Swerve Drivetrain

QVEX

Group 737 Team A

Arandjel Dimitrijevic

Joellie Duffy

Megan Marshall

Avery McFadden

Logan White

Evelyn Morin

Zach Elman

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"We do hereby verify that this written report is our own individual work and contains our own original ideas, concepts, and designs. No portion of this report has been copied in whole or in part from another source, with the possible exception of properly referenced material"

Executive Summary

When competing in VEX robotics, an effective and efficient drivetrain design is crucial to a team's success. The QVEX team is interested in the use of a swerve drivetrain as this design produces a higher torque resulting in better competition results as opposed to other drives. A swerve drivetrain allows each wheel to have free rotation while being able to move forward. There are many configurations of the swerve drivetrain such as the direct, transmission, and differential drives. Through a decision matrix, the differential design was chosen over the direct and transmission due to their wiring and spacing challenges. Although this design is complex, its low profile and cost will give the QVEX team an advantage.

The differential drive has many 3D printed parts and can be easily implemented with the existing robot. The design features two aluminum mounting plates that encased the motors, wheels, and function as the mounting points to the chassis. There are also two gears (upper and lower) powered by a pinion gear attached to the motor shaft that provided torque through rotation and turned the robot by rotating at different speeds.

Custom base gears were designed to cater to the four-inch omni-directional wheel and the VEX generic chain and sprocket kit. The specific relations and measurements of these gears were calculated using research about VEX parts as well as bevel gears. The motor mounts and plates were also custom designed to account for specific height requirements, hole placement, and compatibility with the gear system.

The construction of the physical prototype was completed with some alterations due to unforeseen compatibility issues. The QVEX team was consulted to supply certain VEX parts, but the omni-directional wheels had rollers that exceeded four inches in diameter, and they were only able to supply high-strength chains. As a result, the design was altered to use a gear in the place of chains and a standard 4" wheel instead of an omni-directional one. The mounting plate and virtual model were updated to agree with the new design.

Testing was completed on the virtual model through various Solid works simulation software that analyzed the model's motion, static capability, and sustainability. These sections and the financial analysis were all tested and scored appropriately based on quantifiable specifications that the group set earlier. All sections were scored from one to five, with a score given by how well the model performed in each of these sections. As a result, a scaled equation was used to combine the four sections into one number that determined whether the model was a successful swerve drivetrain. The model received a cumulative score of 3.4, meaning that client expectations were met and, in some cases, exceeded. For further implementation, it is recommended that the gear system is scaled for the omni-directional wheel and all metal parts are welded during construction.

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Part 1: Key Information for Clients

1.1 Problem Statement and Scope Definition

Problem Definition

VEX Robotics is a competition in which two teams of robots will attempt to score as many points as possible during the match to beat the opposing robots. During the latest competition, VEX points can be scored by placing rings on towers and moving the towers to a team's respective base. For many years VEX competitors have had two main drive trains, the tank drive and X drive configuration. The tank drive has more pushing power by keeping the wheels parallel to the direction of movement, whereas the X drive has less torque, but it can move and strafe in any direction. Alternately, the swerve drivetrain design can move in any direction with the wheels parallel to the movement allowing it to maximize the pushing force of the robot. The QVEX team is requesting a swerve drivetrain design as it will elevate their performance in competition in multiple ways.

Problem Scope

With the given time and expectations from both the client and project manager, the group completed a CAD model of the swerve drivetrain that was tested through various simulations. The team physically constructed a quarter of the model to ensure that the physical prototype results resembled the ones obtained from the virtual testing simulation.

Client's Needs

The client requested a swerve drivetrain, 18" x 18" in size, as noted in the VEX robotics competition guidelines. QVEX also requested that the drivetrain could maintain constant orientation while having complete operation mobility at no loss of speed or power. Since space was limited, the model required optimization in size, limiting moving parts and sturdiness. The client also suggested looking into gear ratios and power transfer methods to succeed in designing a successful drivetrain. As a final deliverable, a CAD (Computer-Aided Design) model of a single section of the drive was created and evaluated. Upon completion of the CAD model, a real version of the swerve was created. The model had to be tested as well, either using MATLAB or by physically building the model and completing testing in person. The swerve drivetrain was specifically chosen to maximize power and mobility, resulting in a more agile and competitive robot.

Constraints

- The drivetrain must be able to be built for under $100 and as light as possible (mostly 3D printed parts except for chassis and shafts)
- The drivetrain must be able to produce enough power to compete against other robots.
- All parts must be able to attach to the chassis without interfering with existing components
- The chassis cannot exceed 24" x 24"
- No more than 12 motors can be used while eight is the recommended amount

Functional Requirements

- Be able to switch between modes/directions of movement quickly and efficiently.
- Be able to have the wheels parallel to the direction of travel to maximize power like a Tank drive
- Be able to strafe and move in any direction like an X drive
- Be legal in competition
- The prototype is of at least one section of the drive
- Minimum 4 motors, maximum 12 (ideally 8)
- Build is recommended under 18” x 18”

Relevant Stakeholders

Table 1: Table of stakeholders and their influence towards the project

Stakeholder	Influence on the design process
QVEX	The team will use the design in competition, and it can improve their gameplay. Success in the competition will encourage more students to join the club and will increase funding from the university. The team has set out design requirements for elements they are looking to include such as wheels that are able to rotate independently and the robot is able to move in diagonal lines. The requirements laid out will ensure the drivetrain is compatible with the rest of their design.
VEX Robotics	The rules set out by the VEX robotics competition will constrain the design in terms of chassis/drivetrain size and available components.
Opponents	The opponents are looking to defeat the QVEX team by designing a robot with more torque, higher speeds, and greater ease of maneuverability. The clients' design must be stronger than the opponents in all aspects to defeat them. Since some opponents are expected to use tank-style drivetrains with more torque, this design must be optimized to have the ability to deliver as much torque as possible to maintain proper positioning while the opponent is attacking. The stake of the opponents overlaps with the stake that the Faculty of Engineering and Applied science holds. For the design to be superior to all opponents, it may become very costly and require materials the university isn’t providing.
Queen’s University Faculty of Engineering and Applied Science	The faculty will be investing in the QVEX design and gameplay. The design will need to be within the designated budget set out by the University. If the team is successful in their quest to build a robot containing a swerve drivetrain, it will provide the university with publicity, and presents the potential for the school to draw in more students eager to work and compete with QVEX. The stake of the faculty will overturn the stake of the opponents, without the funding provided by the university, the QVEX team would not be able to develop the design and compete.

1.2 Background Information

Drivetrains

Designing any type of drive train poses the challenge of getting the power from the motor to the wheel. One way of transferring this power is using an indirect transmission system by attaching a belt to the shaft of the DC motor, then attaching that belt to the shaft of a caster. This can also be achieved using bevel gears which results in the motor undergoing far less stress [1]. In the chosen design, it means that the belt can be attached to the motor and then connected to the large driving gears that will be surrounding the wheels. While modifying the gears, the goal of having the swerve drivetrain with all four wheels turning, steering, and driven independently is still the number one priority. This allows the robot to move in any direction with its full pushing force, as the wheels can be parallel to the direction of movement. For a traditional swerve drivetrain to operate, there needs to be one motor to spin the wheel forward and one to pivot the wheel and change direction [2].

Swerve Drivetrain

An issue commonly associated with swerve drivetrains is the lack of power output when the robot is turning [3]. This disadvantage can be minimized with the use of a differential swerve drive configuration. A differential swerve drivetrain has many advantages, such as it can use both gears to drive, which will allow the robot to have more power. This design takes advantage of the power output of the differential systems which will allow the team to spin the top gear and bottom gear at different speeds, effectively turning and powering the robot simultaneously. Another advantage of this design and using 3D printing is that it allows the drivetrain to be very compact as the larger gears can be placed very close together [4]. One drawback of the swerve drivetrain is that the mass is significantly higher than other drivetrain configurations [5]. The weight can be minimized by 3D printing as many parts as possible.

Modeling

For modeling, the program SolidWorks is the most accessible and simple platform to use. The generic VEX parts (gears, belts, motors) can be downloaded and imported from any VEX CAD library which reduces design time since these parts can be complicated [6]. To simplify the online model creation, SolidWorks offers its own robotics section within the software that allows for simple and effective VEX construction [7]. SolidWorks also offers e-drawings that can be used to clearly show the client how the design operates from multiple angles, and if a physical prototype is not able to be constructed, these drawings can be used for the QVEX team to easily build it themselves.

1.3 Design Solution

The chosen design was the differential swerve drive. This was chosen based on criteria identified in the decision matrix, as seen in Table 3. More specifically, after many conceptual iterations, the team settled on the design see in Figure 1 and Figure 2.

In this design, the drivetrain is supported vertically using ball bearings placed on axles. Custom horizontal gears were designed with a groove on the outside for the bearings sit in to allow free, mostly frictionless movement. The two base gears are powered by motors that are mounted to the top mounting plate using custom motor mounts. The motors turn chains that interlock with teeth on the outside of the base gears.

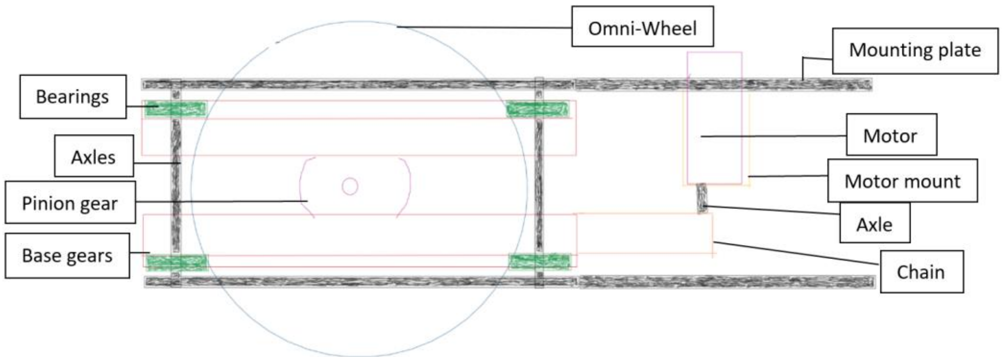

Figure 1: Quarter section side view of the final differential swerve design.

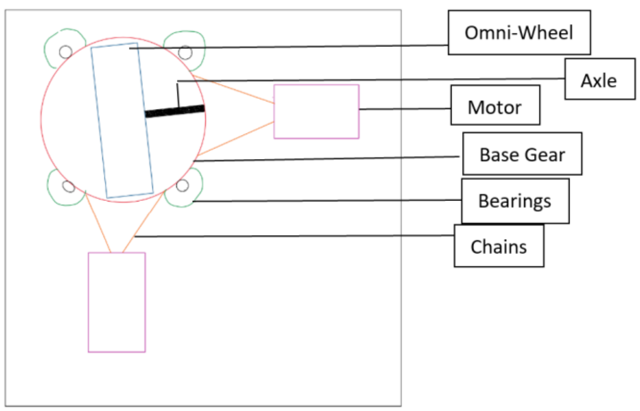

Figure 2: Top view of a quarter section of the differential drive train.

A CAD model was also constructed, which can be seen in Figure 3. The model was used in virtual testing to determine wheel speeds and the drivetrain's ability to resist and support loads. The client will receive a copy of the CAD model, as well as a physical prototype. The physical prototype will display the ease of manufacturing, compactness, and whether the conceptual design will be successful once implemented. The CAD model will be used to demonstrate the drivetrains speed and turning capabilities.

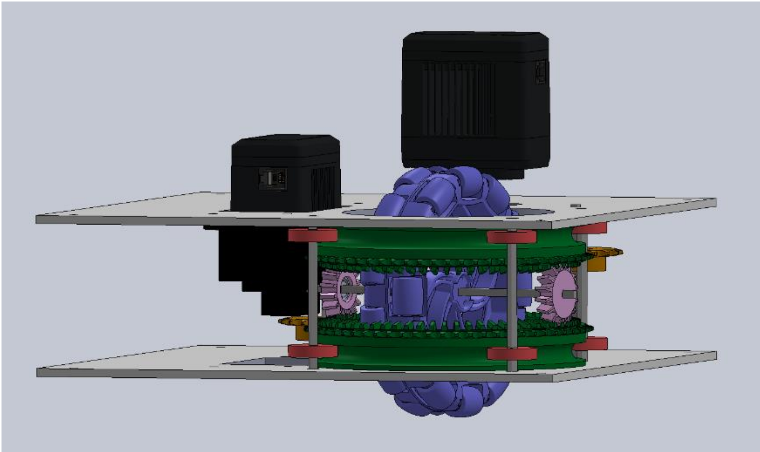

Figure 3: CAD model of the final swerve drivetrain assembly, to be used in virtual testing.

To implement the solution, the client would need to construct three more quarter sections, as well as mounting plates that cover the 18” x 18” base of the robot, instead of 9” x 9” sheets. Table 2 shows the bill of materials that was required to build a quarter section of the drivetrain. A written code would be required to control the speed of the individual motors, as well as the ability to reverse the direction of the motors to turn the wheels in both directions. To build the other sections, it would cost the QVEX team four times the costs outlined in Table 4, approximately $422, assuming they have access to VEX parts such as chains, motors, and wheels.

Table 2: Bill of materials for a quarter section of the swerve drivetrain.

Materials	Quantity
9” x 9” Aluminum Sheet	2
22mm Round Radial Bearing	8
4” Omni-directional Wheel	1
3D Printed Custom Gears	2
Bevel Gear	1
Wheel Axle	1
Bearing Axle	4
VEX Motor	2
VEX Chain	2

1.4 Conclusions

The swerve drivetrain has intricate functions that can be executed with numerous different designs. Three main designs were considered in this project: the direct swerve drive, the transmission drive, and the differential drive. The final design was chosen based on important criteria such as cost, size, weight, and difficulty. Using a weighted decision matrix, the differential swerve drive design was found to be the best design for this project. A differential swerve drive is beneficial due to its low height and low cost. The final design is characterized by two outer gears that encircle the wheel with one upright gear between them that is attached to the axle and powers the wheel. These gears are custom designs that were 3D printed along with the motor mounts. Gears are used to power the upper and lower gears to turn and provide torque to the wheel. The wheel system is mounted to an aluminum sheet which can then be easily mounted to the chassis of the robot. Due to errors, the team went slightly over budget, spending $105.73.

The final model differed from the original design with a standard VEX wheel in place of the omnidirectional one as well as the chains being replaced with gears. These alterations were made due to incompatibility with available parts. To continue this design, it is recommended that the gear system is scaled to fit with the four-inch omnidirectional wheel. The bearings and shafts in the physical model interfere with the chain sprockets so it is recommended that thinner shafts are used with appropriate bearings of smaller inner diameter. The teeth on the upper and lower gears can be updated to be compatible with the high strength VEX chain to fulfill the original design if desired. Finally, it is recommended that the metal connections on the mounting plate are welded to ensure the longevity of the drivetrain.

Part 2: Technical Information

2.1 Conceptual Design Solutions

Design 1: The Direct Drive

This first drivetrain considered by the team was the direct drive swerve drivetrain. This design is characterized by a swivelling wheel where one motor is placed in line with the driving axle, attached to the swivel, and one motor is mounted directly to the chassis, as shown in Figure 4. The strength of this design is its simplicity. By mounting the driving motor in line with the wheel, there is no need for a transmission, drastically reducing the number of moving parts and thus the complexity. The design does have its drawbacks; one is that the wires connecting the driving motor to the chassis and VEX brain controller are unable to spin freely without tangling. To counteract this, the team went through an idea generating process and determined that a central hole through the swivelling axis would be necessary. Other design weaknesses include imbalanced loads on the axle and increased load on the turning motor.

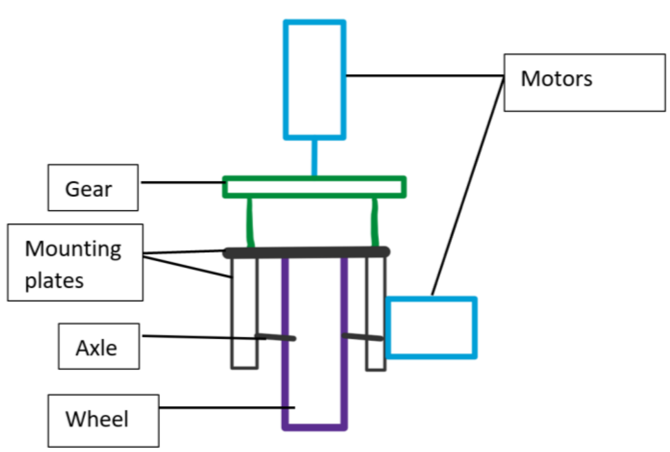

Figure 4: Preliminary sketch of the direct drive.

Design 2: The Transmission Drive

The second drivetrain design conceived by the team is a type of transmission swerve drivetrain. This is another swivel-based design but features both the driving and turning motors mounted to the chassis as seen in Figure 5. Consequently, a gear-based transmission must be used to transfer the power of the driving motor to the appropriate axis. This aspect is one of the weaknesses of this design as it involves many moving parts with a need for high precision at every step. Having a transmission within a swivelling structure would also make the design much harder to repair should the transmission break. The advantage of this design is that it solves most of the issues associated with the direct drive design. This includes the issue of tangling wires, loads on the axle, and a decreased load on the turning motor.

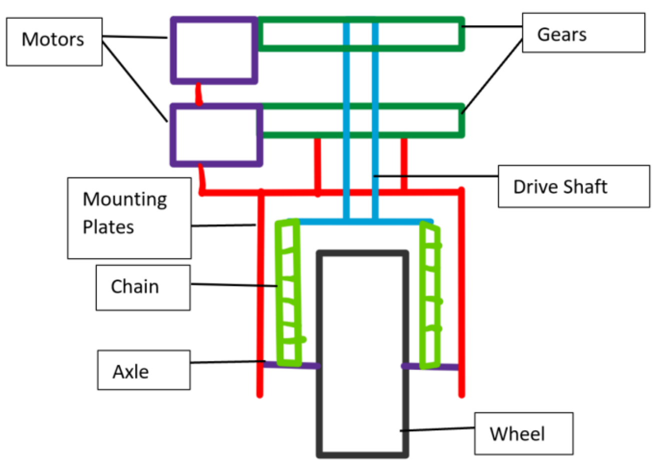

Figure 5: Preliminary sketch of the transmission drive.

It should also be noted that the first two design options require a large amount of vertical space. The client was consulted about this property of the designs and the team was informed that both designs are viable if properly implemented. However, if possible, the drivetrain should take up more horizontal space than vertical as to not interfere with components mounted to the chassis of the robot. This advice was considered in further idea generation and in the design evaluation matrix in Table 3.

Design 3: The Differential Swerve

The third design option that was considered is the differential swerve drivetrain. This is a more complicated design that uses two larger horizontal gears placed around the wheel with a vertical bevel pinion gear attached to the wheel axle, in between the two horizontal gears. Each larger gear is driven independently with its own motor, allowing for differing velocities among the large gears. If the gears are moving at the same speed and in the same direction, the wheel will rotate. If the larger gears have differently velocities, the wheel will spin according to the relative difference in speed. A diagram is shown below in Figure 6. The advantages of this design are that the gears can be placed overlapping the wheel and that the motors can be placed alongside the wheel with relative ease, drastically reducing the vertical footprint of the design. Additionally, by not allocating one motor for turning and one for driving, the max turning and driving speed is increased. The drawbacks of the design are its need for custom designed gears to integrate with the rest of the robot, a time-expensive process, and the lack of space to mount and install all the components without sacrificing the benefits of the design's compactness.

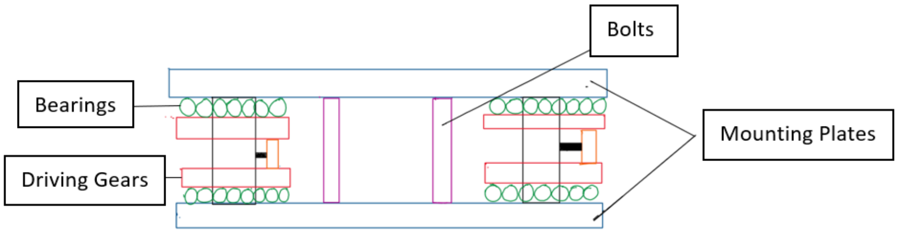

Figure 6: Original concept design for the differential swerve drive.

2.2 Decision Making

A decision matrix, as seen in Table 3, was used to compare the three design options. Each design was analyzed based on the cost, weight, complexity, and compactness. Every aspect was rated on a scale of 1-4, with the highest overall score being 16. Through this process, the team chose the differential swerve as the design proposed to be implemented due to its low weight, minimal vertical height, and low cost.

Table 3: Decision matrix used to evaluate different swerve drivetrain configurations

	Differential Swerve	**Direct Drive Swerve**	**Transmission Swerve**
Weight Optimal weight of 10lbs, maximum weight of 30 lbs **[12]**.	Weighs approximately 12 pounds for four-wheel design [13]. **3**	Weighs approximately 20 pounds for four-wheel design [14]. **2**	Weighs approximately 21 pounds for four-wheel design [15]. **2**
Compactness Design occupies the least amount of vertical and horizontal space.	All parts will be within the height of the 4" wheels. Will be approximately 5" long by 5" wide. **4**	Design is approximately 5.5" wide, and 9.5" tall with the motors included [16]. **3**	Approximately 10" tall by 5" wide, as they allow space for the wheels, motor, and gears in the vertical direction. **2**
Ease of manufacturing/ Implementation Minimize number of custom parts required, and ease of drivetrain assembly	Will be made of mostly custom 3D printed parts; however, it only consists of about 15 pieces per wheel and will be simple to assemble. **3**	Majority of parts will be made of existing metal to ensure structural integrity, can be quite complex to assemble and once assembled still has issues such as loose/excess wires. **2**	Requires many custom metal parts. The complex design will also make it very challenging to assemble. **2**
Cost to Manufacture Maximum budget of $100.	Cost of 3D printed parts will be $30, and the additional metal pieces will be around $30 [8] [9], with an overall cost of $60. **4**	Majority of metal pieces need to be purchased, resulting in costs up to $120 [10]. **1**	The custom fabrication of many metal parts will exceed $180 [11]. This will exceed the set-out budget. **1**
Final Weighting	**14**	**8**	**7**

The low weight, minimal vertical height, and low cost make the differential swerve drivetrain the optimal solution. The differential is the design capable of producing the highest speeds and outputting the most torque, while also being relatively simple to manufacture and assemble. Due to its compactness, it is the ideal solution for QVEX which will allow them the most freedom when constructing the other components of their robot. There are also many varying components of the differential drivetrain that can be customized to fit to the exact specifications the team may be looking for. Within the differential, the team had to conclude which mounting and power transmission options would be implemented. These options have been weighed below.

Mounting Options

Within the differential design, the team investigated different mounting options for attaching the drivetrain to the frame and the rest of the chassis. The first option investigated by the team was to use ball bearings to vertically support the gears. This would see each gear sitting on top of a mounting plate with channels in both the gear and mounting plate for the ball bearings. Unfortunately, the team could not find any VEX-approved ball bearings, so this solution was deemed inviable. The second and chosen option was to support the gears by using shafts fitted with horizontal bearings. These bearings fit into a channel in the side of the gears, allowing them to spin while being supported vertically. Since VEX does sell their own style of radial bearings, this design would both meet the team's need and be legal as per the project constraints.

Power Transmission Options

There were several different methods of power transmission considered for transferring the motor power to the gears. The first option was to use a gear coming directly from the motor and attach to teeth on the side of the large gears. While this option is straightforward, it lacks flexibility presented by the other options. It would necessitate a definitive placement of the motors and the gear ratio between the motor gear and the swerve drive gear would need to be fixed. The second option considered was to use a belt system attached to the motor, and around the large gears. This was eliminated due to the fear of the belt slipping and that it would also necessitate definitive motor place. The third and final power transmission method examined was a chain-based method. This was decided to be the best as it performs very similar to a belt drive with a few key advantages. Chain drives do not struggle with the same slippage as belt drives, can be shortened or lengthened to support different motor placements in the case of unexpected problems, and can be altered for behavioral adjustments.

2.3 Implementation

Preliminary design

The work done after Phase 3 followed the original timeline other than the changes stated in the Contingency Plan. Due to the delay of obtaining the required physical parts, the group had to alter aspects of the design to meet the project deadline. The main dependency of this design is the custom bevel gears; hence, these were designed first. The custom gears were carefully designed with the help of supporting research that ensured the bevel-style gears would interlock properly. These calculations can be found in Appendix IV: Calculations with the corresponding diagram indicating the locations of measurements. To confirm the gears fit together, a preliminary model was constructed of the gear subsystem in SolidWorks. The system had few errors when assembled originally with only the teeth needing to be edited to account for rotational interference.

Following the design of the gears, the motor mounts and mounting plates were created, as the gears defined the specifications of these parts, such as heights and hole placements. Preliminary measurements for the mounting plates that corresponded with the use of chains are shown in Figure 22, found in Appendix IV: Calculations. An assembly was made that included all parts of the system with imported files from the VEX website for the motor, shafts, and wheel.

Considerations

When planning the building process for the physical model, the environmental impact of the design was taken into consideration. Since the project is a one-time-use model, it was important that many of the parts were recycled or could be used again in the future. The standard VEX parts were re-used from previous robots and other parts, such as the bearings, were minimally altered to allow for re-use in future projects. The design and testing process were created to be sufficiently thorough so that the QVEX team could implement a swerve drive into their future robots. With the ability to create a swerve drivetrain, the team could have a higher level of achievement in competition and in turn receive more funding from the university as well as inspire new team members to join. During the building process, safety precautions were taken to ensure all members were protected from harm. Safety glasses were always worn within the workshop, earplugs were worn while drilling and cutting the metal sheets, and nonworking members stayed a safe distance away from working members.

Construction and Alterations

Since some parts of the system were unable to be printed or manufactured, the QVEX team was consulted to supply these parts. Due to 3D printing deadlines, this unfortunately happened after the custom parts were created. As a result, there were issues with the custom gears being compatible with supplied parts. When designing the base gears, a four-inch standard VEX wheel was used, however, the QVEX team was only able to supply a four-inch omni directional wheel. This wheel was incompatible with the design as the rollers on the wheel cause the diameter to be larger than four inches. For the physical model, a four-inch gear was used to simulate the function of the correct wheel so testing could proceed. The custom gears were also designed to be compatible with the basic VEX chain, however, the QVEX team could only provide the High-Strength chain, which was incompatible with the teeth created. To solve this issue, the design was altered to use gears instead of chains. These gears were 3D printed for efficiency and to ensure compatibility. The CAD assembly was altered as well by adding the correct gears and updating the mounting plate holes to account for this change. The overall model, which can be seen in Figure 7, was constructed with the implementation of these changes and was successfully completed.

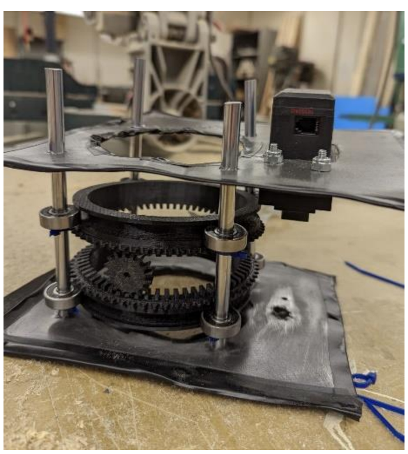

Figure 7: Physical prototype of the teams swerve drivetrain.

Testing Process

After the construction of both the physical prototype and the virtual model, only the virtual model was tested to ensure the functionality of the design. The overall testing was separated into four sections for increased efficiency and organization. The first section was the motion study, which tested that the gear and wheel speeds matched the calculated predictions. The second section was the static simulation, which tested that the design could sustain the load of the robot and any unexpected exterior forces. The third section was about the sustainability and materials used, ensuring that the drive was not harmful to the environment during disposal and that the swerve could be easily reconstructed from anywhere in the world. The quantification of each section is shown in

Appendix V: Evaluation Rubric. The specific quantification of certain criteria was judged based on relative statistics given by a swerve drive with a design like the proposed model [1]. Due to unforeseen errors such as bending as a result of fabrication of the metal sheets, the physical model was unable to be tested. To provide a thorough analysis, the virtual model was more rigorously tested than originally planned with the alteration that resulting values were unable to be compared to the real system.

The virtual modelling was run on the same software that the CAD was designed in. The SolidWorks Dassault System simulation software offers a VEX tutorial course that was used by the team to efficiently test the swerve drive up to VEX standards [7]. The testing of this design focused on the functionality of the gear system, evaluating whether it can effectively spin and rotate the wheel. This specification allowed for the external parts of the system like the mounting plates, bearings, and their respective mounting shafts to be omitted. Since a simulation was used, the motor parts were replaced with simulated motion that is equivalent to what is produced from the VEX motors. After, each section (motion study, static analysis, sustainability, and financial requirements) was calculated using a weighted average using (1):

$$Final\ Score = AVG_{MS} * (0.5) + AVG_{SA} * (0.4) + AVG_{SUS} * (0.05) + AVG_{FR} * (0.05) \quad (1)$$

AVG means the average score of the motion study (MS), static analysis (SA), sustainability (SUS), and financial requirements (FR) respectively. The weightings are due to the client's needs and that they are looking more for a functioning swerve drive that can sustain the load of their robot rather than a swerve that is very good for the environment. A final score of 1 will determine that the group has been unable to meet any needs given by the client. A score of 2 reveals that the group has made a valiant attempt but is still not quite at the level that the client requested. A score of 3 determines that the group has met all the client's needs. A score of 4 determines that the group has exceeded the client's expectations in most categories and that the client will be very satisfied and a score of 5 determines that the client would want to implement this design on the QVEX robot immediately. A final score of at least 3 will determine that the group has succeeded in meeting the client's requirements and thus, has succeeded in the design.

2.4 Project Plan

Work Breakdown Structure

Throughout the duration of this term, there were some events that occurred that caused a delay in project progression. This includes things like a delay arrival for the 3D printed parts, booking and software issues and many more uncontrollable variables. The team did mitigate these events at the start of the term and fell back on the second plan provided in

Appendix III: Updated Gantt Chart and planned an updated work breakdown structure provided in

Appendix II: Project Plan.

Risk Mitigation

After assessing the risks associated with the project completion, there were some that the group was able to mitigate. Unfortunately, due to uncontrollable errors and obstacles, there were some events that caused the group to halt or even reverse the project progression. One of these obstacles was the overall process of obtaining the physical parts to build the swerve. Due to unforeseen delays in delivering the high-strength chain, the group was forced to change the design late into the project as it was more important to have a working prototype rather than relying the entire design on one part being delivered late. As a result, the group was forced to re-iterate a design that did not implement the high-strength chain. Some risks that were mitigated with caution by the team on a consistent basis was the work done on the virtual CAD. SolidWorks is a computationally intensive program that often causes a lot of crashes at random times. The group made a valiant effort to save every file and send copies to one another so that if there was a surprise crash on the program, there would not be major setbacks in progression and backups would be available.

Contingency Plan

The original contingency plan was that there would be two rounds of testing done on the virtual model if a physical prototype was not completed by the given deadline. Although there was an obstacle in the progression of the construction of the physical model, the group still proceeded with its construction and ran the virtual tests simultaneously to complete both by the given deadline. This was done so that the client can still have a physical prototype along with the virtual CAD model.

Potential Changes

If this project was to be done again with the knowledge the group has now as well as assuming that the first two thirds of the project timeline was spent in person rather than online, there would be significant changes made to the design. Online communication was the root of most of the team's obstacles since there was no simple way of getting ideas and designs across through a screen. Having team meetings take place in person from the beginning would have helped the team tremendously in having accurate specifications to the design and assuring that every group member understood what was expected of them. Although the team was content with the number of meetings that were held during the week, a change that would be made is having more meetings being centered around the production of the swerve rather than report writing. With that point being stated, having the meetings held online made it difficult to make major strides in the project completion when it is impossible to have any sort of design and implementations being made to the design when every group member is working remotely.

2.5 Financial Analysis

Many of the parts used in the build were recycled and therefore came at a discounted cost. The omni-directional wheel, VEX chains, and axles were recycled from a previous robot. The VEX motors were acquired from the QVEX team with no cost. Unfortunately, due to a printing error, the original bearings and shafts purchased were incompatible, thus bearings and shafts of the correct size were purchased. This error accounts for the higher cost than previously expected. To save cost, the aluminum sheets were fashioned out of baking trays. All members of the team acquired safety trained in the shop to cut and drill the aluminum sheets at no cost.

Table 4: List of purchased items and their costs

Item	**Price**
Bearings	$24.27
Shafts	$29.48
Printing	$30.00
Baking trays	$21.98
	Total
	$105.73

Due to most of the project being recycled parts from previous robots, the build has a low cost in comparison to other solutions. When implementing this design, it will cost the client approximately four times what was outlined in Table 4, coming to a total of $422.92. The client may be able to save money when implementing this design if they have access to similar materials and resources, but at a discounted price.

2.6 Evaluation

Evaluation was done through SolidWorks simulation software. In terms of the motion study, using the gear ratio of 18:64 and a 4-inch omni-directional wheel, the model achieved a constant a velocity of $3.59\frac{m}{s}$. This performance scores a 3 when referring to the

Appendix V: Evaluation Rubric and meets client expectations. This result implies that the QVEX team can rely on the swerve drive's ability to move and rotate effectively in competition at a pace that is up to their expectations.

In terms of the static analysis section, when applying a force of 270N (about 27.55kg) which is the average weight of a robot, the Solid Works static analysis simulation software produced the following stress diagrams, seen in Figure 8, Figure 9, and Figure 10. The base gears follow the teams' expectations as the bottom gear should have most of the load placed where the pinion gear attaches, as depicted in Figure 8. The rest of the structure has an even distribution for load capabilities which concludes that the bottom gear will not undergo failure when the rest of the robot is built.

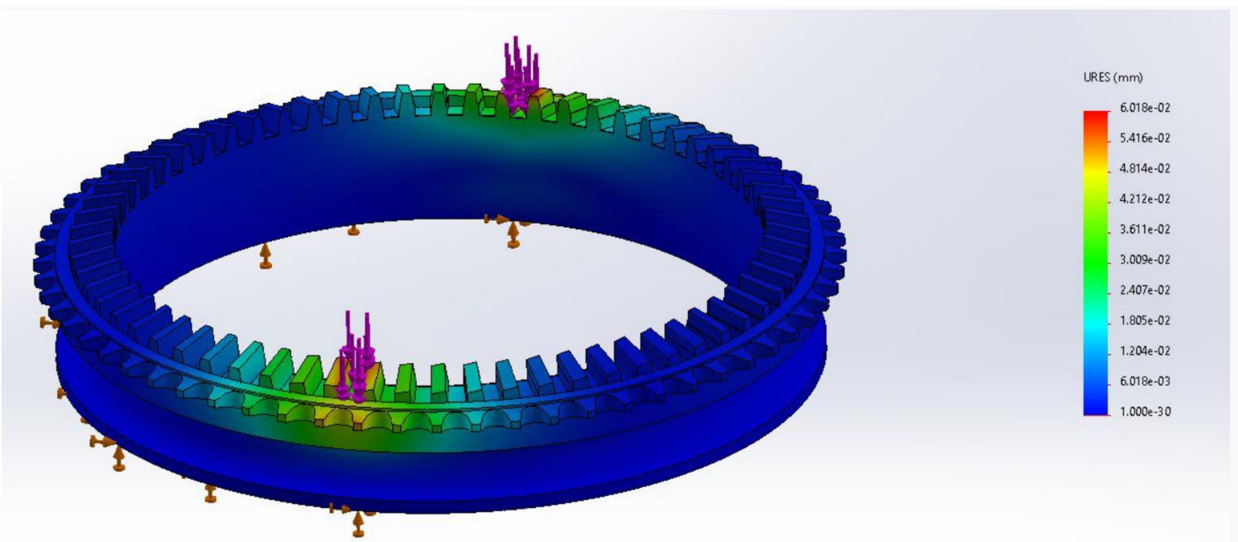

Figure 8: Static analysis of the bottom base gear.

The top base gear will experience a symmetrical load downwards from the weight of the attached QVEX robot and chassis. The SolidWorks analysis shows that the deflections cause by this load will be minimal using the properties of the material. The higher amount of deflection in parts of the gear are cause by the nature of how the gear is supported. Where the displacement in Figure 9 is lowest corresponds to where the two pinion gears attach to the top gear.

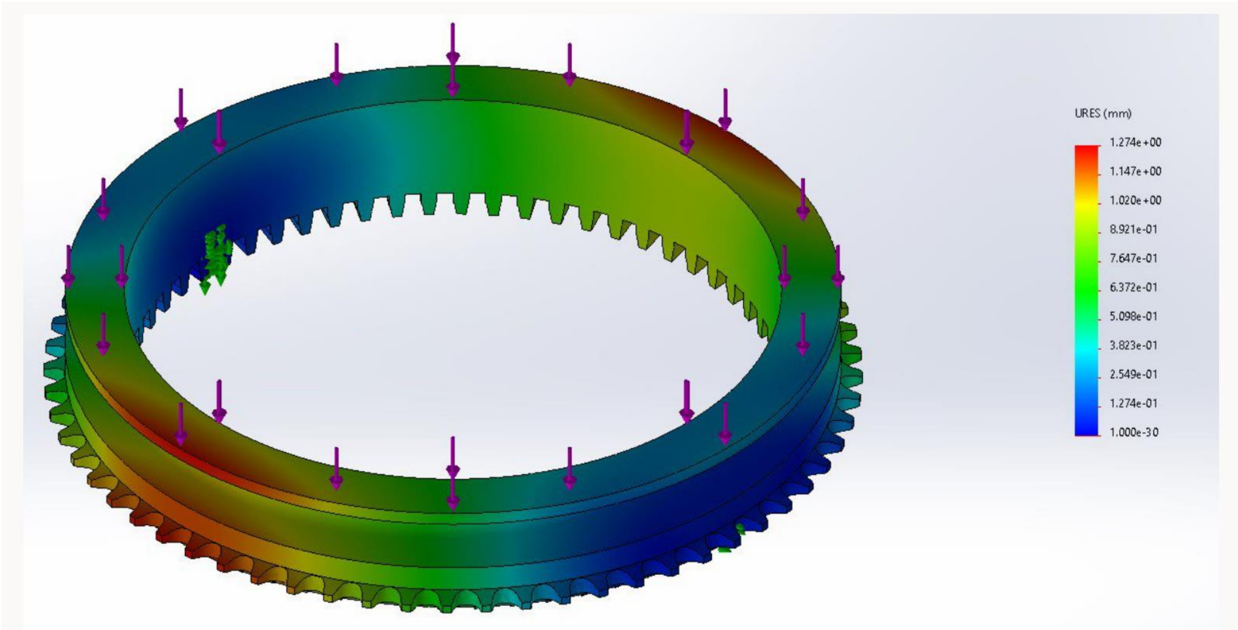

Figure 9: Static analysis of the top the base gear.

As for the pinion gear, for the applied load to the top gear, the pinion gear will experience a portion of the force where the pinion gear contacts the larger gear. Since there are two pinion gears in the design, the overall load is halved. Also of note, since the system is in equilibrium, the pinion gear will experience an equivalent 135 N force from the bottom gear, resisting the force that the pinion gear applies to it. The result of these forces can be seen in Figure 10. Having this symmetrical load distribution and having the pinion gear be centrally fixed through the shaft means that the pinion gear will also not slant and will be able to sustain the load of the top base gear.

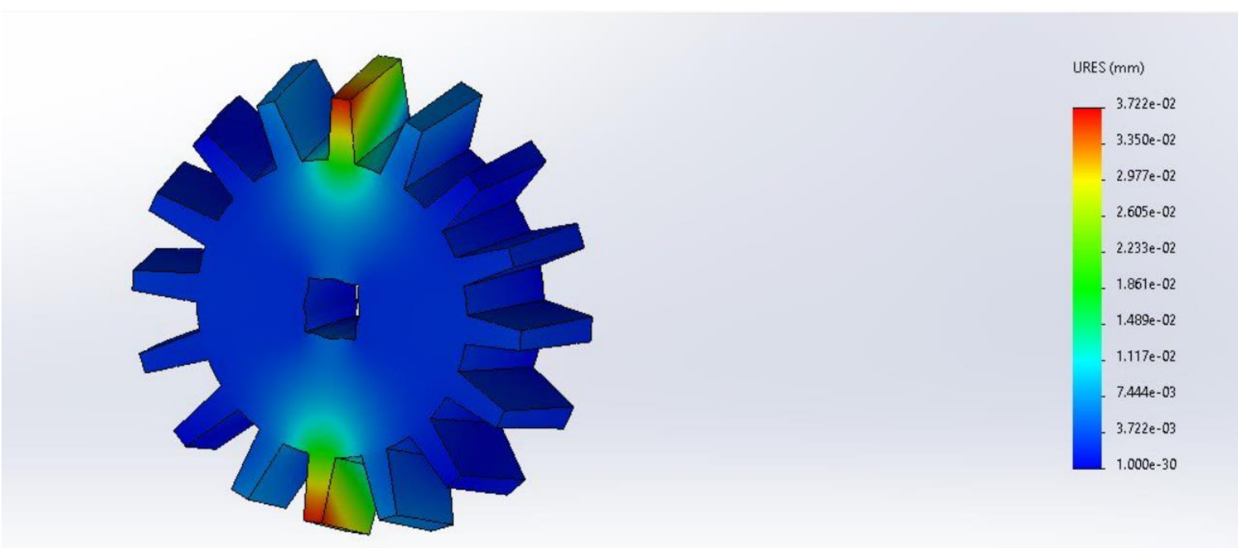

Figure 10: Static analysis of the pinion gear.

Having these promising results concluding from a load of 270N, the model easily scores a 5 in the evaluation scoring. As for the area expectations, the area was calculated by taking the dimensions of a single mounting plate and multiplying each side by two to factor in that there will be four of these models made for the overall robot. This brings the dimensions of the overall frame to 17.98" x 17.98". Although this does meet the clients' expectations and QVEX rules, it still has some room for optimization and will only score a 3 in that section. This brings the overall scoring for the static analysis section to a 4 because although the model can withstand heavy loads and still have structural integrity, the area of the model has not reached full optimization just yet.

The sustainability was tested using the SolidWorks life cycle software where multiple import sources were tested and various length times were used to find the optimal statistics to assure that the model does not cause severe environmental damage.

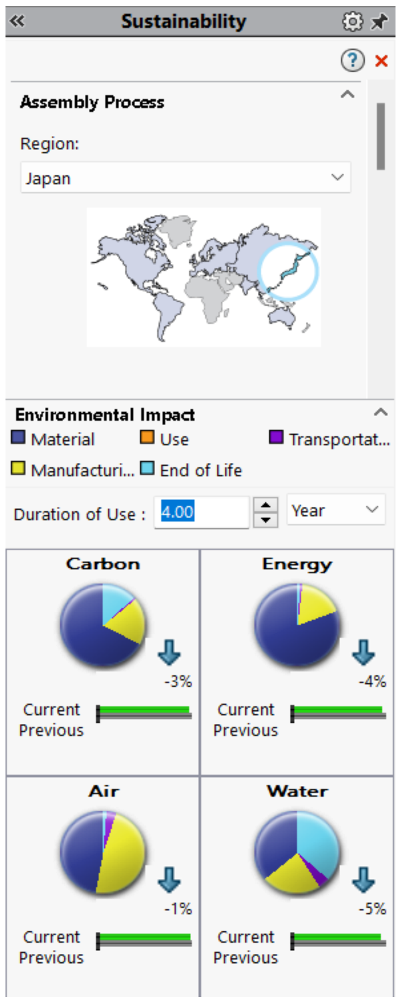

Figure 11: Sustainability of the model using Japan as the region of exported materials.

Multiple regions of material extraction were tested and considered. Japan showed the best results assuming that the team would be using this model for the next four years consistently. As a result, the carbon footprint of the model is 2.4kg after four years which scores a 3 in the evaluation scoring. For the financial section, although minimal printing sessions were required, the group did go over budget and thus resulted in a score of 2.5.

Results

Using the scoring equation (1) provided in Testing Process, the final model had the following scores: Motion study scored a 3, static analysis scored a 5, sustainability scored a 3, and financial analysis scored a 2.5. Overall, using the weighted scaling, the model scored a 3.4. This concludes that the group has succeeded in meeting the clients' expectations and that the client will be satisfied with the model as it will offer optimal motion and load bearing capabilities. The only downside to this design is that it will be expensive and the QVEX team will have to prioritize their budget toward the swerve design. Overall, the groups work over the semester paid off as a successful swerve drivetrain was designed and validated through testing.

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Appendix I: Contributions

Figure 12: Individual Contributions to the Phase 4 Report.

Task	Description	Person Assigned	Duration
Creating Final Assembly	Creating an assembly in SolidWorks to ensure proper fitting and intended design of all individual components.	Arandjel	2 hours
Testing CAD model	Running virtual load and motor simulations in SolidWorks to ensure design will meet clients needs	Logan, Arandjel	9 hours
Building Physical Prototype	Constructing a physical prototype of the design using 3D printed parts. Includes time spent manufacturing custom made mounting plates in the design shop.	Joellie, Megan, Avery	6 hours
Executive Summary	Summary of the objective of the project, scope of the research/design, brief description of the decision process between the different designs, the final chosen solution, the results of any testing/evaluation thus far. Should be understood by a non-technical reader.	Megan, Arandjel	1 hour
Table of Contents	Created the table of contents and updated consistently before submitting.	Joellie	5 minutes
List of Figures and Tables	Made the list of figures and list of tables. Also updated it consistently before submitting.	Logan	15 minutes

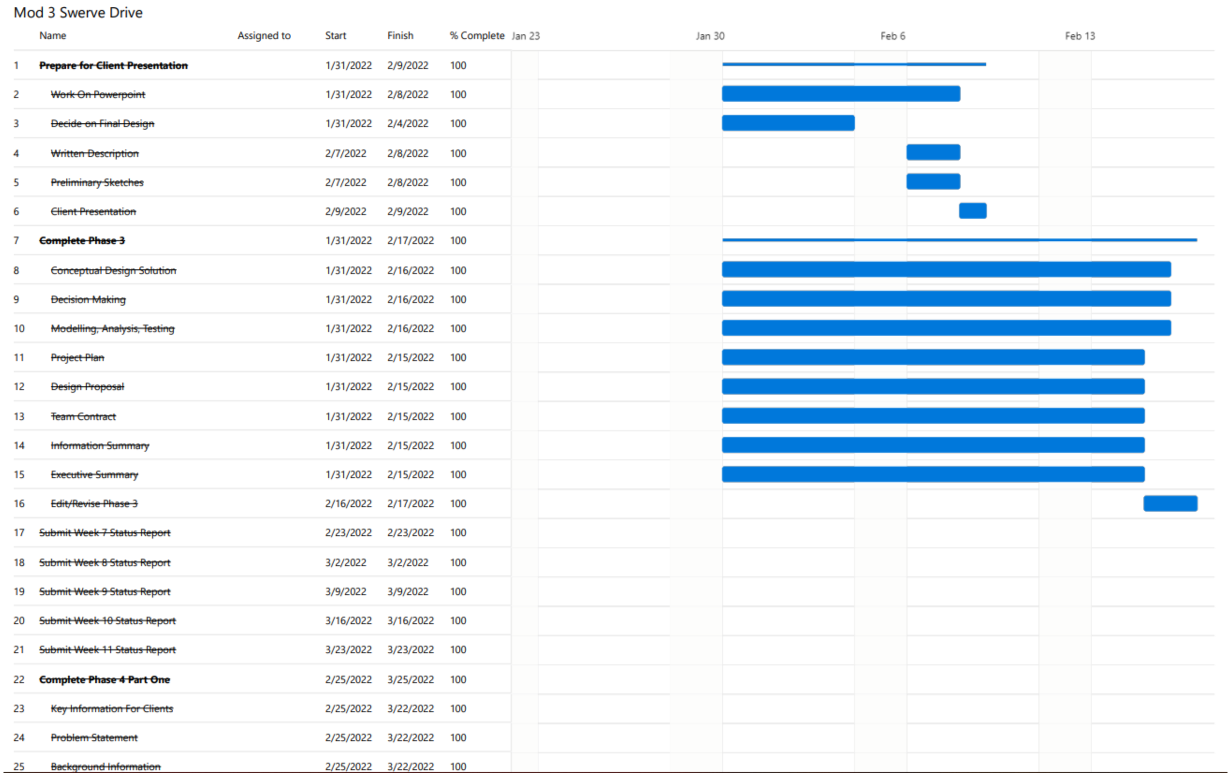
Problem Statement and Scope Definition	Updated version from Phase 3. Any changes made were stated and briefly explained. Also updated quantifiable specifications based on feedback received from Phase 3.	Avery	1 hour
Background Information	Condensed the information summary from Phase 2 and Phase 3. Also provided a summary of any new information that was acquired that affects the design. Also assured to only keep the information that is relevant to the rest of the report.	Megan, Avery	30 minutes
Design Solution	Provide a thorough but concise design solution that was undertaken. The design solution was described to the client effectively. The deliverables resulting from the project (CAD model, physical prototypes) were discussed. Any next steps to the client on how to implement the solution was outlined and the final financial information (expected costs) was summarized.	Joellie	1 hour
Conclusions	Summarized the information so far in the report. Also described recommendations for continuing the design and how the group would change any outcomes given the opportunity.	Megan	1 hour
Conceptual Design Solutions	Updated, edited, and condensed from Phase 3. Described the possible design solutions. The description included the multiple approaches that were taken (different mounting solutions, chain versus belt versus gear).	Logan	1 hour
Decision Making	Updated and condensed from Phase 3. The original assumptions that were made were revisited and any changes were described.	Joellie	45 minutes
Implementation	The work done after Phase 3 that was not mentioned in the Design Solution section was described. The procedure of how the problem was solved was presented and changes made from the original proposal in Phase 3 was described. Any societal and	Megan	2 hours

	environmental factors that impacted the design process was mentioned as well as the modelling used to further the design.		
Project Plan	Any changes made to the timeline were identified. Included a table of the updated work breakdown table with a column explaining significant differences planned and the actual hours spent on certain tasks. An updated Gantt chart was included. Described what would be done differently if the project was to be done again. Described what happened to the risks stated in Phase 3.	Arandjel	1.5 hours
Financial Analysis	The cost and financial benefits to the solution were discussed. Discussed any costs that the group had up until now. A breakdown of materials used to build the prototype was stated.	Joellie	45 minutes
Evaluation	The outcome of the project and the objectives a quantifiable specification stated in the problem statement were compared. Any final tests to validate the design was included as well as an evaluation rubric included in the appendix.	Arandjel	2 hours
References	Created the references section.	Logan	30 minutes
Appendix	Created the individual contributions table and formatted all the appendices in ascending order.	Arandjel	25 minutes

Appendix II: Project Plan

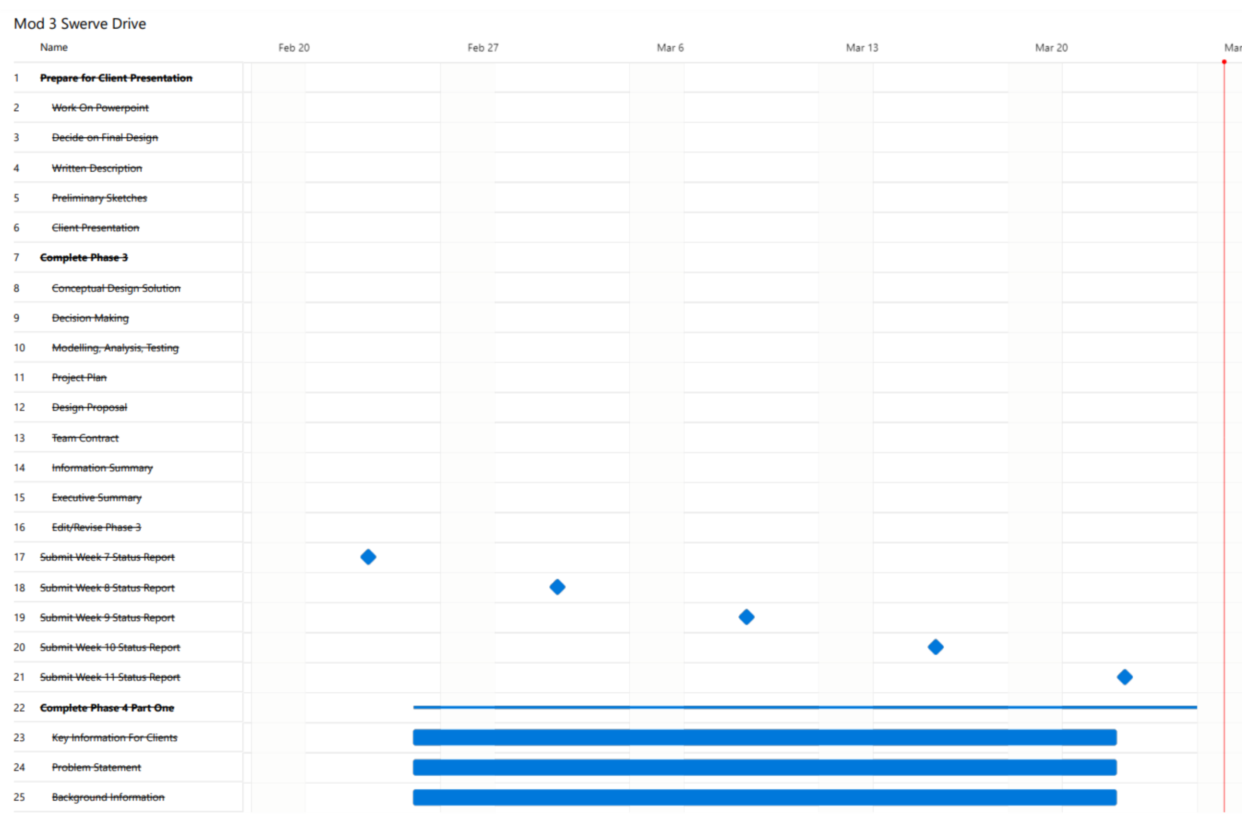
Table 5: Work breakdown structure

Task Identifier	**Description**	**Duration-Expected (days)**	**Duration-Actual (days)**	**Leader**
1	**Problem Definition**	**7**	**7**	**Avery**
1.1	Meet with client to outline problem	1	1	Project Manager
1.2	Identify stakeholders	1	1	Megan
1.3	Create team contract	2	2	Arandjel
1.4	Identify required research	3	3	Avery
2	**Preliminary design**	**18**	18	
2.1	Background research	4	4	Logan
2.2	Create three design options	4	4	Avery
2.3	Choose final design	3	3	Joellie
2.4	Preliminary sketches	2	2	Megan
2.5	Prepare for client presentation	5	5	Arandjel
3	**CAD creation**	**21**	31	
3.1	Research and complete necessary calculations	7	7	Megan
3.2	Create preliminary CAD files	7	12	Joellie
3.4	Finalize CAD files	3	2	Logan
3.4	Create CAD assembly	5	10	Arandjel
4	**Building**	**3**	**2**	
4.1	Machine required parts	2	1	Joellie
4.2	Assemble material parts	1	1	Avery
5	**Testing**	**14**	**7**	
5.1	Simulation test with 3D model	3	2	Arandjel
5.2	Test real model	3	0	Megan
5.3	Evaluate simulation results	3	3	Logan
5.4	Evaluate real model results	3	0	Avery
5.5	Create solutions and next steps	2	2	Joellie



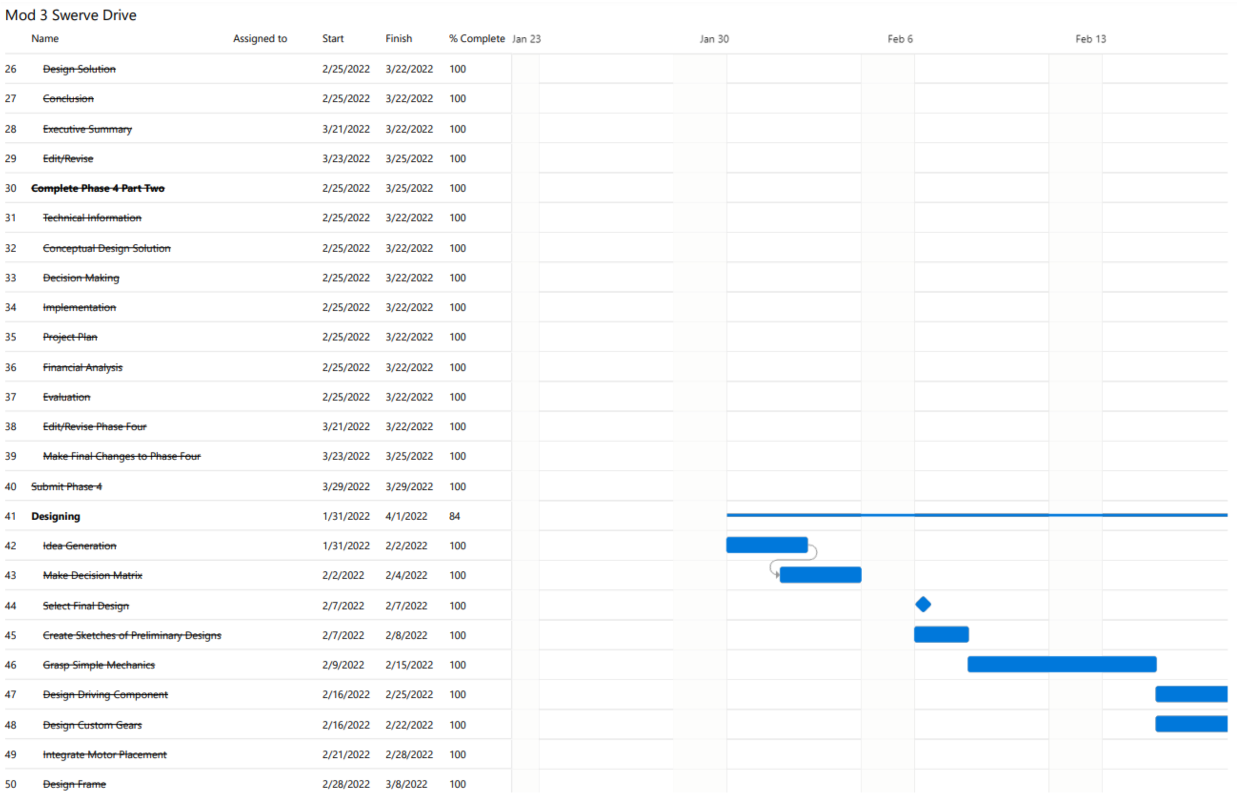
	Name	Assigned to	Start	Finish	% Complete
1	**~~Prepare for Client Presentation~~**		1/31/2022	2/9/2022	100
2	~~Work On Powerpoint~~		1/31/2022	2/8/2022	100
3	~~Decide on Final Design~~		1/31/2022	2/4/2022	100
4	~~Written Description~~		2/7/2022	2/8/2022	100
5	~~Preliminary Sketches~~		2/7/2022	2/8/2022	100
6	~~Client Presentation~~		2/9/2022	2/9/2022	100
7	**~~Complete Phase 3~~**		1/31/2022	2/17/2022	100
8	~~Conceptual Design Solution~~		1/31/2022	2/16/2022	100
9	~~Decision Making~~		1/31/2022	2/16/2022	100
10	~~Modelling, Analysis, Testing~~		1/31/2022	2/16/2022	100
11	~~Project Plan~~		1/31/2022	2/15/2022	100
12	~~Design Proposal~~		1/31/2022	2/15/2022	100
13	~~Team Contract~~		1/31/2022	2/15/2022	100
14	~~Information Summary~~		1/31/2022	2/15/2022	100
15	~~Executive Summary~~		1/31/2022	2/15/2022	100
16	~~Edit/Revise Phase 3~~		2/16/2022	2/17/2022	100
17	~~Submit Week 7 Status Report~~		2/23/2022	2/23/2022	100
18	~~Submit Week 8 Status Report~~		3/2/2022	3/2/2022	100
19	~~Submit Week 9 Status Report~~		3/9/2022	3/9/2022	100
20	~~Submit Week 10 Status Report~~		3/16/2022	3/16/2022	100
21	~~Submit Week 11 Status Report~~		3/23/2022	3/23/2022	100
22	**~~Complete Phase 4 Part One~~**		2/25/2022	3/25/2022	100
23	~~Key Information For Clients~~		2/25/2022	3/22/2022	100
24	~~Problem Statement~~		2/25/2022	3/22/2022	100
25	~~Background Information~~		2/25/2022	3/22/2022	100

Figure 13: Timeline for the Client Presentation and Phase Three Completion.



	Name
1	**~~Prepare for Client Presentation~~**
2	~~Work On Powerpoint~~
3	~~Decide on Final Design~~
4	~~Written Description~~
5	~~Preliminary Sketches~~
6	~~Client Presentation~~
7	**~~Complete Phase 3~~**
8	~~Conceptual Design Solution~~
9	~~Decision Making~~
10	~~Modelling, Analysis, Testing~~
11	~~Project Plan~~
12	~~Design Proposal~~
13	~~Team Contract~~
14	~~Information Summary~~
15	~~Executive Summary~~
16	~~Edit/Revise Phase 3~~
17	~~Submit Week 7 Status Report~~
18	~~Submit Week 8 Status Report~~
19	~~Submit Week 9 Status Report~~
20	~~Submit Week 10 Status Report~~
21	~~Submit Week 11 Status Report~~
22	**~~Complete Phase 4 Part One~~**
23	~~Key Information For Clients~~
24	~~Problem Statement~~
25	~~Background Information~~

Figure 14: Completion of the Status Reports and the start of Phase Four.



Mod 3 Swerve Drive

	Name	Assigned to	Start	Finish	% Complete
26	~~Design Solution~~		2/25/2022	3/22/2022	100
27	~~Conclusion~~		2/25/2022	3/22/2022	100
28	~~Executive Summary~~		3/21/2022	3/22/2022	100
29	~~Edit/Revise~~		3/23/2022	3/25/2022	100
30	**~~Complete Phase 4 Part Two~~**		2/25/2022	3/25/2022	100
31	~~Technical Information~~		2/25/2022	3/22/2022	100
32	~~Conceptual Design Solution~~		2/25/2022	3/22/2022	100
33	~~Decision Making~~		2/25/2022	3/22/2022	100
34	~~Implementation~~		2/25/2022	3/22/2022	100
35	~~Project Plan~~		2/25/2022	3/22/2022	100
36	~~Financial Analysis~~		2/25/2022	3/22/2022	100
37	~~Evaluation~~		2/25/2022	3/22/2022	100
38	~~Edit/Revise Phase Four~~		3/21/2022	3/22/2022	100
39	~~Make Final Changes to Phase Four~~		3/23/2022	3/25/2022	100
40	~~Submit Phase 4~~		3/29/2022	3/29/2022	100
41	**Designing**		1/31/2022	4/1/2022	84
42	~~Idea Generation~~		1/31/2022	2/2/2022	100
43	~~Make Decision Matrix~~		2/2/2022	2/4/2022	100
44	~~Select Final Design~~		2/7/2022	2/7/2022	100
45	~~Create Sketches of Preliminary Designs~~		2/7/2022	2/8/2022	100
46	~~Grasp Simple Mechanics~~		2/9/2022	2/15/2022	100
47	~~Design Driving Component~~		2/16/2022	2/25/2022	100
48	~~Design Custom Gears~~		2/16/2022	2/22/2022	100
49	~~Integrate Motor Placement~~		2/21/2022	2/28/2022	100
50	~~Design Frame~~		2/28/2022	3/8/2022	100

Figure 15: Timeline of the completion of Phase Four Part Two and the Design of the Drive.

Figure 16: Timeline for the completion of Phase Four and the design.

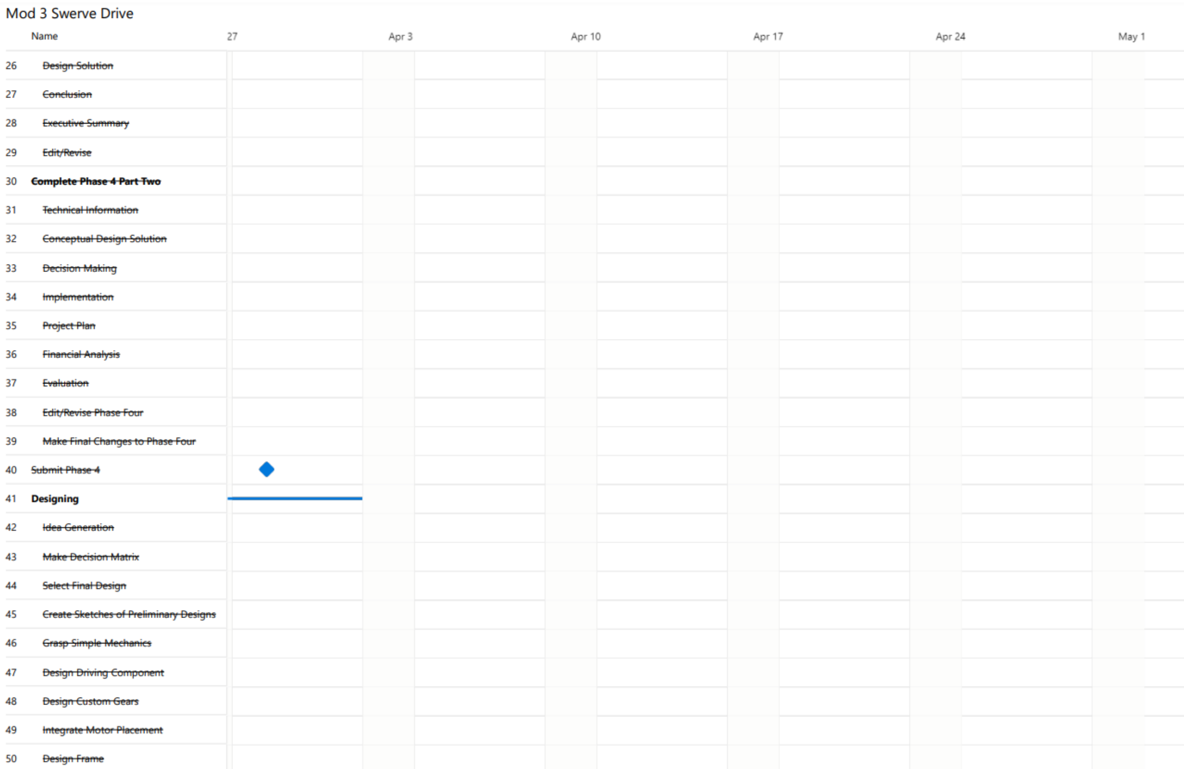


Figure 17: Timeline of the submission of Phase Four.

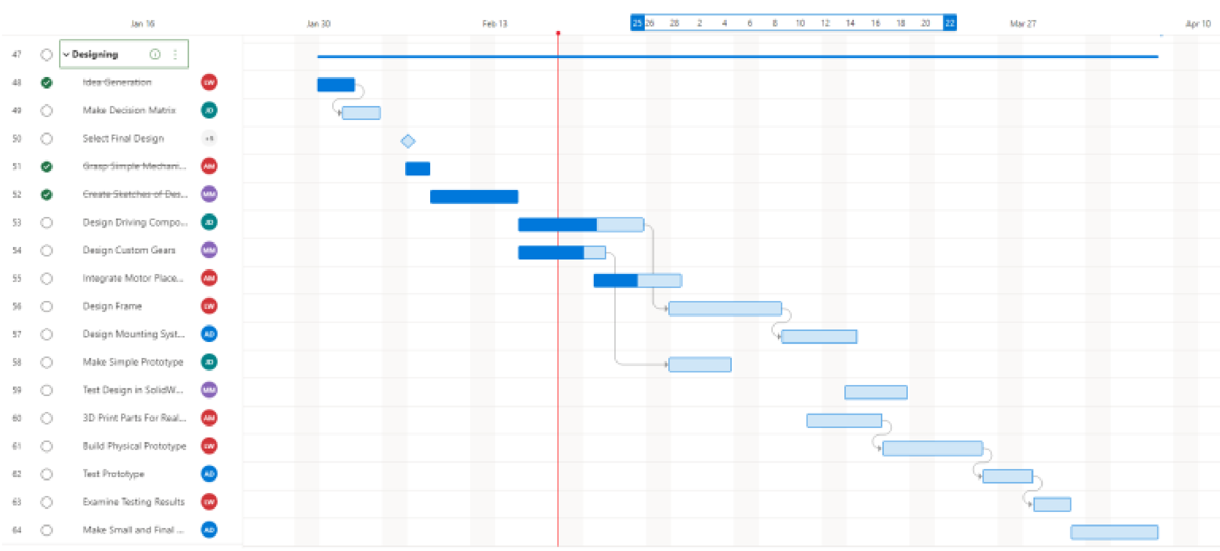


Figure 18: Original project timeline for the second half of the semester.

Appendix III: Updated Gantt Chart

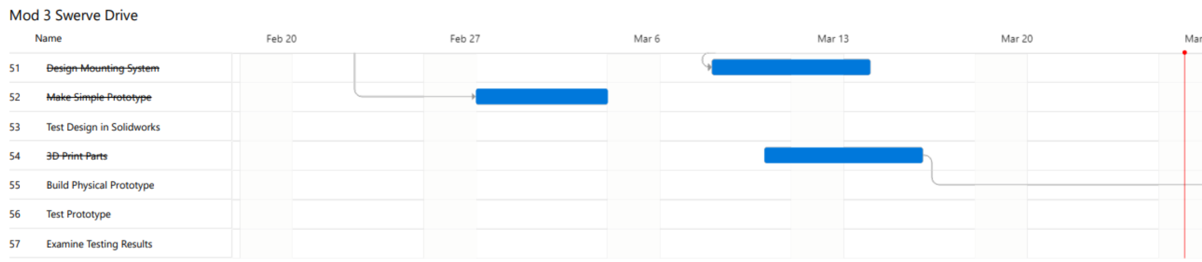


Figure 19: Timeline for the testing phase of the design.

Figure 20: Timeline for the testing phase of the virtual CAD and the build of the physical prototype.

Appendix IV: Calculations

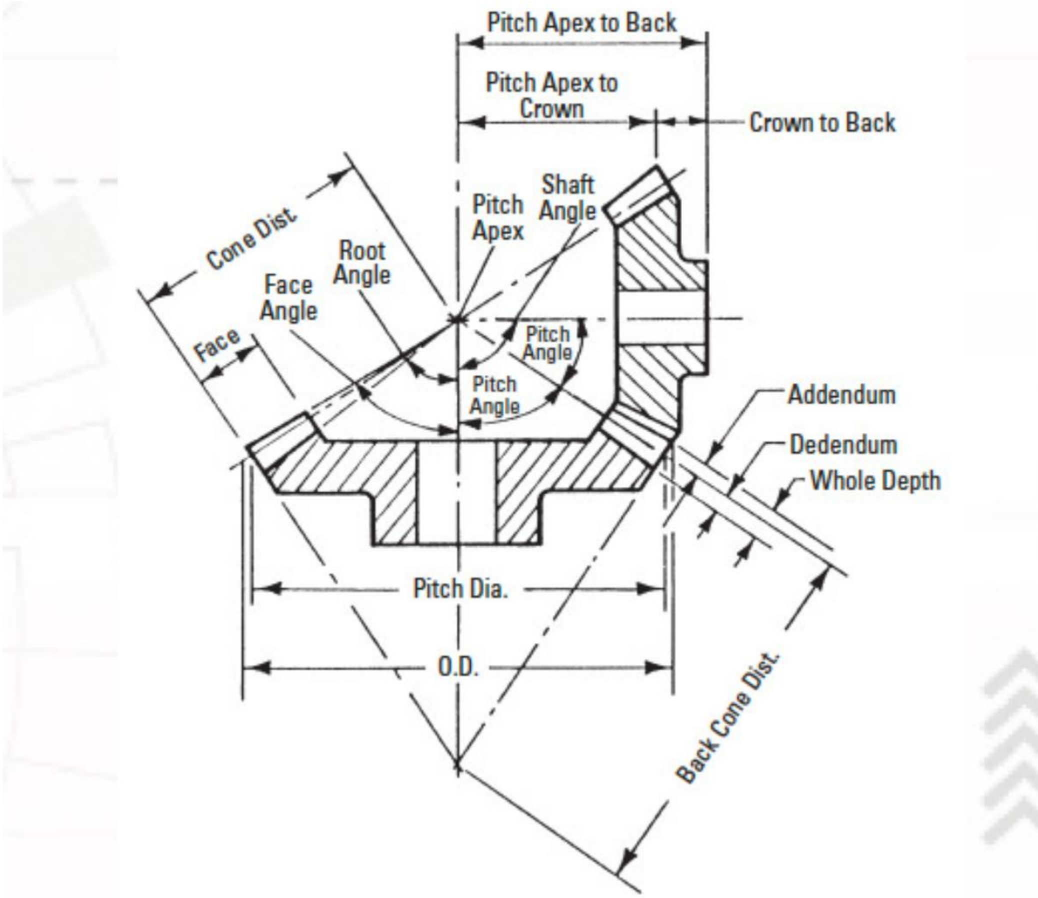


Figure 21: Reference diagram for gear calculations

$$Shaft\ Angle(\theta) = 90\ degrees$$

$$Gear\ ratio = 4:1$$

$$Number\ of\ Teeth - pinion\ (z_p) = 16$$

$$Number\ of\ Teeth - base\ (z_b) = 64$$

$$Pitch\ diameter - pinion\ (d_p) = 27.94\ mm$$

$$Pitch\ diameter - base\ (d_b) = 111.76\ mm$$

$$Module\ (m) = \frac{d_b}{z_b} = 1.746$$

$$Pitch\ angle - pinion\ (\alpha_p) = \tan^{-1}(\,sin\theta / (\left(\frac{z_p}{z_b}\right) + cos\theta)) = 14.04\ degrees$$

$$Pitch\ angle - base\ (\alpha_b) = \theta - \alpha_p = 75.96\ degrees$$

$$Face\ (b) = 6.86\ mm$$

$$Addendum - base\ (h_b) = 0.540m + \frac{0.460m}{\left(\frac{z_b cos\alpha_p}{z_p cos\alpha_b}\right)} = 2\ mm$$

$$Addendum - pinion\ (h_p) = 2.00m - h_b = 1.5\ mm$$

$$Dedendum - pinion\ (f_p) = 2.188m - h_p = 2.32\ mm$$

$$Dedendum - base(f_b) = 2.188m - h_b = 1.82\ mm$$

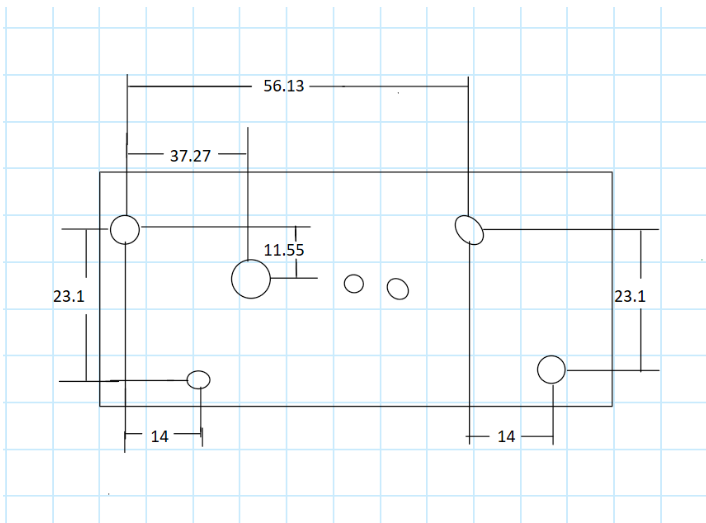


Figure 22: Measurements for hole placements on the motor mount and mounting plate. All measurements in millimeters.

Appendix V: Evaluation Rubric

Table 6: Evaluation Rubric for the Testing Phase for the Model.

Score:	Motion Study	Static Analysis	Sustainability	Financial Requirements
1	-Required velocity of $1\frac{m}{s}$ or less.	-Can sustain a load of 1kg -Area is more than 25”x25”	Carbon footprint of more than 6kg after four years of use.	-Total cost exceeds \$100. -5 or fewer printing sessions were done.
2	-Required velocity of $2\frac{m}{s}$ or more.	-Can sustain a load of 2kg -Area is more than 20”x20”	Carbon footprint of around 4kg or less after 4 years of use.	-Total cost is \$85 or less. -4 or fewer printing sessions were done.
3	-Required velocity of $3\frac{m}{s}$ or more.	-Can sustain a load of 3kg -Area 18”x18” or less	Carbon footprint of around 3kg or less after four years of use.	-Total cost is about \$71 (predicted amount). -3 or fewer printing sessions were done.
4	-Required acceleration of less than $12\frac{m}{s^2}$ -Required velocity of $4\frac{m}{s}$ or more.	-Can sustain a load of 4kg -Area is 16”x16” or less	Carbon footprint of around 2kg or less after 4 years of use.	-Total cost is \$70 or less. -Two or fewer printing sessions were done.
5	-Required velocity of more than $5\frac{m}{s}$.	-Can sustain a load of 5kg -Area is 15”x15” or less	Carbon footprint of around 1kg or less after 4 years of use.	-Total cost is \$60 or less. -Only one printing session was needed.