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Designing and Fabricating a Prototype Air-Powered Remote-Control Car

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Project Inspiration:

Tom Stanton

ABSTRACT

The objective of this project is to develop a prototype air-powered remote-controlled (RC) vehicle that demonstrates the viability and potential advantages of a compressed air-powered drivetrain. The Air-Powered RC Car (APRCC) is uniquely characterized by the integration of subsystems that closely replicate those found in full-scale automobiles. This design approach provides a more complex and realistic driving experience, while also enabling increased opportunities for user-driven mechanical tuning and experimentation. The development of the compressed air engine was guided by prior work related to pneumatic propulsion systems. Given the experimental and evolving nature of this project, it was essential to adopt an iterative design approach. This methodology involved repeated cycles of prototyping, testing, and refinement, which necessitated the extensive use of 3D-printed components to enable rapid fabrication and modification of parts throughout the development process. The project team executed the complete design, fabrication, and assembly of the APRCC. Performance testing of the finalized prototype yielded a maximum runtime of 60 seconds and a peak velocity of 5 miles per hour.

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1 INTRODUCTION

1.1 *MOTIVATION AND NEED*

Battery-powered remote-controlled (RC) cars have long dominated the market, even to the point that there are currently zero alternatives. Battery powered RC cars work well and are efficient; however, there could be a larger skill ceiling in customization and driving of an air-powered RC car (APRCC). By creating an RC car that is powered by compressed air, this project will introduce an entirely new design philosophy into the market.

Another problem with the current designs of battery powered RC cars is the inability for car enthusiasts to enjoy them. Car enthusiasts enjoy everything about cars, including but not limited to the engine, transmission, clutch, differential, electrical system, frame, etc. A battery powered RC car is far from a mini car; however, this project will come very close to being just that. This project will contain a working engine, a transmission which will give the user the ability to change gears, and a clutch that will allow for throttle control and drifting. An enthusiast will be able to enjoy tinkering with a car without any of the potential costs of doing so. This project will be to a car what a sports video game is to the actual sport. The user gets to enjoy the process, and while it may not be as fun as actually participating in the activity itself, does not lend the same risks/costs as the real-life version.

1.2 *OBJECTIVE, DELIVERABLES AND STAKEHOLDERS*

The objective of this project is to design, fabricate, and test a prototype scale car that is powered by compressed air and can function without tethers with a 90 second run time for less than $500 before May 1st, 2025.

1.2.1 Deliverables

- Presentation, poster, and senior design report
- Working prototype of the entire car
- CAD models of each subsystem
- Complete engineering calculations relating to relevant information

1.2.2 Stakeholders

- University of Southern Indiana Engineering Department
- Car hobbyists

2 BACKGROUND

2.1 *PAST PROJECTS*

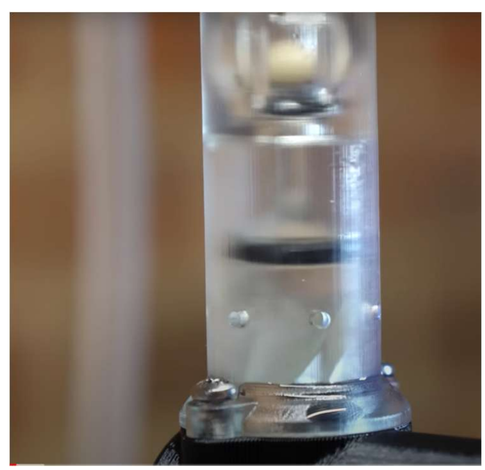
2.1.1 Tom Stanton

The main inspiration for the entire project comes from engineer Tom Stanton **[1]**. Through a series of YouTube videos, he documented how he developed a piston engine powered by compressed air as seen below in

Figure **1**. Detailed in the video series were the many iterations of the design process which was able to outperform the origin of the project, the Air Hogs Air Pressure Plane pictured below in

Figure **1.** Stanton designed prototypes to optimize efficiency and power. This data was paramount to this project, as the team was then able to design and test its own engine design with a prior knowledge of important parameters and how they affected the performance of the engine. The findings of his work are foundational for the APRCC project.

A)



B)

Figure 1: A) Original Airhogs Air Pressure Plane and B) Tom Stanton's Single Cylinder Design

2.1.2 Tom Stanton Air Compressed Powered Car

While the air design mentioned above was used for an airplane, Stanton used a different piston design to power an RC car as seen below in Figure **2**. In this design, three pistons were used and connected directly to the drive train. The middle piston was designed much like a plastic syringe and operated 90 degrees out of phase of the other two [2].

Figure 2: Stanton Air Powered RC Car

The main issue with this design and how it relates to our project is the lack of control offered. While the design is simple, the car cannot move very fast (no speed data was given in the video). Another problem with this design in relation to the APRCC is that the only control the user has with this design is steering. This design also has a very small tank on the car. Since the tank is a simple two-liter bottle, the run time is only about 75 seconds.

2.1.3 Brick Technology Lego Truck

Another air powered RC vehicle that has been created is the Lego truck built by Brick Technology. The truck is designed much like a semi-truck, cab and trailer included. This design solely uses Lego parts including Lego's own piston cylinder and air hoses [3]. The Lego truck cleverly stores its tanks, which consist of two two-liter bottles, on the trailer of the truck as can be seen below in Figure **3**. While customers would likely enjoy putting this design together, it also operates at a slow speed, and other than steering it has no other forms of control.

Figure 3: Brick Technology Air Powered Lego Truck

3 METHODOLOGY

3.1 *CONSTRAINTS AND REQUIREMENTS*

3.1.1 Constraints

This project has certain constraints that are necessary because of the market focus for the final product. The constraints and their relevance can be found in Table **1** below:

Table 1: Constraints for the project with ratings of importance

Constraints:	Importance out of 10
Small/Portable	4
Prototype must cost less than $500	6
Pressures in tanks cannot exceed	10

100 psi	
All parts must be manufacturable using typical methods or processes	10

3.1.2 Requirements

Table 2: System Requirements

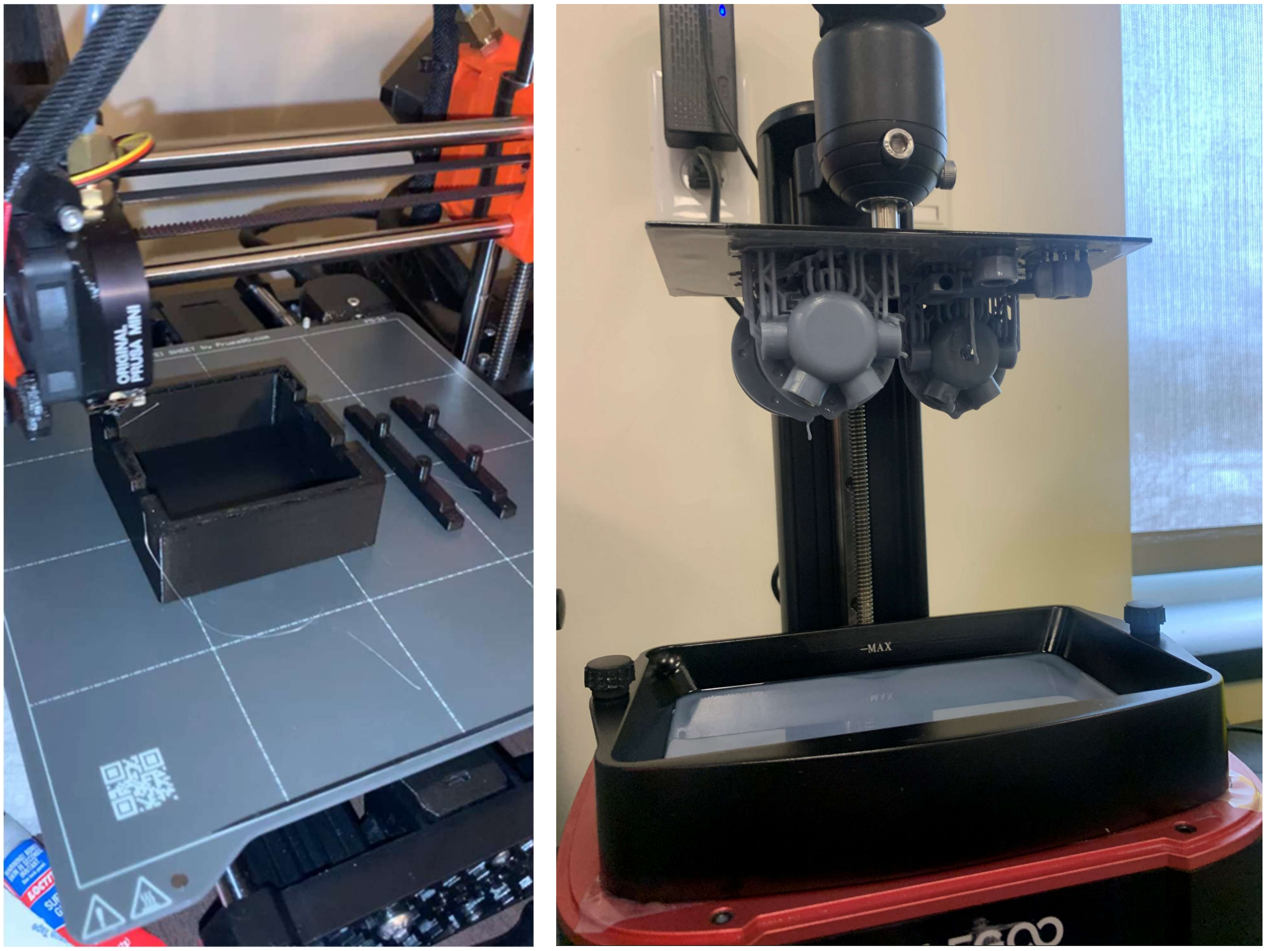
Requirements:	Importance out of 10
Run time of at least 90 seconds	9
Reach speeds of 8 mph	7
Accelerate from 0-8 mph in 5 seconds	5
Turn radius of 6 feet	5
Tank refill time of less than 90 seconds with typical air compressor	10
8 hour run time before maintenance	6
Pressure relief if pressure exceeds 100 psi	10

The project requirements can be seen above in Table **2**. Most of the requirements, such as the turn radius and acceleration, are merely to increase the user experience and interest in the project. However, other requirements are critical to the success of the project. The tank needs to be able to be refilled in less than 90 seconds with a typical air compressor for the project to be considered successful. One of the main goals of the project is to increase the amount of time the user is operating the car, making it imperative to keep the refill time as low as possible. Similarly, the car needs to run as efficiently as possible to maximize run time. Another important requirement is that the car has pressure relief if it starts to exceed 100 psi. The car is designed to operate at 100 psi, but for the safety of the user a relief valve will be implemented.

3.2 *RELEVANT ENGINEERING KNOWLEDGE*

The most used engineering knowledge for the prototype is CAD or computer aided design. CAD goes into every aspect of the design process and is necessary for the main method of fabrication used in this project, 3-dimensional (3D) printing. As far as calculations are concerned, most of the calculations are mechanics for shaft dynamics and strength of materials calculations for sizing the shafts in the transmission and walls of the pressure vessels. The benchtop engine model also necessitates some way of measuring important engine parameters such as power vs. RPM and efficiency. Off the shelf radio receivers and controllers will be used.

Two types of 3D printing are utilized throughout the project. The most common is Fused Deposition Modeling (FDM). This type of printing makes partially hollow, tough parts quickly with good dimensional accuracy and little work needed to fabricate a part. The downsides are that FDM yields a rough surface finish and is not airtight. When an airtight part is needed, Stereo-Lithography (SLA) printing is used. This process yields fully solid parts which are airtight, however, SLA printing is more difficult, time consuming, expensive, and yields brittle parts. The SLA process is used only when necessary.



A) B)

Figure 4: Different 3D print methods A) FDM and B) SLA

To further illustrate the advantages and limitations of various 3D printing methods, the team prepared samples from different manufacturing processes for microscopic examination. The samples were first embedded in epoxy and allowed to cure for at least 24 hours. Once fully cured, the samples required grinding and polishing to achieve a surface suitable for microscopic analysis.

The preparation process began with grinding. Each sample was placed on a rotating wheel and carefully ground against a series of abrasive papers with progressively finer grit levels. This removed surface irregularities and ensured a flat cross-section. Once grinding was complete, the samples were polished using a similar process, but with a felt-covered wheel and polishing compounds to achieve a smooth, reflective surface.

Once polished, the samples were ready for microscopic inspection. The equipment used for sample preparation and microscopic analysis is shown below in Figure **5**.

A) B)

Figure 5: Machines A) used for grinding and polishing and B) microscope

Due to the nature of this project, this project had a different design process than typical. The Iterative Engineering Design Process was used, which is visualized below in Figure **6**. Because this process is used, many test results will be discussed in the Design section. This is because the testing results were a key part of our design process. Almost all material is 3D printed, making it hard to predict the strength and behavior of the subsystems. For these reasons, a trial-and-error approach was more effective, as it quickly gave the team an understanding of what did and didn't work.

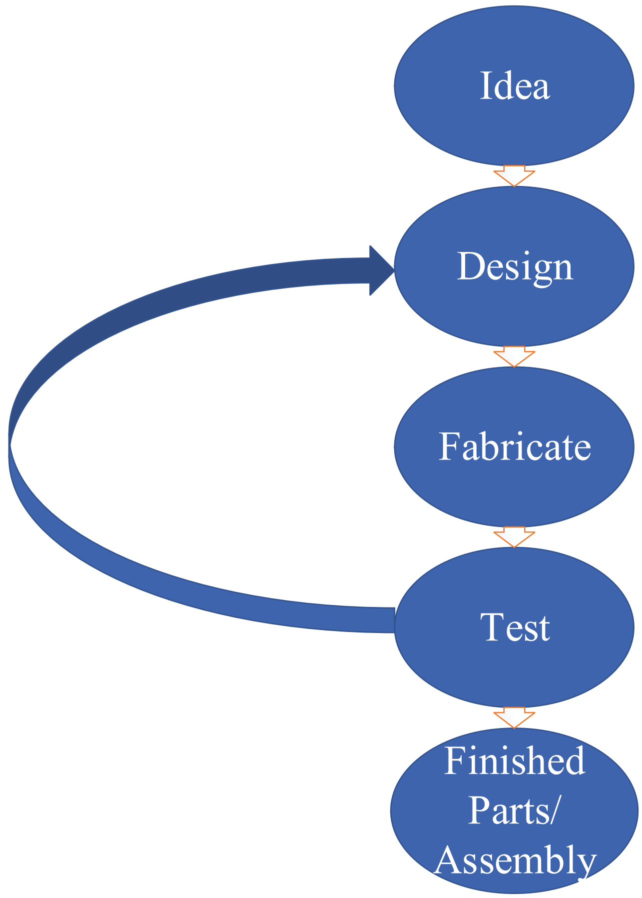


Figure 6: Engineering Design Process

4 DESIGN PROCESS

4.1 *CONCEPTUAL DESIGN*

4.1.1 Turbine Concept

The turbine concept came from a video done by engineer Tom Stanton, who was mentioned previously. This video, titled "Building a Turbine Car," [4] documents the use of different turbines for use in powering a scale car, similar to the objective of this project. In "Building a Turbine Car," Stanton explores the use of different types of turbines and different iterations of turbine types to find the one that works best. The result is the fast but inefficient use of compressed air to push the car forward. The turbine itself would also be difficult to fabricate with tools available.

Figure 7: Tom Stanton's Turbine Design for Scale Car

4.1.2 Simplified Dragster Concept

The simplified dragster concept has its roots in maximizing power and minimizing weight for a fast accelerating, simplified design. This car would have an automatic overrunning clutch or no clutch at all, no transmission, and many cylinders. It could also have no steering, like a pine-wood derby car.

4.1.3 Circuit Racer Concept

The circuit racer is a car that maximizes efficiency and level of interaction with the user. Circuit racers are engineered to reach high speeds while maintaining control and stability. The focus is on creating the fasted lap times, often through construction of the vehicle. The circuit racer is the most complex concept with a manual clutch and transmission, as well as precise steering. It also needs radio control and many servos to actuate key subsystems, like the clutch, transmission, steering and throttle.

4.1.4 Drift Car Concept

The drift car concept is very similar to the circuit racer, except the purpose of the drift car is different, and because of that the power required is much lower. A drift car intentionally loses traction in the rear wheels to slide sideways in a controlled manner. RC drift cars are designed to mimic the dynamics of real-life drifting cars. Much like the circuit racer, the drift car concept also needs radio control for its servo actuation.

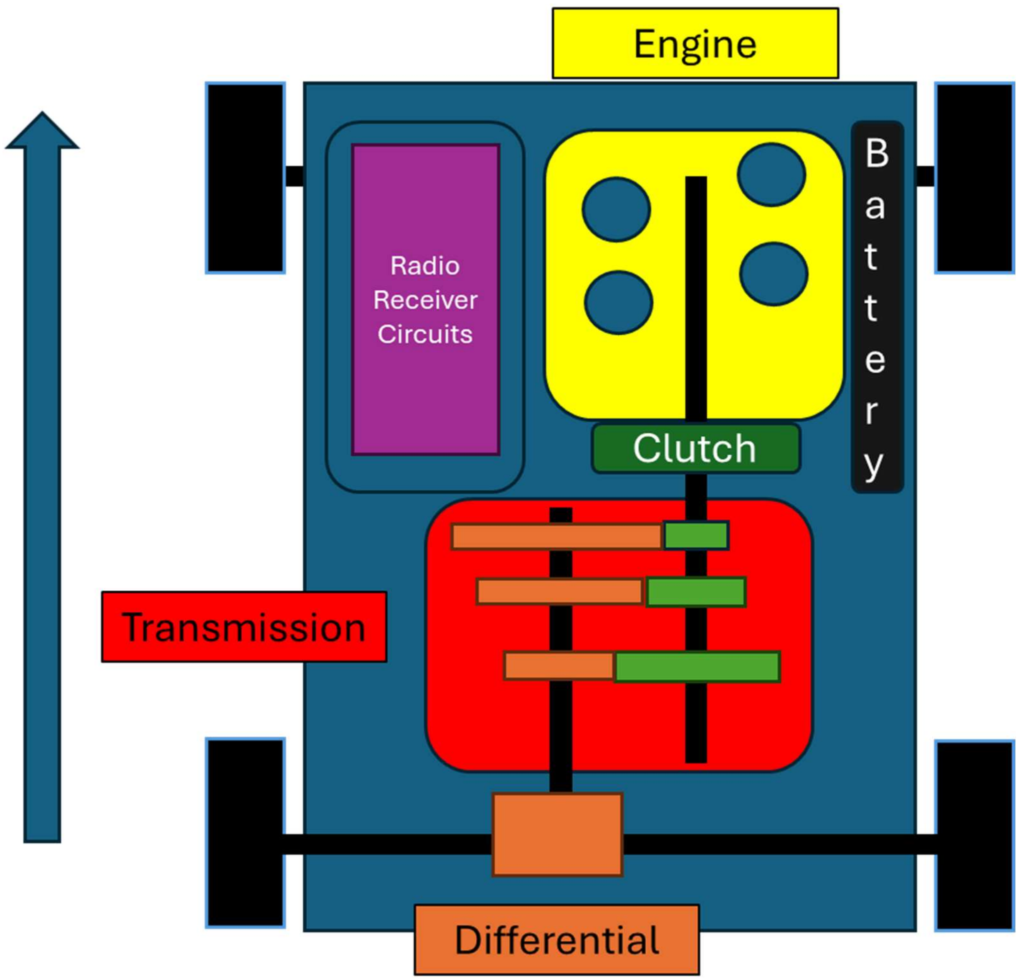


Figure 8: Circuit Racer Concept Drawing

4.1.5 *Concept Pros and Cons*

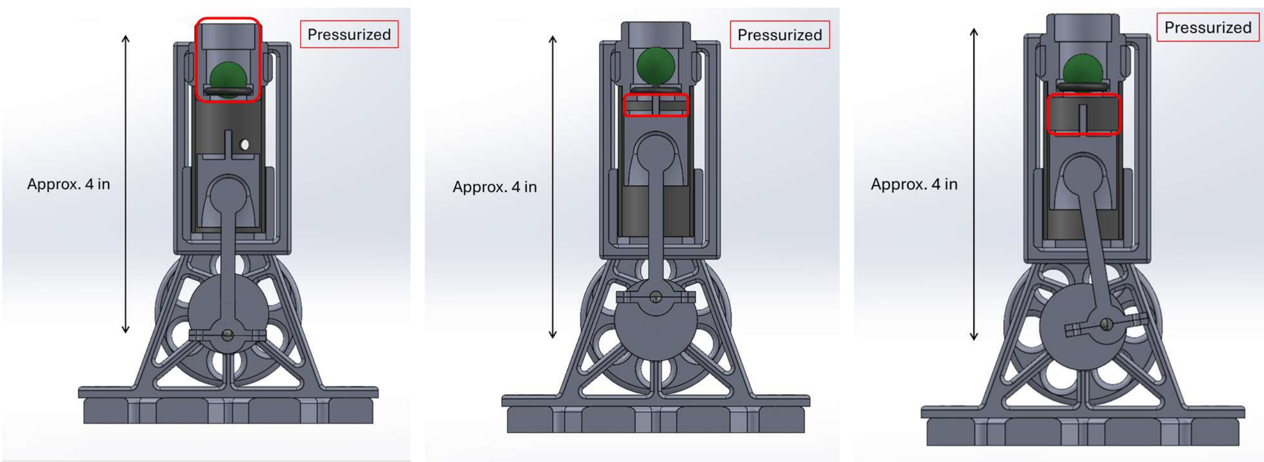
Table 3: Concept Pros and Cons

Concept	Pros	Cons
Turbine	• Fast and lightweight • Simple Design	• Inefficient • Lower User Interaction
Simplified Dragster	• Fast • Simple Design	• Low User Interaction • Low Cusomization
Circuit Racer	• Efficient • Long lasting	• Slower • Complex
Drift	• Less speed and power required • Very high user interaction	• Much higher skill required to drive • Complex

In the end, the drift car was chosen. This is because the drift car design fits closest to the objective of the project, allowing for maximal user interaction. This includes the skill ceiling associated with the shifting of gears and turning/drifting capability. A turbine engine could meet some of these requirements, but the shorter run time and no need for gear shifting oversimplifies the user interaction. The circuit racer was originally chosen, however after more consideration and initial testing and fabrication, the drift car concept was decided upon instead. This is largely because the drift concept does not require as much power or speed as the circuit racer. As mentioned earlier, it was seen very early in the design process that getting the car to the appropriate parameter values for the circuit racer concept would be very difficult and unlikely. In turn, the team pivoted to the drift concept.

4.2 *HOW THE ENGINE WORKS*

Cross sections of the engine are seen below in Figure **9**. The engine cycle repeats with every rotation of the crankshaft. The cycle begins in Figure **9** at the bottom of the stroke, with no pressure in the cylinder. The engine then rotates 180 degrees to reach the top of the stroke where pressurized air enters the chamber around the ball, as seen below in Figure **9**. The pressure normally keeps the ball pressed against the rubber O-ring, making a seal. Now that the cylinder is pressurized, the air acts on the piston, forcing it downwards until the exhaust port is revealed. This removes pressure from the cylinder, allowing the cycle to repeat. Note that there must be enough rotational inertia in the system for the engine to complete a full stroke as there is only power in the downstroke.



A) B) C)

Figure 9: Engine Operation Diagram

4.3 *PRELIMINARY ENGINE DESIGN AND TESTING*

The heart of the car is the engine. Without a well-engineered engine, all other subsystems have no purpose. The most vital parameter to engine function is the quality of the seals, both for the ball in the top valve and between the piston and the side of the cylinder. To test different piston seal types and to find the best ball valve diameter, the design process started with designing and fabricating a single cylinder test engine. The CAD for the single cylinder test model can be seen below in Figure **10**.

Designs for the ball valve were iterated until functional ball O-ring valve clearances were found and no leaks occurred. This ball valve design is used for the remainder of the project.

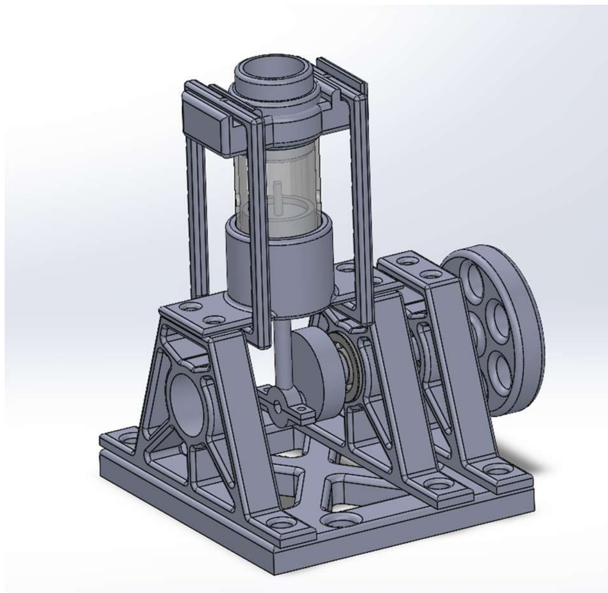


Figure 10: Single Cylinder Benchtop Model

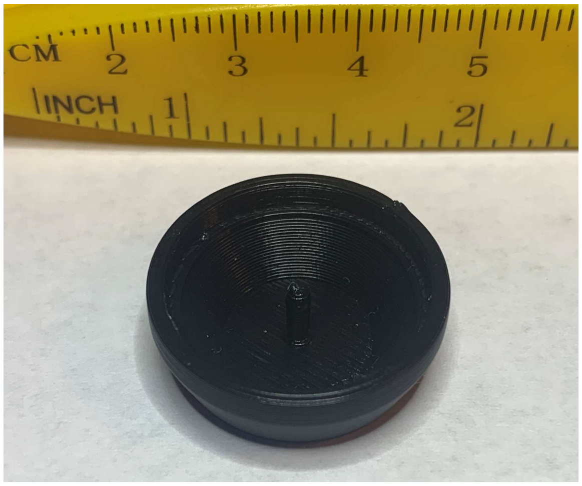
After fabrication, the single cylinder test model can be seen below in Figure **11**.

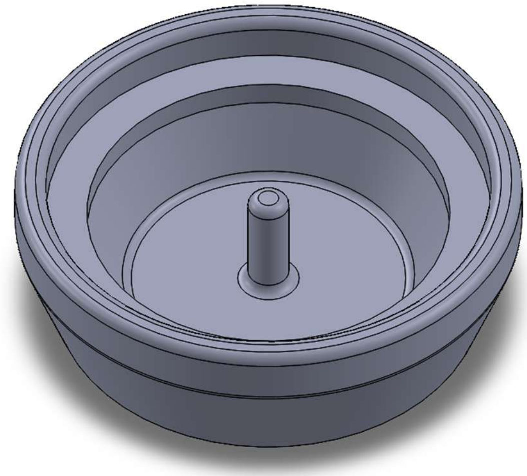
Figure 11: Fabricated Single Cylinder Benchtop Model

The next step was to design and fabricate different seals for the piston (blue rubber piece above in Figure **11**. Different ball sizes were tested on the single cylinder including 6 mm, 8 mm, and 10 mm to learn which ball size gave the best airflow for extending engine runtime (increasing efficiency). The 6mm valve diameter struggled to flow enough air while the 10 mm took too much force to open, leaving the 8mm as the clear choice.

4.3.1 Piston Seal Design and Testing

Using inspiration from Tom Stanton's [1] work with his engine design, different seal geometries, material types, and diameters were designed and fabricated for testing. The seals were fabricated by 3D printing a mold for the seal, then pouring two-part rubber into the cavity. One of the 3D printed molds can be seen below in Figure **12**.





A) B)

Figure 12: Seal Mold A) Fabricated and B) CAD Model

The testing method was simple. First, pressurize a two-liter soda bottle to 40 psi to act as a tank to feed high pressure air to the engine. Next, use a finger to press the piston onto the ball valve manually to see if the seal would contain the air. If not, the seal design was considered a failure. If the seal did contain the air without leaking, the seal was installed in the engine. Finally, the engine was manually started and allowed to run, while listening to which seal was capable of the highest engine speed. The result was that at least 0.1 mm of clearance is needed for the engine to run where:

$$Seal\ Clearance = Cylinder\ Diam. - Seal\ Diam. \quad (1$$

Below in Figure **13** different seal trials can be seen. The testing indicated that exact seal geometry was not vital to efficiency, except for the thickness of the outside edge changing seal longevity.

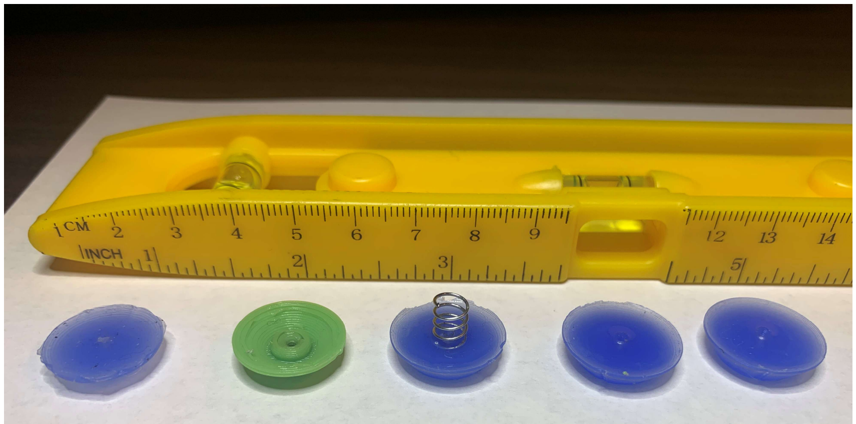


Figure 13: Different Seal Designs and Materials

4.4 *ENGINE DESIGN*

Now that there are effective seal and ball valve designs, a larger engine needs to be designed and fabricated for testing. A four-cylinder, V shaped configuration is chosen to determine the appropriate length of the crankshaft. There were issues with excessive crank bending in the single cylinder. Because of how the engine function is contained in each cylinder individually, different number of cylinders can be installed on the test engine. This allows testing of different configurations on a single design. The CAD can be seen below in Figure 14.

Different piston pin lengths and flywheel rotational inertias were tested. The testing method was the same as with the single cylinder. The engine was run with combinations of pin lengths and inertias until the engine ran as smooth and responsive as possible. The test apparatus can be seen below in Figure **14**. The gear set next to the engine allows for power testing which will be discussed in Results.

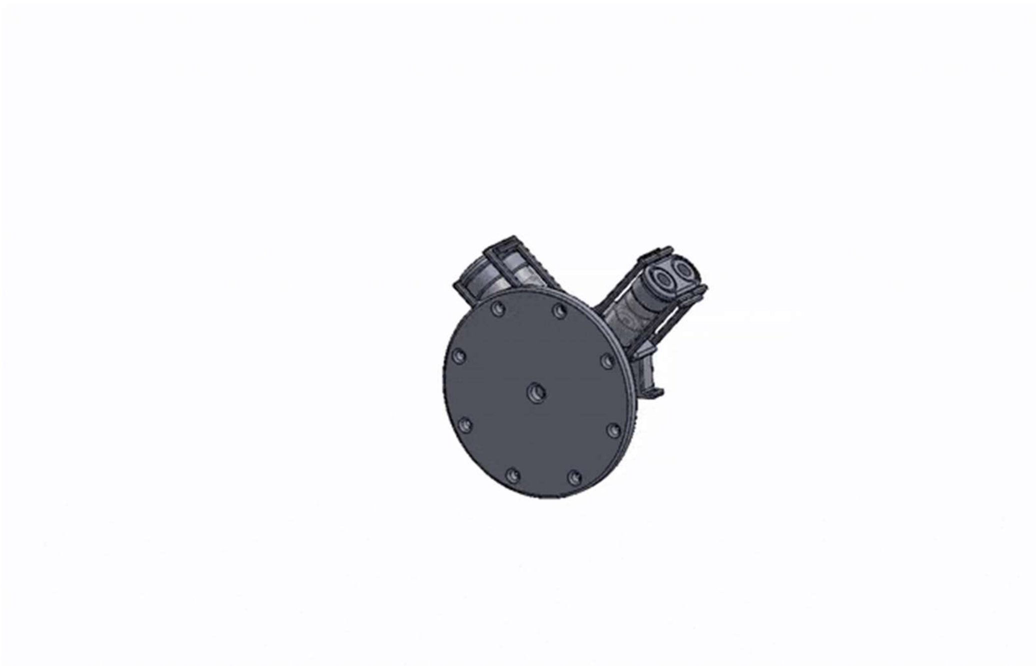


Figure 14: Four Cylinder CAD Model

4.5 *TANK DESIGN*

The tank design refers to how the car stores the necessary volume of air required for operation. Early on, the team determined that the maximum pressure needed to run the car would be approximately 80-100 psi. This decision was made to balance the goal of maintaining a short refill time with the need to create a vehicle that is both enjoyable and safe for the user. Based on these considerations, the team chose empty two-liter soda bottles as the storage method for the compressed air. This choice was made with confidence, as two-liter soda bottles are typically designed to withstand pressures of 40-70 psi [5], and most bottles do not rupture until they reach around 150 psi [6].

In addition to storing the compressed air, the tanks must effectively deliver the stored air to the engine. To achieve this, the team designed a custom bottle cap. This cap screws onto the two-liter bottles in the same manner as the original caps. However, it features a hole designed to securely accommodate commercial tubing, as shown in Figure **15** below. The caps were fabricated using the Stereolithography (SLA) method, as outlined earlier in the report. The team conducted pressure vessel testing to verify that the resin material could withstand the high pressures within the system. To ensure an airtight connection and prevent leaks, the team applied epoxy to securely bond the tubing to the cap.

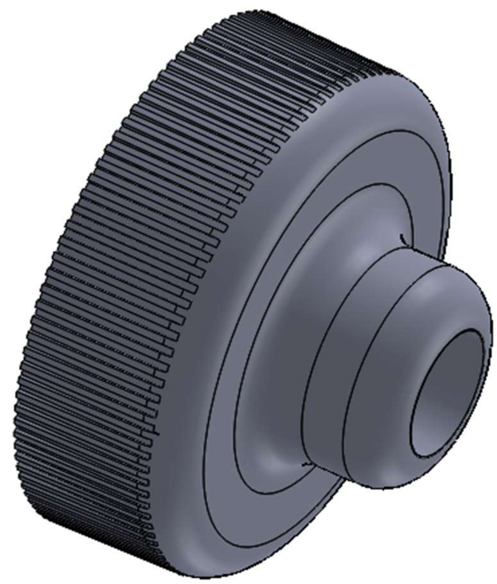


Figure 15: Bottle Cap

After conducting additional tests and obtaining initial values for key parameters, such as runtime and power band information, the team decided to use five two-liter bottles for air storage. This choice was made to optimize the car's run time while avoiding excessive weight and drag. The positioning of the tanks within the car is shown in Figure **16** below.

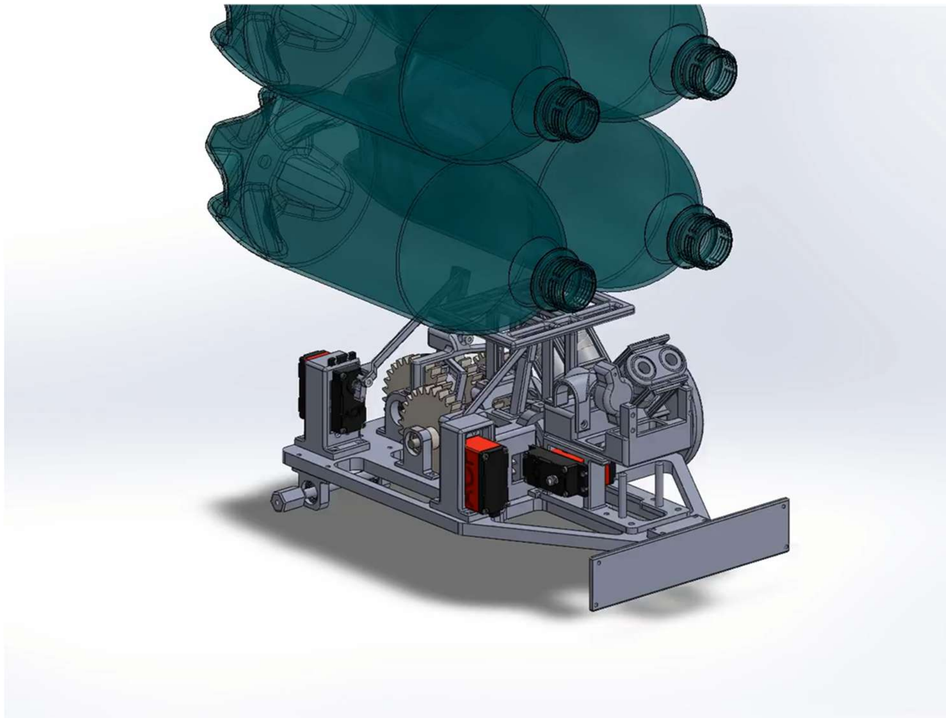
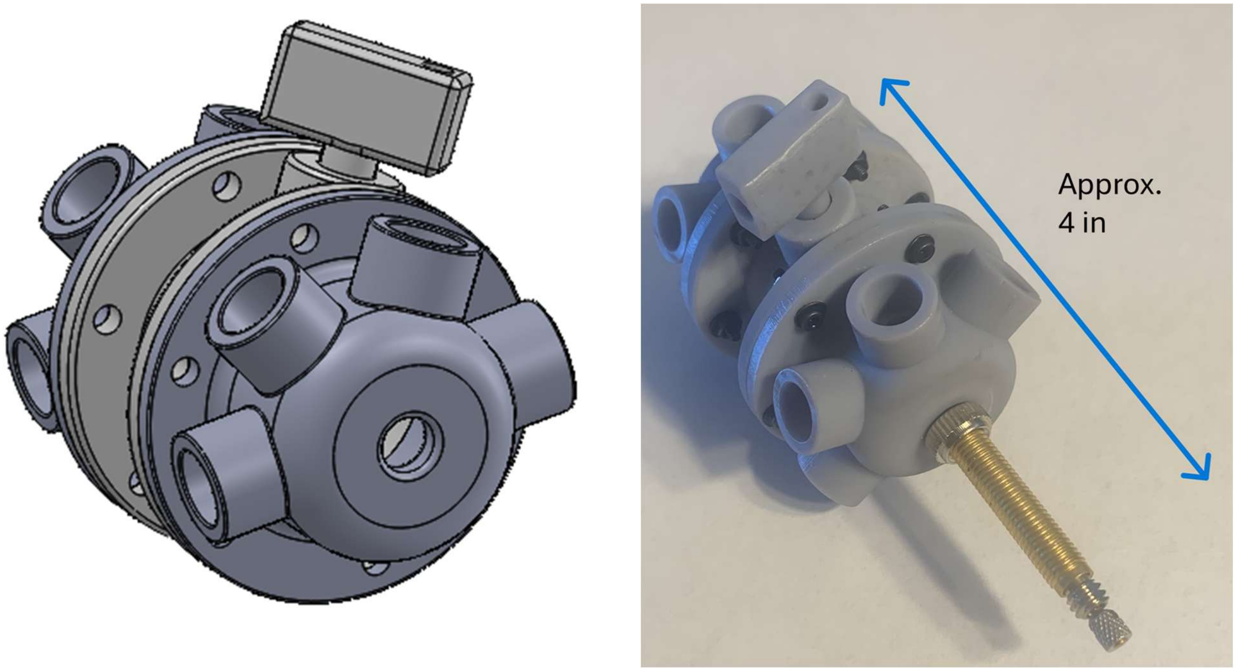


Figure 16: Subsystem Design

4.6 *THROTTLE DESIGN*

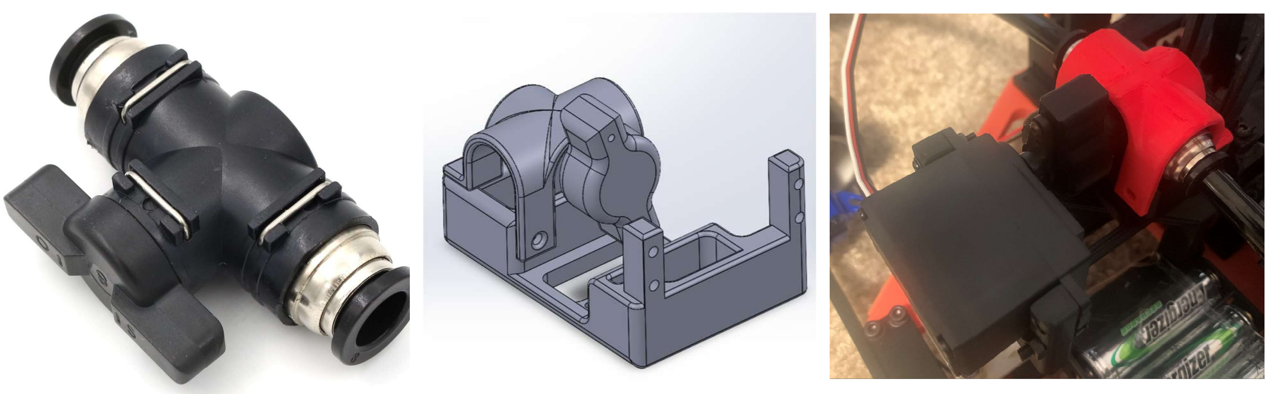
The throttle's purpose is to modulate airflow coming from the tanks to the engine. It is a key aspect of controlling the car as the pressure entering the cylinder must be within the right range for the car to run. The initial idea was to design a custom butterfly valve for the throttle. The CAD and printed version can be seen below in Figure **17**.



A) B)

Figure 17: Throttle Design A) CAD Model and B) Fabricated Piece

The custom design likely could have worked; however, the team was concerned the butterfly portion of the valve would break under such large pressures, sending plastic into the engine. Instead, after extensive research, an off-the-shelf valve was found online that fit the air tubing already being used for the engine, seen in Figure **18** A). An assembly was designed using CAD to attach the valve to a servo to allow control, seen in Figure **18** B) and C).



A) B) C)

Figure 18: A) Commercial throttle B) CAD model for mounting bracket and C) fabricated and installed mounting bracket

4.7 *CLUTCH DESIGN*

While all subsystems are important to the project, the clutch is particularly crucial because it directly affects the user's control of the car. Acting as a link between the engine and transmission, the clutch enables the user to engage and disengage power, making it easier to control the car's movement. Additionally, it functions like a brake, allowing the user to stop the car without shutting off the engine. For this project, one of the clutch's key functions is enabling the car to drift.

Several clutch designs were considered for the car, including the frictional contact axial clutch, cup and cone clutch, and external contracting rim clutch. After careful evaluation, the team chose the cup and cone clutch [7]. This design can withstand high speed and torque, which was a top priority. Additionally, it is easy to manufacture, and since 3D printing is the primary fabrication method for this project, this was a key factor. The simplicity of the cup and cone design also made it a more practical choice for this car.

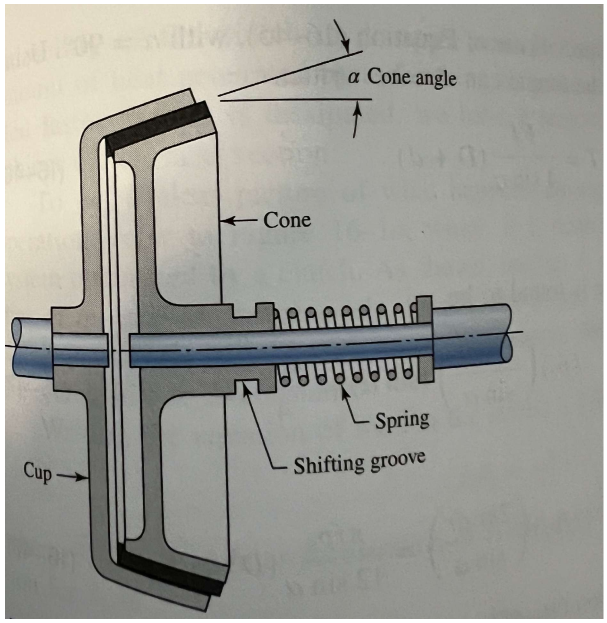


Figure 19: Cup and Cone Clutch Design

The cup and cone design requires friction material to be applied to both the cup and the cone surfaces. This material ensures the cup and cone remain engaged. To disengage the clutch, the cup and cone must be separated. Therefore, it's important to select a friction material that provides enough grip for engagement but doesn't require excessive force to separate. Given the scale of this project, heat and friction were not the primary factors in choosing the friction material. After careful consideration, the team selected an adhesive-backed rubber.

For this car's application, it was essential to have a control arm that could easily engage and disengage the clutch with the engine. The team's solution was to incorporate a snap ring into the cone design. Snap rings prevent axial movement while allowing rotational movement, so by adding one to the cone, the control arm can smoothly move the cone back and forth.

The snap ring effectively serves its purpose, but smooth clutch actuation wasn't solely dependent on it. After several iterations, it became clear that the mechanism connecting the control arm to the cone was causing significant bending, preventing the clutch from engaging and disengaging properly. One of the tested iterations can be seen below in Figure **20**.

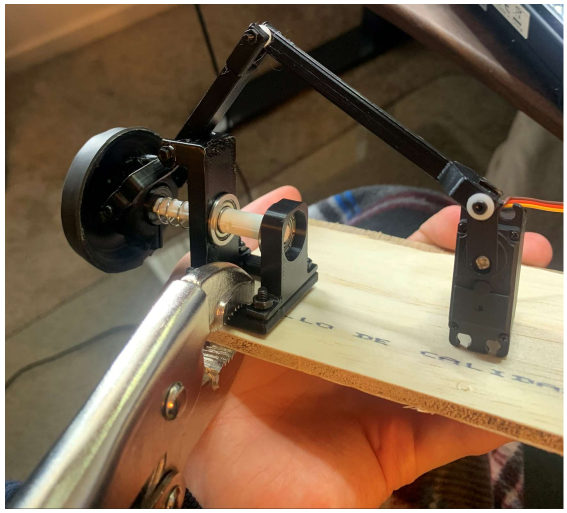
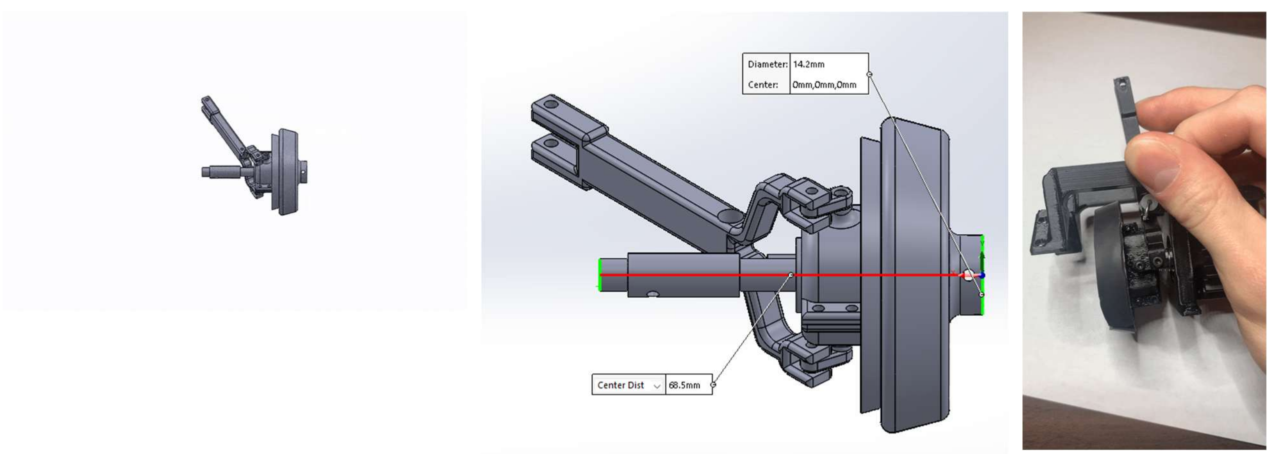


Figure 20: Testing apparatus for initial clutch design

To address this, a six-bar mechanism was designed to align the motion of the control arm with the movement of the cone, eliminating bending and ensuring smooth operation. The final design of the clutch can be seen below in Figure **21** B) with appropriate dimensions.



A) B) C)

Figure 21: Final design of clutch A) exploded B) dimensioned and C) fabricated subsystem

4.8 *TRANSMISSION DESIGN*

The transmission is a key part of the car and the project's goals. Its main job is to transfer power from the engine to the wheels, allowing the vehicle to operate at different speeds. In this project, the transmission lets the user switch between two speeds.

The transmission is based on a simple sliding mesh design. With a few adjustments, it could be changed to a constant mesh, but this would likely add extra friction. One key design feature is the use of two shafts, which allows for two separate gear meshes. This design helps spread the stress across both shafts, rather than having the full gear ratio on just one.

The first step in designing the transmission was to determine the maximum torque the crankshaft could experience. To do this, the team made several assumptions and calculations, which are outlined in Appendix A. Once the theoretical maximum torque was established, the next task was to select appropriately sized gears. This began by reviewing plastic gear manufacturers' catalogs to estimate the required gear width to handle the engine's torque. This information was then used to size the transmission. The shaft sizes were determined based on the gear widths and how they fit with the rest of the car. Much like the shafts, the bearing brackets were designed with the rest of the car in mind. This can be seen in the outermost bracket as seen below in Figure **22**.

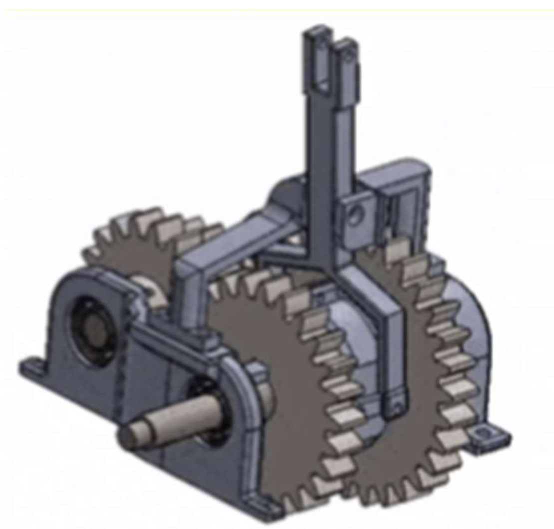


Figure 22: Transmission Design

Since user control is a key aspect of the project, it's crucial that the transmission is easy and efficient to control. Like the clutch design, the team chose to control the transmission with a servo and a control arm connected to one of the shafts. The control arm also includes a snap ring, which restricts axial movement while allowing the shaft to rotate, much like the clutch control. The transmission only has two different gear ratios, so the control arm moves back and forth laterally to switch between different gears and speeds. An exploded view of the transmission as well a final functioning prototype can be seen below in Figure **23** and Figure respectively.

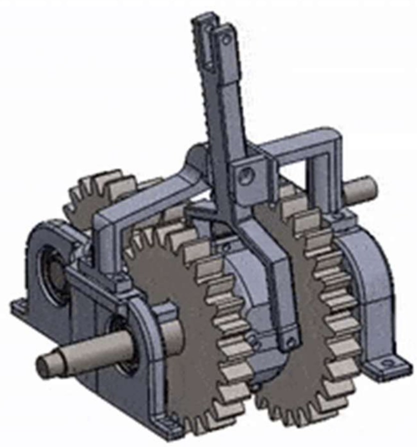


Figure 23: Final tranmission design CAD

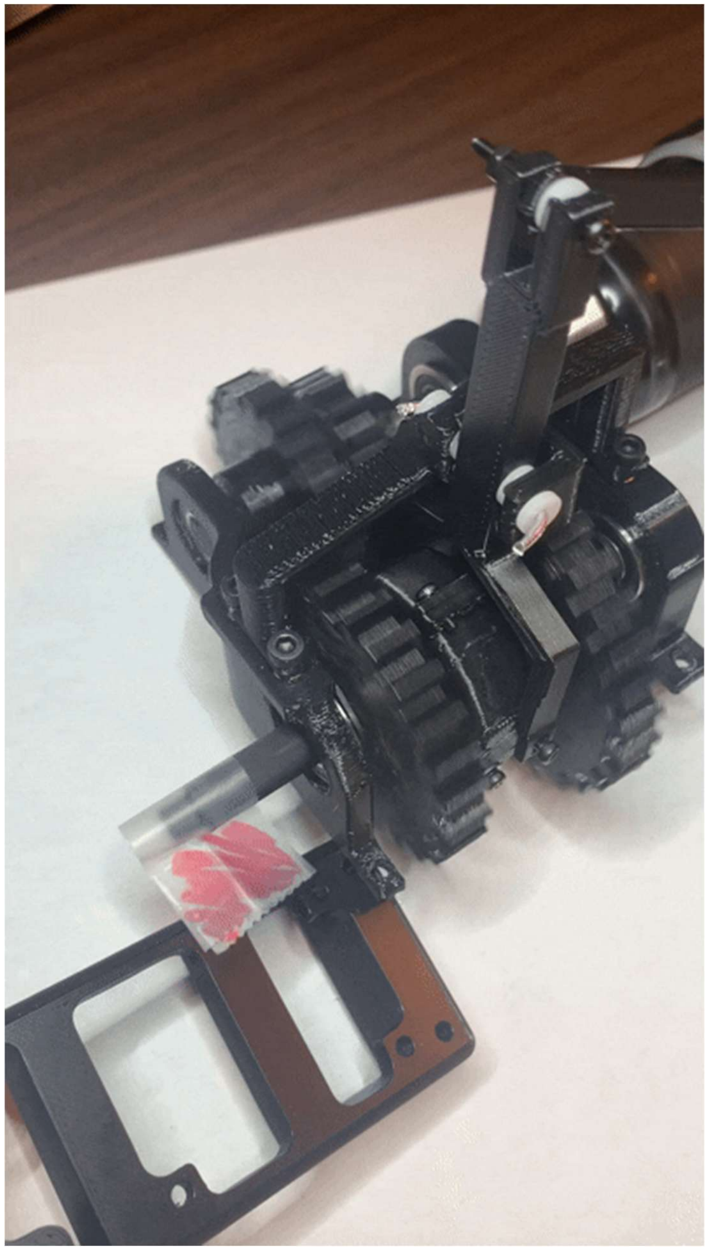


Figure 24: Final transmission design fabricated and spinning

4.9 *CONTROL DESIGN*

The control design refers to how the user interacts with and controls the car. As mentioned earlier, the transmission, clutch, throttle, and steering are all managed by different servos. Three of the servos are identical, except for the throttle servo, which requires more torque to function properly.

The radio receiver used by the team was provided by a faculty member from the USI engineering department. It is the Flysky FS-i6 2.4G RC Transmitter and Receiver, as shown in Figure **25**. The servos are connected to a receiver port on the car, and the radio receiver communicates through this connection. The controls are customizable, allowing the user to choose which joysticks or switches control each subsystem.

Figure 25: Flysky FS-i6 2.4G RC Transmitter used

Figure 26: Example of a servo

5 RESULTS

5.1 *MICROSCOPIC IMAGING OF 3D PRINTS*

To further understand why FDM 3D prints could not be airtight and why SLA prints are, the team ground and polished samples of FDM and SLA prints. Once the samples were prepared, microscope pictures were taken and can be seen below in Figure **27** and Figure **28**. Both pictures are slices of shafts where the view is in the axial direction, looking down the length of the shafts. The FDM picture shows the individual extrusion lines that make up the part. The black areas between the round extrusions are air. Even with this section of the part being as filled in as possible, the part is clearly not air tight. The SLA part, on the other hand, is fully solid and able to hold air at high pressures.

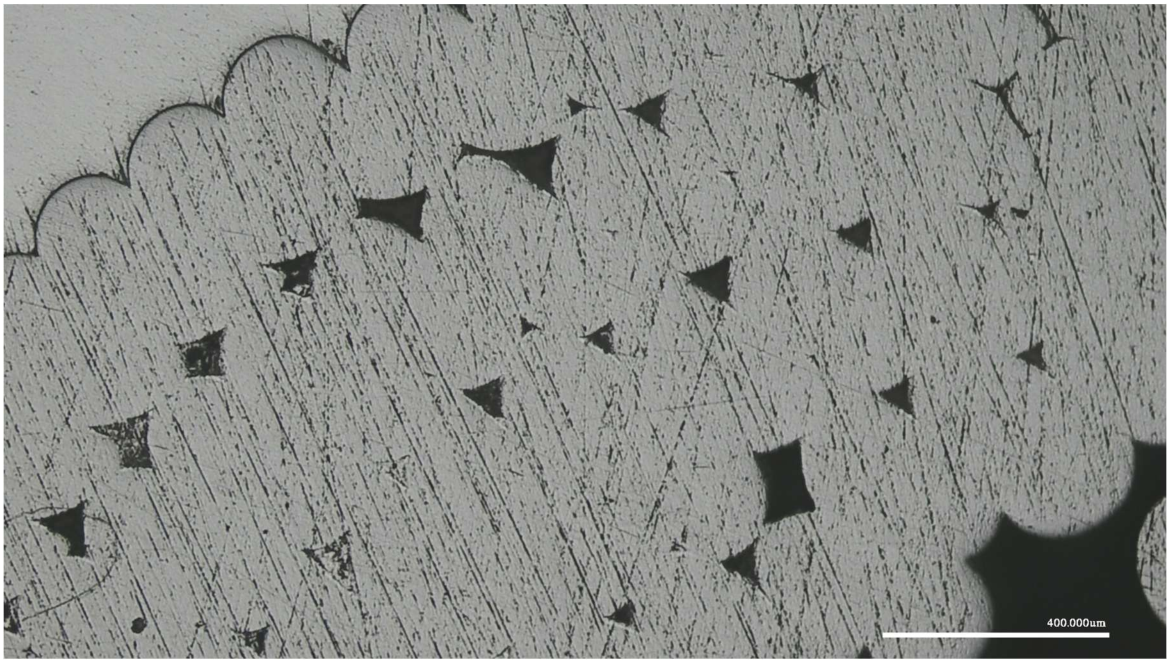


Figure 27: Microscopic picture of FDM 3D print (axial view)

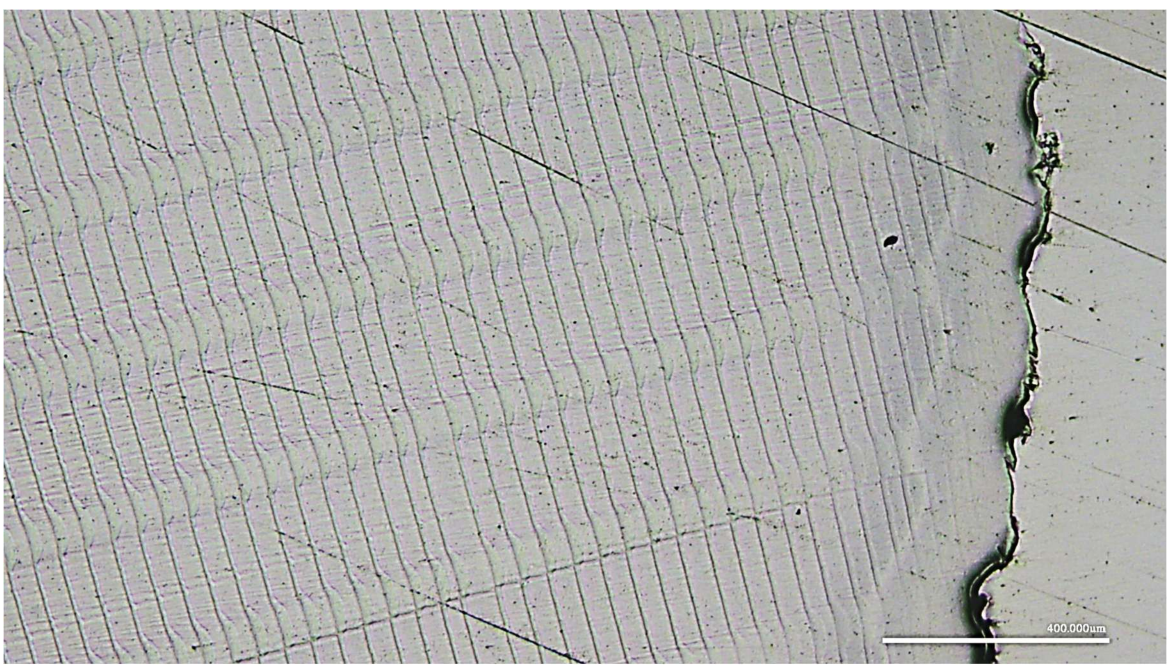


Figure 28: Microscopic picture of SLA 3D print (axial view)

5.2 *FOUR CYLINDER TEST RESULTS*

The four-cylinder engine was constructed and tested to verify its effectiveness and tune parameters such as the seal design, pin length, and number of cylinders used. All testing was done qualitatively where the team listened to how the engine was running both in smoothness and speed. Two cylinders were tested at a time with a picture of the testing conditions shown below in Figure **29**. The team noticed that the vertical position of the pistons at the top of the stroke was slowly migrating downward, leading to the engine not being able to run. On closer inspection, the crankshaft and connecting rods deformed at the bearing surface as can be seen below in Figure **30**.

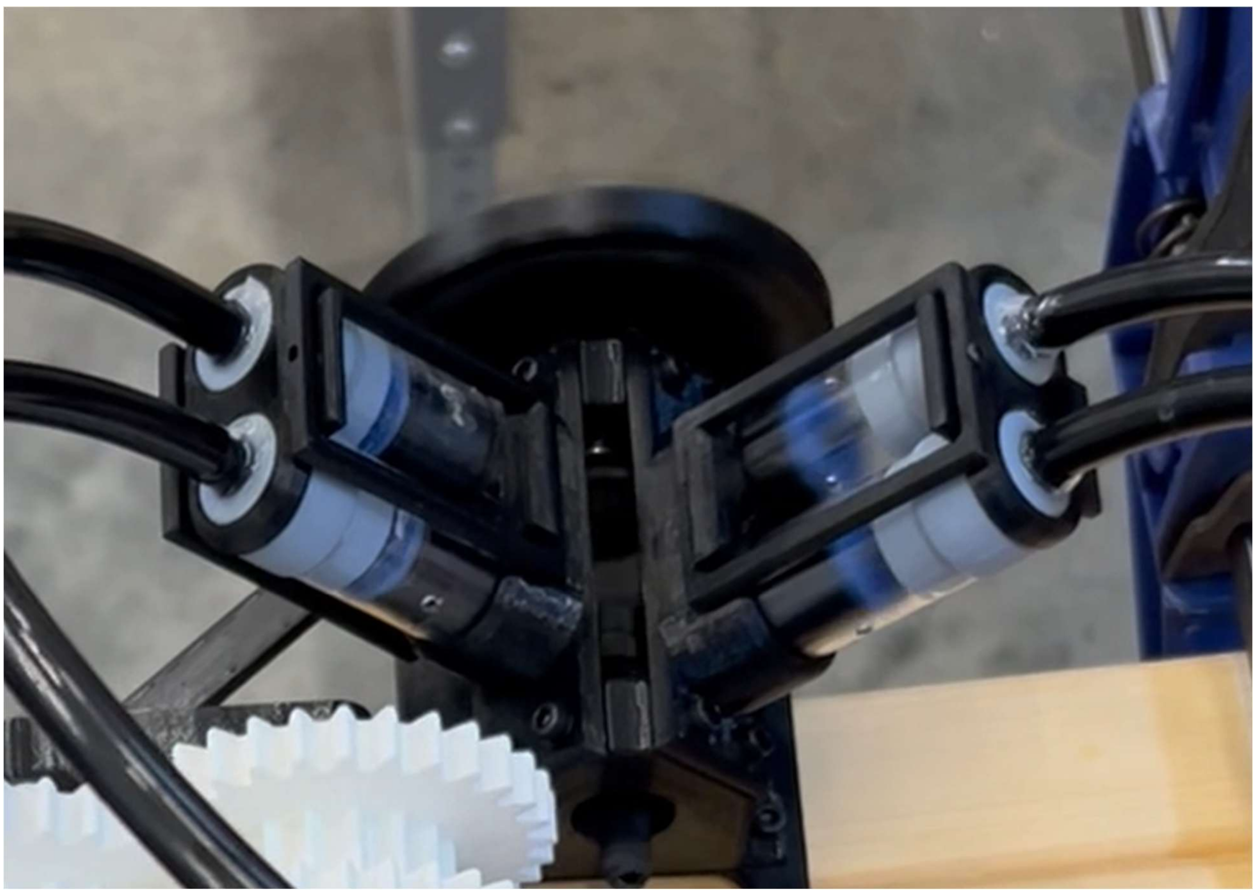


Figure 29: Two cylinders being tested

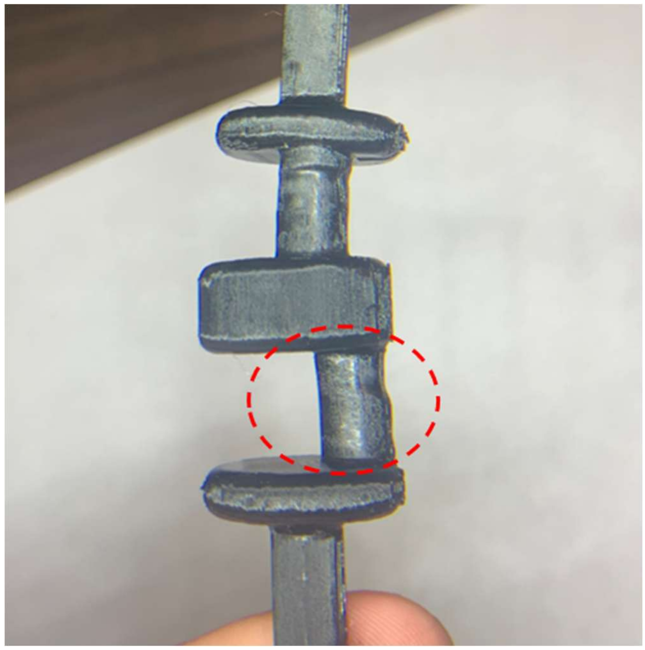


Figure 30: Deformed crankshaft after testing

After some initial testing proved the strength of the crankshaft was inadequate, the team started pursuing other options. One easy fix and the decision that the group ultimately went with was to infill the crankshaft completely. The previous iteration had an infill of only 15%, so the team felt that improving that to 100% would give the strength that was desired.

Continued testing with the benchtop model and setup that is pictured above in Figure **29**. Testing revealed that the four cylinders were too powerful and ran through the air supply too quickly. Two-cylinder testing showed a similar result. With the engine optimized for lower pressures, the engine operates very inefficiently at higher pressures. This coupled with the multiple cylinders saps the air supply far too fast to allow the car to reach the relevant engine parameters such as run time. Due to the results from this initial engine testing, the group decided that it was necessary to shrink the engine to operate with just a single cylinder.

5.3 *SUBSYSTEM INTEGRATION*

Once the team confirmed the engine's performance met expectations, integration of the remaining subsystems onto the vehicle commenced. To ensure reliable operation, each subsystem was individually tested prior to installation. After validation, the focus shifted to achieving full vehicle functionality. A key challenge in this phase was the interdependence of the subsystems, particularly regarding spatial constraints. This necessitated several redesigns—not only of individual subsystems, but primarily of the car's frame. The finalized design is shown in Figure **31** below.

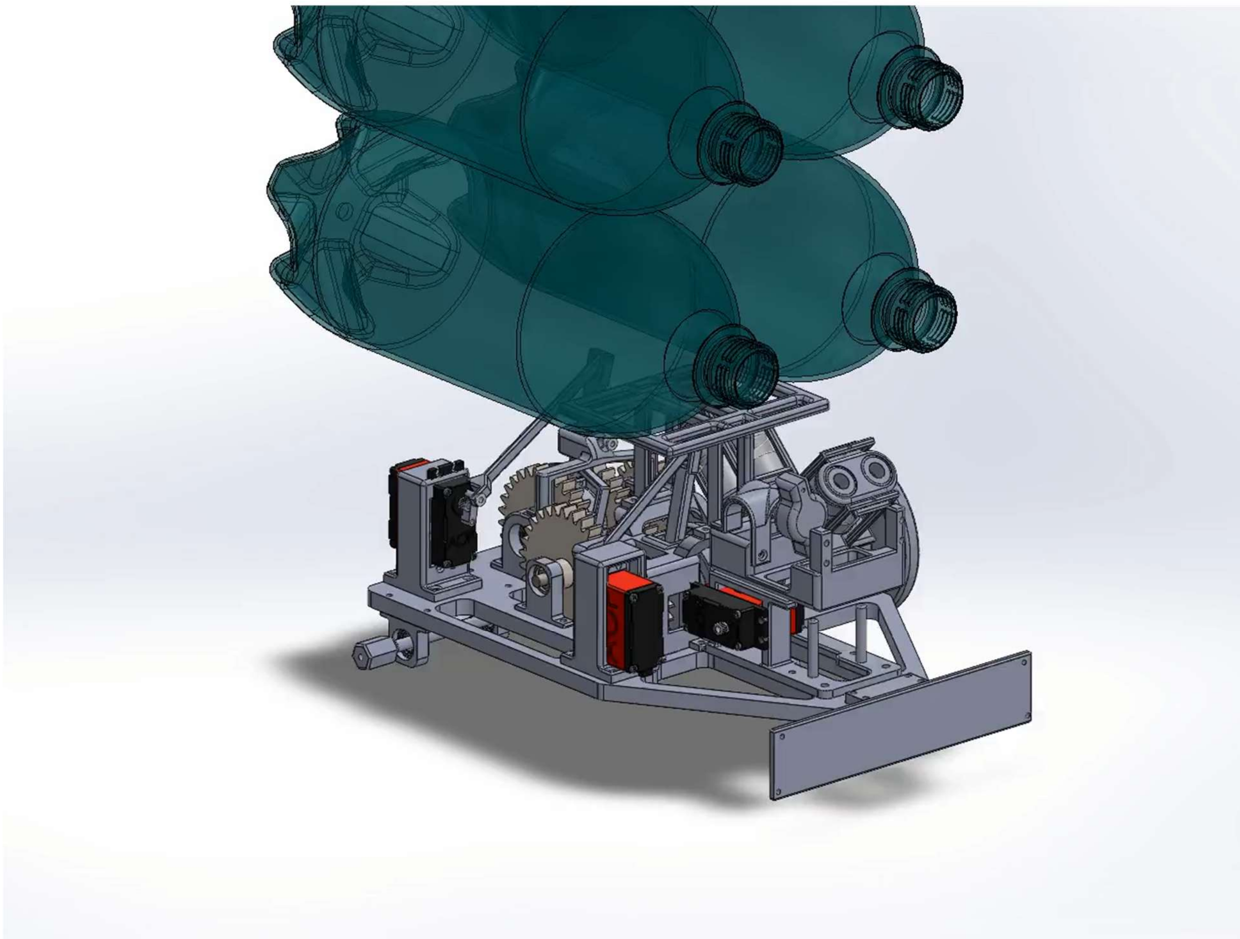


Figure 31: 3D model of full assembly

5.4 *TESTING*

5.4.1 Initial Testing

With all subsystems successfully integrated, the team began full vehicle testing. A photo of the fully assembled car is shown in Figure **32** below. This testing phase enabled a comprehensive evaluation of overall vehicle performance, as well as an assessment of how each subsystem contributed to and interacted within the complete system. The results provided valuable insights into the car's functionality.

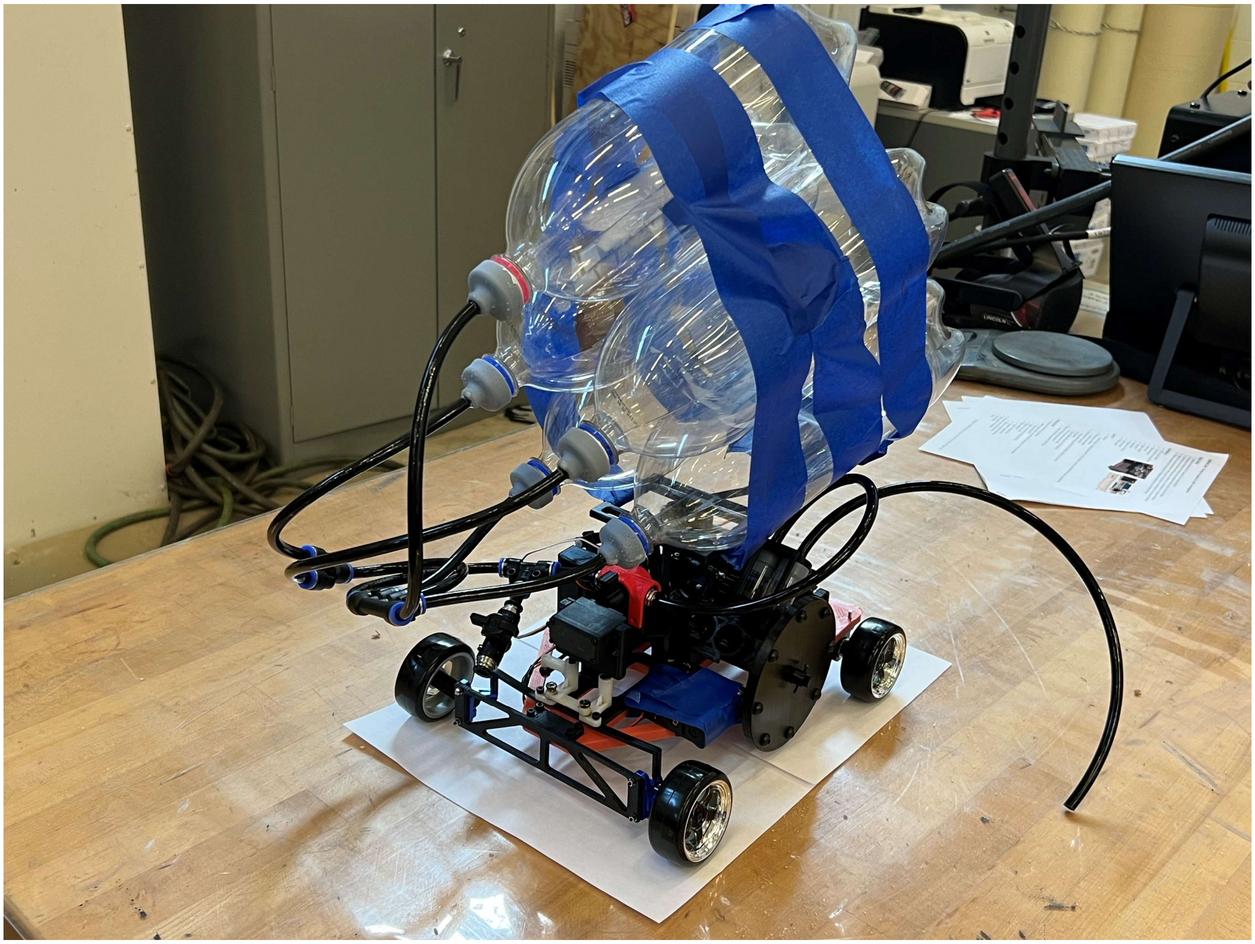


Figure 32: Picture of assembled car

An unexpected issue that emerged during initial testing was the direction in which the car operated—it consistently drove in reverse. Despite multiple attempts to correct the behavior, the vehicle continued to move in the wrong direction. Further testing revealed that operating the car with a different cylinder resolved the issue; however, the underlying cause of this outcome remains unclear. While additional investigation could help determine the reason, the team was unable to prioritize this analysis within the scope of the current project.

During initial testing, several subsystems began experiencing issues, including battery failures, which made it impossible to continue operating the car as intended. As a result, the team conducted additional benchtop tests. For these tests, the rear wheels were lifted off the ground to allow observation without full vehicle movement. The primary goal was to estimate the car's potential runtime. It was found that the car could run for approximately two minutes under these conditions. However, it is important to note that this estimate was based on unloaded operation; actual runtime would likely be shorter when driving on the ground. An alternative view of the final car is shown below in Figure 32.

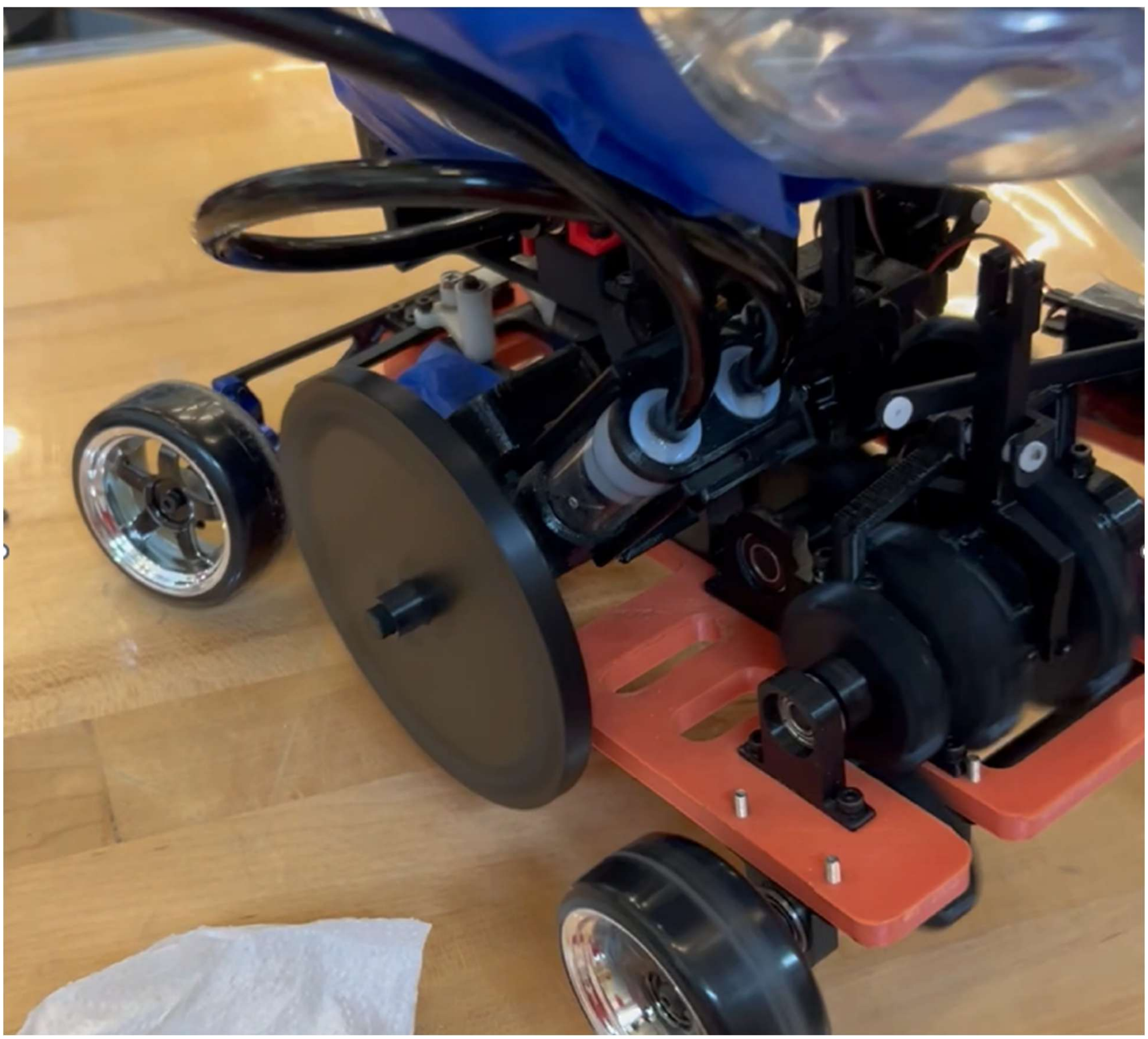


Figure 33: Assembled car benchtop testing

Once testing resumed, another unexpected issue had a significant impact on both the test results and the overall project. While filling the car's air tanks, the team observed air leaking from the attached tanks—a known occurrence, as the custom-designed bottle caps often required tightening before and after refilling to maintain a proper seal. However, during one such adjustment, a cap failed catastrophically, effectively exploding in a team member's hand. This failure was particularly surprising, as prior testing conducted in a previous course indicated that the material used for containing compressed air could withstand pressures up to 100 psi. In this case, the system was operating within the 60–70 psi range. The caps were reinforced with plumber's tape, and it was concluded that additional tape was likely needed. It is also suspected that repeated tightening and loosening may have contributed to the part's failure.

5.4.2 Final Testing

After completing initial testing and implementing the necessary modifications, the team proceeded with final testing of the car. As previously noted, the two primary performance parameters to be measured were runtime and top speed. To calculate the speed of the car, two items were placed 20 feet apart and the team measured the time it took the car to cover this distance. The testing setup is shown below in Figure **34**.

Figure 34: Car testing on the ground with two markers set 20 ft apart

Final testing revealed that the run time for the car was right at 60 seconds. This is largely due to what was mentioned earlier in that one of the bottle caps failed and the car had to operate with only four two liter bottles attached to the car. Using the setup shown above in Figure **34**, and the car completing several circuits, the run time was calculated to be 5 mph.

During earlier testing, it was observed that the crankshaft lacked the strength to withstand the torque generated by the engine. To address this issue, the crankshaft was fully infilled using 3D-printed material. However, despite this modification and the use of only a single cylinder during final testing, the problem reoccurred. The material simply lacked the necessary strength for this application. This weakness likely contributed significantly to the car's low top speed of 5 mph. The deformation and flexibility of the crankshaft likely impaired engine performance and, consequently, the overall speed of the vehicle. While the team believes that using a more robust material and a solid crankshaft design would improve performance, it is unclear to what extent these changes would help or whether they would be sufficient to meet the target speed of 10 mph.

6 CONCLUSIONS

6.1 *PROJECT GOALS*

To conclude the project, it is necessary to examine the goals of the project and how well this project was able/unable to accomplish them. First of all, the goal of having comparable speed to that of battery powered RC cars was not met. The compressed air powered car was only able to reach a top speed of 5 mph, falling far short of the goal of 10-20 mph. The second goal of reaching a 90 second run time was also unsuccessful as the group was only able to achieve a final run time of 60 seconds. Despite being qualitative, the team feels as though the goal of designing a car that is more engaging to control than those currently available on the market was met. The team felt as though the user's ability to change the speed, control the throttle, and steering, as well as being able to engage and disengage the engine deemed this goal a success. Finally, the team also succeeded in showing the functionality of the compressed air power train and introducing an alternative to the RC battery powered car.

✗ Have comparable speed (~10-20 mph) to battery powered cars
✗ Run for at least 90 seconds between fill ups
✓ Be more engaging to control than battery powered RC cars
✓ Show the functionality of a compressed air power train

Figure 35: Project goals reached/failed

6.2 *Future Work*

There is still significant potential for improvement in this project. One of the most critical areas is the crankshaft material. Although aluminum was initially considered, the complex geometry of the crankshaft made fabrication extremely difficult, if not impractical. Future efforts should focus on identifying a material that can withstand the high torque produced by the engine while remaining easy to machine and cost-effective. A structurally sound crankshaft would enable the engine to operate at peak efficiency and improve key performance metrics measured in this project.

Another area for future development is the car's compressed air storage system. While the SLA-printed bottle caps functioned to some extent, they were prone to air leakage, and one ultimately failed during testing. Increasing the volume or reliability of compressed air storage could improve the vehicle's runtime. Efforts should be made to develop a more secure, lightweight, and leak-resistant storage solution. Additionally, refining the configuration of the air tanks—currently composed of several bottles taped together—could enhance both the safety and overall design of the system.

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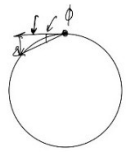
APPENDIX A: MECHANICAL DRAWINGS AND CALCULATIONS

$T_1 = r_2 \cdot F_{ZA}$

$T_1 = T_2$

$T_2 = r_3 \cdot F_{ZC}$

$\tan\phi = \frac{F_{YC}}{F_{ZC}}$



$\tan\phi = \frac{F_{YA}}{F_{ZA}}$

$T_3 = T_1 \cdot n_{2nd}$

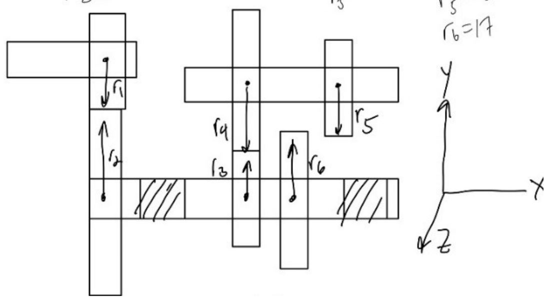
$r_5 + 1.25 r_5 = 30$

$r_5 + r_6 = 30 \quad r_5 = 13.\overline{3}$

$\frac{r_6}{r_5} = 1.25$

$r_5 = 13$

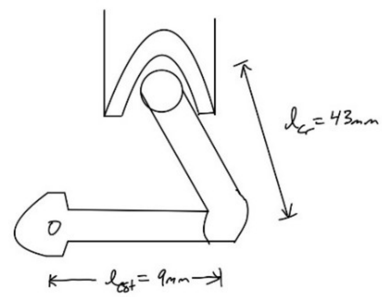
$r_6 = 17$



$d = 17\ mm \quad P_{max} = 100\ psi$ or $689.476\ kPa$

$A_p = \pi r^2 = \pi\left(\frac{0.017}{2}\right)^2 = 2.2698 \times 10^{-4}\ m^2$

$l_{est} = 9mm$



$MA = \frac{T}{F} = \frac{\dot{r}_1}{\omega_2}$

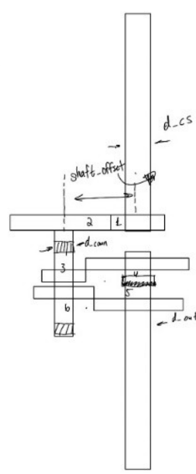
$P = \frac{F}{A} \Rightarrow P_{max} A_p = F_{max} = (689.476\ kPa)(2.2698 \times 10^{-4}\ m^2)$

$F_{max} = 156.5\ N$

Assuming an efficiency of about 80%, F_{max} becomes

$F_{max,real} = 0.8 F_{max}$

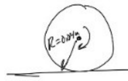
$\boxed{F_{max,real} = 125.2\ N}$



Engine @ 3000 RPM

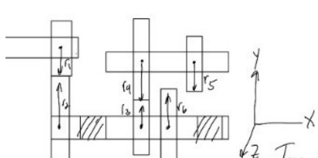
$\frac{1}{1.5^2} \cdot 3{,}000 = 1{,}000$ R[illegible]

assuming 80 mm wheel diam



$V = 1000 \frac{rev}{min} \cdot \frac{2\pi\ rad}{1\ rev} \cdot \frac{1\ min}{60s} \cdot 0.04$

$= 4.2\ m/s$



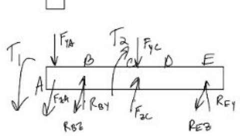
n_{clutch} = Gear ratio b/t clutch and counter shaft

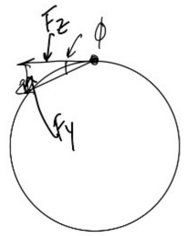
T_{engine} = torque from crank

n_{1st} = 1st gear ratio

n_{2nd} = 2nd gear ratio

$T_1 = T_{eng} \cdot n_{clutch}$





$T_3 = T_1 \cdot n_{2nd}$

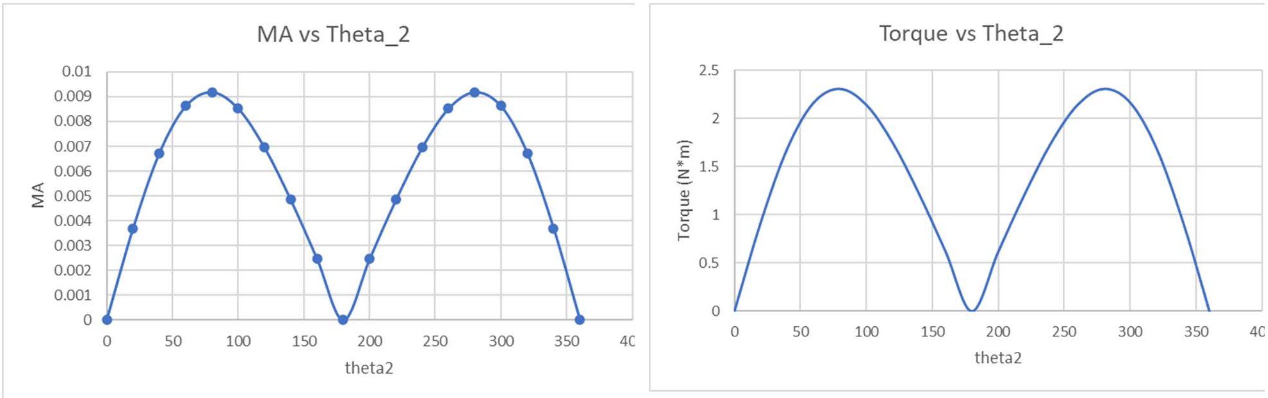
$F_Z \cdot r_5 = T_3$

$F_Z = \frac{T_3}{r_5}$

$F_Y = F_Z \tan\phi$

$\tan\phi = \frac{F_Y}{F_Z}$

Figure 36: Handwork for transmission design



A) B)

Figure 37: A) Mechanical advantage and torque with B) torque at different angles

Appendix B: Applicable Codes and Standards

STANDARDS AND CODES

ASME BPVC.VIII.1-2023

  - 2023 ASME Boiler and Pressure Vessel Code, Section VIII, Division 1: Rules for Construction of Pressure Vessels
  - https://www.standardscollection.com/asme/asme-bpvc-viii-1-2023/?gad_source=1&gclid=CjwKCAjwpbi4BhByEiwAMC8JnR1V1R1dzpR4i-tO2Zzmixq4Rv0A5U--jXzdQ-jckaGi8QFiOQNzNxoC7Z4QAvD_BwE
  - This code collection would be beneficial to ensure that there is no failure of the pressurized tanks, or pressurized headers on the car. The car is expected to have pressures up to 100 psi, which could send significant shrapnel or cause eye or hearing damage.
- ISO 11055:1996
  - Description: “Flywheels for reciprocating internal combustion engines — Installation dimensions for clutches”
  - These standards would aid in the design of the clutch and flywheel assembly and would ensure proper clutch engagement while minimizing the number and size of clutch springs needed. This standard could also help when picking the material and overall design for the friction plate, ensuring clutch engagement and longevity.

APPENDIX C: FMEA

FMEA Table for Clutch/Transmission System												
			Current Situation					Improved Situation				
Failure Mode	Failure Effect	Failure Cause	S	L	D	RPN	Action	S	L	D	RPN
Yielding of Transmission shaft	Total transmission failure	Too much torque on the transmission shaft	10	2	8	160	Design with a large safety factor	10	1	8	80
Clutch Undersprung	Clutch slipping	too weak of spring force	6	6	2	72	Allow swappable springs				
Clutch Oversprung	clutch not fully disengaging	Too strong of spring force relative to the servo	8	6	2	96	Allow swappable springs				
Failure of Clutch Friction Material	Total transmission failure	Excess wear	10	7	5	350	Testing to see how much load per unit area the material can support	10	2	5	100
Shearing of transmission gear teeth	possible seizing	Too large a load on the gear	9	3	8	216	Design with a large safety factor	9	2	6	108
Failure of gears due to shaft displacement	friction increase and efficiency loss/gear teeth skipping	Shaft not stiff enough	8	4	2	64	Increase Shaft diameter or decrease shaft length				
Failure of shaft due to bearing binding	friction increase and possible seize	Shaft not stiff enough	6	10	5	300	Increase Shaft diameter or decrease shaft length	6	4	3	72
Failure of dogs/teeth from yielding/fracture	eventual transmission failure	failure to disengage clutch during shift	7	8	3	168	safety factor and ensure complete clutch disengagement	7	5	2	70
Servo not able to supply enough torque	not able to change gear ratio	Too much load is on the gears during shift	8	6	4	192	with more torque than needed, lubricate the shifter	8	2	4	64

Figure 38: Clutch/Transmission FEA