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Chainless Bike Drive

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CHAINLESS BIKE DRIVE

By

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Abstract

The focus of this project was to design a drive system that could replace the conventional chain drive system, improving on both the efficiency and reliability, in addition to being low cost and lightweight. This report will provide background into why this group chose this as the subject of their project, as well as challenges faced throughout the design process. The design developed was a drive shaft driven by a system of pinions and gears, with a freewheel mechanism that allowed the system to coast when not pedaling. Due to cost and time constraints, only a prototype was created, with additional research into materials selection and testing of our design. Despite this, there is still an enormous amount of potential to explore from this project as to alternatives to the traditional chain and sprocket drive shaft. We would like to thank our advisor David Peters for guiding us through this project, as well as Dr. Greg Morscher for assisting us with the materials selection software.

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1. Introduction

1.1 Background

Since its invention, the bicycle has seen many innovations and design changes. However, one fundamental piece has remained relatively unchanged for nearly one and a half centuries: the chain drive.

The first rear-wheel-chain-driven bicycle was invented in 1885 by J.K. Starley (1). He called his invention the “Rover”, but it soon became unofficially known as the “safety bicycle.” Until this new design, all bicycles were composed of a very large front wheel, with pedals attached to the axle for drive, and a much smaller rear wheel. These bicycles were not a viable means of transportation, being utilized only by enthusiasts. The design made these bicycles difficult to mount and operate, and put the rider at great risk of injury in the case of a collision due to his/her height off the ground. Throughout the years, the chain-drive-mechanism has been improved and modernized, but is still the same basic design. There are many shortcomings with this design: potential for the chain to break, need for cleaning and relubrication of the chain and sprockets due to their exposure to road debris, and the problem of the chain slipping off one of the sprockets. The latter is the issue that cyclists encounter most often when using a multi-speed bicycle. While this is typically an easy fix, it is a messy job because of the grease used to lubricate the parts and the dirt that inevitably sticks to it as the bicycle is ridden. As the parts wear, the problem can become even more common, especially when the rider is changing gear ratios.

1.2 Goals and Objectives

The goal of this project was to improve the drive mechanism and eliminate the issues commonly associated with a chain drive. The desire was to develop a more reliable and efficient design that could become the new standard just as J.K. Starley’s design made the “big wheel” bicycle obsolete.

In order to achieve this goal, we defined metrics for success that would be pursued throughout the project to ensure we stayed on track and used at the end to assess the final outcome. These metrics included the following:

1. A fully 3d printed model
2. The design functions as a drive shaft for a bike
3. The bike gears do not slip in tests from 60rpm-90rpm in increments of 10rpm for 10 minutes at each speed
4. The model can sustain a 12mph speed

1.3 Patent Research

Several chainless-bike patents were studied and evaluated in order to gain insight into different types of existing designs and how each design's objectives aligned or did not align with ours. Links to the studied patents are listed below for reference:

https://patentimages.storage.googleapis.com/1d/89/33/ec1981e5087936/EP1147979A1.pdf

https://patentimages.storage.googleapis.com/0a/b1/7f/c2d995553c9383/US20110062678A1.pdf

https://patentimages.storage.googleapis.com/06/14/b4/63368ea515b562/US4447068.pdf

https://patentimages.storage.googleapis.com/0b/fa/80/78aa6085bb771e/US20100295264A1.pdf

https://patentimages.storage.googleapis.com/44/83/35/dd32b478beaa70/US6394477.pdf

https://patentimages.storage.googleapis.com/0d/1a/ff/07e5f5ccbf1d58/US6199884.pdf

The following chapters will discuss the design process that the group went through, from initial concept to the final revision that was used to create the prototype, the verification of the design, costs involved, and the conclusions drawn.

2. Design

2.1 Conceptual Design

Many of the initial design concepts aligned with our original goals; to have a multi speed drive shaft, where it would be possible to switch gears. Our goals were to design something practical, efficient, and low maintenance. Ultimately, due to time and cost constraints, we were not able to use any of our initial conceptual designs. However, some will be included for the sake of documentation.

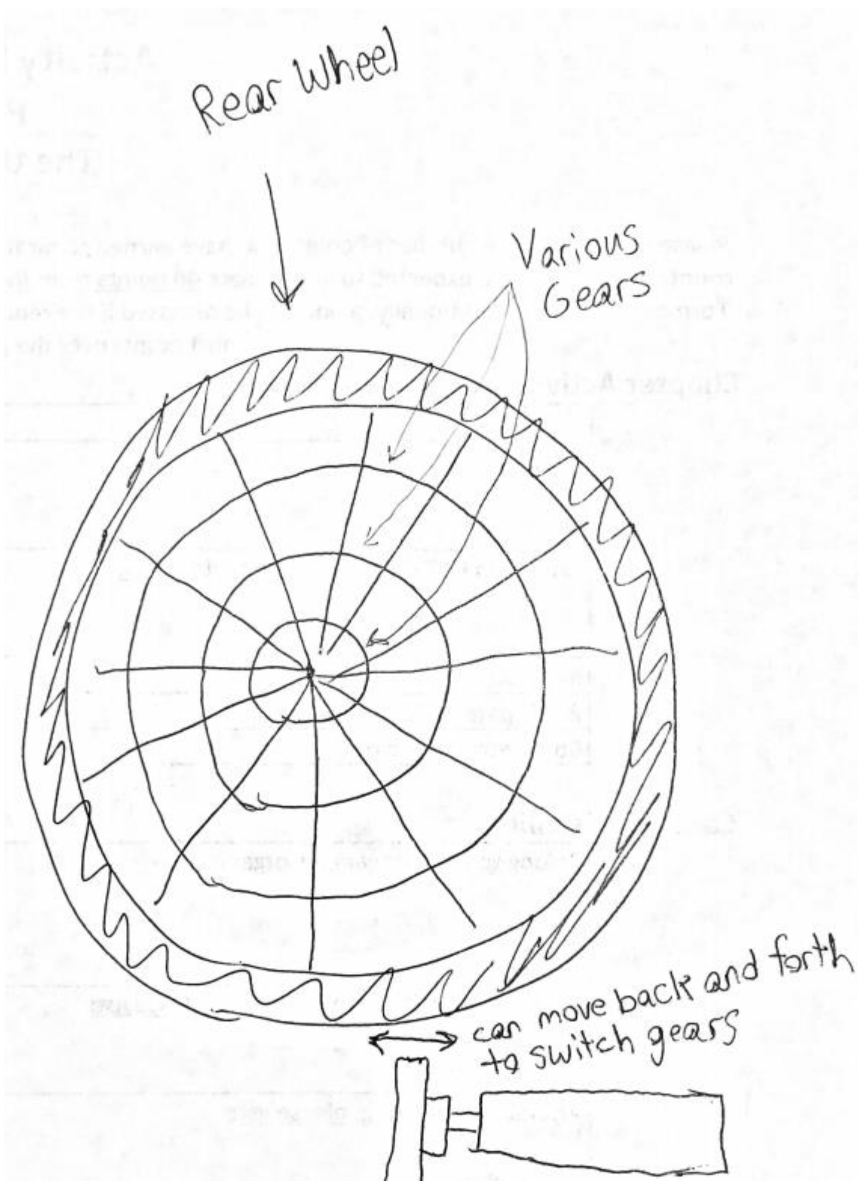


Figure 2.1. A conceptual sketch of a multi speed drive shaft

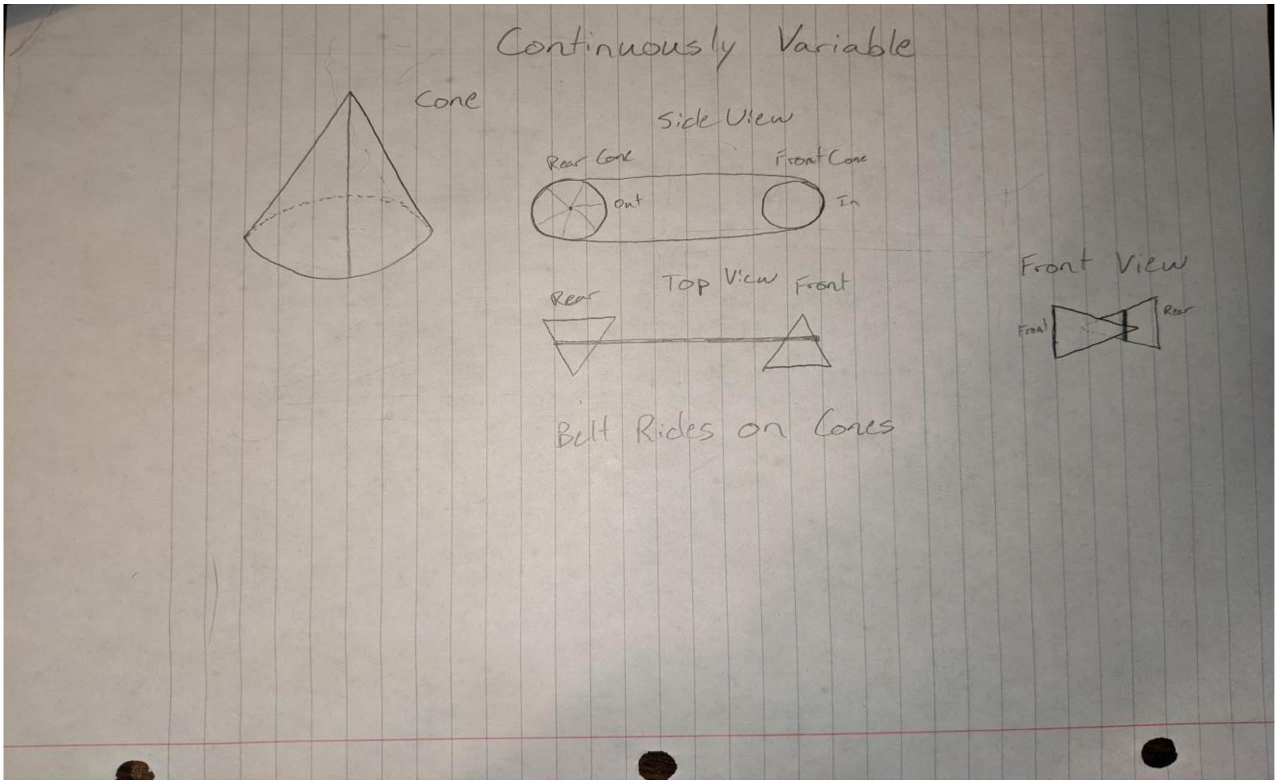


Figure 2.2. A conceptual sketch of a multi speed drive shaft based on a continuous variable transmission

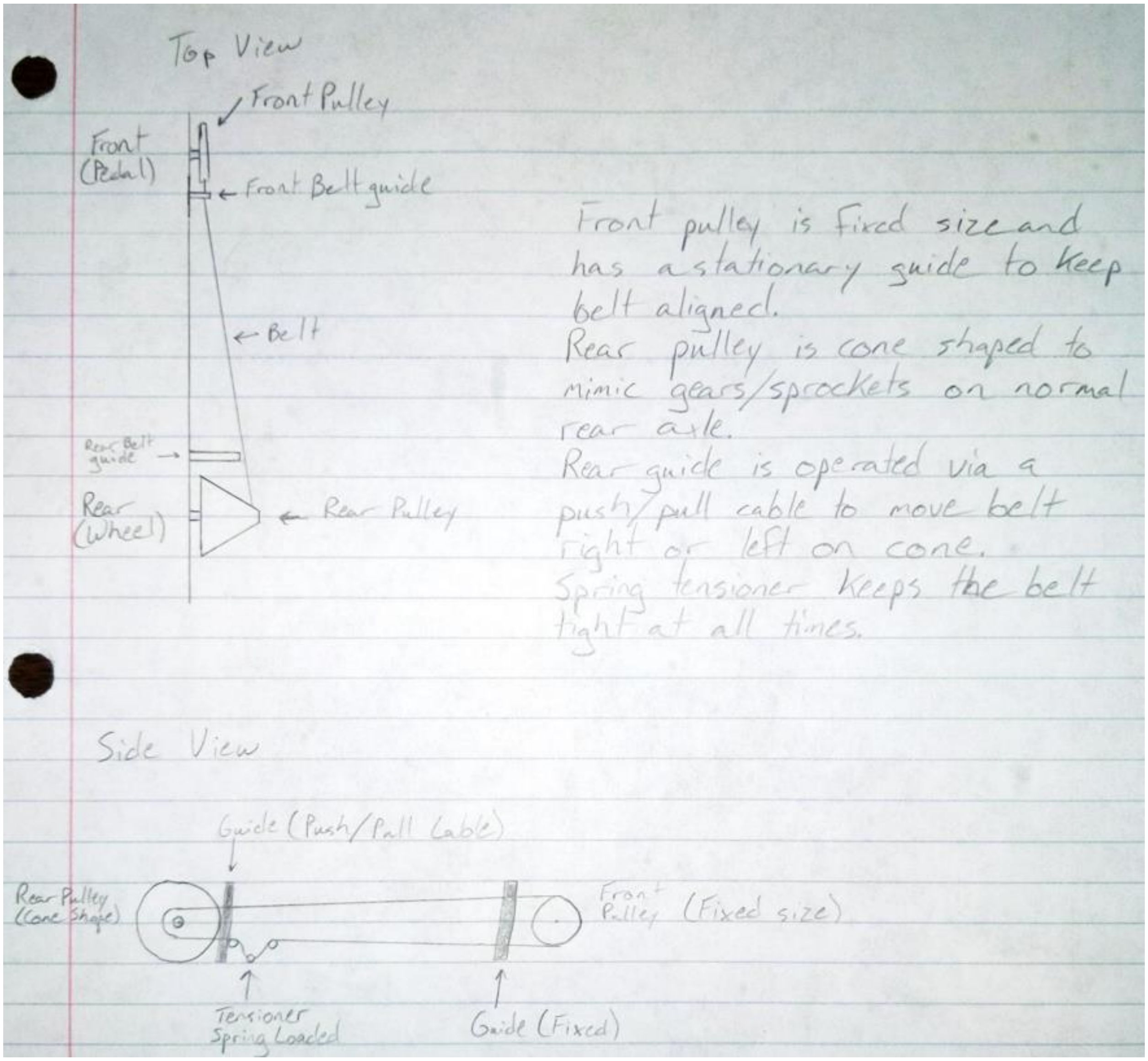


Figure 2.3. A multi speed pulley and cable system

With these concepts in place, an objective and weighted decision matrix were constructed to further narrow down which concept we should choose moving forward.

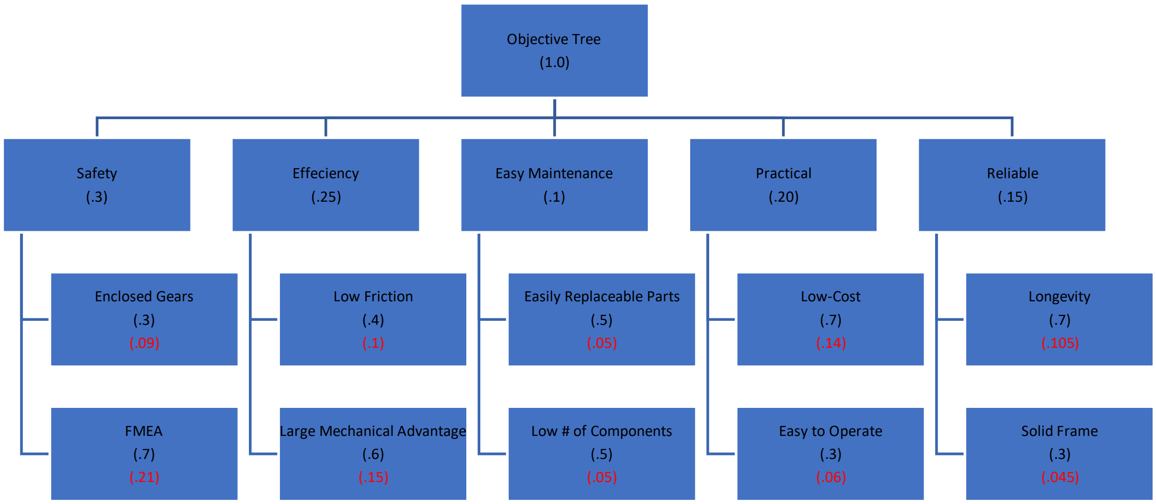


Figure 2.4. Objective Tree for our Chainless Bike Drive

Weighted Descision Matrix											
	Ideas:	Concentric circle gear and pinion		3 Gear Internal Drive Shaft		Belt and Pulley Drive		1 to 1 Miter Gear Drive		Internal Gear Hub 3 Speed Drive	
Criteria	Criteria Weighting	Value	Weight x Value	Value	Weight x Value	Value	Weight x Value	Value	Weight x Value	Value	Weight x Value
Enclosed Gears	0.09	1	0.09	3	0.27	3	0.27	5	0.45	5	0.45
FMEA	0.21	3	0.63	4	0.84	4	0.84	5	1.05	4	0.84
Low Friction	0.1	4	0.4	3	0.3	2	0.2	1	0.1	2	0.2
Large Mechanical Advantage	0.15	5	0.75	5	0.75	3	0.45	2	0.3	5	0.75
Easily Replaceable Parts	0.05	3	0.15	4	0.2	4	0.2	3	0.15	2	0.1
Low # of Components	0.05	4	0.2	2	0.1	3	0.15	5	0.25	1	0.05
Low-Cost	0.14	1	0.14	3	0.42	3	0.42	4	0.56	4	0.56
Easy to Operate	0.06	4	0.24	5	0.3	4	0.24	4	0.24	5	0.3
Longevity	0.105	3	0.315	5	0.525	3	0.315	3	0.315	4	0.42
Solid Frame	0.045	3	0.135	4	0.18	4	0.18	3	0.135	4	0.18
		Total Weighted Value	3.05	Total Weighted Value	3.885	Total Weighted Value	3.265	Total Weighted Value	3.55	Total Weighted Value	3.85

Figure 2.5. Weighted Decision Matrix for choosing a conceptual design

From the decision matrix, it is evident that we would choose either the 3 Gear Internal Drive Shaft or the Internal Gear Hub 3 Speed Drive. Moving forward with the 3 Gear Internal Drive Shaft, we needed to make simplifications to move it to a single speed system.

2.2 Embodiment Design

For our gear selection, we decided to use a pinion and gear system for both the front and rear axles, connected by the drive shaft. We selected both the pinion bevel gear and the straight bevel gear from the Solidworks Toolbox. Constraints for the design of the gears will be mentioned later in this section.

Another important aspect of the design was the freewheel mechanism. We wanted to create something that would spin with the gear while the pedals are engaged, and something that would allow the system to move for a short period of time while the pedals are not engaged, such as when coasting. To create this mechanism, we decided to create a mechanism within the rear gear, with a single spring loaded tooth attached to it. That way, the mechanism does not freely spin forever, and the spring will slow down the system over time. An example of this system is depicted in Figure 2.6.

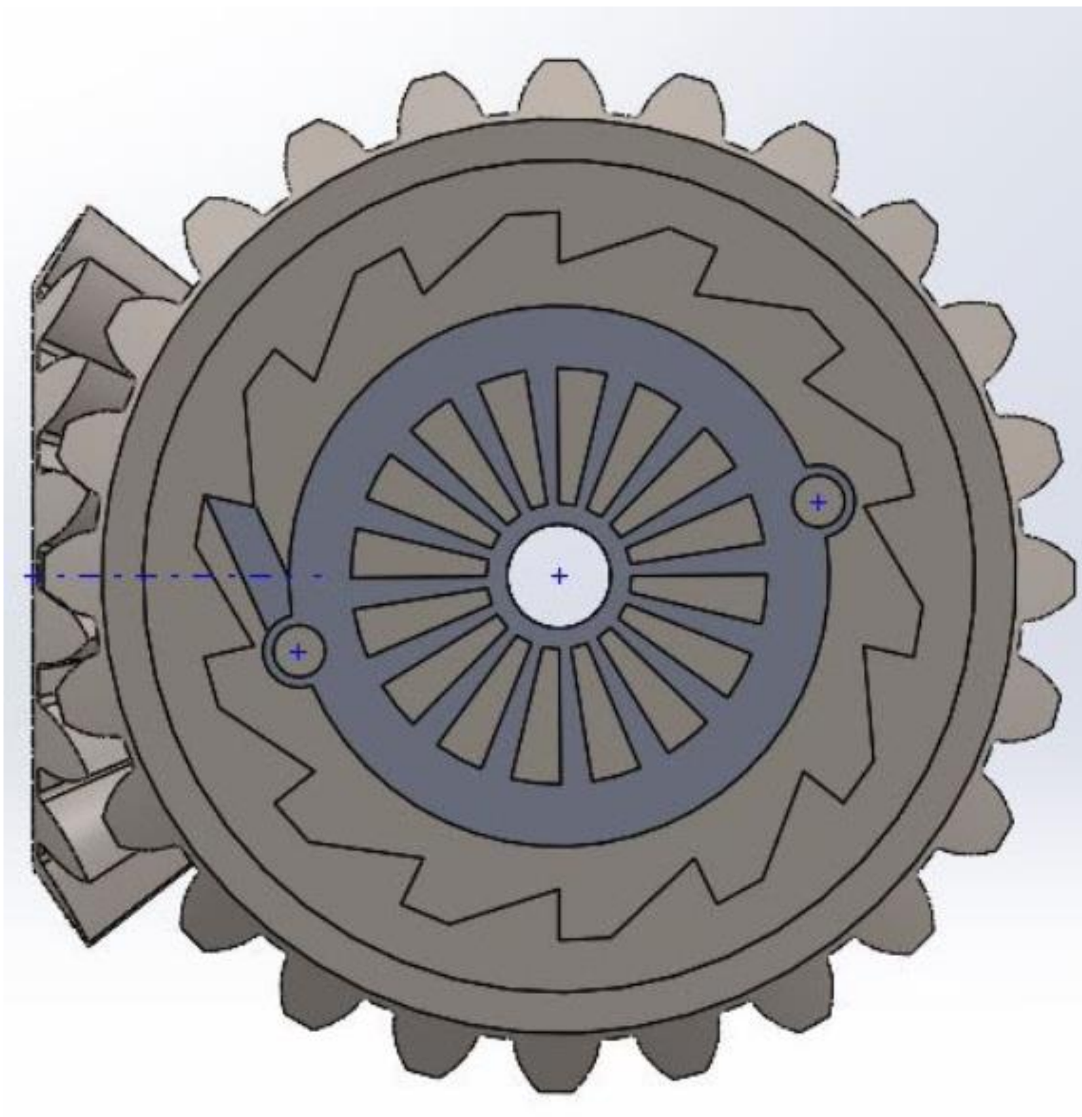


Figure 2.6. Freewheel Mechanism located inside of the front gear

As pictured above, the single blue tooth (ratchet pawl) located on the left side of the freewheel mechanism is clicked into the grooves on the inside of the gear by the spring as it spins, which allows torque to be transferred to the gear when pedalling.

In addition to cost, weight, and our other goals outlined earlier in the report, we also faced several design constraints that had to be addressed. The first constraint we had to face was the size of our gears and pinions. Ultimately, we wanted something small enough to fit on the side of a bicycle, but large enough to withstand the forces and moments created by the rider. Based on existing designs for gear sizes of shaft driven bicycles, we found that the maximum dimensions for the 3D printer we used would be a perfect size for the gears and pinions, while the number of teeth for each gear and pinion were found in Solidworks by creating a good gear ratio.

Another constraint we faced was the size of the freewheel mechanism. Our goal was to create a fine ratchet pawl, but ultimately we wanted to be able to manufacture and 3D print one, sacrificing size for practicality, thus resulting in the design above.

The final design constraint we faced was how long the drive shaft should be. Since our goal was to be able to attach our invention to a normal bicycle, we measured the distance from the front wheel to the rear wheel on a standard bicycle, subtracting the radii of the gears to develop a suitable drive shaft length.

2.3 Detailed Design

An isometric view of the complete drive shaft assembly is depicted below in Figure 2.7.

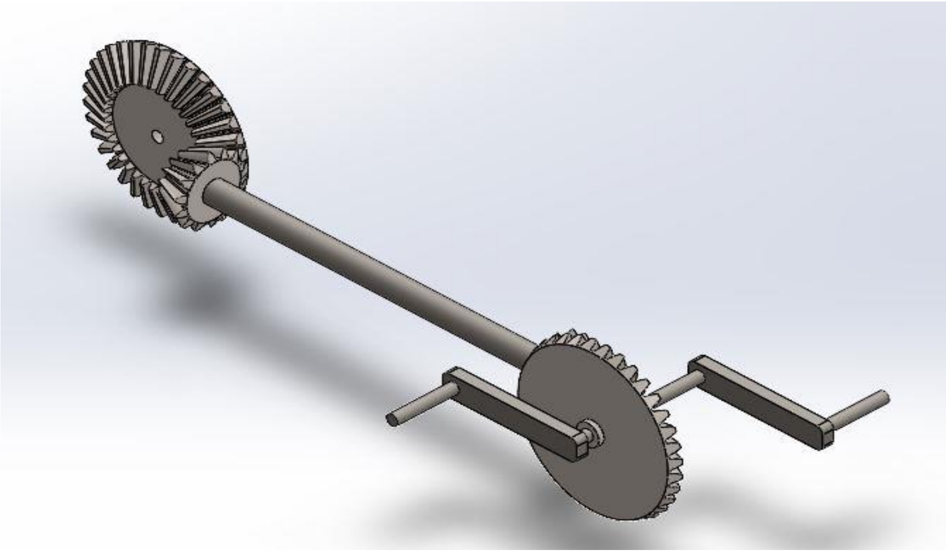


Figure 2.7. Isometric view of Drive Shaft Assembly

The individual components and their measurements are shown in Figures 2.8 through 2.18. All measurements are in inches (Additional sketches are located in the Appendix).

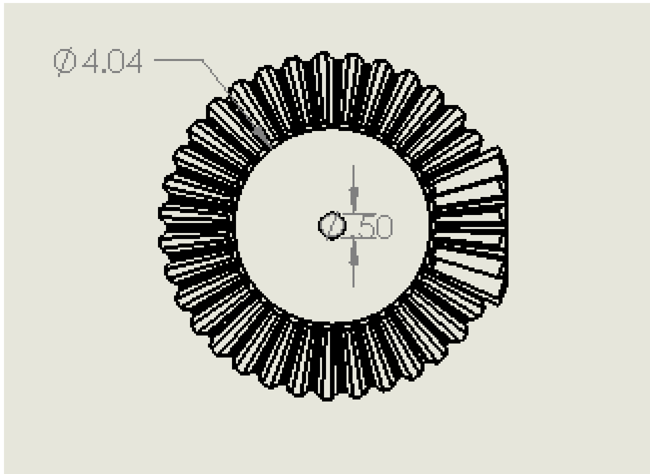


Figure 2.8. Front Gear

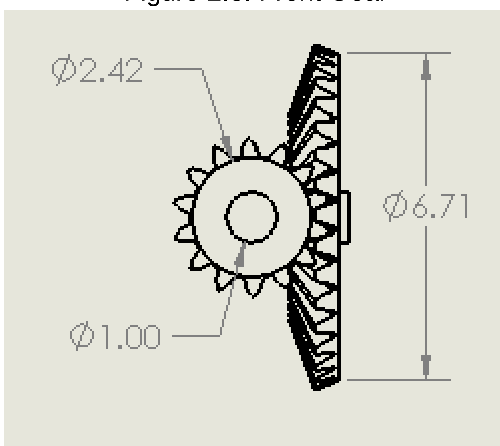


Figure 2.9. Front Gear and Pinion

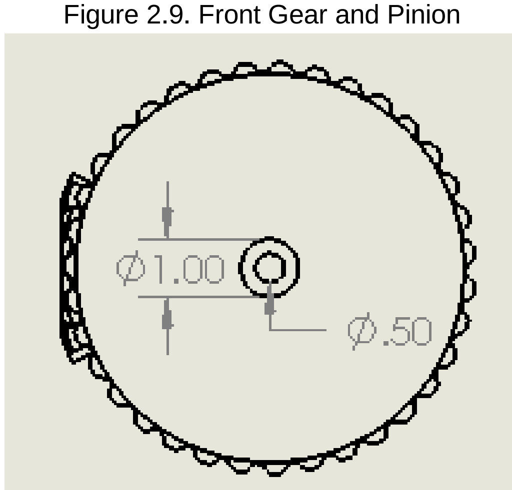


Figure 2.10. Front Gear

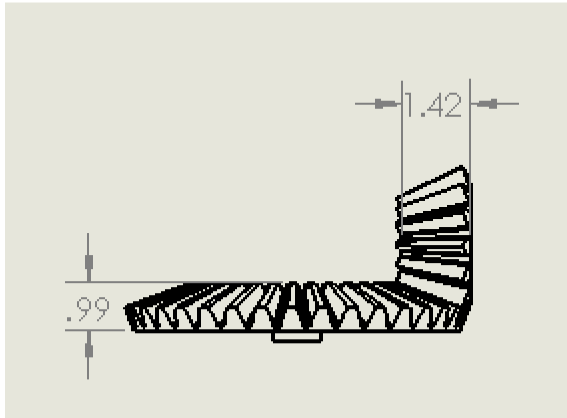


Figure 2.11. Front Gear and Pinion

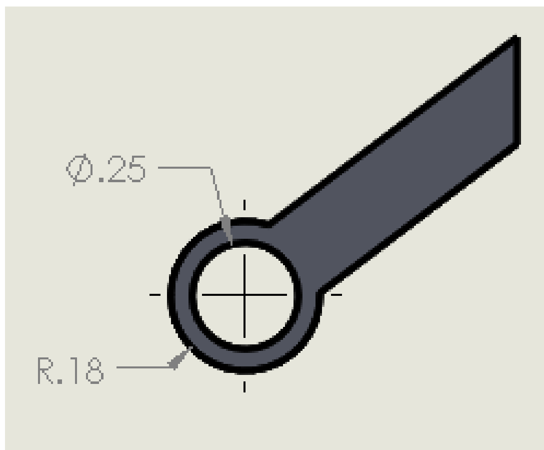


Figure 2.12. Ratchet Pawl

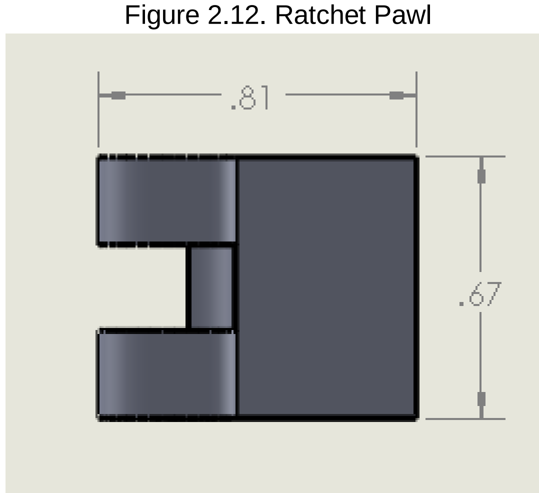


Figure 2.13. Ratchet Pawl

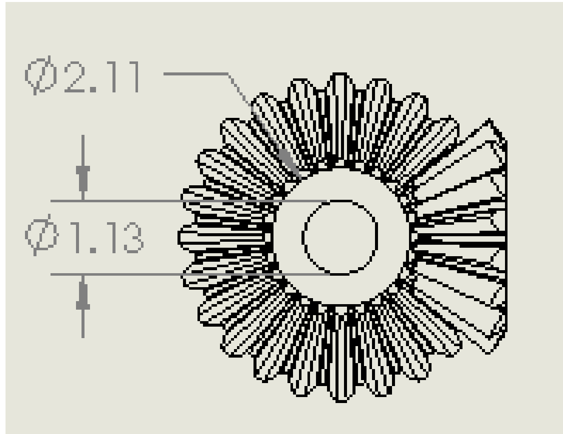


Figure 2.14. Rear Gear

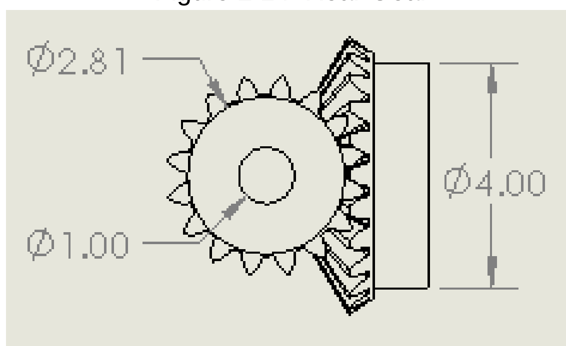


Figure 2.15. Rear Gear and Pinion

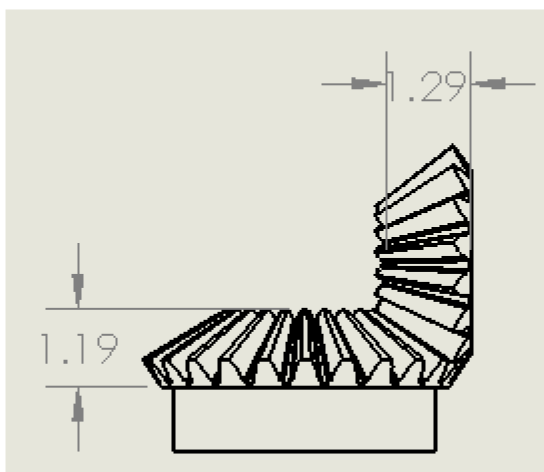


Figure 2.16. Rear Gear and Pinion

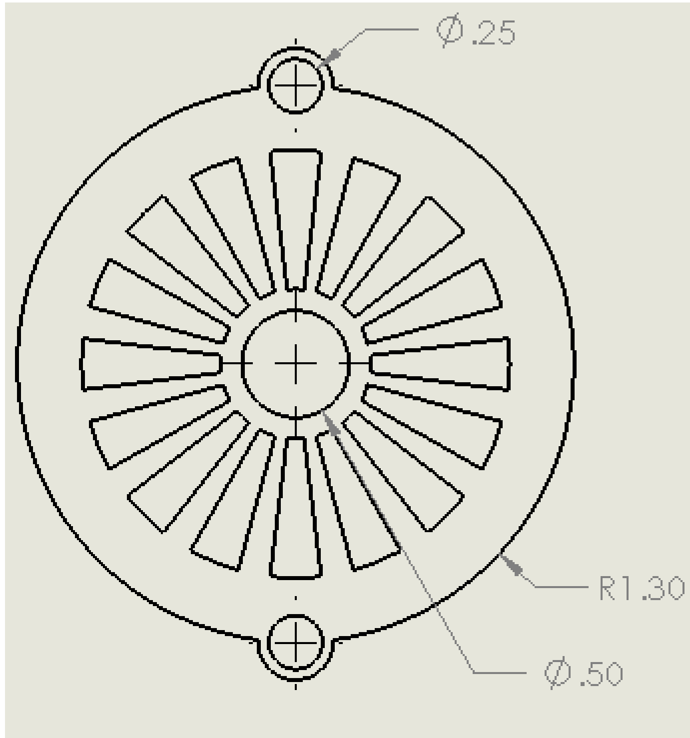


Figure 2.17. Ratchet Holder

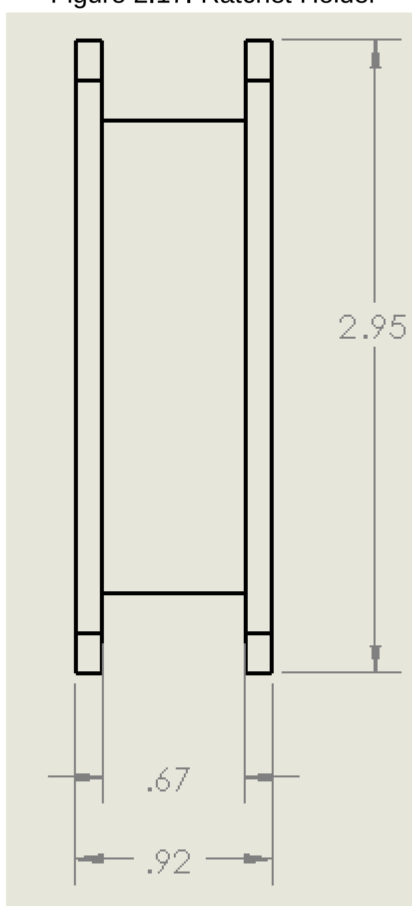


Figure 2.18. Ratchet Holder

As mentioned in section 2.2, Our gear and pinion designs were based on existing designs of bicycles with similar gears, as well as taking into account the size limitations of the 3D printer (for easier replication of a real life drive shaft system). From there, design of the ratchet pawl and ratchet holder were based off of the front gear geometry to ensure a large enough part to 3D print, and small enough to fit inside of the gear.

Being able to take our design from solid works and import it into a 3D printer made designing a prototype easier, and allowed for easy calculations when selecting a material and running various tests. A prototype was constructed from the 3D printed gears, pinions, ratchet pawl and ratchet holder, while the drive shaft was constructed from pvc piping with the measurements of the shaft from Solidworks. A depiction of the prototype is pictured below in Figure 2.19.

Figure 2.19. Prototype of Bicycle Drive Shaft System

There are multiple ASME standards that would apply to the manufacturing of our design, which will be mentioned in section 4. While our design may meet geometrical requirements for mounting on a bike, there is still materials selection to determine a suitable material, and testing to see how our design compares to a traditional bicycle. Both of these topics will be discussed in the next section.

3. Verification

This section consists of two separate parts: verification of the bench prototype that was built and analysis/research of materials that could be used to build a full scale/functional prototype on a bicycle.

3.1 Prototype Testing

For comparison purposes, a Schwinn 21-speed, 26” mountain bike was used as a control for the conventional chain-driven bicycle. With the prototype having a 35 tooth front ring gear, 14 tooth front pinion gear, 24 tooth rear ring gear, and 16 tooth rear pinion gear, we know the rear axle turns roughly 1.667 times for every turn of the front axle by dividing the front ring/pinion ratio by the rear ring/pinion ratio. Testing was done using 5th gear (smallest front sprocket and the 5th rear sprocket), as this was the closest ratio to the prototype.

First, an average pace needed to be determined that the conventional bicycle would operate at. According to Wahoo Fitness, 90 rpm is an ideal target cadence for a cyclist to avoid leg fatigue(2). In the design presentation, this group utilized wheel speed as a more easily relatable metric of success. To calculate wheel speed, we must first determine the wheel rpm by multiplying the pedaling rpm by the 1.667 front/rear axle ratio, in this case being 150 wheel rpm. Then, we multiply the wheel rpm, tire diameter (in inches), Pi, and 60 (minutes per hour). This result is then divided by 63,360 (inches per mile) to come to 11.60 miles per hour, which was rounded to 12 miles per hour.

The first test conducted was to determine the torque needed to drive the bicycle at the above pace without a load. To determine this, the length of the pedal arm was measured so a force gauge could be used on the pedal. On this particular bicycle, the length measured at 6.5 inches. The force gauge used for this testing was a digital luggage scale. To keep a consistent pace, a metronome was used. At 90 rpm, the bicycle with no load required only around 2 pounds of force to be driven, resulting in 13 lbf ・in of torque. To measure the force on the prototype, vice grip pliers were attached to the front axle and the luggage scale was attached to them exactly 6.5 inches from the center of the axle. Unfortunately, even with no wheel attached to the prototype system, it required roughly 19.5 lbf ・in of torque to maintain 90 rpm.

The second test conducted was to determine the torque required to move the bicycle when loaded with a rider. The rider used for testing purposes weighed roughly 170 pounds. The testing setup was the same as the previous test, using the luggage scale to measure force. In this test, the bicycle required roughly 40 pounds of force, or 260 lbf ・in of torque, to move with the rider aboard. Since the prototype is a bench model and cannot be ridden, to compare it in this test, it was decided to apply the same torque while locking the gears in place to check for its ability to withstand the same load. Again, unfortunately, the prototype did not perform as well as the conventional bicycle. In this instance, the failure was due to the attachment of the front axle and ring gear. The design consists of a simple press fit and once 65 lbf ・in of torque was applied to the front axle, it slipped within the gear.

The final test conducted was a test of the prototype’s durability at high rpm, far exceeding what a conventional bicycle would experience during normal operation. This test was performed using an electric drill to drive the front axle. The drill in question is rated at a maximum of 600 rpm with no load and the test was run at full speed for one minute. Assuming the drill was running between 80% and 90% efficiency, this means the prototype was able to withstand roughly 480 to 540 rpm at the front axle and 800 to 900 rpm at the rear axle. With the same size wheel as the conventional bicycle, this translates to a speed between 62 and 70 miles per hour, much higher than it would realistically ever operate at. Happily, the prototype proved to be a successful design in terms of durability.

3.2 Materials Research

There are essentially two types of parts where materials would be selected; bevel gears and the drive shaft. Typically, bevel gears are manufactured with a certain metal, and drive shafts are manufactured with a variety of materials, such as metals, composites, or carbon fiber. Bevel gears are commonly manufactured using steel because of its high strength to weight ratio and high resistance to wear. While our design will likely incorporate metal bevel gears, and a composite drive shaft, it calls into question what type of metal and what type of composite material should be selected. The materials selected should be strong and durable enough to prevent deformation, and cheap enough to be feasible for manufacturing.

To ensure a proper material is selected, the approximate bending stress will be calculated using the Lewis Form Equation, where the bending stress should not exceed the yield stress of the selected material. Similarly, the stress in the drive shaft will be determined, and should not exceed the yield stress of the selected material. To start the calculations, we must first find the moment created by the rider peddling the bike, using the equation below

$$M = mgl \qquad \text{Eq. 1}$$

where m is the mass of the rider, g is gravity, and L is the lever arm of the bike pedals. This moment would be experienced by the system as a whole, so to determine the force acting on a certain tooth, you would just need to divide by the gears pitch radius.

The gear that would experience the largest force would be the smallest gear, which is the front pinion. Assuming the rider weighs 85 kilograms, and the lever arm of the bicycle is 0.1778 meters, then the moment created by the rider is 148.2586 Newton meters. To find the force acting on the tooth, we can divide this moment by the pitch radius of the gear, which is 0.0905 meters. This would give us a force of 1.638 kilonewtons. From here, the Lewis Form Equation can be calculated as

$$S = \frac{FP}{fY} \qquad \text{Eq. 2}$$

where F is the force on the tooth, P is the pitch diameter, f is the face width of the tooth, and Y is the Lewis Form Factor. The pitch diameter is defined as the number of teeth

(14) divided by the diameter (0.0825 meters). In the case of this gear, P would equal 169.697 $meters^{-1}$. The face width of the tooth is measured to be 0.019 meters. The Lewis Form Factor has its own equation, depending on the pitch angle of the gear and the number of teeth. In this case, the Lewis Form factor would be 0.25. Putting all of these values into the equation above, the highest stress experienced by the gears would be 58.5264 MPa.

The highest stress that would be experienced by the shaft would be the shear stress due to torsion. This can be found using the following equation

$$T = M\frac{r}{J} \qquad \text{Eq. 3}$$

where T is the shear stress in the shaft, M is the torsion experienced by the shaft, r is the radius of the shaft, and J is the polar moment of inertia of the shaft. The torsion experienced by the shaft is the moment experienced by the gear connected to it. To find this, the force of 1.638 kilonewtons is multiplied by the pitch radius of the connected gear, which is 0.0413 meters. This yields a torsion of 67.6583 Newton meters. The radius of the shaft is 0.0133 meters. The polar moment of inertia is found to be $1.9*10^{-9}$ $meters^4$. Plugging these values into the equation above yields the result of 473.608 MPa.

With these maximum stresses, we will be able to select a material from the CES software. There are several factors that will be displayed on the graph, which will help us select an appropriate material. First, the yield stress must be higher than the maximum stresses experienced by both the gears and the drive shaft, as to make sure there is no deformation in the part. The density and price of the materials will also be factored in, to show materials which may weigh too much, and materials that may cost too much. In the CES software, we will only be considering composites, metals, and alloys. The lower limit for the yield stress is set to 60 MPa, due to the maximum stress experienced by the gears. There is no maximum limit set to the yield stress, as multiple factors of safety could be applied to manufacturing the necessary parts. Figure 3.1 shows the graph generated by the CES software.

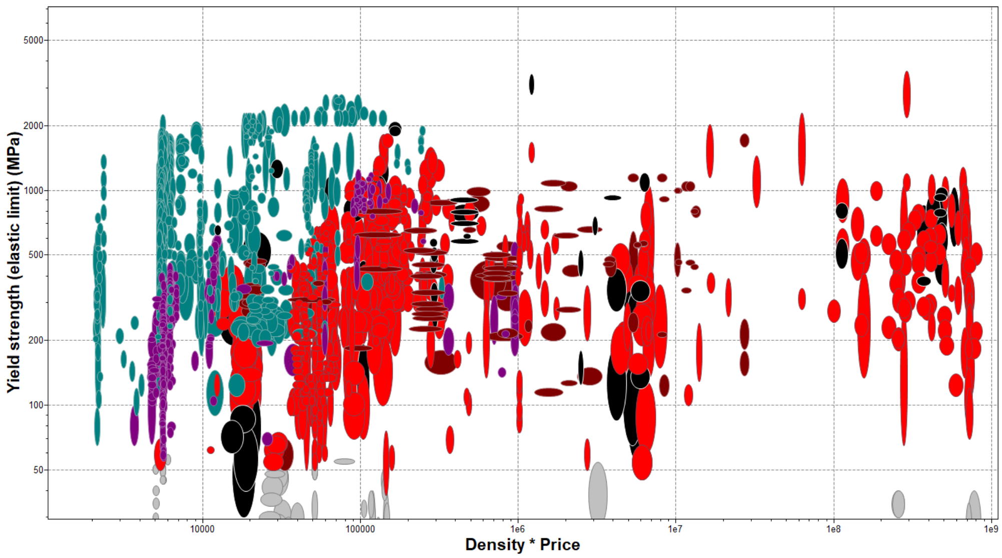


Figure 3.1. A visual representation yield strength vs. density and price of various materials

The materials in black and bright red are alloys, the dark red materials are composites, and the materials in green and purple are metals. From the graph, you can see that some of the most expensive and most dense materials are alloys, which would discourage one from using these materials. On the other hand, you could see that metals are some of the cheapest and least dense materials, making them extremely desirable to use for manufacturing. Their yield strength is also extremely high, which would make them suitable for both gear and drive shaft manufacturing. While composites land somewhere in the middle of the graph, not every composite would be suitable for the design. For example, Unit Directional composites would not be recommended for manufacturing, because the material would fail under a lower stress depending on the direction the material is manufactured in. Because of this, composites would be risky to use and are not recommended. A close up of the most suitable metals is shown in Figure 3.2.

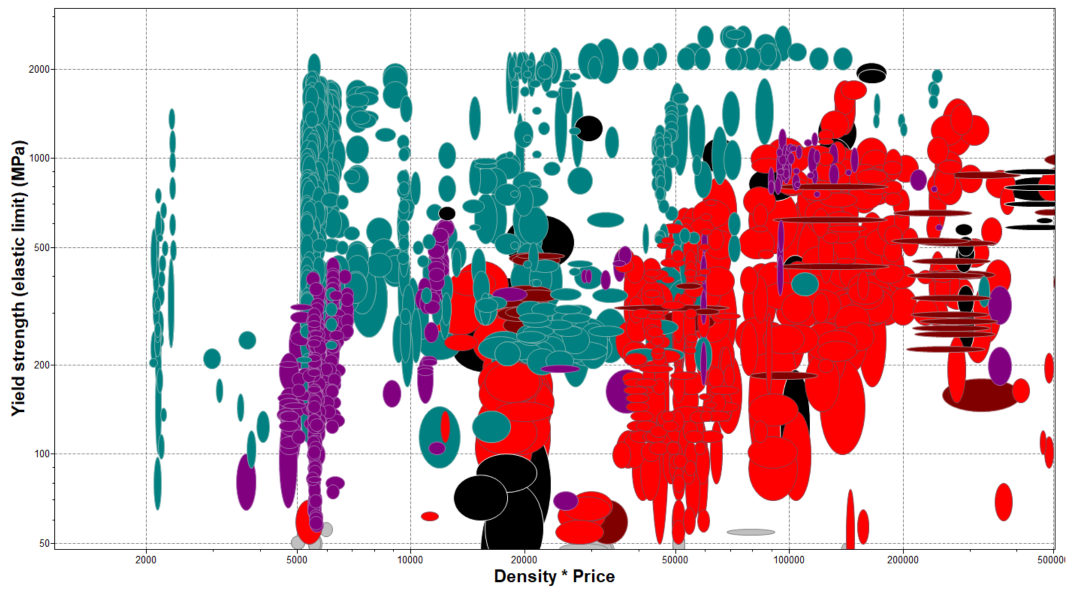


Figure 3.2. A magnified look at the most suitable materials from Figure 1

Many of the metals shown at the top have the highest yield stress of around 2000 MPa. This is well above the maximum stresses experienced by the gears and the shaft. From left to right (least expensive/dense to most expensive/dense), these metals include cast iron, low alloy steel, stainless steel, and tool steel. These same materials would also be suitable for a lower selected maximum yield stress, such as 1000 MPa. Ultimately, the best metal to select is cast iron; not only does it have an extremely high yield stress, but it is also the least dense and the least expensive material. Some examples of suitable cast iron metals are shown in Figure 3.3.

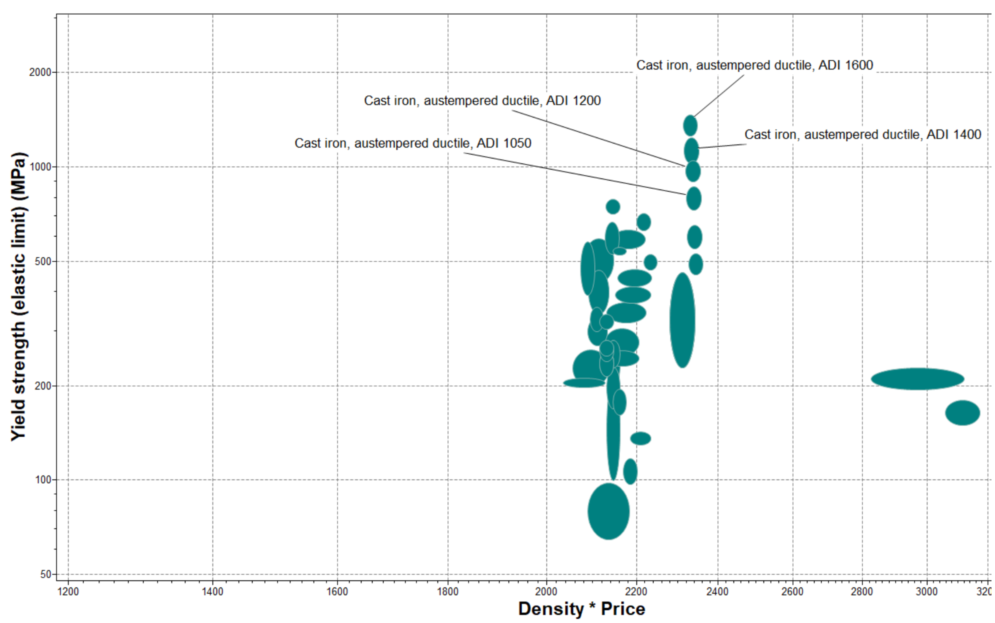


Figure 3.3. Examples of different types of cast iron suitable for manufacturing this design

If, for whatever reason, a different material is desired for the gears (a material closer to the gears maximum stress), these are shown in Figure 3.4.

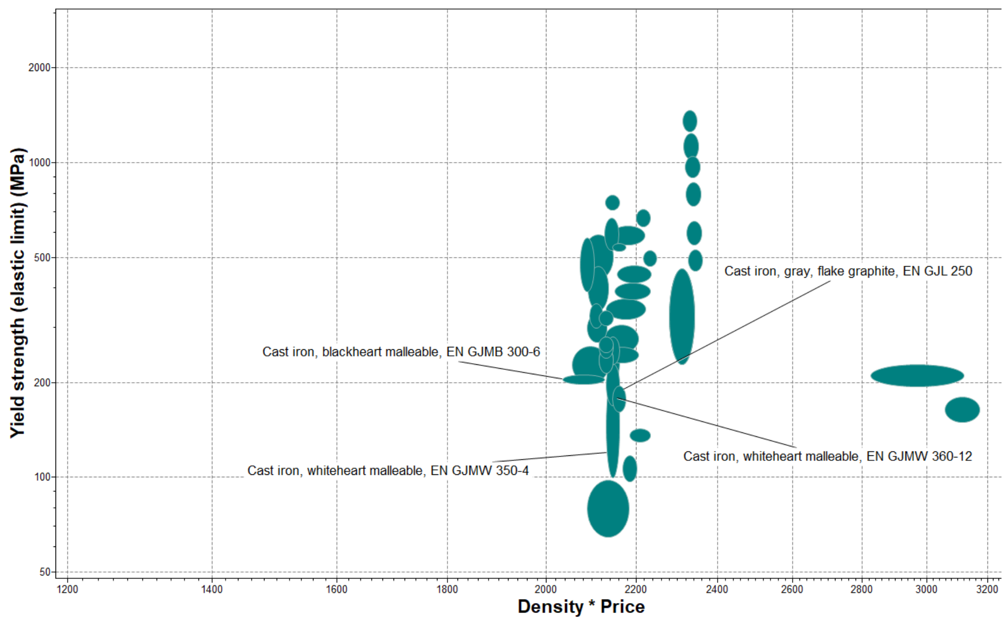


Figure 3.4. Examples of cast irons which are rated close to the maximum stress of the gears

4. Design Standards

There are multiple design standards that need to be met by our project. One such standard is the ANSI/AGMA ISO 22849, which is the code of design recommendations for bevel gears. This standard includes tolerances, manufacturing, strength and efficiency for gears, along with the capacity of how certain bevel gears can be applied. Another standard would be the B30.21, which is standard for lever hoists. This standard would apply to our ratchet pawl and holder, with construction, installation, operation, inspection and maintenance of such ratchet pawl systems.

In addition to the design standards mentioned above, there are other standards that would apply to our design project. In a production environment, in terms of materials, we would need to satisfy ASTM standards. One example of this would be the A291/A291M-19 standards, which are standard specifications for steel forgings, carbon and alloy, for pinions, gears and shafts for reduction gears. This standard covers various chemical requirements the materials must meet, and also covers how the material would be forged and machined.

5. Costs

The costs for this project can be divided into two categories: labor and parts.

5.1 Labor

For labor, the assumption is that each group member spent roughly three hours per week on various parts of this project. Based on data from payscale.com, the average salary of a mechanical engineer in Akron, Ohio with less than one year of experience is $60,992 per year(3). If working 40 hours per week for all 52 weeks of a year, this translates to 2,080 hours worked and an hourly pay rate of $29.32 per hour. The formula to calculate the labor cost for this project was given in the Final Report Guidelines on Brightspace and is shown below(4):

$$Labor\ cost\ estimate\ =\ ideal\ salary\ (hourly\ rate)\ \times\ actual\ hours\ spent\ \times\ 2.5$$

Assuming 15 full weeks over the last two semesters, each student worked for 90 hours. With 4 students involved, there were a total of 360 hours dedicated to this project from start to finish. When inserting these figures into the equation above, the total labor cost estimate comes to $26,388.

5.2 Parts

Many of the parts for this project are off-the-shelf pieces that can easily be found online. However, several custom pieces were 3-D printed utilizing the free service available to University of Akron students in the 3-D Print Lab, therefore, are more difficult to place a price on. The basic components are summarized in Table 4.1.

Table 4.1: Prototype Basic Components Cost

Part	**Use in Model**	**Price**
½” Bore Ball Bearings, qty.10	Axle bearings, rear gear bearing	$19.95
Carrier Bearings, qty. 2	Driveshaft attachment/support	$13.98
Nylon Washers, qty. 50(used 1)	Spacer between gear/ratchet	$8.99
Torsion Spring	Ratchet mechanism	$10.98
Roll Pin, ¼” x 1”	Attach pawl to ratchet hub	$1.02
PVC, ¾” ID x 2’ length	Driveshaft	$1.35

PVC, ½” ID x 1’ length	Axle spacers	$0.99
Aluminum Rod, ½” x 36”	Axles	$7.98
Total		**$65.24**

The 3-D printed pieces consisted of both sets of gears and the pieces for the ratchet mechanism on the rear axle. To determine a rough cost for these pieces, students used a website called PrintAWorld(5), which gives users an instant quote for the cost to print uploaded STL files. The costs are listed in Table 4.2.

Table 4.2: Prototype 3-D Printed Components Cost

Prototype Part	**Price**
Front Ring Gear	$477.26
Front Pinion Gear	$99.14
Rear Ring Gear	$313.33
Rear Pinion Gear	$111.78
Ratchet Mechanism Hub	$44.21
Ratchet Mechanism Pawl	$8.09
Total	**$1,053.81**

6. Conclusion

This design project brought with it many challenges and obstacles in addition to those already inherent to such an involved assignment. This group set a very lofty goal for itself from the beginning by aspiring to invent an alternative to a design that is nearly 140 years old. Initially, the goal was to develop a replacement for a modern multi-speed bicycle, but ultimately this had to be simplified to a single-speed, direct-drive system. While the basic concept of the design was proven functional (power was transferred from the front axle to the rear and the rear wheel was also capable of moving independently of the front axle, such as in a coasting situation), it is clear that this first iteration has not improved upon the conventional design.

The most obvious downfall comes from the simplification of the design. In a world where 21-speed bicycles are commonplace, a single-speed bicycle is a far from desirable alternative. The advantage of having multiple speeds is the adaptability of the bicycle to multiple terrains and riding conditions. A single-speed bicycle is only practical on smooth level surfaces for a leisurely ride. Further disadvantages to this design are that, in testing, it required more pedal effort from the operator than the conventional design, both unloaded and at speed. The one potential advantage to this design is its ability to withstand high rpm. If someone ever desired to create a hybrid out of a bicycle using this drive system that would allow them to either pedal or use an engine to power it, this design would be robust enough to handle the higher potential speeds.

Many lessons were learned over the course of the past two semesters while working on this project. Most importantly it introduced the members of this group to ways for collaborating with one another while working remotely. Group projects are always made most difficult by trying to synchronize several schedules to find meeting times which work for everyone. With the COVID-19 pandemic making software that allowed for virtual meetings more prevalent, it became slightly easier to achieve this. On the other hand, this presented its own set of challenges when physical, hands on work needed to be completed.

Overall, this was a great learning experience that these students can take with them as they begin their careers. There is also still great potential in this design, whether it be continued by members of this group, or adopted by another. Either way, this group is confident that a chainless bike drive is something that will replace the conventional chain-driven system and pave the way for the future of human-powered transportation.

References

1. “1885: First Chain Driven Bicycle - "The Rover."” *History of Innovation*, https://aehistory.wordpress.com/1885/10/05/1885-first-chain-driven-bicycle-the-rover/. Accessed 3 May 2021.

2. “Cycling Cadence: What is it & How to Improve Yours.” *Wahoo Fitness*, https://blog.wahoofitness.com/cycling-cadence-what-is-it-how-to-improve-yours/. Accessed 3 May 2021.

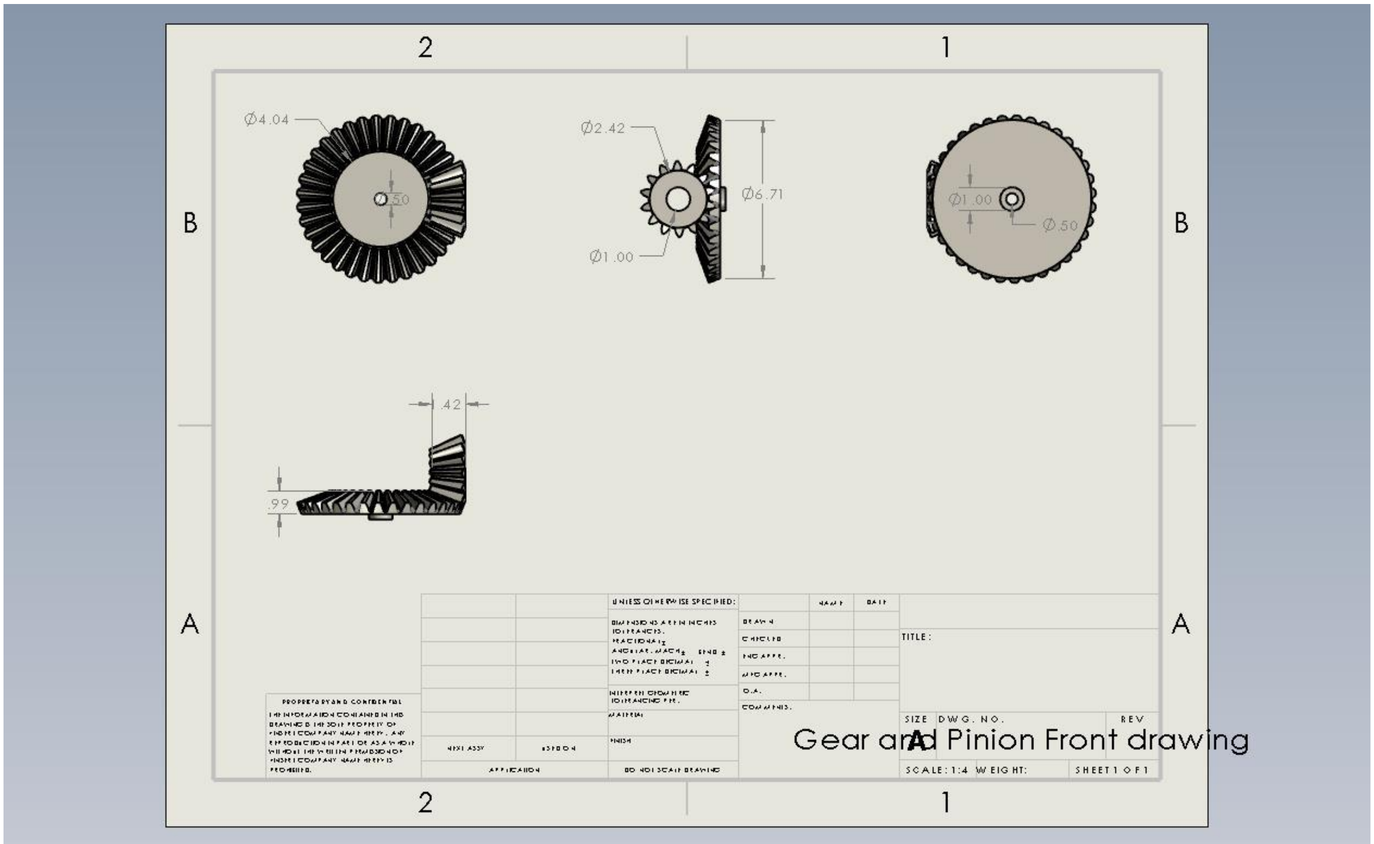
3. “Average Mechanical Engineer Salary in Akron, Ohio.” *Payscale*, https://www.payscale.com/research/US/Job=Mechanical_Engineer/Salary/fef13922/Akron-OH. Accessed 3 May 2021.

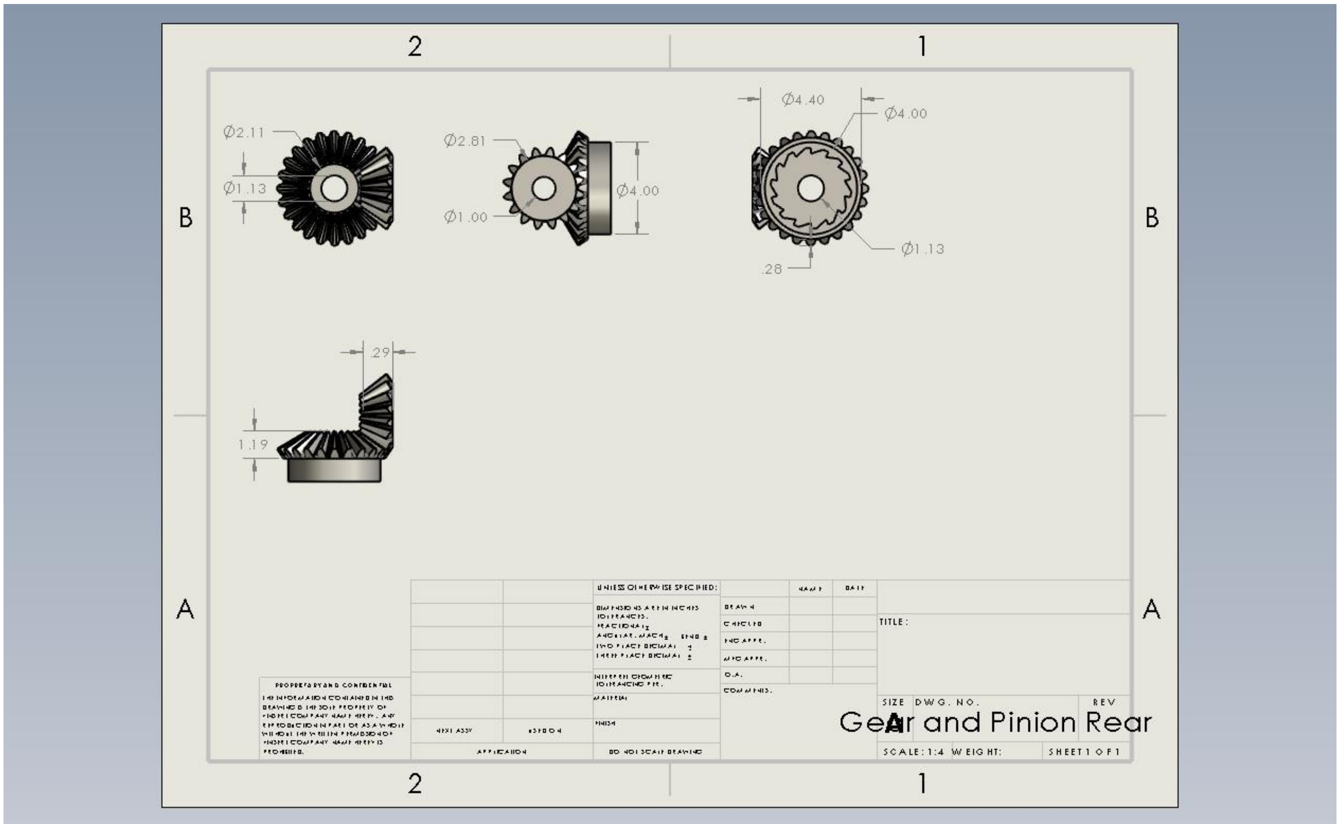
4. Nadkarni, Gopal. “GN_Final_Report_Guidelines-471-497 V1.” *Brightspace*, https://brightspace.uakron.edu/d2l/le/content/4452323/viewContent/6559024/View. Accessed 3 May 2021.

5. *PrintAWorld: A BigTech Company*, https://prtwd.com/instant-quote/3d-printing/. Accessed 3 May 2021.

Appendix:

Engineering Drawings:





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.29
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UNLESS OTHERWISE SPECIFIED:
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Gear and Pinion Rear
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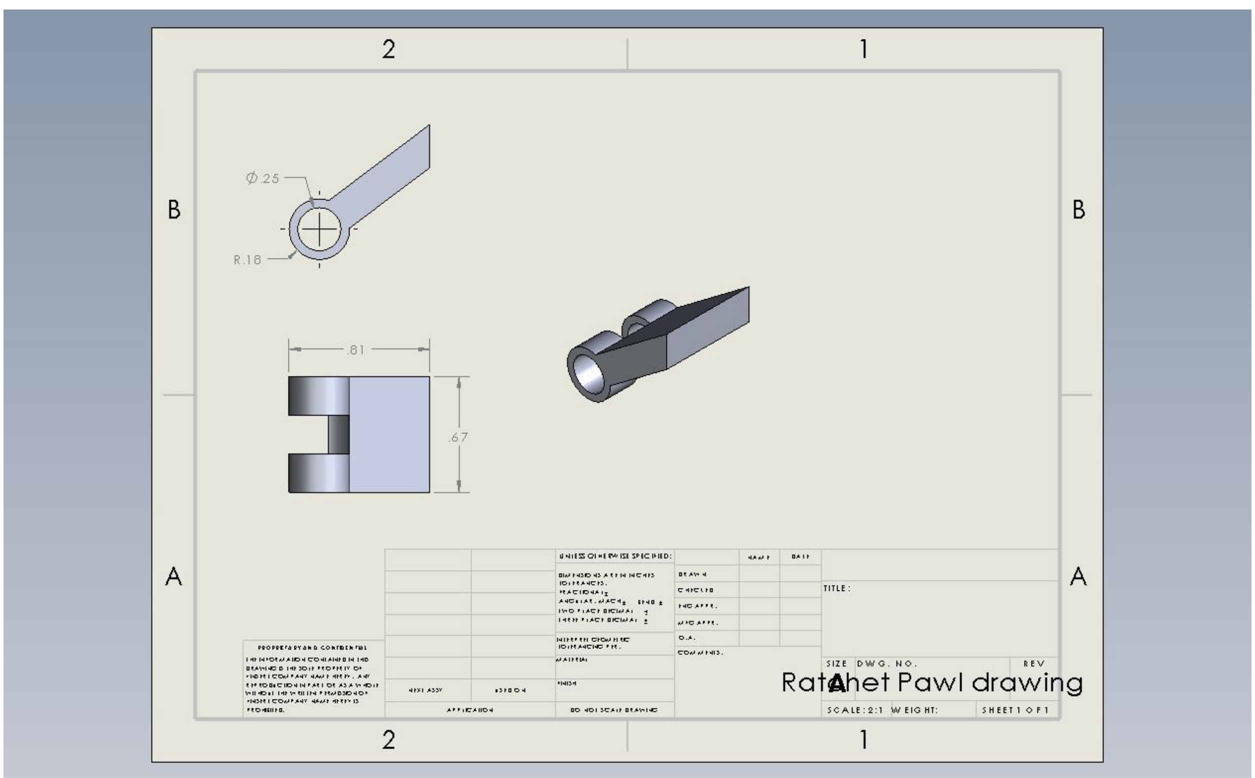
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL



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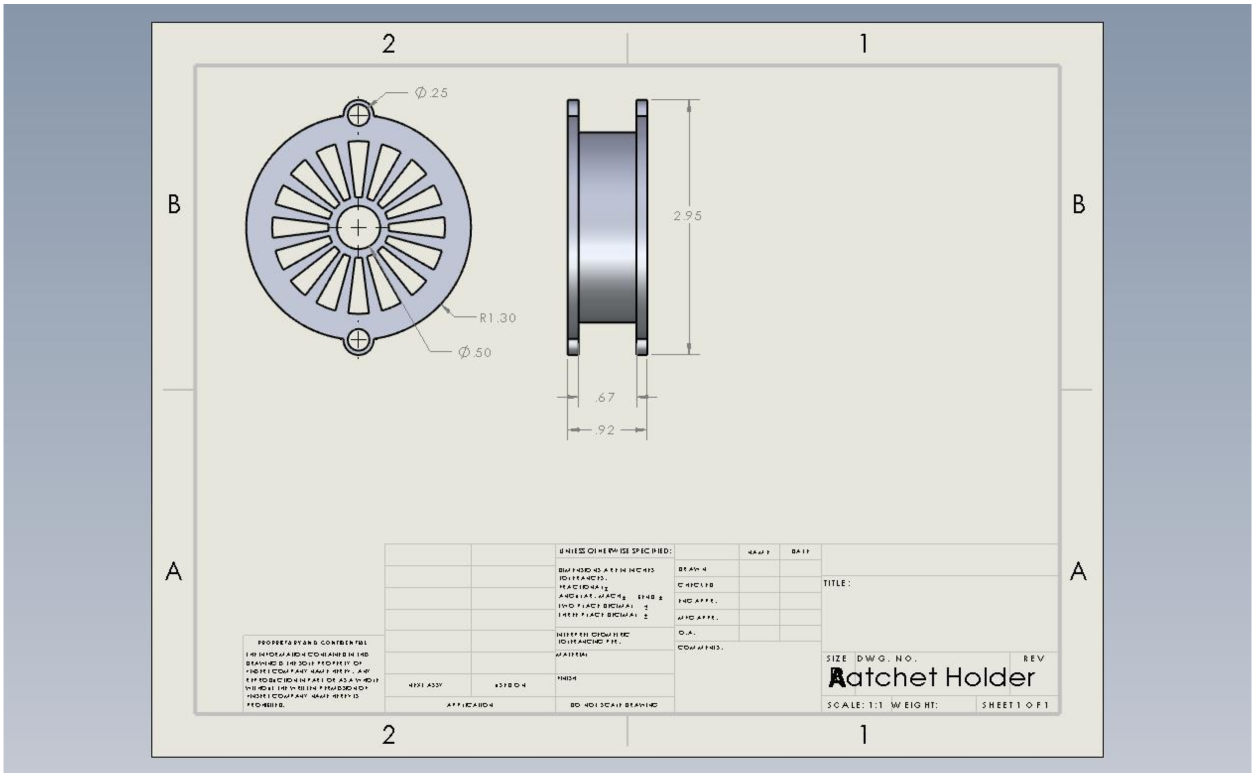
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL



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MFG APPR.
Q.A.
COMMENTS:
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REV
Ratchet Holder
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
APPLICATION
DO NOT SCALE DRAWING