PARV: A 3D Printed Autonomous Robotic Vehicle Platform

A *Major Qualifying Project*
Submitted to the Faculty of Worcester Polytechnic Institute
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By
Dexter Czuba
Rajkumar Dandekar
Steven Gordon
Eric Stultz

Advised by
Professor Pradeep Radhakrishnan (ME)
Professor Kaveh Pahlavan (ECE)

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Abstract

In recent years, there has been a rising demand for autonomous vehicles. Autonomous vehicles have countless uses ranging from transporting people and cargo to completing tasks which are dangerous to humans. Current vehicles are often solutions for a singular problem in the diverse list of autonomous vehicle needs. Events like the COVID-19 pandemic have shown how easily the world can change. Within a span of weeks, employers had to shift to remote work, and companies had to adapt their procedures to reduce contact between people. Autonomous vehicles can help aid in these issues in a variety of ways, such as allowing people to interact or work with each other remotely, or providing a method of supply or tool transport that does not require human touch, preventing the spread of germs. Even without a pandemic, there is still a need for autonomous vehicles. Many tasks, such as package delivery and trash collection, can easily be accomplished by robotic vehicles, and as such can improve the efficiency of package services and prevent excess pollution. Other tasks, such as chemical treatment or environmental surveys, can be hazardous to humans, and having a modular platform to install and program tools such as robotic arms can make accomplishing these tasks safer. As such, a reliable, modular platform that can easily be assembled and operated for various tasks would be extremely helpful. Various consumer options exist on the market for delivery vehicles or scientific rovers, but very few if any are open-sourced, or easily manufactured and adapted by the user. The availability of open-sourced systems would also greatly aid research and development of such autonomous systems and will be valuable in the education field.

In order to achieve these goals, we have developed PARV, a 3D Printed Autonomous Robotic Vehicle that can be used as a modular multi-purpose platform. This vehicle is designed to be mostly 3D printed, increasing the modularity of the system, as you can create custom pieces for the platform. Furthermore, 3D printing allows repairing and increased accessibility for research and commercial applications.

PARV includes various subsystems such as a 3D printed transfer case gearbox, suspension, steering, and limited slip differential systems. One of the key goals of our car was to develop a 4WD system. This 4WD system would allow the vehicle to travel over any type of terrain, such as in treacherous or non-urban environments (grass, dirt, rocks). In addition, we have also developed a motorized trailer system that can be used in conjunction with our car to

carry large payloads or additional tool systems. A commercially available robotic arm was also integrated to demonstrate the modularity and flexibility of PARV as a platform system.

All components and models were made using SolidWorks. We have also utilized ANSYS and Matlab to test the strength and longevity of many of our components. Our ANSYS testing primarily was used to test the strength of 3D printed gears, while we also calculated the bending and shear stress on the teeth. These tests showed us that printing the gears in NylonX will be sufficient for the forces they experience. Power loss and transfer throughout the car was simulated with the help of Matlab; this aided our decisions of gear ratios within the differential. The assembled car was then tested on predetermined paths around our campus which best represent obstacles the car could encounter.

PARV's modularity also allowed us to integrate an array of sensors to enable autonomous driving. The autonomous driving package included a range of sensors, power sources, and microchips that were all installed onto the vehicle. PARV has also been tested outside on a variety of challenging obstacles including steep hills, rocks, and tall grass. The results from testing are very promising and reflect PARV's ability to handle rough terrain.

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2020-2021 Self Driving RC Car CS Sub-Team
    Chris Mercer
    Eric Reardon

2020-2021 Self Driving RC Car ECE Sub-Team
    Enzo Azevedo
    Antonio Jeanlys
    Julien Mugabo
    Taylan Sel

2019-2020 Self Driving RC Car Team

Executive Summary

For a summary of our project, please visit our page on the virtual showcase. Here you will find a video where we summarize our work, as well as a slide deck with additional information.

https://1drv.ms/u/s!AtHIJxxntmsWyXHs5HOUhS62Jt2S?e=DIkgk3

Authorship

Section	Primary Author
Abstract	All
Executive Summary	All
Introduction	Dexter
2019-2020 MQP	Steven, Dexter
Background	All
Project Requirements and Goals	All
Methodology	All
Suspension System	Raj
Steering Linkage	Raj, Dexter
Drivetrain	Steven, Eric
Differential	Dexter, Eric
Vehicle Structure	Eric, Dexter
Trailer System	Steven, Dexter, Eric
Manufacturing	Eric
Modularity	Steven
Testing	Steven
Results	Steven
Conclusion	Main: Raj, Eric; Reflections: All

*Note: All sections were edited together by all project team members.

1. Introduction

Over the couple decades, a lot of research and development has been done by space programs, such as NASA, to develop robotic rovers that can be used to explore extraterrestrial landmasses such as the Moon and Mars. These rovers contain a large amount of scientific tools, and must be able to traverse over a variety of different landmasses. Rovers are also being used on Earth, however they are not used to the full extent that they could. Part of this is due to the massive costs of these rovers, since most of the technology onboard is either new or created by a single company. Creating a vehicle that can be used for scientific research on Earth would be very beneficial, as it would allow us to explore areas that are not safe for humans, such as volcanic tunnels, frozen mountains, or radioactive regions of the planet. Of course, we are not focusing on extreme tasks like that, but this project can be used as a starting point for the development of cheaper scientific rovers. These rovers, using a variety of power transfer and payload mounting systems, can accommodate components such as robotic arms and trailer mounts for scientific experimentation or autonomous operations at various universities and tech companies.

Development of a Modular 3D Printed Vehicle

The concept of additive manufacturing is a relatively new one, yet also one of the most useful in engineering, as it helps facilitate the creation of almost any mechanical or electrical component that can be created using computer aided design. Compared to subtractive manufacturing, these designs can be more complex, can use a variety of different materials such as plastics, metals, and even ceramic, and are much cheaper to produce, especially for ameteur engineers or startup engineering companies. The biggest avenue of additive manufacturing is the concept of 3D printing, which utilizes computer-controlled material extruders to create 3D objects out of layers of material. As such, it is also the most practical for aspiring engineers to learn, as it allows them to experiment with various designs and techniques when developing a part while also giving them a better insight into how a design can turn into a finished product.

The use of 3D printing is particularly helpful for prototyping and can be used to demonstrate design concepts. As such, this open sourced RC car is being developed with 3D printing in mind. As many of the subassemblies on the car as possible will be created via 3D printing, and many others can be redesigned by future teams to create new and more efficient 3D printed components. This also allows the vehicle to be modular, allowing for it to be used and modified in a variety of ways. From this, the car can become both a learning and a testing platform for many students at WPI.

Application as a Delivery Vehicle

The development of off-road capabilities for this car are a great learning opportunity, and could even be used to teach fellow WPI students about these topics. Through further development of these capabilities however, we believe that it is possible to go even further and create a delivery robot for the WPI campus. This delivery robot would be able to travel anywhere on campus, both indoors and outdoors, and be able to carry packages of a decent size between locations so that humans do not have to. This would allow professors and students to request materials and pick up forgotten equipment without needing to physically retrieve them, preventing time waste due to traveling across campus, and preventing unneeded human interaction, especially during the current age of COVID-19. This in turn could be used as a basis for a full sized delivery robot or car, which can be used by package companies such as Amazon or Fedex, to autonomously deliver packages across the United States.

Development of Autonomous Vehicle Control

Over the past decade, there has been a greater focus into the development of autonomous vehicles, partially from car companies such as Tesla, and partially by various militaries looking to autotomize their drones and equipment. Two of the main purposes behind autonomous vehicles are the concepts of greater safety and of greater efficiency. In theory, autonomous vehicles are safer than their human controlled counterparts as they do not rely on human concentration and will not tend to make judgement errors; they are also because they are able to map out the quickest routes to their destinations, and better control their power output to save energy.

However, autonomous vehicle control is very difficult to implement, as you would need to implement a collection of sensors and programs that take into account all of the variables that a vehicle may face. These variables may consist of changes in surface conditions, different amounts of light, or other vehicles around it. As such, full Level 5 autonomy for vehicles is still many years off. However, Level 3 autonomy, or autonomy in specific and controlled circumstances, is being implemented currently by companies such as iRobot with their Roombas or Tesla with their adaptive cruise control. In addition, Level 3 autonomous machines are being used as test platforms for Level 5 testing.

While working with a sister MQP team, we believe we can implement something similar into our RC car. Working with our sister team of Electrical and Computer Science students, we plan to support the development of, and help implement Level 3 autonomous capabilities. The goals of these capabilities are to test over set paths around campus, and create a car that can be used as a basis for future Level 5 tests.

Project Statement

For our project, we are designing, manufacturing, and testing a 3D Printed Autonomous Robotic Vehicle (PARV), which can be used as a delivery robot or scientific platform. A few of the unique systems this car incorporates are a four wheel drive (4WD) and a limited slip differential system (LSD). This car is a platform model that is capable of having many new systems and components added to it. For example, the car currently can add a detachable trailer for payloads, an autonomous driving module, and plans for the integration of a stair climbing module. This car is built very modular so that it can be easily adjusted and improved based on the scenario the car will be used for.

Report Organization

The following report will be organized into various chapters, each of which discusses a specific part of our project development or on a specific component we created for our car. Chapter 2 provides some background on the previous year's MQP, while Chapter 3 will introduce information on the structure and purpose of our various mechanical and electrical based components. Chapter 4 will include the project requirements, and will lay out our general and specific goals for the car.. Chapter 5 will talk about the methodology for the project by discussing the various steps we took to both develop and improve our car's design. Chapters 6 through Chapter 11 will discuss the design process of each subassembly, the final designs of each, and the purpose of each subassembly in the car's development and end goals. Chapter 12 discusses the manufacturing processes and methods used to produce PARV. Chapter 13 will discuss the modularity of PARV and why it is a benefit over other similar vehicles. Chapter 14 will discuss our testing setups and procedure, and Chapter 15 will discuss our results from these tests. Finally, Chapter 16 will discuss our general thoughts on the ethics and development process, and give an insight into where and how this car can be improved upon next year, as well as encompass our personal thoughts on how this MQP and our time as a whole at WPI have helped us develop our engineering, teamwork, and communication skills.

2. 2019-2020 MQP

<u>Project Summary</u>

Last year's MQP by Boggess et al., 2020 focused on creating a RC car that was modular, scalable, and an open-sourced RC mobile platform.

At WPI, one of the more advanced courses, and one our advisor Pradeep Radhakrishnan is teaching, is ME 4320, which at WPI represents the advanced engineering design course. While the coursework can vary depending on the professor, in classes taught by our advisor, the main task is to develop a basic RC car that can race other students' cars at the end of the class on an interior course. Hence, the MQP team wanted to create a high functioning RC car that can be used as an example for the ME 4320 class, a design the students could strive for.

The 2019-2020 MQP's RC car consisted of a motor, planetary gearbox, differential, chassis, steering, and suspension system. Figures 2-1 and 2-2 show the final CAD and manufactured car from last year's MQP. Each of the systems that were built onto this car were individually tested using manufactured test fixtures to test their effectiveness and rate of fatigue.

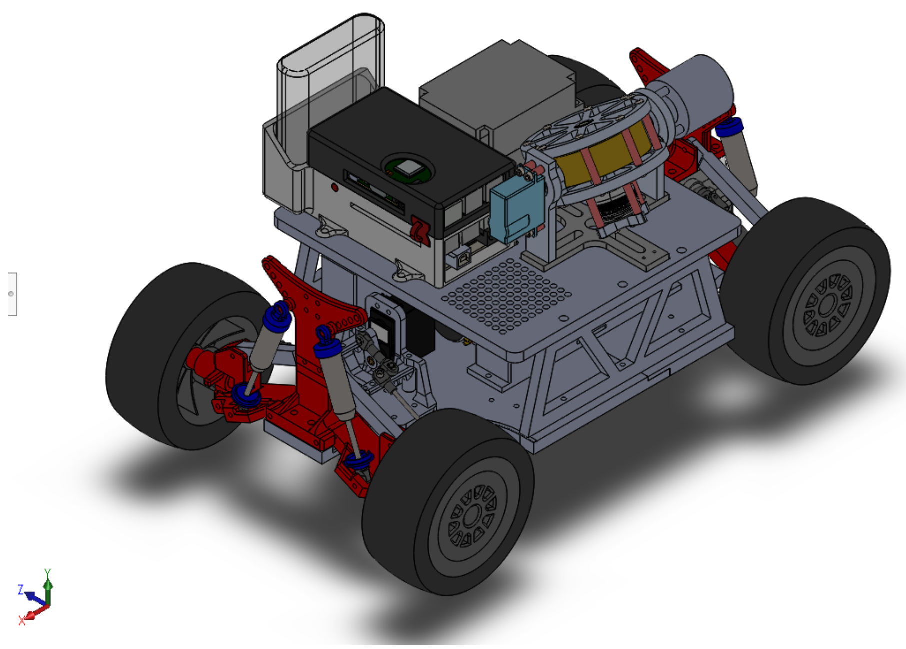


Figure 2-1: Final CAD Model from 2019-2020 MQP Car

Figure 2-2: Final Assembled/Manufactured Car from 2019-2020 MQP

The first system developed during last year's MQP was the chassis. This chassis was developed over four different iterations, each one refined towards their final design. Initially, the plan was to create one unified chassis that could hold all the components of the car; however, after initial 3D printing failures and computational strength testing, the design was modified in various ways to try and solve these problems. The final design comprises two chassis pieces held together using epoxy and strengthened by zinc rods, as shown in Figure 2-3. This final design was 14.14" long by 8.75" wide by 0.35 thick with wheel cutouts that lead to a 12.4" wheelbase.

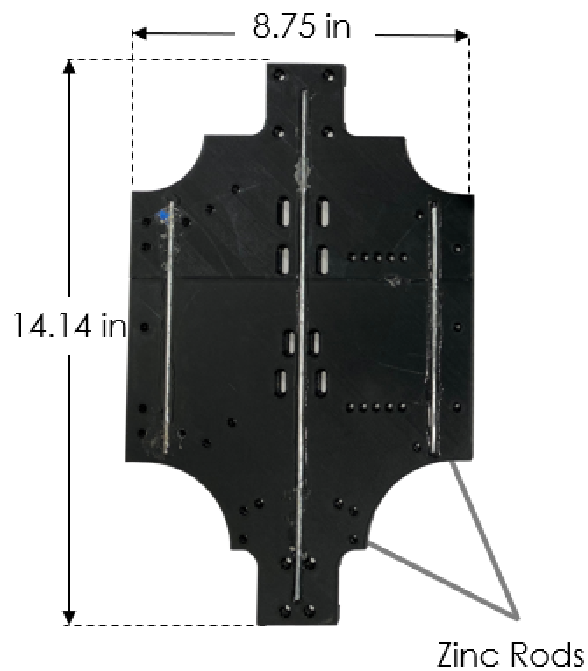


Figure 2-3: Final Chassis Assembly from the 2019-2020 Car

The steering system developed from last year's MQP was developed after three iterations. The final design as seen in Figure 2-4, provided a turning angle of 41.94° and a turning radius of 1.55 ft. This steering linkage was tested by last year's team with a fatigue test that they designed. This test rig is shown in Figure 2-5. The primary goal of this fatigue test was to find a servo motor that would have enough power to turn the wheels.

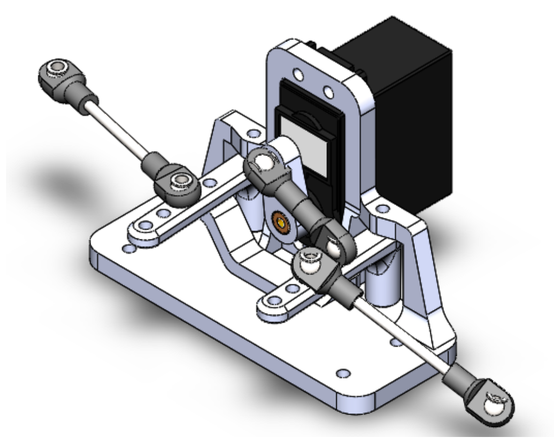


Figure 2-4: Final CAD Assembly for the 2019-2020 Steering Linkage (as Reproduced from Boggess et al.)

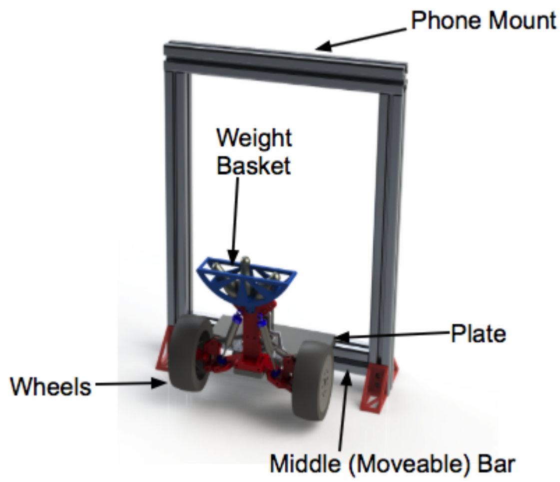


Figure 2-5: Steering Test Rig for Fatigue Test (as Reproduced from Boggess et al.)

Next, the suspension system from last year's MQP also went through multiple iterations till the team finalized the suspension design. The final design results in a wheel travel of 1.3", five different shock mounting positions for different chassis clearances, a spring rate of 5.044 lb./in, a damping rate of 0.429 lb*s/in, and a fatigue life of at least 7,000 cycles. The final suspension design can be seen in Figure 2-6. The suspension was also tested using a test fixture as seen in Figure 2-7. This test fixture was used by last year's MQP team to see the fatigue life of the system.

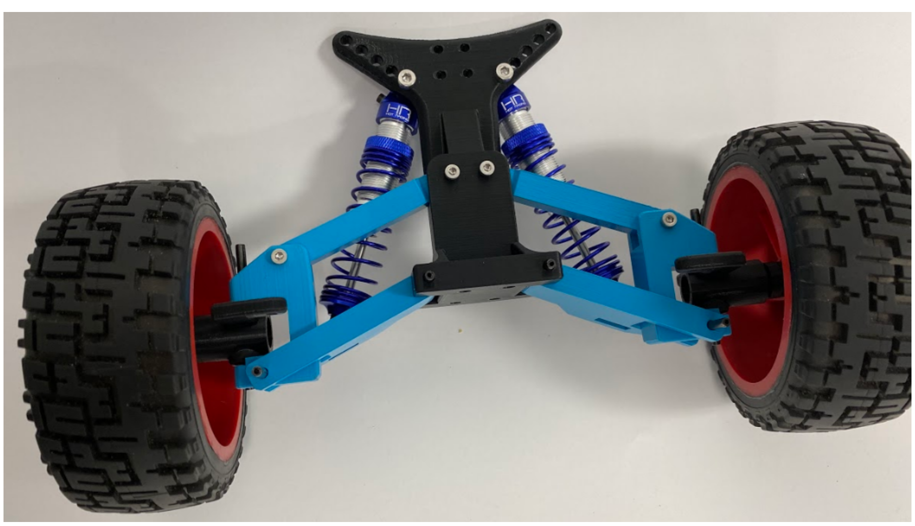


Figure 2-6: Final Front Suspension from 2019-2020 MQP

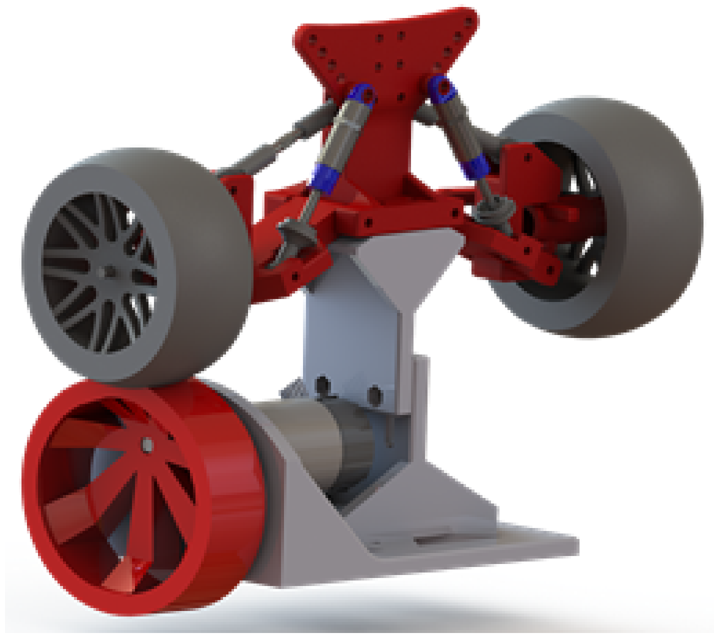


Figure 2-7: Test Rig as Developed by the 2019-2020 MQP Team for the Suspension System (as Reproduced from Boggess et al.)

Next, last year's team also developed a drivetrain for their RC car. This drivetrain included a motor, gearbox, and differential. First off the gearbox selected was a VEX robotics planetary gearbox. This gearbox allowed them to select multiple gear reduction ratios based on what they wanted their car to accomplish (5:1, 7:1, 9:1). The team developed a coupler system to connect the gearbox to the motor and the gearbox to the differential. This system allows for modularity and max performance while driving. Secondly, the differential was chosen as an off the shelf part from Traxxas. Their differential was a 1/10th scaled open differential with a gear reduction ratio of 2.85:1. Thirdly, the motors used in the final car iterations were a Axial AM27 27T 540 Electric Brushed Motor and the Hobbywing XR10 Justock Sensored Brushless ESC/SD G2.1 Motor (21.5T) as seen in Figure 2-8. The final drivetrain assembly can be seen in Figure 2-9.

Figure 2-8: The Two Final Motors Selected for the 2019-2020 MQP Team Cars (as Reproduced from Boggess et al.)

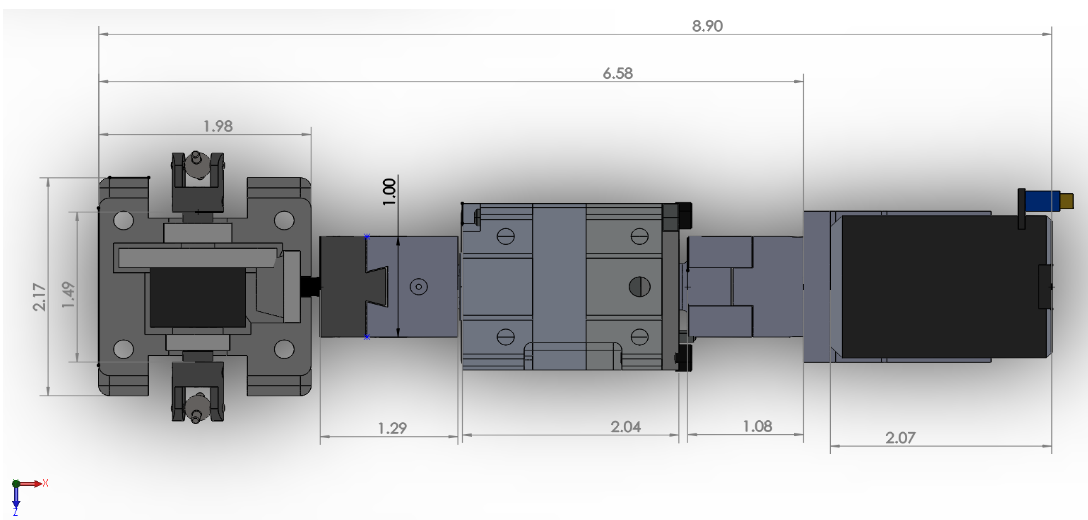


Figure 2-9: Final Drivetrain for the 2019-2020 MQP Team Car (as Reproduced from Boggess et al.)

Another major subsystem last year's team developed for the car is a Control Moment Gyroscope (CMG). A CMG system is a motor-powered mechanism that makes use of the rotation of its components to yield a desired output torque. A CMG is made up of a flywheel and one or more gimbals, which are driven by motors. A CMG works by spinning up its interior flywheel using a motor, which creates an output torque perpendicular to the flywheel axis and helps stabilize the object it is attached to, like a gyroscope. Figure 2-10 shows and example of a

CMG, with the output torque, flywheel axis, and gimbal axis denoted as $H_{w\alpha}$, H_w, and α, respectively. Last year's MQP team utilized an assembled CMG from a previous MQP, with the idea being that it could be used to stabilize the car over obstacles or to right the car if it rolled over. They also considered creating a double-CMG system that could be used to stabilize the car in multiple directions, and to allow the car to climb up steps.

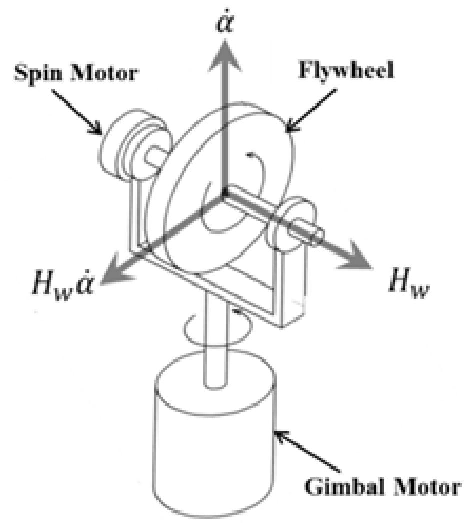


Figure 2-10: Single-Gimbal CMG Example (as Reproduced from Boggess et al.)

When given last year's car, we were able to operate it, and from this initial operation we found it was very maneuverable and easy to use, but was also somewhat unreliable. Hence, we tested the car to see what improvements would be needed and what ideas could we adapt upon for our project and goals with our own car.

Testing

When given last year's car, we were able to operate it, and from this initial operation we found it was very maneuverable and easy to use, but was also somewhat unreliable. Hence, we conducted further testing of the car to see what improvements would be needed and what ideas could we adapt upon for our project and goals with our own car.

For our initial tests, we drove the car around outside on smooth asphalt. The first issue we noticed was the steering. The steering on the car had a very good turning radius, but would wear, and continue to break almost every time we went out driving the car. We noticed that some of the screws continuously became loose, the wheels and linkages seemed to have a large amount of play within them, and the 3D printed linkages had a tendency to break under load. In addition, trying to fix the first problem by tightening these screws would make the second problem worse, as more stress would be placed on the links.

After our initial tests, we decided to take it on some rougher terrain, such as grass, rocks, dirt, and sand. We noticed that the car was able to drive over most of our obstacles on these terrains, but it was always at full throttle; this means that the car did not move in a very controlled manner. Trying to drive the car over obstacles at full throttle could lead to part failure and could potentially lead to the user losing control of the car or at worst the car flipping over. In addition, the rear driveshaft had a tendency to break traction under low grip conditions or over high obstacles, meaning that torque was being wasted, and that the car would occasionally get stuck, even at full throttle.

As a part of our testing, we wanted to add weights to the top of the previous team's car in order to test the strength of their suspension system and chassis. This was done to see how these systems could be improved for our car, as one of our main goals was to develop our new car for payload carrying. During these tests, we put payloads (weights) of 5 lbs and 10 lbs on the top plate of the old car (without the CMG), and drove the car around to see how it could handle it as seen in Figure 2-11. While the 5 lb test yielded no problems, the 10 lb test highlighted a few areas of improvement.

Figure 2-11: 2019-2020 MQP Car with 10lbs on the Top

First off, while the chassis was very strong and managed to handle the load placed upon it, with a 10 lb weight it also began to bottom out on the ground. This was mainly due to the shock absorber system the car used, which was not strong enough to resist the motion of the suspension system caused by the weights. This meant that the car would get stuck on obstacles very easily, and even in more flat terrain such as tall grass. In addition, the extra stress placed on the steering from this weight also highlighted its weaknesses, as it was very fragile in this configuration. Finally, the additional weight caused the RWD drivetrain to struggle somewhat, as while it could still move the car, its top speed was severely decreased.

From testing last year’s car, our team was able to identify the complications and issues with last year's car, and also determined what systems worked very well. With this information, our team planned to improve upon those issues and improve the design for our goals and objectives.

3. Background

The following chapter gives some background into the various systems implemented in last year's MQP (Boggess et al., 2020). Using the recommendations from last year's team, goals we created, we began research into how we could improve each subsystem, as well as research new subsystems that we could add to improve the versatility and driveability of our vehicle (Boggess et al., 2020). This research, as well as the relevant information needed to build PARV, are described in this chapter as well.

Mechanical Components

Suspension System

One of the most important structural systems on both RC cars and full-sized automobiles is the suspension system. The point of this system is to both connect the wheels, and thereby the vehicles connection to the road, to the rest of the car, and to allow the car to move in relation to the ground so traction and stability can be maintained over uneven surfaces. The suspension is also meant to give the car or people within the car a comfortable ride, so when the wheels hit a bump or hole the car does not take a huge hit. The suspension system helps absorb these hits, so the rest of the car does not take damage and the ride is smoother ("Suspension", 2015). The major components of a suspension system consist of springs, shock absorbers, and linkages that connect the vehicle to the wheels while allowing for motion between the two. The type of suspension within a vehicle can vary depending on its intended purpose. For example, some cars use a non-independent suspension while others use an independent suspension.

A non-independent suspension uses a solid axle that connects the two wheels and results in both wheels moving with the same vertical motion. There are two main types of non-independent suspension, coil spring suspension and leaf spring suspension ("Cars"). In contrast, independent suspension allows both wheels to move separately from each other in vertical motion. This independent movement is often seen as an advantage for most cars as allowing individual wheels to move can improve the stability and control of the car. This can make the ride much more enjoyable for the driver. ("Independent"). There are five types of common independent suspension systems: double wishbone, macPherson-strut, trailing arm, swing axle, and leading arm. Of these five, Figure 3-1 demonstrates the differences between non-independent (dependent) and independent suspensions.

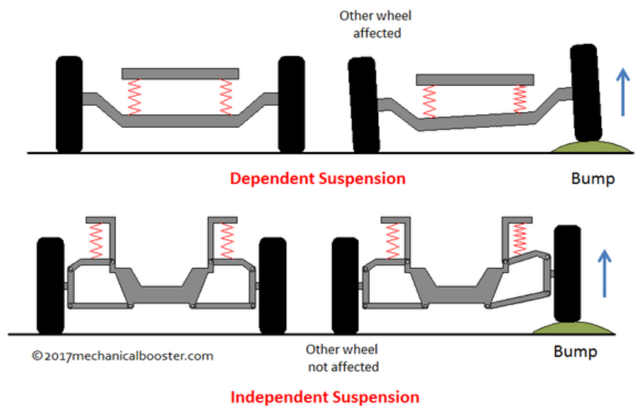


Figure 3-1: Dependent and Independent suspension graphic (as reproduced from mechanical booster, 2020)

One of the most common types of independent suspension systems in use today is the double wishbone system. This system has vertical upper and lower control arms, which can boost negative camber. This system uses two wishbone shaped arms that connect to the wheel. These double wishbones allow for increased control of the wheel unlike the macPherson-strut where there is no upper link/wishbone attached to the wheel. Camber is the inward and outward tilt of the wheels on the car. The suspension system is supposed to decrease the camber as the car drives and goes over bumps and turns; as such, compared to a macPherson-strut, it can maintain higher levels of ground contact, and by extension traction. Hence, the double wishbone system provides a car with better stability as it allows the wheels to touch the ground more. Furthermore, the steering and control of the car will feel better due to this suspension. The only downside of the double wishbones is the cost for integration into a car (Stevens, 2020). As such, these types of systems are usually used for high-performance vehicles such as sports cars, while macPherson-struts are used for more standard sedans and hatchbacks.

For RC cars, an independent suspension is typically used as it provides the best results, especially in a smaller car such as an RC car. The exact type of independent can vary; however, they typically consist of shock absorbers, springs and linkages (Muir, a).

Steering Linkage

Another system that is very important for any car is the steering system. This system allows the car to turn at a desired angle based on the input of the driver. This system consists of a series of linkages that attach to the wheels and steering wheel or (for an RC car) servo motor. For

RC cars, steering linkages typically have a range of motion between 30° and 50° for each wheel measured from the center position of the wheel. The series of linkages amplifies the force input from the servo motor or driver in order to steer the car the desired amount to go the direction needed. While steering systems are seen in every car, the type of system they are can vary. A few of the more common types are rack-and-pinion, Haltenberg, and parallelogram (Muir, b).

A rack-and-pinion steering system uses a pinion gear and a rod or rack. It uses a gear system to turn the wheels a desired amount. The pinion gear is turned by the driver or servo, which in turn will turn the wheels as the pinion gear transfers rotational motion to linear motion on the rack (“Hearst”). Figure 3-2 below shows a simple diagram of a rack and pinion steering system.

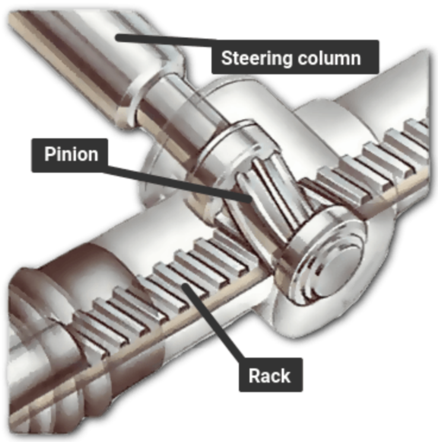


Figure 3-2: Simple Rack and Pinion Diagram (as reproduced from “Hearst”)

Next, a parallelogram steering system only uses linkages to turn the wheels. The linkages consist of a pitman arm, idler arm, center link, and tie rods. Movement is transferred from the pitman arm that is attached to the center link and tie rods. The idler arm keeps the motion steady and within the road (“Steering”, 2013). The figure below illustrates a parallelogram steering system.

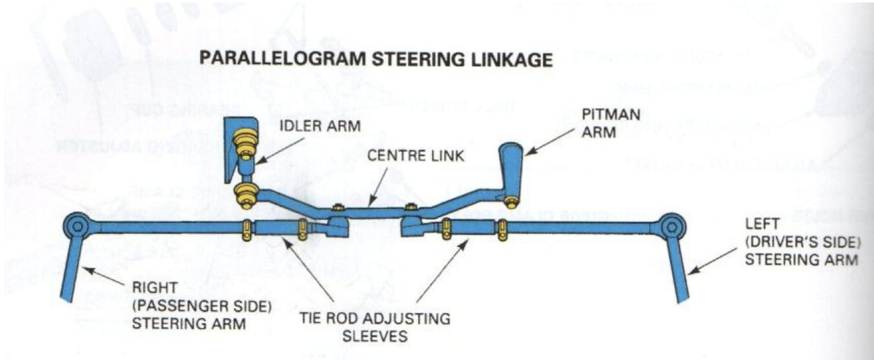


Figure 3-3: Parallelogram Steering Configuration (as reproduced from "Steering", 2013)

Another steering system that many vehicles use is called the Haltenberger steering system. This system uses less linkages then the parallelogram and consists of a tie rods and pitman arm. Figure 3-3 illustrates a Haltenberger linkage; one can notice that one tie rod stretches from the driver side of the car to the passenger side wheels, and the other tie rod is attached to that rod and goes to the other wheels.

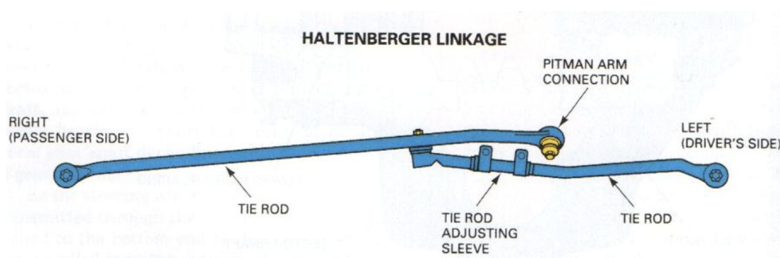


Figure 3-3: Haltenberger Linkage Illustration (as reproduced from "Steering", 2013)

While each of these systems are normally only included on the front wheels of a car, they can also be used on the rear wheels as well. Four-wheel steering is a type of steering system that instead of only turning the front two wheels, all four wheels on the car are turned. Typically, in 4-wheel steering cars the wheel turning can vary depending on the speed of the car. For example, at low speeds the wheels in the front would act normal and turn the direction the driver wants, but the rear wheels will actually turn the opposite direction. This allows the car to have a smaller turning radius and better agility. At high speeds, however, the rear wheels turn at the same angle as the front wheels (Kevin, 2020). This is demonstrated in Figure 3-4.

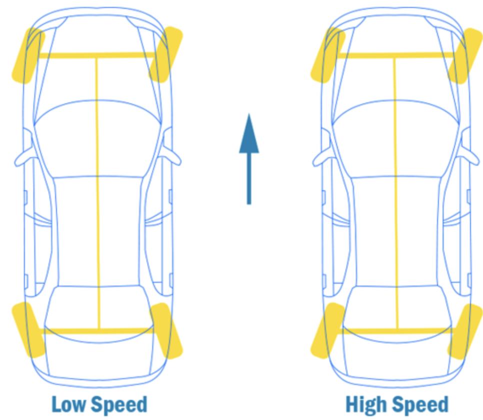


Figure 3-4: Four-Wheels Steering at Different Speeds (as reproduced from "Ackerman", 2016)

Some cars also use an interesting form of geometry with the linkages to create a trapezoidal shape at a location between the wheels of the car. Typically, the geometry is a parallelogram, but some cars use what is called an Ackerman geometry, which allows for one wheel to rotate at a different angle than the other wheels. The outside wheel would turn at a smaller angle than the inside wheel ("Ackerman" 2016).

Since RC cars are essentially just 1:10-1:8 scaled cars, they typically contain a steering system similar to what is seen for a full-sized car. Typically, they use a servo motor, which would act as the driver and linkages to the wheels. Most RC cars use bell cranks, which are basically joints on the linkage that are fixed but allow the linkage to rotate around them. Furthermore, RC steering linkages typically portray a similar form of a parallelogram steering linkage. Figure 3-5 represents a typical RC car steering linkage.

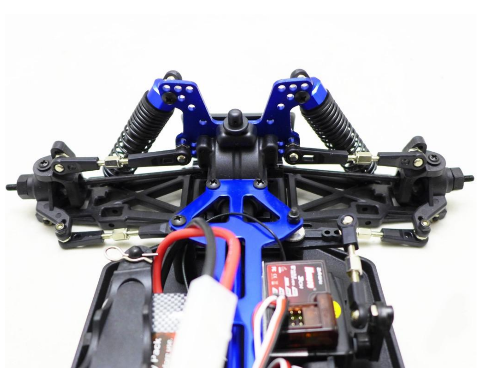


Figure 3-5: RC Car Steering Linkage (as reproduced from "RC", 2016)

Drivetrain

At the heart of a car sits the drivetrain, which works with the engine to move the wheels. Typically, the drivetrain contains the transmission, driveshafts, axles, and wheels. This system takes the power from the engine to produce the desired torque at the wheels. Some of the most common types of drivetrains include four-wheel drive (4WD), all-wheel drive (AWD), and two-wheel drive (2WD) systems ("Mister", 2020).

A four-wheel drive drivetrain is a type of drivetrain that sends torque to all four wheels. In theory, this can increase the amount of traction when driving, as all four wheels will be powered. Typically, 4WD systems are more rugged and can help cars tackle rougher terrain. There are part and full time 4WD systems, where in the full time torque is always sent to all 4 wheels, but in part time the car may have a switch to allow the car to switch between 4WD and 2WD.

An all-wheel drive drivetrain is another type of drivetrain that can send torque to all four wheels. AWD, however, typically do not operate with any input from the driver, all the wheels obtain torque through differentials, couplings, clutches. This series of components help optimize the distribution of power from the engine to the wheels that need the power the most. Full-time AWD always has all four wheels working, while a part-time AWD can switch which wheels get the power; in theory, this means that the car can deliver power to one, two, three, or all four wheels. This process is automatic, unlike in 4WD, and is completed using sensors and a computer (Gareffa, 2021).

Two-wheel drive, as the name states, is a type of drivetrain that sends torque to only two wheels. Those two wheels can be either the front wheels or the rear wheels depending on the car. Front-wheel drive (FWD) is the least complex system and can improve the acceleration and traction of the car while driving. However, steering issues come into play with FWD cars, as the front wheels have less overall traction due to having to both steer and power the car at the same time. Rear-wheel drive (RWD) sends the power to the rear wheels, and this drivetrain can help eliminate the torque steering issues seen in FWD (Gareffa, 2018). However, this system is also more prone to wheel spin, especially if excess power is applied to the wheels.

Typical RC cars use a variety of drivetrain types ranging from 4WD to 2WD configurations. Those drivetrains are combined with different transmissions to help the RC car optimize its capabilities. Typically, 2WD RC cars are cheaper as there are less parts and require a smaller motor when compared to 4WD. However, 4WD RC cars offer better traction, handling, and steering, especially in off-road terrain (Andre, 2014).

Transmission

A transmission converts high rotational speed from a motor or an engine to a desired rotational speed that can be sent to the wheels. There are many different types of transmission, some of the most common including compound gearing, continuous variable transmissions, and a planetary gearbox. These transmissions all take different gear configuration meshes to change the output specifications, torque, and velocity.

Compound gearings use a specific set of gears to increase the torque in the drivetrain. The increase in torque is related to the gear ratio, which refers to the ratio of teeth a gear has compared to the gear it is meshed with. For example, a 5:1 gear reduction means that over five revolutions the output gear will only turn once. There are many advantages that come with using compound gearing as a car's transmission. For example, there is no-slip, large ratios can be achieved, easy to assemble, and capable of handling large loads. However, they can also be bad in situations where a car is driving at high speeds or over a long distance of time and can also be heavy and loud (Warner, 2017).

Continuous variable transmissions, or CVTs, use a belt to drive the wheels instead of gears, and can increase the torque and decrease the rotational speed the motor provides. A CVT system uses two pulleys, one pulley is attached to the engine while the other connects to the wheels. The width of the pulleys is variable and changes based on how much power is needed by the car. So if the car was in need of power the pulleys width would automatically adjust and provide the car with more power. SOme advantages of a CVT can be that it is good for long distances, quiet, no vibration, and automatic so it can have different amounts of torque outputs. CVTs also take up a large amount of space, are prone to fatigue, and the belt can slip. The figure below shows an example of a CVT in an RC car ("Hearst", 2020).

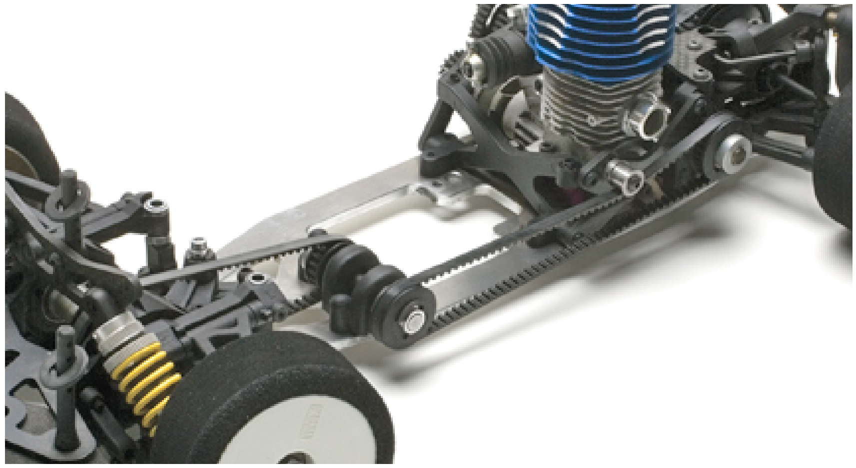


Figure 3-6: CVT in a RC Car (as reproduced from “Hearst”, 2020)

Lastly, some cars may use a planetary gearbox as their transmission. This gearbox is made up of three types of gears: sun gear, planet gears, and a ring gear. 3-7 represents a schematic of a planetary gearbox. The sun gear is represented by the yellow gear and is located at the center. This sun gear transmits the torque from the engine to the planet gears, represented by the blue gears in the figure. These planet gears are typically held together by a carrier represented by the green part. Finally, the ring gear, which is the red gear in the figure, meshes with all the planet gears. This, then provides a set gear reduction ratio for the drivetrain. Planetary gearboxes are very compact, do not slip, and are fully enclosed. Consequently, they are not great at high speeds, are not flexible, and are heavy. Overall, planetary gearboxes are known to transfer the largest amount of torque in the most compact form (“Planetary”, 2019).

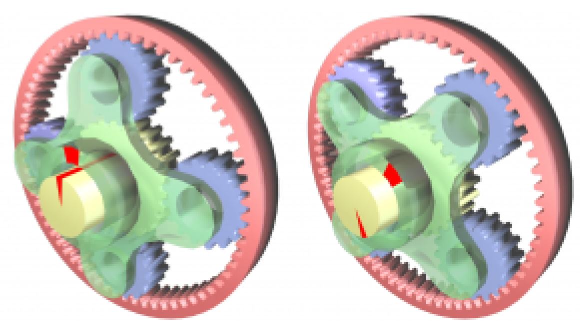


Figure 3-7: Planetary Gear Box Schematic (as reproduced from “Planetary”, 2019)

RC cars can use all of the transmissions listed above to turn the motor power into torque. Each transmission has their own advantages and disadvantages and their use can depend on the intended application of the car. Overall, the transmission, no matter what type, is used to produce a higher amount of torque at the wheels than the motor provides.

Differential

In order to transfer power through a drivetrain and gearbox to the ground, you need to include a differential system. The main purpose of a differential is to transfer power to each wheel on an axle, while allowing each wheel to rotate independently of each other while doing so. This is necessary because, due to differences in turning radii and grip levels on different sides of a car, each wheel on an axle will need to turn at different speeds in order to prevent them from slipping or dragging due to influences from the other wheels (“Types”, 2021). Most differentials consist of a series of interlocking gears and shafts which are powered by the driveshaft using a ring and pinion. However, using this basic design, many different types of driveshafts can be created, each of which perform differently and are used for different purposes.

The most common type of differential used in automobiles is the open differential. This type of differential is essentially just the basic design described before, and its main purpose is to allow each wheel on an axle to spin independently of each other, preventing wheel dragging or slipping during cornering; this decreases wear on the axle and prevents tire damage due to slipping. Of all the differentials, it is the simplest to produce, and by extension the cheapest. An example of this type of differential is shown in Figure 3-8 below.

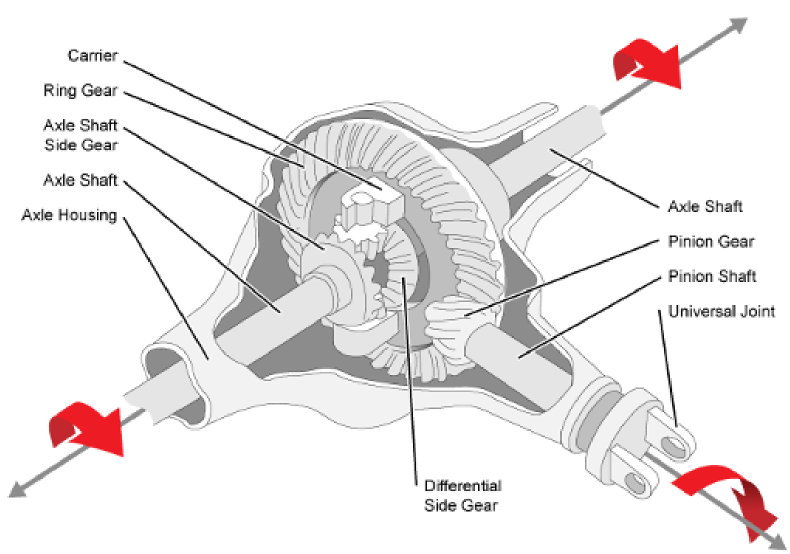


Figure 3-8: Open Differential Illustration (as reproduced from “Types”, 2021)

However, it is also not very useful when dealing with low traction environments, such as those we are looking to tackle. While the wheels spin independently of each other, the design of the gears means that an equal amount of torque is transmitted to each wheel independent of how fast it is spinning ("Types", 2021). This means that, when a wheel loses traction, the wheel will begin to spin faster, decreasing the resistance on the driveshaft. This, in turn, will cause more power to be sent into the wheel, making it spin up even faster and decreasing traction even more. In worse case scenarios, this leads to one wheel spinning freely using all the power of the car while the other does not move at all. Due to this limitation, we decided to pursue a more advanced differential to build for our car.

While many automobiles utilize open differentials, some, especially those that go off-road, include the ability to lock their differentials. This system utilizes a ring and pinion type system similar to the open differential, but includes additional gears that directly connect the two sides of the axle together and can be locked in place, which is shown in Figure 3-9 below.

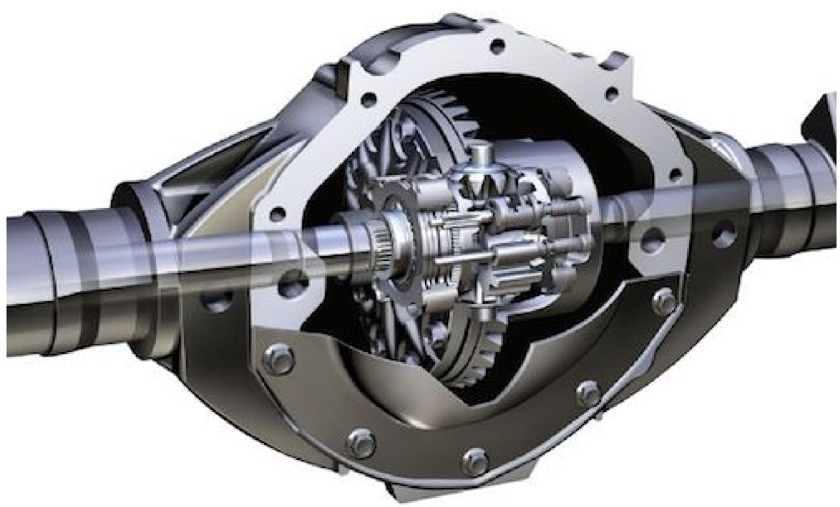


Figure 3-9: Locking Differential Illustration (as reproduced from "What", 2021)

This will force each wheel on the axle to turn at the same speed, as they are essentially on one solid axle. However, unlike with an open differential (diff), the torque applied to each wheel is not necessarily the same, and depends on how much traction each wheel has ("What", 2021). For example, if one wheel on an axle is completely off the ground, all the torque on the car will be sent to the other wheel on the ground, as the force needed to move that wheel would be infinitely higher than the free spinning wheel in the air. As such, traction and torque is never lost, and as such the vehicle can power over obstacles or through slippery surfaces much easier. However, these systems can also lock up at times, especially when an excess amount of torque is built up in the driveshaft, usually caused by a lack of vehicle motion.

As a side note, a direct-drive differential works in the same way, even if it is designed somewhat differently. Instead of using a series of bevel gears, a direct-drive differential simply uses a single ring and pinion gear setup to directly transfer torque and power to a connected axle, and as such is very easy to create. However, this system does not allow for each wheel to rotate independently, meaning that going around any corner will cause wheels on this system to slip.

One of the most common differential systems used in 4WD vehicles is the limited slip differential (LSD). This differential combines the abilities of both an open and a locked/direct-drive differential, as it can mechanically switch between the two depending on the amount of traction through the wheels or torque through the drivetrain. This type of differential consists of a central ring and pinion gear which drives two drive gears, which is similar to an open differential. However, in addition to these gears, there are additional components, such as viscous fluid, friction plates, or as shown in Figure 3-10 below, plate springs, that can either compress or directly lock these two drive gears together under lateral loading. In addition, certain designs, such as a spiral differential, can accomplish the same concept using worm gears to transfer rotational torque between the wheels (Lesics, 2014b).

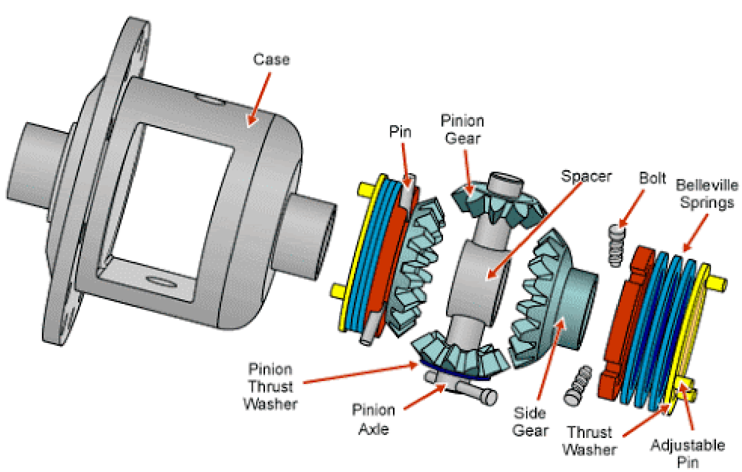


Figure 3-10: Limited Slip Differential Illustration (as reproduced from Lesics, 2014b)

Under normal (or high-friction) scenarios, the differential will spin normally, delivering equal torque to each wheel while allowing each wheel to spin at different speeds, allowing the car to go around corners more efficiently. However, when one wheel loses traction, or when the vehicle is put under heavy lateral load, either from a fast corner or a payload weight shift, the plates around the differential on the side with less traction will compress, locking the differential to the speed of the rest of the drivetrain. This prevents the wheels from spinning up, and also allows for torque transfer between the wheels, preventing one wheel from taking all the torque (Lesics, 2014b). Depending on the design of the LSD, this torque transfer can happen under acceleration, under braking, under turning, or all three.

Another type of limited slip differential is the Torsen Differential. The Torsen Differential is a trademark of JTEKT Torsen North America. Rather than using compressed plates to lock the differential, Torsen uses a combination of spur and worm gears (Lesics, 2014a). The basic idea around the function of the Torsen Differential is that worm gears (orange gears in figure below) are able to rotate worm wheels (blue gears in figure below), but the worm wheel cannot spin the worm gear. Under normal driving conditions, the entire package rotates with the ring gear, the worm wheels do not rotate about their own axis. When the conditions require the wheels to turn at different speeds, the worm gears spin about their own axis at a rate relative to the ring gear. Due to the connection between worm wheels, this system acts as a limited slip differential, connecting each wheel's rotational speed. This connection also solves the issue of torque slipping completely to one wheel when it loses traction.

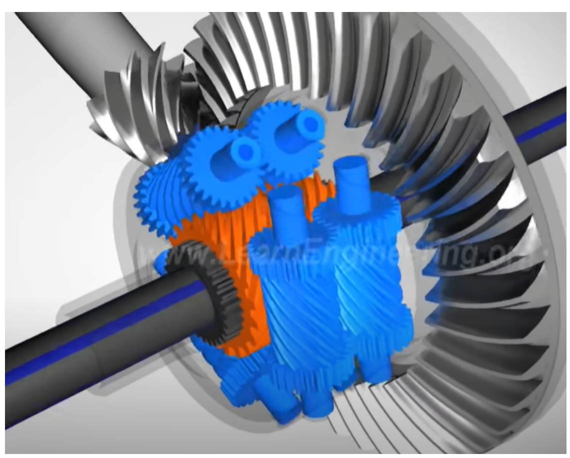


Figure 3-11: Torsen Differential (Reproduced as is from Lesics, 2014) (Trademark of JTEKT Torsen North America)

Many RC cars do not use differentials as they are expensive to purchase, and difficult to make. Rather than using a limited slip differential, most hobbyists use normal differentials, but fill them with viscous oil (“RC”, 2017). Filling the differential with a high viscosity fluid reduces the slip between the two wheels and slightly closes the differential. However, the more viscous the fluid is and the more locked the differential is, the less it acts as a differential in general but rather a direct drive to the wheels.

Compared to other systems, a limited slip differential is very adaptable, as it can change its behavior depending on the driving conditions, and it can allow for greater power and speed control through a vehicle’s wheels. However, it is also one of the most complicated systems to make, and due to its low tolerances, it is more difficult to maintain.

Chassis

While all of the mechanical systems described previously are very important for the operation of a vehicle, they can not work effectively unless they are combined into one package. This is where a chassis comes in; a chassis is the main frame or structure of an automobile, and is the supporting structure for all the machinery and additional payload that a vehicle may have within it (“Chassis”, 2021).

Typical RC cars are made to 1:8 scale of normal cars (James, 2018). This means that an RC car is 1/8th the size of a typical car. This size is small enough to be practical, but also large enough to still be maneuverable and durable. As such, we decided to make our car a similar size. This not only made finding RC components such as motors and transmissions easier, but it also allowed us to compare our car with those RC cars directly.

The chassis of the car is what is responsible for holding all of the components together. This requires a wide range of hardware used to fasten the various components soundly to the car. While also giving a place for components to be mounted, the chassis must also be strong enough to support everything from the various components themselves, or any expected payload.

Trailer System

A trailer system typically is some sort of platform with wheels that can be easily attached to a car. Trailers can come in all different sizes, ranging from ones that use only 2 wheels to ones the same size of a car or larger. Some trailers are made for semi trucks and are primarily used to transport large amounts of cargo. Other trailers are small enough to have a car or pickup truck pull them. Typically, trailers do not have an engine and are just pulled by the car or truck they are attached to. This requires the car or truck to have a powerful enough engine to pull the trailer and whatever cargo the trailer holds ("Home", 2020).

A trailer hitch is required for every trailer as it is a way to attach the car with the trailer very easily. The hitch can be different depending on what is required and what types of trailers will be pulled. Hence, there are smaller, weaker hitches and stronger ones depending on what needs to be pulled. The hitch typically is a form of a tow ball, tow pin, or tow pintle to allow swiveling movement on the trailer. The system also usually has a coupler that can attach to the ball and swivel around it (Daniel, 2020).

RC car trailers are not as common, but do exist. They are typically just scaled down replicas of full size trailers. Hence, they also use a hitch and wheels to allow them to be dragged by the RC car. They are also not usually powered like full sized trailers. However, they are used to help carry an additional payload.

3D Printing

When 3D printing parts, there are many decisions that need to be considered. The first, and most basic decision is material. The most common material used for 3D printing is Polylactic Acid (PLA). This material is both easy to print, and also strong enough for most applications. Almost every part made on PARV uses PLA. Two other materials were also tested for certain applications, Thermoplastic Elastomer (TPE), and NylonX. The application of these materials are talked about in the Trailer, Transfer case, and Differential sections.

3D printing features a vast amount of settings that need to be tweaked in order to achieve the best prints. While a vast majority of these settings vary significantly depending on the type of printer, environment, and age of printer, there are two that are crucial to the performance of the parts. The infill density, and layer height are two of the biggest factors when it comes to 3D printed part performance. Infill density is the amount of material within a 3D printed part. Lower percentages have less material inside, while higher percentages have more material. Figure 3-12 below shows the difference between 15% infill and 100% infill.

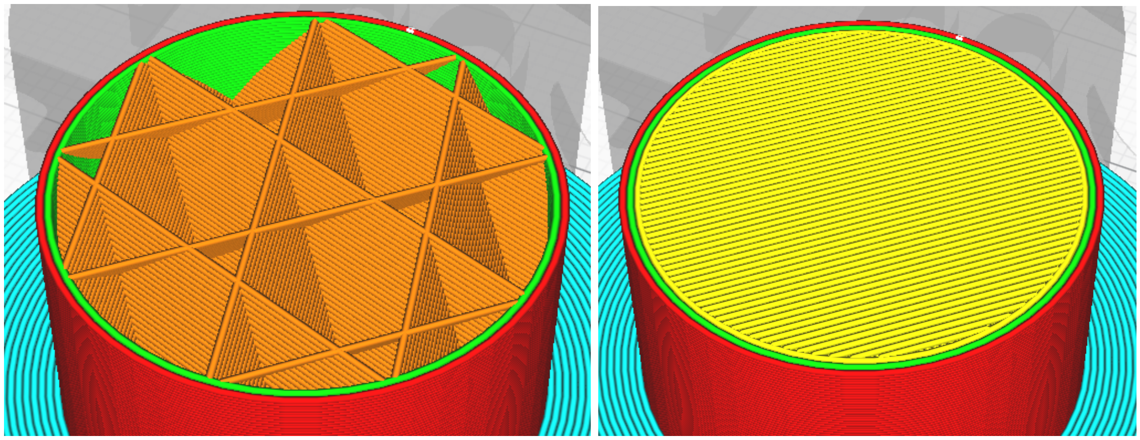


Figure 3-12: Comparison of 15% Infill (Left) and 100% Infill (Right)

As infill density increases (eventually to 100% where the entire inside is filled with material), it gets stronger (Fernandez-Vicente, 2016). The main drawback to this is that as infill increases, so does material costs, and more importantly print time. The example above in Figure 3-12 of a 1" diameter cylinder takes 38 minutes to print at 15% infil, and 2 hours 16 minutes at 100%. For this reason, only parts that would most benefit from the additional strength such as gears or suspension components are printed at 100%.

Another factor that greatly affects print performance and quality is layer height. Most printers can accurately print down to a 0.1 mm (.004") which can result in very accurate prints. A smaller layer height is also important if there are small geometries present. Once again, the main drawback of smaller layer heights is the additional time to print. That same test print from Figure 3-12 (at 15% infill) takes 1 hour 8 minutes to print at 0.1 mm layer height, but 38 minutes at 0.2 mm. For this reason, most prints on PARV are done at 0.2 mm (.008") layer height in order to print quicker. However, when additional dimensional accuracy is required (like in gears, or suspension elements with complicated geometries) 0.1 mm layer height is used.

Since material, infill percentage, and layer height are crucial to the performance of PARV, they have been defined for each component. These specifications, as well as a list of all components for each system can be found within a spreadsheet in Appendix D. This sheet can also double as a print tracking sheet, allowing the user to track and organize the progress of their printing.

Electrical Components

Battery

The battery is a part in all RC cars that holds chemical energy and outputs the energy in an electrical form. The battery powers the receiver, servos, motor, and other electrical components that the RC car may have. The two most popular batteries for RC cars are Nickel–metal hydride (NiMH) and Lithium polymer (LiPo) batteries; the names of these batteries refer to the materials the battery reacts with to release energy. NiMH batteries are rugged, inexpensive, and simple to use; however when under heavy use, especially when driving, one may notice that the car slows down steadily after use of the battery, even at full charge. LiPo batteries are lighter than a NiMH battery and they can also hold their voltage longer as the battery loses power, eliminating the issue with steady decrease in speed with NiMH batteries; however, LiPo batteries are typically more expensive. The most common voltages for batteries are 1.5 V and 3.7 V for NiMH and LiPo batteries respectively ("RC", 2018).

Motor

In RC cars, the motor acts as an engine and is the main factor in the movement of the car. Most motors require a battery, as explained in the previous section, to power them. Most RC car motors can cost around $10 - $100, and need around 4.8V to 9.6V to run. The two main types of motors are brushless and brushed motors. An example of each of these can be seen in Figures 3-13 and 3-14 below.

Figure 3-13: Brushless Motor (as reproduced from Begley, 2019)

Figure 3-14: Brushed Motor (as reproduced from Begley, 2019)

Both of these motors are charged using coil windings to attract and repel magnets, which in turn creates a rotational force and acceleration. Brushed motors have these magnets on the outside shell and the electric coil in the middle. The brushes contact a ring on the coil, which in turn will spin because of the electromagnetic field. In contrast, brushless motors take away the brushes; instead, they work by using a rotor with magnets placed on the inside shell of an electric coil. The coils pulse causing the rotor to spin, with the speed dependent on the amount of voltage through the coil. Figure 3-15 shows a schematic of both a brushed and brushless motor. Brushless motors are more common in RC cars, especially at the hobbyist level. They are more efficient, have higher top speeds, and reduce wear. However, they are more expensive, complex, and have issues cogging, or jumping erratically as it spins. Brushed motors are cheaper and more reliable than brushless motors. However, since the brushes in the brushed motors create physical contact and friction, brushed motors can wear over time and are often inefficient. They also need to be bigger to produce the same angular velocity that a brushless motor can create (Begley, 2019).

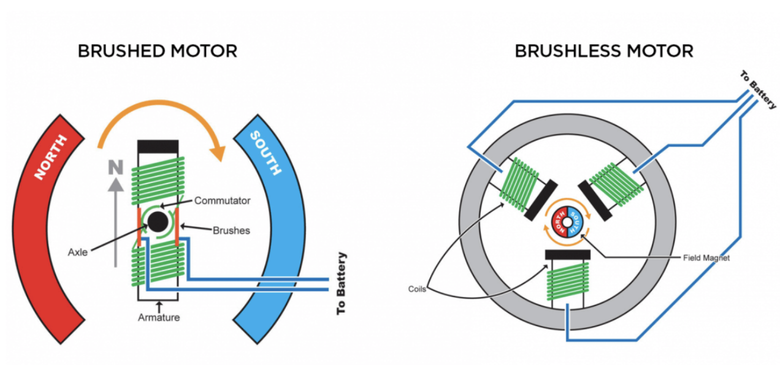


Figure 3-15: A schematic of Both a Brushless and Brushed Motor (as reproduced from Begley, 2019)

Electric motors also use an electronic speed controller (ESC), which controls the power of the motor. They take the reference input from a joystick, throttle, or other input and adjust the duty cycle of the transistors, which in turn changes the speed of the motor. ESCs can come in brushed form or brushless form and they can be used on a brushed and brushless motor respectively.

Servo Motors

Servo motors are used in RC cars for multiple purposes, from operating steering linkages to controlling the throttle of the car. 3-16 shows an example of a servo motor that is used in an RC car. Servo motors typically cost between $40 - $500. A standard servo motor will run at a speed of 0.21 s/60° at 4.8V; 0.16 sec/60° at 6V at no load, and it has a torque of 45.8 oz-in (3.3kg-cm) at 4.8V; 56.9 oz-in (4.1kg-cm) at 6V. They are usually rotary actuators and can be used to gain an exact position of the motor, unlike other brushless or brushed motors. Servos work using a small DC motor and a series of gears to gain the desired amount of torque. They can turn at a desired result using sensors and circuit board configuration. Servos are often used in the steering system because they can be switched on and off and can be very precise with their amount of output and only turn as much as the operator desires (Eglowstein, 2012).

Figure 3-16: Steering Servo (as reproduced from Eglowstein, 2012)

Sensors

Sensors are important tools for any type of mechanical system, as they can help detect events and changes in the environment around them. Sensors can come in all shapes and sizes, and they can have a variety of purposes. For our base RC car, sensors such as hall effect sensors and LiPo battery gauges can be useful, while for our desired autonomous integration, sensors such as temperature/humidity sensors, ultrasonic sensors, orientation IMUs, and wide angle cameras can be used.

Typical temperature/humidity sensors read the air around them using a capacitive and a thermistor. This can be important information to gain in an RC car with a battery, servos, and a motor as all of these components and others can overheat after driving. An ultrasonic sensor measures the distance from a target object by sending sound waves. The reflected signal after hitting a target object is then read by the sensors as an electrical signal. An orientation IMU sensor can measure the specific location or orientation of the body. It uses a combination of accelerometers, gyroscopes, and magnetometers. In an RC car, this sensor can be helpful to measure where the car has traveled. A hall effect sensor uses a magnet which can create a magnetic field which is then read by the sensor. This sensor within an RC car can potentially read the RPMs of the motor or the wheels as it drives (Teja, 2021).

4. Project Requirements and Goals

During the first couple weeks of our project, our team determined the baseline requirements and goals we wanted to accomplish with this year's car. These goals were determined via input from last year's MQP by Boggess et al., our advisor's desired goals, and our own general purpose for this car. In addition, we had to determine the objective of our autonomous RC car, as having specific goals is not helpful if there is no purpose to them. After some deliberation, we decided on making our RC car an outdoor delivery robot, capable of delivering packages to various locations on the WPI campus. This requires a general set of criteria, some relating to its general use, and others relating to required components for the car. Our desired criteria for all of the major components are listed below.

Overall Needs

Our general needs for the car are as follows:

1. The car shall be a 1:8 scale car
2. The car shall be electrically powered
3. Must be modular to allow for multiple new systems to easily be added or swapped
    a. Pieces can be easily swapped, replaced, and recreated
    b. Car can have attachment systems easily added on
4. The car shall include front and rear suspension for bump absorption and a more stable, controlled drive
5. The car shall include a steering system
6. The car shall include 4WD drive, including a transfer case to switch between RWD and 4WD
7. The car shall include a front and rear limited slip differential to improve the cars traction and torque output while driving on off-road terrain
8. The car shall include a brushless motor, and a transmission
9. The car's chassis shall be able to support all components and requirements
10. The car shall have the capability to drive both manually and autonomously

Obstacle Requirements

Our specific requirements for the obstacles the car is expected to navigate are as follows:

1. The car shall navigate a variety of different terrains, including: grass, dirt, rocks, wet road, ice, and snow
2. The car shall traverse all obstacles (up to 4” tall) or terrains (mentioned above in requirement 1) in a controlled manner, meaning at minimal speed
3. The suspension shall be able to go over bumps or steps that are 4” tall, a common size of obstacles found outside
4. The car shall be able to navigate tall grass ranging from 2-3” tall
5. The transmission system must output a torque level that allows the car to traverse up a 30° slope in either RWD or 4WD mode with no payload
6. The transmission system must output a torque level that allows the car to traverse up a 20° slope in 4WD mode at full payload weight (20 lb)

Suspension System Requirements

Our specific requirements for the front and rear suspension system are as follows:

1. The front suspension system shall connect to the steering system and differential, and allow for the passage of a driveshaft through it to the wheels
2. The rear suspension system shall connect to the differential, and allow for the passage of a driveshaft through it to the wheels
3. The suspension shall be able to pass a fatigue test of 7,000 cycles and last for at least half a mile of travel
4. The suspension will include an adjustable shock absorber in order to change the chassis height and suspension travel to better suit different types of terrain
5. The suspension system shall be printable on a 3D printer using standard materials like PLA or ABS which are very common

Steering Linkage Requirements

Our specific requirements for the steering system are as follows:

1. The steering linkage shall have a minimum turning angle of 30° for each wheel
2. The steering linkage shall last least a mile of travel to simulate a delivery
3. The steering system shall be compact in order to take up a small amount of space on the chassis

4. The steering system shall not interfere with the drivetrain or differential systems on the front of the car
5. The steering system shall be printable on a 3D printer using standard materials like PLA or ABS which are very common

Drivetrain Requirements

Our specific requirements for the drivetrain system are as follows:

1. The drivetrain shall power the vehicle up to a minimum of 4 MPH
2. The drivetrain shall be able to be run in both RWD and 4WD modes
3. The drivetrain shall be able to output equal levels of torque to both the front and rear wheels
4. The transfer case shall be switchable between RWD and 4WD with a servo
5. The transfer case shall be printable using either PLA or NylonX on a 3D printer
6. The drivetrain shall be able to connect to both the transmission and differentials without appreciable friction

Gearbox Requirements

Our specific requirements for the gearbox are as follows:

1. The transmission system shall be able to connect to both the motor and the drivetrain system without appreciable friction
2. Shall be able to increase the torque in the drivetrain
3. The gearbox from last years MQP shall be integrated with the 9:1 ratio

Motor Requirements

Our specific requirements for the motor are as follows:

1. The motor shall be able to reliably power a transmission and drivetrain system
2. The motor shall be able to drive the car both forwards and backwards
3. The motor shall be able to connect to the transmission without appreciable friction

Differential Requirements and Goals

Our specific requirements for the front and rear differentials are as follows:

1. In normal conditions, terrains and areas where the wheels do not lose traction, the front and rear differentials shall output an equal amount of torque to both sides of the axle
2. In slippery conditions, where the wheels are raised off the ground or a losing traction to the ground, the differentials shall be able to transfer power between the wheels on each axle
3. The front and rear differentials shall be printable using either PLA, NylonX, or TPU on a 3D printer
4. The differentials shall be able to connect to both the drivetrain and wheels without appreciable friction

Chassis Requirements and Goals

Our specific requirements for the chassis are as follows:

1. The chassis shall be able to support a maximum load of 20 lb total on the car (payload and components) with negligible deflection of a quarter inch
2. The chassis shall be shaped so all subassemblies and components can fit on it without appreciable overhang
3. The chassis shall not interfere with the operation of any other component meaning another component should be able to move freely without hitting the chassis
4. The chassis shall include mounting points for carrying payload
5. The chassis shall be designed with allowing for the easy swapping of modular subassemblies in mind
6. The chassis shall be printable on a 3D printer using standard materials like PLA or ABS which are very common

Trailer System Requirements and Goals

Our specific requirements for the trailer system are as follows:

1. The trailer system shall be powered with rear wheel drive similar to the main car
2. The trailer system shall be able to support a maximum load of 5 lb total on it (payload and components) with negligible deflection
3. The trailer system shall include attachment points that can be used to attach it to the main chassis

4. The trailer system shall include mounting points and walls that can be used to attach and hold a payload or other equipment

Battery, Servo, and Electronics Requirements and Goals

Our specific requirements for the battery and servo systems are as follows:

1. The battery shall be able to run the car and all its subsystems for a minimum of half a mile continuously
2. The battery shall include an easy to reach power switch
3. The steering servo shall be able to run for half a mile intermittently without appreciable loss in performance
4. The transfer case servo shall be able to switch the mode of the car from RWD to 4WD and back again reliably during the lifetime of the battery
5. The electronics shall be organized in a centralized spot on the car in order to prevent excessive wires

Autonomous Driving Package Integration Requirements and Goals

Our specific requirements for the autonomous driving package integration are as follows:

1. All components shall be mounted to the car in appropriate positions (as determined by sister MQP team)
2. Package mounting shall be adaptable to changing component requirements
3. Support sister MQP team with wire management
4. The electronics shall reliably run and receive data from various sensors on the car (ultrasonics, hall-effect, etc.)

5. Methodology

This chapter describes the basic objectives we had for PARV and each of its various subsystems. These objectives were based on the research we did in Section 2 and our goals in Section 3. This chapter also describes many of the ideas we came up with and tested during the development process, as well as the methods behind most of our manufacturing, assembly, and testing procedures.

Concept of PARV

From the start of the development process, PARV, which stands for 3D Printed Autonomous Robotic Vehicle, was designed with a few basic concepts in mind. While the previous team's car was very good at handling indoor tracks and small obstacles, we felt that it was not advanced enough to accomplish their main goal of being a rigorous self-driving package or like a Mars rover. One of the biggest downsides to last year's car was its inability to reliably travel over rough outdoor terrain such as high grass, rocks, or snow. As such, one of the main goals behind PARV was to create a package that could be driven in both RWD and 4WD modes, so that it could be used in all (or at least nearly all) environments. Developing a package like this would require multiple new components, such as a transfer case and limited slip differentials to control power output through the wheels. Another goal behind PARV was to create a modular platform that could use a number of different types of subsystems, such as various steering and suspension linkages, to achieve multiple different end goals, some of which are described later. As a part of this modularity, we designed most of the subsystems, or at minimum their housings, to be printable on a 3D printer so that any of these subsystems could be replaced, repaired, or recreated very quickly and cheaply.

Our end goal behind PARV was to create a vehicle platform that could be used for more than experimentation. Using our desire to create a modular 4WD platform, as well as our sister team's desire to create an autonomous vehicle, we came up with the idea of turning PARV into an autonomous delivery vehicle. This vehicle could in theory go anywhere, and as such could help save time and manpower in the package industry, as well as, in the time of COVID-19, increase safety by preventing human to human contact. As a part of this goal, we also came up with the idea of creating a trailer system for PARV as well; this system would attach to PARV using a universal system, and become an auxiliary payload carrying device for the vehicle, allowing for the transportation of multiple packages or scientific instruments.

<u>Overall Development of PARV</u>

Our overall development process for PARV is described below. This process describes the general design, manufacturing, assembly, and testing methods we used for all of our individual parts and subassemblies.

Our MQP was a continuation of a previous team's project; as such, we began by reviewing the work last year's team did on the car. While their work was disrupted by the COVID-19 lockdown, they still managed to develop a working prototype of their car, and through their report, we were able to determine how to recreate it as a starting point for ours. In addition, we also took note of any ideas or suggestions they had to improve the car, and compared them to our ideas to see which ones could be combined or refined. Once we had finished reviewing the previous MQP, we began research on various different mechanical systems for our car; this research was detailed in the Background section of this paper. As part of this research, we also created Matlab code to test various types of drivetrain configurations, such as different motors and transmission ratios, to see which combination would deliver the best ratio between torque and power. This Matlab code used a variety of power equations to simulate the driving of the car, and the power losses due to different efficiencies of the systems in the car.

Around the time A-Term ended, we had begun work on creating our vehicle in CAD. We started by determining which parts we were going to keep, or at least use as a base for our current car, and created a general chassis outline using those parts. From there, we either redesigned these parts to better fit our vision of the car, or we designed new ones based on subassemblies we wanted to include into the car. These individual parts were then mated to the main assembly and redesigned to better fit onto the car. We then used free body diagrams and ANSYS simulations to do stress calculations and testing of critical parts.

Once each of our parts were refined, we turned the CAD models into STL files so they could be sliced and printed on a 3D printer. These initial prints were designed to be rough prototypes, with the idea being to see how these parts fit together in the real world compared to how they were displayed in CAD; as a part of this, we created a verification document that compared our desired part dimensions and the actual ones. We then began the assembly process for the first iteration of our car, testing the individual components as we attached them, reprinting and remachining parts as needed. Once the first iteration was completed, we began doing physical testing of the entire vehicle to see where weaknesses in the design or the material of the car were. Any parts that failed or performed worse than expected were either redesigned and reprinted or replaced with stronger purchased parts. In addition, new components were created that would add onto and improve the operation of the 1st iteration of the car. Initially, our plan was to create an entirely new 2nd iteration of the car, with new versions of every part. However, as we assembled the car and redesigned each part, we found it was more efficient to just maintain the same base chassis and mounting points and just make 2nd iterations of parts that needed to be heavily redesigned; this would not only save time, as printing an entire car would take a long time, but also save money and 3D printer filament. Once each of these parts were redesigned and remanufactured, they were assembled together into the final version of our car. Figure 5-1 shows a picture of the final car, PARV, completely assembled.

Once the second iteration of components were fitted, we began more rigorous testing on it. This involved doing distance, obstacle, and strength tests on the vehicle as a whole, and doing individual tests on each subassembly. In addition, we also gave our 1st iteration of our car to another MQP team so they could begin integrating various sensors and a self-driving program into the operation of the car. Any problems we encountered during this part of the project were noted and fixed if there was time to do so. However, not every component was able to be redesigned from this point on as we were in D-Term as this point. In addition, we had also begun assembly of our trailer system at this time, which was essentially a simplified version of our main car, so we switched our focus towards that part of the project for the last half of the term.

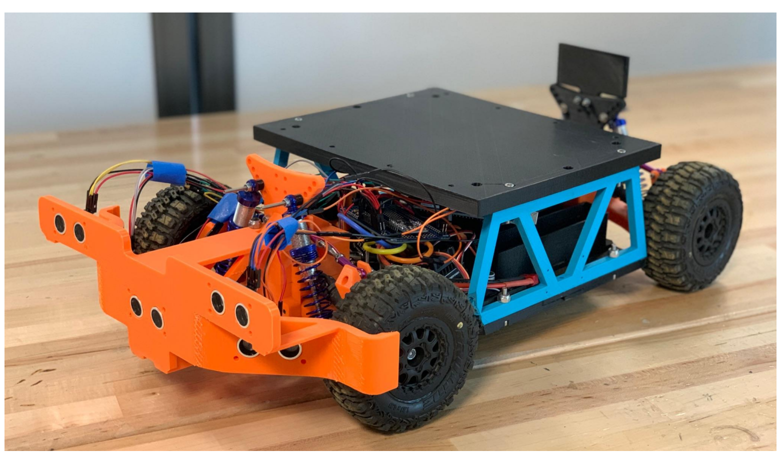


Figure 5-1: Final Picture of PARV

Refinement of the Suspension System

Looking at the development of last year's suspension system, the previous team went through multiple iterations of its design. In addition, they had managed to create a testing fixture for the suspension before COVID slowed their project down, meaning that their suspension was the best developed part of their car. As such, we wanted to keep the same suspension concept on our car.

Instead of having to develop a brand new suspension concept, the primary challenge presented to our team was the need to have a drivetrain/shaft go to the front wheels. The suspension system last year did not account for this need as they were a primarily rear-wheel drive car. Hence, the need to redesign the suspension system was crucial for our goals. Also, after testing last year's car, this year's team noticed that with additional payload on the car the suspension system was not strong enough to hold 15 lbs of additional weight and the car would bottom out. Therefore, the ride height and the shock absorbers need to be adjusted.

The first iteration of our suspension involved creating new parts that were based off of last year’s parts. These parts were adjusted to perform better and become more modular. We used screws to connect all of our suspension pieces to allow for movement. To compensate for the drive train in the front wheels, we designed new parts that allowed the drivetrain to be sent through them while also allowing movement both for the steering and suspension systems. The parts were designed in a similar way to the rear suspension parts.

Our final iteration of the suspension system was pretty similar to our first iteration, but with adjusted hole sizing and swapped out screws for pins to allow for better movement. We also ended up using the same shock absorbers as last year but increased their height. We had some difficulties with the new stronger springs that we ordered not fitting correctly, so had to revert to the old springs. Figure 5-2 below shows the final product of our suspension system.

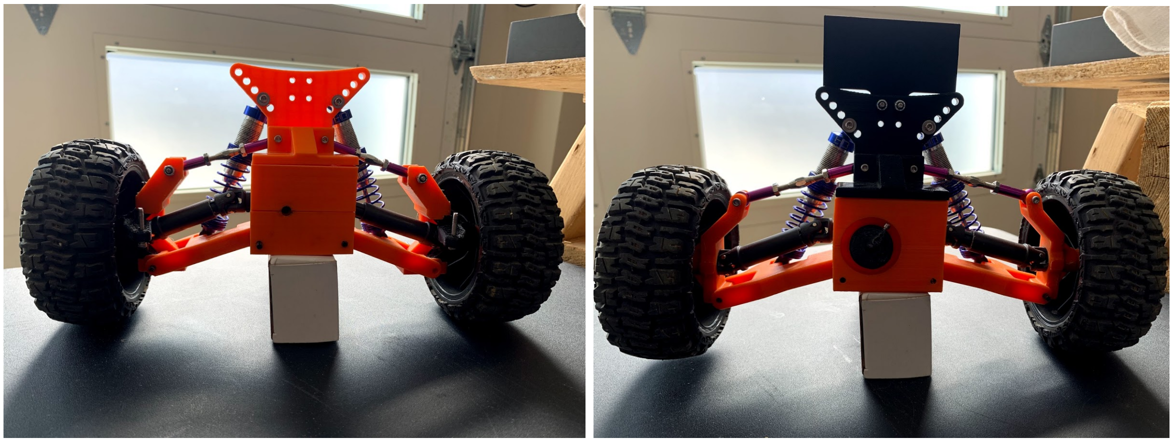


Figure 5-2: Front (Left Image) and Rear (Right Image) Suspension

Redevelopment of the Steering Linkage

The steering system the team developed last year performed very well initially, but the design was not very durable, with the links loseinging, and servo weakening after little driving. Our team knew that the addition of four wheel drive, and the required front drive shafts would result in a new steering design, since there was little room for the linkages. The motion of the steering was also limited by driveshafts and would not be able to achieve the 45° of turning from last year. The steering linkage was one of the last components to be designed because we were unsure of how much space would be available for it. Unlike the parallelogram design from last year, our steering linkage used an Ackerman design, which had geometry more similar to a trapezoid. This allowed the inner wheel to turn slightly more than the outer wheel to better accommodate the different turning radii each wheel experienced.

Our first iteration of the steering linkage was based on a basic bell crank mechanism and Ackerman linkage. The linkage was simulated in Working Model to ensure it would be able to achieve a steering angle of 30°. All the parts were designed to fit together with screws and lock nuts to remove the durability issue. Two links were designed to be adjustable turnbuckles to fine tune the steering system. A turnbuckle was also used as the drive link for the linkage from the servo.

These turnbuckles proved to be a large source of the issues in our linkage. For our final iteration, we changed the turnbuckles for rigid links with ball joint ends. This greatly reduced the amount of play in the linkage and its performance. We also made changes to stop the linkage from reaching a toggle position. The use of lock nuts, washers, and a stronger servo made the linkage much more durable as well. The final iteration of the steering system is shown in Figure 5-3.

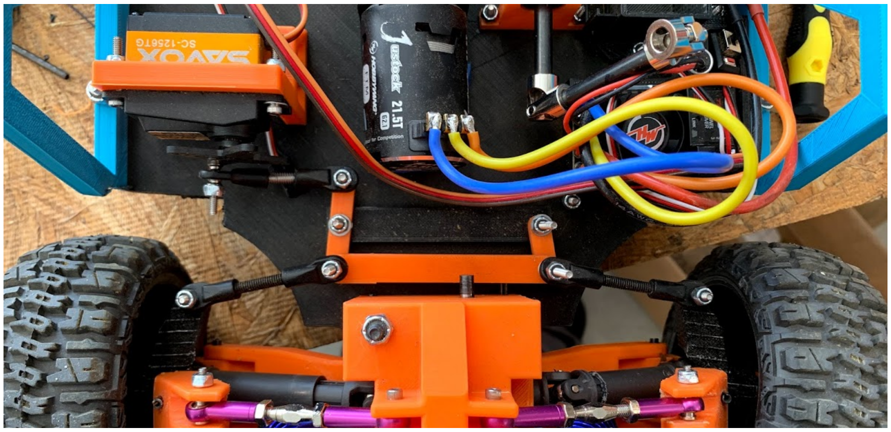


Figure 5-3: Final Steering System

The team last year also had a lot of troubles with servo selection. The initial servo used was far too weak, and while they did purchase a new one, they were not able to test because of COVID-19 lockdowns. We used this new servo to great success.

Development of the Drivetrain

The drivetrain required a good amount of redesign, while at the same time used various components from last year. In order to integrate four wheel drive a transfer case needed to be added, requiring all of the couplings and mounting positions to be redesigned. Figure 5-4 shows a top down view of the final assembly of the car and each part of the drivetrain labeled.

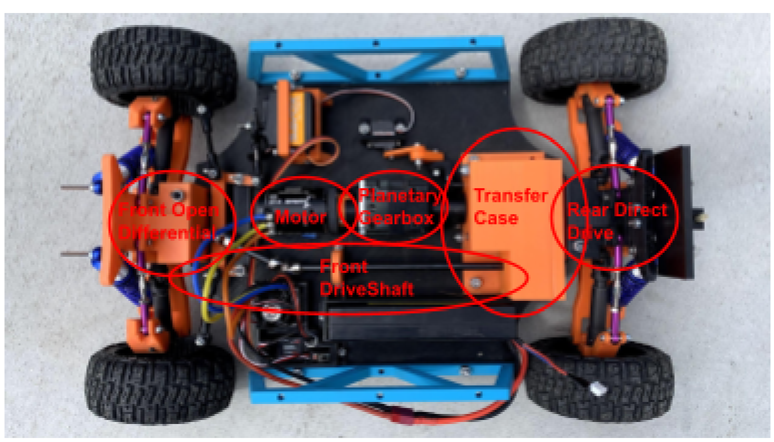


Figure 5-4: Top Down View of the Final Car with Labeled Drivetrain Components

Motor

As mentioned in the Background section, a Matlab analysis was done for the drivetrain. One of the main goals of this analysis was to determine the needed specs of the motor. The team last year went through various iterations of motors, but the motor they used for the final iteration of their car worked the best for them. Using this motor as a starting point, we created some Matlab simulations that compared it to other motors we found online to see which ones could handle a 4WD system the best. The goal was to determine which motor could distribute enough torque to each wheel so that it could move even under a full payload. Following our own calculations, we found that this motor would also meet our requirements. We decided to re-use this motor as it allowed us to save money, as well as use a motor the team last year was familiar with and documented in their report. This motor comes packaged with an electronic speed controller (ESC), and is purpose built for RC cars so it can easily connect to remote control receivers. The motor is driven using a 7.4 V, 5200 mAh Lipo battery. Figure 5-5 and 5-6 represent the motor and battery used in PARV

Figure 5-5: Brushless Motor and Electronic Speed Controller (ESC) (Hobby Wing, 2019)

Figure 5-6: 7.4 V 5200 mAh Lipo Battery (Common Sense, R.C., 2018)

Gearbox

The team last year used a store bought, VEX Planetary gearbox. This gearbox reduced the RPMs of the motor, but greatly increased the torque created. We saw no issues with using the same gearbox as them following our Matlab analysis into the drivetrain. While we considered designing a 3D printed gearbox to replace it, we decided that may be too difficult with the strength of 3D printing, and to prioritize other components. Figure 5-7 represents the VEX planetary gearbox used in PARV.

Figure 5-7: VEX Planetary Gearbox (VEX, 2020)

Four-wheel Drive

As mentioned previously the addition of a 4WD system and the capability to change from 4WD and 2WD was a large goal of this project. Hence, the team had to design a 4WD system for the car. This would give the car more torque split between all four wheels instead of just two. Having four wheels allows the car to have more frictional surface contact to the ground with powered wheels, which can help it overcome larger, slippier obstacles. To design this system, our team used a motor and gearbox as discussed above, a transfer case, and two differentials.

A transfer case is a system that can split the power from the motor or engine of a car and send it to the front wheels and back wheels. For this project, we created a transfer case that used three 3D printed gears. These printed gears created a 1:1 ratio so as to not lose any rotational speed, therefore the front and back wheels will not obtain the same torque and power. The transfer case also used a sleeve that was attached to a four-bar linkage. This sleeve can move back and forth on the metal shaft from the transmission. When 4WD is needed the sleeve will be moved to lock onto the gear mesh, which will split the power to the front and rear driveshafts. The four-bar slider-crank linkage is connected to a small servo motor that when engaged usually a controller can move the sleeve back and forth engaging and disengaging 4WD. When 4WD is not engaged the gears will not turn and the driveshaft from the transmission will be sent directly to the rear driveshaft. The entirety of the transfer case was 3D printed using PLA at first except for the shaft and a few bearings. Initially, the team wanted to print the gears using a material called NylonX as we believed it would be stronger than PLA, but we had some issues being able to print it; hence, the final design of the car used PLA printed gears. However, these gears have been able to hold up very well, mainly due to their individual designs where the gear teeth are parallel to the outer surface of the gear. The transfer case can be seen below in Figure 5-8.

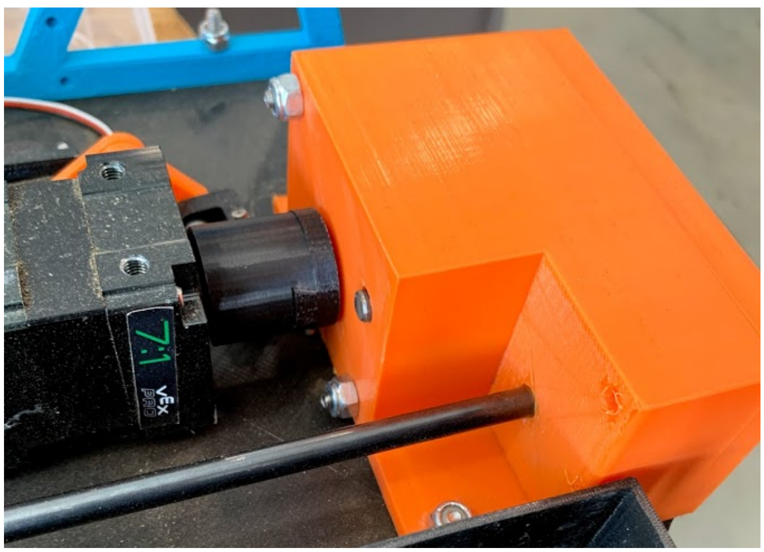


Figure 5-8: Transfer Case

As mentioned before the 4WD system uses two differentials. The differentials allow the power and torque to be split between the two wheels either in the front or the rear. The design of this system will be discussed in the next section. Additionally, to design the driveshafts the team purchased metal quarter-inch bars, metal universal joints, and Traxxas driveshafts that connect to the wheels from the differentials.

Development of a Differential System

One of the biggest points of improvement we identified based on the car from last year was the open differential. When driving the car around uneven, or slippery obstacles, the open differential would often allow power to slip to one wheel. Since torque is split equally between wheels in an open differential, when a wheel loses traction, the wheel will begin to spin faster, decreasing the resistance on the driveshaft. This in turn will cause more power to be sent into the wheel, making it spin up even faster and decreasing traction even more. In worse case scenarios, this leads to one wheel spinning freely using all the power of the car while the other does not move at all (Lesics, 2014). We found that this would often happen to last year's car, as one wheel was elevated off the ground due to an obstacle, or on some loose sand or grass. As described in the Background section, we identified various types of differentials through research that solve this problem, one of which is a Limited Slip Differential (LSD).

We decided to research and design our own version of a Limited Slip Differential. The LSD would allow for the same required functions of a differential, while preventing power being able to freely slip to wheels with less traction.

The LSD was designed on CAD, and 3D printed, however a good amount of obstacles were encountered. The first of which were the results from stress analysis on the gears, which pointed at the possibility of the gear teeth being too weak. Once the parts were printed there were also issues with manufacturability. Due to the complexity and small size of the gears, the 3D printers were at the limit of the tolerances. This meant that many of the smallest gears, despite their shapes actually matching the CAD models, had no support within them, so they could easily break. The actual assembly of the LSD's themselves was also difficult due to the number and size of parts, and the fact that many parts relied on tight tolerances. The attempted assembly of the LSD can be seen in Figure 5-9.

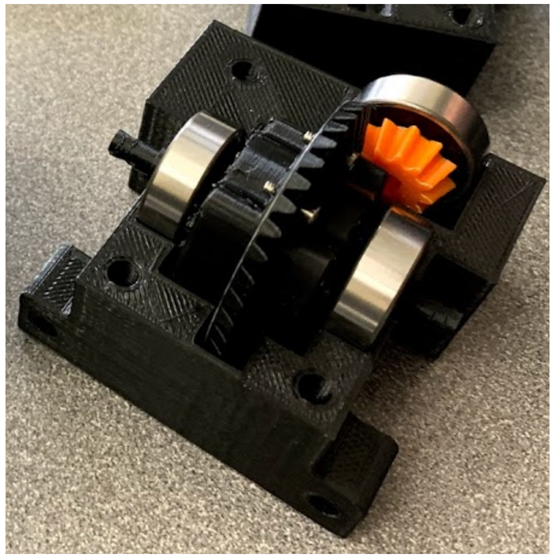


Figure 5-9: 3D Printed Limited Slip Differential

We had some ideas on how to fix problems, and rework the LSD, however we determined it may be best to put the design on the back burner and use a simpler design. This simpler design included a direct drive gearing on the rear axle, and the open RC car differential used last year on the front axle. Figure 5-10 represents the RC car differential assembled within PARV. This combination allowed us to overcome the power distribution issues caused by certain obstacles, as well as maintain the essential properties of a differential allowing different rotation speeds at the front of the car under turning.

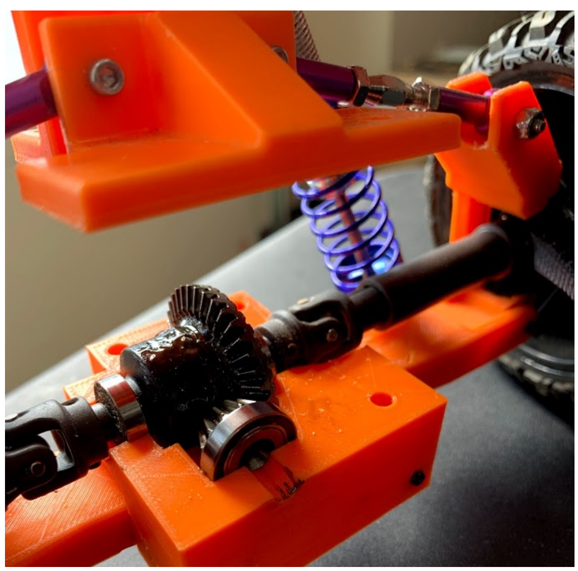


Figure 5-10: Traxxas RC Car Differential

The direct drive on the rear axle was initially conceived to be a fully 3D printed part, and would utilize the same ring and pinion gear design as for the LSD; the main difference would be that there would be no gears within the ring gear, and the wheels would be connected directly to the ring gear. However, during testing we found that the 3D printed gears were not strong enough to handle the torque through them, which meant that they would either break off or bend and misalign. As such, we changed this design to a fully metal direct-drive differential that we included within our original 3D printed housing and can be seen in Figure 5-11.

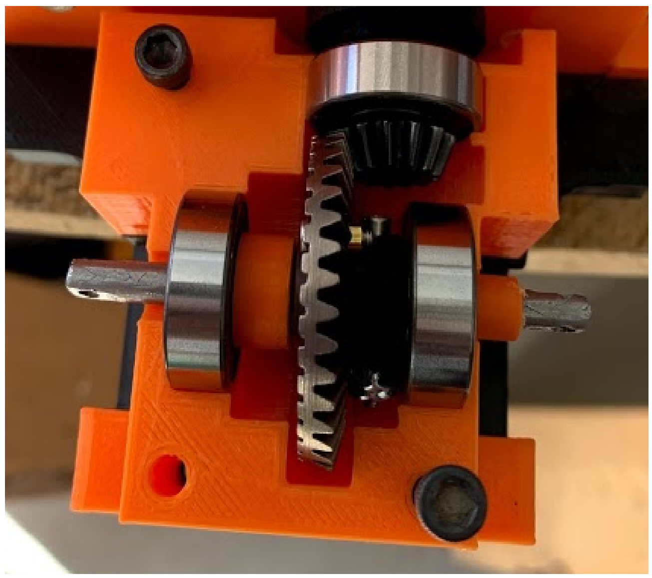


Figure 5-11: Direct Drive Differential

Redevelopment of the Vehicle Structure

As discussed in previous sections, the car from last years MQP team performed relatively well especially on an indoor track. But with this team's goal of having a modular delivery robot that can tackle many terrains, the team had to develop and redesign many new systems. Hence, to attach these systems to the car a great amount of redesigning of the chassis and top plate needed to be completed.

Chassis

The chassis developed for this project held a similar shape to last year's chassis. The main goal and purpose of the chassis was to be able to hold and mount all of the car’s components and system. While the chassis was built off of the design from last year’s chassis, the overall dimensions of the chassis increased and now measures 15.475” by 9.6” by 0.35” (L x W x D). Additionally, the wheel cut outs were increased to handle the change of positions of some systems. While the size of the chassis increased, the RC car is still considered to be a 1:8 scale model of a car. Hence, when designing the layout of the car with all the systems on it, some systems had to be designed to fit in a small space to maximize the size of the chassis. Figure 5-12 demonstrates the CAD model for the chassis.

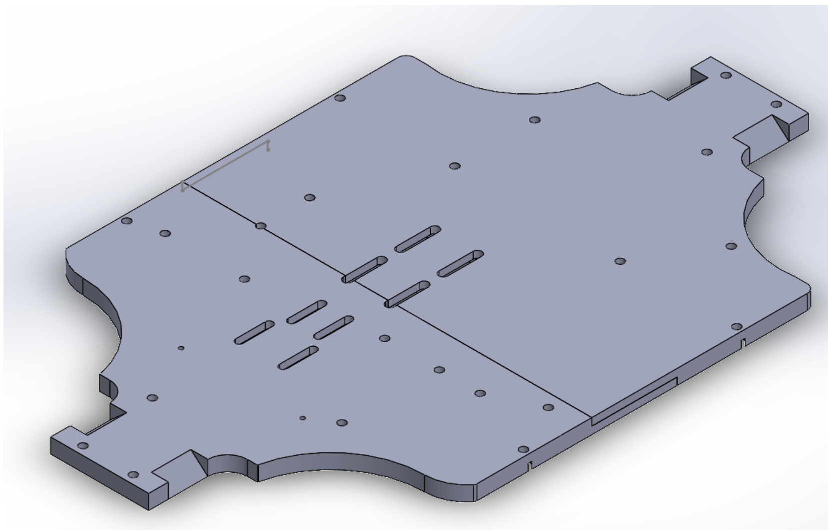


Figure 5-12: CAD Model of the Chassis

Using MathCAD, an analysis was completed on the chassis to see the maximum deflection of the chassis with a 25lb payload. Furthermore, to help the strength of the chassis, the team used three zinc rods that were epoxied to slots made on the bottom of the chassis. The chassis was manufactured using a PLA and a 3D printer. To complete this print the chassis had to be split into two sections to fit the print bed. These pieces were then epoxied together after printing.

Top Plate

The top plate served a few purposes for the car. The team designed the plate as two separate pieces. One that attached to the car, and one that would be used for the sensor package and would be screwed into the other plate. The idea for the two plates/pieces would allow for modularity and easy access and changeability of the sensor plate.

The plate that was attached to the car was designed to hold a payload as well as other attachments that could be easily attached depending on the purpose of the car for the user. The team added a series of mounting holes that can allow for an additional part to be designed that can hold any attachment. For example, the team purchased a LeArm manufactured robotic arm and designed an attachment plate that would both hold the robotic arm and mount it to the top plate. The robotic arm also showed the use of the car as a delivery robot as the arm could pick up a box or object with limited user assistance. Figure 5-13 represents the CAD model of the top plate and robotic arm mount.

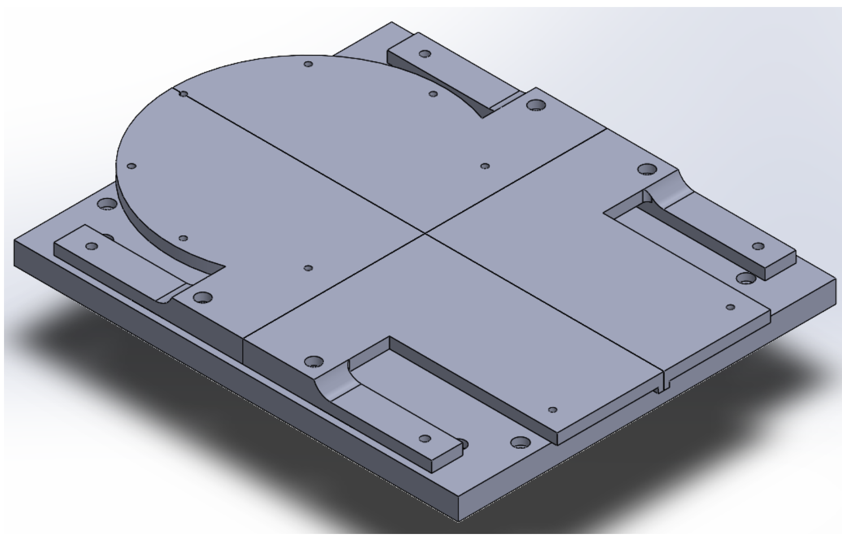


Figure 5-13: Top Plate and Robotic Arm Mount in CAD

Integration of Electronic Systems

One of the goals of this project was to mount or attach a sensor package. This was completed last year, but as the team noticed early on in this project, the actual mounting of the sensors was not organized and precise. Hence, the team strived to organize the sensors into concise places on the car that would make the car look a great amount cleaner.

As mentioned in the previous section, one of the top plate pieces was designed to hold part of the sensor package. The team designed the layout of this plate to fit arduinos, a breadboard, a battery and a few sensors. The plate would hold the electronics upside down and off the chassis, which allows for more room on the chassis. Additionally, the plate can be detached if it is not needed. The team followed instructions from the ECE MQP team with specific locations of some of the sensors, Figure 5-14 represents the CAD model of the designed sensor plate.

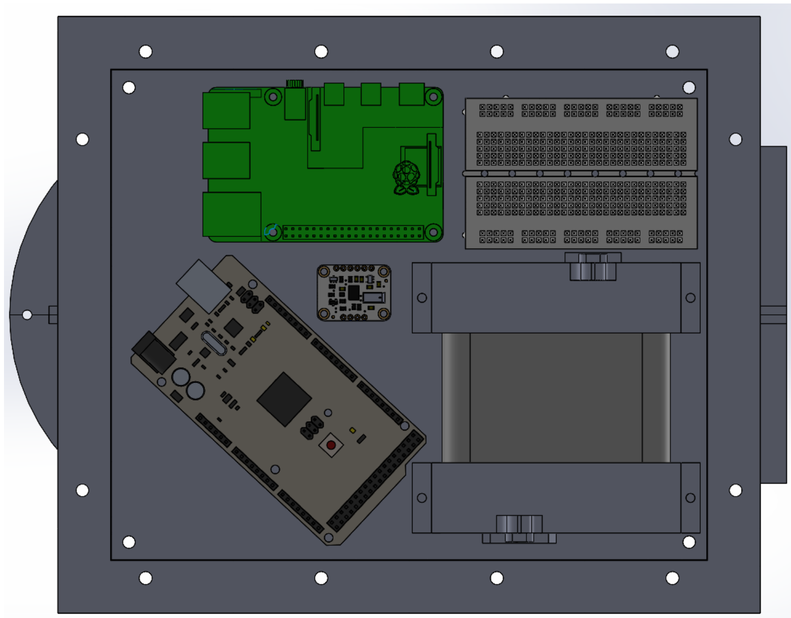


Figure 5-14: Sensor Mounting Plate in CAD

Besides the sensor top plate, other locations and mounts for sensors were developed by the team. These sensors needed specific locations around the car such as close to the motor, battery, or in the front and sides of the car. The developed bumpers that can also hold sensors, this is discussed more in the next section.

Bumpers

Despite the increased strength and toughness of our newly designed components, we still wanted to add an extra layer of protection to them in case the chassis they were attached to crashed into an object. While this may not seem like a big problem for a small RC car, it is a very reasonable concern when dealing with 3D printed materials. As 3D printed materials consist of multiple layers of material, there are natural weak spots between each of these layers. As such, any force acting perpendicular to these layers could easily cause damage to their internal structure, such as gaps or strands of material (Dwamena, 2020).

Our concerns about protection were partially down to the fact we wanted to integrate a self-driving system into this car. As such, it is likely that at some point the car would run into an obstacle, and as such an extra layer of protection would be useful. However, this integration with a self-driving system would also require us to create mounting points for ultrasonic sensors, some of which would need to be mounted on the front of the car. In order to try and accomplish both the goal of self-driving integration and vehicle protection, we decided to create a front bumper that could accomplish both.

Our front bumper was created in CAD and manufactured using PLA on a 3D printer. It was designed around both the shape and dimensions of the front of PARV and the required locations and angles of the ultrasonic sensors for the self-driving package. Due to the positioning requirements, the bumper itself was mounted to the differential housing and stuck out very far from the vehicle, meaning that the mounting struts needed to be reinforced to take any load they might receive both from obstacles or the car itself. While the front plate of the bumper and the mounting points were very structurally sound, the initial designs of our mounting struts ended up being too weak, partially due to the vibration of PARV over the road surface causing stress points. As such, we had to redesign them multiple times until they were strong enough.

The rear bumper was much simpler to design, as it did not require any mounting points for the ultrasonics. This bumper was essentially just a flat plate that mounted to the rear differential housing, and was created to protect both that housing and the rear wheels of the car. This bumper was made easily removable so other components, such as a trailer system, could be attached instead when needed.

<u>Development of a Trailer System</u>

As part of our goal to make PARV a delivery robot, we wanted to add additional payload carrying capacity to the car. While this was partially accomplished with the top plate, the small size of this plate meant that it would be unable to carry packages or devices with large surface areas. In addition, if the top plate was taken up by a tool, such as the robotic arm, there would be no room for additional payloads, meaning the car was only able to do one thing at a time.

In order to overcome this, we came up with the idea of creating a trailer system that could be mounted to the rear bumper of PARV. A final assembly of the trailer can be seen in Figure 5-15. The mounting system was inspired by standard truck-trailer hitches, with modifications made to match the shape at the rear of PARV. It consists of four separate pieces that are hinged together to allow for movement in all 3 dimensions. This trailer system was designed with a large footprint so that it could carry large packages or as storage space for onboard tools. The overall dimensions of this trailer are similar to PARV itself, and measure 15.475” by 9.6” by 0.38” (L x W x D). This platform also contains locking side guards so that any package, even if unsecured to the trailer itself, would stay inside the trailer, preventing damage or lost delivery time.

As one of our goals for PARV was to allow it to travel off-road, we wanted to make sure the trailer was able to do so as well, as the trailer would not be very useful if it could only travel on flat surfaces. In order to make sure it could follow PARV, the trailer was designed to be powered by a drivetrain system similar to PARV, with the main difference between the two being that the trailer would only be a RWD system. This trailer would in theory travel at the same speed as PARV and essentially turn the system into a 6WD vehicle. In addition, while the trailer system did not include a suspension system, it still includes a simple steering system which was connected to the trailer mounting system, allowing it to follow the motion of PARV exactly. Finally, so the could would have better traction off-road, we designed custom 3D printed wheels with tread patterns that could cut into dirt or other rough surfaces. These wheels were created using a mix of PLA and TPE plastic material in order to try and match the texture of rubber. While this system worked successfully, we had some problems with the trailer motor, as it could not deliver the power we wanted it to due to electronic limits on the motor. These limits can be fixed in the future when necessary.

Figure 5-15: Photograph of the Final Trailer Assembly

In the following chapters, we will go into greater detail for each of these subsystems, starting first with details into our manufacturing process.

6. Suspension System

In this chapter, we will be discussing the redevelopment of the previous MQP's suspension system into the system we used for PARV. This section will mainly discuss the different design iterations and modifications we made of the subsystem, and the analysis we did for each.

Suspension System Requirements

While the previous team's suspension system worked reasonably well for indoor driving (Boggess et al., 2020), we did not believe it was robust enough to work offroad. In addition, we had to make design changes to both give us more control over our ride height, and to incorporate a front drivetrain into PARV. However, our first requirement was that the suspension system could work at least as well as the previous version, meaning that it could pass the same amount of fatigue tests and handle the same amount of movement over obstacles. While keeping this in mind, we needed to find a way to connect this suspension system to the other components of the car, and allow the suspension system to be created using a 3D printer, with the purpose being to allow the suspension system to be modular. Finally, we wanted to include an adjustable shock absorber in order to change the chassis height and suspension travel to better suit different types of terrain.

Design Process

The double wishbone suspension design on PARV is heavily based on the design from the previous year's MQP. When testing their design, we identified areas where the system was weak and added reinforcements to the design. This was mainly done to the lower wishbone links in the system, as those were the links to fail most often in our testing. All the suspension components were also printed at 100% infill to increase their durability. PARV is designed to take a large payload weight of 25 lbs, and the springs from last year are not strong enough to support this load. Our team decided to keep the same shock absorbers and change the springs. We used Hooke's Law to calculate the required spring constant to hold this load half way through the shock absorber travel. A spring with a constant of 8lb/in that would need a 1.25" spacer to be the proper length of 3" was chosen for PARV, but was ¼" in diameter too small to fit over the shock absorber (Custom Works, 2019).

While the design is based on last year's, the geometry of the system changed due to our larger rear differential housing and the addition of one in the front, as seen in Figure 6-1 and 6-2. The suspension linkage must create a parallelogram in order to move freely, so we calculated the geometry required for the wheel hubs based on the new differential dimensions. We also added turnbuckles as the upper wishbone to allow the camber angle of each wheel to be adjusted.

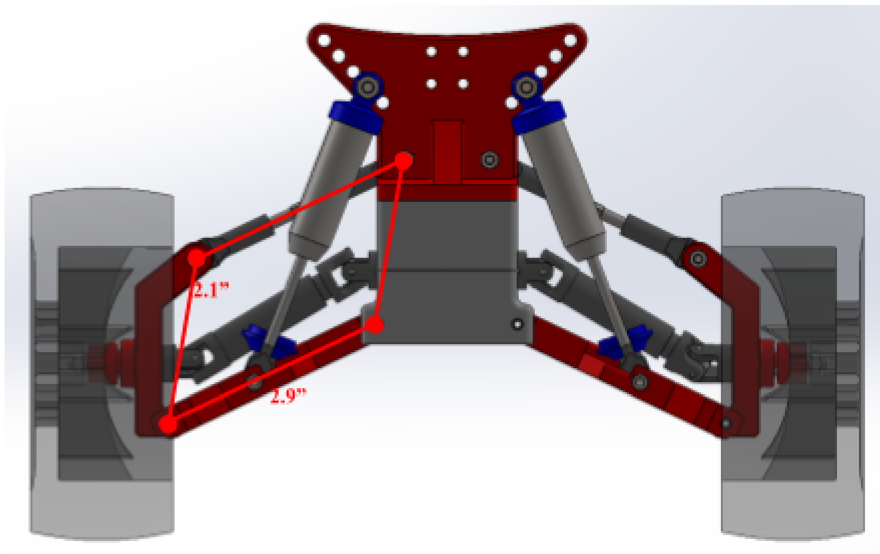


Figure 6-1: 2019-2020 MQP Rear Suspension Design

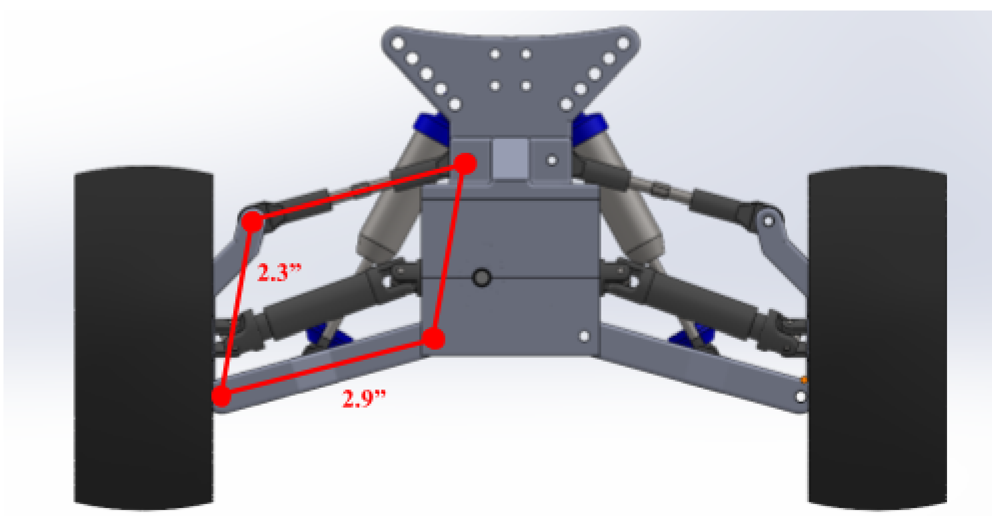


Figure 6-2: PARV Rear Suspension Geometry

The largest difference between PARV's suspension system and the previous year's design was the addition of drive shafts through the front spindles and hubs as seen in Figures 6-3 and 6-4. This required a completely different design as last year's wheel hubs and spindles had pins fully through them. PARV's spindles were designed to have a smaller upper and lower pin to allow the driveshaft to pass through. The back of the hub is also open for the same reason. Just before manufacturing our first iteration, we changed the design to use #4 screws instead of pins.

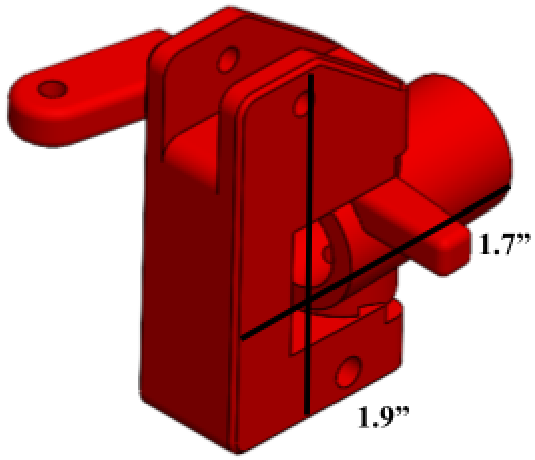


Figure 6-3: 2019-2020 MQP Front Hub and Spindle Design

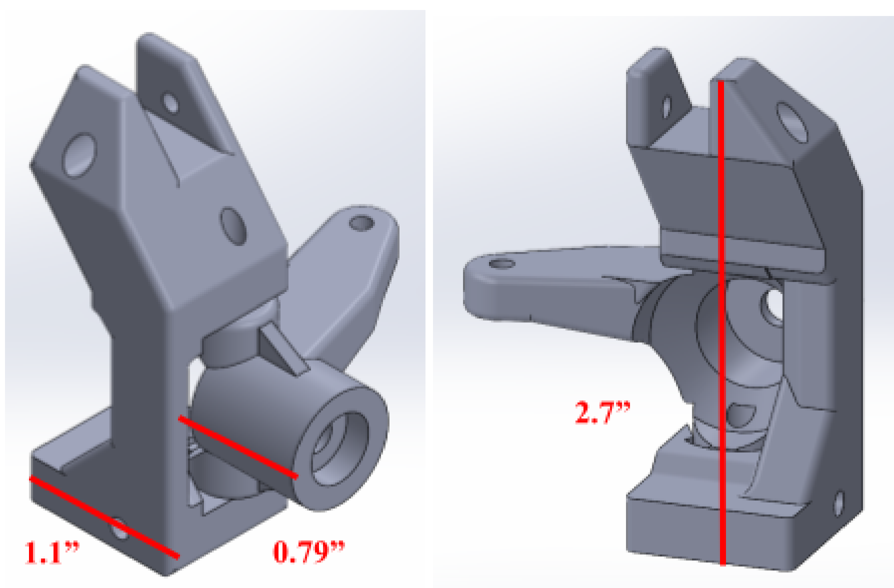


Figure 6-4: PARV Front Hub and Spindle Design

Manufacturing Process

When we began manufacturing, we realized that pins were a better solution to screws as we would not have to worry about screws coming loose after the suspension experiences repeated cycles. We also found that the bearing spacing for our drive shafts was slightly different than last year. We redesigned the spindle to hold the driveshaft in the proper place and utilized pins instead of screws. Our first iteration with pins had poor hole tolerancing, using a hole size of 0.139” for a tight fit, which caused many of them to come loose and fall out. We designed and printed a test piece to find the optimal pin hole tolerance, and printed it in multiple orientations to ensure proper fitment. We decided to use a hole size of 0.137” for a tight fit and 0.141” for a loose fit, and that orientation did not have a large effect on the tolerance.

PARV’s final design utilized the same shock absorbers and springs as last year’s design and performed well throughout testing. We found that vertical pins were still prone to falling out with our hole tolerances, and used tape to keep them in place. The team last year flattened the top of the vertical pins to keep them in place, but this was not possible for the lower pins. The suspension still sank to its bottom position with a large payload of 10lbs, but this was a result of using the same springs as last year. Despite this, PARV’s suspension design was successful in keeping the wheels on the ground on all terrain.

7. Steering Linkage

In this chapter, we will be discussing the development of PARV's steering linkage. This section will mainly discuss the different design iterations we made of the subsystem, the analysis we did for each, and of the manufacturing process for these linkages.

Steering Linkage Requirements

The main focus of our project was to redevelop the steering linkage to make it more reliable, easier to manufacture, and stronger, as the previous team had some issues on this front. As such, we had a few primary requirements we wanted to meet. These were that the steering linkage should have a minimum turning angle of 30° for each wheel, that the steering system should survive at least a mile of travel over a variety of surfaces, and that the system should be able to be created using a 3D printer. All of these goals are necessary if we want PARV to be able to be a delivery vehicle, as this would allow it to travel around tight corners, travel long distances, and survive sudden changes in terrain, all factors that exist on campus, or in a residential area. In addition, we wanted to make this system as small and unobtrusive as possible, as we needed a lot of space up front for the differential and drivetrain systems (which will be discussed in Chapters 8 and 9.

Base Design

PARV's steering linkage was one of the last systems to be designed. Its design is also vastly different from last year's MQP. While both designs use a parallelogram design, PARV's utilized Ackerman geometry to reduce wear on parts. Ackerman geometry uses a trapezoidal geometry to allow the inner wheel on a turn to achieve a greater angle than the outer. As seen in Figure 7-1, the wheel on the inside of a turn experiences a larger turning radius than the inside wheel. We also researched a variety of popular RC car steering designs. The majority of these designs offset the servo to the side, allowing more space for drivetrain components in the center of the car. PARV uses a powerful Savox 1256TG High Torque Servo that last year's team did not have time to test (Savox, 2014). This servo is designed to ensure long term reliable operation, and outputs a torque of 277.7 oz-in. Turnbuckles were also used for the green links in the figures below and for the servo arm link to allow the linkage to be adjusted easily (ShareGoo, 2021).

PARV's low profile steering linkage is designed to fit under the front drive shaft and in the tight space between drivetrain components.

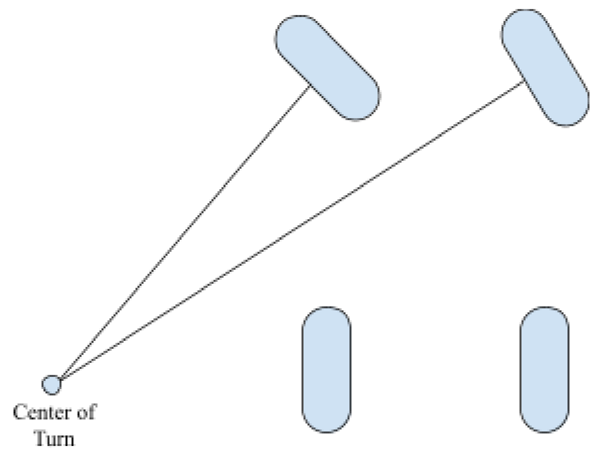


Figure 7-1: Ackerman Geometry Diagram

Analysis

We first determined the Degrees of Freedom (DOF) of our steering linkage using Gruebler's equation. With 8 links and 10 joints, the steering linkage has only 1 Degree of Freedom. This is what we expect from a steering linkage and showed our design would produce the desired basic motion.

Once we had come up with the base design for our steering system, we began to do computer analysis on it to determine its capabilities. This analysis was done using Working Model 2D, as it allowed us to see the movement of our steering linkage, and to calculate the dimensions, linkage angles, and locking point of our potential linkage. Unfortunately, due to WPI license errors and having to use a remote desktop to do this analysis, we were not able to do fully automated tests using Working Model 2D. However, we were able to do manual tests of each linkage using the software, and were able to create a number of different linkages that we could test this way.

Our initial design consisted of a total of 7 links, a number that we would keep for most of the analysis process. This initial linkage had a width of 5.7396 in and had both wheels start at an initial angle of 0° from the y axis (blue links). This is shown in Figure 7-2 below.

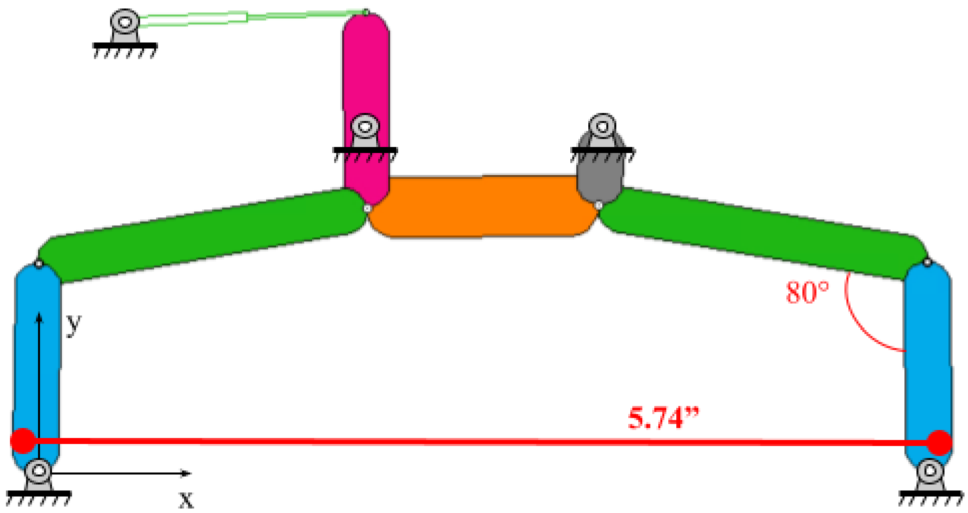


Figure 7-2: Initial Steering Linkage Design

When testing this model, we found that, while turning both left and right gave similar turning angles, the blue links could only reach about 26° from the y-axis before the mounting joints on the pink and gray links would overlap with the central (orange) link. This meant that the turning angle of the wheels would not meet the requirement of 30° and would be unable to make the turns we needed for testing. In addition, this linkage turned out to be 1 in too short for our chassis, and as such, would cause assembly problems to fit the wheels onto them. Figure 7-3 shows the initial steering linkage at a full turn.

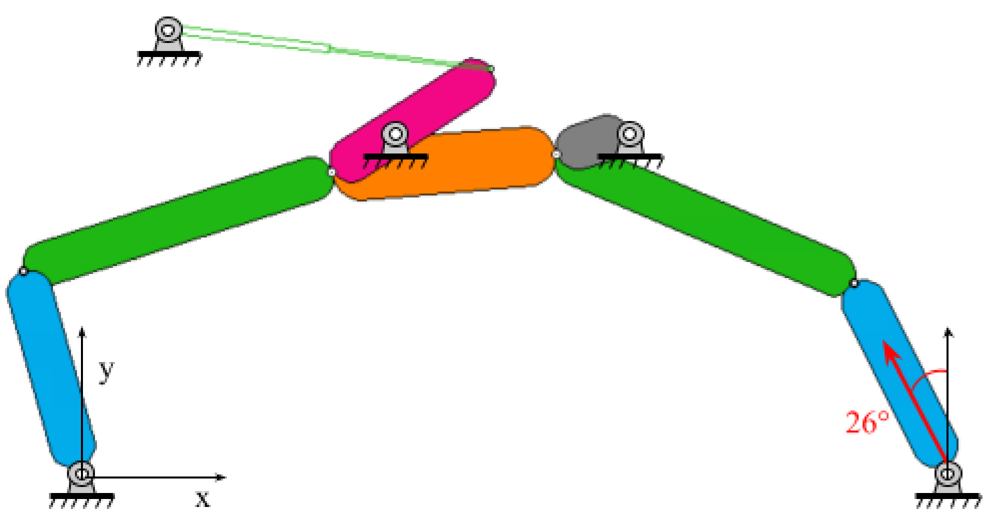


Figure 7-3: Initial Steering Linkage Full Turn

As such, we revised this model to better fit the width of the car, and to give more room to the linkage while turning. To do this, we moved the mounting point in the pink link to its center instead of offsetting it, and lengthened both the pink and gray links as well. In addition, we also lengthened the orange link and decreased the angle of the green links from about 80° to about 62° to allow the central linkage to sit farther back; this was done to better fit it behind the differential housing. This rearrangement of the linkage also increased its width to 6.7843 in, meaning that it would better fit on the chassis. Figure 7-4 shoes the 2nd iteration steering linkage.

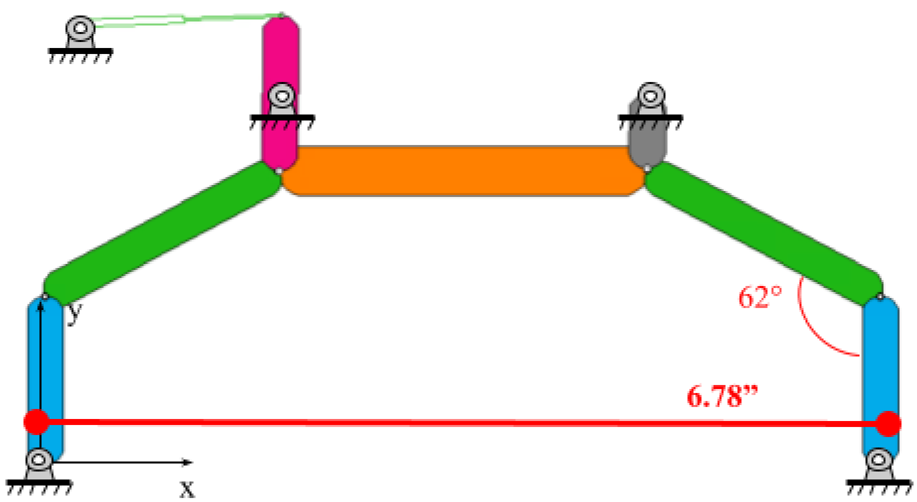


Figure 7-4: Second Iteration Steering Linkage Design

When testing this model, we found that the blue links could now turn up to 42° from the y-axis, which means that it would have a much smaller turning radius than the original linkage. In addition, this linkage was no longer limited by the positions of the mounting joints, meaning it could keep moving until the linkage reached its buckling point. However, this also means that the linkage has the possibility of locking in place if this buckling point is passed. In addition, the angle reached by the non-active wheel (opposite to the direction of linkage input) was actually smaller than in the first iteration, which would hurt the turning radius somewhat. Figure 7-5 shows the 2nd iteration of the steering linkage at full turn.

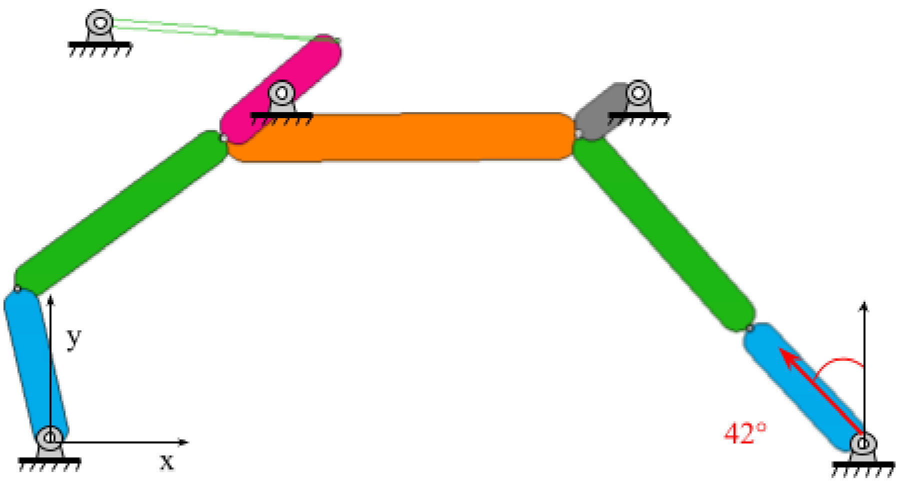


Figure 7-5: Second Iteration Steering Linkage Full Turn

Design Process and Iterations

PARV's steering linkage was designed to be assembled using #4 screws and lock nuts. This ensured that the linkage's performance would not degrade over time. Upon assembling our second iteration, we found that the #4 screws we had ordered were not long enough and used #2 screws with washers. These were also used to fasten the turnbuckles and servo arm to the linkage. Upton testing this early iteration, we found that it performed much better turning to the right than the left. We combatted this problem by lengthening the servo turnbuckle. The turning radii were more equal but still large, taking almost an entire road to make a u-turn. We noticed that it performed much better when the car was lifted off the ground than in normal driving. Upon examining the linkage, we noticed play in the #2 screws in the holes originally designed for #4 screws. We ordered properly sized #4 screws to tighten the linkage but there were still issues with play.

The linkage is very close to a toggle position when it is at its maximum turning angle, and the play allows certain links to slip into the toggle position during operation. We tried many iterations to move certain links farther from toggle positions, such as the longer spindles in Figure 7-6, and the 90° links in Figure 7-7. Both of these iterations proved to perform worse than our original design, so we examined other points of weakness in the linkage. We noticed that the turnbuckle had a large amount of internal play between the ball joints.

Figure 7-6: Spindle Redesign

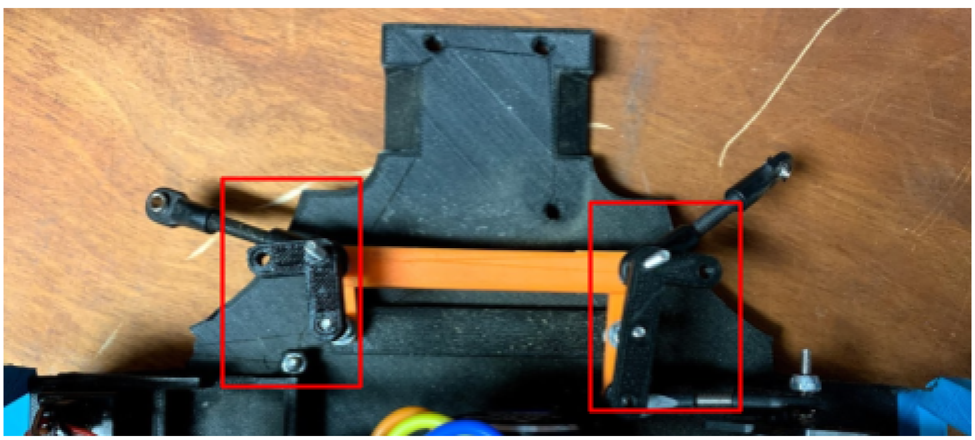


Figure 7-7: Front Link Redesign

To combat this, the turnbuckles were removed in favor of fixed rods with ball joint ends. We used cut #8 screws as the fixed rods and tapped the ball joint ends to allow for some adjustability. These had almost zero internal play and better fit the #4 screws. We changed all three of the turnbuckles to these ball joint rods, seen in Figure 7-8, allowing PARV to achieve a turning radius at slow speeds of 43” to the left and 36” to the right.

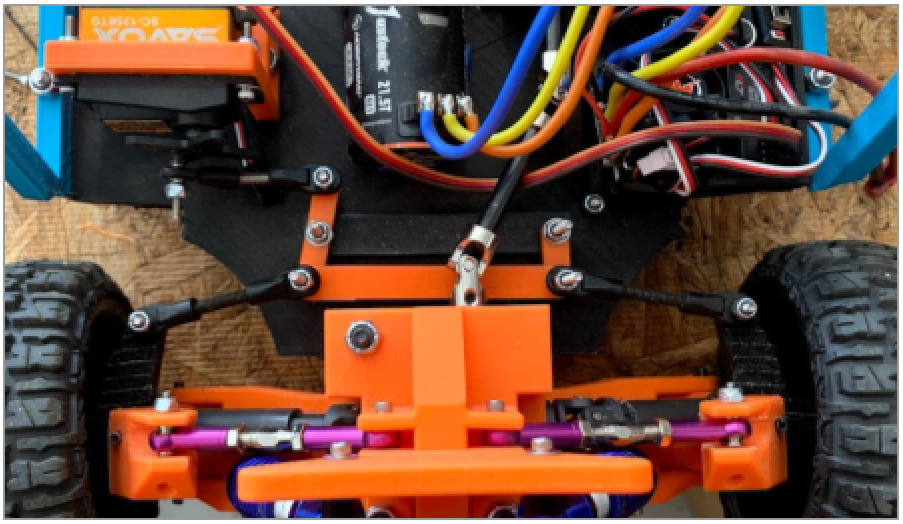


Figure 7-8: Final Steering Linkage

Our team identified some areas where the steering linkage could further be improved. Many popular RC cars have their servo moving in a horizontal direction as opposed to the vertical orientation of PARV's. This would remove the difference in turning radii between right and left, and also can allow for the system to be even more compact. Another area of improvement for PARV's steering is in the drive shafts. The thickness of the front driveshafts limit the turning angle the linkage can achieve. Using thinner ones or increasing the clearance around them would increase steering performance.

8. Drivetrain

In this chapter, we will be discussing the development of PARV's drivetrain. This section will discuss the requirements we made while designing the system, the analysis we completed through the process, and the different iterations we went through. Overall, designing the drivetrain focused on taking last year's MQP 2WD drivetrain and changing it to incorporate 4WD. This section will go into depth about the subsystems developed and purchased to create this system.

Drivetrain Requirements

For our drivetrain, our main goal was to turn it into a 4WD system, which means that we needed to create a transfer case that would allow torque to be transferred between the front and rear wheels equally. We also wanted this transfer case to be switchable so the car could be run in either RWD or 4WD, with the purpose being that each system has specific advantages and disadvantages to them, and allowing PARV to use both will in turn make it more modular. For our final speed, we wanted PARV to run at a minimum of 4 MPH, and we also wanted it to be able to move both forward and backward, as that would allow it to be more maneuverable.

Analysis of the Drivetrain

To start the design of the drivetrain, the team completed a few different analyses of the drivetrain in 4WD to see what gearing ratios are needed in the different subsystems, as well as what motor, gearbox would be needed. The first analysis the team completed that dealt with the drivetrain was an overall, theoretical simulation of the system. We used Matlab and a series of power and efficiency loss equations to calculate the torque at each subsystem. The efficiencies of bearings were considered to be 98%, 99% for universal joints, 95% for rack and pinion gears, 94% for spur gear, and 97% for the planetary gearbox. As this simulation was to help find a motor and gear ratios that would move a car that weighed ~25lbs, the team worked from each individual wheel then into the system to end at the motor and gear ratios within the differentials and gearbox. Hence, the team created a free body diagram as seen in Figure 8-1. Using this free body diagram, the team calculated the static frictional force at each wheel for a variety of terrains (ie. concrete - 6.284 lb_f). This static frictional force would then create a max torque on the driveshaft that is attached to the wheel. From there, the team went through the differential and tested a variety of gear ratios, the transfer case, the gearbox, and then back to the motor to see what the max torque would be at the motor. The team then went through the same process for rolling frictional force as well.

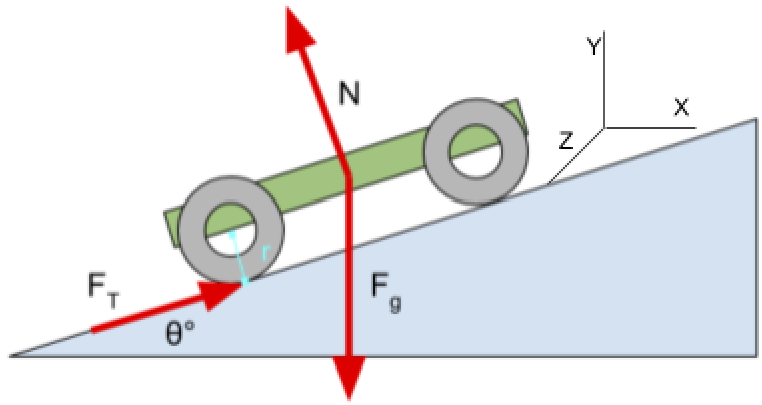


Figure 8-1: Free Body Diagram of the Car

Rolling frictional force when referring to cars is the minimum force required to push a car and have it move. Hence, the torque that the motor produces needs to be greater than the rolling frictional force. For concrete, this value of rolling frictional force was found to be 0.0628 lb_f. However, the static frictional force is the max force that can be given to the wheels from a motor. If this force is surpassed, then the wheels will begin to slip, which is not the goal of a car. Hence, through the use of Matlab and the design process explained before, we were able to produce graphs as seen in Figure 8-2 that illustrate the torque differences as well as the torque that would be produced by the motor that the team intended to use. The code for the simulation can be seen in the Appendix H. The graph uses a varying differential gear ratio as the team was also looking to choose one. As one can see in the graph the torque produced by the engine (0.037 lb_f*ft) was greater than the required torque to move the car but not greater than the max torque. Hence, the team intended to use a differential gear ratio around 3:1 when designing the differential.

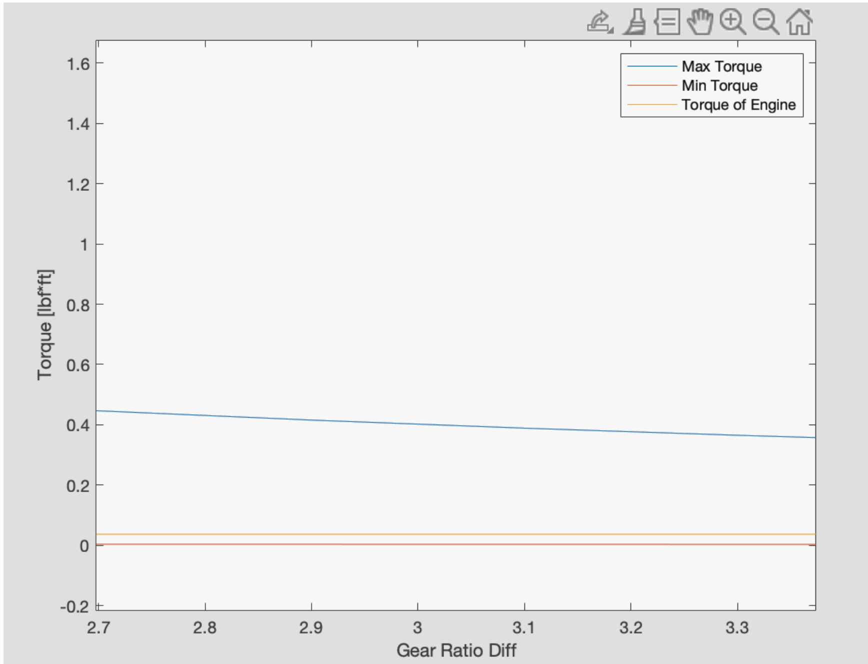


Figure 8-2: Results from the Torque Simulation

Additionally, the team started another simulation to see what velocity the car would move at. The team used the motor and efficiencies of each system from the previous simulation. This time instead of starting at the wheels the team started at the motor and worked through each system calculating the torque until we got to the wheels. With the torque, the team could find the total force on each wheel. From there, the team found the power of the engine and divided that by four to find the power at each wheel. Then using the equation P = Fv, the team could find the velocity of the car, which was approximately 10 ft/s. Figure 8-3 illustrates the results of this Matlab script, which can be found in the Appendix H.

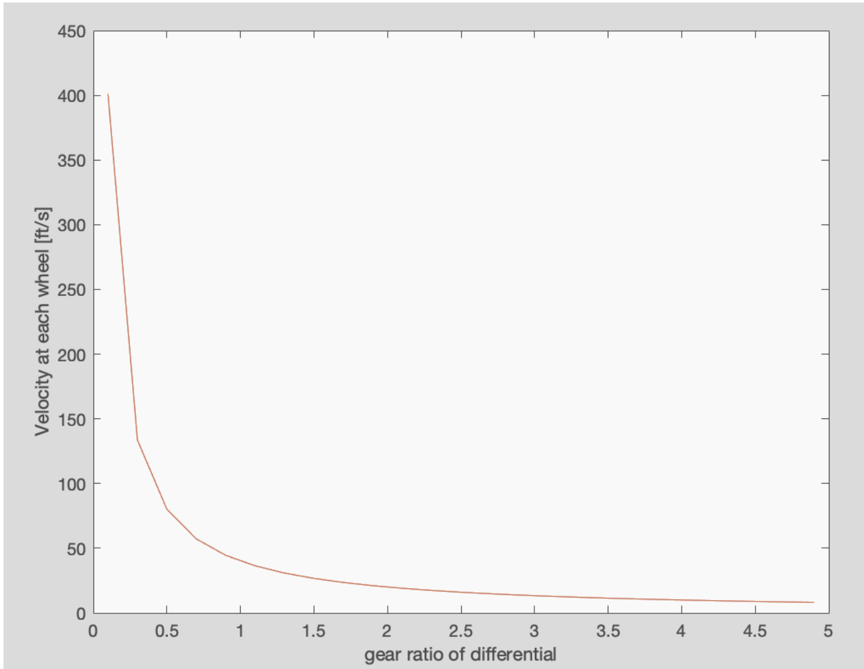


Figure 8-3: Results from the Velocity Analysis through Matlab

Using these simulations of the drivetrain, the team was able to select gear ratios and a motor for the car. Which were the Hobbywing XR10 Justock Sensored Brushless motor and a differential gear ratio of approximately 3:1 (Hobbywing, 2019). From here, the team could start designing specific parts for the drivetrain in CAD.

Design Process and Iterations

Starting with last year's car gave us a good idea of a gearbox and motor to use, and after the analysis, we were sure that the motor selected and gearbox would work for our 4WD system. The team designed the layout of the drivetrain through CAD, Solidworks. Some of the parts designed were purchased while others were 3D printed. For example, in the final iteration the gearbox, motor, and differentials were purchased while the transfer case and couplers were 3D printed. The team tried to purchase as few parts as possible as one of our goals was to make an RC that was primarily 3D printed. The team designed 3D printed couplers that would connect each individual subsystem of the drivetrain to the next one. These couplers consisted of a female and male connection and allowed for the easy changeability of the system that used the coupler. A Solidworks photograph of the entire drivetrain can be seen below in Figure 8-4, the next few sections will go into the design process of each subsystem.

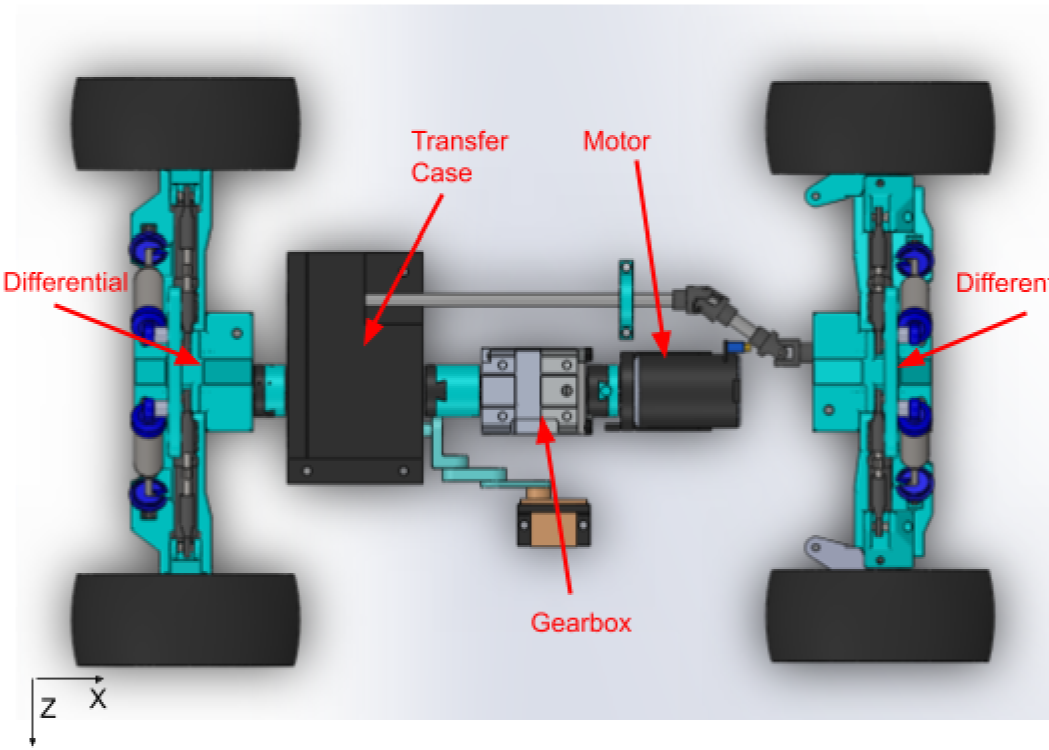


Figure 8-4: Overview of a Top Down View of Drivetrain in Solidworks

Motor

For PARV, we selected the Hobbywing XR 10 Justock motor; this motor was what was used in last year's MQP (Boggess et al., 2020). The motor would be able to provide enough torque for the system to move the car at a suitable speed as envisioned in our testing of last year's car as discussed in Chapter 2. The motor that was ordered is a sensored brushless motor that came with an electronic speed controller (ESC) and power switch, these were mounted to the car in a specific spot to keep the car organized and clean. This motor was meant for 1/10th scale cars with outdoor applications, hence making it a good reliable choice for this project. The motor and steering servo is powered by a 7.4 V 5200 mAh Lipo battery.

To attach the motor to the chassis, a motor mounting part was created. This part was designed to hold the motor in place and at the same level as the rest of the drivetrain. To hold the motor the mount created had 4 mounting holes to the chassis, and 6 mounting holes to connect the motor to the mount itself. The mounting holes to the chassis were made for #8 button head socket screws. The holes for the motor used were M3 screws as those are what is needed for the motor. This motor mount part can be seen in Figure 8-5.

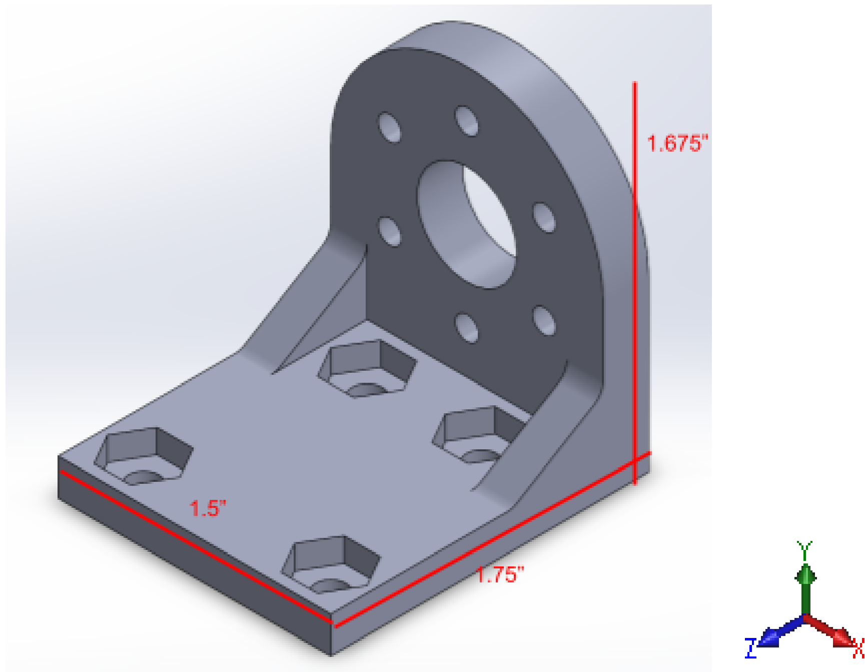


Figure 8-5: Final CAD Design of the Motor Mount

The motor shaft, when powered would create angular velocity, was attached to a coupler which could then go to the gearbox coupler and the gearbox. The gearbox and transmission will be discussed next within the drivetrain section.

In the second iteration of the motor mount, the team realized that the transfer case and differential housings were taller than the motor mount. Hence, the drive shaft did not line up properly. The team created a spacer plate for the motor mount to correctly line up the motor shaft with the rest of the driveshaft. This spacer measured 0.075” in thickness. Instead of countersunk holes in the chassis in specific spots to mount the motor, the team used a slot that would allow the motor to be easily moved back and forth if needed to help line up systems in the drivetrain.

Transmission

The transmission selected for PARV was based on results from the previous MQP. Their results showed that this VEX planetary gearbox was ideal for this application (VEX, 2020). The planetary gearbox allowed the transmission to be compact and durable which was necessary for the car (Boggess et al., 2020). The team initially had thoughts of 3D printing a transmission but realized that the durability and complications of printing plastic gears for the transmission would be challenging and decided against this idea to focus on other aspects of the car. Therefore, the team purchased VEX Versaplanetary Gearbox in a 9:1 gear ratio as seen in Figure 8-6. This gearbox uses three 31 tooth planet gears, a nine tooth sun gear, and a ring gear to make the 9:1 gear reduction. The gears were manufactured out of Rockwell C 55-62 Case Hardened Steel. The gearbox was mounted to the chassis using four 10-32 socket screws. Additionally, the output shaft is a hex shape, which we were able to profile into the coupler that connects to the transfer case.

Figure 8-6: VEX Versaplanetary Gearbox (VEX, 2020)

The team designed couplers that are going to be 3D printed that can attach to the input and output shafts of the gearbox. The output of the gearbox connects to the transfer case section of the drivetrain.

In the second iteration of this system, the team realized similar issues to the motor subsystem. Hence, a 3D printed spacer was created to line up the shaft of the drivetrain and the mounting holes in the chassis were adjusted to slots for the same reason as before with the motor mount. This spacer measured 0.125” in thickness.

Transfer Case

The transfer case is a subsystem that is used within 4WD automotives to split the power between the front and rear driveshafts. Hence, this team decided to design and 3D print our own transfer case. Our initial goals of the transfer case were to split the power using gears and have some mechanical adjustability that can switch the cars drivetrain from 4WD to 2WD.

First Iteration

The initial iteration of the transfer case was developed in Solidworks and can be seen in Figure 8-7. This design used three gears in a 1:1 ratio to split the power. The teeth on the larger two gears were 30 and the smaller gear which was set in the middle of the other two had 18 teeth. The pressure angle of these gears is 20° and the module is 0.03937”. A grooved sleeve was also developed that could be pushed back and forth using a four bar crank slider mechanism and a servo. This grooved sleeve, when the 4WD is engaged, would move up the drive shaft and lock into the first gear which also has a profile that matched the sleeve. The gear would then turn with the driveshaft and split the power to the rest of the gear mesh and the front driveshaft. The grooved sleeve consisted of three parts, the outer sleeve which is attached to the slider crank linkage, the inner grooved part, and a shaft profile piece that rotates with the shaft. Ideally, the inner grooved part and outer sleeve would move back and forth with the shaft when desired and lock into place with the gear. The shaft profile part was designed to rotate with the shaft and then rotate the inner grooved sleeve. Additionally, a simple box shaped housing was created to cover the internals of the transfer case.

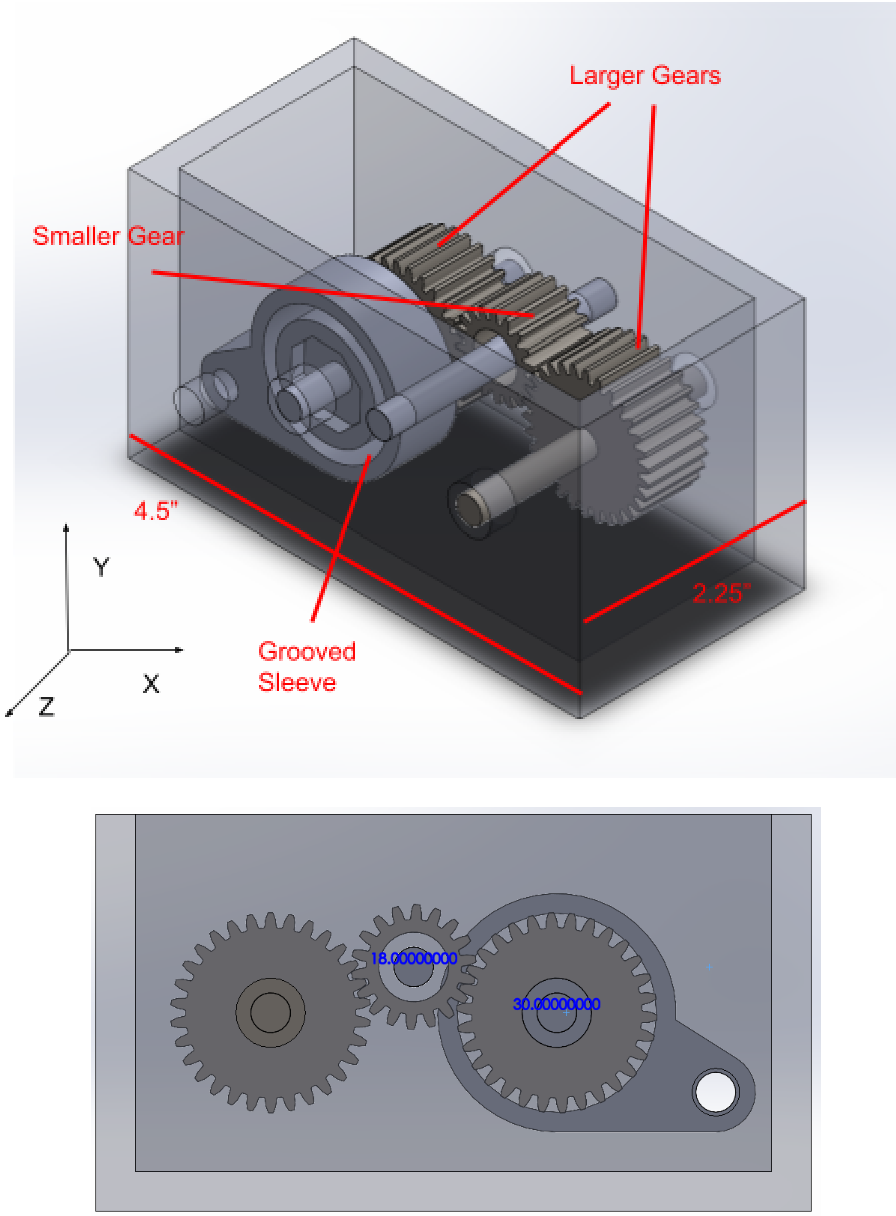


Figure 8-7: The Initial Design of the Transfer Case

<u>Second Iteration</u>

Next, the second iteration of the transfer case dealt with adding bearings into the transfer case so the shafts could easily move as well as the gears. These parts can be seen in Figure 8-8 below.

Part	Quantity
¼” diameter shaft	4 of varying lengths through drivetrain
1” sealed roller bearing	1
¼” sealed ball bearings	5
¼” sealed roller bearings	3

Figure 8-8: List of Hardware Parts with in the Transfer Case

As seen in Figure 8-8, there was one shaft for each of the three gears and an additional shaft was used for the grooved sleeve, which would connect to the slider crank linkage. All of the ¼” bearings were used to hold the gears on the shafts as well as holding the shaft with the housing. The 1” bearing was placed in between the inner grooved sleeve part and the outer sleeve to allow the inner part to rotate with the shaft without the outer part rotating. To attach the gears to the shafts and have them move together, if needed, a set screw was added. This set screw was a #2 socket screw. Furthermore, the housing was also adjusted for the transfer case; the outside still resembled a box, but the inside now was designed to more closely fit the gear and part profiles. The overall dimensions of the housing are 2.175” x 4.5” x 2” (L x W x H). This transfer case iteration can be seen below in Figure 8-9.

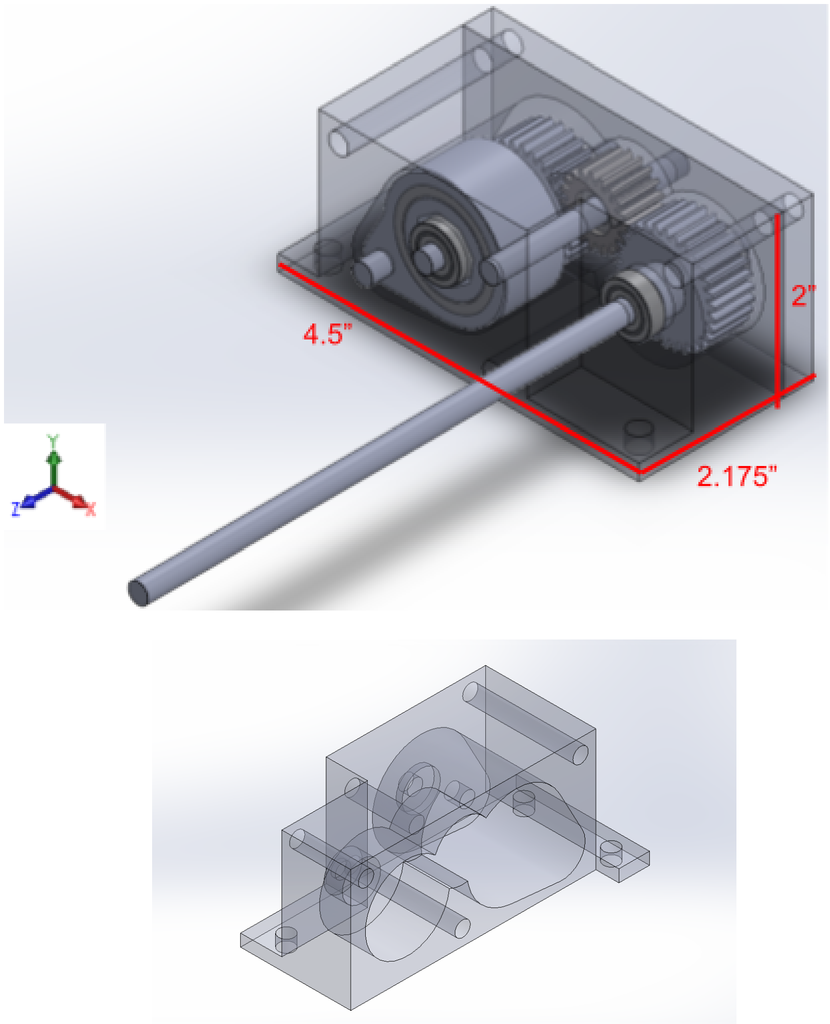


Figure 8-9: Second Iteration of the Transfer Case within Solidworks

<u>Final Iteration</u>

The final iteration of the transfer case came after manufacturing the second iteration. This iteration dealt with solving manufacturing issues and hardware issues. First, the 1” roller bearing that was ordered ended up being larger than expected. The bearing was a ¼” wider than expected and thus the entire design of the transfer case needed to be adjusted, specifically the housing needed to be ¼” longer.

Additionally, adjustments need to be made for a better connection from gear to shaft. Specifically, the third gear, the one that is on the front driveshaft needed a better connection to hold the gear onto the shaft. We then created a box and keyed the shaft where the box would be placed. This box would sit inside of the gear and on the shaft. This gave the gear a tighter fit onto the shaft and now they moved together very well. The new shape of the gear with the outline of the box insert can be seen in Figure 8-10. The shaft profile part within the grooved sleeve also needed the same adjustments that this gear needed. The shaft was then keyed as before and a box insert was added to the part as well.

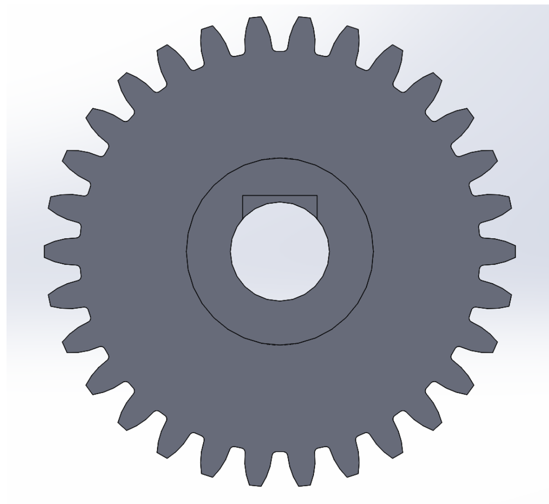


Figure 8-10: Third Transfer Case Gear Attached to the Front Driveshaft Profile

Also, the final iteration for the grooved sleeve and the first gear which profile matches the sleeve can be seen in Figure 8-11 below. To allow for additional ease of operation, the profile on the teeth has a fillet on it so that the grooved sleeve could more easily slide onto the gear when 4WD was engaged as seen in Figure 8-11.

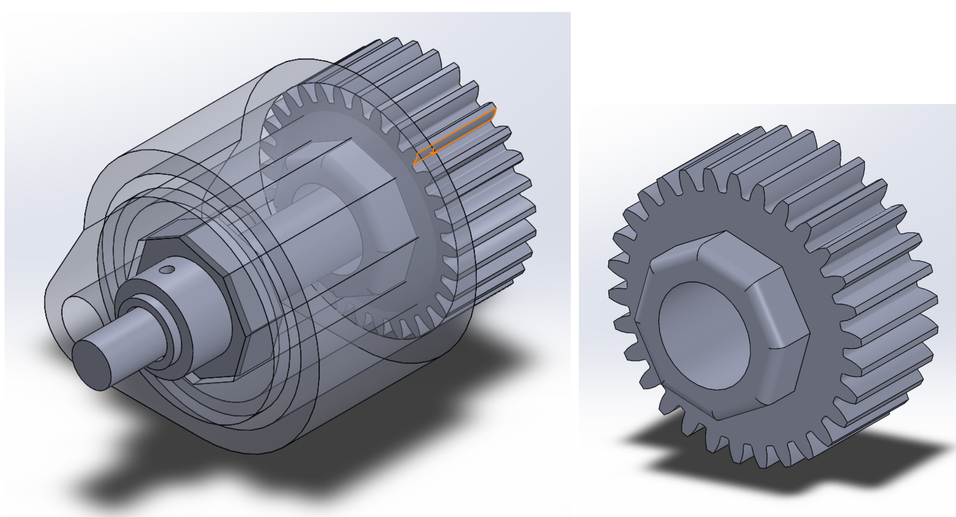


Figure 8-11: Grooved Sleeve and First Transfer Case Gear Solidwork Parts

Furthermore, the grooved sleeve inner and outer sleeve parts needed an adjustment to lock them into place with each other as the fit between those parts and thue bearing in between was not tight enough. Hence, the team then extended the inner sleeve part slightly on both sides, one side had a lip added to go over the outer grooved sleeve part, and the other side we added a spot for an external snap ring. These two adjustments would now lock the two parts of the grooved sleeve together when moved linearly. The final position of the gears to allow them to move freely and mesh with each other without interference is demonstrated in Figure 8-12.

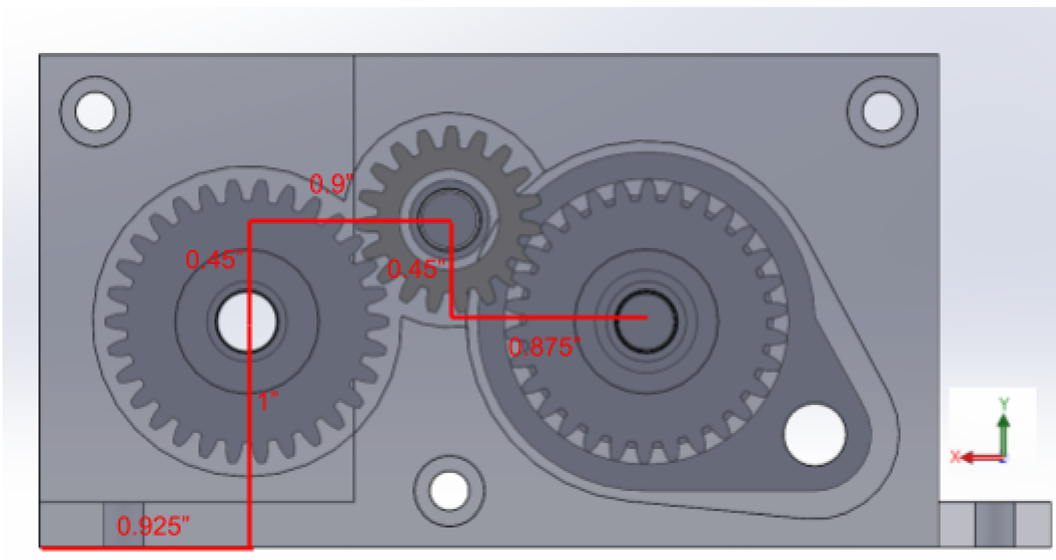


Figure 8-12: Final Position of the Transfer Case Gears

In the final design, we added 3D printed spacers on the shafts that would also help hold the gears in their respective places. Some pictures illustrating the manufactured transfer case internals can be seen below in Figure 8-13. Figure 8-14 shows two images of the transfer, the first shows the 4WD system engaged and the second shows the system disengaged. One can see that within the figure that the grooved sleeve is moved back and forth off and on the gear.

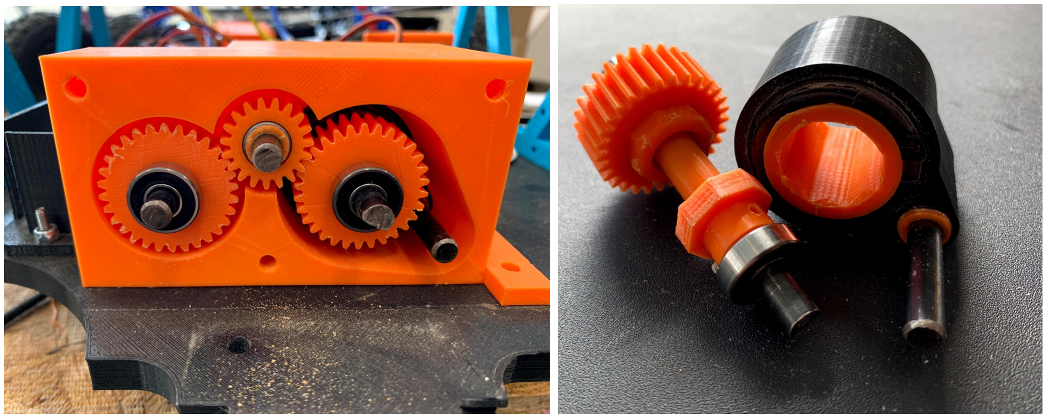


Figure 8-13: Manufactured Transfer Case Internals (Right Figure - Fully Assembled Transfer Case with Gears Meshed Together, Left Figure - Grooved Sleeve Assembly and First Transfer Case Gear)

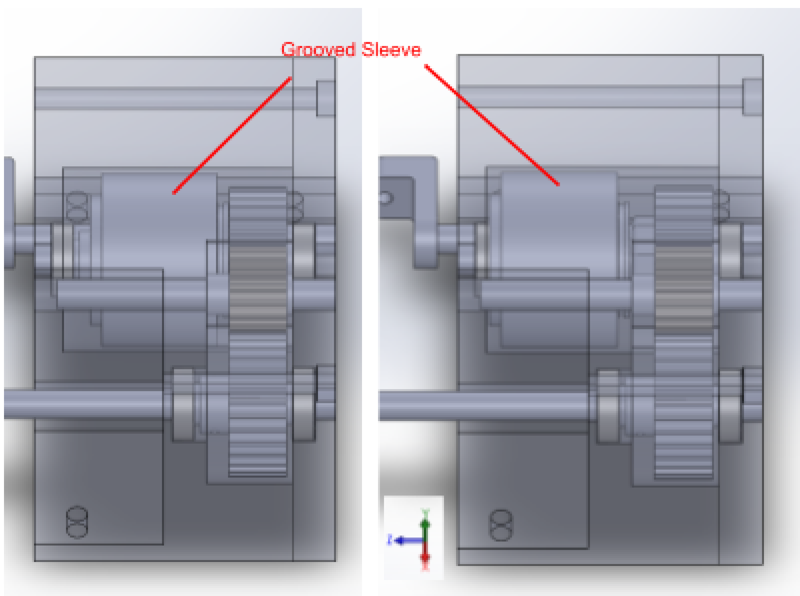


Figure 8-14: Shows the Grooved Sleeve and the 4WD System Engaged and Disengaged, (Left - Engaged, Right - Disengaged)

The transfer case housing used two parts: a cover and a housing part. The cover would be placed on the housing when the transfer was ready to be closed up and used three #8 socket screws. Mounting the transfer case onto the chassis was completed using another three #8 socket screws. A final CAD assembly of the transfer can also be seen below in Figure 8-15 and Figure 8-16 shows an exploded view of the transfer case.

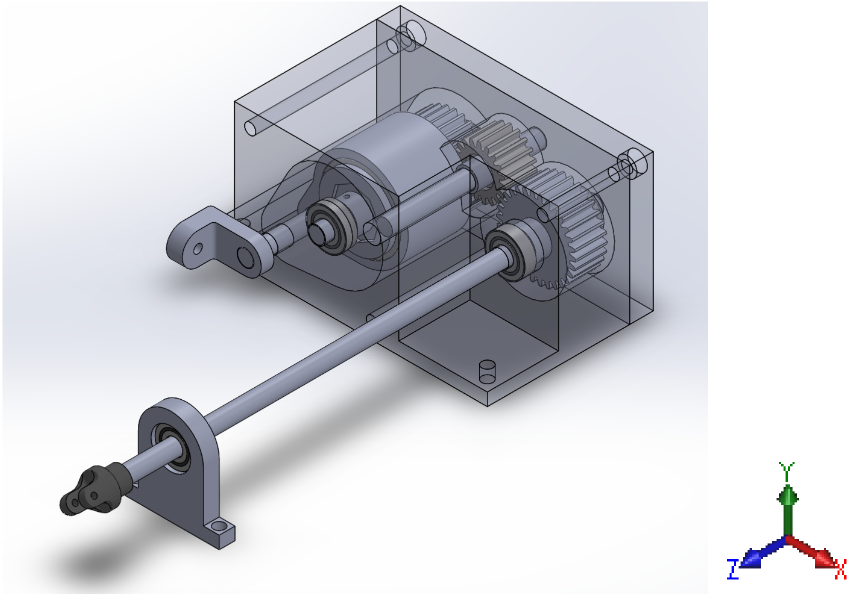


Figure 8-15: Final Solidworks Assembly of the Transfer Case

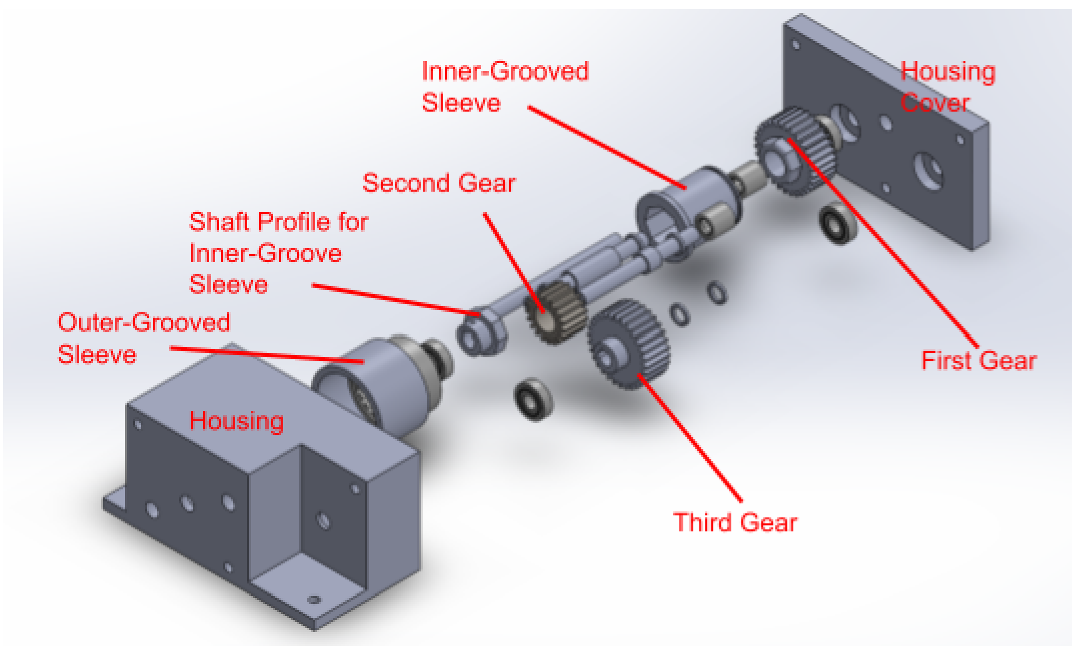


Figure 8-16: Exploded View of the Transfer Case

<u>Slider Crank Mechanism</u>

The slider crank linkage that moves the grooved sleeve to engage and disengage 4WD is a four-bar linkage that uses a small servo to move the linkages. The diagram below in Figure

8-17 illustrates a slider crank mechanism. In this diagram link 4 would be the shaft in the grooved sleeve and the other links would be 3D printed linkages that connect to the servo. The servo we used is a micro servo. This micro servo used is a KS-HD47MG servo and provides 1.2 kg of torque and a speed of 0.10 sec/60°. This slider crank linkage that was created for PARV, measured 3.95” x 1” (L x W) for its overall shape. The CAD assembly for this mechanism is shown in Figure 8-18.

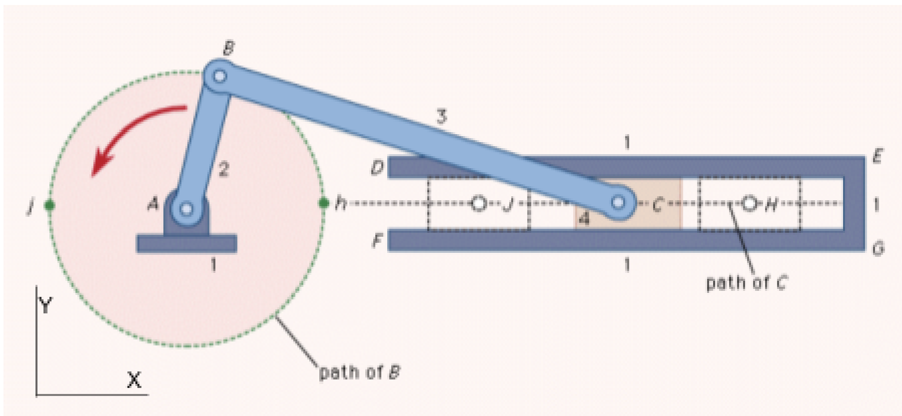


Figure 8-17: Slider Crank Linkage Schematic

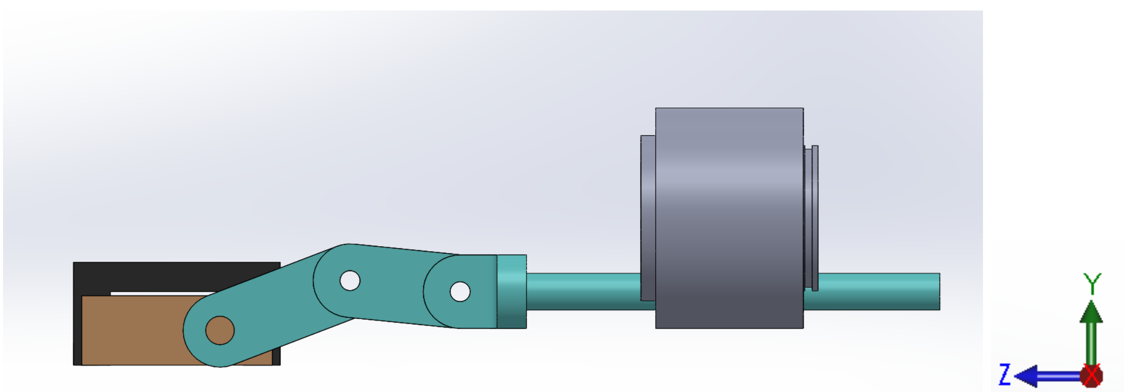


Figure 8-18: CAD Assembly for Slider Crank Mechanism

With the 4WD engaged, the output to the front shaft uses a ¼” shaft and travels up the car and uses a ¼” bearing and mounting part to hold the shaft above the chassis in line with the rest of the drivetrain. The shaft then uses Hobby Power universal joints to bring the position of the shaft back to the center of the differential in the front (Hobby Power, 2020). For the rear drive shaft output from the transfer case, the team used a set of couplers to connect to the rear differential.

Gear Analysis

We also completed an ANSYS tensile stress analysis on the gears as represented in Figure 8-18. The team used the torque values calculated previously through the drive train Matlab analysis earlier in this chapter to calculate the tangential, radial, and resultant forces on the gears. The tangential, radial, and resultant forces on the gears were calculated using KHK Stock Gears' table (shown below in Figure 8-19). This table shows how to calculate these forces for different types of gears (KHK Stock Gears, n.d.). For the case of the Transfer Case gears, the equations for spur gears were used. Using the resultant force on each gear, the ANSYS simulation was defined with the resultant force acting on a face of one tooth, while the center of the gear is fixed in all axes.

Types of gears		F_t : Tangential force	F_x : Axial force	F_r : Radial force
Spur gear		$F_t = \frac{2000T}{d}$	————	$F_t \tan\alpha$
Helical gear			$F_t \tan\beta$	$F_t \frac{\tan\alpha_n}{\cos\beta}$
Straight bevel gear		$F_t = \frac{2000T}{d_m}$ d_m is the central reference diameter $d_m = d - b\sin\delta$	$F_t \tan\alpha \sin\delta$	$F_t \tan\alpha \cos\delta$
Spiral bevel gear			When convex surface is working :	
			$\frac{F_t}{\cos\beta_m}(\tan\alpha_n \sin\delta - \sin\beta_m \cos\delta)$	$\frac{F_t}{\cos\beta_m}(\tan\alpha_n \cos\delta + \sin\beta_m \sin\delta)$
			When concave surface is working :	
			$\frac{F_t}{\cos\beta_m}(\tan\alpha_n \sin\delta + \sin\beta_m \cos\delta)$	$\frac{F_t}{\cos\beta_m}(\tan\alpha_n \cos\delta - \sin\beta_m \sin\delta)$
Worm gear pair	Worm (Driver)	$F_{t1} = \frac{2000T_1}{d_1}$	$F_{t1}\frac{\cos\alpha_n \cos\gamma - \mu\sin\gamma}{\cos\alpha_n \sin\gamma + \mu\cos\gamma}$	$F_{t1}\frac{\sin\alpha_n}{\cos\alpha_n \sin\gamma + \mu\cos\gamma}$
	Worm Wheel (Driven)	$F_{t2} = F_{t1}\frac{\cos\alpha_n \cos\gamma - \mu\sin\gamma}{\cos\alpha_n \sin\gamma + \mu\cos\gamma}$	F_{t1}	
Screw gear ($\Sigma = 90°$, $\beta = 45°$)	Driver gear	$F_{t1} = \frac{2000T_1}{d_1}$	$F_{t1}\frac{\cos\alpha_n \sin\beta - \mu\cos\beta}{\cos\alpha_n \cos\beta + \mu\sin\beta}$	$F_{t1}\frac{\sin\alpha_n}{\cos\alpha_n \cos\beta + \mu\sin\beta}$
	Driven gear	$F_{t2} = F_{t1}\frac{\cos\alpha_n \sin\beta - \mu\cos\beta}{\cos\alpha_n \cos\beta + \mu\sin\beta}$	F_{t1}	

Figure 8-19: Forces Acting on a Gear (KHK Stock Gears, n.d.)

The team inserted the properties of NylonX (shown in Figure 8-20), which is the material that was intended to be used to print the gears. However, due to difficulties with repairing the printer which was able to print NylonX, the gears were printed with PLA to test. One disadvantage of using a 3D printable material is that the material properties change after 3D printing, and depend heavily on infill percentage, print quality, and even print orientation. Because of these factors, it is hard to know exact material properties when performing analysis.

According to MatterHackers, the manufacturer who makes NylonX, the material has a tensile strength of 100 MPa (2020). The true tensile strength after printing is likely much lower as most manufacturers report the material properties of the material straight off the spool, not after being 3D printed. Research into PLA found the tensile strength of an 80% infill PLA part is 32.938 MPa (S.R. Subramaniam et al., 2019).

Properties of Outline Row 4: 3D Printed NylonX

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	1	g cm^-3		
4	Melting Temperature	180	C		
5	Isotropic Elasticity				
6	Derive from	Young's Modulus and Poisson...			
7	Young's Modulus	6000	MPa		
8	Poisson's Ratio	0.39			
9	Bulk Modulus	9.0909E+09	Pa		
10	Shear Modulus	2158.3	MPa		
11	Tensile Ultimate Strength	100	MPa		

Figure 8-20: Material Properties Used Within ANSYS for NylonX

The results from the ANSYS analyses were very promising, with a maximum equivalent stress of 9.46 MPa on the middle gear (Figure 8-21), and 12.34 MPa on the side gears (Figure 8-22). These values were well below the tensile strengths of NylonX and PLA.

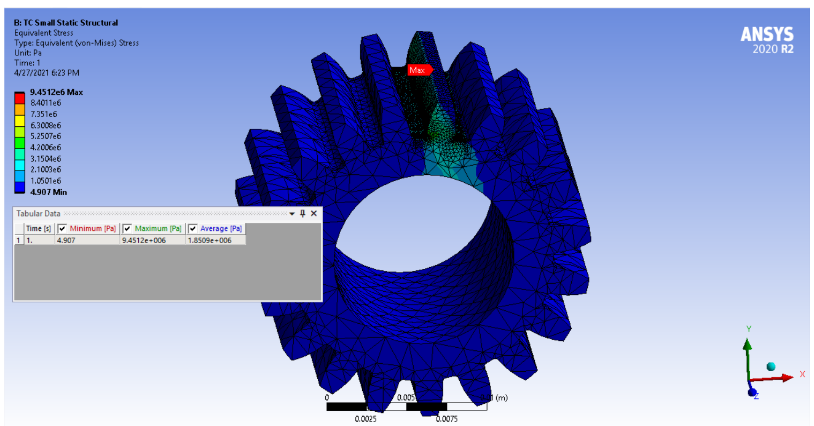


Figure 8-21: ANSYS Analysis of the Transfer Case Middle Gear

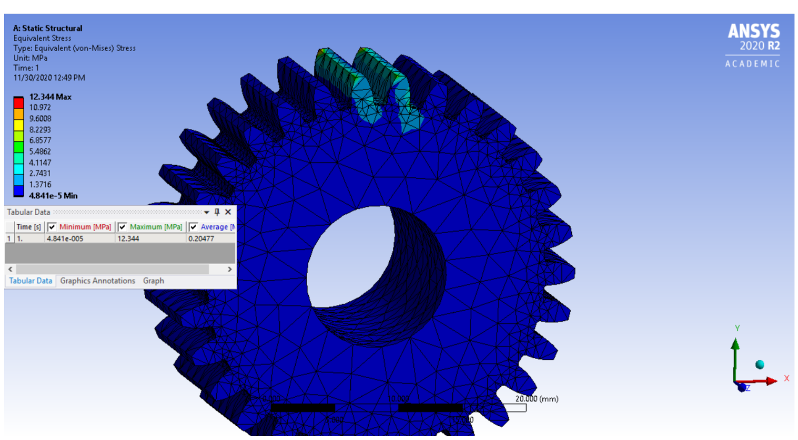


Figure 8-22: ANSYS Analysis of the Transfer Case Side Gears

Along with the finite element analysis using ANSYS, bending and surface stress calculations were also done on each gear. The calculations were done using Google Sheets, which can be found in Appendix C. For both bending and surface stress, the tangential, radial, and resultant forces on each gear were also needed. They were calculated using the same KHK Stock Gears source previously mentioned (KHK Stock Gears, n.d.).

Bending stress is the force that is trying to bend and shear the teeth away from the gear, and is important to look at when designing plastic gears (GE Plastics, 2006). Bending stress is calculated using the Lewis Equation shown below in Figure 8-23.

$$S_b = \frac{FP_d}{fY}$$

where:
S_b = bending stress
F = tangential tooth loading at the pitch line
P_d = diametral pitch
f = face width
Y = Lewis form factor for plastic gears, loaded at the pitch point

Figure 8-23: Lewis Equation Used for Calculating Bending Stress (GE Plastics, 2006)

Surface stress (also known as contact, or Hertzian Stress) looks at the interaction between the teeth of the gears (GE Plastics, 2006). Due to the relative motion of the gears, the surface stresses created can lead to failures on the teeth surfaces, or wear (GE Plastics, 2006). The equation used to calculate surface stress is shown below in Figure 8-24.

$$S_H = \sqrt{\frac{W_t}{fD_p} \cdot \frac{1}{\pi\left(\frac{1-\mu_p^2}{E_p} + \frac{1-\mu_g^2}{E_g}\right)} \cdot \frac{1}{\frac{\cos ø \sin ø}{2} \cdot \frac{m_g}{m_g+1}}}$$

where:
S_H = surface contact stress (Hertzian stress)
W_t = transmitted load
D_p = pitch diameter, pinion
μ = Poisson's ratio
E = Modulus of Elasticity
$ø$ = pressure angle
m = speed ratio, Ng/Np
N = number of teeth

Figure 8-24: Equation for Calculating Surface Stresses (GE Plastics, 2006)

Using the Google Spreadsheet mentioned above (Appendix C), the bending and surface stresses of each gear were calculated. The bending stresses were found to be 7.67 MPa for the middle gear, and 6.6 MPa for the side gears. The bending stress and ANSYS calculations are very similar, and along with the ANSYS calculations, these bending stresses were well under the tensile strength of both NylonX and PLA. On the middle gear the surface stress was found to be 56.74 MPa, and 58.4 MPa on the side gear. These stresses were still under the estimated tensile strength of NylonX, but were over that of PLA. These results mean that there will likely be wear on the teeth within the transfer case. Performance of these gears under testing is discussed in section 14, Results.

Between the two methods of gear analysis (ANSYS and Bending/Surface Stresses), we were able to consider the feasibility of using 3D printed gears. Based on the results, we considered 3D printing to be a practical method of creating the gears for our transfer case.

Differential

The team also designed two new differentials that will split the power again to both wheels. There will be one differential in the front and one differential in the rear. The design of these differentials will be discussed in detail in Chapter 9 of this report.

Wheels

After the power is split within the differentials, the power is sent through two drive shafts on either side of the differential in both the front and rear. These driveshafts are Traxxas driveshaft assemblies as seen in Figure 8-25 (Traxxas, 2021). These driveshafts are made out of two parts that fit inside of one another. This way the parts can slide back and forth while still transferring the power to the wheels. If the car hits a bump the parts can slide within each other to shrink the overall length of the driveshaft.

Figure 8-25: Traxxas Driveshaft assembly (Traxxas, 2021)

To connect the driveshaft to the wheel, the final part of the drivetrain, the team designed wheel hub connections that can hold a pin that goes through the drive shaft and therefore the part will rotate with the driveshaft. Then the hub connection part will be profiled to match the wheel hub connecting the wheel to the drive shaft and allowing the wheel to spin with the driveshaft. This connection part can be seen below in the figure.

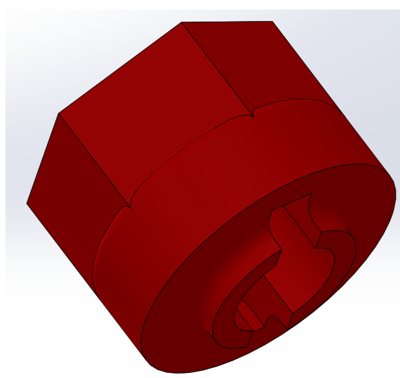


Figure 8-26: Wheel Hub Connection CAD Model

The wheels selected for this car were Pro-Line Trencher X SC Tires with Renegade wheels. The diameter is 4.35” and the width is 1.86”. These wheels are made of a medium compound and are ideal for multiple different terrains due to their thick treads (Pro-Line, 2020). This makes them a great choice for our car that can tackle difficult terrain.

9. Differential

In this chapter, we will be discussing the design and manufacturing phases of PARV's front and rear differential systems. Initially, this system was designed to be a fully 3D printable limited slip differential; however, over time, due to manufacturing problems it transformed first into a 3D printed direct drive differential system, and then into purchased open and direct drive differential systems that utilize 3D printed housings and spacers. This chapter will go over the development process of each and explain why each design concept was successful or not.

One of the main goals we set for PARV was for it to be able to travel off-road reliably and in a controlled manner. While the 4WD system we mentioned in the Drivetrain chapter helped us accomplish part of this goal, it would not be useful if the wheels it was connected to spun up or got stuck when going over obstacles. This was the problem we had with the previous team's car, as they had designed it to use an open differential or the rear wheels (Boggess et al., 2020). While an open differential allows each wheel to turn independently, and thereby reduce wheel lock during cornering, it also means that in any low traction environment, they could also begin to wheelspin and stop moving. This wheelspin is caused by the open differential sending all the power to the slipping wheel, preventing the other wheel on the same axle from moving at all.

Differential Requirements

As such, we needed to design a new system that would allow better torque and power control to each wheel. Specifically, we wanted to develop a system where in normal conditions, the front and rear differentials would output an equal amount of torque to both sides of the axle, while in slippery conditions, the differentials would be able to reliably transfer power and torque between the wheels on each axle. In addition, as we wanted to make the car as modular and 3D printable as possible, we wanted to create this differential system out of 3D printed material.

3D Printed Limited Slip Differential

In order to accomplish these goals, we decided to pursue a 3D printed limited slip differential (LSD) that could be used both on the front and rear axles of PARV. While many full-sized LSD systems use clutches or viscous fluid to lock the wheels together on low traction surfaces, we decided instead to pursue a system that used worm gears to lock the differential together. This design idea was inspired by a spiral differential design we found from GrabCAD

(Bhagat, 2015). While this system was not as proven, it was much easier to manufacture on a 3D printer than the other designs, as well as potentially being even more compact, which was necessary to make it fit within the chassis.

When designing the LSD, we wanted it to fit within the same sized housing as last year's differential; this housing had dimensions of 2.29 in x 2.3 in x 2 in (L x W x H). While we were using the same dimensions as last year's housing, we decided to create our housing out of 3D printed material as well. This would allow us to better fit our LSD design within these dimensions, and also allow the system to be more modular, as it could be modified much easier this way.

Using these dimensions as limits, we created a ring and pinion system, as seen in Figure 9-1, that would be able to fit within this small space. This ring and pinion gear system was the primary method of power transfer from the drivetrain to the wheels, and in normal conditions would work like an open differential, transferring equal torque and power to each wheel. The ring gear has an outer diameter of 1.74" and an inner diameter of 1.34" and is about 0.2" thick at its thickest point. A small amount of material is added on beyond this inner diameter for mounting gear guards and containing the central gear system that we will discuss later. The pinion gear has an outer diameter of about 0.72" and has a thickness of 0.24" when not including the shaft and 0.53" when including it.

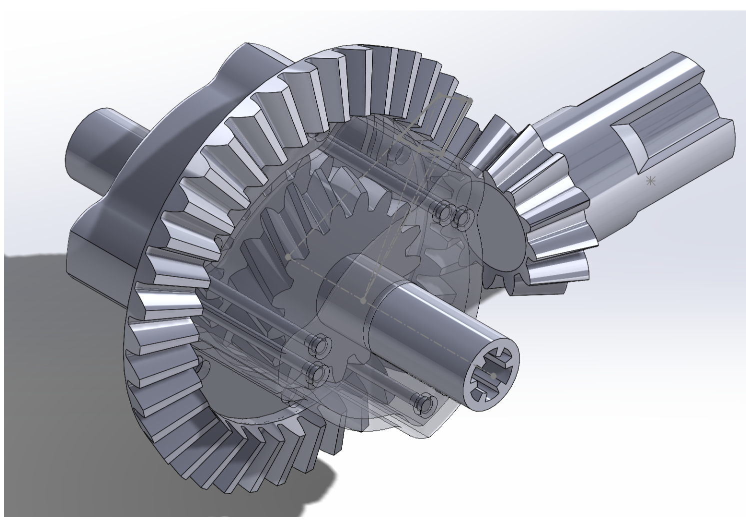


Figure 9-1: Initial LSD Design (Note: Worm Gears Not Shown)

This system has a gear ratio of 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. The teeth on the ring gear are about 0.4" long and about 0.11" thick at their base, while the teeth on the pinion gear are about 0.22" long and about 0.07" thick at their base. This ring and pinion system was designed to be a bevel gear system, which allows the teeth on each gear to interlock with each other more efficiently. As creating bevel gears in SOLIDWORKS is difficult, we utilized a GrabCAD model as a template (McGuire, 2021).

In the initial design for our pinion gear, we used a connecting shaft with a diameter of 0.45" that was 3D printed directly onto the pinion, which meant that the driveshaft it connected to would need to be very large. This can be seen in Figure 9-2 below. This turned out to be very impractical, both from a cost and a machining perspective, and as such we redesigned the pinion shaft to be both a separate piece and made out of a metal shaft, allowing us to connect to the metal driveshaft with less friction and less required machining. In order to connect this metal shaft to the pinion, we added a 0.22" diameter hole into the pinion gear and keyed the hole to allow the metal shaft to sit within it. This can be seen in the figure below.

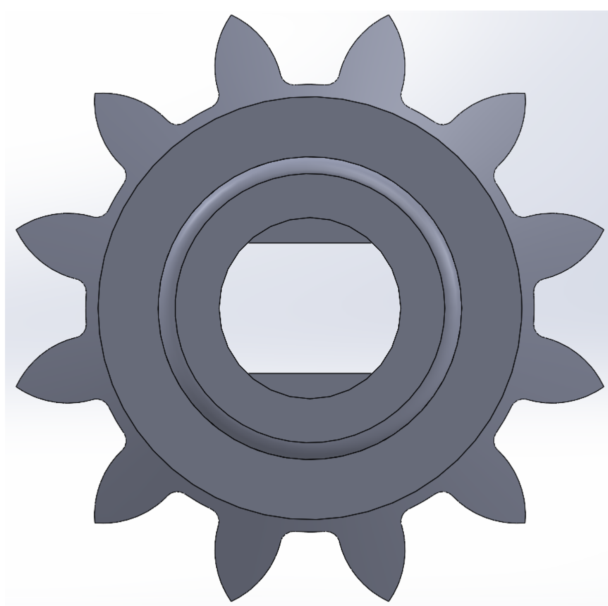


Figure 9-2: New Pinion Design

In order to turn this system into a limited slip differential, we needed to create a gear system within the inner diameter of the ring gear. This inner space within the ring gear was made to be 1.28" across in the x-direction and 0.88" across in the y-direction; this is shown in Figure 9-3 below. This was mainly done to keep everything as compact as possible; however, this also meant that each of the gears with it would need to be very small.

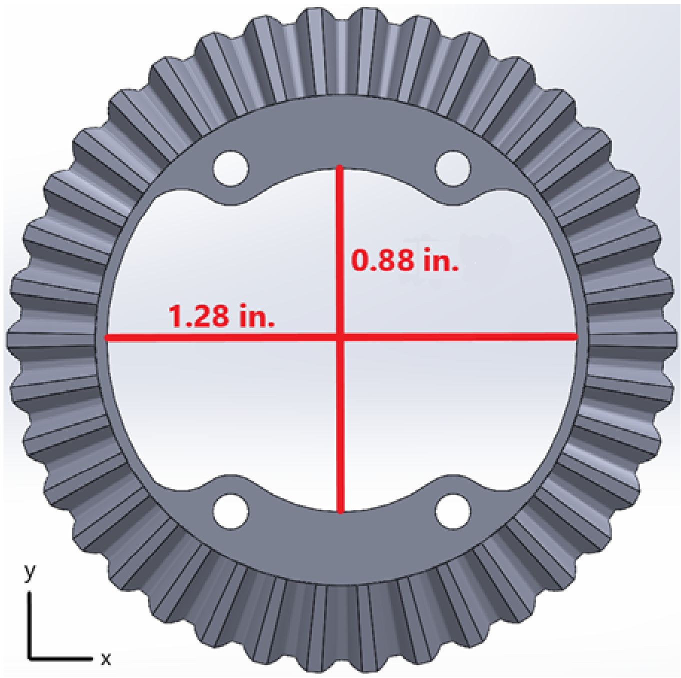


Figure 9-3: LSD Ring Gear

In the first iteration of our design, we utilized a gear system consisting of two central gears that connected directly to each of the individual wheels, and six worm gears, which interlocked with the central gears in two sets of three for each central gear. These worm gears would be set on independent shafts that allowed them to rotate freely when force was placed upon them. The gear system would sit inside a guard that would connect to the ring gear; the main purpose of this guard was both to connect the central gears directly to the ring gear and to allow the whole system to better fit within the differential housing. These guards, as well as the pinion gear mentioned before, would be surrounded by bearings so they could rotate within the housing effectively, as trying to rotate 3D printed parts against other 3D printed parts can cause excessive friction and heat.

However, when we began looking into 3D printing these worm gears, we found that, not only would they only consist of 3 or 4 teeth, but also they would be too small and not too strong. The idea of six worm gears was so power could be transferred more easily between the wheels.

However, it became clear that their lack of strength would outway any power advantages we might get. As such, we decided to redesign the interior gear system to utilize four worm gears instead. This would not only give us more teeth on the worm gears (due to the additional space cleared up), but also allow it to have some underlying strength from the 3D printed material.

In addition, we also had to make a change to the central gear shaft. The initial connecting shaft we made did not match with the dimensions or layout of the Traxxas drivetrain links we planned to use to connect the differential to the wheels (Traxxas, 2021). As such, we needed to redesign the end of these shafts to allow for a set screw to go through them, which was accomplished by adding a 0.117” diameter hole 0.1” from the end of the shaft, as well as making them shorter to be less fragile under load. This can be seen in the figure below.

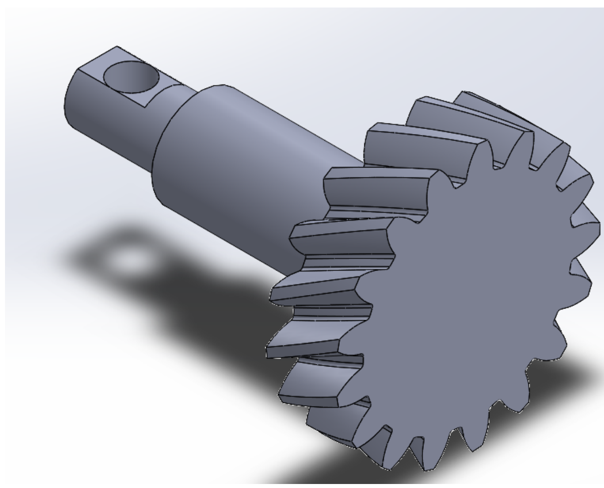


Figure 9-4: New Central Gear Design

Once this change was done, we made only minor changes from this point on, as the system was able to fit within our dimensions and seemed to lock together correctly. A CAD model of this final design is shown in Figure 9-5.

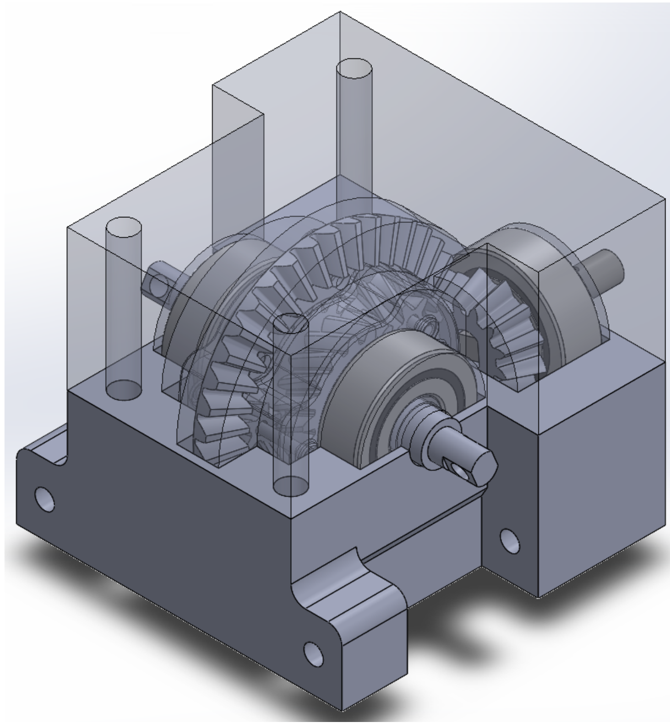


Figure 9-5: Final LSD Design

The main idea of this LSD is that while under normal conditions, the central gears would follow the motion of the ring gear. This would transfer equal power to each wheel while also allowing them to travel at different speeds. However, when a wheel loses traction, excess slippage is transmitted through the differential, which causes the worm gears to lock the central gears to each other. More specifically, the central gear system works as follows:

1. One of the wheels on the axle begins to slip
2. The central gear the wheel is connected to (Center Gear 1) brakes the friction between it and the guard around it and starts to spin faster
3. The two worm gears interlinked with it begin spinning (Ex.: Worm Gear 1)
4. These worm gears connect to two other worm gears, which then begin spinning themselves (Ex.: Worm Gear 2)
5. These worm gears then connect to the other central gear (Center Gear 2), allowing power to transfer between the gears, and by extension the wheels
6. The fast spinning central gear (Center Gear 1) is slowed back down by the inertia from the slower moving central gear (Center Gear 2)

A close up view of one side of this system is shown in Figure 9-6 below, and a more detailed view of all the components is found in Figure 9-7.

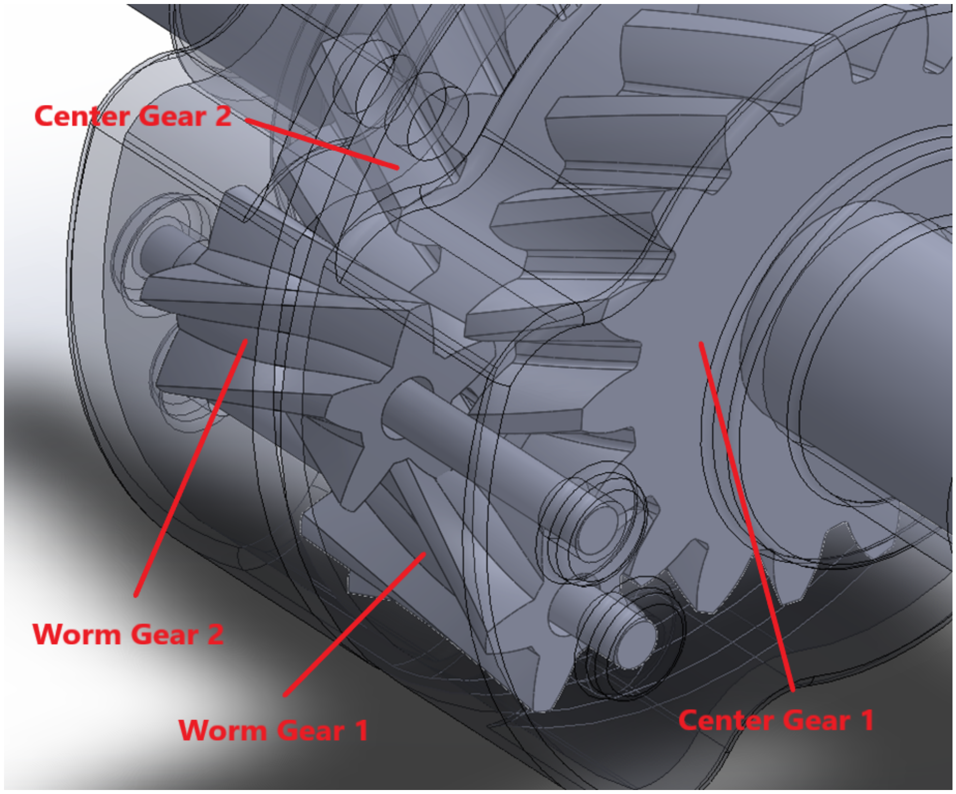


Figure 9-6: Central-Worm Gear System (One Side)

Each of these central gears contain 17 teeth, are 0.783" in diameter, and are 0.2075" thick. When manufactured, they are connected to a shaft which is about 0.2875" in diameter and 0.8925" long from the back of the gear. Each worm gear contains 5 teeth, are about 0.33" long, and have an outer diameter of about 0.25" and an inner diameter of 0.08". Despite the difference in teeth number, the combination of these gears does not induce a gear ratio as they only act on each other when in low traction situations. In addition, on each side of the differential these gears are mirrored, as that allows them to interconnect with each other. All of these components were then mated and combined into the housing, which is closed using #8 screws. In addition to containing the differential, this 3D printed housing also includes mounting points to both the chassis (using #8 screws) and the suspension system (using pins); as the differential sits along the centerline of the car, this is a necessity. An exploded view of our final model is shown in Figure 9-7, with an associated table listing the various components listed below in Figure 9-8.

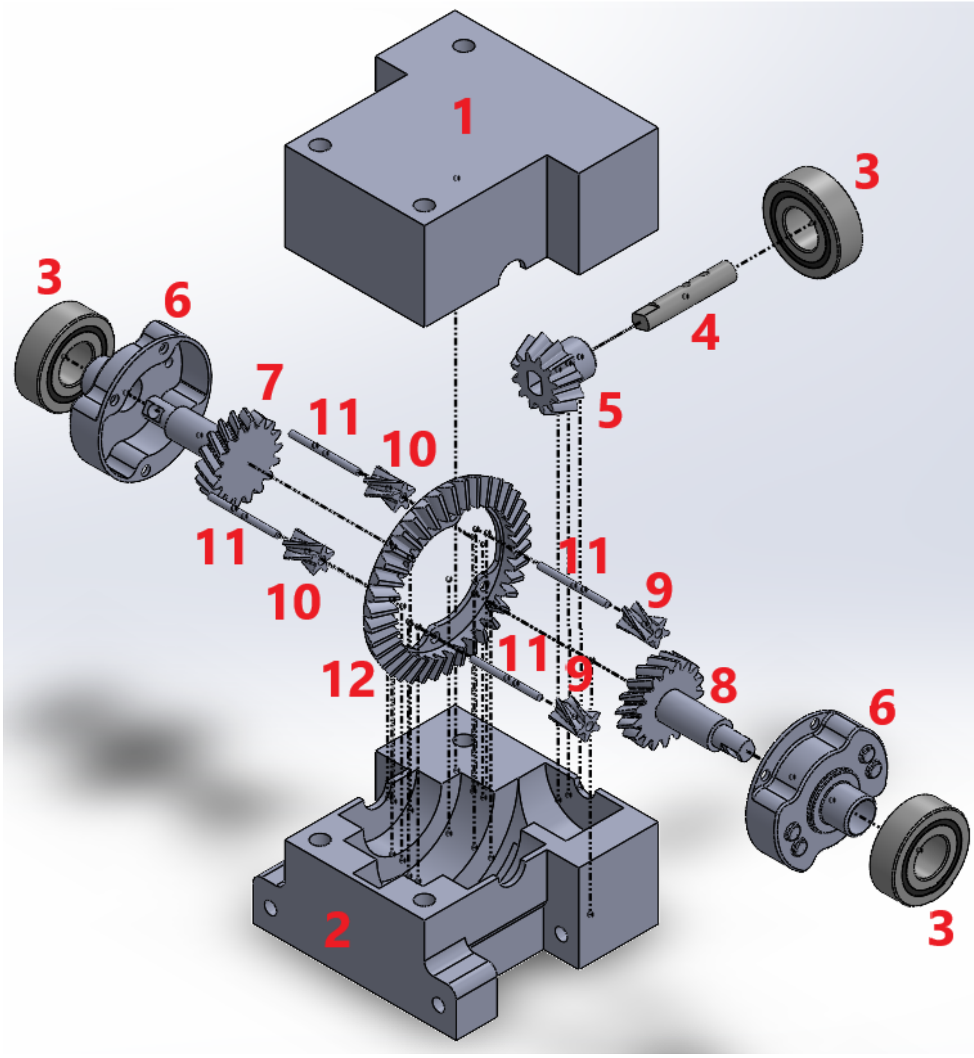


Figure 9-7: Limited Slip Differential Exploded View

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	Diff Pinion Shaft	1
5	LSD Pinion Gear	1
6	LSD Guard	2

7	Central Gear	1
8	Central Gear Reverse	1
9	Worm Gear Reverse	2
10	Worm Gear	2
11	Worm Bar	4
12	LSD Ring Gear	1

Figure 9-8: LSD Parts Table

Once each gear was modeled in CAD, we began to do an analysis into the feasibility of the 3D printed gears. This analysis falls under the same format of the one done for the Transfer Case gears. Refer to Chapter 8 Section Transfer Case for a more in depth dive into the material properties, set up, and calculator methods. Like the Transfer Case gears, ANSYS simulations, as well as bending and surface stress calculations considered, all using the torque values throughout the drive train calculated in Matlab earlier in Chapter 8.

As mentioned previously the Limited Slip Differential features four different types of gears, a beveled ring gear, a beveled pinion gear, four worm gears, and two beveled center gears. The resultant forces on each gear were calculated and input into ANSYS, acting on the face of a tooth.

Based off of the researched tensile strength of NylonX being 100 MPa (but likely weaker due to the nature of 3D printing), and the tensile strength of 80% infill PLA part being 32.938 MPa, the results from ANSYS were less promising for the differential gears compared to the transfer case gears (MatterHackers, 2020)(Subramaniam et al., 2019). The ring gear experienced a maximum Von-Mises stress of 46.43 MPa, worm gears experienced 10.27 MPa, and the center gear got 64.74 Mpa. These results can be seen below in Figures 9-9 through 9-11.

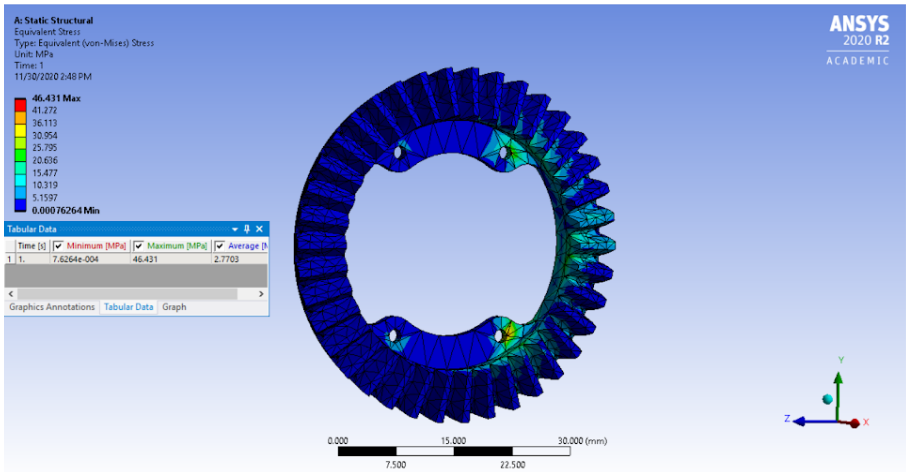


Figure 9-9: Ring Gear ANSYS Results

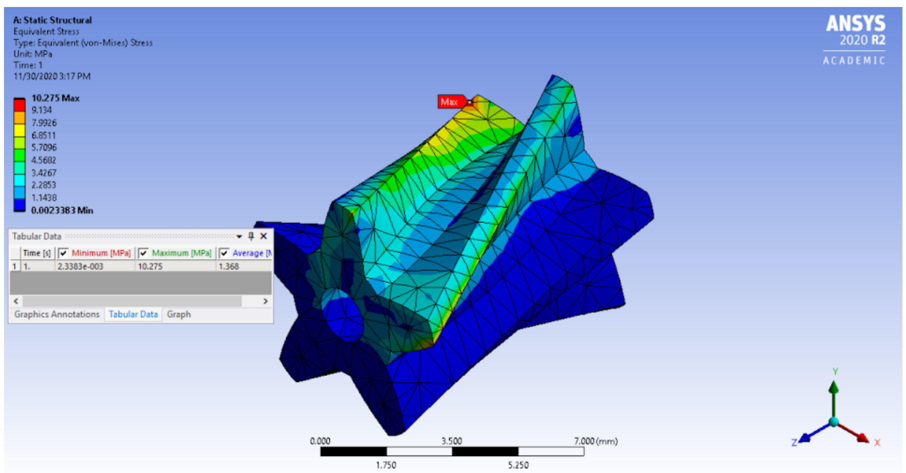


Figure 9-10: Worm Gear ANSYS Results

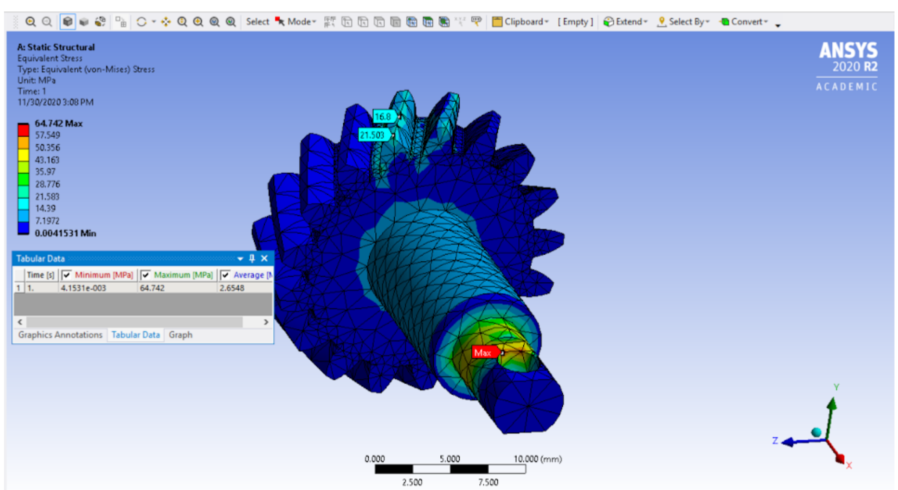


Figure 9-11: Center Gear ANSYS Results

For the calculated Bending and Surface Stress, the results can be seen below in Figure 9-12.

Calculations	Ring Gear	Bevel Pinion Gear	Worm Gear	LSD Center Gear
Tangential Force (N)	59.06	59.06	45.00	90.00
Radial Force (N)	21.49	21.49	46.23	92.45
Resultant Force (N)	62.85	62.85	64.51	129.03
Bending Stress (MPa)	31.19	54.96	10.57	25.95
Surface Stress (Mpa)	77.72	83.18	93.21	156.64

Figure 9-12: Limited Slip Differential Gear Surface and Bending Stress Calculations

The combination of the results from ANSYS and the surface / bending stress casted some doubt on the performance of the Limited Slip Differential gears if they were 3D printed. While some gears (specifically the worm gears) had results that were under the researched tensile strength of printed parts, concerns over their sizes overshadowed these results. Because of the small size of these gears, not a lot of material will be able to be printed within the parts. Since most printers use extruders with a 0.4 mm (.016”) diameter hole to extrude plastic through, features smaller than this may not be printed. Figure 9-13 below shows a sliced view of one of the worm gears. Due to the small size of the teeth, the extruded layers may not fully fill the teeth in. Because of this, their strength may be compromised.

Figure 9-13: Sliced Layer view of Worm Gear

With these issues, we still continued to print the gears as a proof of concept and assemble the Limited Slip Differential. Using our CR-10 V2, our gears came out pretty well, however we ran into other issues with assembly. Due to the size constraints of the system, the worm gears and axles used are very small as seen in Figures 9-14 and 9-15. These gears were extremely difficult to put in the right spot. The pins are required to be slid into small holes, and to be a certain length up on the rod. Since the whole assembly was closed around the inner gears, it was extremely difficult to both fit them in the right spot, and close the differential.

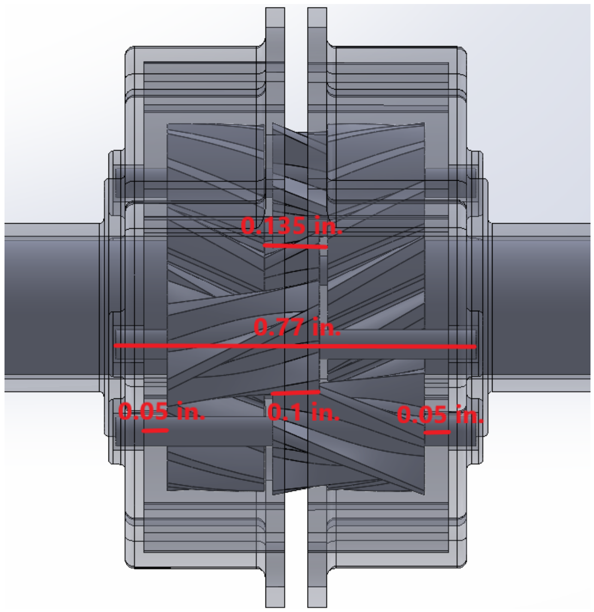


Figure 9-14: Tight Dimensions in LSD (Side View)

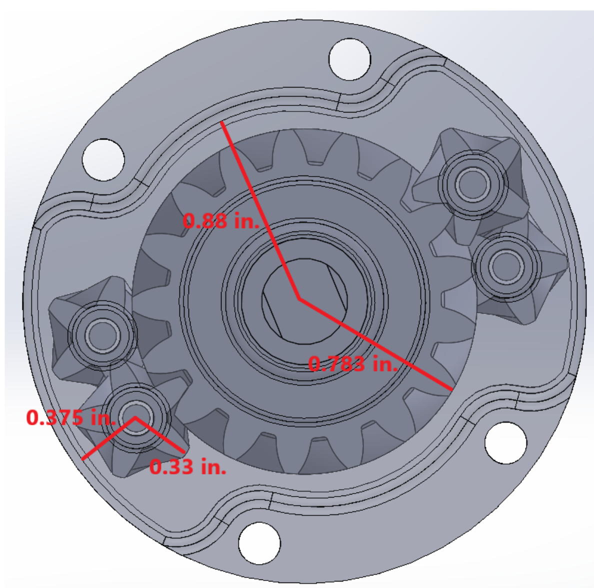


Figure 9-15: Tight Dimensions in LSD (Front View)

On a few occasions, we were able to get two worm gears in position to test the movement of the differential. With two worm gears in position, we spun the two center gears using our hands. The gears did not spin well with each other and frequently caught on each other. Upon inspection, this was likely because of the print quality and tolerances of the gears. Gears need to be printed perfectly in order to mesh properly, and any inaccuracy in the gears can lead to issues. While these gears did pass our print tolerancing procedure, the surface finish of the teeth was not perfect, which was likely due to the teeth being too small for the printer to accurately print.

On top of this, when the gears were spun, they did not perform in the way they were expected to. As the nature of the differential, each center gear should be attached to each other, but also allowed to rotate with a certain degree of independence. When rotated, each gear spun independently from each other. We were not able to see inside of the differential to see what was causing this, but our assumption was that the worm gears were falling out of alignment. Figure 9-16 shows two assembled LSDs without the worm gears installed.

We have developed some ideas to remedy these issues and make new iterations, however we had to make the difficult decision to put the Limited Slip Differential on the back burner. At that point in the developmental process, we wanted to get a full assembly of the car working as soon as possible. We were not confident that we would be able to get the differential working within the desired time frame, so we decided to create a simpler system for the time being. All of the ideas and solutions we thought of for the Limited Slip Differential can be found in Chapter 16 section Recommendations for Future Work.

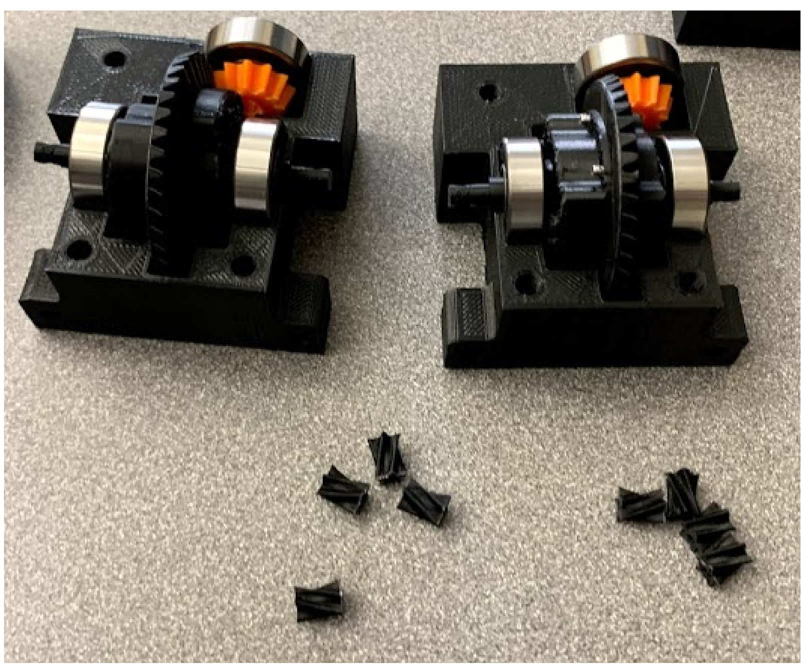


Figure 9-16: Two Assembled LSD (Minus the Problematic Worm Gears)

3D Printed Direct Drive Differential

After we realized we could not create a limited slip differential due to manufacturing problems, we began to analyze different alternatives that we could create for PARV. For the front differential, we decided to use a 1/10 scale Traxxas open differential, which was the same system that the previous team used for their car (Traxxas, 2021). This was mainly done because an open differential was required so the front wheels could turn effectively. However, for the rear differential, we decided to revise our initial LSD design into a direct-drive differential.

The main difference between a direct drive differential and a limited slip differential is that, instead of only locking the wheels together under low traction, a direct drive always keeps all the wheels at the same speed, even when grip is high. While this does not allow free wheel movement like with an LSD, it is still very useful when going off-road, as no matter what environment the vehicle is in, it will always be applying power to the wheels. In addition, the torque received by each wheel does change depending on the conditions, meaning that even if one wheel is stuck, the other will receive all the torque, allowing it to pull itself out of low grip situations or over high obstacles.

When designing the direct drive, we wanted to keep many of the same dimensions as our LSD design; as such, our ring and pinion gears stayed at the same diameter and teeth number, and the housing we were using kept the same outer dimensions. However, the interior of the housing was modified to better fit our new direct-drive.

To create the direct-drive, we started by removing the central gears, worm gears, and LSD guards from the design, and filled in the interior of the ring gear. We then extruded a new drivetrain shaft from the center of the ring gear, and gave it an end profile that was the same shape as the original from the LSD, so it could still connect to the wheels. This meant that there was now a direct connection between the drive shaft to the wheels, with the ring and pinion system simply acting as a torque amplifier (with its 2.8:1 ratio) and power redirector. A picture of the 3D printed direct drive assembly can be seen below in Figure 9-17.

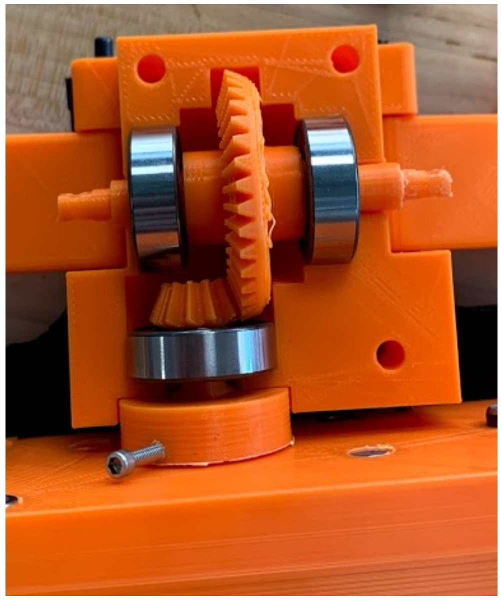


Figure 9-17: 3D Printed Direct-Drive (Initial Iteration)

These new direct-drive gears were 3D printed using PLA plastic. During our initial tests of this new system, we ran into an immediate problem: the 3D printed driveshaft connectors were breaking under load, as seen in Figure 9-18 below. When testing our gears in ANSYS previously, we had noticed that a large stress concentration was possible at this point, which was verified by this part failure. Unfortunately, due to the nature of the drivetrain connectors, we could not make this part any stronger, as these dimensions were limited by the shape and set screws for those connectors.

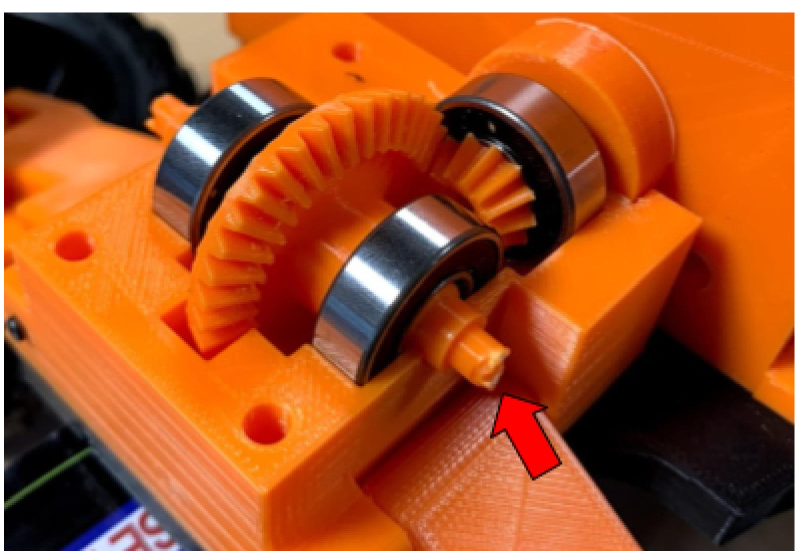


Figure 9-18: Example of 3D Printed Shaft Failure

From these failures, we determined that it would not be possible to utilize 3D printed shafts for the differential, as the torque through them would be too high for them to take. As such, we decided to redesign the direct-drive to instead use an aluminum shaft. To use this type of shaft, we changed the design of the differential again, this time to include a hole that went through the center of the ring gear; this is where the aluminum shaft would be placed. This aluminum shaft would be profiled so it could fit within this hole without spinning and have small holes drilled into it so it could be locked in place with set screws. This final design is shown in Figure 9-19 below (with the aluminum shaft shown below in Figure 9-20).

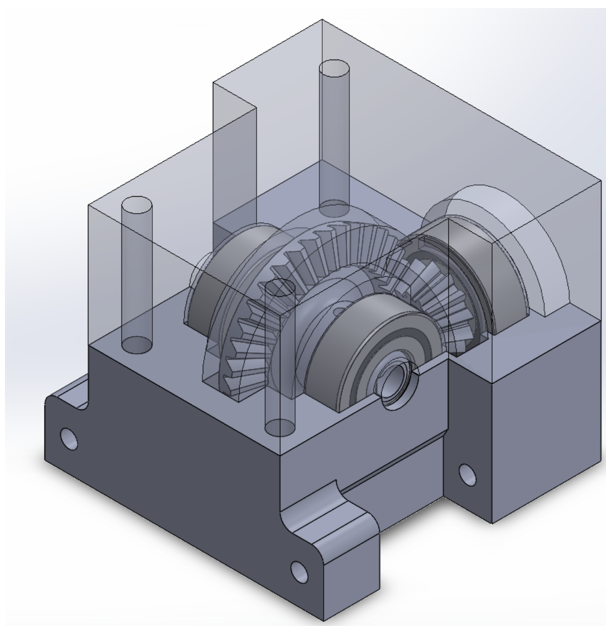


Figure 9-19: Final Direct-Drive Design

Figure 9-20: 3D Printed Ring Gear With Metal Shaft

During our initial tests, we had problems with the set screws falling out due to the vibration of the differential. However, once those issues were solved by using lock nuts, we found that the pinion gears on the differential were being torn up. This was mainly due to the torque demands of the differential, as the 3D printed teeth were not strong enough to handle the friction generated by grinding against 3D printed material at the torque level required from the drivetrain. We attempted to fix this by using different types of 3D printed materials, including Tough Resin and NylonX. Tough resin is a different form of 3D printing using a Stereolithography (SLA) printer and resin. NylonX is a 3D printed nylon material with carbon fiber mixed in with the nylon. These carbon fibers can increase the strength of the part. When testing with Tough Resin, the pinion gear failed almost immediately, but instead of shredding like the PLA, they snapped off the center of the pinion. As for the NylonX, we were not able to do any reliable tests with it, as the NylonX printer we needed was continuously going down. We were able to test print the gears in NylonX using another printer on campus, however the print quality was not good enough for the gear teeth to mesh properly. However, they seemed to be stronger, at least from rudimentary strength testing of the teeth using pliers, so in the future this may be an area to pursue when creating 3D printed differentials. However, for our car at least, this meant that the idea of a fully 3D printable differential was not possible. Figure 9-21 shows an example of the pinion failure.

Figures 9-21: Example of Pinion Failure (Left Image: PLA, Right Image: Tough Resin)

A final issue we ran into when designing the direct drive was plastic on plastic contact. Initially in our design, the coupler coming out of the transfer case into the drive housing was sometimes able to slide forward on the axle and rub against the housing. After a short amount of testing with the plastic coupler and housing rubbing together, the plastic reached its melting point (around 365℉ or 185℃), and fused the two parts together, locking the drive train up (shown in Figure 9-22). In order to remedy this issue, the coupler's profile was shortened by an eight of an inch. Future iterations of this housing, and all drive line components were designed to prevent plastic to plastic contact.

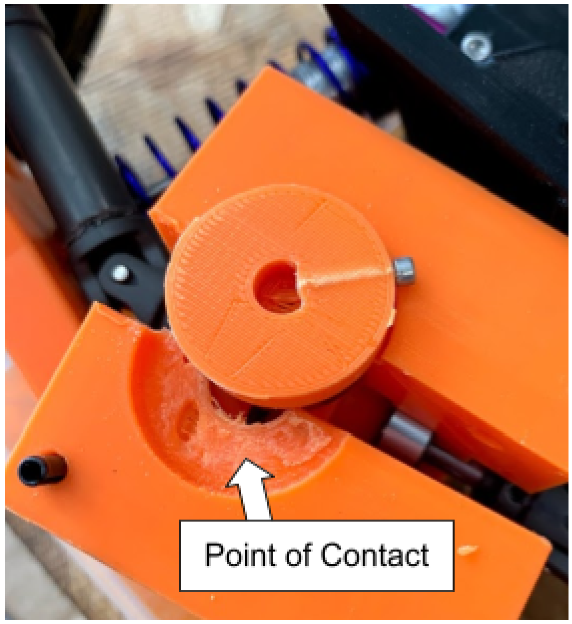


Figure 9-22: Transfer Case to Direct Drive Interference

Final Differentials

While the 3D printed direct-drive differential we created did not work, we still believed the concept of a direct drive differential would work, especially when travelling off-road. As such, we decided to purchase a 1/10 scale Traxxas direct-drive ring and pinion that could be used on the rear axle of PARV (Traxxas, 2021). While this system was fully machined using metal, we still were able to enclose it within our 3D printed housings, partially through redesigning them, and partially through creating 3D printed spacers for the direct drive. As such, this showed the modularity of our differential housing, as the constant modifications we made to it showed that it could be customized to fit a number of different differential systems. Figure 9-23 shows the final rear differential.

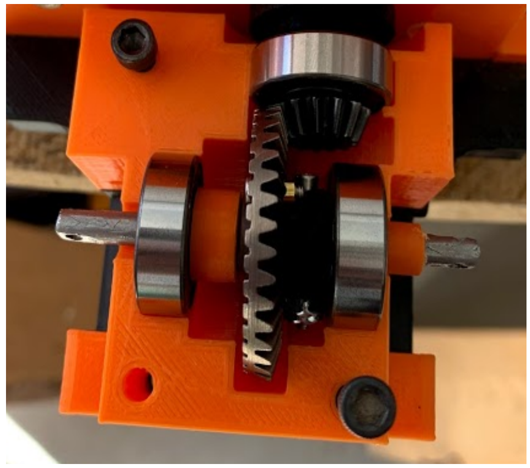


Figure 9-23: Final Rear Differential

As mentioned in the previous section, while the rear differential would become a direct-drive, the front differential would use the same open differential used last year, a 1/10 scale Traxxas Sealed Differential. This is because the open differential allows for each wheel on the axle to spin at different speeds, which prevents wheel locking or slipping due to changes in angular velocity. This is especially important at the front wheels of a 4WD system, as they are both receiving power from the drivetrain and having to steer the car at the same time. As such, using a locked or direct-drive differential could cause wheel locking or prevent the front wheels from turning correctly. Like the rear differential, this differential was enclosed within a custom 3D printed housing, again showing the modularity of this system. Figure 9-24 shows the final manufactured front differential.

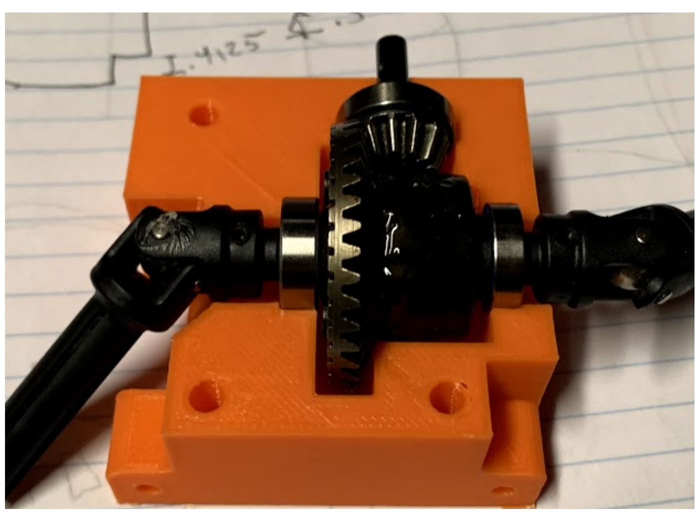


Figure 9-24: Final Front Differential

Unfortunately, utilizing these differentials did not allow us to accomplish our goal of creating a fully 3D printed differential. However, using these systems was necessary to prove the effectiveness of all of the other subsystems on PARV, as we could not test them effectively if we did not have a fully functional and tested differential system.

10. Vehicle Structure

In this chapter, we will be discussing the development and manufacturing process of the 3D printed structure of PARV. The structure of PARV was mainly based around the 3D printed chassis, as it is the central component that every mechanical, structural, and electrical sub assembly discussed previously mounts to. In addition to the chassis, we also developed other structural components such as a top plate, bumpers, and various mechanical spacers and housings that allowed us to unify all of these components together and to accomplish our end goals for PARV.

Vehicle Structure Requirements

The structure of our vehicle needs to support the weight of and contain all the subassemblies of PARV. As such, the chassis needs to be able to support the weight of all of the standard components with no noticeable deflection and must also be big enough to fit all the subassemblies without them hanging over the side of the chassis and its related structures. In order to fit our goal of payload carrying, it also needs to have negligible or non damaging deflection at our maximum expected load of 20 lbs on the car, and the top plate needs to have mounting points for the payload, whether that be a package or a tool. We also want the structure to be modular, so as such it needs to be fully 3D printable, or at least be designed primarily out of 3D printed materials.

Chassis

The main idea and structure of PARV's chassis was carried over from last year's MQP (Boggess et al., 2020). While the chassis is 3D printed, it has three slots for 3/16" zinc rods which run down the length of the chassis, and increase its strength and resistance to bending. Due to the size of the chassis last year and available 3D printers, it had to be printed in two halves. These halves were then epoxied together (Boggess et al., 2020).

Since the chassis acts as the main body for the rest of the car, it was created following the development of the other components of the car. As initial models were made of the Transfer Case, Limited Slip Differential, and Steering Mechanism, the chassis was running out of room. In order to fit the entire drive line, including the various couplers between components, the chassis was made 1" longer than the one last year. This allowed for everything to fit between the

Limited Slip Differentials at each end of the chassis. At this point the sizes, locations, and materials of the components were laid out. The chassis was also edited with holes for hardware for each component. Countersunk screws coming from the bottom of the chassis and nuts on top hold each component tight to the chassis. Figure 10-1 shows the initial chassis layout.

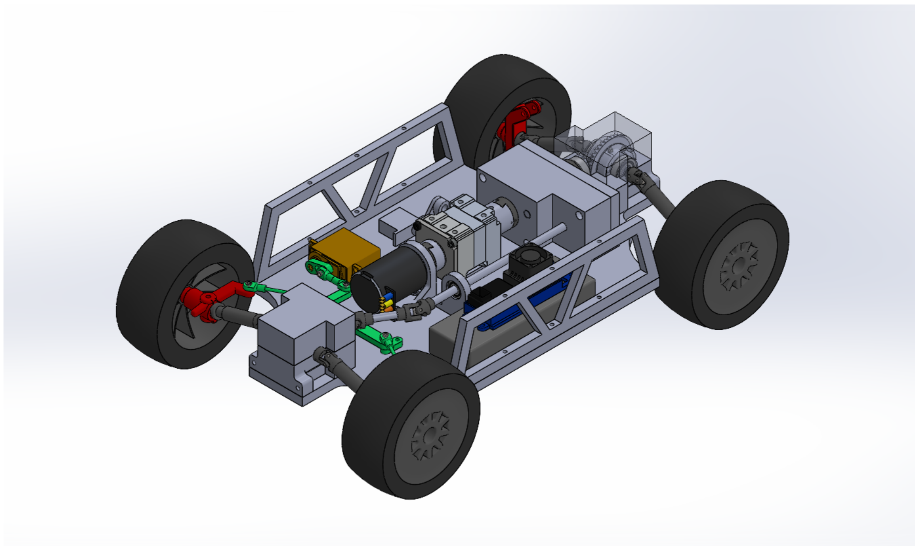


Figure 10-1: Initial Layout of Chassis

With the locations and sizes determined for the chassis components, an analysis was done on MathCAD to test the strength of the chassis. The MQP team last year developed a MathCAD script to test their chassis, and this same script was used for ours with minor adjustments for the longer chassis, and additional components (Boggess et al., 2020). The weights of purchased components like the battery, gear box, and motor were found online through their distributor. The weight of custom made components like the transfer case and steering were determined through a combination of weights from purchased hardware, as well as estimates based on 3D printing slicers which give an estimated material cost in grams. A link to the MathCAD script can be found in Appendix B. Using the combined distributed forces of each component on the chassis, deflection across the chassis was calculated. Figure 10-2 below shows the free body diagram of the chassis. Note that this calculator also includes the weight of the payload mounted to the top plate (top plate covered in next section). For this analysis the weight of the payload was made to be 25 lbs rather than our requirement of 20 lbs. This weight was increased from the requirement in order to test a worst case scenario.

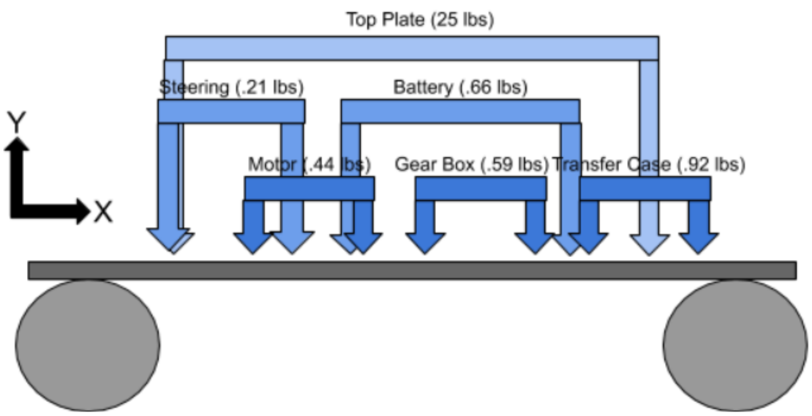
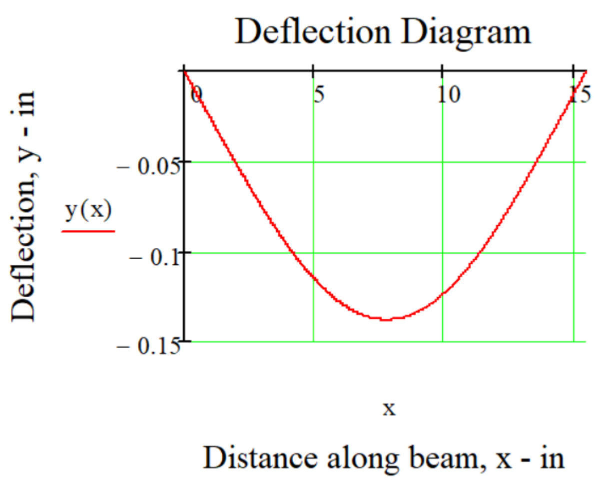


Figure 10-2: Free Body Diagram of Chassis (Side View)

The maximum deflection determined through our calculations was 0.138", located at the center of the chassis relative to the front and rear wheels. This result was well under our requirement of a maximum deflection of a quarter inch. This showed us that the combination of zinc rods within a 3D printed chassis would be sufficient to support all of our components and payload. Figure 10-3 shows a graph of the deflection along the chassis.



$$y_{max} := y(x_{critical}) = -0.138$$

Figure 10-3: Graph of Deflection Along Chassis

Once the analysis was completed and verified our manufacturing and design methods for the chassis, 3D printing began. As mentioned previously, the size of the chassis meant it needed to be printed in two halves. This year one of the printers being used does have a larger buildplate than last year (CR-10 with a 12"x12" build plate), but it was still not enough for the total length of the chassis (15.47”). With each half of the chassis being 8.73” long, and 9.6” wide, each print took just over 25 hours.

In order to combine the two halves, a split was made down the middle. The split was made with a 2” overlap between each part (as shown in Figure 10-4). This overlap provides a surface area of 19.2” squared for the JB Weld Clear Weld epoxy to adhere the two halves together.

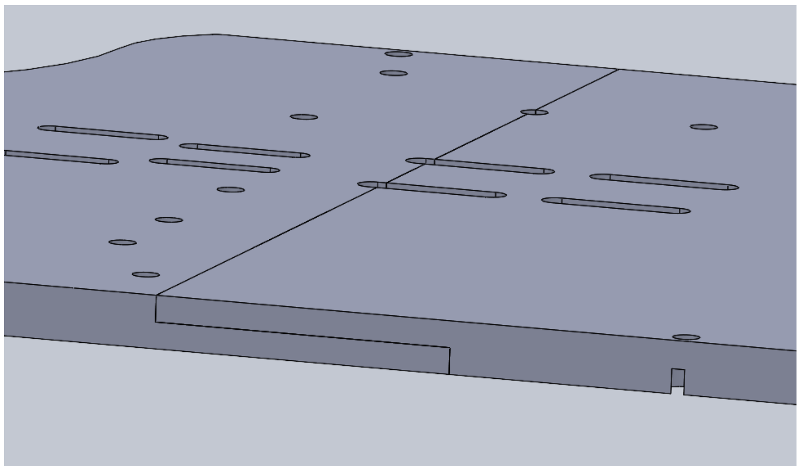


Figure 10-4: Overlap Between Two Halves

Once the halves were connected, the zinc rods were embedded. This required three 3/16” zinc rods, two cut to 7”, and one cut to 13”. These rods were cut to length, then epoxied into their appropriate slots using the same JB Weld used to connect the chassis halves. Figure 10-5 below shows the rods within the chassis.

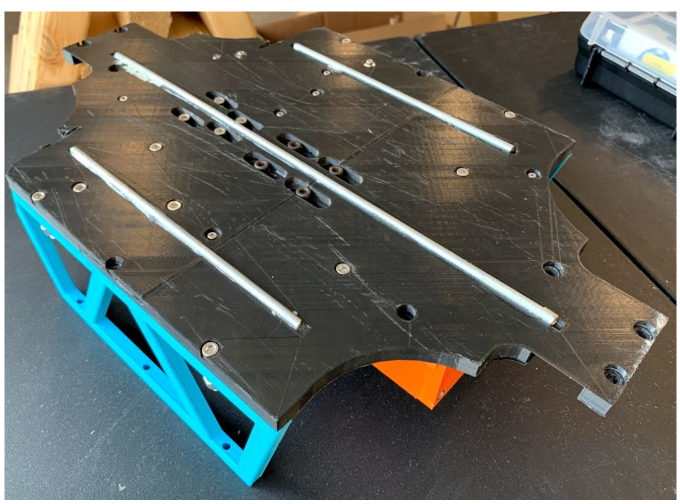


Figure 10-5: Underside of Chassis with Zinc Rods

Each component had its mounting holes made in cad that were printed into the chassis. Most components either use #8 or #4 screws. The gearbox and motor mounting holes were made as slots in order to allow for fine adjustments when mounting. Each slot allows for 1” of adjustment. Since these components are all connected together through 3D printed couplers, any inaccuracies in printing or assembly could mess with the alignment of the mounting holes. A final picture of all components on the chassis is shown below in Figure 10-6.

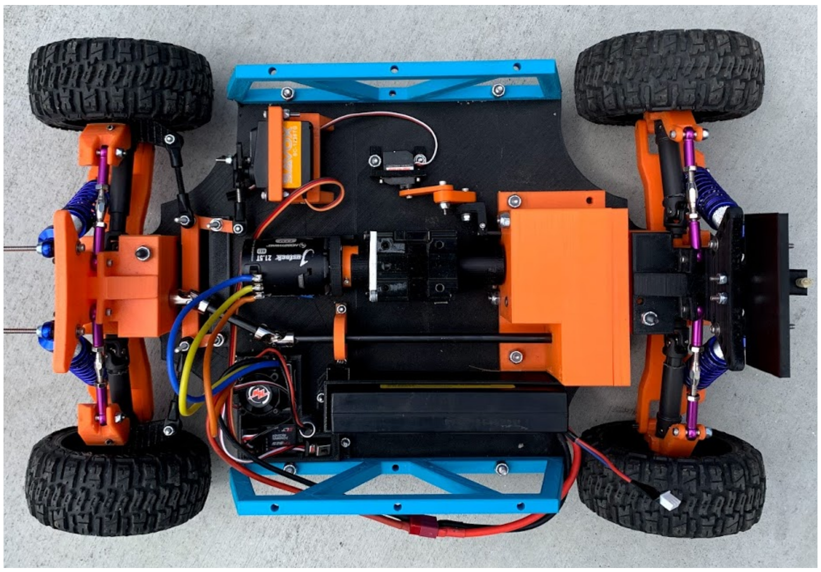


Figure 10-6: All Components Mounted to Chassis

Top Plate

Coming off of the chassis, two supports connect to the top plate. The main purpose of the top plate is to be a location where a payload, or any modular package could be integrated. The top plate connects to the stands with four #8 screws. The top plate also has eight #4 screw holes for payload mounting. These holes are aligned along the front and back of the plate, allowing for a payload of any size to be attached. Depending on the mounting requirements of the payload, a mounting adapter can be made to connect it to the top plate. The top plate can be seen below in Figure 10-7, it is 10”x8.5”x0.5”.

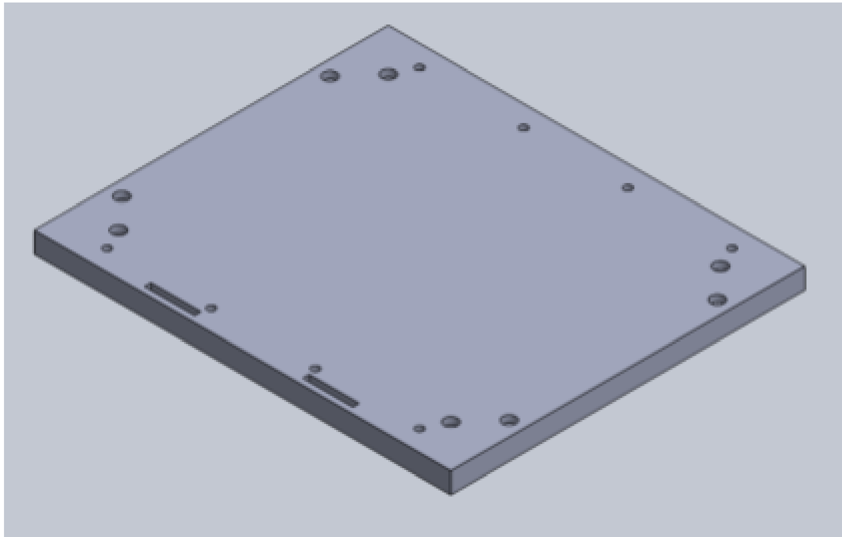


Figure 10-7: PARV Top Plate

The top plate also features a smaller plate underneath which connects underneath the top plate. The main benefit of having a smaller plate within the large plate is that it can be removed, and reprinted quicker to adapt for a changing package. Figure 10-8 below shows the small plate with the main top plate set to be transparent.

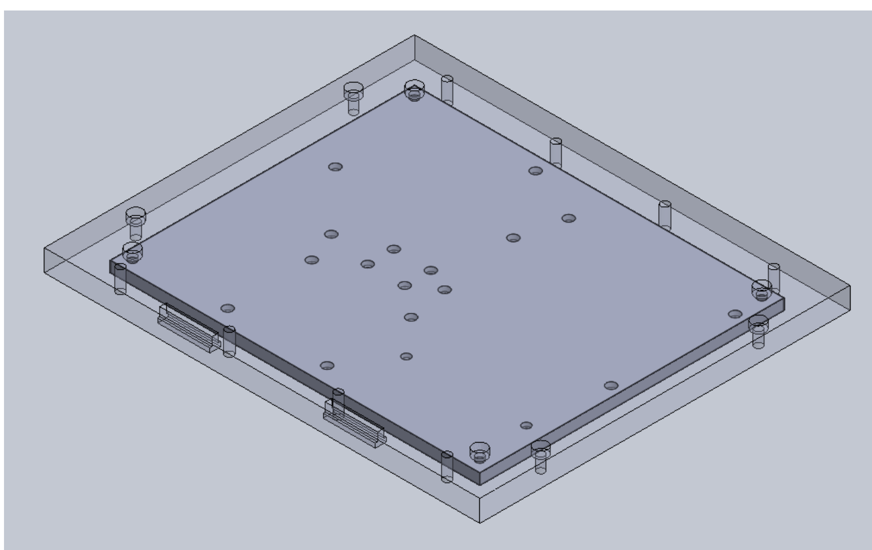


Figure 10-8: Small Plate Within Top Plate

Figure 10-9 below shows an example of how the small plate can be used as a modular system. The self driving package (explained more in Chapter 13) for example requires a battery, Arduino Uno, Raspberry Pi, breadboard, and an Inertial Measurement Unit (IMU). The small plate was adapted with mounting holes, and printed.

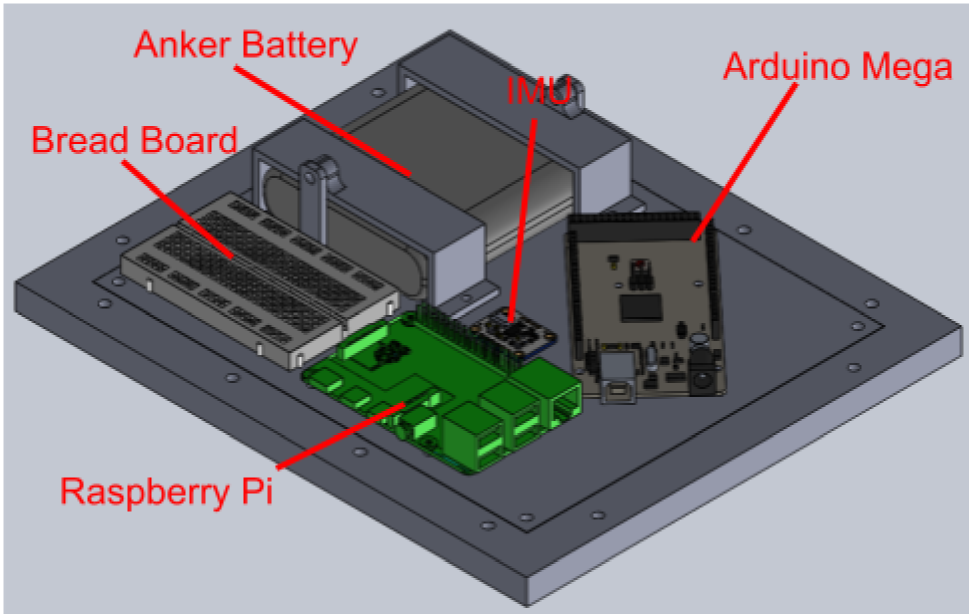


Figure 10-9: Self Driving Package Mounted on Small Plate

Bumpers

The bumper system on PARV consists of a front bumper that is used both for vehicle protection and sensor integration, and a rear bumper solely for vehicle protection. As such, both had to be designed somewhat differently.

Front Bumper

The front bumper on PARV was designed to fulfill two tasks: it needs to protect the front of the car from damage, and it needs to be used as a mounting plate for ultrasonic sensors, which can be added in a self-driving package (described more in Chapter 13). Testing the car from last year showed that when a front impact occurs, the front suspension wishbones often failed. Because of this, the front bumper was needed to protect the crucial elements of the car. The bumper also needed to be small enough to not decrease the mobility of the car, or interfere with the turning angle of the wheels.

For our initial bumper design, we created a thin, curved plate that would stick out in front of the wheels of PARV, with the idea being that the bumper would not only protect the front suspension, but also the front wheels and front drivetrain as well. This plate was flat on the front, curved to a 45° angle on both sides, and then reverted back to a flat surface before doing a 90° turn around the front wheels to offer some side protection. These angles were chosen specifically to fit the requirements given to us by the ECE team, as they needed their side ultrasonic sensors to be 8.5" apart and each at a 45° angle. At these positions, holes were created for the ultrasonics to stick out from and to mount to.

However, this also meant that the bumper had to stick out far from the front of the chassis, as that was the only way to achieve their requirements for this setup. However, this meant the connection arms to the chassis, which were about 5" long, were a high stress zone that could easily break. As shown below in Figure 10-10, the initial design of these arms that connect the bumper to the car were only .125" thick which we expected to be too thin and flimsy without additional supports.

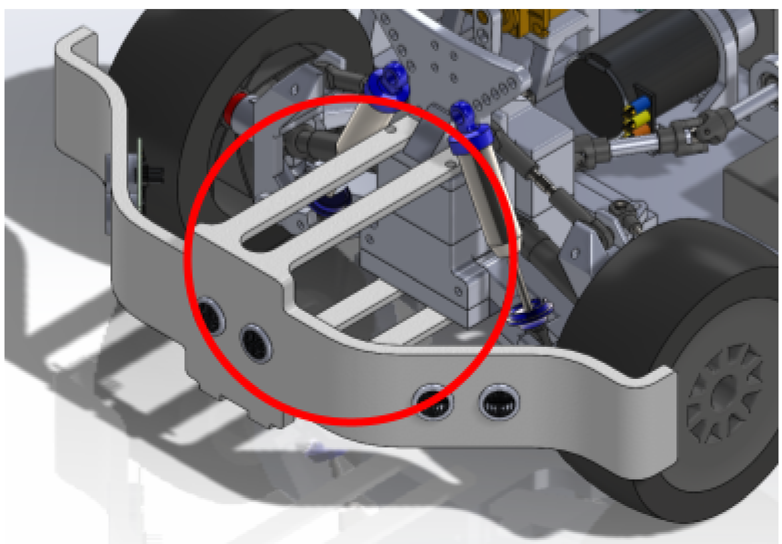


Figure 10-10: Initial Design of the Front Bumper with Arms Highlighted

In order to strengthen the connection and stability of the connections, struts were added. The top connections were also combined. The second iteration of the bumper is seen below in Figure 10-11.

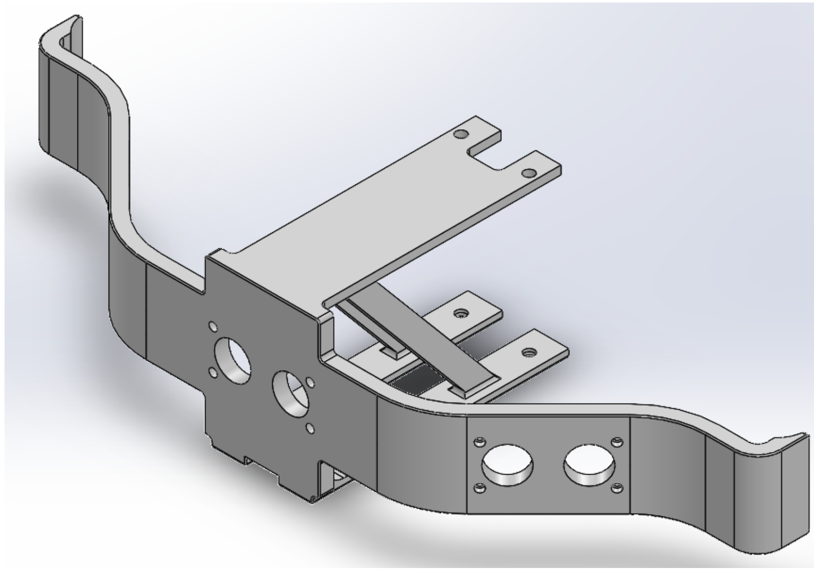


Figure 10-11: Second Iteration of the Front Bumper

The second iteration of the front bumper was the first bumper to be printed. Using PLA with 30% infill, the sides were very strong. The connections to the car were still a little weak, so additional struts were added for the third iteration.

Through basic collision testing with the bumper, we found two main areas that were likely to break. The first area was the point where the connections to the chassis meet the front of the bumper. Shown below in Figure 10-12, there was only a small fillet between these connections. In the third iteration these fillets were changed to larger chamfers. Since then, this point of the bumper has not failed.

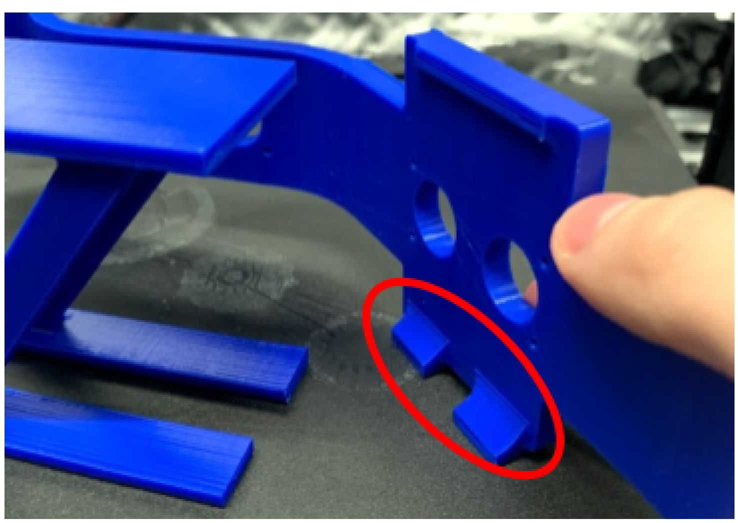


Figure 10-12: Example of Front Bumper Failure with Small Fillet Highlighted

The other part which experienced failures on the bumper were the points that connected to the chassis (circled below in Figure 10-13). These parts are a little too thin and fragile and would fail after a crash at moderate speed. Various options including thickening the supports or increasing infill were explored, but each option severely increased print time, complexity, and weight.

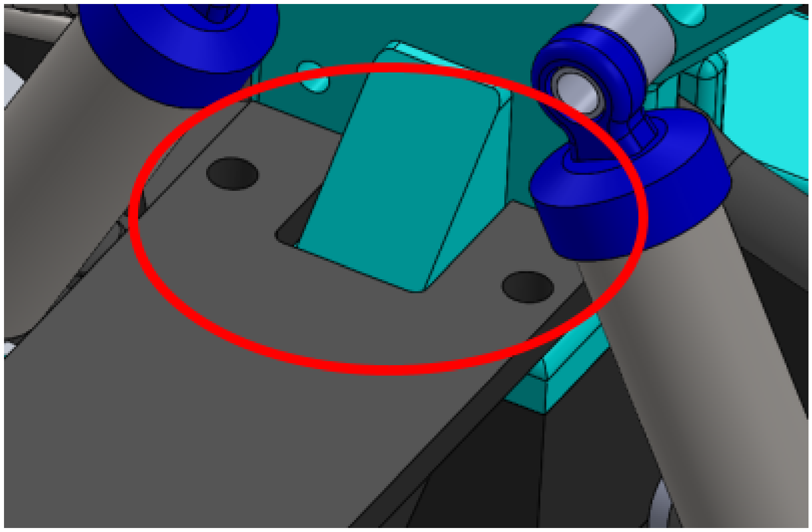


Figure 10-13: Highlight of Weak Spot on Front Bumper

The idea of printing the front bumper out of TPU or TPE was also explored. TPU and TPE are 3D printable materials which are very flexible. Making the bumpers out of TPU or TPE would make them more compliable, and allow the bumpers to bend and deform under stress rather than fracture. Unfortunately, we did not have a printer capable of printing TPU or TPE with a large enough build plate for the bumper.

It was also determined through testing by the ECE/CS team working on a self driving and obstacle avoidance package, that two additional ultrasonics were needed. These two needed to be orientated forward alongside the front ultrasonic. Shown below in Figure 10-14, mounting strips and holes for these sensors were added, along with additional struts that essentially turned the mounting arms into triangular-struts, as well as thicker connectors to the car.

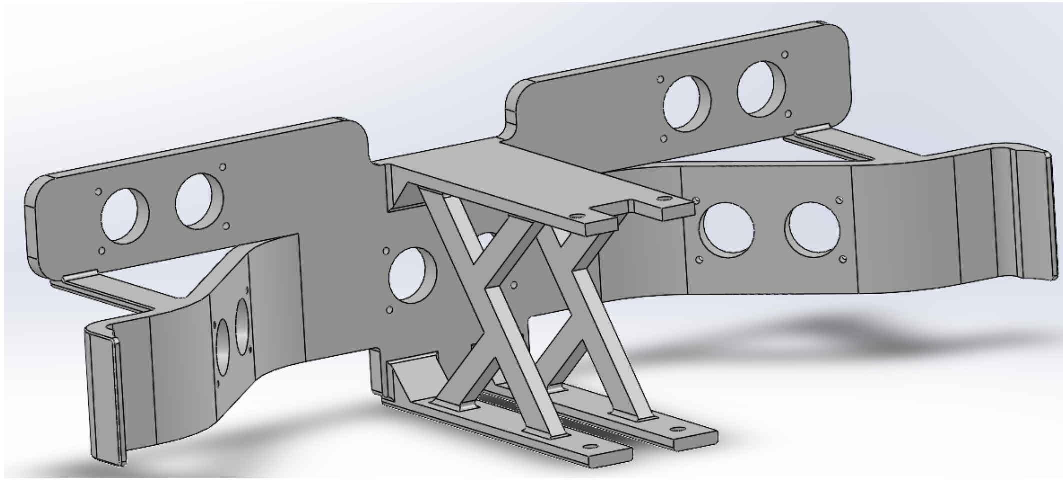


Figure 10-14: Final Iteration of the Front Bumper

The final iteration for the front bumper is 0.23” thick, with a height of 3.45” and a width of 12.69”. The connections to the chassis stick out 4.45” measuring from the front of the bumper. The bumper is mounted using #8 screws to the differential housing and chassis.

Rear Bumper

Compared to the front bumper, the development process of the rear bumper was much more straightforward. As it simply needed to protect the rear wheels and differential in an impact, it did not need to stick out far from the rear of the car. This meant that the issues we had with the strength of the mounting arms on the front bumpers were not as prevalent here. As such, the initial design of the rear bumper, shown in Figure 10-15 below, was not much different from the final design, at least in terms of its surface area.

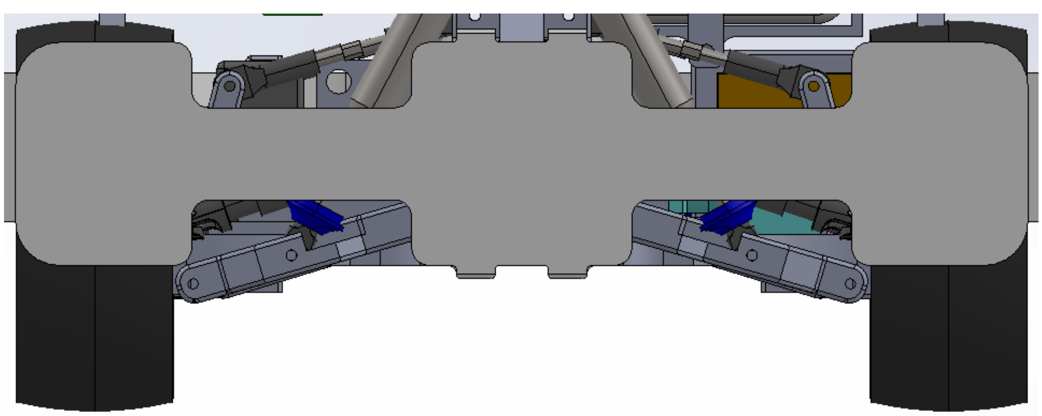


Figure 10-15: Rear Bumper First Iteration

The rear bumper itself was created to be 0.25” thick, with a height of 2.55” and a width of 11.5”. Within this area, we cut out some of the middle sections in order to save component weight, as a straight 3D printed piece of this thickness would be around 0.5 lbs, while our cutout design was about 0.31 lbs. The mounting arms were of a similar design to the front bumper, and stuck out 2.25” from the back of the bumper. Like the front bumper, this bumper can be mounted to the differential housing on the top and the chassis on the bottom, and use #8 screws to mount them.

Despite the shorter mounting arms, we were still concerned about their strength, especially after our tests with the front bumper. As such, we decided to add the same triangle-style struts we added to the front bumper to the rear bumper as well. Figure 10-16 shows the CAD model of the final rear bumper iteration.

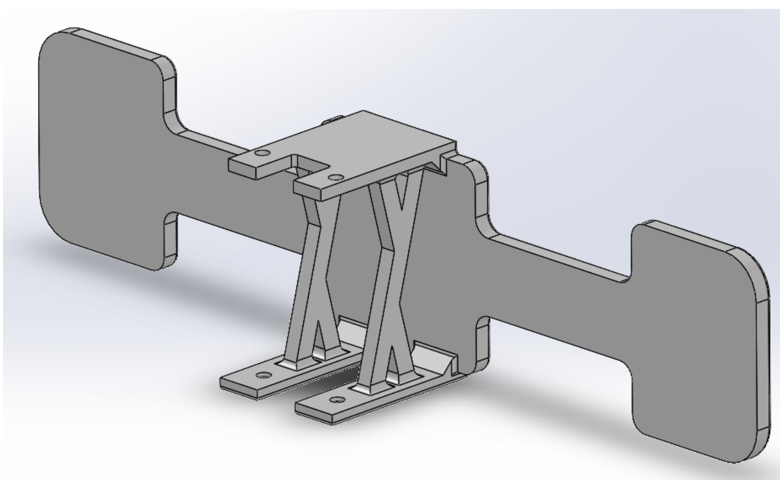


Figure 10-16: Rear Bumper Final Iteration

Electronics

As mentioned previously in the drive train section, PARV uses a Hobbywing XR 10 Justock motor. The specs of this motor can be found in Chapter 8 Drivetrain. In order to control this motor, it requires an on off switch, receiver, electronic speed controller, and a 7.4 V battery. In order to keep all of the components organized, a mounting bracket was made to hold these parts. The Receiver, ESC, and switch were all mounted together in close proximity to the motor (shown in Figure 10-17). The battery was mounted using the same holder designed last year as shown in Figure 10-18 (Boggess et al., 2020).

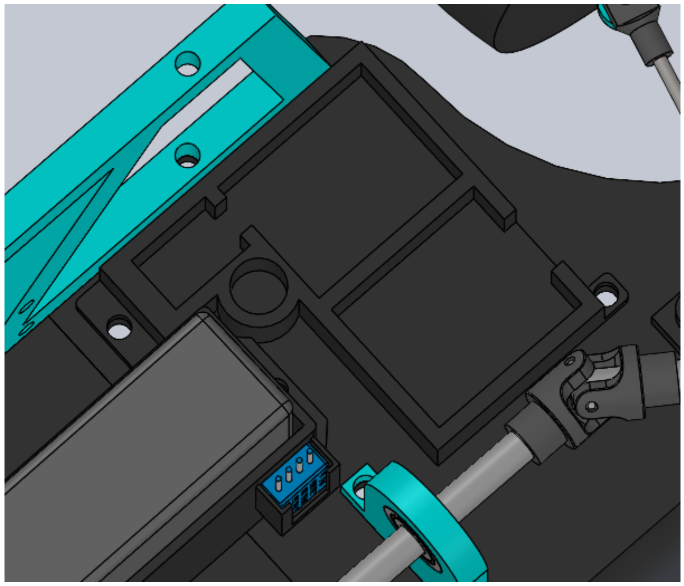


Figure 10-17: Receiver, ESC, and Switch Mount

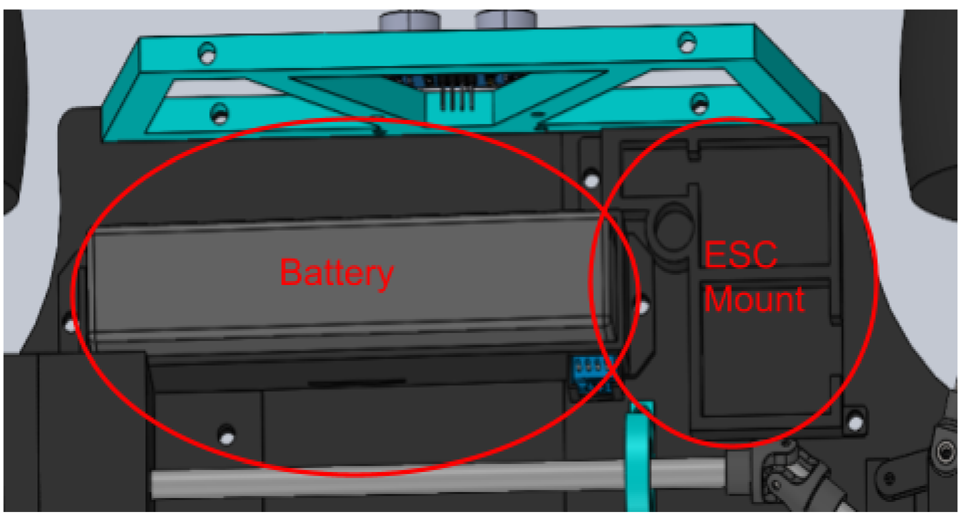


Figure 10-18: ESC and Battery Mounts Relative to Motor

Two servos are also used on PARV, one for steering, and one for switching the transfer case from 2WD to 4WD. Both of these servos are powered by the same 7.4 V battery, and plugged into the three channel receiver. The steering uses a Savox SC-1256TG digital servo, while the transfer case uses a KS-HD47MG micro servo. Each servo was mounted to the chassis using 3D printed parts, which can be seen below in Figure 10-19.

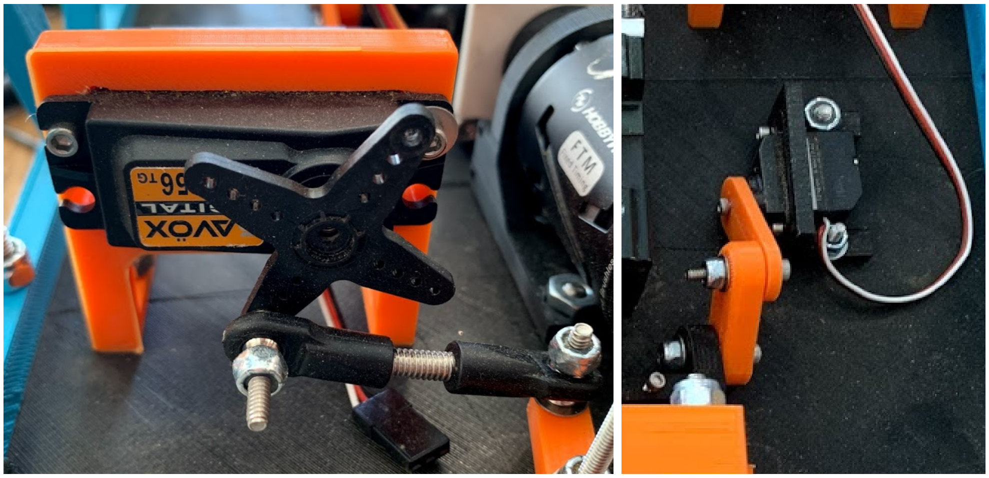


Figure 10-19: Mounted Steering Servo (Left) and Transfer Case Servo (Right)

Since we intended to drive a motor and two servos on our car, a three channel remote control was needed. Both servos, and the motor are controlled by driver input using a TTX300 Three Channel remote controller along with a TR325 Receiver as shown in Figure 10-20. The steering servo plugs directly into the first receiver channel, while the transfer case servo plugs into channel three, and the ESC plugs into channel two. The three communication channels allow for each servo, and the motor to be controlled independently by the user.

Figure 10-20: Tactic 3 Channel Controller and Receiver

11. Trailer System

In this chapter, we will be discussing the development and manufacturing process of the powered trailer system as an attachment for PARV. This trailer system was developed in a similar manner to PARV, including many similar subsystems such as a chassis and drivetrain, but was also simplified to both better follow PARV and make it easier to manufacture. The overall final iteration of the trailer can be seen in Figure 11-1.

Figure 11-1: Final Manufactured Assembly of the Trailer

Chassis

The primary idea of the trailer is to hold an additional payload so PARV can carry more when acting as a delivery vehicle. Hence, the chassis for the trailer needs to be a large flat surface that can hold as large of a payload as possible. Being familiar with 3D printing and having experience with 3D printing the chassis for PARV, the team realized that having a completely 3D printed bed would not be strong enough to hold much of any load. Hence, ideally we would have added zinc rods like we did for PARV's chassis, but as the trailer was more a proof of concept and an example of a modular attachment for PARV, the team decided not to add these.

The design of the chassis resulted in a basic rectangle with the dimensions 15.475" x 9.6" (L x W). The chassis had many countersunk holes for each of the systems that needed to be attached. Most of these systems were attached on the bottom of the chassis. The chassis had specific mounting spots for the ESC and power switch as well as the battery to keep the layout clean and organized. The chassis had to be split into two sections before 3D printing because the dimensions were too large for the print bed. The two chassis pieces were epoxied together using JB Weld Clear Weld Epoxy. The Solidworks model of the chassis can be seen below in Figure 11-2.

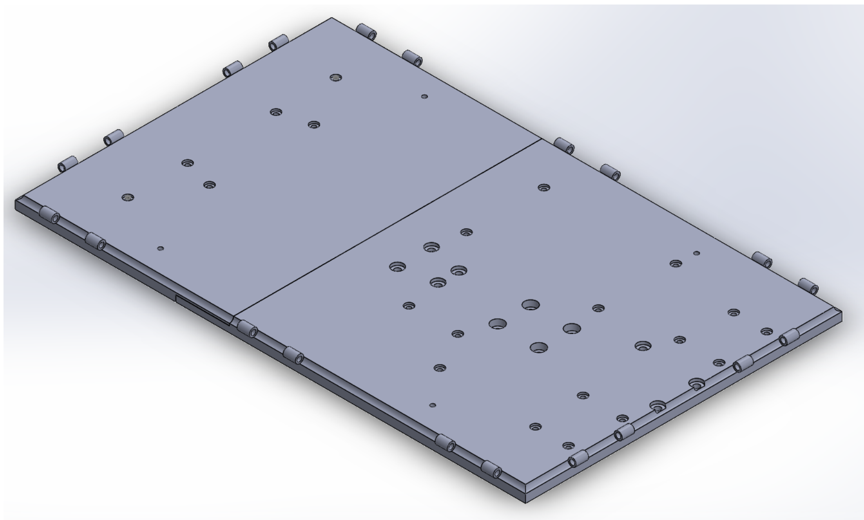


Figure 11-2: Trailer Chassis in CAD

Additionally, the side of the chassis had hinge-like pin slots that would allow the trailer sides to attach to the chassis using these pins slots. This would also allow the sides of the trailer to be open and closed as they were attached to the chassis with pins that could rotate. Also, the trailer sides all had to be split to fit the print bed of the 3D printer before printing. These pieces were epoxied using the same epoxy as what was used on the chassis.

Wheel System

This section will discuss the wheels and the wheel mounting onto the trailer. The wheels for the trailer were 3D printed and were attached to the car using different 3D printed CAD designed parts that acted as suspension links.

Wheels

In order to make the trailer have the same ride height as the car, we needed to use wheels that were no larger than 3.2” in diameter. RC car wheels are surprisingly expensive, so we decided to print these wheels. RC car wheels can range from $20 - $80, but the more high quality and longer lasting wheels are typically closer to the $50 - $80 range. The main design requirements of the wheels were that they had to have a strong rim that connects to drive shafts the same way the purchased wheels do, and also have a tire able to grip the terrain it is running on. Thermoplastic Elastomer (TPE) is a type of plastic that can be 3D printed and is known for its flexibility. We wanted to evaluate the use of this material as a tire, and the trailer was the perfect platform to test on.

The rim was designed to be very similar to the purchased wheel rims. Printed in PLA, the rim will provide the sturdiness needed to stay mounted to the car, and drive shaft coming from the trailer's driveline. The rim was made with the same hexagonal shape that the wheel hubs mentioned in Chapter 8 Drive Train, subchapter Wheels discussed.

The tires fit around the rim, and are printed out of TPE. TPE is much more sensitive when printing, and requires much slower speeds compared to PLA. While four rims could be printed in roughly 8 hours, each wheel took 9 hours.

TPE has a higher coefficient of friction of 0.69 compared to PLA's being 0.492, which makes it better for tires which need to grib the surface they are on (Farstada, 2017)(Wojciech, 2018). Upon initial testing, the material was still not grippy enough for smooth surfaces like tile or concrete. However, in conditions like this, PARV will have more than enough grip to pull the trailer. The trailer will need additional grip in off road scenarios possibly on sand or grass. To remedy this, quarter inch deep treads were cut into the tire. These treads help dig into the terrain the trailer is on. The initial tire design shown in Figure 11-3 below featured a solid ring of material down the center of the tire for added contact area between the tire and ground. This was later removed in the final iteration to increase contact of the treds (shown in Figures 11-4).

Figure 11-3: First Iteration of Printed Wheel

Figure 11-4: Final Iteration of Printed Wheel

Between the first and final iteration, the inner diameter of the tire was also increased by .1”. The initial tire had an extremely tight fit onto the rim, and could have easily been damaged during assembly. This inner diameter was opened up a bit, with a dab of JB Weld Clear Weld epoxy between the tire and rim to hold them together.

Rather than using a foam insert within the wheel to give the tire squishiness like typical RC wheels, the infill of the wheel can be altered to make a sturdier, or more pliable tire. The first iteration was printed at 20% infil, which was far too sturdy and had little to no squish. The final tires were printed at 12.5% infill, which supplied ample squishiness but also sturdiness as seen in 11-5.

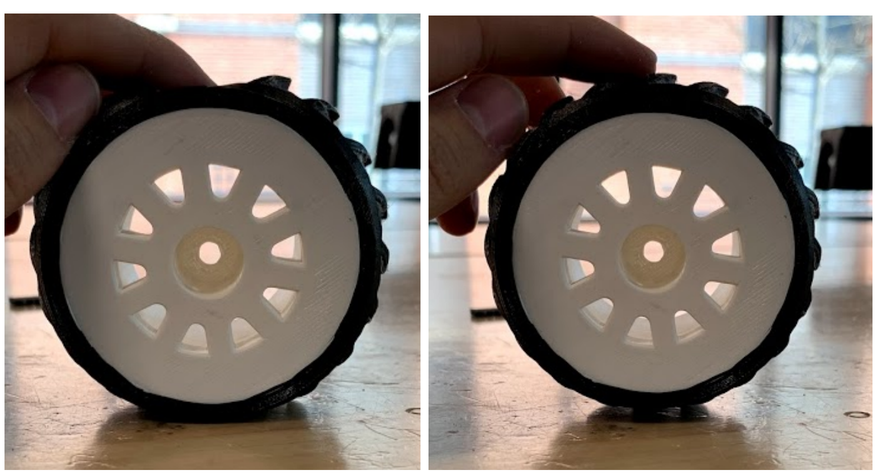


Figure 11-5: Demonstration of Squished (Left) Versus Unsquished (Right) Wheel

Suspension Mounts

To mount the wheels to the chassis a variety of parts needed to be designed. For the rear wheels, the mounting needed to be stationary and hold the wheels in place without them turning. Additionally, these parts needed to be able to withstand the weight of the trailer as well as a payload. So the parts were designed and had extra support pieces to help spread out the stress that would be on the piece. This piece also allowed for a driveshaft similar to PARV's driveshaft to be put through this piece. Figure 11-6 shows the CAD model of this part.

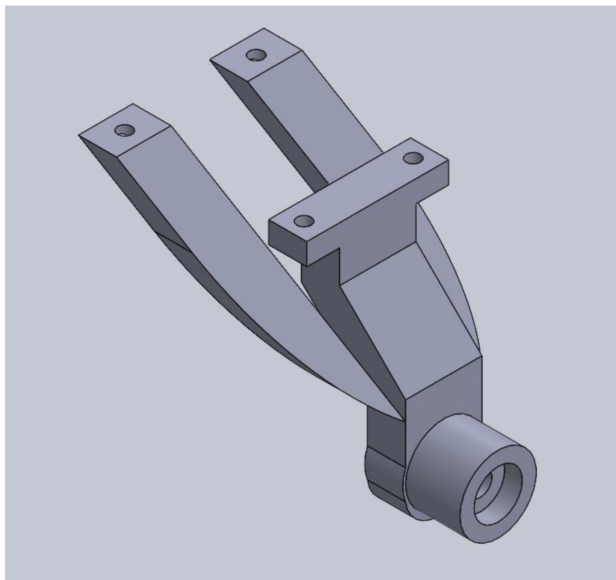


Figure 11-6: Rear suspension trailer Solidworks Part

For the front wheels, the wheels mounting pieces were a little more difficult to design as the front wheels needed to be able to turn. Therefore, unlike the rear suspension wheel mounts, the front ones need to turn with the steering. Hence, when designing this system, the team split it into three parts. One part that attaches to the chassis and uses a #4 socket screw to keep the part in place, and the middle part is made to turn with the steering and is the wheel spindle piece. This part is connected to the first part by a pin so it can turn. Finally, the last part is on the other side of the spindle and is there for extra support, this part allows the spindle to sit on top of the part. Then this part stretches back to the chassis and is screwed in using #4 socket screws. Figure 11-7 illustrates this assembly in Solidworks.

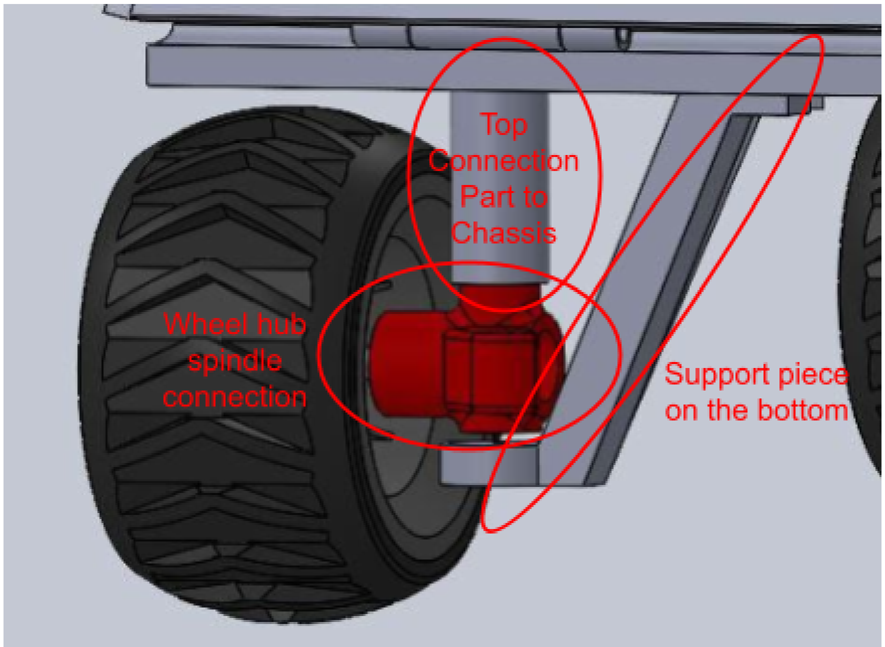


Figure 11-7: Front Suspension Trailer Solidworks Parts

Trailer Mount

As this trailer is made to be attached to PARV in a modular way, the team needed to design a system that can attach the trailer to PARV while also allowing the trailer to be steered depending on what direction PARV turns. This system also needs to be easily attached to the car to show the modularity of PARV. Within this section, the team will discuss the design of the trailer hitch and the steering assembly.

Mounting Hitch

To start, the mounting hitch was designed to attach to the car the same way the rear bumper was mounted. That means it needed to be mounted using the two #8 screw holes on the back of the rear differential/direct drive. From there, the team used the research we had completed on trailers for cars to develop a hitch that could be simple and still work for our purpose. Hence, the team designed a connection of two parts with a vertical pin going through them to serve as the hitch for this system. The part that is attached to PARV holds the ends of the pin, and the other part of the hitch fits in the middle and holds the pin loosely so that part can rotate around the pin. From here, the team designed a three part assembly that would give the hitch vertical movement. These three parts used pins placed in a horizontal manner to connect the parts and allow for rotation around the pins, giving vertical motion to the hitch. Figure 11-8 shows the hitch assembly as designed through Solidworks. Figure 11-9 shows the trailer hitch attached to PARV.

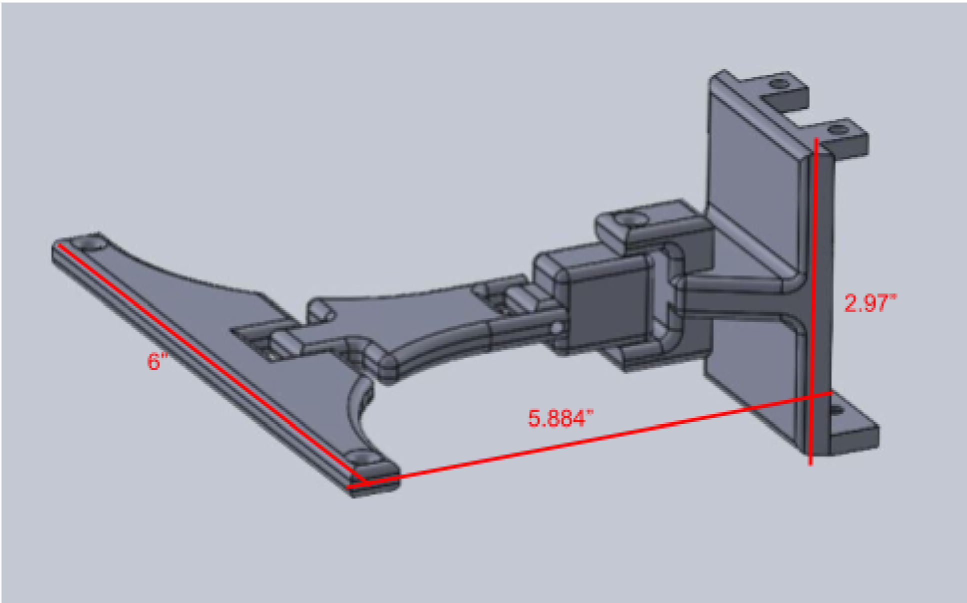


Figure 11-8: Trailer Hitch Assembly

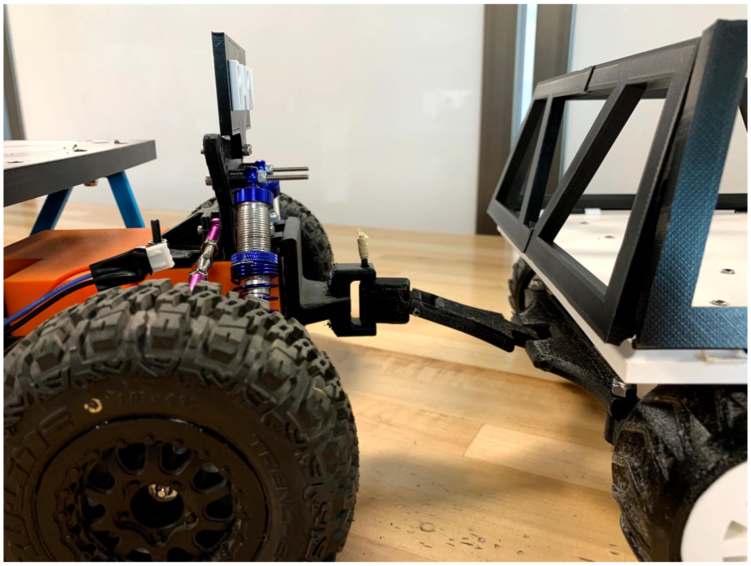


Figure 11-9: Trailer Hitch Assembly Attached to PARV

The trailer hitch also allows for the trailer to be steering depending on the direction PARV turns. As described in the previous section, the vertical pin that allows the hitch assembly to rotate will also allow the car to steer. Additionally, the last piece of the hitch system will attach to each of the wheel spindles. Those wheel spindles are attached using screws and can rotate. Hence, the trailer's wheels will turn based on the direction PARV drives.

Drivetrain

While our trailer system could work as a passive system, we believed it would be more beneficial to make it an active system with its own power source; as such, we developed a RWD drivetrain system for the trailer. This system would power the trailer's rear wheels, allowing it to pull itself over small obstacles as well as reducing the drag that would be created if PARV had to pull the trailer by itself. This drivetrain was developed in a similar manner as the one for PARV, with the main difference being the lack of a transfer case due to its RWD nature. However, due to needing space on top of the trailer for payloads, this drivetrain system was attached to the bottom of the trailer's chassis as seen in Figure 11-10. One issue arose when developing and testing the drivetrain, we realized after building the trailer that the motor was configured to drive in the opposite direction then the way we expected it to go. Hence the drivetrain was based on the motor running in the opposite direction. We tried fixing this issue, but were unable to complete this due the fact that we were at the end of the project cycle. Therefore, we were able to get the motor to run the trailer in its backwards rotation, which would push the motor forward. However, due to the programming of the motor and ESC, when the motor runs backwards it is much slower than when it is run forwards and to adjust this setting additional programming needs to be bought from the manufacturer. So the trailer could be powered to run the wheels forward but at a slower pace than desired.

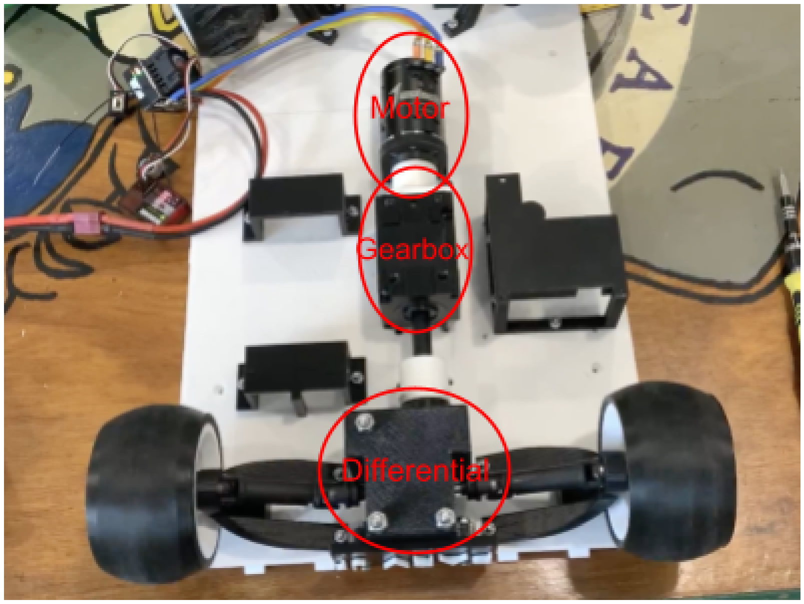


Figure 11-10: Photograph of the Bottom of the Trailer; Illustrates the Drivetrain System

Motor

For the trailer, we decided to use the Hobbywing XR 10 Justock motor, the same motor that is used on PARV. This motor is a sensored brushless motor that came with an ESC and power switch, which were mounted underneath the car in a specific mounting setup to keep the car organized and clean. This motor was chosen because one of the goals the team had was to connect the motors so they could be run off of the same receiver. To complete this the team would need to use the same motor for each and split/conjoin the connections.

As the trailer was designed near the end of the project cycle, we utilized the same mounting method for the trailer motor as the motor on PARV. This consisted of a specialized motor mount that not only lined up the motor with the gearbox next to it, but also connected it to the trailer's chassis. As this is the same mounting procedure we used with PARV, more information about this can be found in the Drivetrain section (Chapter 8).

Transmission

The transmission on the trailer was similar to PARV's transmission. It utilizes a planetary gearbox from VEX (Versaplanetary gearbox) (VEX, 2020). The main difference between the trailer transmission and PARV's transmission is that the gear ratio in the trailer is 12:1 instead of the 9:1 in PARV. This was selected to slow the velocity of the wheels down, so the trailer would not overpower and push PARV as that is not the intent of the trailer being powered. This higher gear ratio gave the wheels less speed but more torque. More information about the transmission can be found in Chapter 8.

Differential

The differential we used for our trailer's drivetrain was the same as we used for the rear differential on PARV: a Traxxas Direct-Drive Differential. A direct-drive was chosen over an open one mainly because it allowed better power transfer between the rear wheels when going over obstacles. This differential was mounted to the rear wheels in the same manner as PARV, utilizing a Traxxas driveshaft assembly that used set screws and profiled hub connections to connect the wheels to the drivetrain. More information about this is found in Chapters 8 and 9.

12. Manufacturing

In this chapter, we will be discussing PARV's manufacturing process. This section will mainly discuss the methods of 3D printing, print verifications, and the hardware procurement process. As mentioned previously, one of the main focuses for our project was to make as much of PARV 3D printed as possible. This allows for ease of manufacturing, as well as modularity since the parts can be easily edited and reprinted.

3D Printing Specifications

Additive manufacturing, the most popular of which being 3D printing, allows for rapid prototyping and development of projects. With the growth in popularity of 3D printing, having our designs made for 3D printing improves accessibility of PARV. For this project we used four different 3D printers, a Monoprice Maker Select Plus, Creality CR-10 V2, Creality CR-10s Pro V2, and a Creality Ender 3 V2 (Monoprice, 2021) ("Fast and High Precision", 2020). All of these printers are readily available commercially, and while we had access to four different printers, this is not necessary. Three of these printers were our team members personal printers, that we used in order to speed up production.

To manufacture and test PARV, parts were designed within SolidWorks. From there, the files were converted into .stl format, to be sliced in Cura for 3D printing ("Ultimaker Cura", n.d.). Slicing is the process of using software to create tool paths for additive manufacturing that are read by the 3D printers to make the parts.

3D Printing Verifications

When 3D printing components, it is important to make sure the parts come out as they were designed. 3D printing is not perfect, and it is not uncommon to have any range of issues from slight dimensional inaccuracies, to print defects and failures. These issues can range from overheating, warping, gaps or even layer separating / shifting. These issues typically require the part to be remade, but depending on the severity or location of the defect, the part may still be usable. Figure 12-1 below shows an example of severe layer shifting and gaps while printing suspension components for PARV, and warping while printing the sensor plate. The first step following printing to ensure there are no obvious defects or issues with the print. These issues are pretty obvious, and there are a vast number of printer related issues that can cause them. They require tweaking of printer settings in order to prevent them from occurring.

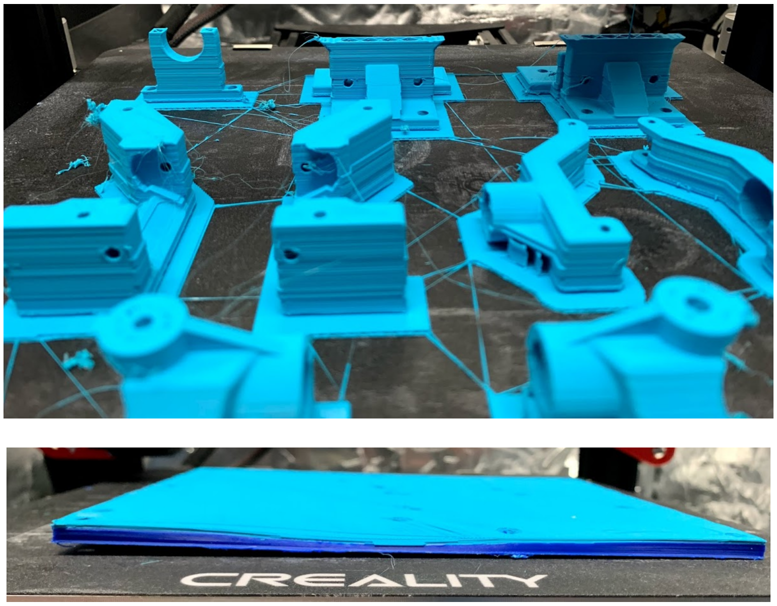


Figure 12-1: Example of Print Defects, Layer Shifting (Top) and Warping (Bottom)

Once the parts are cleared from any obvious defects or failures, the next step when verifying 3D printed parts is to check for dimensional accuracy. Verifying dimensions ensures that the part is the correct size compared to the CAD models. This is especially important for parts that fit together, or mesh with other parts. Within PARV, parts that fit together, or must be a certain size to fit hardware, were designed with a 0.02" clearance for tight fits, or 0.03" clearances for loose fits. For PARV, we are aiming for a dimensional accuracy of ±0.04". This accuracy is well within the realm of possibility of 3D printing, and is within the tolerances we designed into our parts. In order to verify dimensional accuracies, we developed a verification procedure and sheet (located in Appendix E). The procedure document contains pictures of parts with labels to certain called out dimensions. On the verification spreadsheet, the CAD specified dimension is listed, as well as a spot to input the real measurement. The difference is then calculated in the next cell over. Figure 12-2 and 12-3 below shows an example part with the verification document, and spreadsheet. Depending on if the measured dimension is critical to the performance, the part may need to be reprinted. Incorrect dimensions can lead to unnecessary wear, friction, or even parts not fitting together at all.

Drive Couplings

Motor to Gearbox Male:

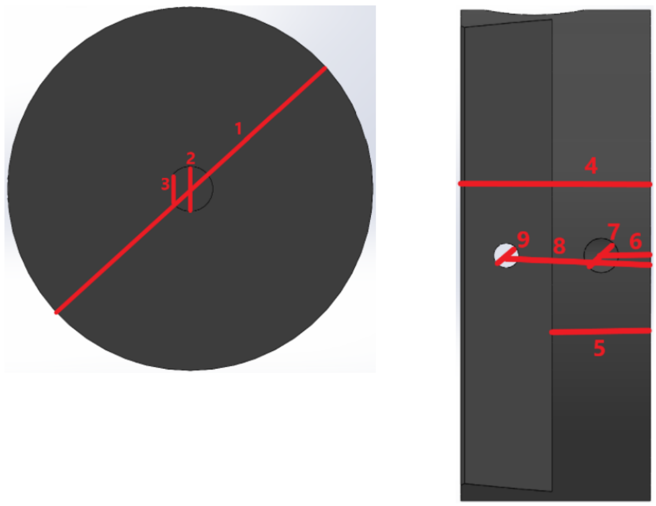


Figure 12-2: Print Verification Dimension Labels For Motor to Gearbox Male Coupler

Drive Couplings					
Part	**Measurements**	**Tolerance**	**Solidworks Dimension**	**Printed Dimension**	**Difference**
Motor to Gearbox Male	1		1	1.01	-0.01
	2		0.124	0.11	0.014
	3		0.083	0.085	-0.002
	4		0.385	0.389	-0.004
	5		0.2	0.204	-0.004
	6		0.1	0.106	-0.006
	7		0.07	0.065	0.005
	8		0.293	0.296	-0.003
	9		0.05	0.05	0
	10		0.2	0.186	0.014
	11		0.356	0.372	-0.016
	12		0.275	0.294	-0.019
	13		0.185	0.178	0.007

Figure 12-3: Print Verification Results For Motor to Gearbox Male Coupler

Hardware

PARV requires a range of imperial sized screws, as well as various hobbyist RC car components, and bearings. Throughout the design process, mounting holes for screws and nuts were designed to all be either #2, #4, or #8 hardware, all with similar lengths . This allowed for a minimal number of screw variations to order. All hardware was ordered through McMaster Carr, but could have been purchased at any other hardware store. In total PARV and the Trailer required 28 #2 screws and nuts, 56 #4 screws and nuts, and 43 #8 screws and nuts. A more specific breakdown of lengths, as well as the types of screws used for each component can be found in Appendix F.

There is also a wide range of RC car components used on PARV. The shocks, turnbuckles, drive shaft joints, and gears are all typical RC car components that can be bought at most hobby stores. The shocks, turnbuckles, and drive shaft joints were all purchased from Amazon. The exact specifications of these components can be found in Appendix F. Figure 12-4 showed the purchased parts in the front left suspension.

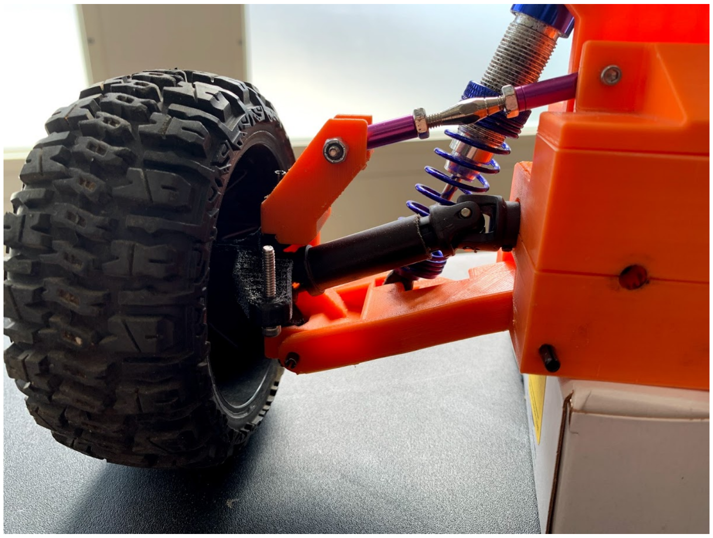


Figure 12-4: Picture of Front Left Suspension With Hobby Store Drive Shaft, Turnbuckles, and Shocks

The entire driveline of PARV uses ¼” diameter steel shafts. With these shafts, bearings were especially important to prevent contact with the plastic components, as well as to reduce friction. For the transfer case, eight ¼”, and one 1” ball bearings were required. While the Limited Slip Differentials, and Direct Drives required six ⅜” ball bearings. All bearings and drive shafts were purchased online at McMaster Carr. Specifications of bearings can be found in the hardware list in Appendix F.

13. Modularity

As stated in Chapter 4, the project requirement section, modularity is a very important part of this project. Modularity refers to the degree of which a system's components can be removed, adjusted, and recombined within the system (Encyclopedia, 2008). So, for an RC car, this would refer to how easy one can take the wheels off the car and replace them with different wheels depending on the car's application, or if the motor can be taken off with ease to attach a more powerful one. Hence, we wanted to build PARV to be very modular, so systems could easily be changed and replaced or redesigned even with ease to improve the car or to change PARV's application.

The team showed the modularity of the car through primarily 3D printing the entire car, creating the top plate payload mounting, creating the trailer, and attaching a self-driving package. The team also demonstrated the payload mounting capabilities through the use of a LeArm robotic arm with bluetooth arduino connection capabilities that was purchased through Amazon. Also, when designing each subsystem and part, the team thought about manufacturing and assembling the system with ease as those are important factors that lead to a modular system. Figure 13-1 shows the car with all its modular packages that we designed and created this year.

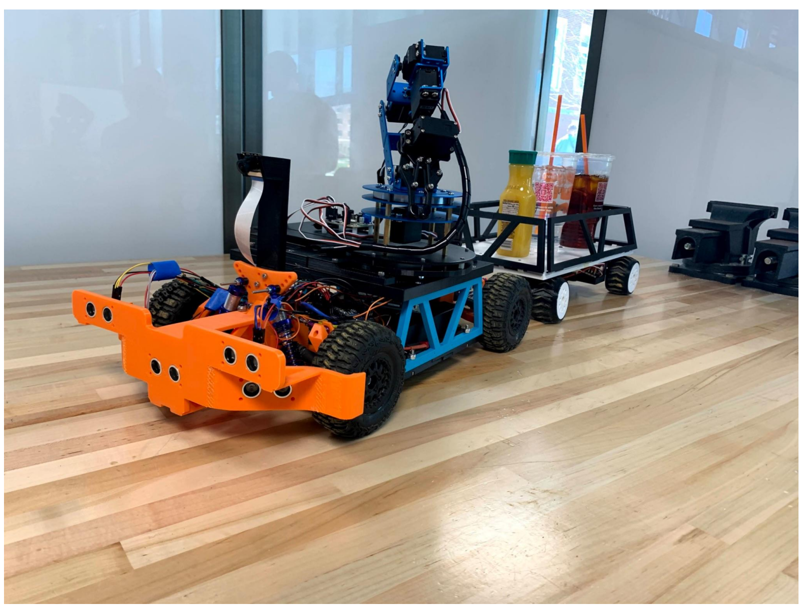


Figure 13-1: PARV Fully Assembled with All the Modular Systems Attached

3D Printability

3D printing is a relatively new process that can be very useful for lots of different engineering and medical applications. It is typically used for fast, cheap prototyping. In this project 3D printing was used to not build a prototype but to build a final product. The use of 3D printing the majority of the parts in PARV, allows the parts to be easily changed and replaced efficiently and effectively.

For example, if one of the gears broke within the transfer case, one would not need to go through the hassle of ordering a new part online and hoping that it is the right gear. Instead, they could go onto SolidWorks and find the part and 3D print it again. Additionally, if they wanted a different gear ratio, they could redesign the part/parts and then 3D print them, and the parts would easily replace the old gear system. Overall, the use of 3D printing allows for increased modularity within the parts because parts can be easily changeable and remade at a fast and easy pace.

Top Plate Payload Mounting

As discussed in Chapter 10, Vehicle Structure, the team designed a top plate for PARV, that can mount a sensor plate and can mount other attachments with ease. First, the top plate was 3D printed and attached to the sides of PARV using four #8 screws. The team additionally developed a secondary plate that could be connected or disconnected depending on the application of PARV at that time. This secondary plate holds sensors and electrical equipment that was needed for the self-driving, sensor package that the ECE/CS MQP team was developing. This plate will be discussed more in terms of its modularity in the upcoming Self-Driving section. The top plate was intended to serve multiple purposes. It can hold a payload and has strap slots if the payload needed to be fastened on. Additionally, the top plate has eight standard mounting holes that can be used to attach any part that the user may need. All they would need to do is make a plate, spacer, or connector that can attach to the top plate and the attachment they want to add. The purpose of these holes was to create a standardized mounting layout so that any tool or payload could be added to the top plate using a personalized attachment. The mounting holes on the top plate can be seen in Figure 13-2 below.

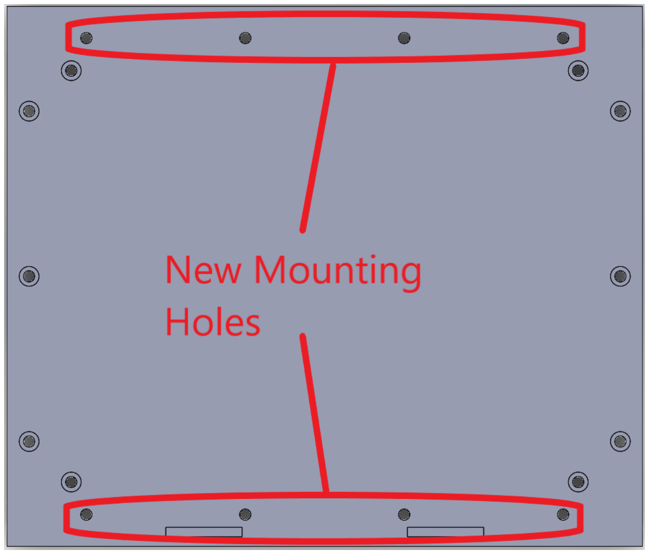


Figure 13-2: Mounting Holes on the Top Plate

The team demonstrated the use of these mounting holes on the top plate using a purchased LeArm robotic arm. The LeArm robotic arm is a full metal size DOF robotic arm. It utilizes a bluetooth and arduino system. The arm can lift approximately 250 grams. This robotic arm demonstrates the payload capacity of the top plate as well, as it weighs about four lbs and as such could classify as a payload as well. In order to attach the arm to the top plate, we developed a mounting plate that could be used to connect the robotic arm to PARV using the mounting holes on the top plate. This mounting plate is fully 3D printed, and was designed to follow both the spacing of the mounting holes and the shape of the robotic arm's base. In addition, it was split into four pieces so it could be printed using a standard 3D printer, and locked together through mounting the arm on top of it. Figure 13-3 shows the use of both this mounting plate and the mounting holes on the top plate with the robotic arm attached.

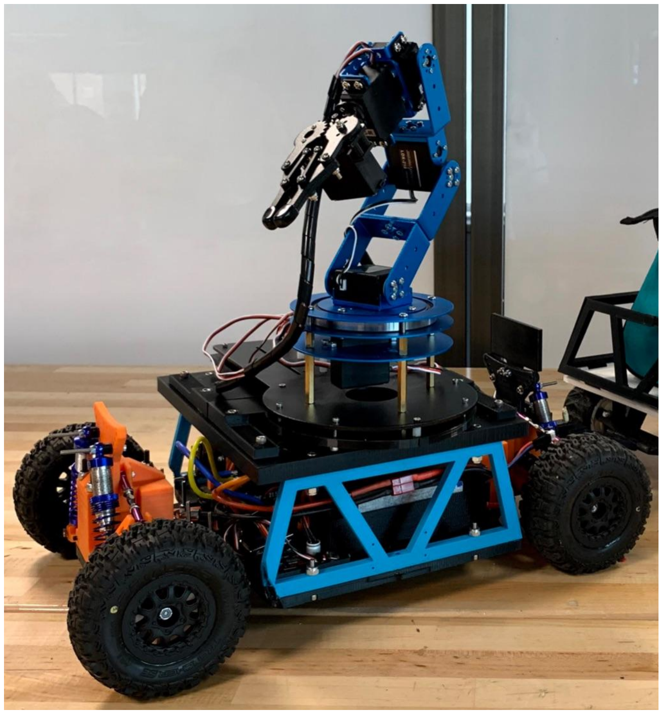


Figure 13-3: Robotic Arm Attached to PARV Using the Mounting Plate

Trailer

The trailer system, which was described in detail in Chapter 11, was designed and manufactured primarily as a proof of concept to show the modularity of PARV and the ability to create an additional payload carry to help PARV with deliveries. One goal, when designing the trailer, was to make it easily attachable to PARV. Hence, the trailer connected to the car using the same screws and screw holes that the rear bumper would use. The trailer increases the max payload capacity of the entire system as it is powered as well, so PARV will not need to completely drag the trailer.

Also, within the trailer the team made it all primarily 3D printed and designed it to be easily manufactured so the parts can be easily swapped out and replaced or changed. Furthermore, the sides of the trailer also add modularity because they are attached to the chassis with hinges. Thus, the sides can drop down and open up so larger objects and payloads can be added on top of the chassis. The trailer with the sides dropped down can be seen in Figure 13-4.

Figure 13-4: Trailer with its Sides Dropped Down

Overall, the trailer was created with the idea to show the modularity of PARV with a system attachment. The design of the trailer within itself also exhibited a great bit of modularity as well.

Self-Driving Package

The self-driving package was the project completed by the ECE/CS MQP team. Their goal was to create a self driving system that can be easily moved from RC car to RC car to make them drive autonomously. Hence, we used their package to illustrate how another system attachment could be hooked up on PARV and work properly. We created different mounting spots that can make it easy to hook up their self-driving package such as the sensor plate that is attached to the top plate, the bumper, and other mounts for sensors on the chassis of PARV. For more information on the sensor plate, Chapter 10 goes into detail on its design. The bumper was designed to hold ultrasonic sensors that are helpful for the autonomous driving code. Additionally, the sensor plate has spots for bread boards and arduinos for the package as well.

14. Testing

After designing, manufacturing and assembling PARV, we also wanted to test the car's performance against obstacles and different terrains. Last year's MQP team completed a large amount of tests that looked at individual systems, but since we used their systems as a starting point and designed our systems to improve upon their initial design, we wanted to test the performance of the car as a whole when completely assembled (Boggess et al., 2020). For example, at the start of this project, we designed tracks around the WPI campus that would test and challenge our car. Also, we found obstacles and different terrains such as rocks, small steps, sand, grass, and steep hills that we planned on testing our car as well to see its performance on these paths. These paths and obstacles were designed to challenge our car in ways that we found last year's MQP car struggled in. As described in Chapter 3, the background, the team tested last year's car on different terrains and over some rough obstacles such as tall grass, steep hills, and sand. After those tests the team realized that the car was able to complete some of the obstacles but not in a controlled manner. The driver would typically have to drive the car with full throttle to get the car over these obstacles or terrains. Hence, we wanted to improve upon the car, so PARV can tackle these obstacles with ease and in a controlled manner.Furthermore, we also wanted to test PARV with the powered trailer attached. The tests for this were again performance tests to see how well the car and trailer could drive together.

This section will go into depth on how the team decided to test PARV and the trailer to show the capabilities of PARV as a delivery robot. The next few sections will describe the paths that the team laid out to test PARV, the obstacles and terrains that will test PARV's systems, and some basic analysis of specific systems such as the steering and speed.

Pathway Testing

In terms of pathway testing, we designed a path that would be similar to a delivery path that PARV may take when acting as a delivery vehicle. This path was laid out on the WPI campus and took the car over sidewalks, small roads, and a few grass/dirt sections. The path that was designed was 0.44 miles, hence this path would also test PARV's battery capacity. This pathway can be seen in Figure 14-1.

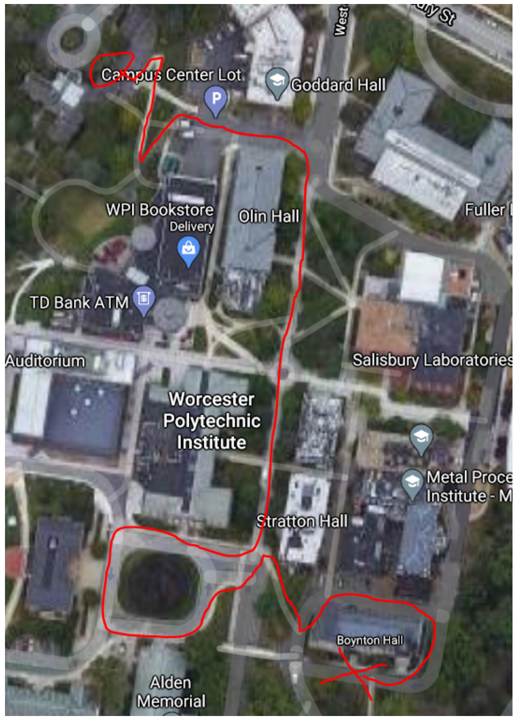


Figure 14-1: Pathway to Test PARV on the WPI Campus

This pathway has a variety of terrains. A few of these terrains and obstacles can be seen in the figures below.

Figure 14-2: The Start of the Pathway we Designed

Figure 14-3: Some of the Rough Terrain PARV would Encounter on the Designed Pathway

Obstacle Testing

This part of testing PARV's performance entails testing PARV against challenging obstacles such as rocks, steep hills, or steps. We walked around our community and WPI campus to find good outdoor obstacles that parv could tackle. The obstacles found can be summarized in the list below, the figures following show some pictures of the obstacles:

- 34-40° hill
- Rocks of approximately 4" tall and 15" wide
- 3-4" Grass
- 5" Sidewalk bumps
- 4" steps
- Cracked sidewalks of varying depths
- Loose gravel and dirt / sand
- Curbs on roads
- Rock Ditch with tree roots

Figure 14-4: Small 4” Tall Steps

Figure 14-5: Steep Grass Hill with 34-40° Slopes

Figure 14-6: Bump on Sidewalk, ~5" Tall

Figure 14-7: Rock and Root Ditch with 1 ½" Bumps

Additionally, the trailer attachment was also tested on obstacles to test PARV's performance with the attachment addition. The list of obstacles this system was tested on are listed below:

- Sloped curbs on the side of roads
- Small rocks
- Hills
- Tall grass
- Loose dirt / sand

Terrain Testing

Next, one of our goals as a team was to create a delivery vehicle that can tackle different terrains. This can be important for a delivery vehicle as it may need to travel over sand or gravel for example to deliver the package to the desired location. We determined specific locations that would be ideal to test the car on to see how well the car's systems perform. The different terrains that we selected are grass, loose sand, gravel (small rocks), loose dirt, and asphalt. The figures below show examples of the terrains we tested PARV with.

Figure 14-8: Gravel Type Terrain

Figure 14-9: Loose Sandy Terrain

Additionally, PARV and the trailer attachment are planned to be tested as well on different terrains. These terrains are similar to the ones that were laid out for PARV.

Individual Analysis

We also wanted to test some of PARV's individual systems such as the steering and speed of the car. To complete the speed test, we used a measuring tape and measured out 10 ft. Then we ran PARV at full speed and started a timer when PARV crossed the start of the 10 ft and then at the end of the 10 ft. We did this three times and took the average time, then divided the 10 ft by the time to get the speed in ft/s of PARV. This test was completed while the car was in 4WD and 2WD.

For the steering test, we wanted to test the steering radius and angle of the car. To test the steering radius, we stretched a measuring tape out and placed PARV at the end of the tape measure. We then drove PARV at full left and full right and marked where the car crossed the tape measure again. This was completed in both 2WD and 4WD.

We also intend to test the suspension of the system by attaching a payload to the top plate and then driving PARV around on various surface types.

15. Results

This section will discuss the results we found when testing PARV on the tests that are specified in the previous chapter, Chapter 14. First, we will discuss the results of performance testing for both PARV by itself and with the trailer attached. These performance testing results will discuss the results of PARV on our laid out path, against the laid out obstacles, and PARV's steering radius/angle and speed.

Performance Testing

Path

After testing PARV on the laid out pathway through the WPI campus, we found that PARV performed exceptionally well. PARV was able to complete the path with one battery life. Additionally, PARV was able to travel in a controlled manner, less than half the max throttle, for the entire course. It was evident that the new 4WD and differential systems that we focused on designing for the project helped the car greatly, especially when a bump appeared or when PARV went onto a terrain separate from asphalt. Being able to complete this track with ease showed that PARV is capable to act as a delivery vehicle. Videos of PARV driving along the path are linked in Appendix G.

Obstacles and Different Terrains

We also tested PARV on the obstacles listed in Chapter 14. When testing on these obstacles, we tried to attack them in a controlled manner and not at full throttle. If PARV was holding a payload, the payload would be at greater risk of becoming damaged at full throttle as compared to PARV driving in a controlled safe manner.

First, PARV was able to climb up a 34-40° hill very well. The car was able to complete this obstacle at a medium throttle and in 4WD. Additionally, PARV was tested against a separate hill that was steeper and was approximately a 40-50° incline. Last year's MQP car was not able to climb this hill when we tested it. When testing our car on this hill we had to nearly set the throttle to max, but the car was able to complete the hill. We noticed that the 4WD system was a big advantage and a large reason why PARV was able to complete the hill. The powered front wheels helped propel the car up the hill greatly. Also, the direct drive in the rear was an advantage as well because now both wheels were in constant power. When testing PARV on the rocky ditch, another obstacle that last year's car struggled to drive on, PARV was able to travel up and down this ditch very well. This is another obstacle that showed the real advantage of having the direct drive and 4WD on PARV.

We then tested PARV on the tall grass and bumps on the sidewalks. These obstacles were completed by last year's car through our testing but not in a very controlled manner. PARV on the other hand was able to complete these obstacles with ease. Both cars performed very well on the sidewalk cracks obstacles, however, similar to other obstacles, PARV's 4WD system seemed to help the car tackle this obstacle with greater efficiency.

After these very promising results of testing PARV on these obstacles, we tested PARV on some obstacles that proved to be much more challenging. These obstacles included having PARV drive up 4" steps and road curbs. PARV was able to get up 4" steps, but not in a very controlled manner. Certain curbs proved to be a little too challenging for PARV as the car could not drive up them. The largest issue with tackling these obstacles came from ride height as the 4WD and new differential system were able to consistently get up the step or curb, but then specifically on the curbs the chassis would bottom out and then the car would stop climbing up the curb. Another obstacle that PARV was tested on were rocks. These rocks varied in size ranging from approximately 2" to 4" tall. PARV performed pretty well on these rocks, the only time the car had issues was if the car bottomed out because of its ride height. When considering that PARV is a 1:8 scaled car, some of the rocks that PARV drove over were proportional to a 11.8 foot wide boulder for a real car.

Finally, in terms of obstacle and terrain testing, PARV performed very well on all terrains tested. Appendix G shows videos of PARV attacking these obstacles described. The car was able to drive efficiently and in a controlled manner on all of the terrains described in Chapter 14.

Payload

When testing a payload on PARV's top plate, the team added two different sets of weights. One set was 5 lbs and the second set was 10 lbs. At first, when the weight was added to the car, it drove well for both sets of weight, but after a short amount of driving the steering would lock up in the toggle point and the car would then have trouble steering. But after some redesign and part swapping with the steering, which is discussed more in detail in Chapter 7, the steering stopped locking up. The car performed pretty well, the largest issues were that the turning was slightly worsened and the shocks had difficulty holding the weight. But as discussed in Chapter 6, changing the springs to have a higher spring constant could help this issue.

Steering and Speed

After testing the steering radius using the method described in Chapter 14, we found that PARV could turn left with a turning radius of 42.5” and right with a radius of 32” in 2WD. In 4WD the left turning radius was 43” and was 32” for right.

The speed of PARV, after following the method as described in Chapter 14, was found to be the same for both 4WD and 2WD. The speed was 8.77 ft/s or 5.98 MPH.

Modular Systems Testing

As described in Chapter 14, we tested the powered trailer when it was attached to PARV. We found that the powered trailer performed very well. One issue we came across was the issue that the motor we had for the trailer could not full throttle so it could not send max power to the wheels. More details on this is described in the trailer design section in Chapter 11. But at slow speeds the trailer being powered helped the car trailer system get up some steep hills or bumps. At higher speeds, the system still worked very well and trailer hitch worked well. The trailer was able to steer as the car dragged it which was good as well. The 3D printed wheels performed relatively well, sometimes there was slippage between the TPE wheel part and the PLA hub. Furthermore, there seemed to be less friction with the TPE wheels. Appendix G shows some videos of PARV and the trailer driving together.

Also, we added the robotic arm to the car as well as the self-driving package. The self-driving package through some limited testing was able to drive the car. The sensor package was not able to be constructed early enough in the project cycle to be tested with the car. However, through mounting certain sensors such as the ultrasonics, they were successfully mounted to PARV and the bumper. The robotic arm was also successfully mounted onto the top plate and proved the modularity of the mounting holes on the plate. The robotic arm worked well in conjunction with the PARV and the trailer and successfully picked up a small box and placed it in the trailer as intended. This video can be seen in Appendix G.

3D Printed Parts

While testing PARV, a close eye was kept on the performance of the 3D printed components of the car. Key areas of emphasis we looked at were the suspension components, steering linkages, drive couplers, and gears. After testing we would frequently examine these systems to ensure there were no cracks, visible wear, or weakening of the components.

Suspension

Suspension components experience the brunt of the forces during driving. As such, it is important to make sure these components are not worn over time. Upon examination, there have been no noticeable cracks or damage to any suspension components. In testing the previous year's car, the front wishbones would frequently break after collisions. This year we have lowered these links to better protect them, and increased the infill percentage to 100%. Following these changes, we never had a wishbone break from collisions (with or without the bumper).

The only issues the suspension parts had revolved around the pin holes that hold the system together. When printed, the holes are very tight and the pins stay in place. However throughout the course of running the car, or removing pins to change components, the holes open up. This allows the pins to sometimes fall out of position. We solved this solution by adding a little Elmers glue within the pin holes. This added enough adhesion to hold the pins in place, but also not so much so that they could not be removed.

Steering

The 3D printed components in last year's car all performed very well, with the exception of the steering linkages. Over time, these components would become more and more flexible, until they eventually broke. Shown below in Figure 15-1, as the car drove, the entire mounting mechanism began to rotate and flex.

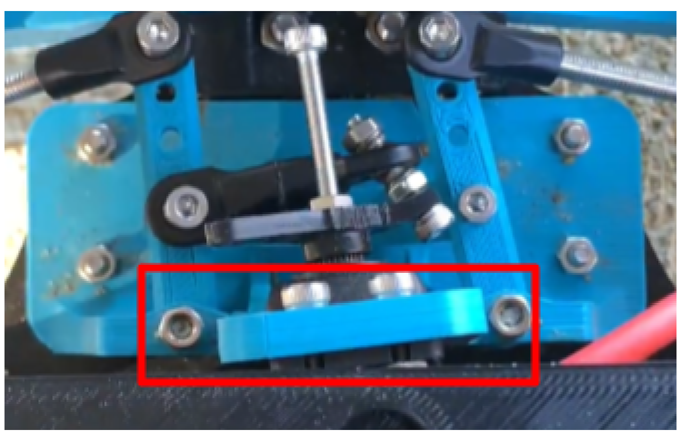


Figure 15-1: Flex of Printed Parts in Old Car

To remedy this in our design we printed our steering linkages at 100% infill. After all of our testing, there were no cracks or flex in any of our steering linkages.

Drive Couplers

The drive couplers on PARV experience a high amount of forces (defined in Chapter 8's Drive Train Analysis) as they are directly driven by the motor, and connect the power from the motor to the ground and turn it into movement. The main area of focus within the couplers is where they connect to the drive shafts. In order to rotate with the shafts, the couplers use a combination of keys and set screws. Keying is when a flat profile is grinded into the shaft, and that same profile is matched on the 3D printed part. Through testing this alone was often not enough to keep the components fixed together. The key on the printed part would get carved away until it was not enough to hold the shaft. To remedy this, set screws were used in combination with the keys. In the direct drive on both PARV and the Trailer, the shaft had holes drilled through that set screws go direct through as seen in Figure 15-2. This results in an extremely strong mate between the 3D printed parts and shafts.

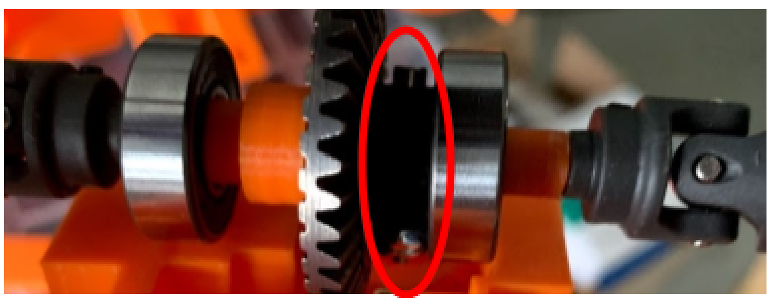


Figure 15-2: Highlight of Set Screw Through Shaft in Direct Drive

Gears

As mentioned in Chapter 9 Section 3D Printed Direct Drive Differential, the initial gears printed for use within the direct drive did not hold up to the forces required. This was expected through our analysis, but we wanted to test them to validate our analysis. We tested with PLA and Tough Resin material, but they were still not strong enough. In these instances, the pinion gears failed, but ring gears stayed mostly intact with minor damage as seen in Figure 15-3. This is likely because the pinion gear teeth were smaller than ring gear, and gave way first.

Figure 15-3: Damage On Direct Drive Ring and Pinion Gears

The gears in the Transfer Case however performed with no issues, and no noticeable wear as seen in Figure 15-4. We expected these gears not to break, but we did expect some wear. We were presently surprised by the results from these gears.

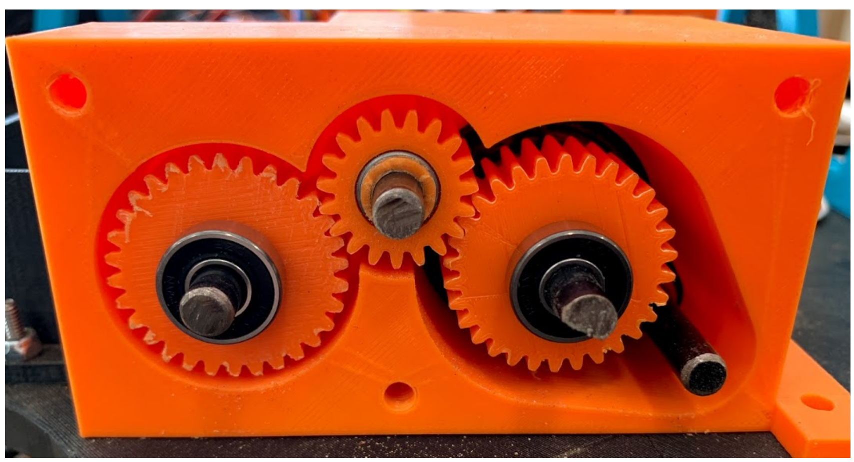


Figure 15-4: Gears Within Transfer Case After All Testing

The only 3D printed components that showed wear within the Transfer case were the inner shaft profile, inner groove sleeves, and outer sleeves as demonstrated in Figure 15-5. These profiles have experience wear because of the nature of their use. While driving, these components are all spinning relative to each other, and are slid together, causing the profiles to catch and spin together.

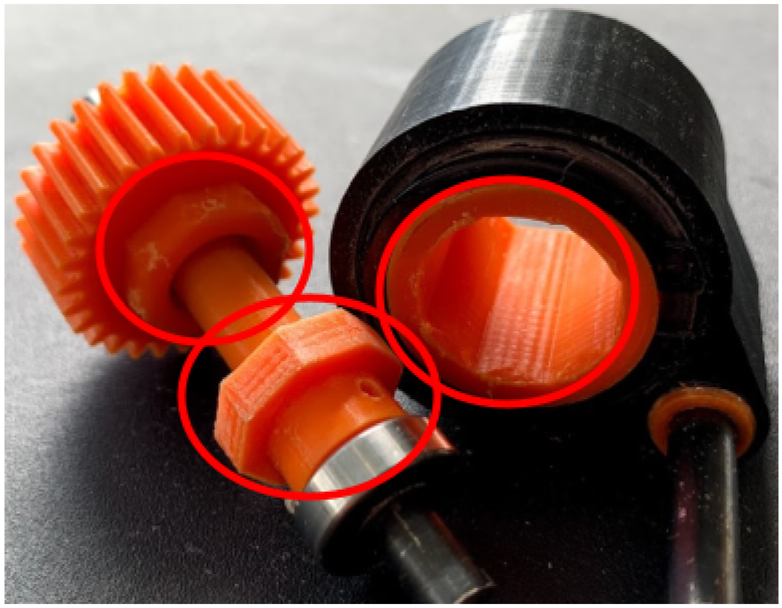


Figure 15-5: Highlights of Wear on Transfer Case Sleeve Profiles Following Testing

Following all of our testing these components still worked, however they should be monitored further after more use. Over time these components may need to be replaced if they are not performing as intended as wear increases. Our testing suggests this is not a frequent maintenance item, but rather something to keep an eye on whenever working on the car.

16. Conclusion

Through this project, PARV was created to be a modular remote controlled delivery vehicle capable of traveling over a variety of terrain. It proved to be very capable outdoors as a result of the robust design, 4WD, and direct drive rear differential. It also served as a platform that systems can easily be added to, such as the robotic arm, trailer system, and self driving system developed by our partner team. We were impressed to see that PARV was able to drive up a 4" step and a 30°-40° hill, in addition to being able to conquer all obstacles in a controlled manner. Our expectations from analysis also proved to be correct through practice, such as components failing where predicted and our expected top speed from our gear analysis.

PARV was successful in meeting almost all requirements outlined in Chapter 4. Unfortunately, our team was not able to create limited slip differentials nor 3D print the components for the differentials. We found that even with filaments designed for increased tensile strength, such as NylonX and Tough Resin, 3D printed gears were still unable to survive the forces in the differentials. While the solution of using metal ring and pinion gears in the rear, and an open differential in the front proved to perform well, PARV would have been a more capable platform with some form of limited slip differentials.

Broader Impacts

Engineering Ethics

As our team has worked on this project, we have been improving our skills as engineers as we should in the engineering code of ethics. Along with that, we have been keeping in the forefront of our minds the applications of our project that can help better the lives of others. From day one we have had the goal to make our car as adaptable as possible for any application. The COVID-19 pandemic has made the importance of non-contact ways of deliveries and interaction clear. On top of this, our goal of keeping as much of the car 3D printed as possible allows the car to be easily recreated by other users as 3D printing becomes more and more popular.

Societal and Global Impact

As an autonomous delivery platform, our car can have a large impact on both individuals, companies and universities. As mentioned previously, the COVID-19 pandemic has made the importance of non-contact delivery and interactions clear. Individuals can not only safely pick up essentials, but also save time if they need to transport something across a campus or town. Universities and companies can also benefit from this as it can automate anything from package/mail delivery across campus, to food transportation. In addition, this platform can be used as a learning tool for engineering students, as through the experimentation and development of this modular system, a greater understanding of engineering and the development process behind large scale projects can be achieved.

Environmental Impact

From the point of manufacturing, the car negatively impacts the environment. Since the car is primarily 3D printed, there is a relatively large amount of plastic needed. Once you consider the accuracies and consistencies of 3D printing, there may be additional waste from failed prints. 3D printer filament recycling is a new and evolving science, as well as organic or biodegradable plastics. While these technologies do exist, they are not mainstream or reliable enough to be used for this project. In the future this is a key area of improvement.

Since the car is powered by electricity, depending on how Green the region's energy is made, the car is very clean to operate as there are no emissions. On top of this, the modularity and payload capability of the car would allow for a component like a solar panel to be added to recharge the car as it drives.

Codes and Standards

Our car is not directly governed by certain codes or standards beyond those of hardware regularity. All fasteners used are within the Imperial standard, as well as all dimensions. This keeps the car uniform so as to not cause any confusion. While the remote control car industry does not have specific standards or codes, the car does use readily available components from this industry. This allows for the accessibility of parts, as well as the wealth of knowledge and possibilities offered by these components.

Economic Factors

The economic factors behind our car depend heavily on the user's available resources. 3D printers for example have become more and more mainstream in recent years, but can still cost anywhere from $100-$300 depending on the model. Since our car is primarily 3D printed, the user will first need to invest in a 3D printer (which can be used for many things outside of just PARV). There are plenty of options available on the market for RC cars, but what sets ours apart is its unique systems including the transfer case, four wheel drive, differentials, trailer system, payload system, and modularity.

Recommendations for Future Work

Where we were able to meet the majority of our goals with PARV's design, our team identified some areas where further work can be done.

The limited slip differential design based on small worm gears was not successful, and other designs should be attempted. This was mainly because of their micro size, which led to their 3D printed versions being too brittle or inaccurate due to tolerancing and layer height limitations. As such, it might be a good idea to consider ways of increasing the size of these gears or using new materials to produce them. Other manufacturing methods can also be explored to create a limited slip differential based on a clutch or viscous fluid system as well. This would allow both front wheels to retain power even when grip is lost and cause less wear on the rear components as well.

By extension, a redesign of our direct drive differential system may be a stepping stone to this goal. While we briefly experimented with NylonX for 3D printing, issues with the printers themselves and time constraints meant we couldn't test those parts in PARV itself. As such, designing a differential system out of NylonX might be useful in understanding the size and strength limitations of 3D printed gears.

PARV's steering design also has further room for improvement. Currently the turning angle of each wheel is limited by the thick driveshaft that must travel to the front wheels. Our team used the same driveshaft in the front and rear that allowed their length to be adjusted. Smaller alternatives to these driveshafts are available and should be explored as an option for the front wheels. Additionally, the steering servo can be rotated so it travels in a horizontal direction as opposed to its current vertical orientation. Our team believed this was the main reason the linkage performed better when turning to the right than the left. This change in addition to thinner driveshafts should largely improve steering performance.

The car's suspension shocks could also be improved. As mentioned earlier in Chapter 6, we tried to implement a new set of springs to improve the suspensions system. Future work could be used to look into strengthening the suspension shocks for payload integration.

While our team did experiment with flexible printing filament in printing the trailer tires from TPE, more components could benefit from being printed using this material. Other than the use of TPE for PARV's tires, one of the most expensive components, it can be used for the car's bumpers as well. Being printed with PLA, they are very brittle and do not hold up well when there is an impact. Making these parts from a flexible filament would increase the part's durability.

The reduction of the total number of fasteners required is another area for future work. Fasteners are a large part of the BOM cost of PARV and a number of different sizes and lengths are needed for assembly. While some components, such as the wheels and motor will always require fasteners, locating pins can be used on housings to align components on the chassis and reduce the total number of fasteners. For components under less stress, such as the ECU bracket and battery holder, snap fits can be used to remove the need for fasteners all together. Our team wanted to explore this option, but did not have time to do so.

Additionally, as mentioned in the trailer section (Chapter 11), we had issues reversing the direction the motor could spin. This is an area that could be looked into further to make the trailer optimized and provide more power to the entire system. The trailer could also be implemented into the self-driving package to control the motor and power autonomously. Also, to increase the payload capacity on the trailer, future work could involve implementing zinc rods into the trailer's chassis design.

Personal Reflections

Dexter Czuba

This MQP project allowed me to utilize a series of skills I had learned throughout my time at WPI, as well as learn new ones that may be useful in the future. One of the most important skills I had to use for this project was the development of parts and assemblies using CAD software, which I mainly learned through the WPI course ES 1310 (Introduction to Computer-Aided Design). This, paired with the skills in stress analysis I learned from ES 2502 (Stress Analysis) and ME 4512 (Introduction to Finite Element Method), helped me analyze most of our static parts, such as the chassis, before manufacturing them. In addition to these skills, I also used prior knowledge from ME 3310 (Kinematics of Mechanisms) and ME 2300 (Introduction to Engineering Design) to help analyze our steering linkages and plan out our project timeline respectively. I was also able to utilize skills I gained from outside the engineering field, as a lot of the presentation and report work I did was inspired by the lessons I learned from doing my Interactive Qualifying Project.

During the MQP project itself, I learned a couple useful skills in the engineering field. One of the main focuses of our project was 3D printing, so as such I spent a lot of time learning how to develop CAD models to best work on a 3D printer, as well as understanding how a 3D printer works. While I did not have a personal 3D printer for this project, the knowledge I have learned from working with my teammates on this will help me in the future when working with this type of manufacturing. In addition, as this MQP project was a year-long engineering project and was based on a previous project, it actually is set up in a very similar manner to engineering projects in the working world. As such, the skills I learned in time management, prototyping, research and development, and teamwork will help me succeed in this field after graduation.

In addition to these technical skills, I also improved my interpersonal skills as well. I am a very socially anxious person, and as such it is hard for me to express myself in team projects, let alone understand certain social cues when working with others. In working with my team members and advisors so closely, I was able to come out of my shell, at least somewhat, and begin to develop many of these skills while working on this project. In addition, I was also able to become the leader on certain aspects of this project, which gave me a chance to be in a leadership role, something I had never really experienced before. While I still have room for improvement, I feel like my ability to work with others has increased, as I also feel like that, by the end of the project, I was able to express myself correctly, if not always the most concisely.

Rajkumar Dandekar

Over the course of the MQP project, I used a number of skills and concepts that I have learned through my coursework at WPI, in addition to learning some new concepts. The classes that stand out most to me are ES1310 (Intro to Computer Aided Design, and ES3323 (Advanced Computer Aided Design). These courses gave me the knowledge and skills for the majority of the CAD and some of the analisis that we completed. Knowledge from classes such as ME2501 (Static Systems), ES2502 (Stress Analysis), and ES2503 (Dynamic Systems) was also useful for analysis along with more specialized classes such as ME3310 (Kinematics of Mechanisms) and ME3320 (Design of Machine Elements). These courses in particular helped with the gear and linkage analysis. I was also able to utilize design knowledge I learned from ME4320 (Advanced

Engineering Design) and ME 5441 (Design for Manufacturability) this year. These design courses were useful in the development of PARV and also provided some inspiration for future work as we did not have time to implement some concepts such as snap fits.

While I did have a general knowledge about cars prior to this project, I learned a number of things about the systems involved on a car and ways that they can be scaled down and implemented on an RC car. We explored this for many components, and were forced to find alternative designs to make the components viable for an RC car. This required a number of skills that I learned throughout my time at WPI. Other than modeling and analysis skills in Solidworks and ANSYS, I utilized a number of manufacturing methods I learned about. A large part of our project was 3D printing, which I knew very little about before entering this project. Since then I have learned a great deal about 3D printing with different materials, printers, and optimizing settings for a high quality print. I became so interested in this process that I purchased a printer that ended up being crystal to the completion of our project. Tolerancing was also a large part of this project as we had to ensure all the parts would fit together correctly.

Apart from the technical skills I utilized and learned, this MQP project has taught me a great deal about working in a team. While I have been a part of many groups and teams at WPI, this MQP group has taught me the most about group skills. Communication and time management were large parts of this project, and I was able to improve my performance in these areas. It also relied on organizational skills being such a large project with many small parts. I was able to learn and utilize a number of skills throughout the course of this MQP project.

Steven Colin Gordon

Throughout this MQP, I have been able to use an assortment of skills and knowledge that I have learned at WPI. In terms of the classes I took that helped with this MQP, almost all of my mechanical engineering classes as well as my engineering sciences have helped me while completing this MQP. For example, my statics, stress, and dynamics courses have helped me learn ways to analyze the systems in PARV (ES 2501, ES 2502, ES 2503). Furthermore, my kinematics course (ME 3310) helped me learn about linkages and gears, which was very important when designing the steering and gear mesh systems. Furthermore, my introduction to engineering design course (ME 2300) and advanced engineering design course (ME 4320) were the most important as they helped me learn about how to approach a project and problem in an engineering sense.

In terms of the skills I learned throughout WPI, the most important skills were SolidWorks, Matlab, and Ansys for this project. SolidWorks and the use of CAD was crucial to designing PARV and all the subsystem, assemblies, and parts. Matlab was helpful when simulating the cars systems in the torque and velocity analysis. Also, Ansys was helpful for completing stress analysis tests on the 3D printed gears within PARV's differentials and transfer case. Many skills, I was able to enhance throughout this year-long project, while others I had to learn to be successful in MQP.

Additionally, leadership and organizational skills also played an important role to my success in this project. At times, I needed to take the lead and help run MQP meetings or plan out what needed to be done during the MQP. Also, in a long project like this, organization is very important to understand what needs to get done and by when.

Eric Stultz

This MQP ended up being the perfect cap to my four years at WPI. These last four years have been huge for my growth not only as a person, but as an engineer. Through both course work at WPI, and work experience during internships, I have gained the skills needed to work on the project as an individual, and a team member.

All of my courses from intro level engineering classes, to engineer capstones, to even my humanities classes have helped me with this project. Engineering classes like ES 2501 Statics, ES 2502 Stress, and ME 3310 Kinematics have given me the knowledge and tools to analyze various systems within PARV. These classes helped me perform structural analysis on the chassis and gears to determine the feasibility of them in our design. Other engineering classes like ME 2300 Intro to Engineering Design and ME 4320 Advanced Engineering Design helped me develop the skills to take a large project one step at a time and work through the problems that come up.

My personal interests and skills were also crucial to the outcome of our project. At my first internship before freshman year I got to experience how 3D printing has changed the world of engineering. At the time 3D printers were very common place, but I never saw many projects made 100% from printing. We primarily used the printers to test fittings and concepts that would later be manufactured in metal. Since then I have bought a 3D printer and it has become a passion of mine. These skills I developed greatly helped during our project as I was already very comfortable with 3D printing, which was important as a majority of PARV was printed. This extended beyond the simple manufacturing of the project, as designing parts for 3D printing requires certain design decisions to be made for printability, and tolerances for fitting parts together. Having this knowledge prior to starting saved what could have been a full term of learning to 3D print.

Finally, this project also gave me a chance to exercise and expand my leadership and group work skills. Whether that be through meetings with our advisor, sister MQP, or potential students next year, these meetings were great to expand my organization and leadership skills. My skills as a leader also allowed me to help organize these meetings, and the various sub systems I worked on.

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18. Appendix

Appendix A: E-Project Link to 2019-2020 MQP

https://web.wpi.edu/Pubs/E-project/Available/E-project-051820-200753/

https://docs.google.com/document/d/1TfspL1m9zqvKNEmMwr0kL7IACGZ7C-4f3enZzvmdt5s/edit

Appendix B: MathCAD Script

Link to MathCAD Script Download:

https://drive.google.com/file/d/1anJfVzvxdZmswj476u0JVzI7cMjaPjAB/view?usp=sharing

Appendix C: Gear Calculations- Bending and Surface Stress

Link to spreadsheet:

https://docs.google.com/spreadsheets/d/1_boc2p7W3F8X6NdIbUEc_fZaKg8sCS1PI7KsPg4DqHM/edit?usp=sharing

	Ring Gear	Bevel Pinion Gear	Worm Gear	LSD Center Gear	TC (Large)	TC (Small)	
Diametral Pitch (in)	20	20	1.39				
Module (dia pitch in mm)	1.27	1.27	1.412	1.06	1.00	1.06	
# of Teeth	36	12	5	17	30	18	
Diameter (mm)	45.72	15.24	7.06	18.00	29.97	19.05	TC dias measured from models
Input Torque (N*m)	1.35	0.45		0.81	0.45	0.27	
Pressure Angle (deg)	20	20	22.79	22.79	20	20	
Pressure Angle (rad)	0.35	0.35	0.40	0.40	0.35	0.35	
Spiral Angle	0	0	0	0	0	0	
Lewis Form Factor	0.377	0.245	0.175	0.302	0.358	0.308	
Face Width of Tooth (mm)	6.379	5.57	8.585	6.08	12.7	12.7	
Young's Modulus (Mpa)	6000	6000	6000	6000	6000	6000	
Pinion pitch diameter	15.24	15.24	7.06	7.06	19.05	19.05	
Speed Ratio	3	3	3.4	3.4	1.67	1.67	
Poisson's Ratio	0.39	0.39	0.39	0.39	0.39	0.39	

	Gear Ratio	Torque Leaving (N*m)
Motor	n/a	0.05
Gear Box	1:9	0.45
TC Internal Gears	1:.6	0.27
Transfer Case Overall	1:1	0.45
LSD (Pinion to Ring)	1:3	1.35

Calculations	Ring Gear	Bevel Pinion Gear	Worm Gear	LSD Center Gear	TC (Large)	TC (Small)
Tangential Force (N)	59.06	59.06	45.00	90.00	30.03	28.35
Radial Force (N)	21.49	21.49	46.23	92.45	67.18	63.42
Resultant Force (N)	62.85	62.85	64.51	129.03	73.58	69.46
Bending Stress (MPa)	31.19	54.96	10.57	25.95	6.60	7.67
Surface Stress (Mpa)	77.72	83.18	93.21	156.64	58.40	56.74
	These are same equation for radial		These ones are same equation for radial			

Appendix D: Printing Specification and Tracking Sheet

Link to spreadsheet:

https://docs.google.com/spreadsheets/d/1-GDppQfyOtmwAjtIxmzF9jT4uj6sHaIh1mT5AgW9csc/edit?usp=sharing

Appendix E: Print Verification Documents

Link to folder that includes verification procedure, and sheet used for PARV:
https://drive.google.com/drive/folders/19hXcHUdJMKRyctB7PL5h7dQFIeaWb473?usp=sharing

Appendix F: Hardware and Other Purchased Components List

Below is a link to a spreadsheet with all required hardware and purchased components.
https://docs.google.com/spreadsheets/d/1T6ueZjtmwKs1GXdCD6xxzTXBm5KEx9r55sP3n-FWNw0/edit?usp=sharing

Appendix G: PARV Driving Videos

Below are links to PARV driving own our designed path:
https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipOWM1_WcTVCwoTITlI70IAKwcbhLLuc4lJ6ohOf
https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipPSLOiHUI_pqRxfDW6kjQxnZ1BgtfXTWP5Imy5B
https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipOd8j13QJzryZu_PBceah8a5kvtLUlFJag4X0V7
Below are links to PARV driving steep hills:
https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipM0RQYd4geXVm4FKeVinXoXLVP5AA5CQwbBXF3E

https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipPrHQgfxo3DghPTb8qCy5UCAcQtEUCwZgdxTysJ

Below are links to PARV driving on tall grass and bumps:

https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipM0hJSdYWyWWil2D25Me2BlYX2_J6ZEjfBt5uNY

https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipMzV_eH8GJVkmZLl6hoI66hRQI-XMGDggsCRZS0

Below are links to PARV driving on steps and curbs and rocks:

https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipNikfN9fnzyMBJs1lQqZQMB1LmrutBxber2iU_2

https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipPcAARPd5p_gCFEEyOEK8ewyc4SwY5U6AdYT5bP

https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipMBJ8j5lWduYa0MFac0WYePsN1jDyPgjHJP7vjh

Below are links to PARV driving with the trailer:

https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipPEb0DnLgmBL2S5gjFOuzrbPN9XqkLrfpEpxbC8

https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipOHO_503NfOl9mnM1GtRD5eNLXZQqLkscYtWf7l

https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipOqLW7dr49V8iVPcI7lrtzruqfi0vT7z-AArVRm

Below is a link to PARV and the Robotic Arm working together:

https://photos.google.com/share/AF1QipNPZ5pzLT0MSJmf0-WO-E7eFRZjy_0qW4nG2lUBgubOJFS22BJP3jDulHETrgBQOQ/photo/AF1QipNY8mkn5T9RoRHbOcQ8-l8iGdHPvKmTwncP6CY-

Appendix H: Torque/Velocity Simulations

https://drive.google.com/drive/folders/1dRLghI7d_Pu0YWFLnZpfyNog6aoSSMDJ

Appendix I: CAD Files

https://github.com/rkprad/20-21-SelfDriveCar-CAD.git

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