Design Project

MECH 323 Machine Design (Winter 2024)
Team 49

Team Number	Group 49 - Section 4

Phase Number	Phase IIII

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Executive Summary

The gearbox design process included the design, fabrication, and assembly of a gearbox to fit into a prefabricated test car and compete in two events, a top speed event and a hill climb event. The design was created through several iterations of modeling and simulation and was optimized into a single stage shifting gearbox that exhibits two gear ratios to effectively compete in both events. Within the project, emphasis was placed on creating a gearbox with high performance metrics while adhering to constraints of the project. The final design included an input and output shaft, two pinions, two gears, bearings, and housing. Within the overall gearbox design, a shifting one stage gearbox was decided to allow for two gear ratios, a high one to maximize torque output for the hill climb, and an inversed low gear ratio to allow for maximum RPM output for the speed event. The housing was important in creating proper fitment of the transmission into the car and worked to balance structural integrity with reducing print time through a series of triangular cut outs. There were two shafts included in the design, an input and an output shaft which were designed with considerations of tolerancing, durability, and performance. These shafts have design features of cylindrical shoulders to hold gears and pinions in place, hex sections on which the gears and pinions lay with a friction fit, and a 20 mm extension from the housing with a D cut shaft to ensure proper alignment of the sprocket and applied torque to the shafts. Additionally, the design features four metal bearings on which the shafts lay which ensures limited friction in shaft rotation. Gears and pinions were chosen for their gear ratio and full depth teeth were used to enhance torque transmission and minimize slippage.

To meet design parameters and to ensure constraints such as successful and consistent performance, low print time, ease of assembly, and scalability of production there were several iterations in the evolution of the gearbox design to reach the final design as described above. Additionally, changes had to be made to the design from the previous theoretical design process and the actuation of printing and assembly. This is inclusive of optimal gear ratios initially being chosen based on performance metrics for both events from initial software modeling, however gear ratios had to be adapted due to modulus limitations and clearance issues during the final CAD preparations. Decisions to adjust the gearbox were carefully considered and weighed against other alternatives to find the best solutions. For the instance of the gear ratios, the team opted to modify the gear ratios rather than adding additional shafts thus maintaining the gearbox integrity. These choices, and the gearbox evolutions were successful and led to performance success in both events.

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1.0 Introduction

In the final phase of this project, Phase 4 directed the focus onto modifying the gearbox to be more suitable for 3D printing. Housing for the gear and pinion shafts were designed to meet the dimensional constraints outlined in Phase 1. Modifications of the shaft designs were made to work with a maximum limit of six standard-sized bushings. The keyway features were also changed to hexagonal profiles for better torque transmission. Consequently, the bore holes of the pinion and gear were also adapted to hexagonal profiles to match the shaft designs. This report outlines the evolution of Team 49's gearbox design specifically relating to the transition from AISI 4130 steel to plastic.

2.0 Gear Box Design

2.1 Overall

This gear box design was created to effectively compete in a high torque hill climb event and a high-speed race event. The design was iterated with factors of performance, durability, design complexity, space constraints, print time constraints and ease of assembly as paramount in the creation of the final gearbox. The finalized design consisted of a one stage shifting gearbox with two shafts, two pinions, and two gears. In this design two gear ratios could be used to optimize the performance in both the hill climb and speed events. Design constraints such as fixed shaft locations, print time, and housing dimensions governed the final design and had implications on specific parameters for the gearbox.

2.2 Design

As mentioned above, the overall design is a one stage, shifting gearbox with an input and output shaft and two different gear ratios. This design was chosen to maximize performance in both events, one being a hill climb which required a high output torque, and the other being a speed event, which required a low gear ratio to maximize the output rotation. For success in the hill climb, maximum torque input without causing the DC motor to stall is desired; this in conjunction with a high gear ratio increases the torque on the output shaft which allows the gearbox to climb up the hill. A maximum input torque of 1.9 Nm was used to allow for proper propulsion of the car, without causing the motor to fail, as the motor stall torque is 2.25 Nm. The gear ratio between the pinion and the gear was 2.5, which increased maximized the input torque to 3.01 Nm which led to a theoretical slip angle of 31.3°. In addition to the hill climb, a secondary gear ratio of 0.40 was used for the top speed event. In preliminary design iterations, a gear ratio of 0.61 was chosen, however, as discussed in detail below, physical space constraints and ease of assembly factors led to the top speed gear ratio being the inverse of the hill climb gear ratio. With the same input torque, a low gear ratio allows for a lower input torque and therefore an increased speed. Additionally, by lowering the gear ratio a higher RPM was found for the output shaft which in turn caused faster rotation of the car’s tires, and therefore a faster speed.

2.3 Housing

One factor in the gearbox design was the housing in which the transmission components were located. The purpose of the housing was to effectively contain the pinions, gears, and shafts and to have the gearbox fit snugly into the prefabricated car. With this constraint, care was taken to ensure that proper dimensioning and geometry were used in the construction of the housing. There were four bushings located within the housing to fit the input and output shafts on both sides of the housing which worked to reduce the friction on the shafts and housing. An additional consideration for the housing was in the print time required to construct the housing walls. It was important to consider durability in the housing during testing as torque applied to the shafts could apply a force on the housing while balancing the necessity of cutouts to reduce print time. With these factors paramount, triangular cutouts were utilized to maintain the structural integrity of the housing while also reducing print time. Ease of assembly and disassembly was also considered in the design of the housing as the housing repeatedly must be constructed and deconstructed during the geartrain assembly.

2.4 Shafts

Two shafts, as input and an output shaft each with a pinion and gear were utilized in the gearbox design. These shafts had several shapes across the length with cylindrical shoulders in place to keep the gears and pinions where desired, hex sections where the pinions and gears sit, and a 20 mm extension from the gearbox housing with a D cut to ensure proper fitment of the sprockets which actuate rotation of the wheels. Tolerance was of importance for the shafts as there were several sections of friction fit along the shaft. These consisted of the shaft inside the bushing, a preset dimension, the pinions and gears on the hex sections, and the sprockets on the D cut shaft extension. Had the shafts been dimensioned improperly, successful performance in events would not be possible. A concern for the shafts was the strength under applied torque, especially in sections, such as the D cut, where the shaft had a small diameter. This is of concern as there is a large, applied torque to the output shaft in the hill climb and an insufficient shaft diameter could lead to shaft failure by mechanism of shear.

2.5 Pinions and Gears

The design utilizes two gears and two pinions in the one stage shifting gearbox to transmit torque for each of the events. By using an inverse gear ratio for both events, there is simplicity in production which is an asset for any form of mass production of a gearbox of this design. Additionally, the chosen gear ratios allowed for the use of full depth teeth, rather than stub, as the transmission of torque is not high enough to be of concern for breakage of teeth. This attribute of the pinions as gears has positive effects on the construction of the gearbox as there is increased contact between gears and pinions and there is a decreased risk of slippage, especially when utilizing a friction fit. For the hill climb event, the pinion has eth and the corresponding gear has 37 teeth and the inverse is true for the top speed event.

2.6 Additional Performance Parameters

A module of 1.5 mm was utilized for the gearbox design. This module allowed for an increased number of teeth on the gears and pinions without a notable increase in the physical space consumed by each member. Additionally, in the gearbox design a pressure angle of 20 ˚ which represents the angle between the tooth face and the gear wheel tangent, dictating the point of impact for applied tangential load. With a standard gearbox design with curved teeth this pressure angle is the most appropriate to avoid an increase in applied radial force which could lead to failure in the teeth.

Overall, the gearbox design is intended to function with high performance in both events, with a low print time and with a high degree of reliability. Through the one stage shifting gearbox a variety of performance metrics can be met while adhering to constraints of physical space and ensuring ease of assembly and disassembly, which is impactful for scalability of the design.

3.0 Evolution of Gear Box

3.1 Initial Design Choices

Early in the design process it was decided to make the gearbox a 1 stage shifting design. The main reason for this was that it would reduce mechanical losses in the system. These reduced losses would be in the form of less shafts being needed, and therefore less frictional resistance between shafts and bushing, along with less contact/sliding friction between the teeth of gears. For example, in a basic one stage gearbox design only two shafts are needed, and therefore losses come from 4 bushings and 1 location of contact friction between gears. In a two-stage gearbox, these losses are increased to 6 bushings and 2 points of contact friction between gears. This is a 50% increase in bushing losses and a 100% increase in gear contact losses.

Furthermore, when using the motor torque graph, and having to account for 10 Newtons of expected losses, excluding the gearbox, it was figured that there was minimal room to work with in terms of adding losses, as with too much additional friction the gearbox simply might not run. The only reason to have potentially strayed from a 1 stage shifting, would have been if the gearbox parameters simply did not allow the optimized gear ratios (or something close them) to fit. This likely would be in the form of interference with the gearbox's 10x10 mm cutouts placed at the top and bottom of case, or if a gear/pinion had to stick more than 10 mm out from the gearbox's sides. These key points of interference mostly limited very high or low ratio, where one gear/pinion had to be significantly larger than the other. However, weather this was an issue would be found out as the optimized ratios were decided and the calculations on gear/pinion sizes were made.

3.2 Weights and gear ratio choices

During the writing of phase 1 the option of adding weights to the car was given, this was a key design choice and would greatly affect the cars performance. To figure out the ideal choice, the optimal ratios for all 8 possible scenarios were done (each event with four possible weight options.
In doing this it was found that by adding just one weight to the car it was expected to slow the top speed event from 2.7 second, down to 3.5 seconds (an increase of 30%) This change was even more pronounced with adding a second and third weight, where the car would slow down even further all the way to 6.5 seconds. Meanwhile, at its base weight the car was expected to reach 31.1 degrees in the hill climb, but with the addition of all three weight the expected peak hill climb angle would only increase to approximately 35 degrees. For this reason, no weights were decided on at all, as it seemed to drastically hurt the top speed event but only yield minimal improvement in the hill climb. As such, the car would mainly be optimized for top speed.
With this decided, it was found that a gear ratio of 0.61 was optimal for the speed event while a ratio of 2.5 was optimal for hill climb.

However, as additional calculations were done, slight further changes were found to be need. First and foremost, the gear ratios were found not to be achievable, this was due to modulus limitations and other design parameters. As such they had to be modified slightly and instead ratios of 0.636 and 2.467 (in place of 0.61 and 2.5 respectively) were planned for. This translated to 11 and 7 teeth for the top speed event and 15 and 37 teeth for the hill climb event. At the time this was believed to be the final major design choice needed, with much of the timeline moving forward spent on analysis.

Calculations

Now that a gearbox was designed, in depth calculations were needed to ensure that everything functioned correctly. The first set of calculations included the torques and forces at play in the system. With these it was determined that the maximum torque anywhere in the system would be on the output shaft at 2.43 Nm. This torque would occur during the hill climb event, right before stall. Furthermore, the gear teeth would also be facing their peak force at this time of 127.65 Newtons. To ensure that everything would function correctly, factors of safety were to be determined for both gear and pinion of the hill climb.

These calculations took into account many factors. The first of these is the quality index, a measure of what accuracy is needed in such a system. Since this is a small RC car, that doesn't require high accuracy precision in starting/stopping, it was placed at a level 8, putting it in a similar category as a small power drill. Another such factor is the rim thickness factor, a determinant of the distance between the gear dedendum circle and the outer shaft hole. This measure considers gears that have too thin of a wall, and as such might result in premature warping or cracking. One of the most significant factors in a scenario such as this is the overload factor, this considers any sharp shocks that might be placed in the system. If for example, the car suddenly hit a wall after moving at full speed, a very high force would be placed on the gears for a split second, and, if not accounted for could make them fail. Fortunately, all the scenarios the car would be driven in were known, and no such shocks would be present.

All of these factors and more helped to calculate a resultant factor of safety for bending fatigue failure and for contact/pitting failure. These were calculated for both gear and pinion with the goal of having the lowest FOS be 1.50. Since many of the parameters are already decided, such as material strength, hardness, cycles, etc., very little can be change if one of the safety factors lower than desired. As such, the only factor that can be edited to maintain the systems integrity, is face width. As such, all of the calculations were run at 7 mm face width and then increased until the factors of safety reached a minimum of 1.50. This trial and error could have resulted in another issues, as if the minimum face width was too wide, there would not be enough room in the gearbox to shift between ratios. Fortunately, this did not become a problem and a final face width of 13 mm was ideal.

3.3 Final Cad for Printing

Unfortunately, during the final CAD preparation, a slightly clearance was found. Where the larger gear/pinion of each ratio interfered with the 10x10mm cutouts placed at the top and bottom of the gearbox. As aforementioned, these could not be obstructed and were required for mounting the gearbox in the car. At this point, two options were given for the group, either modify the gear ratios so that they no longer interfere with the cutouts, this would be in the form of having to reduce them (i.e. reduce size of larger gear/pinion, and then increase size of the opposing gear/pinion). Or, the second option was to keep the calculated gear ratios, but this would require adding an extra shaft to the gearbox (converting it to a two stage), this would allow for the gear reduction/increase to be done in steps with smaller gears.

Ultimately the group decided on option 1, as it meant the least amount of the overall design had to be changed. Allowing the previously designed frame, shafts, gear widths, number of gears, and shifting method to all be kept the same. Furthermore, this option allowed the gearbox to stay in line with the main design choice of trying to reduce mechanical losses. Which as aforementioned if an extra shaft had to be added, it would add significant losses into the system. As such, the only design change made was to the number of teeth on each pinion/gear. This meant that the ratios had to be slightly adjusted, but kept the rest of the design the same. Furthermore, by choosing this option, most of the calculations done in previous reports were still valid, with the added benefit of some becoming even more favorable. Such as the factor of safety, where having to slightly reduce the gear ratios reduced the torque in the secondary shaft (mainly for hill climb) and made the design stronger.

Overall, these design choices proved to be well founded. And, in the hill climb, the wheels of the car started to only slip slightly, right as it reached stall height. This was the goal for this challenge and placed the team 18th.
In the top speed event similarly, promising results showed. With a faster than expected speed of 1.700 seconds, placing the team 11th overall, and only 0.28 seconds behind first place.

4.0 Technical Specifications

4.1 Assembly Instructions

4.1.1 Parts List

All parts necessary for assembly of the gearbox can be found in Table 1, within 4.2 Technical specifications summary. These parts include to assemble the gearbox are as followed: two 17-tooth pinions, two 37-tooth gears, a gear shaft, a pinion shaft, one front housing, one back housing, one right housing, and one left housing, and 4 bushings.

4.1.2 Tools Required

Within the construction of the gearbox sandpaper was used to ensure proper fitment of all gears and pinions on shafts and to allow for a friction fit of shafts to bushings. No other tools were required for assembly of the gearbox, as high tolerance fits were used to connect all sides of the housing, as well as shoulders to prevent the bushings from sliding out.

4.1.3 Assembly Summary

The gearbox was designed to be assembled by hand without the use of tools. Depending on the 3D printer resolution, some pieces will need some minor sanding to achieve the optimal fit and to fit within the filament. Steps take to assemble the gearbox are:

1- Place the both the front and back of the gearbox onto a solid surface with the shoulder of the shaft holes on the side of the housing resting on the surface. Place one bushing inside each hole, and ensure they are fully pressed into the housing.
2- Orient the pinion shaft so the d-shaft is on the right side. Slide a pinion onto the left side of the shoulder, making sure the hexagon of both pieces are aligned. Then slide a gear onto the right side of the shoulder. Again, making sure both hexagons are aligned before applying force.
3- Orient the gear shaft so the d-shaft is on the right side when looking at it. Then slide the second gear all the way to the shoulder, making sure both hexagons are aligned. Then slide the second pinion all the way down the shaft, but stopping before the gear and pinion touch, making sure both hexagons are aligned.
4- While both shafts are still oriented to have the d-shaft on the right side, place the left side of both assembled shafts into the holes on the back housing. Making sure they fit withing the inner

diameter of the bushings. Noting that the pinion shaft is in the hole on the left side of the housing.

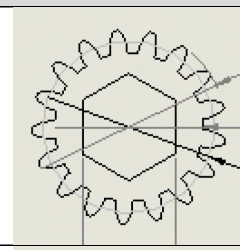
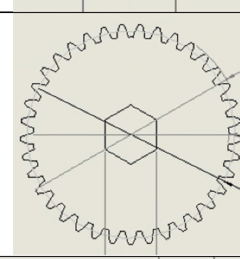
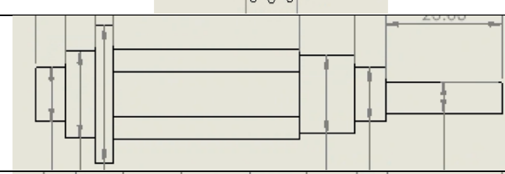
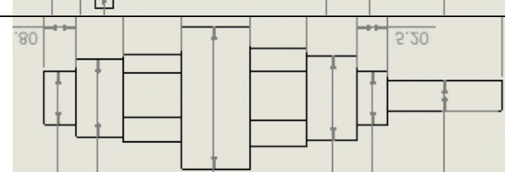
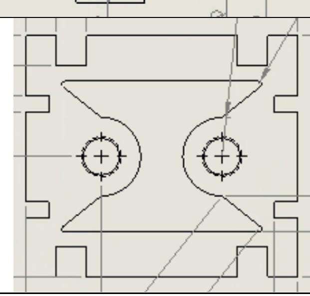
5- Attach both the left and right housings to the back housing by snapping the prongs into their respective slots. Ensuring that the right and left housings are flush with the back housing.

6- Attach the front housing to the rest of the assembly, making sure that the shoulder of the shaft holes are facing outwards before sliding the d-shaft through. As well as ensuring that the right and left housings are flush with the front housing after attachment.

7- Check that both shafts can spin freely, and that both sets of gears can interface correctly, while also being able to be connected and disconnected smoothly.

4.2 Technical Specification Summary

Table 1: Sample parts list

Part #	Name	Quantity	Description	Drawing
1	17-tooth Pinion	2	Small pinion receiving speed for the top speed test, and transmitting torque for the hill climb test	
2	37-tooth Gear	2	Large gear transmitting speed for the top speed test, and receiving torque for the hill climb test	
3	Gear Shaft	1	Shaft transmitting torque from the gears to the output pulley	
4	Pinion Shaft	1	Shaft receiving torque from the motor's input pulley	
5	Front/Back Housing	2	Front and backside of the gearbox's housing	

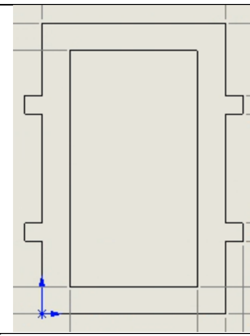
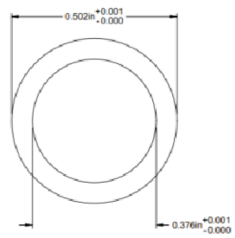
6	Left/Right Housing	2	Left and right side of the gearbox's housing	
7	Bushing	4	Bushings to allow the shafts to rotate with minimal resistance	

Table 2: Technical specifications summary table

Gearbox Technical Specifications	Value	Units
Gearbox Type	Stage 1	-
Motor Operating Torque – Hill Climb	1.9	Nm
Motor Operating Torque – Top speed	1.9	Nm
Pinion Lowest Safety Factor	10.3	-
Gear Lowest Safety Factor	23.3	-
Gear Ratio – Hill Climb	2.5	-
Gear Ratio – Top Speed	0.4	-
Print Time	7.32	Hours
Gearbox Footprint (L*W*H)	432000	mm

5.0 Future Work Recommendations

Given the limited twelve-week timeframe allocated for this project, the complexity and scope of development were constrained; however, for future iterations of this project, there are several recommendations aimed to optimize the vehicle performance. Transitioning from a single-stage gearbox to a two-stage gearbox is highly recommended as this would allow for higher gear ratios that would optimize torque output for both events. Further analyses and simulations to optimize gear ratios for the specified events could enhance power transmission efficiency and overall performance. The utilization of helical gears would also be recommended, as this shape increases the strength and can handle greater loads compared to spur gears. One may also consider integrating some sort of lubrication system to help maintain its functionality over a longer period, ultimately reducing wear and minimizing the risk of component failure. Lubrication will also reduce friction, resulting in smoother operation and prolonged gearbox lifespan. The exploration of other materials and manufacturing techniques would also be advised. The adoption of materials with better mechanical properties could improve strength-weight ratios. Another future consideration would be to refine the layout and packaging of the gears, bearings and shafts to minimize weight and reduce mechanical losses. Finally, more testing and validation of the designed gearbox would help provide valuable insights into the performance and reliability of the gearbox design facilitating further refinement.

6.0 Conclusion

Upon development a gearbox suitable for high torque hill climb and top speed events. Transitioning from AISI 4130 steel to plastic for the gearbox involved modifications to the CAD schematics to accommodate for 3D printing, while maintaining functionality and reliability. Key design choices such as opting for a one-stage shifting gearbox to reduce mechanical losses between events, and optimizing gear ratio for different events, contributed to the overall success of the project.

Despite encountering challenged during the final CAD preparations before printing, informed decisions allowed for the insurance that the gearbox designing not only aligned with objectives set, but also allowing it to fit together smoothly. Opting for designs which allowed for minimal changes to the overall design without major mechanical losses. Allowing for the maximum achievable results in both the hill climb and top speed events.

Future recommendations for the future iterations of this project include transitioning to a two-stage gearbox, allowing for higher gear ratios to be achieved. While also exploring the use for helical gears, increasing the strength of the design, or even lubricating the system to improve performance and longevity should the gearbox be in constant use. Lastly refining the layout and the overall packaging of components to minimize the weight and decrease any mechanical losses there might be. Further testing of the gearbox design will be essential for continuation and improvements for the optimal performance and reliability in the future.

References

Appendix A – Drawing Package

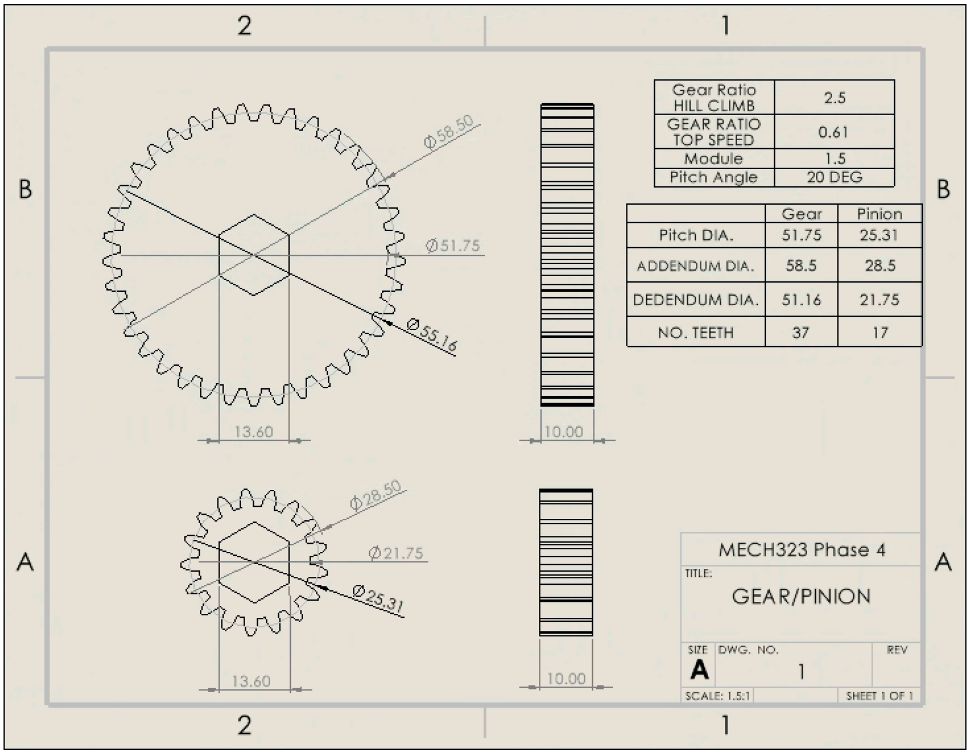


Figure 1: Fully dimensioned gear and pinion designs. With relevant parameters when machining the gears

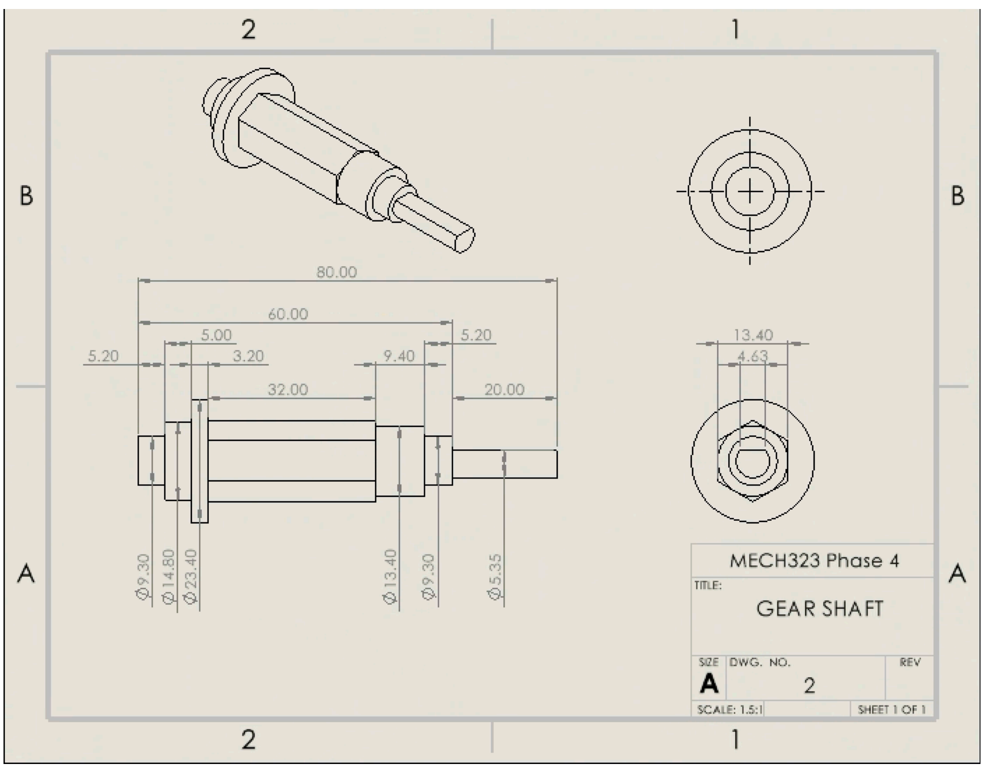


Figure 2: Fully dimensioned drawing of the gear shaft. Drawing includes the front, back and right views, as well as an isometric view of the part.

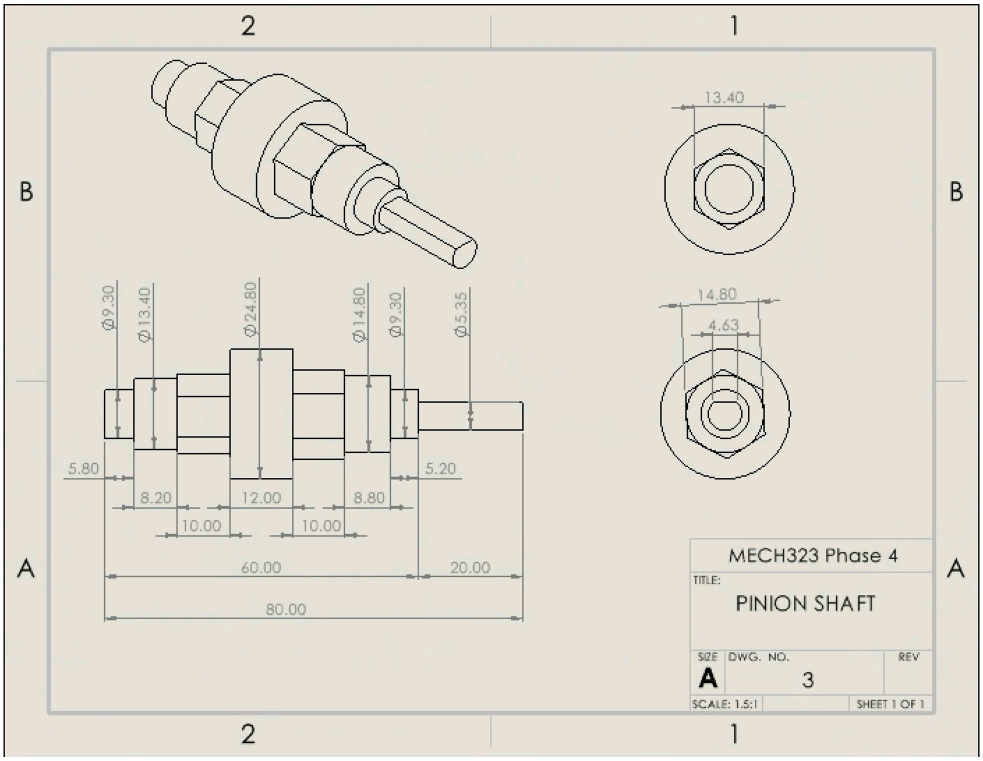


Figure 3: Fully dimensioned drawing of the pinion shaft. Drawing includes the front, back and right views, as well as an isometric view of the part.

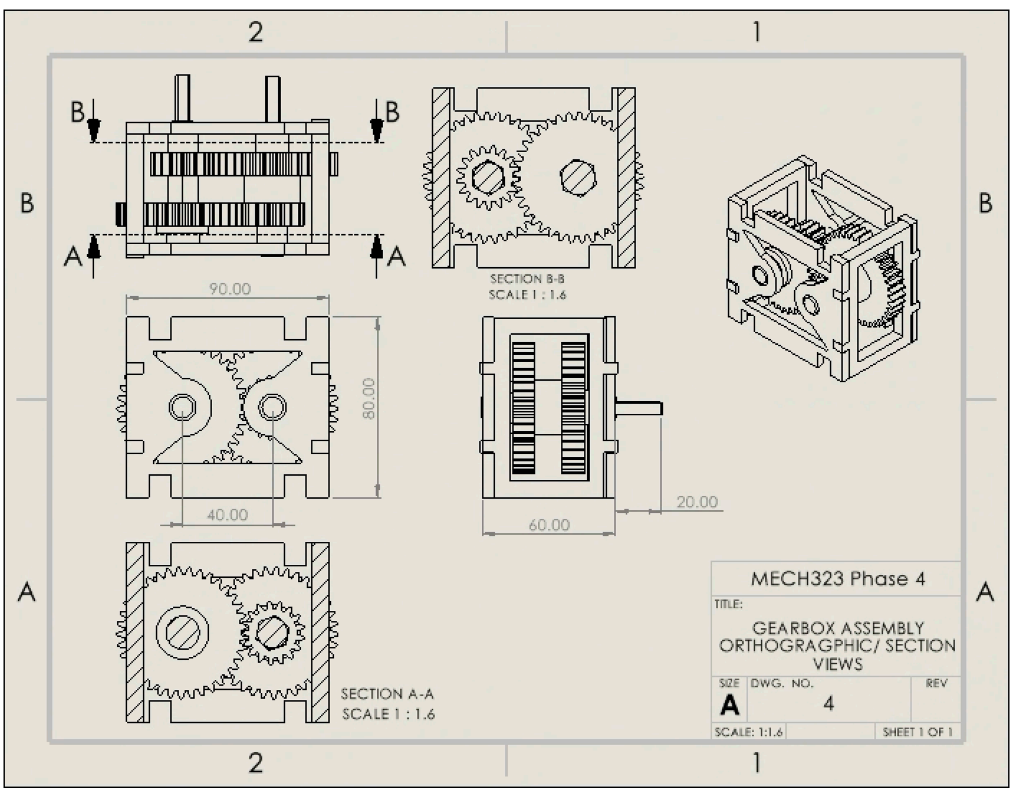


Figure 4: Orthographic, section, and isometric views of the gearbox with all relevant design criteria shown. Such as design parameters, fully assembled housing dimensions and d-shaft protrusion distance.

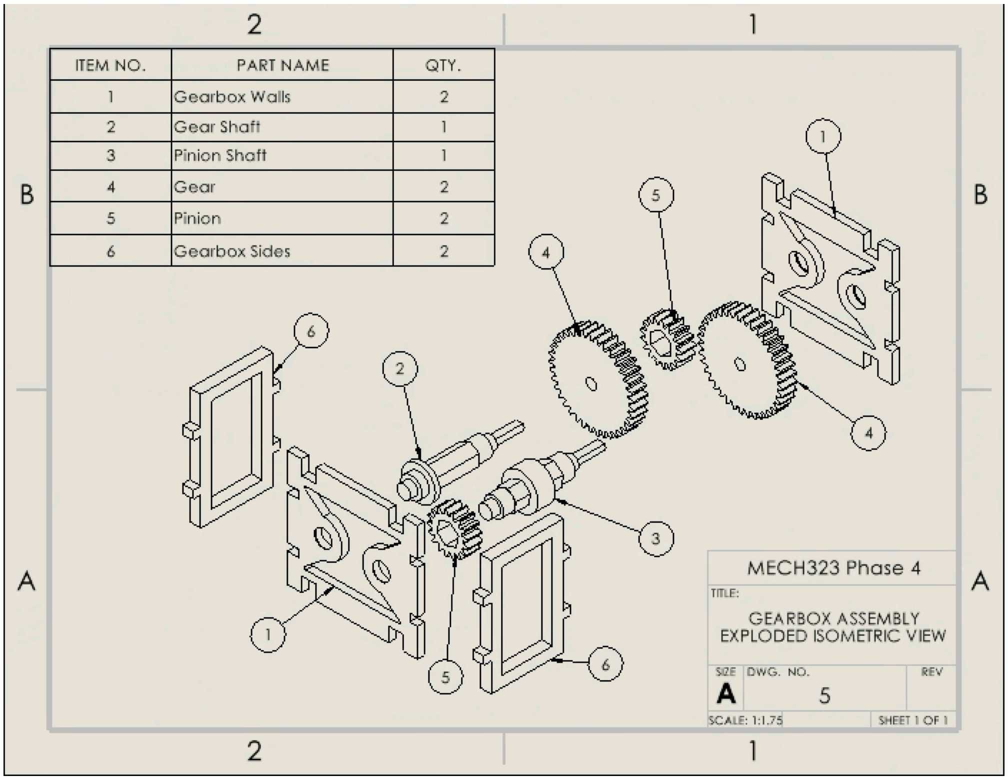


Figure 5: Exploded isometric view of the fully assembled gearbox, highlighting all gearbox parts with numbers and their respective names and quantities

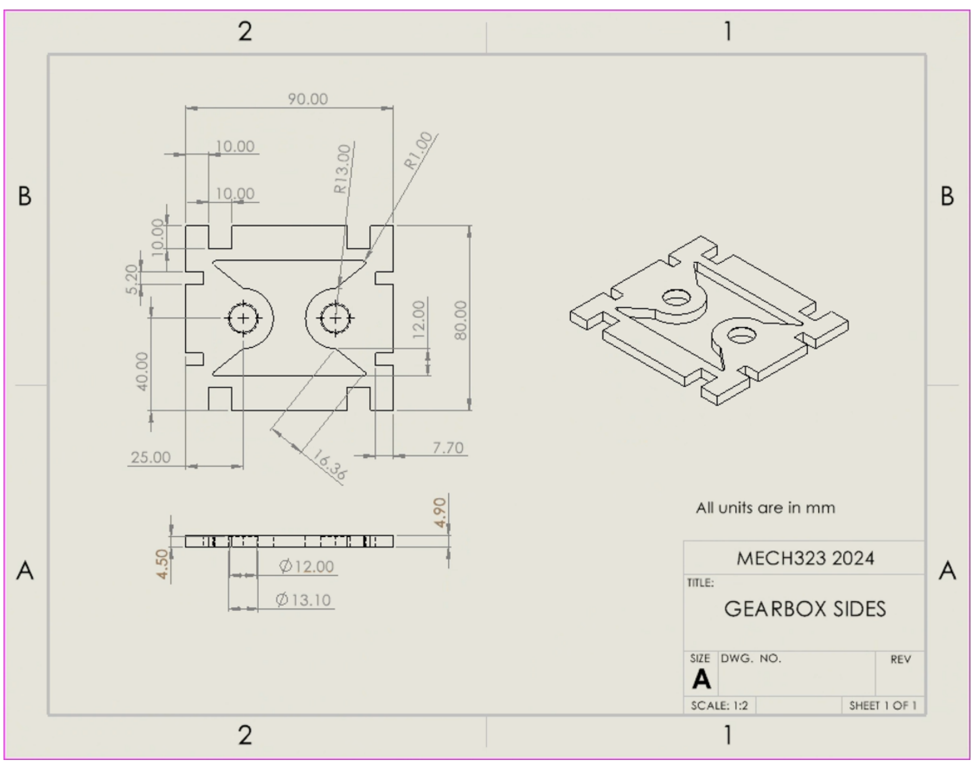


Figure 6: Fully dimensioned drawing of the housing's front/ back sides. The drawing includes front, top and isometric views, highlighting the dimensions for the bushing's placement

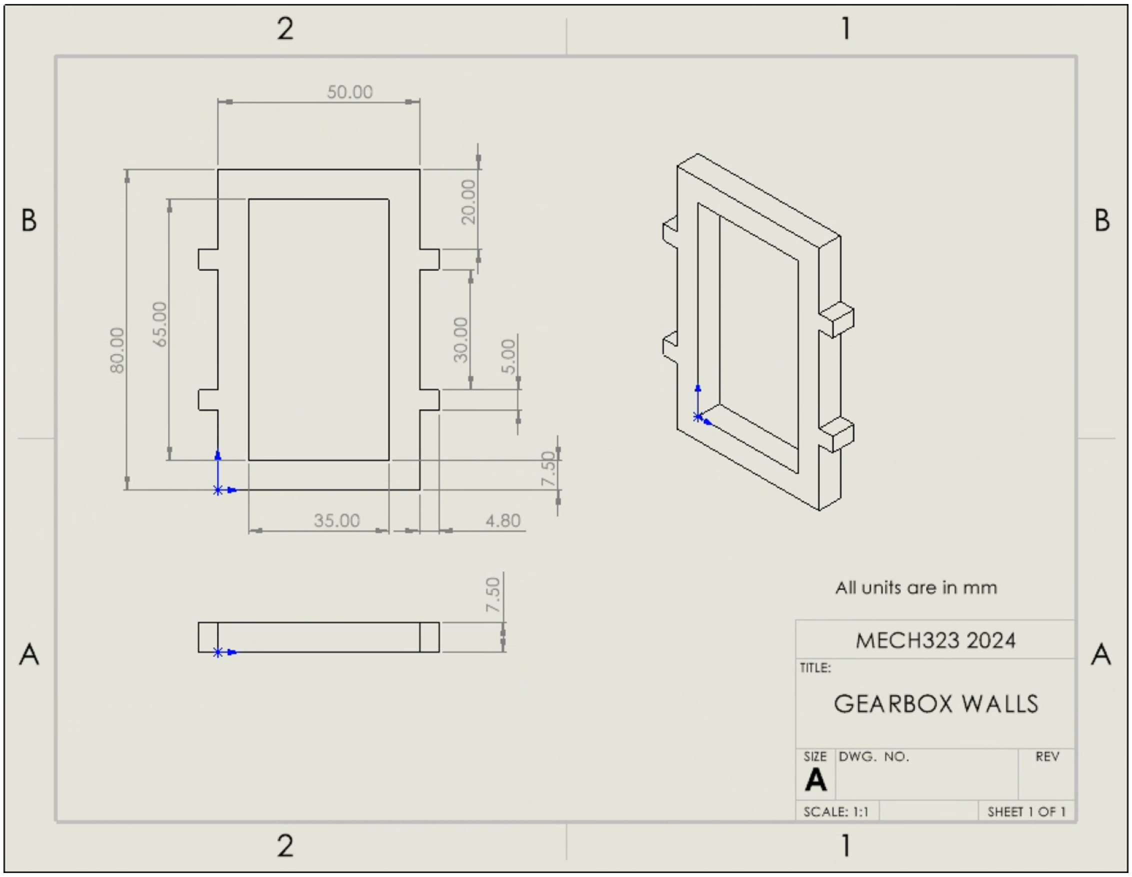


Figure 7: Fully dimensioned drawing of the housings left and right sides. The drawing includes front, top and isometric views of the part.

Phase 4 Summary Page

(Attach to the end of your Phase 4 Report on a separate page)

Team Number	**49**

Phase Number	**IIII**

Global Design Characteristics		
Gear Box Parameters	**Number of Stages**	**1**
	Speed Gear Ratio	**2.5**
	Hill Climb Gear Ratio	**0.4**
Vehicle Weights	**Total Number of Weights**	**0**

Predicted Event Performance		
Speed Event	**3m Top Speed Zone Time (s)**	**1.7**
	Top Speed (m/s)	**1.1**
	Motor Operating Torque (Nm)	**1.9**
	Motor Operating Speed (rpm)	**50**
Hill Climb Event	**Distance (m)**	**0.57**