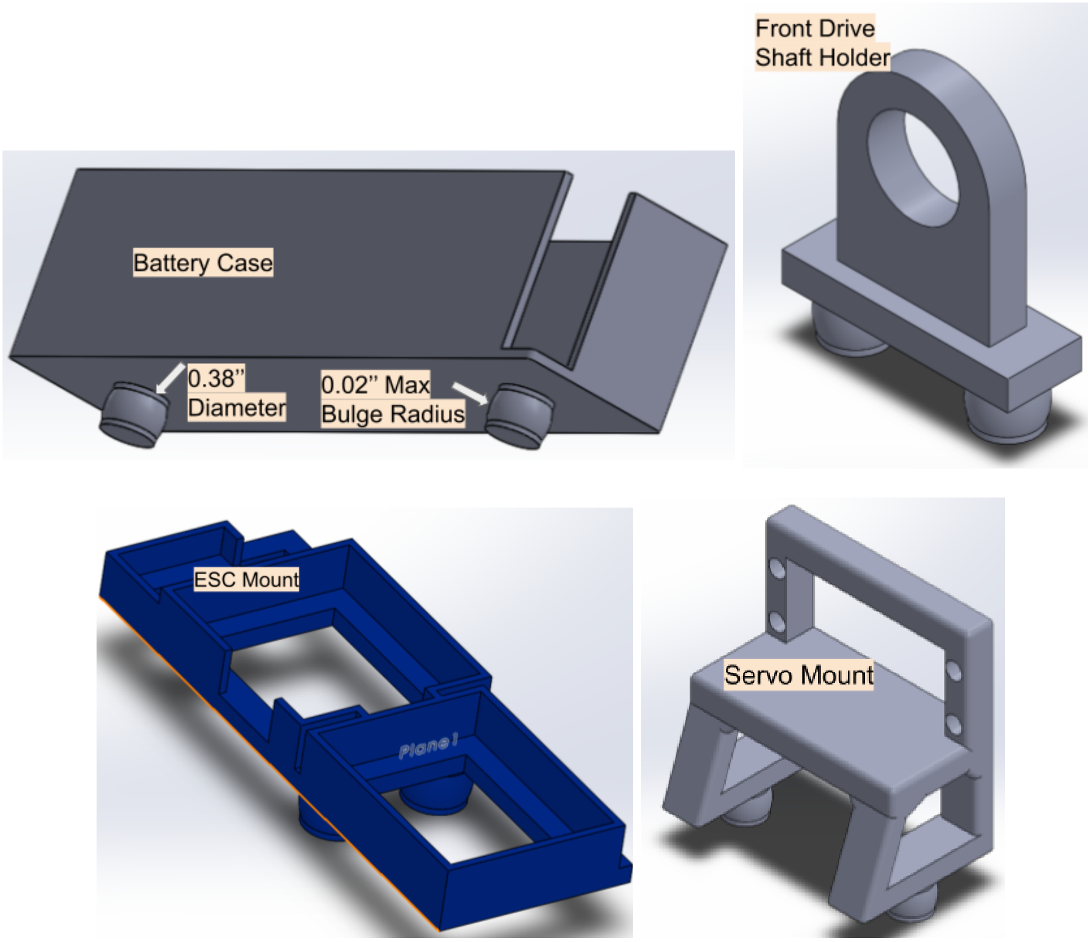

Figure 7-48: Snap Fit Components

With the addition of these snap-fits into the design of the chassis, 10 fasteners were eliminated from the assembly of FETCH. To eliminate even more fasteners from FETCH's assembly, slide fits were incorporated into the chassis as well. There were three slides in the chassis for the front LSD, transfer case, and rear LSD. The slide fit connections were essential for these three subassemblies due to the high force they experience while the car is functioning. Slide fits provide a more secure and stable fit compared to snap fits due to the larger surface area contacting the chassis. The locations of the slide fits can be seen in Figure 7-49 and the components with the slide can be seen in Figure 7-50 below.

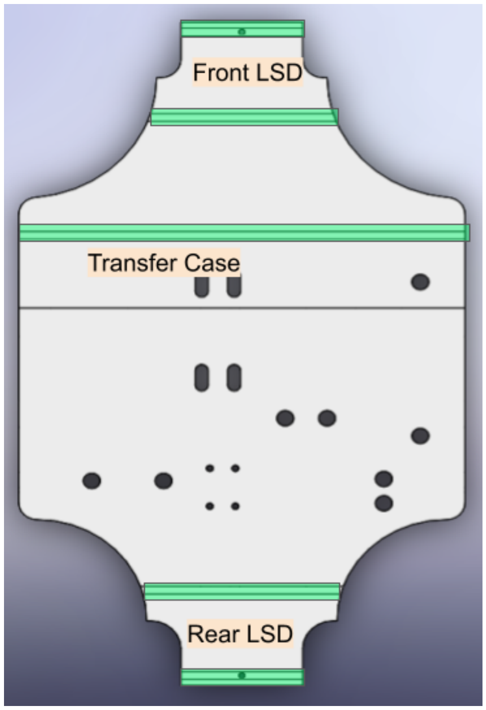

Figure 7-49: Slide Fit Locations on Chassis

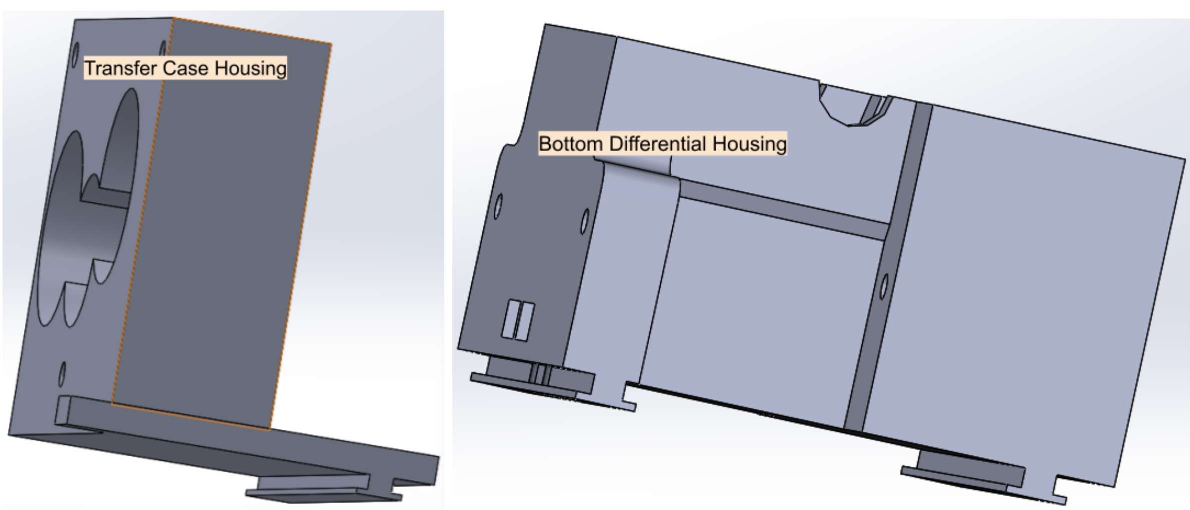

Figure 7-50: Slide Fit Components

The slide fit connections eliminated 11 fasteners from the previous version of the vehicle. In conjunction with the snap fits and other design changes, FETCH eliminated 27 fasteners over its predecessor vehicle, a reduction to 60 fasteners from 87. The first print of the chassis was not successful. This was due to mismatched sizing and shrinking due to the chassis being printed on two different printers in the WPI Prototyping Lab. This shrink error can be seen in Figure 7-51 below.

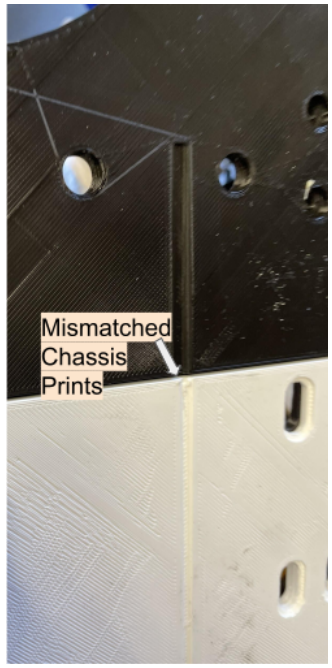

Figure 7-51: Misaligned Chassis Halves

To combat these errors, the chassis required printing on the same printer for consistency. This delayed our build time since the front and back of the chassis take 18 hours to print each. However, with these changes, we found success and printed correctly sized chassis halves. Additionally in combination with the snap and slide fit connections, the chassis was integral to allowing FETCH to reduce the number of fasteners for assembly.

7.8 Scissor Lift

With the incorporation of slide and snap fits as used on the FETCH assembly, the team succeeded in proving a concept for a fully 3D printed scissor lift. After modeling the assembly in Solidworks and simulating maximum loads attainable on MatLab, we printed the various components of the scissor lift. In total, we printed 37 components. The only outsourced components of the lift included a 55-turn motor, a quarter-inch lead screw, and a motor coupler.

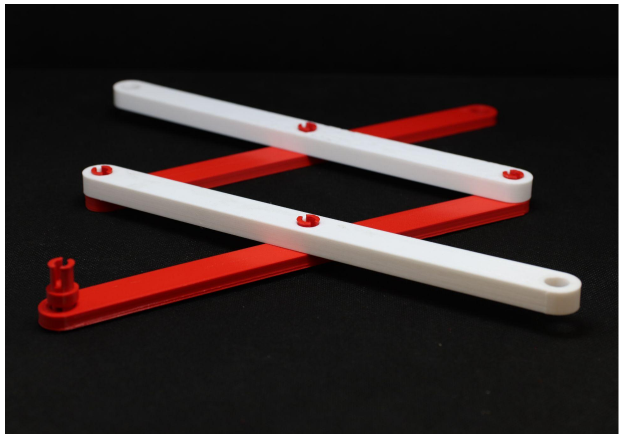

Figure 7-52: Scissor Lift Mechanism

The linkages of the scissor lift were printed using PETG exterior links and PLA interior links and snap-fit fasteners. The greater tensile strength of the load-bearing PETG links ensured that failure of the lift would occur at the fasteners. This failure mode allowed printing lead times to be preserved as fasteners could be reprinted more rapidly than whole linkages.

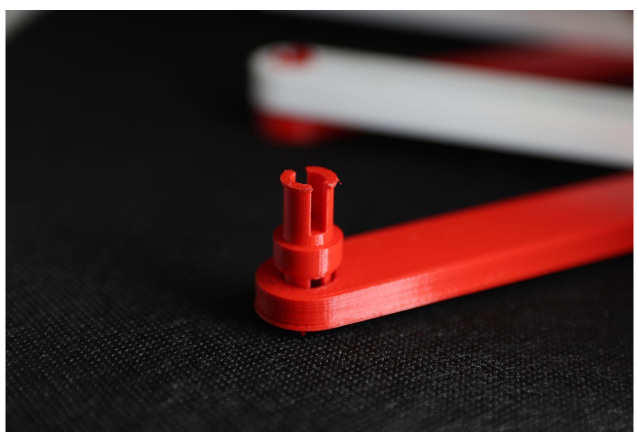

Figure 7-53: PLA printed fastener on scissor lift linkages

The top and bottom platforms of the scissor lift were printed to fasten with a hybrid of snap and slide fits. Two rails were printed with male T-slot profiles for two halves of the top plate to slide on to. As a locking mechanism, a male and female snap profile are joined between each half of the top plate.

Figure 7-54: Assembly of Printed Scissor Lift Components

8. 3D Printing Conclusions

The following chapters will summarize the lessons learned as our team explored the possibilities of 3D printing. We faced different 3D printing challenges at various stages of the project, and we want to offer our experiences and advice on how to combat these difficulties. This guidance is reflective of our team's printing experience using the WPI Prototyping Lab, the resin printers available in the Higgins student project lab, and Matt and Anthony's personal printers (Creality Ender V2).

8.1 Results of Resin Printing

While the majority of the car was printed using FDM and PLA filament, we incorporated SLA resin printing to achieve specific material properties and mitigate costs. PLA is effective in producing fairly rigid components with adequate appearances, but it does not afford the opportunity for flexible components. Our team explored TPU and TPE printing early in the design process as these are flexible filaments, but we had difficulty in producing desired results due to the challenges of extruding these sticky elastomers. Consequently, we explored resin printing and observed the results.

While FDM printing produces high-quality profiles when the part is aligned perpendicular to the extruder, we learned SLA printed parts demonstrate improved quality when the part is printed at an angle relative to the built plate. Because the resin is cured by the LCD screen in whole layer increments, an angled orientation reduces the surface area (and weight) that is localized on the build plate. In printing the tire, we found that printing it at a 30° angle ensured the entire print could be completed without portions collapsing off the built plate.

While FDM print times are largely dictated by overall part size, SLA print times are dictated almost entirely by part height. Due to the print volume constraints of the ELegoo printer we used, the tire was required to print in the vertical orientation, resulting in a print time twice as much as if it were oriented horizontally.

The last printing parameter that influenced print success was exposure time. Because we were using a flexible resin, the time each layer needed to cure under light exposure was much higher than that of a typical hard-tough resin. While the latter warrants an exposure time of about 6 seconds, we needed to increase the exposure times of the flexible resin to 10 seconds to ensure the material would maintain its shape on the built plate.

With the combination of vertical alignment, angling of the piece at 30°, and increased exposure time, each tire would print within 18 hours.

8.2 Using Prototyping Lab (Print Farm)

Using the prototyping lab presented a number of challenges when 3D printing our components we had available to us the Taz Bot and the Ultimaker 3 and 3 Extended printers. Aside from common and expected challenges such as print times, and failed prints, we also faced issues unique to this project. The first was struggling to maintain tolerances using the print farm. Due to the fact that the prototyping lab has multiple types of 3D printers, there were different levels of shrinkage depending on which printer we had to use. It took some trial and error to figure out how much shrinkage we were getting with certain printers and get our tolerances correct. Important components such as the gears are more susceptible to stripping, for gears we maintained a high quality 70% infill density with a raft layer base. Other 3D printed components including the chassis were printed at a high quality 50% infill density.

Another challenge was printing the spur gears for the gearbox. Through our iterations, we discovered that there was a certain threshold for the pitch diameter of the spur gears and if we dipped below this threshold (0.85in) the gears would begin to slip. The other big challenge we faced was printing high-precision parts in small sizes. This specifically applies to the worm gears in the LSD. These gears were relatively small, at 0.33in long, so trying to maintain precision in order to get a good mesh was very difficult, and led to a struggle with the LSD. Overall, between FETCH and the scissor lift, we have 117 total 3D printed components which totaled over 2000 hours of printing.

A large issue experienced during our project centered around improving the print quality of 3D printed gears. Due to warping during printing, gears that normally would mesh tended to lock up or grind the gear teeth until breaking. This is a result of the PLA material properties and an unfortunate consequence of 3D printing. Additionally, we found these errors to be more prevalent the smaller the size of the gear. Specifically, when the gear pitch diameter reached below 0.85 inches, the gears would not mesh, and locking ensued. For overall size limitations, the smallest gears printed successfully were the worm gears in the limited-slip differential. These worm gears had an inner diameter of 0.09 inches and an outer diameter of 0.18 inches. Any smaller print quality would be limited to the extent that gears would not mesh.

9. Project Exhibition

This section details the two opportunities our team had to present our project. The first of which is Touch Tomorrow, an event where students in kindergarten through 12th grade interact with hands-on experiments, demonstrations, and lab tours that promote STEM principles. The second and final exhibition opportunity was WPI's Mechanical and Materials Engineering Department Project Presentation Day, or MME PPD, where all senior groups in the department presented their capstone projects to friends, family, and a panel of judges.

9.1 Touch Tomorrow

TouchTomorrow is an event WPI has hosted every year since its beginning in 2012. Our MQP team was fortunate this year to showcase our MQP at the event. Each subassembly was arranged on our table for students to explore and ask questions. The overall goal of our presentation was to teach students about 3D printing, and general aspects of a car, and to excite the students about engineering. Alongside that, this worked as a practice round for us to present our project to curious kids and parents while also helping us learn how to interact with people for our upcoming MQP final presentation day. Showcasing our project while exposing kids to the world of 3D printing technology was a nice and fulfilling way to also show children the amazing world of STEM and its possibilities.

After describing our project to kindergarten through 12th-grade students, we learned how to better explain our project to a younger audience. Additionally, the questions they asked helped our team understand areas that need more explanation such as creating a fully 3D printed gearbox and a limited-slip differential. There were lots of curious parents and children who wanted to know more about 3D printing, the challenges we faced, and the progress of the project overall. The questions posed helped frame our narrative for how we would present to the judges during our final project presentation.

Figure 9-1: Joe Calcasola ‘22 talking about 3D Printing to Younger Audiences

Figure 9-2: Picture of Touch Tomorrow Table Set-Up

Overall, we were very excited and thankful for having the opportunity to present our project, as it helped as a practice run, but most importantly introduced young minds to the world of STEM and 3D printing as well. Seeing the spark in the eyes and their curiosity to know more was a memory we cherished as a team and feeling knowing we are currently inspiring the next generation of engineers.

9.2 Mechanical and Materials Engineering Project Presentation Day (MME PPD)

At Project Presentation Day, each team is tasked with creating a poster that provides audiences with a summary of their project goals, methods, results, and recommendations. Our group was happy to showcase a completed FETCH assembly as well as visuals that demonstrated the step-by-step assembly of the vehicle and presented exploded views of the printed subassembly models. A picture of our station can be observed in Figure 9-3 below.

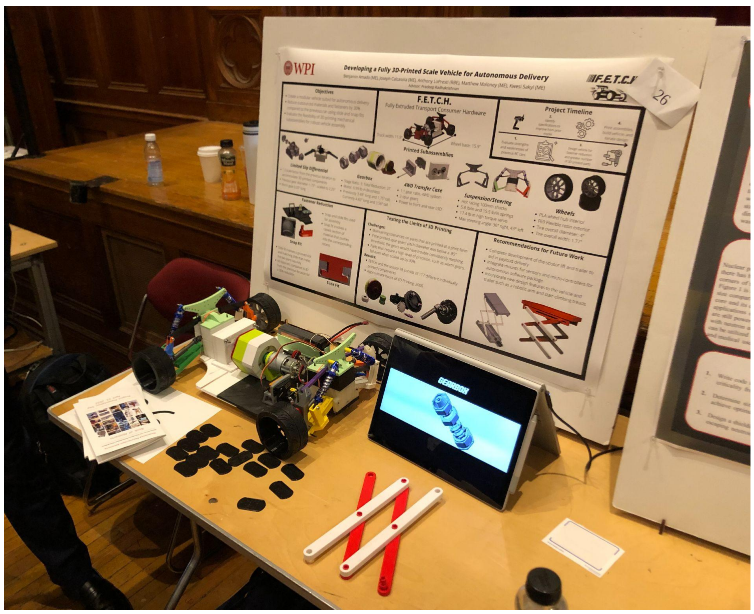

Figure 9-3: Our team's Station at MME PPD

From discussions with observers at PPD, our team was able to elaborate on design considerations, successes and failures, 3D printing challenges, and potential opportunities for our technology to extend in future years. We valued suggestions and critiques made by judges, as their feedback was reflective of their experiences in different industries and work environments. Some notable feedback we received included an improved slide fit design that is self-locking due to its geometry and exploration of Glowforge printing, a laser cutting printer that can produce shapes to the accuracy of a human hair (GlowForge, 2022).

10. Discussion

This chapter readdresses initial goals as detailed in Chapter 2 and evaluates the degree to which they were accomplished. From the results obtained, we reflect on these goals to provide guidance on the feasibility and scope of future project objectives.

10.1 Suspension System Requirements and Goals

The suspension was not able to be fully tested due to the late start we got to designing the car. The car was not finished with enough time to drive the car and test the capabilities of the suspension system. We were never able to see if the car would be able to hold a load without bottoming out, however, we did make design considerations to allow for this. This also means we were not able to test the suspension system's durability over a long delivery or test whether the suspension kept the car from bottoming out over rough surfaces. However, our focus for the car shifted to more indoor environments, so the ride height would likely be too low for the car to not bottom out on uneven off-road surfaces. That being said, we were able to meet other goals and requirements for the suspension such as, allowing for the axles to pass through the wheel hubs, and being fully printed in PLA.

10.2 Steering System Requirements and Goals

Similar to the suspension system, we were not able to fully test the steering system to see how many degrees of rotation we could get for each direction. However, due to the mounting location of the snap-fit mount for the steering servo, as well as the size of the LSD housing, we were not able to mount the steering in a position that would allow for maximum performance. This suggests that the steering would likely have underperformed, and suggestions to improve this system are made in section 13.5. We never ended up using a slide or snap fits for the steering system due to concerns about having too much play in the snap-fit or slide fit housings, which would hurt the performance of the steering system. However, we were able to 3D print the linkages out of PLA and were able to ensure that the steering system did not interfere with the drivetrain or the suspension systems, while also taking up minimal space on the chassis.

10.3 3D Printed Gears

Our primary objective, when it came to 3D printing gears, was ensuring we got the right tolerance and ensuring we could prevent stripping of the gear when it's running as previous years' team faced that problem. To prevent that possibility we conducted research when it came to designing and printing gears ensuring we had the right tolerance, especially when printing with PLA (Gonzalez et al. 2017). When it came to the gearbox gears since these gears were spur gears we conducted different print iterations. We noticed our best spur gear prints worked when we had a raft base as it prevents what is called 'footing' with the gears. We also printed at a 90% infill density at a slow and quality print setting. We noticed by slowing down our print speed and focusing more on quality, we produced better and more accurate gears that could perform at the speeds necessary for the gearbox without stripping. It is important to note in slowing the print speed we sacrificed time, so our prints took longer but our main focus was on quality. If next year's team decides to use the WPI Prototyping Lab for any of their 3D prints, especially if it involves gears, we recommend using the Ultimaker prints, at the quality print setting and a raft base.

Following our gearbox spur gear prints, our biggest challenge was printing the worm gears for the LSD. Even though we scaled up the LSD, we still faced challenges with the worm gears. We ended up redesigning the worm gears and the rod holding the worm gears hoping it would generate better results. Even with these iterations we still faced problems having our LSD run as expected. Our main diagnostics come back to the worm gears, especially how small they are. We eventually concluded that 3D printing small worm gears for the LSD were unsuccessful in the general mechanism for an LSD to function properly. More recommendations regarding the LSD and the worm gear mechanism can be found in section 11.1.4.

Overall we had successful iterations and 3D prints of the gears for the gearbox and to a point the worm gears for the LSD as we saw less stripping. If we had more time we would have conducted more research on designing and printing worm gears but when it came to our spur gears for the gearbox and transfer case, we produced very successful prints.

10.4 Trailer

As problems arose in validating 3D printed subassemblies within the main drivetrain (gearbox, LSD, and steering), we transitioned efforts more towards the completion of the main

FETCH vehicle. Initial goals for the trailer included the incorporation of modular housings and a 3D printed drivetrain, suspension system, and wheels as used on FETCH. As the team progressed through the project timeline, we reiterated various models of the gearbox and LSD before being successful. From the results we obtained on the gearbox, we decided to forego the inclusion of a gearbox on the trailer for reasons discussed in the next section. While our team did not complete a full assembly of a modular trailer, the validation of snap/slide fits, 3D printed wheels, and suspension system on FETCH can facilitate the fulfillment of our team's trailer goals in future projects.

10.5 Snap and Slide Fit

With fastener reduction as one of our primary objectives, we wanted to implement the use of snap and slide fit technology as discussed in Chapter 5. In comparison to our car the previous year's team PARV was assembled with 87 fasteners when in full form. Through the successful implementation of snap and slide fit, the team reduced the total number of fasteners to 60 which is a 30% reduction. Places, where this technology was used on FETCH, were the LSD casing, Gearbox, Servo Mount, Battery Case, ESC Case, Transfer Case, Wheel Spacer, Base plate of the scissor lift, and links for the scissor lift. A further breakdown is provided below:

- LSD Casing: Slide Fit into the chassis
- Gearbox: Snap-fit into the chassis and slide fit for connection
- Servo Mount: Snap Fit
- Battery Case: Snap Fit
- ESC Case: Snap Fit
- Transfer Case: Slide Fit into the chassis
- Wheel spacer: Push-Fit
- Scissor Lift Base Plate: Push-Fit
- Scissor Life Links: Snap Fit

10.6 Broader Impacts

As engineers, it is important to consider the relationship between our project and the impact it will have on our environment, society and the people around us. As our society becomes more aware of our relationship with sustainability efforts, as engineers we analyzed the breakdown of this project to get a clear understanding of the different aspects of society it will impact while also understanding the ethical implication of our project and the people it will affect.

10.6.1 Engineering Ethics

Throughout the project, the team took every course of action with consideration of the ASME Code of Ethics. This includes using our knowledge and skill for the enhancement of human welfare, being honest and impartial to the quality and competency of the product design, and striving to increase the competence and prestige of the engineering profession. Even more so, each team member was encouraged by each other to uphold these values. A link to the code of ethics is provided in Appendix I.

10.6.2 Societal and Global Impact

With autonomous technology becoming more prevalent in our current society, as engineers we play an important role in analyzing our current infrastructure from a regional to a global perspective on if this technology is ready to be incorporated into our everyday lives.

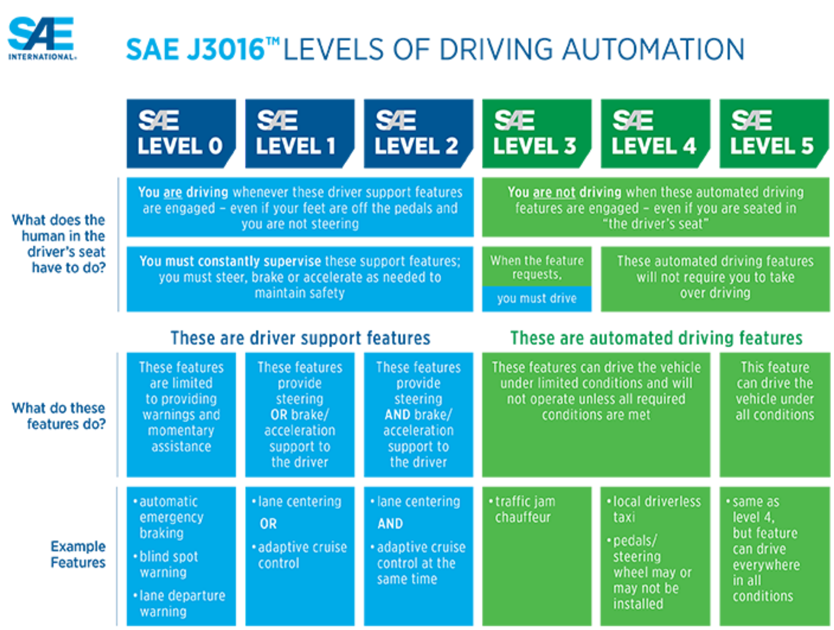

Figure 10-1: Levels of Driving Automation

With self-driving cars becoming a debate in the engineering world, as engineers we need to look at our current infrastructure and system to measure if we are ready for the transition to fully autonomous capabilities. Figure 10-1 provides a detailed breakdown of the driving levels of automation available. As a society, we are currently at a level 2 stage of automation. While it can be argued some features of Tesla's self-driving car breach into level 3, it still requires a level of attention of the driver and the driver still holding the steering wheel whilst paying attention to current road conditions.

Our project according to current societal standards is still in its research and trial phase as our society has not developed the needed infrastructure and system needed in handling various complex autonomous technologies. It is still important for us to test these principles as we learn from them, but for us to fully transition into an autonomous world, there needs to be a global discussion and societal breakdown on what this autonomous technology looks like and the relationship it will have with humans in our everyday lives.

10.6.3 Environmental Impact

As our project has demonstrated extensive use of 3D printing, it is important to regard this manufacturing process for its effect on the environment. As 3D printing is an additive manufacturing process, it reduces waste in comparison to subtractive manufacturing processes where the removed material is harder to repurpose. By being a layer-by-layer digital process, it is easier to optimize raw materials and preserve resources. 3D printing also boasts a lower carbon footprint as it is not dependent on complex supply chains. Printed components are manufactured at the point of assembly and fewer transporting resources are required. 3D printing also promotes a circular economy as it is becoming easier to produce filaments from recycled materials and consumers can use home printers to replace parts that may traditionally need to be purchased off the shelf (Mesa Sanchez, 2019).

As autonomous delivery technology progresses, we can see drastic reductions in carbon emissions as these devices require significantly less power. According to the EPA, 29% of U.S. carbon emissions were accounted for by transportation in 2019. As more autonomous delivery vehicles are adopted by consumers, this percentage could be reduced substantially (Miller, 2022).

10.6.4 Codes and Standards

Table 10-2: ASME Fundamental Canons

ASME Fundamental Canons
1. Engineers shall hold paramount the safety, health, and welfare of the public in the performance of their professional duties.
2. Engineers shall perform services only in the areas of their competence; they shall build their professional reputation on the merit of their services and shall not compete unfairly with others.
3. Engineers shall continue their professional development throughout their careers and shall provide opportunities for the professional and ethical development of those engineers under their supervision.
4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees and shall avoid conflicts of interest or the appearance of conflicts of interest.
5. Engineers shall respect the proprietary information and intellectual property rights of others, including charitable organizations and professional societies in the engineering field.
6. Engineers shall associate only with reputable persons or organizations
7. Engineers shall issue public statements only in an objective and truthful manner and shall avoid any conduct which brings discredit to the profession.
8. Engineers shall consider environmental impact and sustainable development in the performance of their professional duties.
9. Engineers shall not seek ethical sanction against another engineer unless there is good reason to do so under the relevant codes, policies, and procedures governing that engineer's ethical conduct.
10. Engineers who are members of the Society shall endeavor to abide by the Constitution, By-Laws, and Policies of the Society, and they shall disclose knowledge of any matter involving another member's alleged violation of this Code of Ethics or the Society's Conflicts of Interest Policy in a prompt, complete and truthful manner to the chair of the Ethics Committee.

The ASME Fundamental Canons governed the work related to our project. As seen in Table 10-2 above, these canons ensure that engineers put safety and honesty first when doing their work. It means that an engineer will work with standard and approved material and that they will follow the set engineering procedures during their career. It was important for us as aspiring engineers to keep these fundamental canons in mind when conducting ourselves over the course of this project.

10.6.5 Economic Factors

The cost of an autonomous driving vehicle can be very large due to the complex requirements of such a machine. Our project can reduce these costs by transitioning expensive and machined parts to 3D printed parts. This has the benefit of producing a scale vehicle at a much lower cost to manufacture. Additionally, the benefit of 3D printing also extends to repairs. When a 3D printed component fails, the user can simply print the same part again resulting in a reduction in waste. Additionally, our project utilizes snap and slide fits to reduce fasteners in assembly. Reducing fasteners reduces outsourcing material cost as well as assembly time thus reducing assembly cost when producing at a large scale.

11. Conclusion

In conclusion, this project provided the opportunity to research, design, print, and test a fully 3D-printed vehicle. Part of our project was the new incorporation of subassemblies to offer a new form of modularity for consumers when printing their vehicles. We were able to take advantage of our campus resources such as the Prototyping Lab and Resin Printer to explore our manufacturing process.

This concluding chapter is designed to better reach different aspects of our project and the results made. As part of this chapter, we included recommendations for next year's team on different subassemblies they can better analyze to ensure a smooth transition of the project. Through our time working on this project, we were able to successfully:

1. Scaled up the size of our car to a 1/8th scale
2. Reduce the number of fasteners and outsourced parts by 30%
3. Successfully incorporate the use of 3D printed snap and slide fit technology
4. Successfully 3D print and test a limited-slip differential
5. Successfully 3D print and test a gearbox
6. Successfully 3D print scaled up gears and casings
7. Successfully create better quality 3D printed gears using PLA for the gearbox
8. Explore 3D printed scissor lift system
9. Publish downloadable models to a platform GrabCAD

This project provided lots of successful phases for us to design, print, and test our ideas. Additionally, this project provided the opportunity for redesign and the creation of better iterations when needed. Though we saw some success, there were phases in our project that we wished we spent more time on research. Through that, we created a recommendation chapter on the various subassemblies that we hope can be analyzed. As a team, this project challenged us to be better engineers, think outside the box and find ways to solve our challenges through research, design, testing, and simplification.

11.1 Recommendations for Future Work

This section covers improvements and advice we are providing next year's team on how to better handle the various subassemblies of the project. Additionally, we included the challenges we faced and ways to make their design and testing process easier. We also provided recommendations on ways to better improve different design components when working on next year's car and its components.

11.1.1 Trailer

While the previous iteration, PARV, introduced a trailer, our team focused on the validation of FETCH as an operational vehicle. The previous team's trailer incorporated an additional outsourced VEX planetary gearbox, battery, and 56 fasteners. As the main goal of our project was to reduce outsourced materials and fasteners in FETCH, we recommend similar design considerations be followed with trailer reiterations.

With the results we obtained from the 3D printed subassemblies, we recommend a trailer be designed to accommodate a variety of payloads. Considering this, we suggest not including a gearbox on the trailer. With FETCH's incorporation of a large 3D printed gearbox and improved torque through the 3-stage system, there is less need for a powered drivetrain on the trailer. This revision will eliminate the need for an outsourced motor, associated fasteners, and battery for the trailer. Furthermore, this benefits the project through cost and weight reduction while all providing more real estate and driving height clearance.

In order for FETCH to operate in tandem with a trailer, the trailer must succeed in matching the driving capabilities of the main drivetrain. The previous team's trailer chassis sat flat on TPE printed wheels and lacked a suspension system to handle the same terrains as the main vehicle. If FETCH is to introduce larger, heavier payloads onto the trailer modules, a suspension system is warranted. In future iterations, we advise the inclusion of a suspension system to support payloads as well as a platform with snap or slide fit profiles to afford interchangeable housings. While a scissor lift was explored by our team, we also saw the opportunity for climate-controlled containers or a rake attachment for combing trash on beaches.

11.1.2 Scissor Lift

As the focus shifted more towards FETCH performance testing at the close of the project timeline, the scissor lift was left in a proof-of-concept state. While we validated the printability of the linkages, slide rails, and top/bottom plates, more testing is required to validate the elevation of varying payloads. We recommend a closer analysis of strain on the linkages when loads are placed on the platform at full extension and the maneuverability of FETCH when loading and unloading cargo.

While our team first designed this lift to enable coffee delivery with a cupholder housing, there is an opportunity to explore other housings that accommodate other payloads. This could include climate-controlled containers for food, beverages, or medicine. Furthermore, with this model achieving an elevation of 17.53 inches, studies can be done to assess the feasibility of adding more linkage stages to increase the maximum height.

11.1.3 Autonomous Driving Package Integration

This project is affiliated with another project here at WPI, called the Modular Package for Autonomous Driving (mPAD). With this in mind, we designed FETCH with enough extra space on the chassis so that the hardware needed to implement this autonomous driving package could be easily added. Moving forward, we recommend that future teams continue integrating MPAD into FETCH by adding proper mounts tailored directly to the hardware needed. These mounts can be added using snap-fit implementation the same way the battery case and ESC case were mounted to the chassis.

11.1.4 LSD Improvement

In its current design, the LSD has trouble performing consistently. Specifically, the worm gears fail to mesh properly which leads to jams and/or teeth shearing. The team recommends moving away from using worm gears in the LSD design and trying to redesign the inner part of the LSD using spur or herringbone gears. During our testing with the transfer case and the gearbox, the spur gears work a lot more consistently. Some other alternative options could try to use a harder resin material, find some more precise form of 3D printing to use, or completely overhaul the design of the LSD which is not recommended since when the worm gears mesh the LSD does behave as intended.

11.1.5 Suspension/steering improvements

There are a number of improvements to be made to the steering and suspension systems that our group was not able to accomplish. The upper suspension mount at the rear end of the car is an older model than the one at the front end. The timeline did not allow for the newest iteration of the rear suspension mount. This forced us to mount the front shocks on the lowest hole of the upper suspension mount in order to keep the ride heights consistent, reducing their effectiveness. Longer shocks, or reducing the distance between the upper and lower shock mounting points by adjusting the lower wishbone, or the upper suspension mount, will be necessary to raise the ride height. Although replacing the rear upper suspension mount with the same design as the one at the front and then mounting the shocks at the widest mounting point will also increase ride height. This increase will be necessary to allow the car to travel outside and off-road. The mounting point for the lower wishbone on the LSD should be moved lower on the LSD housing, so the wishbone is closer to horizontal. This will give the car lower roll centers and prevent the jacking force from lifting the tires off the ground, reducing grip.

For the steering, make sure to slide the mounting point for the steering servo back far enough so the servo link can be connected to the drive link and then properly fastened, so the link does not move vertically during servo motion. The tail of the spindles may also need to be lengthened to make sure that the tie rods are pushing the spindle, rather than rotating at the joint.

11.1.6 Other Applications

While the scope of this project was limited to consumers with access to personal printers or print farms, we see the concepts validated by this project extend towards assistive services. With the rapid prototyping capabilities of this vehicle and its modular design, we hope to see FETCH prove efficacious in the delivery and retrieval of payloads that can aid elderly or disabled individuals. Paired with an autonomous driving package like mPAD, we can see this vehicle provides much value to these demographics with limited user intervention.

12. Personal Reflections

This section covers our personal reflections on the project, the challenges we faced, how we solved those challenges, and the impact this project had on our engineering journey as college students entering the workforce.

12.1 Ben Amado

This project definitely helped me improve my skills as an engineer, particularly in using Solidworks. The main reason I chose this project was that I already had a strong interest in cars prior to this, due to the fact that I drive race cars and have been following NASCAR for years. I also knew that I needed to improve my abilities in Solidworks, and I knew the nature of this project would allow me to do that. My background in racing really helped me with designing the suspension system, by allowing me to have a solid base of knowledge for the principles of what a good suspension system is able to accomplish, and how to go about making sure the suspension can accomplish these tasks. ME 3310, Kinematic of Mechanisms, helped me to understand the way linkages move together in a system, allowing me to have an understanding of how the steering system needed to work as well. Overall I feel as though this project will allow me to bring valuable skills to any workplace in the future.

12.2 Joe Calcasola

This project was very rewarding to build upon the skills I have learned over the 4 years at WPI. I chose this project because the end goal of an autonomous driving vehicle intrigued me and I knew this project would involve lots of design which is the aspect of mechanical engineering that interests me the most. There were many classes that prepared me for this project. To start, Kinematics of Mechanisms (ME 3310) prepared me to understand linkages and structures in detail allowing me to design FETCH with these concepts in mind. Additionally, this project developed these skills further since I designed various moving components of the vehicle. Another class that greatly prepared me for this project was Advanced Engineering Design (ME 4320). In this class, I learned how to more effectively analyze problems and divide up large tasks efficiently. For a project of this magnitude, these skills were crucial in allowing me to envision the final product as well as maintain the project timeline.

The skills learned from this project can be applied for similar projects in the future after graduation. I also found this project useful in developing team-building skills since this project would not have been possible without the contributions of my other partners. Overall, I am very pleased with what we have accomplished throughout this year and look forward to using the knowledge and experience gained from this MQP.

12.3 Anthony LoPresti

This project was a great learning experience for me. I was a member of both sides of this project, the hardware and the software and there was a lot to learn from both sides. On the hardware side of things, I learned to collaborate properly on a large-scale CAD assembly. Also, I learned to work on a large-scale additive manufacturing project. I learned a ton about 3D printing and 3D modeling which will surely help me tremendously further on in my career. The software side of the project was a lot of problem-solving. Early on it was a lot of bug fixing both code and hardware issues. I also had the opportunity to learn more about LiDAR and other obstacle detection technology. Another large aspect of the software side of the project was learning to communicate engineering work in a simple manner that is easy to understand and follow. Overall I feel like I have developed a lot more as an engineer and I hope to put my skills to the test in the future.

12.4 Matthew Maloney

Throughout this MQP, I exercised engineering and behavioral skills that I have learned in my time at WPI while also developing new skill sets that I will equip for future projects and career opportunities. I am fortunate to have competency with CAD as a result of my enrollment in ES1310: Introduction to Computer-Aided Design in which I earned my Associate Level Mechanical Design Certificate in Solidworks. With the creative freedom we had in the designs of subassemblies throughout this project, I built upon modeling skills. I learned to use more tools that would ensure consistency across the entire assembly and ultimately improve the workflow at which models were completed.

As a large portion of this project concerned 3D printing, my experience in classes such as ES2502: Stress Analysis and ME5312: Properties and Performance of Engineering Materials helped me make educated decisions on which filaments to use for certain applications. The material properties discussed in these classes made the selection process easier when the team determined filament types, infill densities, and infill patterns. Other classes such as ES2501: Introduction to Static Systems helped me when simulating the scissor lift and calculating maximum loads.

In the initial phases of this project, I utilized design practices I had learned in classes such as Introduction to Engineering Design, Fundamentals of Axiomatic Design of Manufacturing Processes, and Design for Manufacturability (ME2300, ME5420, and ME5441). Different planning models like Pugh matrices, functional requirement/design parameter decompositions, and QFD analyses discussed in these classes helped clarify our design and ensure our decisions were well supported by customer needs and cost reduction.

Overall, this project challenged my design engineer competencies as well as employed project management skill sets. I will walk away from this project with a clear understanding of the communication and organization that is warranted by a 28-week project. In some stages of the timeline, action items were revised as a result of unforeseen print failures. At these times, I made quick decisions to ensure the long-term goals were still progressing. Ultimately, I am happy our team learned from mistakes after every failure and exemplified passion through continuous improvement of our product. I am thankful for the skills I have developed as a result of this project, and look forward to furthering them in opportunities to come.

12.5 Kwesi Sakyi

This project challenged my mindset as an engineer and how to think from a design and analytical perspective. I was able to rely on the skills I learned in WPI over the past four years. Our advisor forced us to think outside the box and truly understand different perspectives, to always question 'what if' and ask 'why' in solving our needed problems. I chose this project because I was curious about learning more about autonomous technology and 3D printing. As someone who works in the prototyping lab, I wanted to learn more about 3D printing, especially being tasked with 3D printing a car with various requirements and end goals. As a mechanical engineer, I wanted a project that I could design, build and test. Taking classes like Mechatronics, Kinematics, and SolidWorks helped me prepare for the design and analysis of FETCH. This project helps me enhance my communication and problem-solving skills. As an engineer I learned how to think outside the box, research, collaborate, and effectively analyze a problem and find ways to solve it. In having a timeline, we could track the progress and updates we made throughout our project. Our journal entries were effective in making sure we kept ourselves accountable for our work and any improvements we needed to make. Overall, I'm very pleased with our progress as a team, the challenges we faced, and the accomplishments we made over the year. I'm happy to take concepts and principles learned this year to future projects in my full-time job.

I. General Information about Vehicles and their Components

This chapter provides additional information and research conducted when understanding the basic components of vehicles. Before designing our car, we had to understand the basic concepts of how a vehicle functions and the components of RC cars. It helped set the foundation for our project when designing the various components of our car. In addition, we have the link to our CAD files for FETCH in Appendix H.

Appendix A: Vehicle Driving Dynamics

Vehicle dynamics describes how any car will act while under dynamic driving conditions. This includes accelerating, braking, and cornering. Understanding how a car acts under these conditions is crucial to understanding how to design the car effectively.

First, rubber tires connect the vehicle to the road and our RC car will be using rubber tires. Friction between the road and the tire produces cornering forces allowing the tire to grip the road. Slip angle is the angular difference between the direction the car is traveling and the direction the wheels are pointed. This would mean that the tires are sliding, which is ideal to a certain degree. The grip produced by a tire can be modeled as a graph of slip angle vs coefficient of friction as shown in Figure I-1.

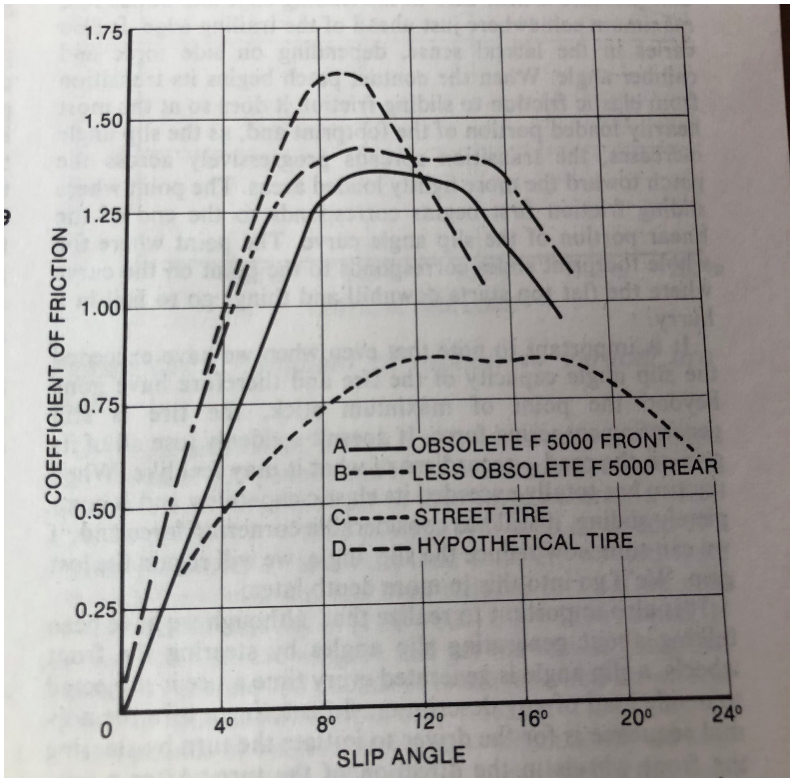

Figure I-1: Slip Angle vs Coefficient of Friction Graph (Smith, 1978)

The coefficient of friction of the tire increases sharply as the slip angle increases, and then slowly begins to taper off at a peak. Then, past that peak, the coefficient of friction decreases with increasing slip angle. This shows here is an optimal slip angle range where the tire will produce the most grip. Tires can also create more cornering power through a more vertical load. This vertical load pushes the tires into the pavement more, which will increase the friction and therefore the grip. However, this does not increase exponentially over time. Eventually, there is a point where the tire must do too much work and becomes overloaded.

The dynamics of the car as it accelerates decelerates, and corners are crucial to how a car drives. First, we need to develop a distinction between lateral load transfer and chassis roll. Lateral load transfer is the weight of the car shifting towards the outside tires during cornering. Every kind of vehicle transfers load in this manner. The grip of the inside tires is decreased, and the grip of the outside tires is increased. However, the inside tires will lose more grip than the outside tires will gain grip, causing a loss in overall traction. Since lateral load transfer reduces grip, we want to try to limit how much the car receives. Chassis roll is dependent on weight, roll center height, CoG, and roll resistance however chassis roll only occurs in vehicles with springs and pneumatic tires. Stiffer springs and components like anti-roll bars will restrict chassis roll, which will make the car more responsive at that end but will reduce overall grip. Reducing chassis roll using stiffer components, specifically a stiffer anti-roll bar, will increase lateral load transfer. So there is a trade-off here between reducing chassis roll and reducing lateral load transfer. Raising the roll centers is another way to reduce chassis roll, but it comes with certain negatives, like jacking and poor camber curves. Longitudinal load transfer is the load transferred during braking and acceleration. Braking or letting off the throttle shifts weight to the front end of the car, while accelerating shafts weight to the rear end of the car. Longitudinal load transfer is a function of CoG height, vehicle weight, and rate of acceleration. In the same way that lateral load transfer reduces overall grip, longitudinal load transfer also reduces overall grip, therefore it is ideal to minimize longitudinal load transfer as much as possible. Understanding how the vehicle will react to various inputs is crucial for understanding how to design the suspension geometry. Since PARV and our iteration of PARV have fully operational suspensions, it is crucial to understand how vehicles react to various inputs from a driver or from an autonomous guidance system. Understanding these basics of vehicle dynamics will allow the team to more effectively test PARV, find its weaknesses, and understand what potential adjustments to the suspension system would improve vehicle performance.

Appendix B: Mechanical Components of a Vehicle

Suspension System

One of the most important components of any type of car, whether it's a remote-controlled (or RC for short) car, a streetcar, or a race car, is the suspension. The main purpose of a vehicle's suspension is to ensure that all four tires have as much of their contact patch on the road at all times. The suspension controls the linear and angular path of a wheel during vertical acceleration of the wheel (hitting a bump) and horizontal movement of the sprung mass as a result of various load transfers due to various accelerators (Smith 1978). Some of the components that make up a suspension system include springs, shocks, and suspension links. There are two basic types of suspensions, dependent and independent. A dependent suspension system is when both front wheels or both rear wheels are connected through the suspension system, meaning that any disturbance to one wheel will also affect the other wheel (Smith 1978).

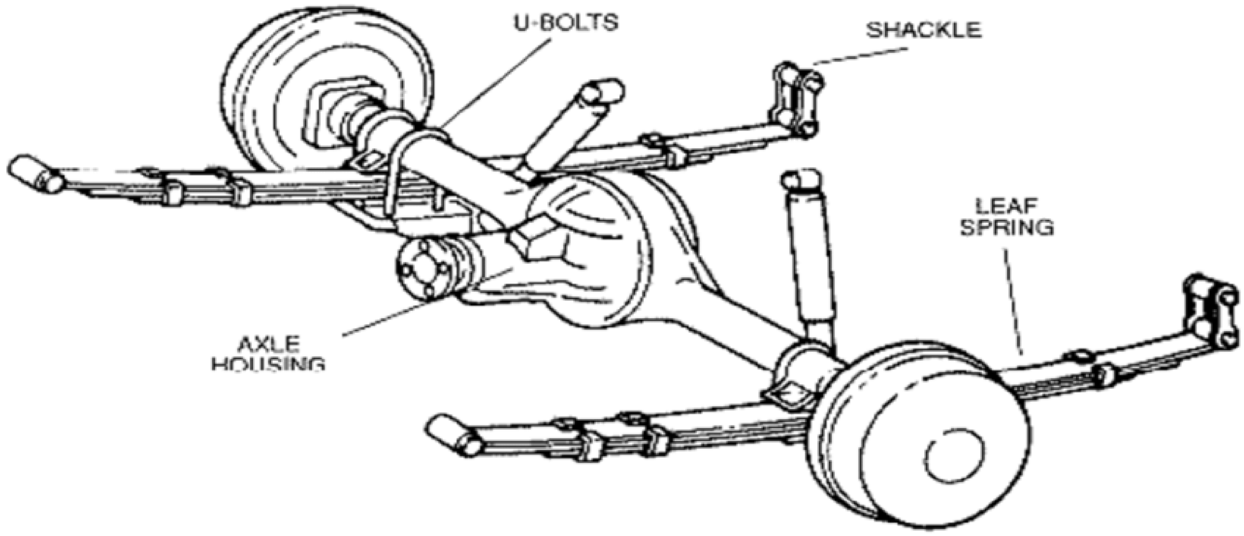

Figure I-2: Dependent Suspension System (Kishore, 2018)

An independent suspension system is when the two wheels on the same end of the car each have their own suspension system and are not connected to each other through the suspension (Smith 1978). This allows each wheel to react to bumps independently from the other wheels. An independent suspension system provides better overall traction, making it the better choice for most types of vehicles.

There are a number of different types of independent suspension systems, but the most relevant is the MacPherson Strut, and the double-wishbone (Smith 1978). The MacPherson Strut system gets its name from the spring/shock assembly it uses. With this system, you have a coil spring with the shock absorber, or damper, in the center of it, as seen in Figure I-3 (EngineeringExplained, 2012).

Figure I-3: Coil Spring (Holden, 2017)

This device is also sometimes called a coilover because it's a coil spring over a damper. A damper, more commonly known as a shock absorber, is a device used to dampen the oscillation of another structure. In automotive applications, it is used to dampen the oscillations of the spring after dealing with some sort of bump or during transient maneuvers like accelerating, decelerating, or turning the steering wheel. The amount of damping can be adjusted on some dampers based on the bump (compression) or rebound (extension). The kind of packaging does not take up as much space horizontally as having the suspension and damper mounted separately. This makes the MacPherson Strut great for FWD vehicles because it leaves much more space for the driveshaft at the front of the vehicle. The MacPherson Strut only uses a lower control arm (A-arm) mounted to the bottom of the wheel hub (Engineering Explained 2012), while the top of the strut mounts to the top of the wheel hub and directly to the frame. This results in less camber control than a double-wishbone suspension system could provide. However, due to its low cost and simplicity, the MacPherson Strut is the most widely used suspension system in everyday cars (Engineering Explained 2012).

The double-wishbone suspension consists of an upper and a lower A-arm that both connect to the wheel hub and the frame of the car. Originally the system would use equal length control arms to keep the camber the same when the wheel underwent vertical movement; however, that created an issue where, during cornering, the outside wheel would develop positive camber, while the inside wheel would develop negative camber. This greatly reduced the cornering power the car could produce because the suspension was actually taking part of the contact patch off the road. So designers started using a shorter upper control arm, which induced negative camber on the outside wheel while inducing positive camber on the inside wheel. This actually helps to keep the contact patch on the road during cornering, producing more overall grip for the car (Smith 1978).

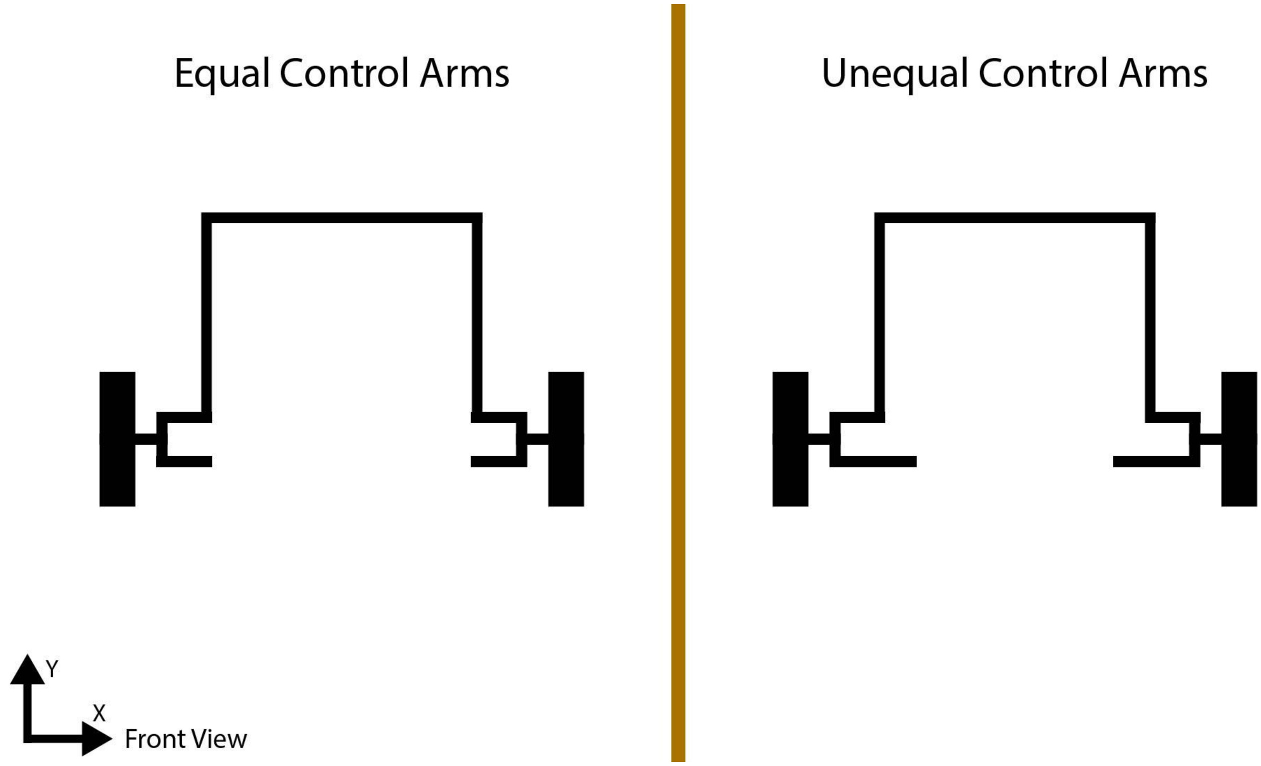

Figure I-4: Equal and Unequal Control Arms

There are a number of other potential control arm layouts for the double-wishbone suspension, each with its own set of advantages and drawbacks. The shorter upper control arm and parallel upper and lower control arms became the most popular choice, not only for the reasons listed before but also because this design keeps the roll center the most consistent during cornering (Smith 1978).

The roll center is the point at which the front or rear end of the car rotates about during cornering. The roll center can be found by extending the upper and lower control arms for each side of the front suspension until these extended lines for the upper and lower control arms meet. This point is the instant center for that side of the suspension and will usually be located outside of the opposite side's wheel. Once the instant center for the right and left sides have been found, a line is drawn from the point where the center of the contact patch contacts the road to the instant center for that side of the suspension. Once you do this for both sets of tires and instant centers, you'll have an intersection point of these two lines, and that point is the roll center (Vogel et al., 2021). Figure I-5 below shows how this process works.

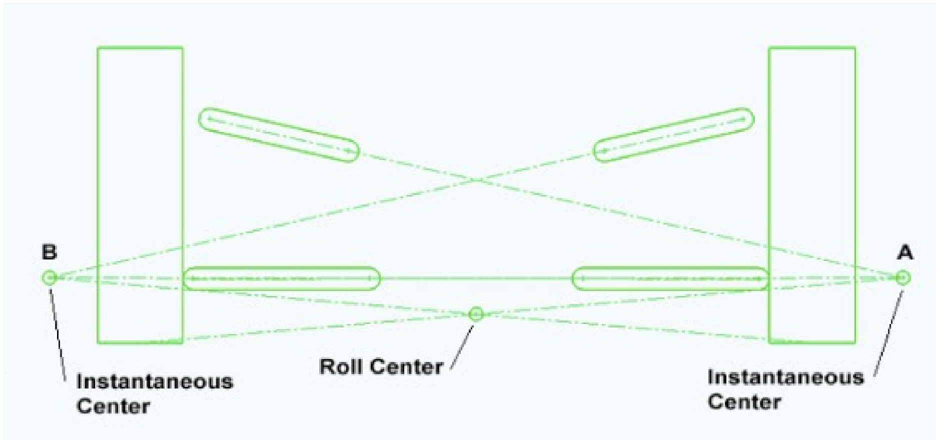

Figure I-5: Roll Center Diagram (Suspension front view) (Vogel et al., 2021)

The roll center plays a significant role in the handling of the car. Chassis roll produces grip for a car (up to a certain point) and understanding the location of a car's front and rear roll centers is critical to understanding and controlling the amount of chassis roll a car will produce.

There are a few basic truths and compromises that we need to keep in mind when designing a suspension system. One of which is that the suspension system can control camber well in vertical wheel movement or chassis roll, but not when both occur at the same time (Smith 1978). This means that we will need to accept that we may lose traction when going over a bump while cornering. Longer suspension links place more of a limit on the amount of vertical wheel travel per unit chassis roll (Smith 1978). Other factors, such as the space needed in the front end of the car, will limit the length of the suspension links. Increasing the inclination of the paper link will increase the negative camber in bump travel, and will decrease the amount of positive camber on the laden wheel during chassis roll (Smith 1978). This is useful because having negative camber on the wheel taking most of the load during cornering will help keep the entire contact patch on the road, which will maximize the grip. When designing a suspension system there are two main goals to design for. It is important to produce good camber control via the suspension, and limited movement of the roll center during braking, accelerating and cornering (Smith 1978). These two areas will have the largest effect on the handling of the vehicle. And finally, as a rule, there are four primary ways to reduce chassis roll. The first is to use higher roll centers to reduce the roll moment; however, as mentioned before, this creates issues with high jacking forces and bad camber curves that supersedes any benefit of less chassis roll. A more effective way to restrict chassis roll is to use an anti-roll bar, which is simply a torsion bar connected to each side of the car at either end that twists during chassis roll. The length and diameter of this bar can be adjusted in order to increase or decrease its stiffness. Stiffer springs can be used to reduce chassis roll, but this is not the most effective method because stiffer springs at a given corner of the car will reduce grip. The last method would be to use longer suspension links to reduce the amount of camber change per unit roll.

Track width and wheelbase are two crucial pieces to any vehicle's design. The wheelbase is the distance between the front axle and the rear axle. Longer wheelbases will provide more straight-line stability, but will have a higher moment of inertia hindering responsiveness and cornering ability Smith 1978). Cars with a shorter wheelbase will have less straight-line stability, but a smaller moment of inertia, allowing them to be more responsive and corner harder. Track width is the distance between the two wheels on the same end of the car. A wider track width will make a car less stable but will allow for more cornering power, while a more narrow track width allows for more stability, but less cornering power. Short wheelbase cars with wide track widths will have better cornering ability but less overall stability, while long-wheelbase cars with a narrow track width will have more straight-line stability but less overall cornering ability. The wheelbase and track width one should choose when designing a car are dependent on the application of the car, as well as any ergonomic demands that may need to be met. Typically in any racing series, there will be a rule for the minimum wheelbase of a vehicle, which will allow for all ergonomic requirements to be addressed (Smith 1978).

A car's suspension system is crucial to its performance, and the suspension geometry of a car will be different depending on various characteristics of the car. These characteristics include weight, tire size, power to weight ratio, and others. Another important factor is the terrain the vehicle is being designed for. With consideration of these factors, suspension geometry can be designed to ensure the car is well suited for its application.

Steering System

The purpose of the steering system of any vehicle is to work with the suspension to provide directional control for the car (Melior Inc, 2004). The steering system must function while still allowing the suspension to function properly. Due to this, there will be components that will be used by both the suspension and the steering system. A typical steering system will consist of steering linkages, a steering gear, a steering column, and a steering wheel (Melior Inc, 2004). In the case of an RC car, the steering wheel is replaced by a servo motor. The two most common designs for a steering system are the rack and pinion system and the conventional system (Melior Inc, 2004). A rack and pinion system transmits the steering motion of the wheel through a pinion gear that rests on a grooved track. The rack moves side to side and the tie rods on each end are connected at the bottom of the wheel hubs with steering knuckles, allowing the wheels to be turned. This system is commonly used with MacPherson Strut suspension geometry and is commonly paired with this steering system on FWD cars and other small cars and minivans. Part of the appeal to the rack and pinion system is that they are cheap to produce and are easier to work on (Melior Inc, 2004). An image of the rack and pinion steering system can be seen below in Figure I-6.

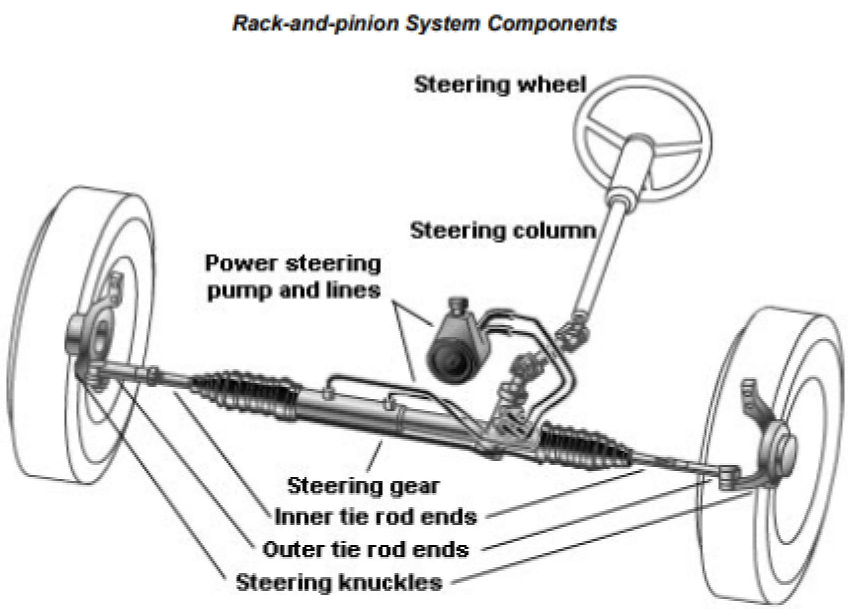

Figure I-6: Rack and Pinion Steering System (Melior Inc, 2004)

The conventional steering system, also known as the parallelogram system, transmits motion from the steering wheel through a recirculating gear that moves an arm in a back and forth motion. The motion of this arm acts on a set of linkages that are attached to the wheel and allows the wheel to turn. Figure I-7 below shows a diagram of how the parallelogram steering system works and some of the system's components.

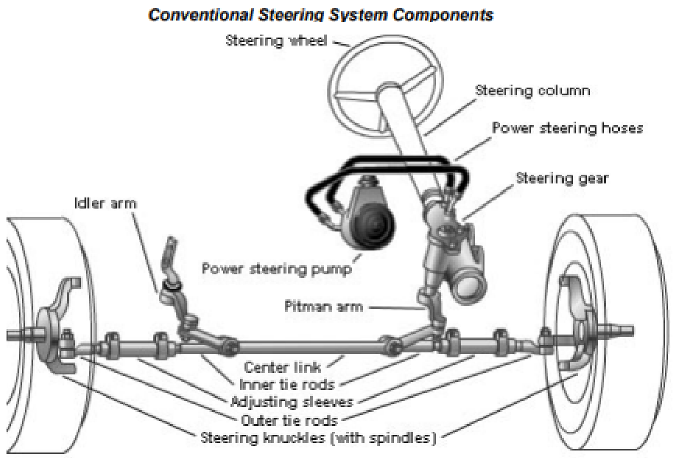

Figure I-7: Conventional Steering System (Melior Inc, 2004)

Some common parts you'll see in any steering system are tie rods, spindles, steering columns, and steering knuckles. Spindles are attached to where the wheel is mounted and connect the steering arms to the wheel. Tie rods are the steering arms that connect to the spindle via steering knuckles. Steering knuckles are joints that are connected to the spindles and translate the linear motion of the steering linkages into rotational motion at the wheels. The steering column is what connects the steering wheel to the gear used to transfer the motion to the steering linkages (Melior Inc, 2004).

Ackermann steering is a steering geometry designed to make the inside tire turn more than the outside tire to minimize slip angle (Vogel et al., 2021). A vehicle turns around a turning center shared by each wheel when you extend the axis of each wheel until they intersect, forming a single point. Without Ackermann steering, this would not happen and you'd get large amounts of slip when cornering (Vogel et al., 2021). Figure I-8 displays this idea of a shared turn center.

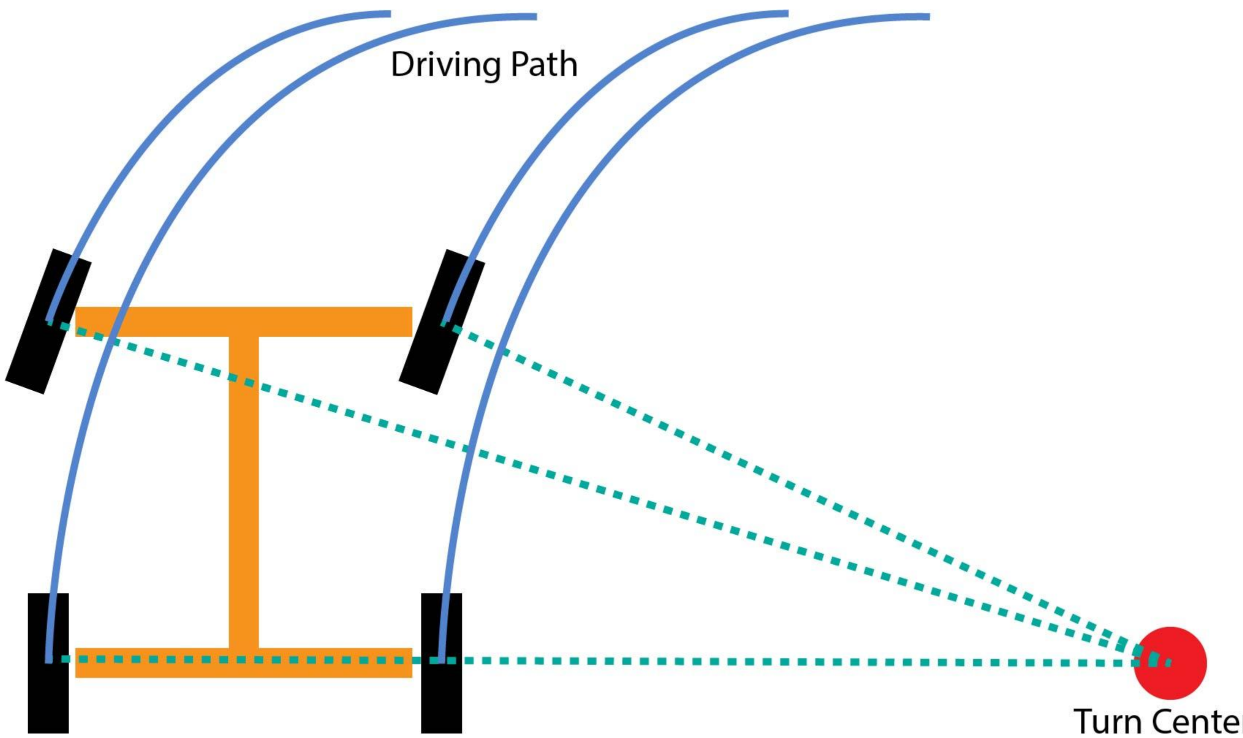

Figure I-8: Turn Center Location on a Vehicle

Ackermann steering is good for tight, low-speed turning. In these situations, the Ackermann steering will help the car turn with less slip; however, at higher speeds, this is not the case. Tires produce more grip under higher loads, which requires higher slip angles to take advantage of that grip (Vogel et al., 2021). This means anti-Ackermann steering, where the outside tire turns more than the inside tire to help the car turn, would be required. For race cars, a certain amount of anti-Ackermann steering is optimal, but for our purposes with an RC car, negotiating slow, tighter corners, a small amount of Ackermann steering would be helpful to us.

Front end alignment, specifical toe, can have a significant effect on how well the car turns. Toe refers to the direction in which the front wheels are pointed. They can be pointed inward, towards each other (toe-in), or pointed outward away from each other (toe-out). Toe-in provides more rolling resistance which increases grip while turning, while toe-out provides better grip during straightaways, but takes away some stability. Too much toe in either direction will cause excessive sliding of the front or rear tires if the rear end of the vehicle is designed for adjustable toe. Bump steer is used to build small amounts of toe-out on the outside tire to decrease the slip angle of the outside tire at small steering angles. This is intended to help the car turn better during the initial turn-in point. Bump steer can also be used in the rear end to build toe-in during acceleration to point the rear tires inward slightly and add more rear stability to the vehicle.

It is crucial that the steering system of a vehicle works well with the suspension system of the vehicle. If the steering linkages interfere with the suspension's ability to let the wheels travel the designed amount, it can have a negative effect on the handling of the car. It is also important that the steering system allows for a certain degree of rotation for each wheel. For RC cars, this is typically 30-50 degrees of rotation.

Appendix C: The Workings of a Differential

Another important component of a car is the differential. Differentials provide power through the drivetrain and gearbox to the ground. Its main purpose is to transfer power to each wheel on an axle while also allowing each wheel to independently rotate. Differentials help prevent cars from slipping on dragging since there is a difference in turning radii and grip on different sides of the car. In addition, each wheel turns at different speeds which leads to the importance of a differential system. Differentials help provide the needed torque in low traction environments such as off-roading.

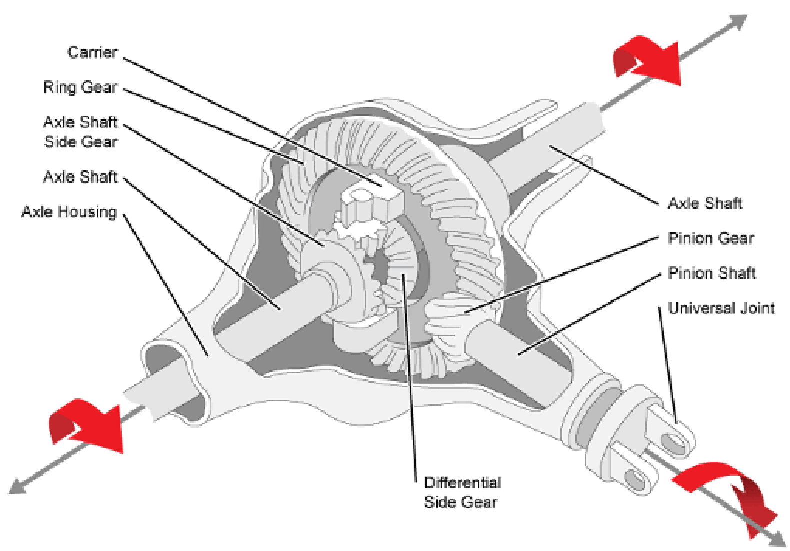

Figure I-9: Open Differential System

The most common type of differential is an open differential. An open differential system provides the axle of each wheel of the car to spin independently of each other. An important thing to understand about direct drive differential systems is the gear setup directs power and torque to a connected axle. Meaning the wheels on the system cannot rotate independently which can cause slipping when wheels turn around a corner. For more environmentally demanding cars, there's an added feature to their open differential system. This feature provides the car the ability to lock its differentials using a ring and pinion type system and additional gears connecting to two sides of an axle. This design makes each wheel on the axle turn at the same speed, but an important thing to note is the torque applied to each wheel can be different, depending on the amount of traction in each wheel.

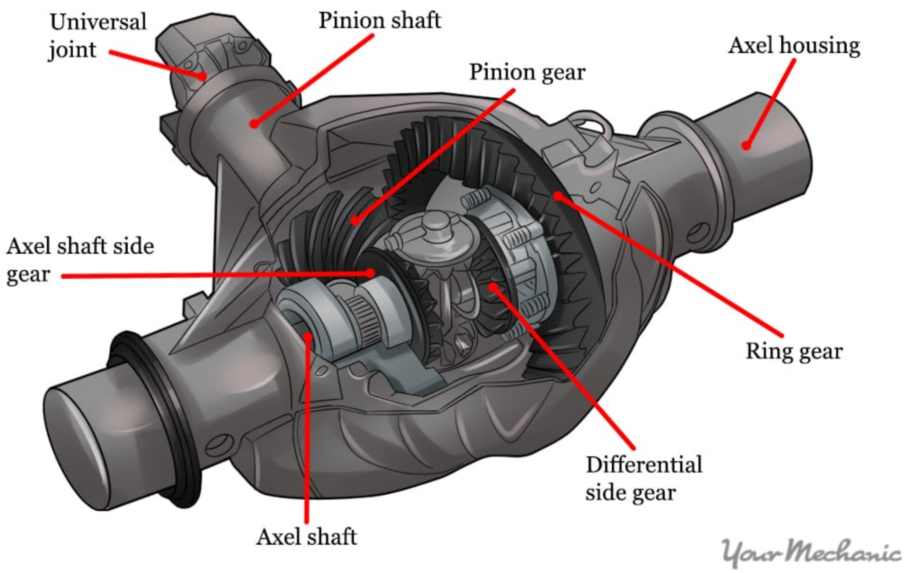

Figure I-10: Locking Differential System

For 4WD vehicles, a limited-slip differential (LSD) system is used. This system merges an open and locked and direct drive differential into one system that switches automatically based on the traction and torque demanded on the drivetrain. The core makeup of this system is a central ring and pinion gear, viscous fluid, friction plates, and plate springs to provide the necessary moments, power, and torque deliveries. With the various conditions 4WD cars face, an LSD system transfers power and torque based on the different speeds of the vehicle around corners, high friction scenarios, or when under heavy load.

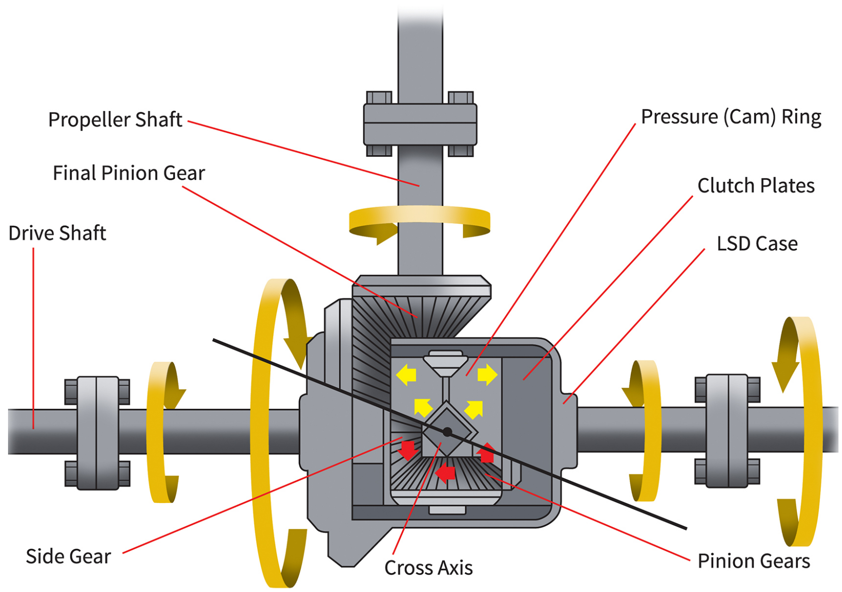

Figure I-11: Limited Slip Differential

Most RC cars do not have differentials due to how expensive it is to manufacture. Some RC cars come with differentials with viscous oil to help reduce slip. Differentials in RC cars are rare but will be important for our project.

Appendix D: Electrical Components of a Remote Control Car

Motor

The motor is the most integral electrical device in making a vehicle move. A motor provides the mechanical energy to move a vehicle forward or backward. By turning energy from a direct current (DC) into mechanical energy, axles and wheels can spin. A motor works by exploiting electromagnetic induction, which can be achieved through a stator-rotor relationship. The stator is a fixed magnet that surrounds the rotor. The rotor (also called an armature) is a coil of wire powered by a battery. When electricity flows through the wire, an electromagnetic field develops between the rotor and the stator causing the rotor to spin. A full rotation is made possible by a commutator. A commutator is a circular metal device that is split into two halves and each half connects to each end of the rotor coil. If the commutator was not split, the motor would only produce a single 180-degree turn because there is no torque when the rotor reaches this angle. By splitting the commutator into two halves, electricity flows through one half into a copper brush to the rotor, allowing it to spin half a rotation. Next, the current flows through the other half of the commutator in the opposite direction. This allows the current to alternate at each halfway point of a rotation and apply torque in the correct direction at the correct time. Full rotation can also be achieved through the incorporation of more armatures to maintain positive torque even if one another is in the top position. A simple DC motor can be seen below:

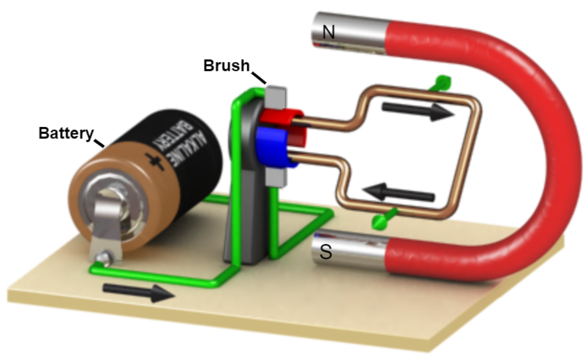

Figure I-12: Basic DC Motor Configuration (Brushed)

When working with RC cars, typically one will use brushed or brushless motors. A brushed motor, such as the one discussed above, uses the armature as its two-pole electromagnet. The direction of the current is reversed twice per cycle by the commutator, causing the electromagnet's poles to push and pull against permanent magnets which are placed on the outside of the motor.

In comparison, a brushless motor uses a permanent magnet as the external rotor. Rather than alternating current, it uses a three-phase system of driving coils. A sensor tracks the rotor position and senses reference signals to the controller, which activates the coil phases sequentially.

Each type of motor has its advantages and disadvantages which can be summarized by the tables below:

Table I-13: Comparison of Brushed and Brushless Motors

Appendix E: Brushed Motors

Pros	*Cons*
Cheaper construction costs	Friction of brushes yields heat output (energy loss)
Typically rebuildable to extend life	Constant electrical supply
Controller is cheap and simple	High maintenance and replacement costs
Fixed speed does not require controller	
Ideal for extreme environments	

Appendix F: Brushless Motors

Pros	*Cons*
Less maintenance with no brushes	Higher cost of construction
Operates well with variable speeds and loads	Controller is complex and expensive
High efficiency and output power: size	Controller is required to keep the motor running
Reduced size with superior thermal characteristics	
Higher speed range	

Appendix G: PARV Specifications

https://docs.google.com/presentation/d/18e1j4GId8xK2mP8dSYQDNWuA8sKxQiakjQ3GYyQ3FvE/edit#slide=id.g10162625664_0_0

PARV Specifications

Appendix H: Link to GrabCAD

https://workbench.grabcad.com/workbench/projects/gctMcABs14d56lsjQYIGOuy1wZ7mD3dWyxykazW_asdpDR#/space/gcLeFljLZ_LtW99V-cUi4281hBY_oEES61YoeRxdRFzJzP

Appendix I: Link to ASME Code of Ethics

https://www.asme.org/wwwasmeorg/media/resourcefiles/aboutasme/get%20involved/advocacy/policy-publications/p-15-7-ethics.pdf

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