California State University Los Angeles

Gearbox Design Competition

Team

Jonathan Flores

[SolidWorks Design, Stress Analysis Laser Cutting Assembly]

Carlito Ferrer Jr.

[Theoretical Calculations, Design Sketches, Assembly]

Jose Reyes

[Manufacturing and Assembly]

ME 2030-07

Intro to Mechanical Design

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I. Introduction

The purpose of this report is to manufacture an efficient gearbox that improves on the characteristic of insufficient power corresponding to the torque and velocity of the source. In accordance to the design process in mechanical design, this project undertakes multiple phases that correspond to the motion and power transmission in a gearbox system.

Keywords: Power Transmission, Gear Ratio, diametric pitch, spur gear

***See Appendix A for Gantt schedule**

1.1 Design Problem/Constraints

Design problem/need

A power source is a component in a system where energy is utilized for a purpose. There are numerous power sources that provide a sufficient amount of power; however, due to characteristics in torque and velocity, the sufficient power becomes inadequate. Based on design concepts, the mechanism in a gear train correlates to either a transmission in power, changes in the torque or angular velocity of a shaft. Therefore, under certain circumstances, a particular design of a gear can be applied.

Requirements:

A 1 kg steel mass must be pulled up on a 50 cm aluminum ramp with an incline of 45 degrees. The gear system must motion the mass up the ramp in less than 10 seconds. A Mabuchi RE280RA electric motor shown below as figure 1, will drive the gear system powered by a 3-volt supply.

Figure 1. Mabuchi RE280RA electric motor

Material Limitations

- 12” x 6” of 3/16” thick acrylic
- 12 in of 3/8” aluminum rod,
- 1 m of string

- Fasteners under #10 in size

Constraints:

No liquid adhesive such as glue are to be used. The incline of the ramp shown below as figure 2, is fixed and the physical features of the ramp and mass are not allowed to be altered.

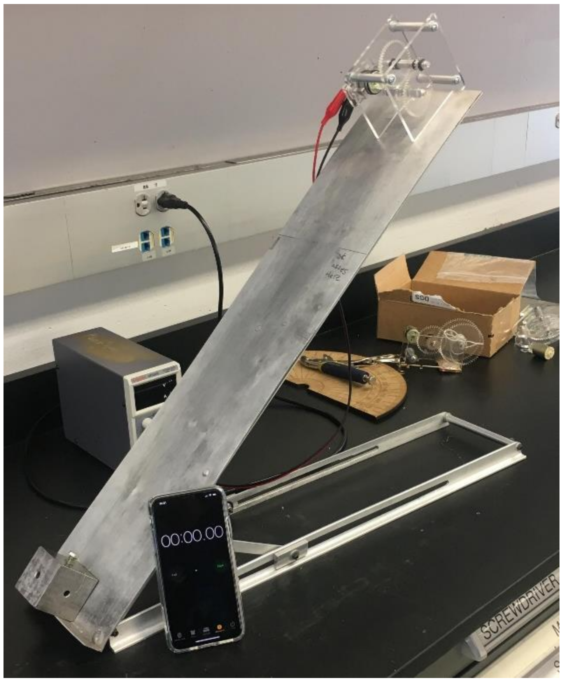


Figure 2. Test Ramp with 1 kg mass and final design attached.

1.2 Concept Review

The efficiency of energy usage in a system is a significant concept to understand in mechanical engineering. Power transmission is the movement of energy from the point it is generated to other locations where it will perform work; more so, "...the conversion of speed and torque from a rotary power source that outputs into another system" [1]. The group of components that generate power and deliver it to the intended surface are known as powertrains. Powertrains are used to transmit stored energy into kinematic motion. In most applications powertrains include a drivetrain or driveline; however, in this application the powertrain will only include a motor and a transmission (gear train).

The style of a gear pertains to the circumstances that allow it to be the most efficient for a specific purpose. The significance of the gear ratio in a mechanism corresponds to the size, shape, and number of teeth of a gear. Figure 3 shown below displays the elements of a gear that constitute to its rotational motion. The mathematical relationship of the gear ratio in a system is given as equation 1 in the methods section of this report.

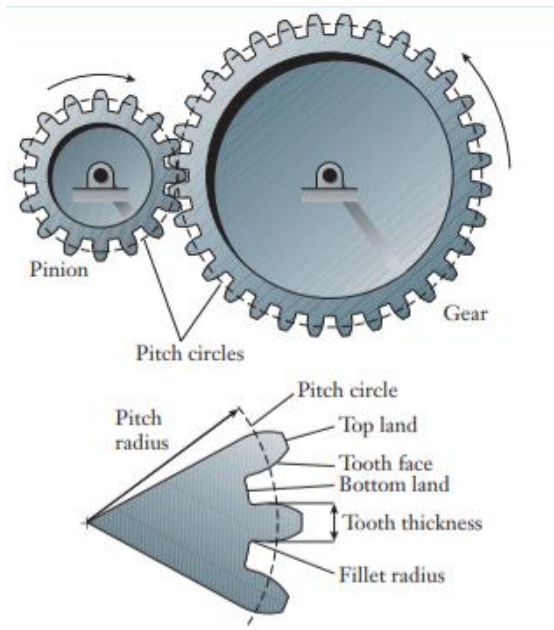


Figure 3. Pinion and Output Gear

The gear teeth are specifically designed so there is a smooth rotational transmission in the pitch circle between two neighboring gears. The point of contact of gear teeth require the same pressure angle in order to simulate a proper mesh. This is demonstrated in figure 4. shown below. In order to operate smoothly, gears must have the same diametric pitch in order for the teeth to mesh correctly and prevent slipping. This mathematical relationship is further explained in the methods section of this report as equation 2.

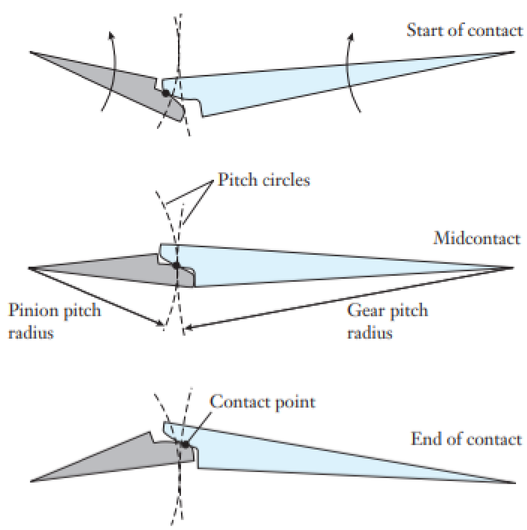


Figure 4. Interaction of Gear Teeth

Below are examples of types of gears:

The faces of an external spur gear are oriented parallel to the shaft on which the gear is mounted. An example of a spur gear is shown below as figure 5.

Figure 5. Aluminum Spur Gear

Helical gears comprise of angled teeth so the face of the tooth does not fully engage with another in an instance. The teeth in bevel gears are also angled but unlike helical gears, the faces do fully engage in order to turn a consistent 90^{o} angle. A rack and pinion gear is unique compared to the other gears aforementioned as the rack is a linear row of teeth that performs translational motion; whereas, the pinion gear performs in rotational motion. Accordingly, the rack will move horizontally as the pinion rotates. A worm gear is similar to the rack and pinion gear which also takes elements from bevel and helical gears. This type of gear provides a good measure of transmitting a higher torque and altering the rotational speed of a neighboring gear, if needed.

Non fully circular gears are uncommon due to their unorthodox design and gear characteristics regarding speed and torque. Examples of unusual designs are crescent (moon) shaped and nautilus gears. Crescent shaped gears were perhaps inspired by the notion of planetary gears revolving around a centered sun. Half-moon gears are split components of actual gears, that would exhibit differences in pressure similar to how a pump operates [2]. Nautilus gears are inspired by the shells that house marine mollusks and are part of the cephalopod family. Nautilus gears are shown to come in pairs, the motion of one gear at a constant speed will fluctuate the speed of its partnered gear during the course of its rotation [3]. Therefore, these unconventional gears are mainly used for aesthetic practices rather than functionality in operation.

II. Methods

2.1 Theoretical Calculations

Equation 1: Gear Ratio

$$GR = 2mgr[(\cos(\Theta))\ (\mu_k) + \sin \Theta]/\ T_{Stall}$$

- GR: gear ratio
- m: mass
- g: acceleration of gravity
- r: radius of aluminum rod
- μ_k: coefficient of kinetic friction
- Θ: angle of ramp incline
- T_{Stall}: max torque of motor

Equation 2: Diameter of Individual Gears

$$d = N/dp$$

Gears must have the same diametric pitch in order to mesh correctly/smoothly

- Dp**:** Diametric Pitch
- N: Number of Teeth
- d: diameter of gear

Equation 3: Predicted Time given a distance

$$x(t)=[(ca)/b^2] \times [1-e^{-bt/a}]-[ct/b]$$

*equation 3 is modified since $[(ca)/b^2] \times [1-e^{-bt/a}]$ contributes a miniscule value to the point where it is negligible in the result

$$x(t) = -[ct/b]$$

Equation a:

$$a = m$$

- m: mass

Equation b:

$$b = [(T_{Stall})\ (GR)^2]/\ [(w_{no\ load})\ (r^2)]$$

- T_{Stall}: max torque of motor

- GR: gear ratio
- $w_{no\ load}$: angular velocity without load
- r: radius of aluminum rod

Equation c:

$$c = mg[(\cos(\Theta)) (\mu_k) + \sin \Theta] - (T_{Stall})(GR)/r$$

- m: mass
- g: acceleration of gravity
- μ_k: coefficient of kinetic friction
- Θ: angle of ramp incline
- T_{Stall}: max torque of motor
- GR: gear ratio
- r: radius of aluminum rod

Sample Calculations:

Table of known values	
mass	1 kg
g	9.81 m/s^2
Θ	45^o
r	0.00476 m
T_{Stall}	0.00565 Nm
μ_k	0.3
$w_{no\ load}$	628.318 rad/s
Distance (x)	0.5 m

Calculation of Gear Ratio

Using equation 1:

$$GR = 2mgr[(\cos(\Theta)) (\mu_k) + \sin \Theta] / T_{Stall}$$

Substitute known values:

$$GR = 2(1\ kg)(9.81\ m/s^2)[(\cos(45^o))(0.3) + \sin 45^o] / (0.00565\ Nm)$$

$$GR = 15.2$$

Calculation of predicted time with corresponding gear ratio:

Use equations 3; a-c:

$$a = 1\ kg$$

$$b = [(0.00565 \text{ Nm})(15.2)^2] / [(628.318 \text{ rad/s})(0.00476 \text{ m})^2]$$

$$b = 91.69$$

$$c = (1 \text{ kg})(9.81 \text{m/s}^2)[(\cos(45^o))(0.3) + \sin 45^o] - (0.00565 \text{ Nm})(15.2)/(0.00476 \text{ m})$$

$$c = -9.024$$

$$x(t) = -[ct/b]$$

$$0.5 \text{ m} = -[9.024t/91.69]$$

$$t = 5.08 \text{ s}$$

The predicted time the 1 kg block travels the 45^o ramp incline corresponding to a gear ratio of 15.2 is 5.08 seconds.

Calculation of the diameter of a gear:

Using equation 2:

Number of teeth for first pinion: 12 teeth

Diametric Pitch: 24

$$d = N/dp$$

$$d = 12/24$$

Diameter of the first pinion is 2 inches.

To calculate the teeth of the first large gear:

$$\text{Number of Teeth for large gear} = 12(15.2)^{0.5}$$

N_{large} is estimated to have 46 teeth.

2.2 Design Concepts

Miscellaneous concept designs were taken into account; however, the materials that were provided for this project limited what can be possibly manufactured and assembled. Laser incision of the provided acrylic sheet were only oriented vertically; therefore, the creation of bevel, worm, and helical gears were excluded. Spur gears were the primary focus when producing the design concepts. According to *An Introduction to Mechanical Engineering by* Johnathan Wickert and Hubert Lewis, examples of simple gear trains comprised of spur gears that did not enhance the angular velocity and torque within the system [3]. In contrast to simple gear systems, compound gear trains recondition torque and angular velocity of the system. Spur gears are also used to produce a planetary gear system that compose of a sun gear and planetary gears that simulate a visual orbit.

Design 1: Planetary gear inspired from wind turbines

An internal gear system composed of a centered sun with three planetary gears was briefly considered as a design concept. The angular velocity of the sun gear would be driven from the motor. The sun gear would be centered between three planetary gears and surrounded by an internal gear. Each planetary gear would have an aluminum rod attached at its center to gather the string. Figure 6 shown below showcases a design sketch based on the ideas of this design concept. In terms of manufacturing, this design was predicted to require the most acrylic due to the size of the components. The planetary system proved to be complex in regards to calculating the gear ratio. Therefore, this design concept was declined.

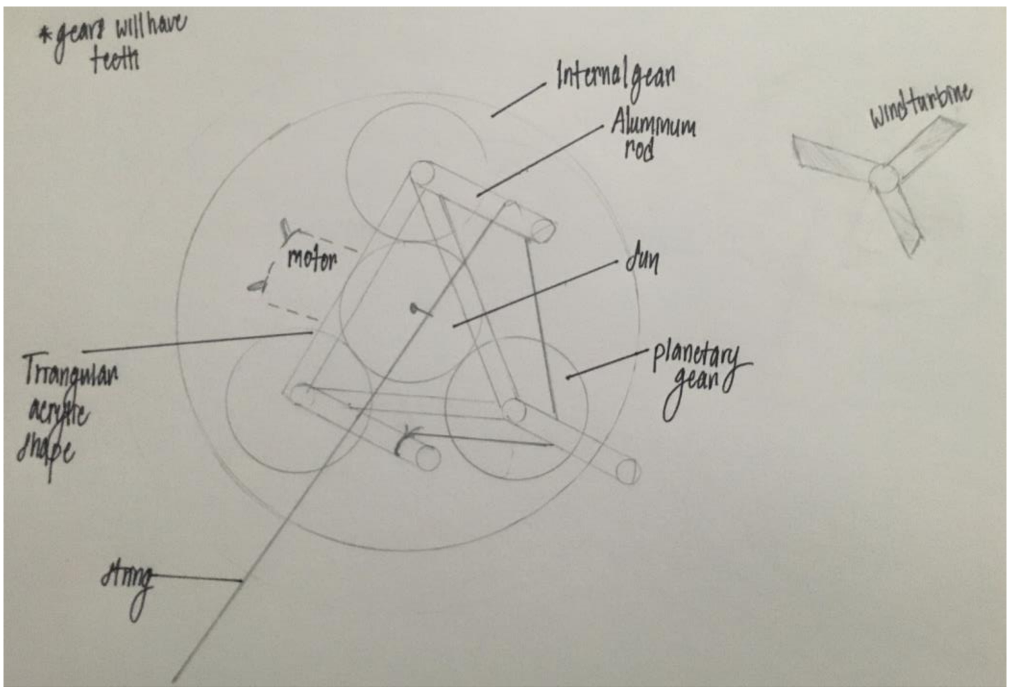


Figure 6. Planetary Gear System

Design 2: Unorthodox gear system

The purpose of the project is to pull a mass uphill under a limited required time. Accordingly, under these circumstances, the conception of speed influenced more than the basic functionality of the gearbox. Figure 7 showcases a design sketch of the gears shown below. Aforementioned, the unorthodox gears showcased constrictions towards the angular velocity of the gears. Nautilus gears are inspired from the shape of nautilus shells found in nature. This intricate gear shape allows for a perplexing visual of gear rotation; consequently, the inherent rotation of this type produces an inconsistency in torque at observed intervals. Moon gears are uncommon and are rarely applied except for distinct operations. Therefore, under these circumstances and constrained time, this concept design was unfortunately declined.

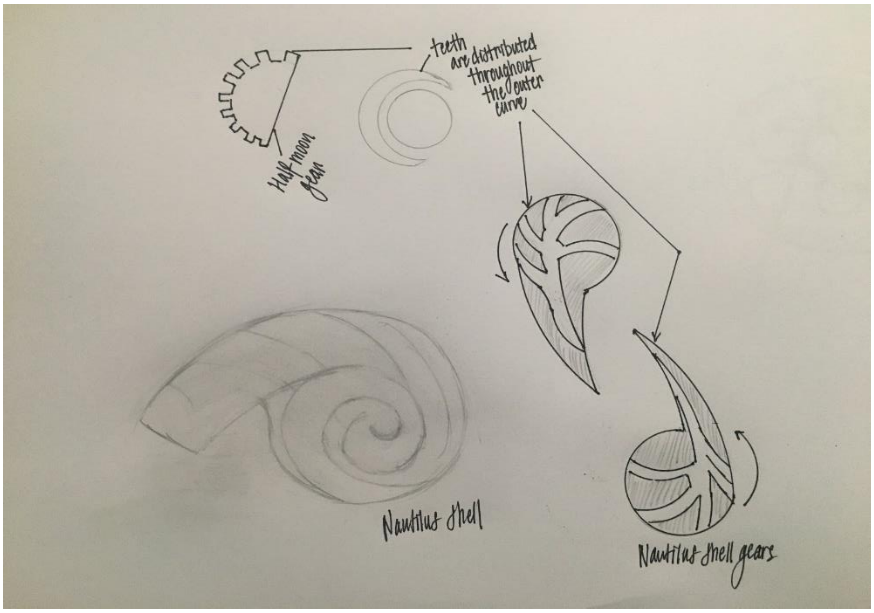


Figure 7. Unorthodox Gear Designs

Design 3: Compound gear system

The final design was decided to be a compound gear system. In terms of manufacturing and assembly, this design was considered to be the simplest compared to the other gear concepts. This design composes of four gears, two pinion and two large gears. The gears are oriented in a C-shape configuration. This configuration was chosen to reduce the length of the gear train. All the gears in the system are pressed fitted into half-moon shape shafts. This unorthodox shape of the shafts was believed to be more beneficial in locking the gears in position rather than a common circular shape. The Mabuchi motor was also given a mount to assist in minimal movement while the gearbox is in operation. Furthermore, string guards were incorporated as a safety measure to keep the string from interfering with the gears. Figure 8 showcases a design sketch of the gear mechanism shown below.

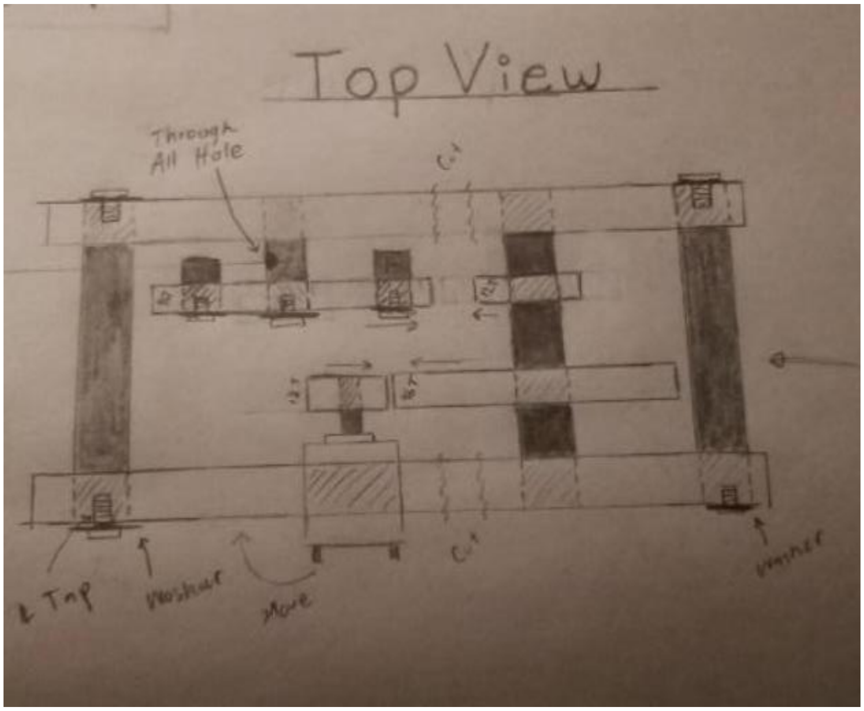


Figure 8. Final Design of Gearbox System

2.3 Assembly/Design Selection

Table 1: Design Selection			
Factors	**Design 1**	**Design 2**	**Design 3**
Materials	1	2	4
Calculations	1	3	4
Manufacturing	2	3	4
Assembly	2	3	4
Production Time	1	2	4
Size	1	2	3
Prediction of Operation	8	15	23
Rubric Scale	Numerical values of 1-4 based on difficulty		
1	Inadequate (complex)		
2	Poor		
3	Acceptable		
4	Exceptional		

***Justification of Gear Ratios are analyzed in results**

Based on the results of the Design Selection Matrix, Design 3 proved to be the most effective in operation compared to the other gear mechanisms.

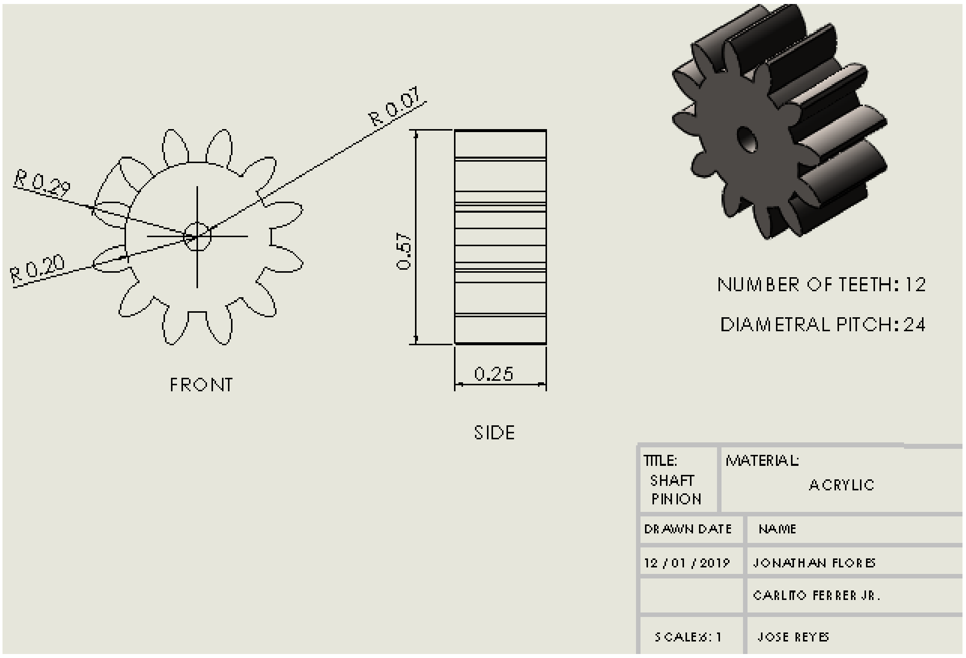


Figure 9: First Pinion Gear attached to Mabuchi Motor

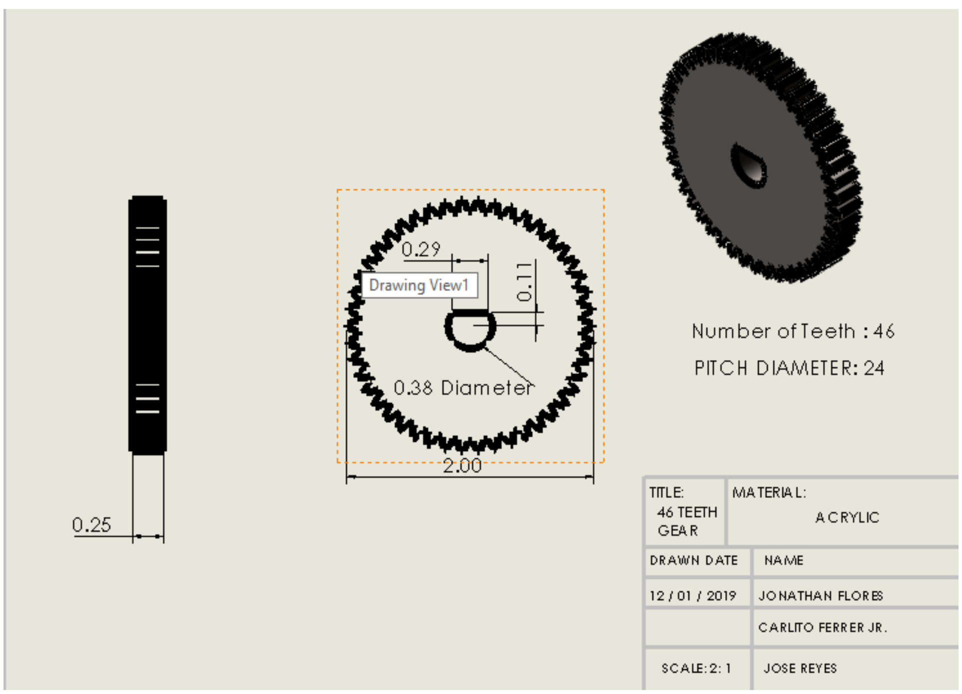


Figure 10: Large Gear

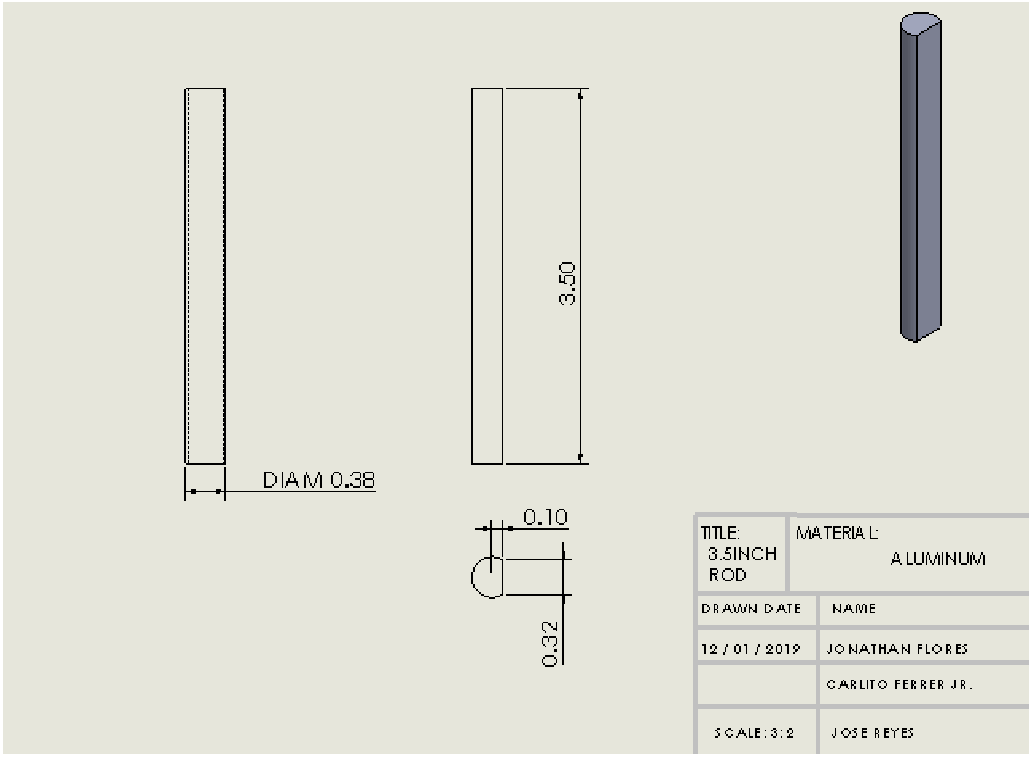


Figure 11: Half-Moon Shaft

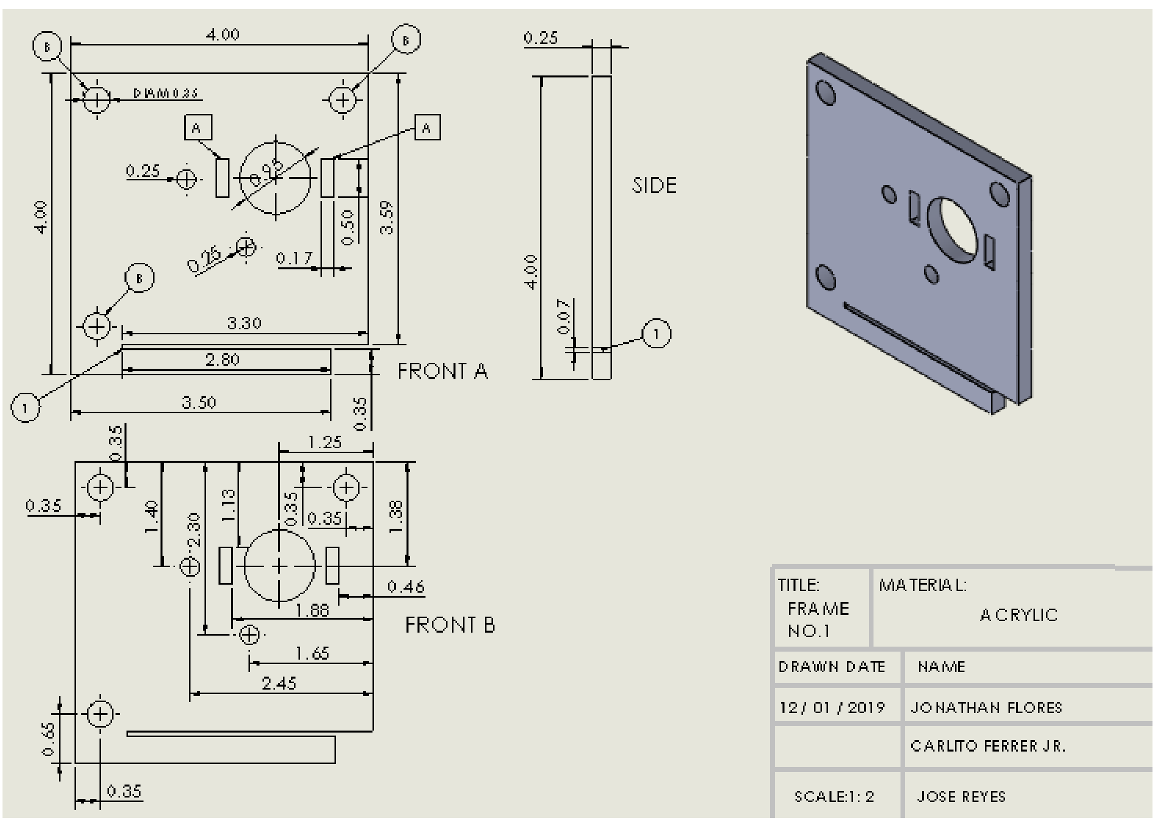


Figure 12: Frame 1 with motor mount slots

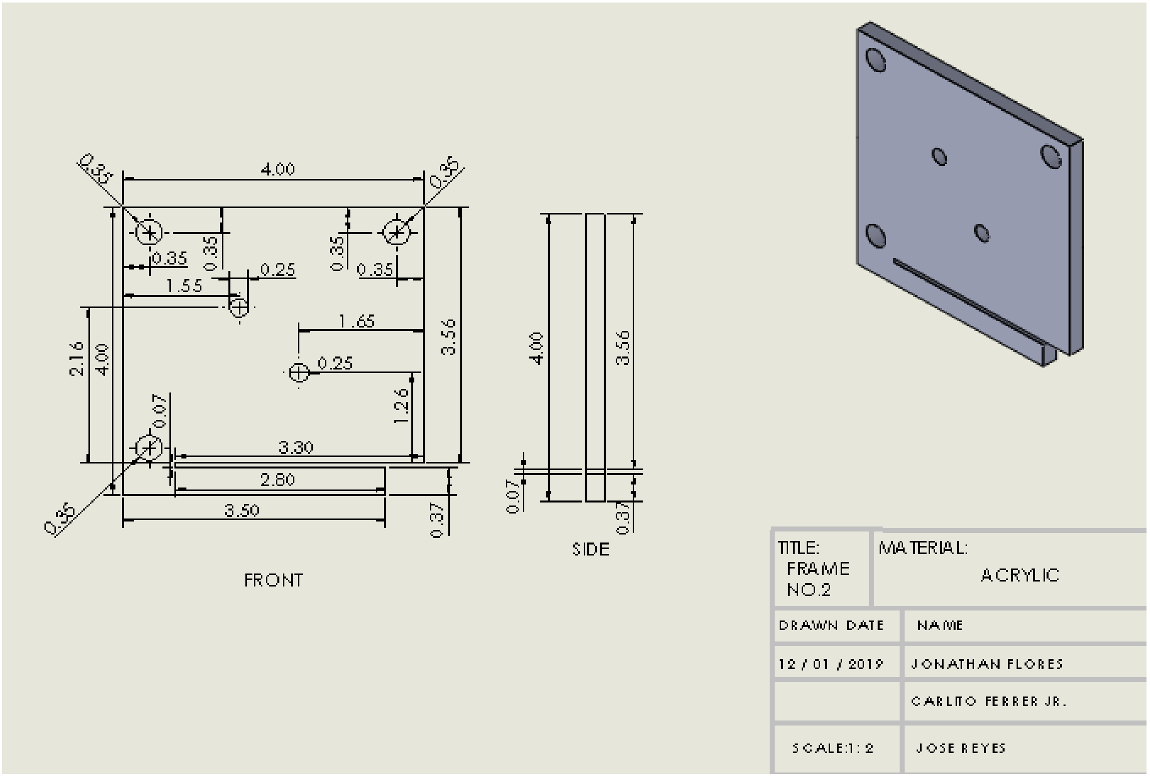
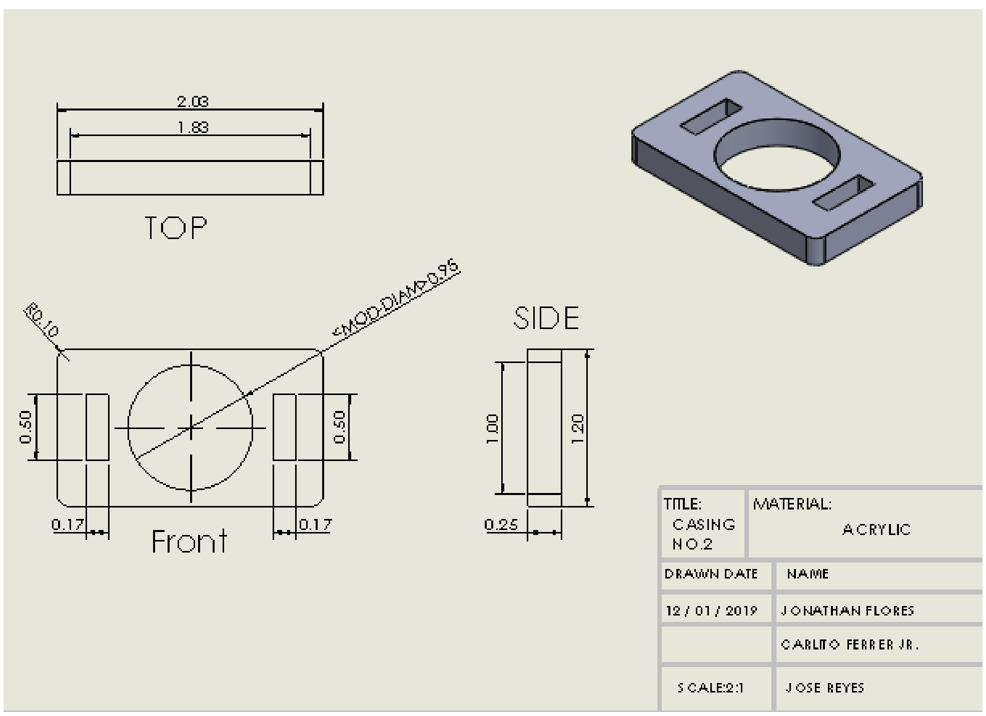


Figure 13: Frame 2



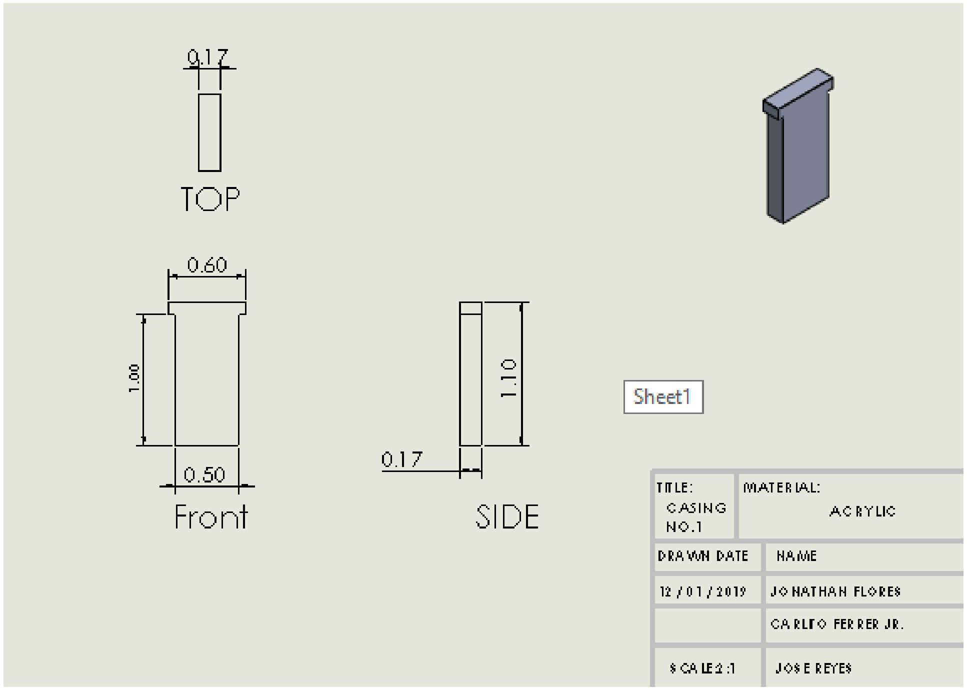


Figure 14: Motor Mount Components

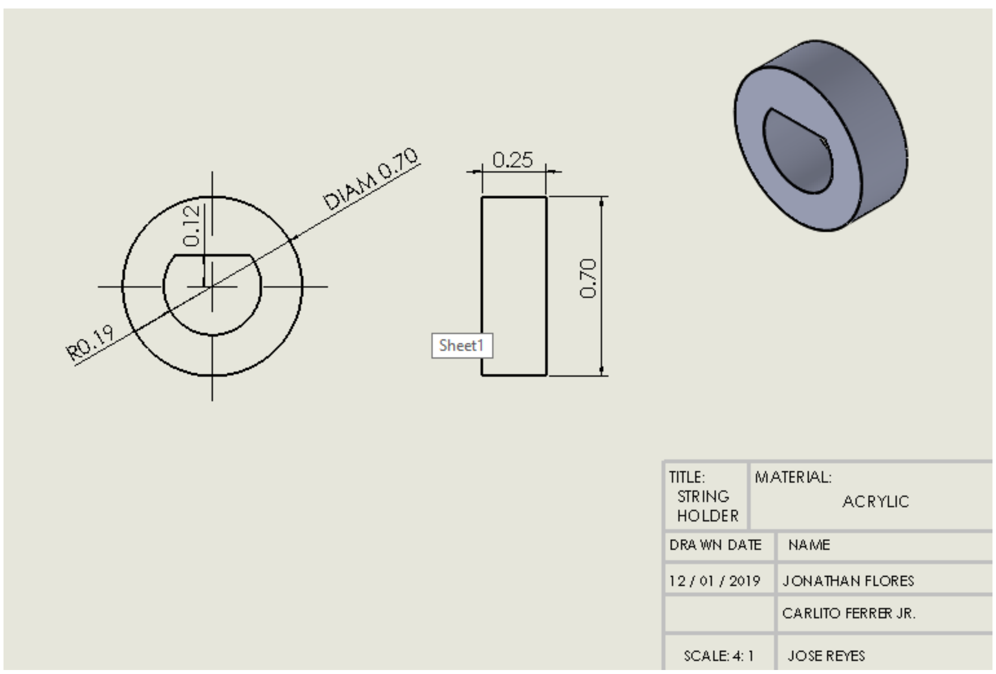


Figure 15: String Guards

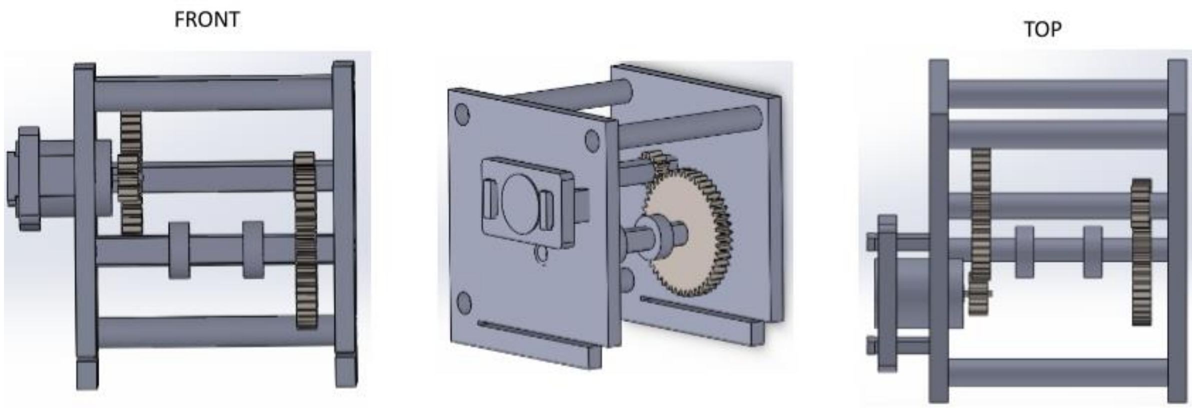


Figure 16: Assembly of Gearbox

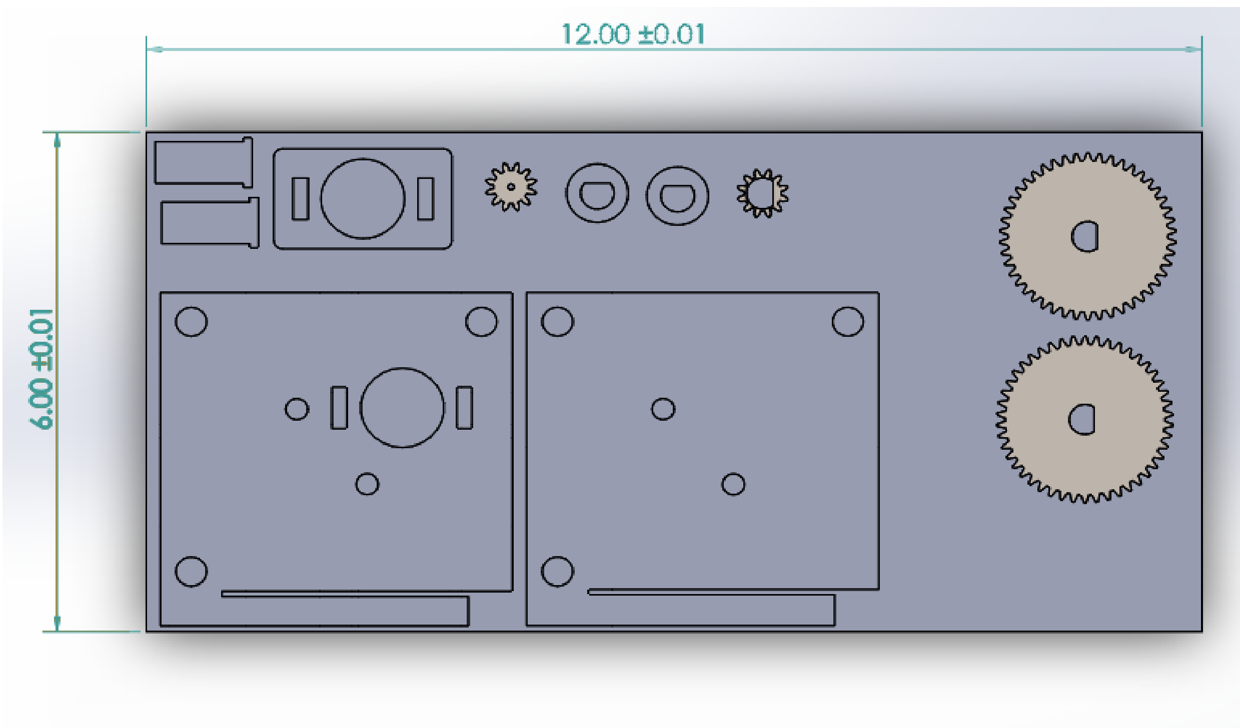
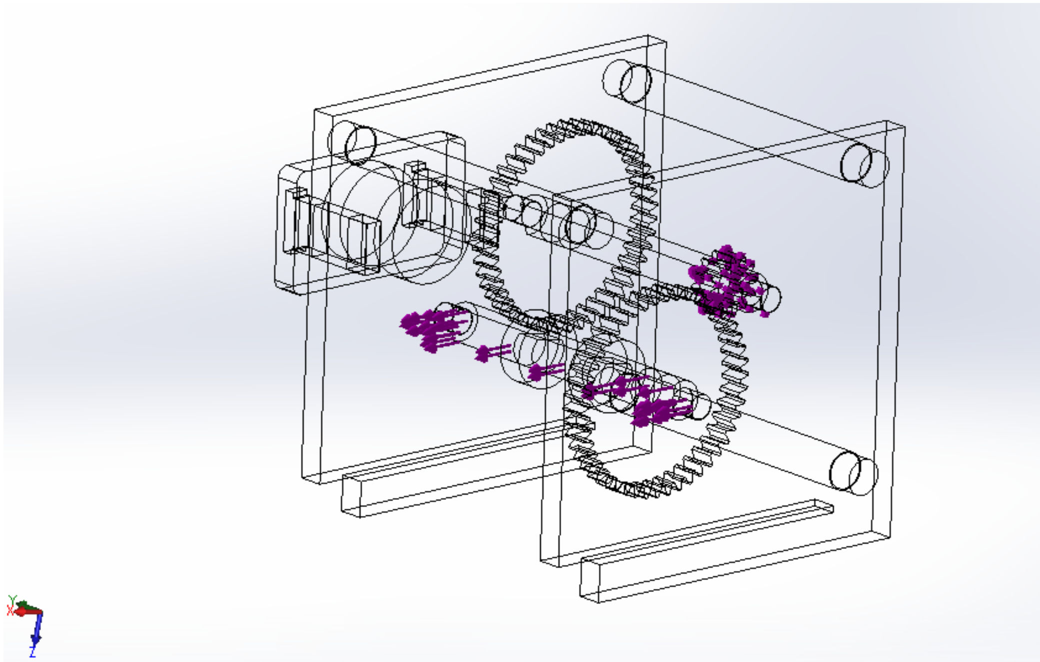
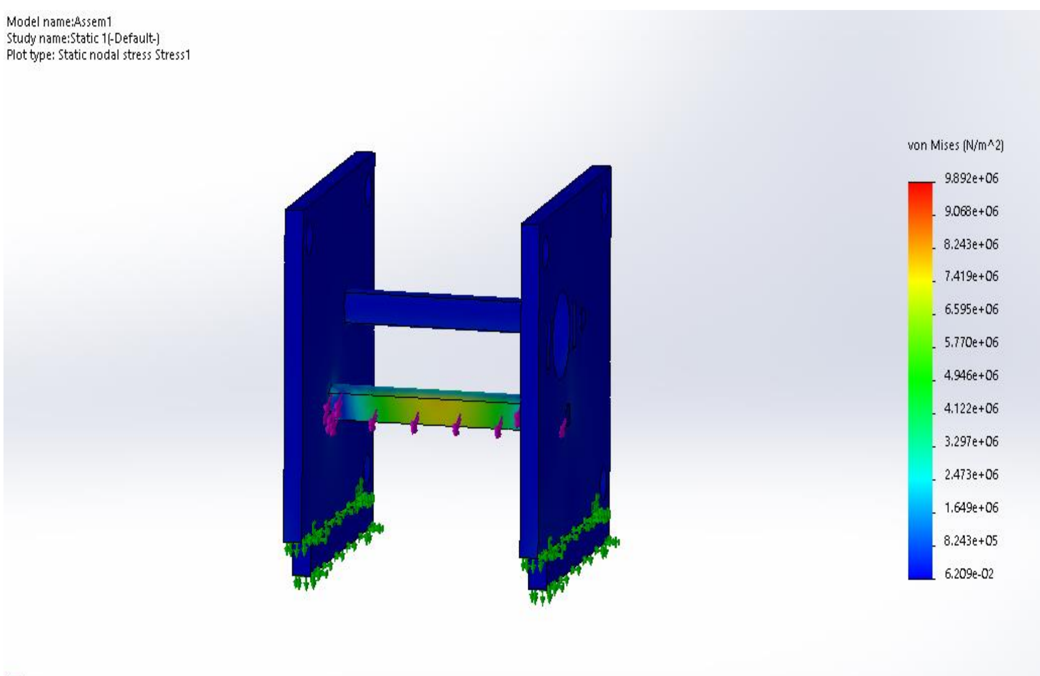


Figure 17: 12" x 6" Acrylic Sheet with all components

2.4 Stress Analysis



(a)



(b)

Figures 18(a-b): Stress Analysis of Gearbox components

Figure 18 displays the stress analysis profile of the simple compound gearbox. Based on observation the three components that are most likely to fail due to stress are the 1st pinion, 2nd pinion, and the aluminum shaft holding the string.

III. Results/Discussion

3.1 Testing and Performance

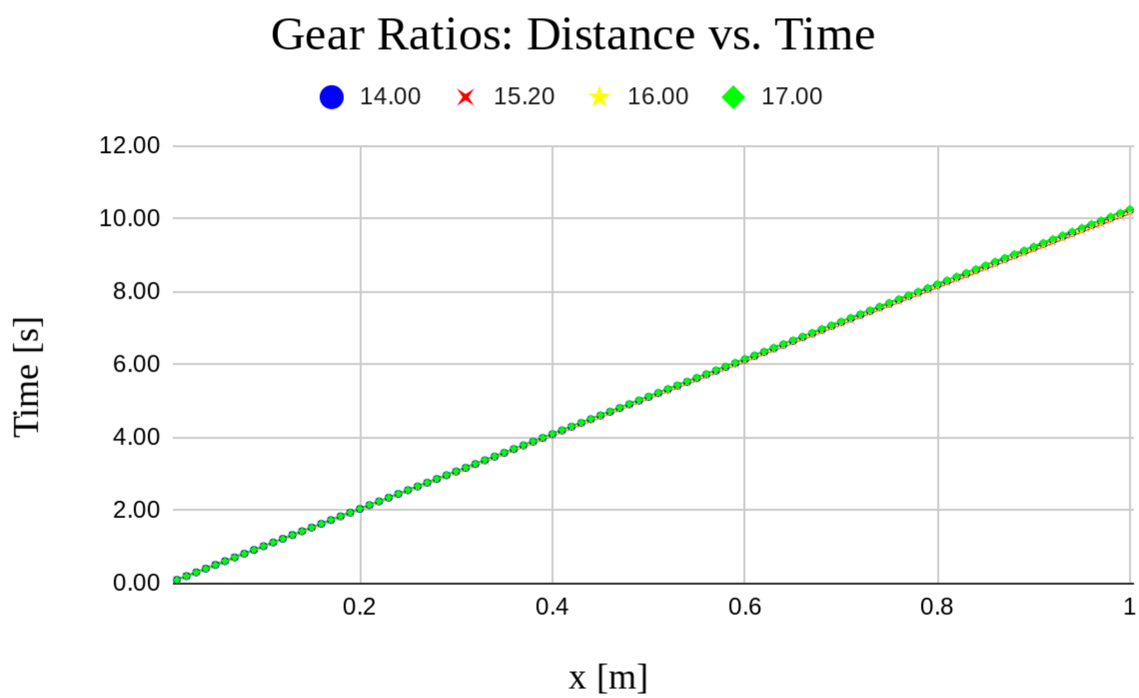


Figure 18. Gear Ratio: Distance vs. Time

Table 2. Gear Ratio: Distance vs. Time				
Gear Ratios				
x [m]	14	15.2	16	17
Time [s]				
0.5	5.12	5.08	5.09	5.14

***See Appendix A for further data points**

Figure 18. displays the distance vs. time graph corresponding to four gear ratios. The difference between the gear ratios are minimal and is further evident in table 2. In table 2. the times in seconds from lowest to highest are the following: 5.08, 5.09, 5.12, and 5.14. Therefore, the gear ratio with the smallest predicted time to pull the 1 kg is 15.2.

The final design of the gearbox system was tested several times to observe a measure of how many seconds the mass would take to travel 0.5 m. The average estimate time ranged between 7-9 seconds. Based on observations, the rods were suspected to have some friction between the frames, reducing the angular velocity of the gears. Furthermore, two of the gears were observed to slide slightly from where they were positioned on the rods; these were the first large gear and second-pinion gear. Therefore, due to this misalignment the teeth between each gear did not mesh together at all times. The incorporation of drilling a hole at the center to guide the string rather than simply tying around the rod showcased positive results. Incorporating string guards also kept the string from disturbing the gears. Although the mass reached the 0.5m mark in under 10 seconds, there is still room for improvement.

3.2 Improvements

To make the simple compound gear system more optimal, the primary focus was to reduce the amount of friction between the shafts and the acrylic frames. One option was to machine the ends of the shafts to a smaller diameter and have a circular shape instead of the half-moon shape. The circular shaped ends provided more stability as the shaft rotated. Another option was to insert washers between the locking rods that held the frames. Ultimately, both options were taken into consideration. Another challenge in optimizing the system was to lock the positions of the sliding gears. First, the cause of the problem was suspected to root from manufacturing the gears using the laser cutter. The multiple cycles of cutting at the same place in the acrylic may have slightly deformed the shape of the gears especially the diameter of the center holes in each gear. Therefore, gears were not fully press fitted into the shafts. As a resolution, multiple O-rings were double inserted on either side of the gears. Although a temporary fix, the translational movement of the large gear and second-pinion was minimal to null. Figures 19-20., shown below displays the gearbox after all the improvements were integrated. Fortunately, the performance time after final testing was ultimately 5.66 seconds; however, although unofficial, the performance time of the gearbox with a lubricant was 4.96 seconds.

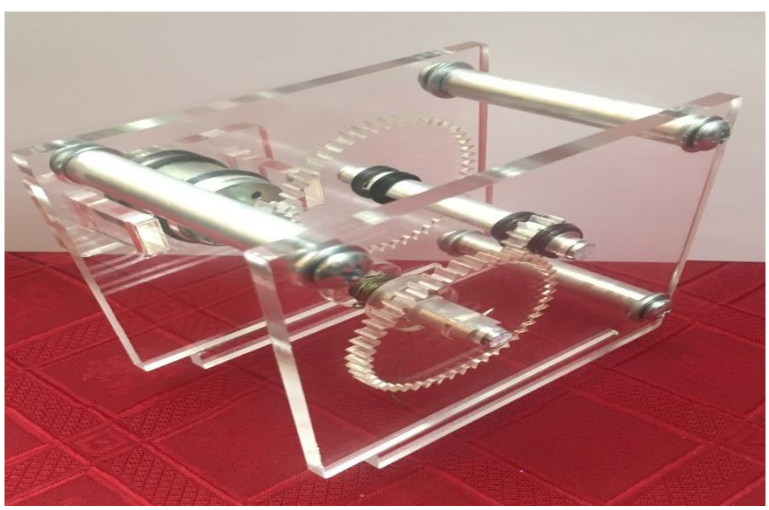


Figure 19: Gearbox System after Improvements

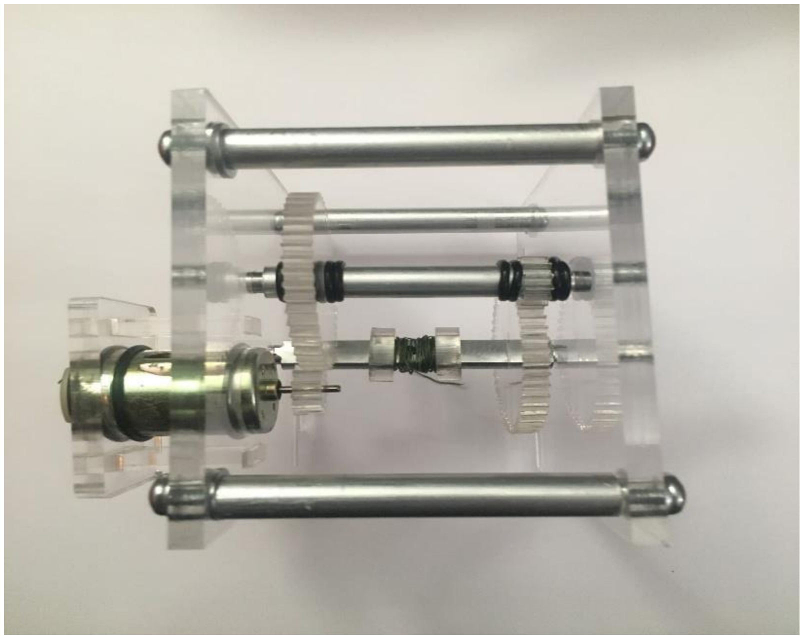


Figure 20. O-rings are wrapped around system components

Figure 21: Team with Professor Nurullah

IV. Conclusion

The time performances of the gearbox with a gear ratio of 15.2 was higher than determined from the calculations. The team suspected this was caused by an irregularity, where the teeth of the gears did not fully mesh together. Possible reasons are the calibration of the laser cutting machine and the number of cutting cycles applied to the acrylic glass that would deform its shape. Overall, the team was satisfied with the final test performance time of 5.66 seconds.

***See Appendix A for Design Competition times**

References

[1] Wickert, J., & Lewis, K. (2013). *An introduction to mechanical engineering* (3rd ed.). Stamford, CT: Cengage Learning.

[2] Molly, H. (1973). *U.S. Patent No. 3,759,639*. Washington, DC: U.S. Patent and Trademark Office

[3] Limer, E. (2017, November 14). 11 of the Most Bizarre Non-Circular Gears You Will Ever See. Retrieved from https://www.popularmechanics.com/technology/gear/g2344/11-of-the-most-bizarre-non-circular-gears-you-will-ever-see/.

Appendix A.

Video links:

Design Concept observations

Unorthodox Gears

https://youtu.be/ixCDIhIC-ZM

Nautilus Gears

https://youtu.be/IUR-T4Nw-Sk

Planetary Gears

https://youtu.be/ePwhYyF2ESY

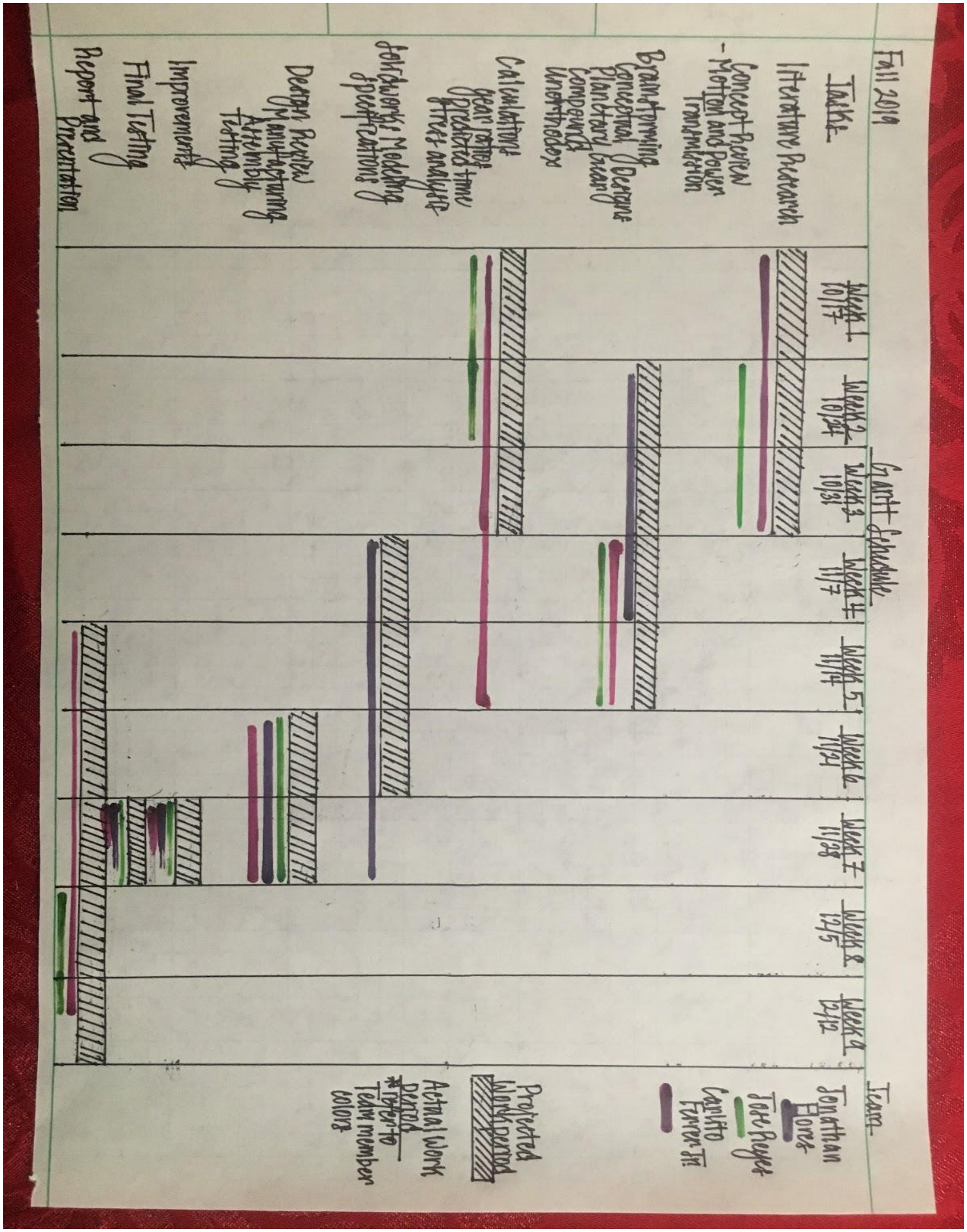
Video of the gearbox link:

https://youtu.be/LsXvEA1grq0

Table 2* Gear Ratio: Distance vs. Time				
Time [s]				
	Gear Ratios			
x[m]	14.00	15.20	16.00	17.00
0.01	0.10	0.10	0.10	0.10
0.02	0.20	0.20	0.20	0.21
0.03	0.31	0.30	0.31	0.31
0.04	0.41	0.41	0.41	0.41
0.05	0.51	0.51	0.51	0.51
0.06	0.61	0.61	0.61	0.62
0.07	0.72	0.71	0.71	0.72
0.08	0.82	0.81	0.81	0.82
0.09	0.92	0.91	0.92	0.92
0.1	1.02	1.02	1.02	1.03
0.11	1.13	1.12	1.12	1.13
0.12	1.23	1.22	1.22	1.23
0.13	1.33	1.32	1.32	1.34
0.14	1.43	1.42	1.43	1.44
0.15	1.54	1.52	1.53	1.54
0.16	1.64	1.63	1.63	1.64
0.17	1.74	1.73	1.73	1.75
0.18	1.84	1.83	1.83	1.85
0.19	1.94	1.93	1.94	1.95
0.2	2.05	2.03	2.04	2.06
0.21	2.15	2.13	2.14	2.16
0.22	2.25	2.24	2.24	2.26
0.23	2.35	2.34	2.34	2.36
0.24	2.46	2.44	2.44	2.47
0.25	2.56	2.54	2.55	2.57
0.26	2.66	2.64	2.65	2.67
0.27	2.76	2.74	2.75	2.77
0.28	2.87	2.85	2.85	2.88
0.29	2.97	2.95	2.95	2.98
0.3	3.07	3.05	3.06	3.08
0.31	3.17	3.15	3.16	3.19
0.32	3.28	3.25	3.26	3.29
0.33	3.38	3.35	3.36	3.39
0.34	3.48	3.45	3.46	3.49
0.35	3.58	3.56	3.57	3.60
0.36	3.68	3.66	3.67	3.70

0.37	3.79	3.76	3.77	3.80
0.38	3.89	3.86	3.87	3.91
0.39	3.99	3.96	3.97	4.01
0.4	4.09	4.06	4.07	4.11
0.41	4.20	4.17	4.18	4.21
0.42	4.30	4.27	4.28	4.32
0.43	4.40	4.37	4.38	4.42
0.44	4.50	4.47	4.48	4.52
0.45	4.61	4.57	4.58	4.62
0.46	4.71	4.67	4.69	4.73
0.47	4.81	4.78	4.79	4.83
0.48	4.91	4.88	4.89	4.93
0.49	5.02	4.98	4.99	5.04
0.5	5.12	5.08	5.09	5.14
0.51	5.22	5.18	5.20	5.24
0.52	5.32	5.28	5.30	5.34
0.53	5.42	5.39	5.40	5.45
0.54	5.53	5.49	5.50	5.55
0.55	5.63	5.59	5.60	5.65
0.56	5.73	5.69	5.70	5.75
0.57	5.83	5.79	5.81	5.86
0.58	5.94	5.89	5.91	5.96
0.59	6.04	5.99	6.01	6.06
0.6	6.14	6.10	6.11	6.17
0.61	6.24	6.20	6.21	6.27
0.62	6.35	6.30	6.32	6.37
0.63	6.45	6.40	6.42	6.47
0.64	6.55	6.50	6.52	6.58
0.65	6.65	6.60	6.62	6.68
0.66	6.76	6.71	6.72	6.78
0.67	6.86	6.81	6.83	6.89
0.68	6.96	6.91	6.93	6.99
0.69	7.06	7.01	7.03	7.09
0.7	7.16	7.11	7.13	7.19
0.71	7.27	7.21	7.23	7.30
0.72	7.37	7.32	7.33	7.40
0.73	7.47	7.42	7.44	7.50
0.74	7.57	7.52	7.54	7.60
0.75	7.68	7.62	7.64	7.71
0.76	7.78	7.72	7.74	7.81
0.77	7.88	7.82	7.84	7.91
0.78	7.98	7.93	7.95	8.02
0.79	8.09	8.03	8.05	8.12
0.8	8.19	8.13	8.15	8.22
0.81	8.29	8.23	8.25	8.32

0.82	8.39	8.33	8.35	8.43
0.83	8.50	8.43	8.45	8.53
0.84	8.60	8.54	8.56	8.63
0.85	8.70	8.64	8.66	8.74
0.86	8.80	8.74	8.76	8.84
0.87	8.90	8.84	8.86	8.94
0.88	9.01	8.94	8.96	9.04
0.89	9.11	9.04	9.07	9.15
0.9	9.21	9.14	9.17	9.25
0.91	9.31	9.25	9.27	9.35
0.92	9.42	9.35	9.37	9.45
0.93	9.52	9.45	9.47	9.56
0.94	9.62	9.55	9.58	9.66
0.95	9.72	9.65	9.68	9.76
0.96	9.83	9.75	9.78	9.87
0.97	9.93	9.86	9.88	9.97
0.98	10.03	9.96	9.98	10.07
0.99	10.13	10.06	10.08	10.17
1	10.24	10.16	10.19	10.28



Gantt Chart Schedule

Design Competition Time (Team Representative Jose)