4-wheel Independent Steering "Swerve Drive"

Senior Design Proposal submitted to the
Department of Mechanical and Materials Engineering
College of Engineering and Applied Science
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Bachelor of Science

in Mechanical Engineering Technology

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Problem Statement

Drive trains are used in a wide range of applications from competition robots to the automotive industry, but one thing remains the same: the need to be lighter, cheaper, and more compact. One drive train in particular, “swerve drive” is superior when it comes to rapidly changing a robot/vehicle’s direction. Drawbacks include weight and expense (1). These drawbacks keep this drive train out of reach of many applications including robotics competitions. Our intention is to design, protype, build, and test a drive system, comprised of four independent steering modules that are more cost effective, compact, and less weight than what is currently available on the market, making this drive train a viable option for robotic applications. This project will be broken down into 3 major mechanical sub-sections (structure/frame, steering train, and drive train). Our group will design and select components using the engineering design process. Programming will be done collectively as a team.

Research

Background of the Problem

Swerve drive is a drive train that is designed to be omnidirectional. In this application, omnidirectional is the ability of the robot to move in any direction at any moment (2). Swerve drive modules are composed of two motors, a gearbox, encoders, and a wheel. One of the motors drives the wheel, while the other motor controls the steering. The gearbox is what controls the rotation of the wheel. The encoders are used to detect the rotational position of the drive wheel.

Swerve drive train is considered a premium in the competitive robotics world, however with cost and complexity the mechanism is unattainable for the average team. This problem can be directed towards any robotics team, but more directly to those who lack funding/experience. While currently swerve drive is considered a component of competitive robotics, with more research and development of the mechanisms involved, it could have more real-world applications.

Current swerve modules on the market are bulky, expensive, and often cannot fit into robot project budgets. A single module costs about 300 dollars and weighs between 4.9 pounds to 8.5 pounds. In competition robotics, weight limits are traditionally 120 pounds, giving teams with lighter drive trains an advantage (3).To accomplish this goal, our newly designed swerve modules will need to be lighter and more affordable so that all teams can be competitive regardless of budget.

The problem of weight is being addressed by companies making variations of their existing product. For example, the MK3 module from Swerve Drive Specialties has four different variations. The main components that are being interchanged are the motors and wheel types, with the heaviest module weighing 5.2 lbs. and the lightest module weighing 4.9 lbs. The problem of cost is not really being addressed. With the MK3 modules, the price varies depending on the motor selection and if a wheel is included; however, the cheapest module you can get, without a wheel, is still $300 per module (4). Looking at the Swerve & Steer module from Andymark, the price varies from $198-$439 per module. The variation of price is based on the type of drive motor, encoder, steer motor, and if the buyer wants a kit or the module to be assembled (5).

The current solutions are inadequate since the price per module is still too high, and the efficiency of the modules can be improved upon. Through research and material selection our senior design project will create a competitive swerve drive module that will be cost effective, light weight, and more compact than what is currently available on the market.

The magnitude of this problem reaches past time, money, or safety. Developing a more efficient swerve module that is cost effective for any team is important from a STEM Education standpoint. Allowing young adults to be exposed to complex yet affordable drive systems such as swerve is paramount for the future of STEM. This would allow all robotics teams the opportunity to build or program this drivetrain, giving them more experience needed for their futures in STEM. As far as time saving is concerned, the development of swerve drive can be broken down into manufacturing, assembly, and programming. These aspects all take a lot of time and resources that teams might not have. The creation of the physical module can be too daunting, and the development of code can be far too complex. The robotics competition that we are gearing this towards is FIRST Robotics which has a 6-week time limit for developing a robot. With this short time frame to work with it is easy to see why teams may steer away from such a complex mechanism. While safety in robotics is heavily emphasized, there are no reported safety hazards in regard to drive train development (at least in FIRST). While safety is not an issue, cost, weight, and size are the main focus of this problem. Our goal is to provide the most cost-effective swerve possible in order to allow all teams a chance of owning this drivetrain.

Standards

For this project we will be abiding by relevant electrical standards in the FRC 2020/2021 game rules. The electrical controls used for this project will be the standard FRC controls system (3). Relevant electrical standards are listed below. If this project were to be scaled up for industrial use, OSHA and ANSI standards would be followed. There are currently no specific OSHA standards for the robotic industry, but the American National Standards Institute includes several robotic safety standards that should be followed (6). See the ANSI and Motors & Actuators sections in Appendix A.

State of the Art (Frame)

The frame for the swerve drive modules varies depending on its application. Regardless of the applications, the frame is used to store the components needed to operate, power, and control the swerve drive modules. Along with storing the technology to make the modules function properly, the frame is used to protect the technology from outside forces. Common frame types that are used in competition robots are aluminum tubing riveted together, aluminum tubing welded together, and the use of aluminum extrusion.

Kyber Robot Aluminum Riveted Frame

The first type of frame used in competitive robotics is the aluminum tubing riveted together. Figure 1 below illustrates the Kyber robot used by FRC Team 144. This compact frame is a 28-inch by 28-inch square frame using 1-inch x 1-inch aluminum tubing allowing for a low profile and easy maneuverability (7).

The benefits of the aluminum frame being riveted is that the assembly process of riveting is simple and cost effective. Rivets have been used on structures for of half a century and have proven to hold up well. They do not fail under static or repeated loads. If the rivets are selected and set properly, they will not corrode. One downfall to rivets is that they require predrilled or punched holes. This will increase the machining time and cost. Another disadvantage to rivets is that there will be an increase in hardware and hardware cost for all the rivets (8).

The biggest benefit of using an aluminum frame is that it is light weight, especially in instances where there is a weight requirement. Also being able to use tubing, reduces the amount of weight. This also helps when holes need to be drilled or punched because there is less material to be removed. A benefit from being light weight, is that aluminum tubing is cheaper than other types of tubing. Aluminum tubing also has a good strength to weight ratio. Some of the disadvantages of using aluminum tubing includes that it can be abrasive to tooling. The oxide coating that forms on the aluminum tubing can dull the tools that are being used. Another disadvantage is that it is not as strong as other metals such as steel. For applications where the frame needs to carry a heavy load, steel would be the better option to support the load (9).

Figure 1: Kyber Robot Aluminum Riveted Frame

Pros:

- Cheap raw material
- Strong lightweight frame
- Cheap assembly process

Cons:

- Increase in machining time
- Increase in hardware

Dreadnought Robot Aluminum Welded Frame

The next type of frame is the aluminum tubing welded together. Figure 2 below illustrates the frame of the Dreadnought robot used by FRC Team 254. The frame is 29.75 inches by 30 inches welded together with 2-inch x 1-inch x 1/16-inch aluminum tubing (10).

The advantages and disadvantages of using the aluminum frame are similar to that of the frame used on the Kyber robot. The only difference is that this frame is being welded. The big disadvantage to aluminum tubing is that it requires special processes to be welded (9). Aluminum is sensitive to heat, so in order to create a sound weld, the best procedures and planning techniques need to be used (11). This will increase the amount of fabrication time and cost. By welding the frame, it will not require much, if any, machining time compared to that of the riveted frame. It also will not require any hardware to assemble the frame.

Pros:

- Cheap raw material
- Strong lightweight frame
- Decrease in machining time
- Decrease in hardware

Cons:

- Expensive fabrication process

Figure 2: Dreadnought Robot Aluminum Welded Frame

Swerve/Crab Platform Aluminum Extrusion

The last type of frame that is used for competitive robots is the aluminum extrusion frame. The Aluminum extrusion frame, Swerve/Crab Platform, and is sold by 221 Robotics Systems. The frame is 31-inches by 24-inches by 13-inches and is assembled using T-slot aluminum extrusion and hardware specifically for aluminum extrusion (12).

The benefits of using aluminum extrusion include the ease of use. Aluminum extrusion is very easy to work with and assemble. There is hardware made specifically for aluminum extrusion allowing for easy assembly. Another advantage is that the is very limited machine time needed for aluminum extrusion. Since everything is able to be assembled using hardware and extrusion tracks on the aluminum bar, machining is only needed to add special features. Another big advantage is that aluminum extrusion is versatile. The extrusions are easily able to be disassembled and used for other applications with little or no alterations. Other advantage is that it is cost effective since minimal machining and no welding is needed to be done (13). A disadvantage of the T-slot extrusion is that it is heavy when being compared to aluminum tubing. In a setting where there is a maximum weight limit, only the lightest materials will be considered. Another disadvantage is that the cost of the extrusion is expensive. Since the extrusion process is more involved than that of tubing, the cost to produce extrusions is more.

Figure 3: Swerve/Crab Platform Aluminum Extrustion Frame

Pros:
- Cheap assembly process
- Decrease in machining time

Cons:
- More expensive raw material
- Strong heavier frame
- Increase in hardware

State of the Art (Steering train)

There are two main types of omnidirectional steering trains used in competition robotics. The first is called mecanum drive which doesn’t require the drive wheel to be actuated to change direction. The second is called swerve drive which requires the drive wheel to be rotated along a vertical axis to change direction. The steering train in a swerve drive module is responsible for controlling the direction of the robot. This drive train requires closed loop sensor feedback in conjunction with an algorithm to determine the physical position of the drive wheel (1). To obtain a high-performance swerve drive module, the steering train should have low backlash and be able to change direction as quickly as possible while being strong enough to hold position accurately.

Mecanum Drive

The mecanum wheel was invented in 1972 by Bengt Erland llon. The mecanum wheel is an omnidirectional wheel designed to move land vehicles in any direction. The mecanum wheel is comprised of a series of external rollers that line the circumference of the wheel. Each wheel operates independently. When the wheel is turned it generates a propelling force perpendicular to the roller axle. The direction of the robot can be determined by varying the rotational speed and direction of each wheel (14). Since this drive system relies on the use of rollers, it is susceptible to undesired wheel slippage and can be pushed around by outside forces like opposing robots. This style of omnidirectional drive train has been referred to as “Poor man’s swerve drive” since it is considerably cheaper and lower performing compared to swerve modules. When strafing, a portion of drive force is lost due to varying rotational speed and direction of each wheel. Mecanum drives are often used in the logistics industry. Omnidirectional forklifts are used in close quarter warehouses to make product moving more efficient.

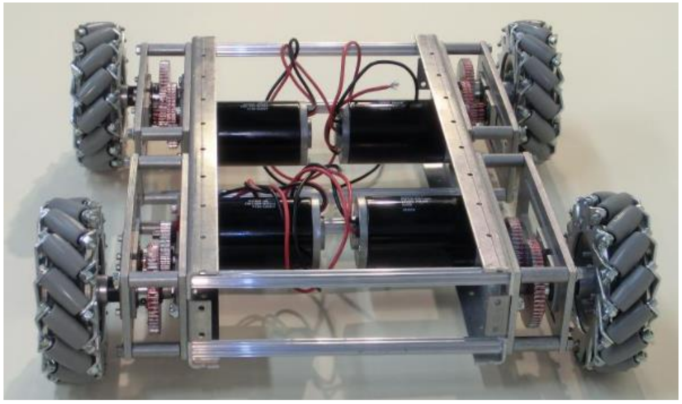


Figure 4: Mecanum Drive

Pros:

- Cheap
- Easy kinematics
- High load application

Cons:

- Wheel slippage/push able
- Steering decreases drive force
- Slow acceleration (high rotational inertia)

Andymark Swerve & Steer

The Andymark Swerve & Steer module was one of the first independent steering modules available for purchase in the FIRST community in 2016 (5). This design is referred to as a swerve module. The standard robot frame has 4 swerve modules, one attached to each corner. This module operates using 2 motors. The first motor rotates the drive wheel around a vertical axis for changing direction while the second motor rotates the drive wheel around a horizontal axis for propulsion. This module has an upfront cost of $295 and includes an MA3 Absolute encoder. The Absolute encoder is driven by two gears that are on a 1:1 ratio and is used to offset the wheel position upon start up. This module only accepts a PG17 motor and uses a planetary gearbox feeding into a second gear reduction to move the steering train (5). Since the steering train uses gears, the module requires lubrication to prevent ware and is susceptible to backlash when changing steering direction.

Pros:

- Reliable
- Cheaper compared to other swerve modules
- Continuous rotation

Cons:

- Steering train gear ratio is fixed
- Slow max steer speed (90 RPM)
- Steering motor must be PG17 Motor
- Heavy (6.5lbs-8.5lbs)

Figure 5: Andymark Swerve and Steer

MK3 Module

The MK3 module is available from Swerve Drive Specialties starting at $310 not including motors (4). This module operates on the same principles as the Andymark swerve and steer module. The first motor rotates the drive wheel around a vertical axis for changing direction while the second motor rotates the drive wheel around a horizontal axis for propulsion. Swerve modules like this have an advantage compared to other omnidirectional steering trains because all drive wheels are colinear with the drive force produced by the wheels. This results in a highly efficient and powerful drive force in any direction. This module includes an absolute encoder connected along the vertical axis of rotation without the use of gears or belts to eliminate encoder backlash. This steering train uses a combination of gears and belts to reduce the speed and increase torque from the steering motor (4). The use of belting reduces backlash, reduces weight, and reduces mechanical wear in the system. All non-purchased parts are machined aluminum resulting in greater manufacturing cost. The standard motors used for this module need to be modified or will require a spacer to assemble properly (4).

Figure 6: Swerve Drive Specialties

Pros:

- Lightweight (4.9 lbs.)
- Low encoder backlash
- Compact
- Low steering train wear
- Continuous rotation

Cons:

- Expensive
- Difficult to manufacture (all machined parts)
- Motor shaft modification or spacer required

State of the Art (Drivetrain)

The drive train of swerve drive is the greatest advantage of using swerve. Various gearing techniques allows swerve drive to have the same speed and force as a direct drive/tank drive while not compromising like the use of mecanum drive. The key to swerve drive is the drive motor working to drive as the modules makes turns via encoder and motor. With every drive system certain motor and gearing are needed to maximize performance towards the teams intended purpose.

FRC Team 254 – Tank Drive (Custom 3 motor, gear change gearbox)

The first example is a traditional tank drivetrain developed by FRC team 254. You can see the use of three motors with the combination of gear changing capabilities. The use of these three motors allows for flexibility while driving to achieve high speed in high gear and ample torque in low gear. This configuration is built for tank drive train which does the best in linear paths of travel where speed forward and backwards is key. We can see the benefit in speed with the 8:1 gear ratio in high gear equating to 21.4 ft/s, while the low gear option provides a 13:1 gear ratio equating to 13.2 ft/s. The change in speeds also can provide easier maneuverability which is the downside to these high-powered gear boxes. This configuration of gearbox requires two mounted to the base on each side powering 6 6” WCP pneumatic wheels (10).Looking at the motors, we can see 400 W of power per motor at 40A/12VDC (Typical Max Power) (15). Multiply this by 6 we can understand the demand for speed and torque out of this configuration. The size and weight of these gearboxes still has its shortcomings, the size of the gearing paired with the motors takes up a lot of space and takes up a good portion of your allotted weight. The work around to this is customizing a custom gearbox which requires precise design and fabrication which cannot be completed by most competing teams.

Figure 7: FRC Team 254 – Tank Drive

Pros:

- Easily programmable
- Provides high torque
- high speed

Cons:

- Not space efficient
- Low maneuverability
- Very Heavy

FRC Team 144 – Mecanum Drive (Toughbox Micro)

The next example is a simple mecanum wheel configuration used in FRC team 144's 2021 Robot. This drive train is the closest option to swerve with minimal physical complexity. The system uses four gearboxes consisting of one NEO brushless motor per gear box. So essentially one gearbox per wheel. This gearbox consists of a 12.75:1 gearbox ratio, this ratio is similar to the previous low gear configuration of team 254's gearbox (7) (16). This low geared configuration is not based off torque advantage as much as it is complimenting the nature of mecanum wheel configuration. The use of mecanum wheels consists of wheels that are angled around the base wheel providing lateral movement. These wheels do not provide much traction meaning a higher gearing configuration would equate to more slippage. This slippage can cause error within the encoders providing positional feedback, along with mitigating efficient movement regarding speed. These gearboxes are bought from stock making them obtainable by many teams and can be used in either tank or mecanum configuration. The motor use is a NEO brushless motor, which provides a typical max output power of 380 W at 40A/12VDC making it a perfect motor to minimize slippage and not compromise on speed (17). The gearbox is a Toughbox micro, which is mainly focused on space and weight conservation, with a price tag of $85.00 it makes it a good option for more simple designs and obtainable for most teams (16).

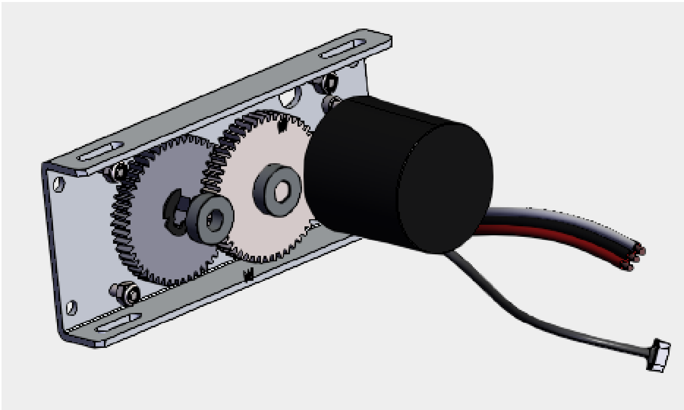


Figure 8: Mecanum Drive (Toughbox Micro)

Pros:

- Efficient use of space
- Lighter weight
- Added maneuverability
- Cheaper Alternative

Cons:

- Nature of wheels means low traction
- Slower speed, less torque

AndyMark – Swerve & Steer Kit

Lastly, we meet in the middle with AndyMark's Swerve & Steer module which is the most basic swerve system on the market. The reason this configuration meets in the middle is the combination of torque and speed that can be achieved alongside the benefit of maneuverability. It utilizes one Falcon 500 Motor, utilizing the 400 W of power per motor at 40A/12VDC (15) for the drive motor with a 6.67:1 total gearing ratio (5). So, we can see this configuration has an emphasis on torque but does not sacrifice speed with a max speed of 13.5 ft/s which is close to team 254's low gear speed and faster than team 144's mecanum configuration due to the use of a solid wheel (5). This gearing can be complex due to the nature of swerve, each module turning. The module utilizes the use of beveled gears to continue to power the motor while turning. The muddle turns via encoder and a simple PG71 gearmotor. The complexity of this system shows in the price tag. The most powerful configuration outlined here is $404.00 for a kit (1 module, you need 4) that needs to be assembled (5). This does not bode well for most teams due to the hefty price and complex assembly. The size of the modules also takes away the four corners causing for a cramped space for other assemblies.

Figure 9: *Andymark Swerve and Steer Kit*

Pros:

- High Torque, High Speed
- Complete maneuverability
- Ease of operation

Cons:

- Expensive
- Complex Parts to manufacture
- Vertical nature of motors poorly utilizes space

End User

The primary end user of swerve drive would be the operator of the robot. This technology would allow for easy adaptability and less accumulated error. This is especially important in FRC Robotics competitions where time is of the essence. There is also major turn over from year to year seeing as this is a high school program. Having the operator learn how to drive quickly is important. With traditional drive trains "tank" drive is usually the most popular. This drive train accumulates error and allows for less mobility.

The secondary end user of a swerve drive train would fit the profile of any robotics team that wishes to obtain an easily adaptable driving mechanism for operators for their competition/recreational robot. The main setbacks of traditional swerve drive train are the complexity of mechanisms and coding, the cost for off the shelf units are extremely expensive, and units are traditionally not space efficient. Ideally a team looking to upgrade to swerve drive would be looking for an easily integrated system with limited complexity of coding, manufacturing, and assembly.

Summary of Research

In conclusion, the current state of FRC drive mechanisms has developed a competitive gap between teams. Swerve drive is the best overall option for teams from a competitive and design standpoint due to its complete maneuverability combined with the necessary torque and speed to compete at a high level. The drawbacks of swerve consist of the price per module, poor utilization of spacing, and overall complexity. These drawbacks are enough to make many teams refrain from using this drive, making them sacrifice focus in other design areas. This means an overall less competitive robot, and more importantly, stunting the creativity in design that students may want to achieve. To open the door to more efficient and competitive robot designs, a module is to be designed that is low cost, does not sacrifice the speed and torque needed to compete, is both space and weight efficient, is easily maintainable, and is not too complex to implement.

Quality Function Deployment

This survey was conducted on September 20th, 2021, by thirty Butler Tech Engineering students (robotics team 144) via Google Forms. The survey given to the students is below with the majority results shown in bold font.

This survey will be used to prioritize various features to maximize customer satisfaction. The system in question will address issues in current swerve modules that can currently be purchased.

Survey Example

How important is each feature to you in a swerve drive module? Please select the appropriate answer. 1= Low importance 5= High importance

Reliability	1	2	3	4	**5**
Small Size	1	2	**3**	4	5
Low Cost	1	2	3	**4**	5
Manufacturability/ease of assembly	1	2	3	**4**	5
Agility	1	2	3	4	**5**
Light Weight	1	2	**3**	4	5
Robustness	1	2	3	**4**	5
Ease of maintenance	1	2	3	4	**5**

How satisfied are you with current swerve drive technology? Please select the appropriate answer. 1= Low satisfaction 5= High satisfaction

Reliability	1	2	**3**	4	5
Small Size	1	2	**3**	4	5
Low Cost	1	2	**3**	4	5
Manufacturability/ease of assembly	1	2	**3**	4	5
Agility	1	2	3	4	**5**
Light Weight	1	2	**3**	4	5
Robustness	1	2	**3**	4	5
Ease of maintenance	1	2	3	**4**	5

How much would you be willing to pay per swerve module?

$100-$175
$175-$250
$250-$325 **($250-$325)**
$325-$400

Summary of Results

Looking at our results we can pinpoint the short comings of current swerve mechanisms. Looking at the customer features graph we can see the most important features of a swerve module is the Reliability, Agility, and robustness. What this tells us is that the teams would like a robust design that requires little maintenance while still having the desired maneuverability, this would entail a simple and reinforced design of its mechanisms. These three factors being the most important due to the average importance values of 4.4, 4.5, and 4.13 which are the three highest averages for our customer responses. Looking at standard deviation of these three options we can see a value of 1.07 for the first, 0.86 for the second, and 0.94 for the last. This shows us that many of the students were aligned with this answer coming around within ~1 importance level. Next, we look at the current satisfaction of existing swerve modules. Coming first cost is the main concern coming in at a low satisfaction of 2.53, next is the light weight of the module coming at an average of 2.8, and last, we have small size coming at an average of 2.86. From this we can see a better design would focus on low cost, light weight nature, and smaller size. We can see that many of the students were also aligned due to standard deviation values of 1.2, 1.2, and 1.1. This shows that many of the students are around the answer 3 showing that they are more in the middle of satisfaction, with definite room to improve. The last graph explains the realistic price we should look at for a new design. The majority (56%) of students say that their teams could purchase a module in the $250-$325 range, which is interesting because it was our second highest price range given, despite the emphasis on lower cost shown previously.

Refer to Appendix B for survey results.

Customer Features:

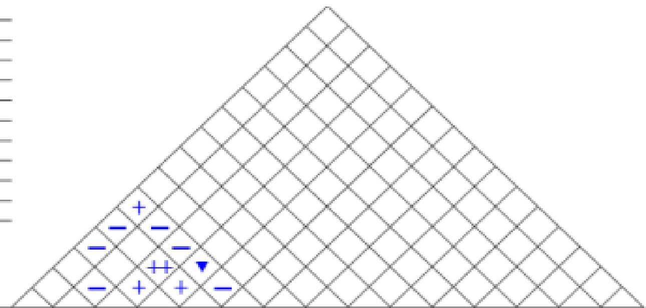
- Reliability
- Small Size
- Cost
- Manufacturability/ ease of assembly
- Agility
- Light weight
- Robustness
- Ease of maintenance

Engineering Characteristics:

- Electrical component selection ($)
- Material selection (lbs)
- Complexity of machined parts ($/hr)
- Number of kit components (count)
- Gearing selection (ft/s and ft-lbs)
- Modular design (minutes to take apart)

House of Quality

Title: House of Quality for Swerve Drive Module(s)
Author: Nicholas Poulos, Michael Kendal, Ben DeNoma
Date: 9/28/2021
Notes:



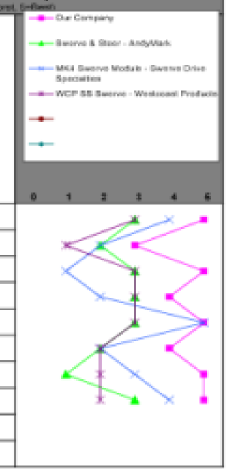
Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
X	Objective Is To Hit Target	

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column # → / Demanded Quality (a.k.a. "Customer Requirements" or "Whats") ↓ Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") →	1 Electrical Component Selection	2 Material Selection	3 Complexity of Machined Parts	4 Number of Kit Components	5 Gearing Selection	6 Modular Design
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	X	▼	▼	▼	▲	▲
1	9	19.4	7	Reliability	O	▲		Θ	O	▲
2	9	2.8	1	Small Size	O		▲	Θ	Θ	O
3	9	8.3	3	Cost	Θ	Θ	Θ	O	O	▲
4	9	11.1	4	Manufacturability/Ease of Assembly	▲	▲	Θ	Θ	O	Θ
5	9	22.2	8	Agility	Θ	O		▲	Θ	
6	9	5.6	2	Light Weight	O	Θ		Θ	O	▲
7	9	13.9	5	Robustness		Θ	▲	O		O
8	9	16.7	6	Ease of Maintenance	O	▲	O	Θ	O	Θ
9										
10										
				Target or Limit Value	Motors: $390 Controllers: $640 Micro Controller: $435				Gearing Ratio 8:1	
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	2	4	7	5	7	7
				Max Relationship Value in Column	9	9	9	9	9	9
				Weight / Importance	419.4	363.9	241.7	588.9	408.3	333.3
				Relative Weight	17.8	15.4	10.3	25.0	17.3	14.2

Columns 7–15 are empty.

Competitive Analysis (0=Worst, 5=Best)

	Our Company	Swerve & Steer - AndyMark	MK4 Swerve Module - Swerve Drive Specialties	WCP SS Swerve - Westcoast Products
1	5	3	4	3
2	3	2	2	1
3	5	3	1	3
4	4	3	2	3
5	5	3	5	3
6	4	2	2	2
7	5	1	3	2
8	5	3	4	2



Product objectives:

- **Reliability (19.4%)**
    - The design should have a reliable design to minimize interference between gearing, maximize power of motors, and ensure consistency of speed/turning radius.
- **Small Size (2.8%)**
    - The design should focus on minimizing the space taken up on the base, this will be in the x, y, and z directions. Includes smaller sizing for mounting plates, smaller profile motors, incorporating smaller/different profile gears.
- **Cost (8.3%)**
    - Components and manufacturing methods should be selected to reduce the cost as much as possible.
- **Manufacturability/Ease of assembly (11.1%)**
    - All components should be easily manufacturable or possible to manufacture by basic machining equipment and allow for easy assembly so that customers are able to replicate or replace parts if one breaks.
- **Agility (22.2%)**
    - Between the use of motors and gearing used the design should be able to achieve maximum speed provided by the motor and allow for a maximum turning radius.
- **Light weight (5.6%)**
    - The material and components should be selected to reduce weight as much as possible without sacrificing performance.
- **Robustness (13.9%)**
    - The overall design of the module should not sacrifice strength, durability, and robustness. The design should be rugged enough to withstand collisions in a competition setting.
- **Ease of maintenance (16.7%)**
    - The design of this project should allow for tool accessibility as well as easy access for lubrication. The module should be able to be taken apart easily to replace worn parts.

Concept Drawings

Concept 1

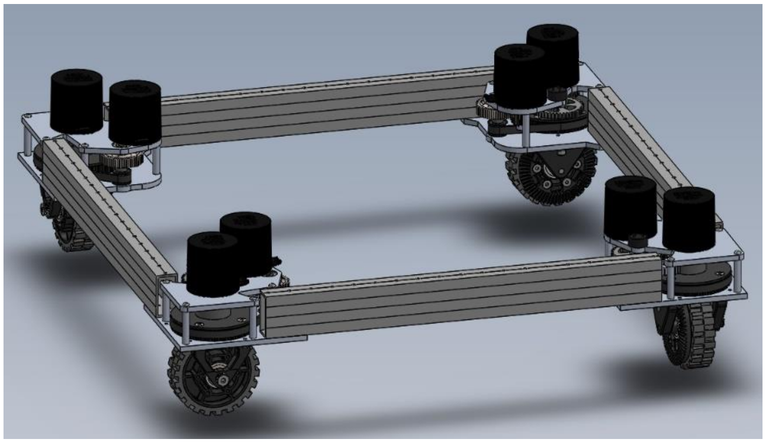


Figure 7: Design Concept 1

Design concept one consists of a modular design where the swerve modules are mounted in the corners of the robot frame. The frame and modules are aluminum and are fastened together with standard bolt hardware which can be easily taken apart if maintenance is required. The steering train consists of a combination of gears and belts to reduce the speed and increase torque from the steering motor. The use of belting reduces backlash, reduces weight, and reduces mechanical wear in the system. The drive train uses a two-stage gear reduction that passes though the steering pulley which reduces part count. Gears are chosen for the drive train because they are efficient, cheap and backlash does not matter. One of the key features about this design is that the motors are mounted above the top plate of the gearbox. This allows for all bearings, shafts, gears, belts, and pulleys to be sandwiched in-between both gearbox plates. This eliminates points of failure such as shaft collars, set screws, and ring clips which often come loose during robotics competitions. The elimination of this shaft hardware creates a more reliable design with fewer components. Higher ground clearance can be helpful in certain situations but for our application lower clearance would be desired. The motors are located on the top of the module and reduce the usable volume for the robot.

Pros:

- Lightweight
- Low steering backlash
- Continuous rotation
- Inexpensive

Cons:

- Complex
- Pressed motor pinion
- Not as strong as welded frame
- Not compact

Concept 2

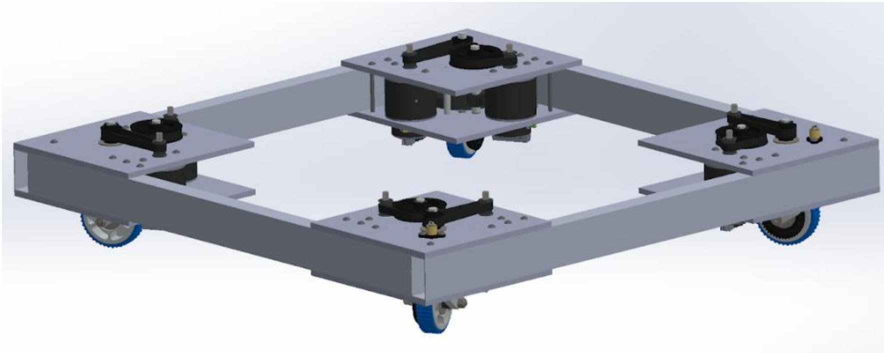


Figure 8: Design Concept 2

Design concept two consists of a modular design where the swerve modules are inside of the frame. This increases the material needed for the frame compared to Concept One; however, this provides more protection for the modules, being shielded by the frame. Like Concept One, the frame and modules are aluminum and are fastened together with standard bolt hardware, allowing for ease of assembly incase maintenance is required. Very similar to Concept One, the steering train consists of a combination of gears and belts to reduce the speed and increase torque from the steering motor. The use of belting reduces backlash, reduces weight, and reduces mechanical wear in the system. The drive train uses a two-stage gear reduction for the steering train and a three-stage reduction for the drive train. The use of a three-stage reduction helps to keep the module more compact and gives us the option to change the gear ratio easily. Gears are included in the drive train because they are efficient, cheap and backlash does not matter. The major design difference from Concept One to Concept Two is that Concept Two has the motors mounted upside down within the gearbox. This makes the module much more compact. The belts and pulleys will not be outside of both gearbox plates. This concept will likely include a few set screws, but this will be minimized. All parts are designed for easy manufacturing methods such as metal fiber laser, lathe, and 3D printer, thus making this concept inexpensive and light weight. The overall size of the module is smaller than that of Concept One because the module is fully integrated into the frame and the motors are in a more compact location. The small ground clearance of this design, compared to Concept One will be a better use of space and keep center of gravity low. The ends of the motors are exposed allowing objects to potentially damage the motors if they come into contact with one another, but this is an unlikely situation.

Pros:

- Lightweight
- Low steering backlash
- Continuous rotation
- Inexpensive
- Durable
- Compact

Cons:

- Increased points of failure
- Not as strong as welded frame

Concept 3

Figure 9: Design Concept 3

Design concept three consists of a 4-module design where each module is mounted at each corner. This configuration consists of modules that sit within the frame, completing the frame for added rigidity. All fabricated components (plates, frame, etc.) are made from aluminum which are also assembled with standard bolting. The frame is made using T-Slotted extrusion, which can be heavier than the previous two concepts. The benefit of the T-Slots is the T-Slot nuts that you can use. The nature of these nuts allows the module to be completely removed as a whole, making maintenance quicker due to not having to take the module apart. The module itself is in a vertical configuration, with the motor laying horizontal. It is paired with a steering motor flipped under the frame to allow for more room for the drive components and keep them truly separate. The idea is that the nature of the drive motor flipped will allow for a slimmer design around the module and a lower clearance than the traditional vertical motor setup. It also allows for an easier transition of the motor rotation due to the motor's horizontal nature. The drive motor utilizes gearing to reduce speed and increase torque, to eliminate some additional weight some of the gearing is replaced with belting which is much lighter. The steering motor also uses belting which can provide a more accurate position.

Pros:

- Lower Motor Clearance
- Low steering backlash
- Continuous rotation Modular Design for Maintenance

Cons:

- Heavy frame
- With added enclosure, modules can be heavy
- Not compact
- Durability issues due to T-Slot nature to unscrew over time.

Weighted Matrix

		Concept 1		Concept 2		Concept 3	
Criteria:	Importance weight (%)	Rating	Weighted rating	Rating	Weighted rating	Rating	Weighted rating
Reliability (# of breakdowns)	19.4	3	58.2	3	58.2	2	38.8
Small Size (in^3)	2.8	2	5.6	4	11.2	2	5.6
Low Cost ($)	8.3	4	33.2	3	24.9	3	24.9
Manufacturability/ ease of assembly (sec)	11.1	3	33.3	3	33.3	4	44.4
Agility (m/s^2)(m/s)	22.2	3	66.6	4	88.8	3	66.6
Light Weight (lbs)	5.6	3	16.8	3	16.8	3	16.8
Robustness (yield strength Mpa)	13.9	2	27.8	4	55.6	2	27.8
Ease of Maintenance (sec)	16.7	3	50.1	3	50.1	3	50.1
	100		291.6		338.9		275

Rating:	
Unsatisfactory	0
Tolerable	1
Adequate	2
Good	3
Very Good	4

Design Model

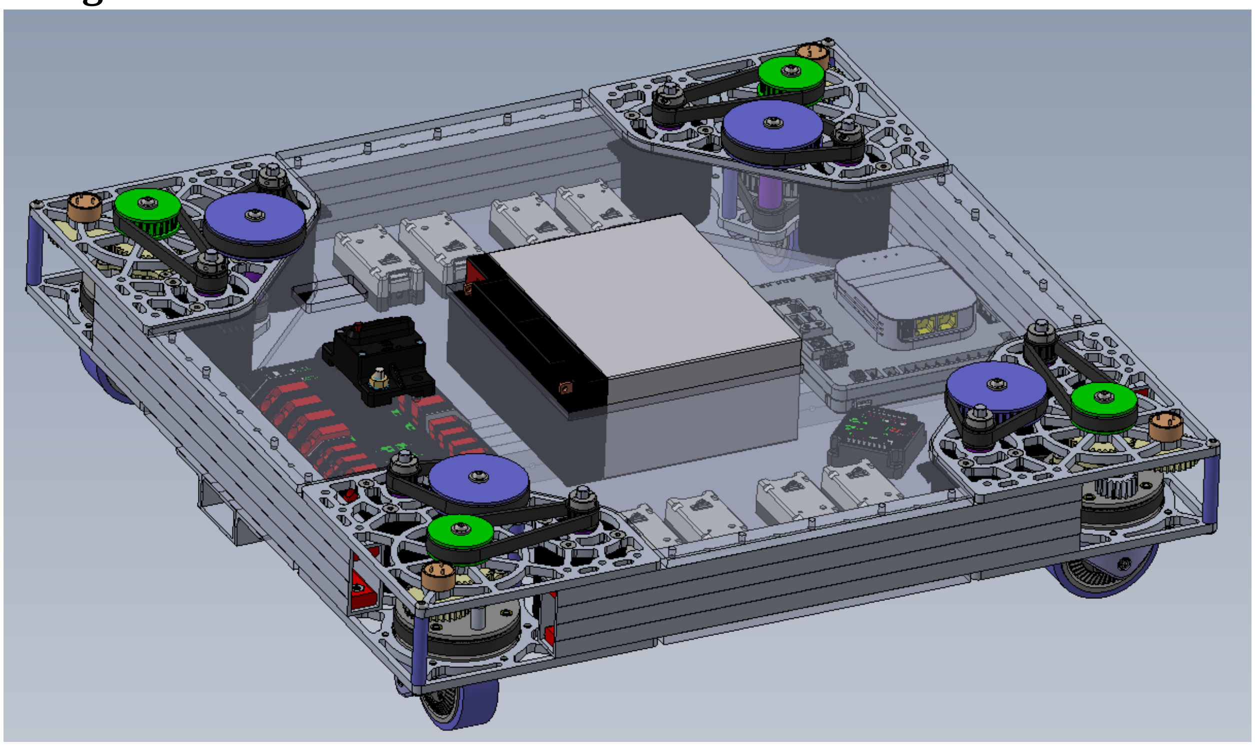


Figure 10: Completed Robot Design

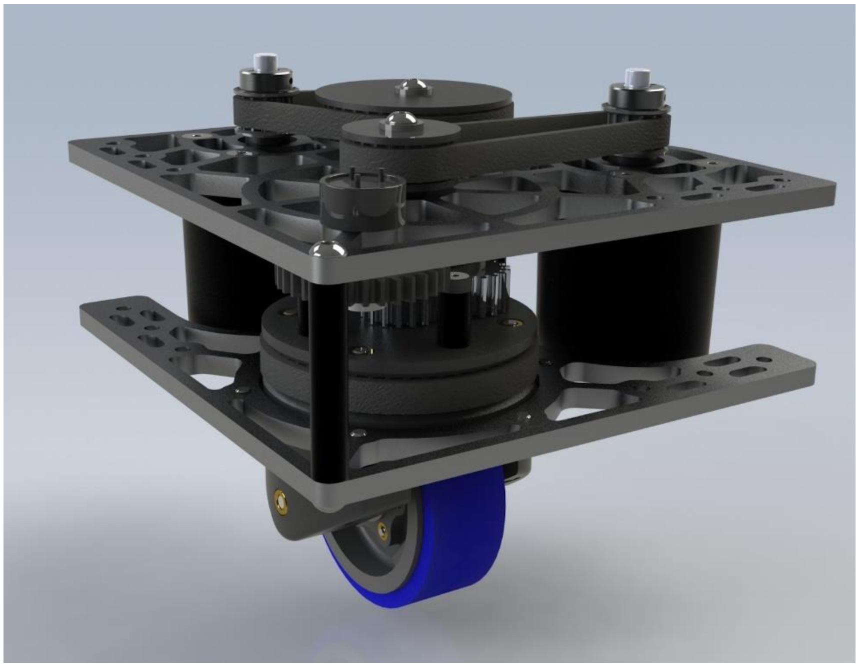


Figure 11: Completed Swerve Modular Design

Calculations

Steer train Calculations

Gear Ratio

Input shaft 12: 40 gear ratio

Output shaft 12:50 gear ratio

$(12 \times 12) : (40 \times 50)$

$144\ input : 2000\ output$

$\frac{2000}{144} input : \frac{2000}{2000}\ output$

$13.89\ input : 1\ output$

Turning Speed and Turning Torque

Neo Brushless Motor Max free speed: 5676 rpm

Neo Brushless Motor Stall torque: 2.6 N*m (23 in-lbs.)

$Turning\ speed = 5676\ (rpm) \times (\frac{1}{13.89})$

$Turning\ speed = 408.6\ rpm$

$\frac{408.6\ rpm}{1\ min} \times \frac{1\ min}{60\ sec} = 6.8\ rotations\ per\ second$

$Turning\ torque = 23(in - lbs) \times 13.89$

$Turning\ torque = 319.47\ in - lbs$

Adjusted Speed

Assumptions:

Turning speed= 408.6 rpm

Speed loss constant= 85%

$Speed = \ (\boldsymbol{RPM})\ \times (\boldsymbol{speed\ loss\ constant})$

$Speed = \ 408.6\ (rpm)\ \times 0.85$

$Speed = \ 347.31\ rpm$

$$\frac{347.31\ rpm}{1\ min} \times \frac{1\ min}{60\ sec} = 5.79\ rotations\ per\ second$$

Drivetrain Calculations

Gear Ratio

Input shaft 12:20 gear ratio

Middle shaft 16:20 gear ratio

Output shaft 15:45 gear ratio

$(12\ \times\ 16) : (20\ \times\ 20)$

$192\ input : 400\ output$

$(192\ \times\ 15) : (400\ \times\ 45)$

$2880\ input : 18000\ output$

$$\frac{18000}{2880} input : \frac{18000}{18000}\ output$$

$6.25\ input : 1\ output$

Drive Speed and Drive Torque

Neo Brushless Motor Max free speed: 5676 rpm

Neo Brushless Motor Stall torque: 2.6 N*m (23 in-lbs.)

$$Drive\ speed = 5676(rpm) \times (\frac{1}{6.25})$$

$Drive\ speed = 908.16\ rpm$

$$\frac{908.16\ rpm}{1\ min} \times \frac{1\ min}{60\ sec} = 15.14\ rotations\ per\ second$$

$$Drive\ torque = 23\ (in - lbs) \times 6.35$$

$$Drive\ torque = 143.75\ in - lbs$$

Adjusted Speed

Assumptions:

Drive speed= 908.16 rpm

Speed loss constant= 85%

Wheel diameter = 3 in

$$Speed = (\boldsymbol{RPM}) \times (\boldsymbol{speed\ loss\ constant}) \times \left(\frac{2\pi}{60}\right) \times (wheel\ radius)$$

$$Speed = 908.16\ (rpm) \times (0.85) \times \left(\frac{2\pi}{60}\right) \times (\frac{1.5(in)}{12\ (in)})$$

$$Speed = 10.10\ ft/sec$$

Force Calculations

Torque to overcome static friction

Assumptions:

coefficient of friction between wheels and tight pile carpet = 1.0, (Reference (18))

Robot weight= 150 lbs

$$Wheel\ load = (\frac{weight}{numberof\ wheels})$$

$$Wheel\ load = (\frac{150\ (lbs)}{4})$$

$$Wheel\ load = 37.5\ lb_f/wheel$$

Friction Force on Wheels

$$F_f = \boldsymbol{coefficient\ of\ friction} \times \boldsymbol{Wheel\ load}$$

$$F_f = 1.0 \times 37.5(lb_f)$$

$$F_f = 37.5\ \boldsymbol{lb_f}$$

Wheel Friction Torque

$$Wheel\ Friction\ Torque = \boldsymbol{coefficient\ of\ friction} \times \boldsymbol{Wheel\ load}$$

$$Wheel\ Friction\ Torque = F_f \times Wheel\ radius$$

$$Wheel\ Friction\ Torque = 37.5\ (lb_f) \times (\frac{1.5(in)}{12\ (in)})$$

$$Wheel\ Friction\ Torque = \mathbf{4.69}\ \boldsymbol{in - lbs}$$

Turn radius

$$Arc\ length\ of\ 360^o\ Turn = \boldsymbol{\pi} \times \boldsymbol{D}$$

$$Arc\ length\ of\ 360^o\ Turn = \boldsymbol{\pi} \times (\frac{26\ (in)}{12\ (in)})$$

$$Arc\ length\ of\ 360^o\ Turn = 6.8\ \boldsymbol{ft}$$

$$Time\ to\ complete\ 360^o\ Turn = \frac{arc\ length}{speed}$$

$$Time\ to\ complete\ 360^o\ Turn = \frac{6.8\ (ft)}{10.10\ (\frac{ft}{sec})}$$

$$Time\ to\ complete\ 360^o\ Turn = 0.67\ sec$$

Battery

Battery Life without Load

$$Battery\ life = \frac{Batery\ capacity}{Current\ draw}$$

$$Battery\ life = \frac{18\ (Ah)}{16.23\ (A)}$$

$$Battery\ life = 1.11\ hrs$$

Battery Life with Load

Assumptions:

Running at 75% max load

$$Battery\ life = \frac{Batery\ capacity}{maximum\ current\ draw\ \times 0.75}$$

$$Battery\ life = \frac{18\ (Ah)}{120(A) \times 0.75}$$

$$Battery\ life = 0.2\ hrs$$

$$\frac{0.2\ hrs}{1} \times \frac{60\ min}{1\ hr} = 12\ min$$

Wire Schematic

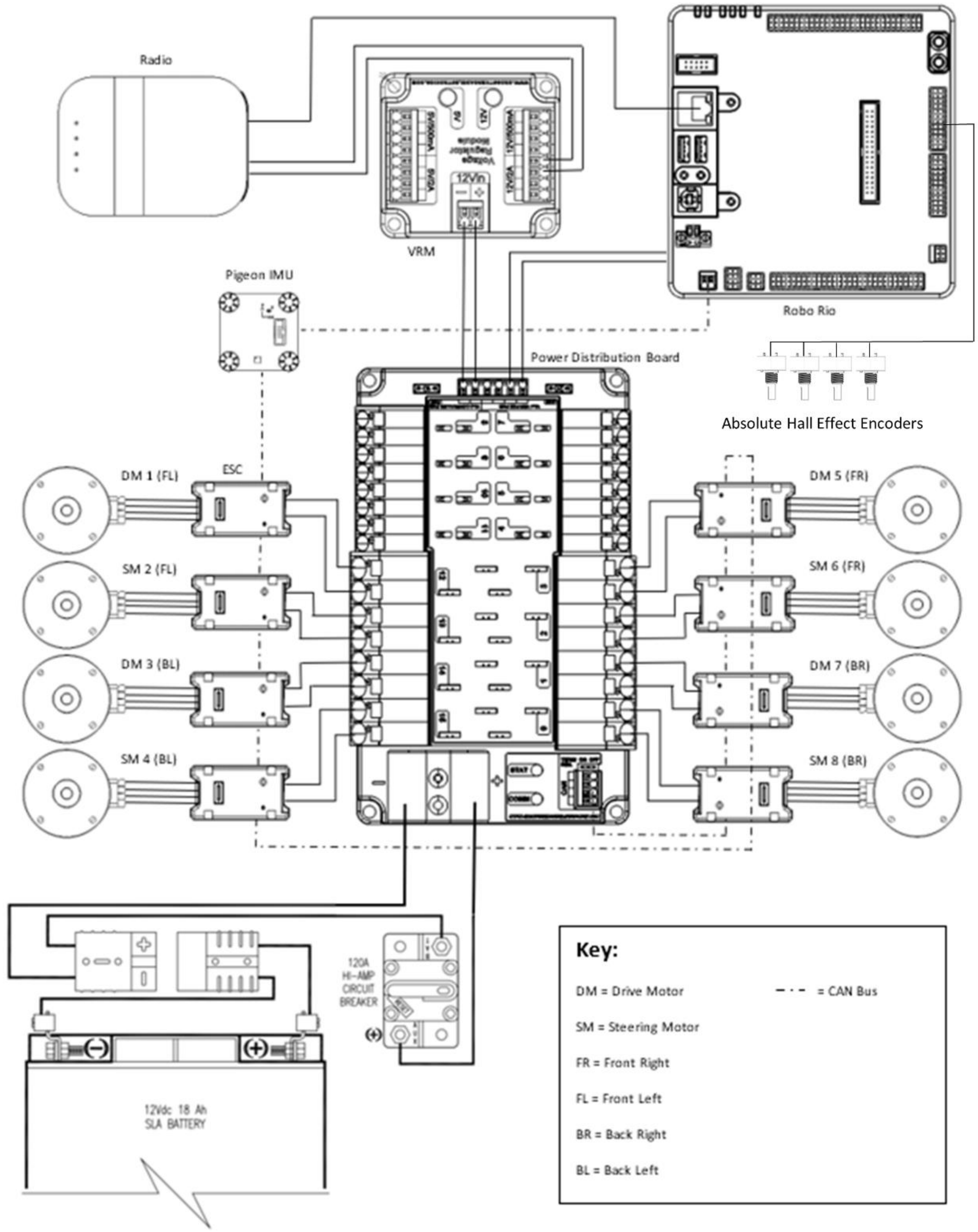


Figure 12: Completed Wire Schematic

FEA Simulations

The manner of loading chosen for our design is impact or shock because we are looking for a robust design that can handle the stress of competitions. These safety factors were obtained from Design stress guidelines: Direct normal stresses chart in the sixth edition of Robert L. Mott's Applied Strength of Materials (19).

TABLE 3–2 Design stress guidelines: Direct normal stresses.

Manner of loading	Ductile material	Brittle material
Static	$\sigma_d = s_y/2$	$\sigma_d = s_u/6$
Repeated	$\sigma_d = s_u/8$	$\sigma_d = s_u/10$
Impact or shock	$\sigma_d = s_u/12$	$\sigma_d = s_u/15$

Table 4: Safety Factor Table for Multiple Loading Conditions

Figure 13: Design Stress Guidelines

The acceptable safety factor for impact or shock for ductile material from the table is 12.

The acceptable safety factor for impact or shock for brittle material from the table is 15.

Hub Stress Analysis

A 38 lb_f was applied to the bottom of the wheel hub.

Maximum observed stress: 0.392 ksi

Yield strength of Onyx: 5.8 ksi

Percent elongation at yield: 25% → ductile

Meets the safety factor of 12 for ductile material

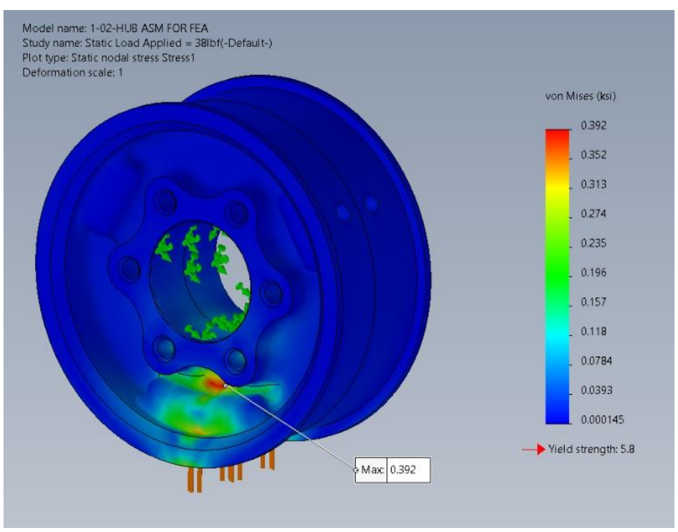


Figure 14: Hub Assembly Stress Analysis

Wheel Mount Stress Analysis

A 38 lb_f was applied to the bottom of the wheel mount.

Maximum observed stress: 2.38 ksi

Yield strength of 6061 T6: 40 ksi

Percent elongation at yield: 17% → ductile

Meets the safety factor of 12 for ductile material

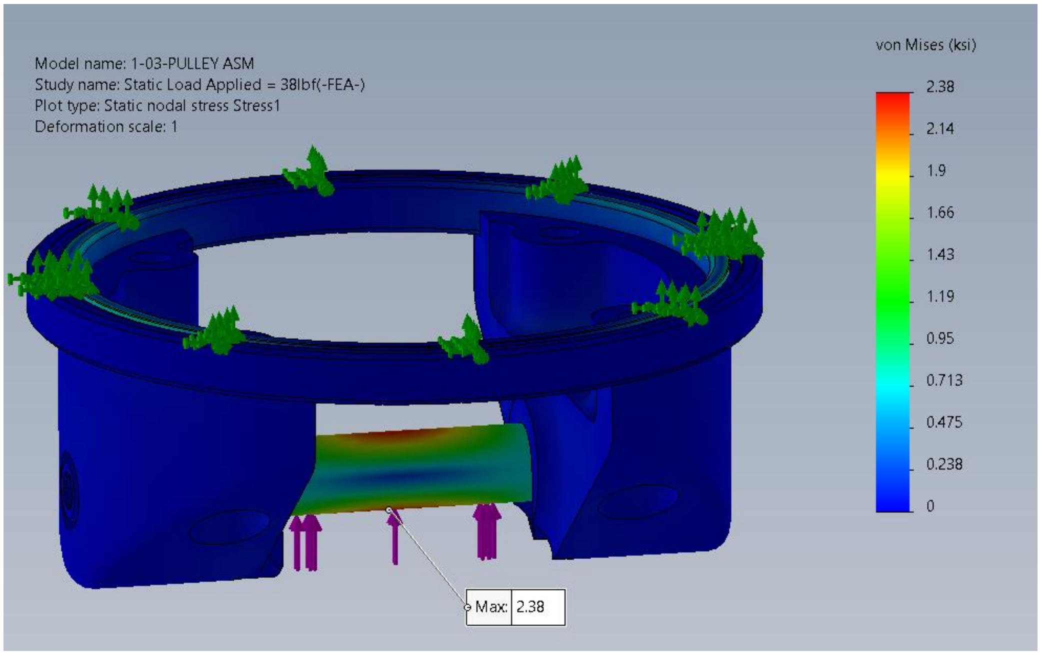


Figure 15: Wheel Mount Assembly Stress Analysis

Frame Stress Analysis

A 150 lb_f was applied to the top of the frame.

Maximum observed stress: 1.92 ksi

Yield strength of 6061 T6: 40 ksi

Percent elongation at yield: 17% → ductile

Meets the safety factor of 12 for ductile material

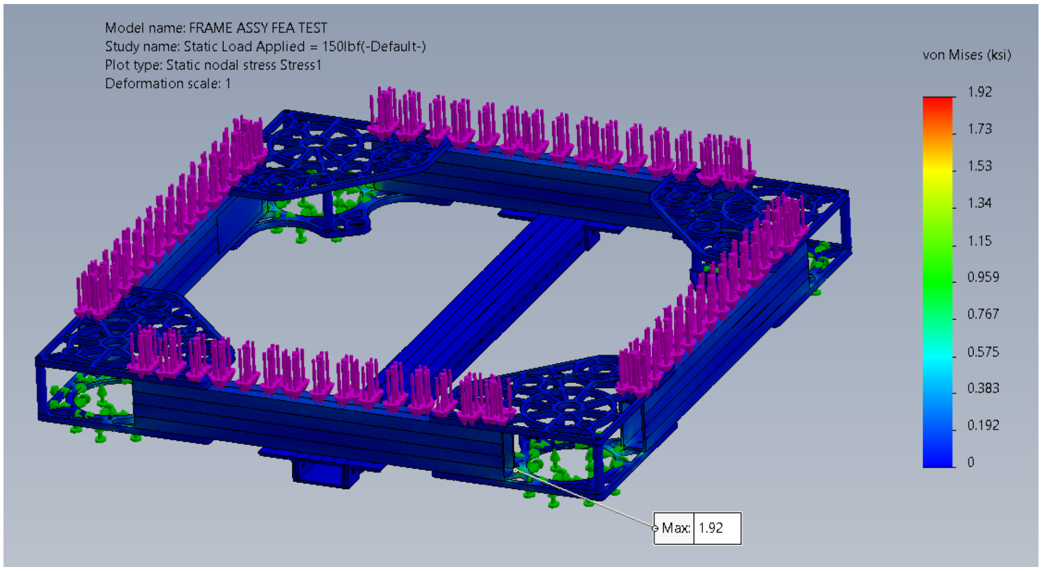


Figure 16: Frame Assembly Stress Analysis

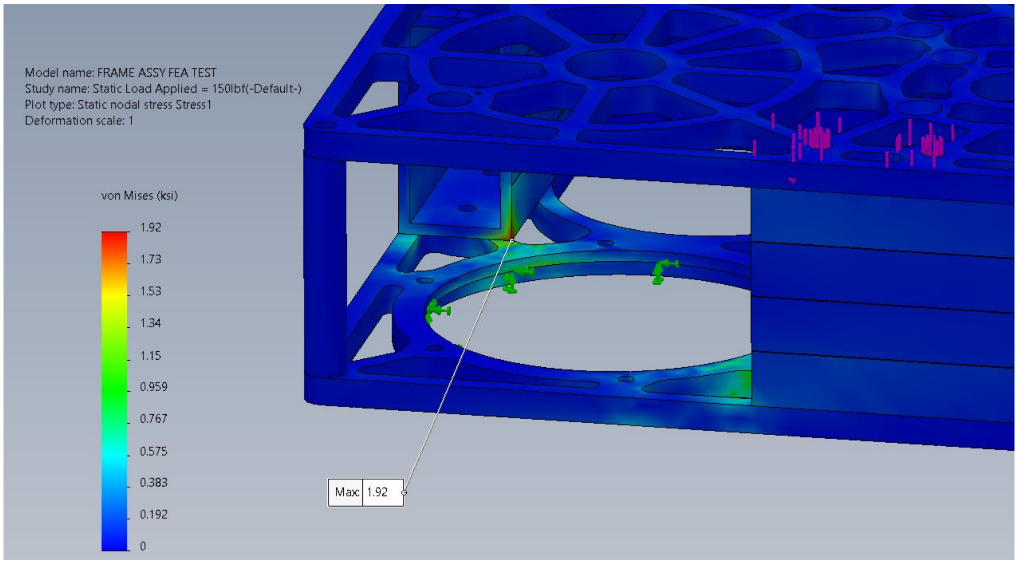


Figure 17: Frame Assembly Stress Analysis: Modular Plate

Side Frame Stress Analysis

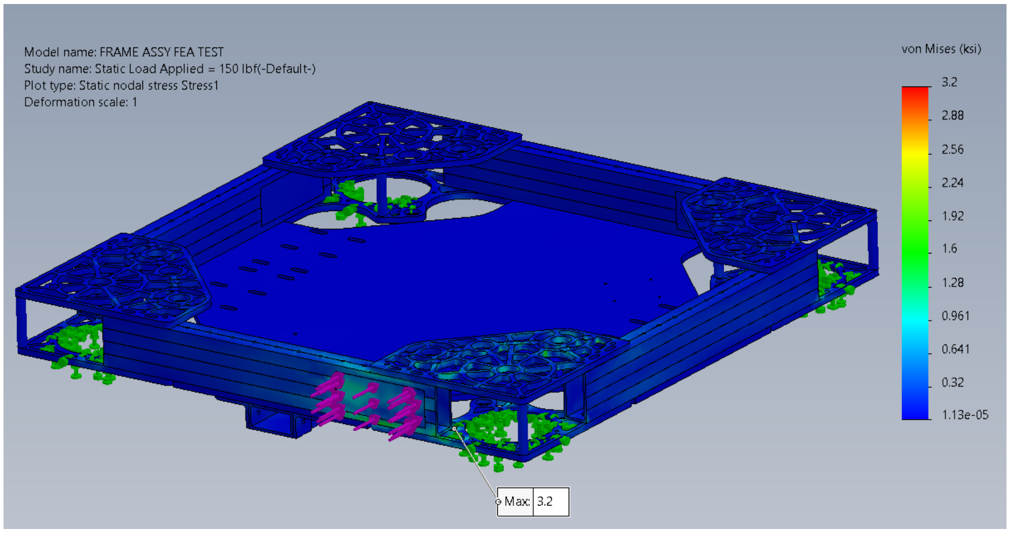
A 150 lb_f was applied to the side of the frame.

Maximum observed stress: 3.2 ksi

Yield strength of 6061 T6: 40 ksi

Percent elongation at yield: 17% → ductile

Meets the safety factor of 12 for ductile material



Frame 18: Side Frame Stress Analysis

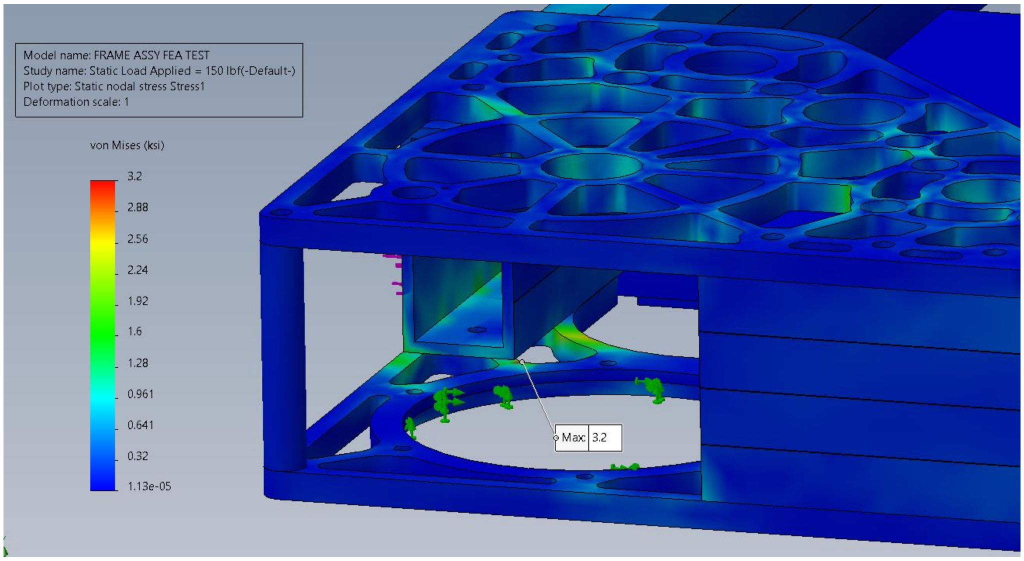


Figure 19: Side Frame Stress Analysis: Modular Plate

Component and Material Selection

For our components and material, we had four main categories for the material selection:

3D printed Onyx, 6061 T6 aluminum, 3D printed ABS and AISI 1045 alloy steel.

Here is a break down parts made from each material:

3D Printed Onyx

- Steering pulley
- Drive pulleys
- Wheel mounts
- Wheel hub

6061 T6 Aluminum

- Frame
- Module plates
- Drive shafts
- Spur gears
- 12 tooth pulleys

3D Printed ABS

- Spacers
- Nut plates

AISI 1045 Alloy Steel

- Hardware
- Bearings
- 15 tooth bevel gear
- 45 tooth bevel gear

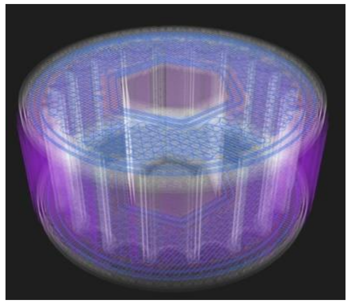


Figure 20: 3D Printed Onyx

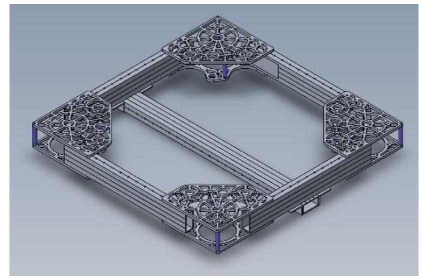


Figure 21: 6061 T6 Aluminum

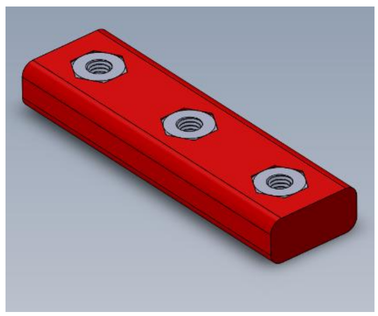


Figure 22: 3D Printed ABS Nut Plate

Figure 23: AISI 1045 Alloy Steel Bevel Gears

Proposed Fabrication

Our proposed fabrication includes utilizing two 3D printer to produce our parts made from Onyx and ABS materials. We also plan to use a lathe located at FRC Team 144's robotic lab to manufacture the drive shafts and wheel axles. Lastly, we plan to utilize RA Jones' fiber laser cutting capabilities to cutout the modular plates.

Actual Fabrication

For the actual fabrication of the module components, we utilized FRC Team 144's robotic lab, located at Colerain High School. We also used the fiber laser cutters at RA Jones, where one of our team members works. For the steering pulley, drive pulleys, wheel mounts, and wheel hubs we used a 3D printer (Mark forged Mark 2) with Onyx filament with a carbon fiber inlay. These parts were printed to size, and we did not see any defects within the prints.

The spacers, nut plates, and encoder gears were 3D printed (LulzBot) using ABS filament. We forgot to account for the printer under sizing the ABS material and all the spacers came out under sized. We hand filed the spacers with circular inner diameters to size. The spacers that were printed for hex shafts were broached to size using a 3 ton arbor press. The nut plates were printed to size, and we did not encounter any clearance issues. The encoder gears printed to size; however, there was about 2 degrees of backlash between the gears. Therefore, we reprinted the gears to provide mechanical offset.

The Drive shafts and wheel axles were machined using the lathe at the robotics lab. The wheel axles were machined to size, without any problems. The drive shafts were machined about 0.001 inches undersized. To remove the small amount of material, the parts were placed back onto the lathe and Scotch-Brite was applied to the shafts and the parts were measured periodically with calipers until they were to size.

The module plates were manufactured at RA Jones using their Fiber laser cutter. The parts were then sent out to be powder coated. 3D printed inserts to prevent the plate being painted where the bearings and shafts are inserted. Instructions were also included to help prevent those areas from being painted. Once we received the parts back, the bearing holes were sanded using Scotch-Brite to remove overspray.

Proposed Assembly

Our plan for assembly is based on how we designed the modules and robot, by sub-assemblies. We plan to assemble the following assemblies in this order:

1. 1-02-HUB ASM

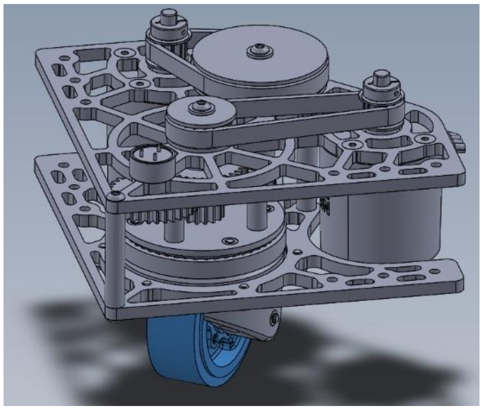


Figure 24: 1-02-Hub Assembly

2. 1-03-PULLEY ASM

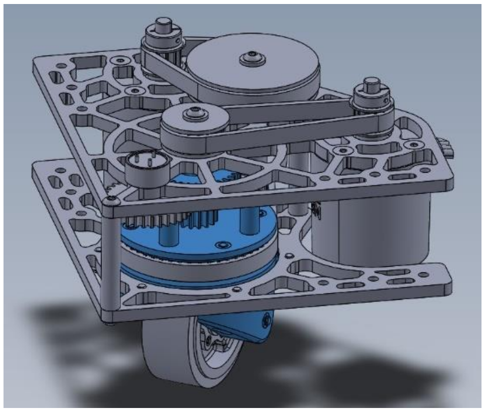


Figure 25: 1-03-Pulley Assembly

3. 1-05-NUT PLATE ASM

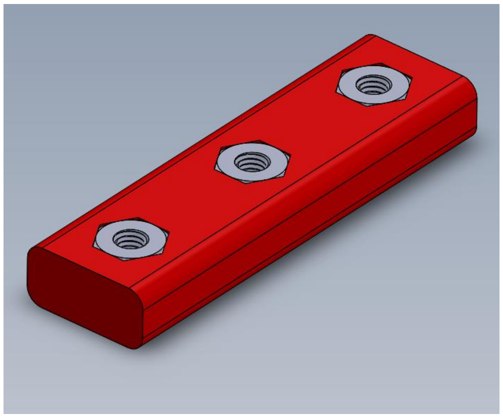


Figure 26: 1-05-Nut Plate Assembly

4. 1-06-FRAME ASM

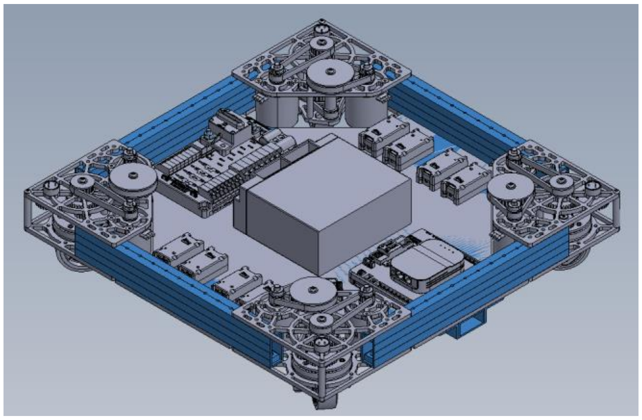


Figure 27: 1-06-Frame Assembly

5. 1-04-ELECTRONICS PLATE ASM

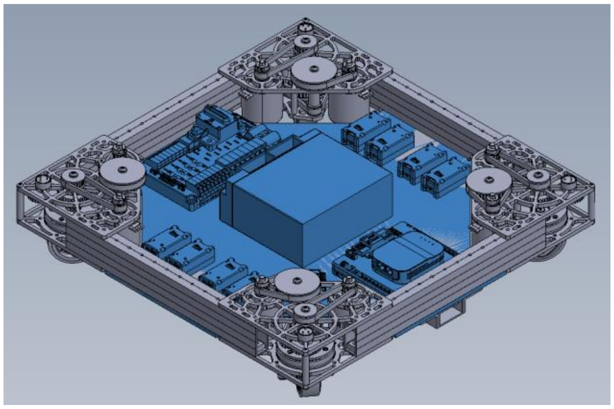


Figure 28: 1-04 Electronics Plate Assembly

6. 1-01-SWERVE DRIVE MODULE ASM

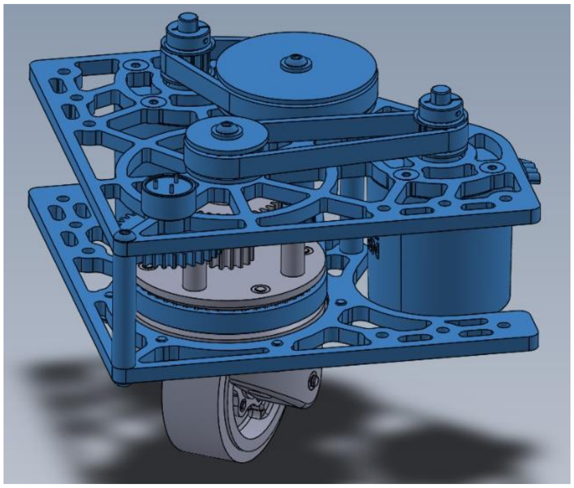


Figure 29: 1-01-Swerve Drive Module Assembly

Actual Assembly

As planned, we assembled the components by sub-assembly. We assembled the parts in the following order:

1. 1-02-HUB ASM
2. 1-03-Pulley ASM
3. 1-05-NUT PLATE ASM
4. 1-06-FRAME ASM
5. 1-04-ELECTRONICS PLATE ASM
6. 1-01-SWERVE DRIVE MODULE ASM

1-02-HUB ASM

1-02-HUB ASM	
ITEM NO.	PART NUMBER
1	1-02-100-HUB, WHEEL, A, 3IN OD, ONYX
2	1-02-101-HUB, WHEEL, B, 3IN OD, ONYX

3	1-02-400-TREAD, NITRILE, 0.28IN THK X 1IN WD, BLUE, PART NO. TTB-0037, THRIFTY BOT
4	1-02-401-GEAR, BEVEL, 45T, PART NO. 1-25MOD_TTB-S-016, THRIFTY BOT
5	1-02-402- BEARING, FLANGE, 0.375 ID X 0.875 OD X 0.280 WD, PART NO. 217-2733, VEX
6	1-02-403-INSERT, 6-32 BRASS HEAT SET, PART NO. 93365A130, MCMASTER-CARR
7	6-32 X 0.375 LONG, BUTTON HEAD SCREW
8	6-32 X 1.000 LONG, FLAT HEAD SCREW
9	6-32, HEX NUT

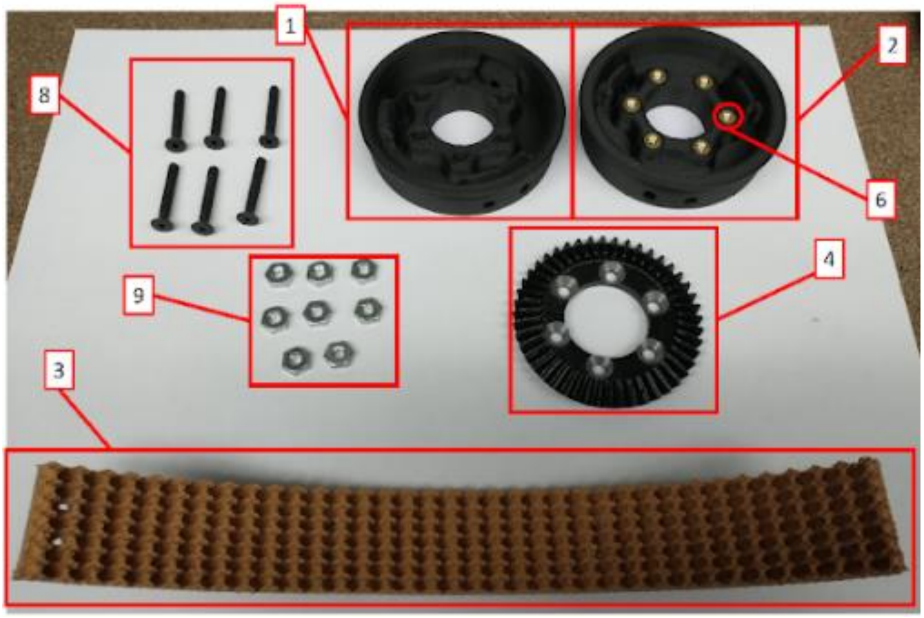


Figure 30: 1-02-HUB ASM Components

The first step to assembling the wheel hub is to install the 6x brass heat set inserts (item 6) into wheel hub B (item 2). Using the pre-drilled holes and a soldering iron, the brass heat set inserts are put onto the soldering tip and heated up and pressed into the 6x holes.

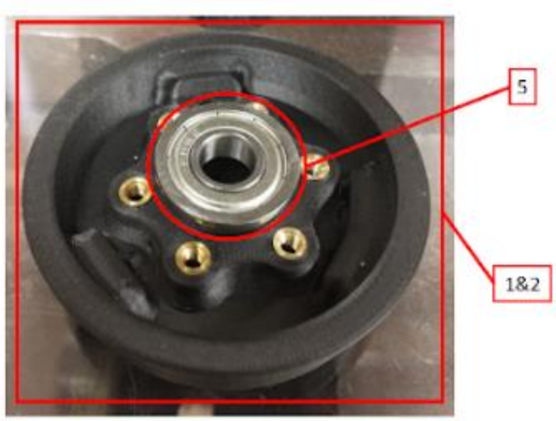


Figure 310: Wheel Hubs A & B

The next step is to press fit the bearing (item 5) into wheel hub A and B (items 1 and 2). This was done using the 3 Ton Arbor Press. After the bearings are installed, the 8x hex nuts (item 9) are installed into the hex cut outs inside wheel hub A and B (items 1 and 2).

Figure 32: Wheel Hub Assembled

Then wheel hub A (item 1) is placed on top of wheel hub B (item 2). Then the bevel gear (item 4) is placed on top of hub A (item 1). Then all three are fastened together using 6x flat head screws (items 8).

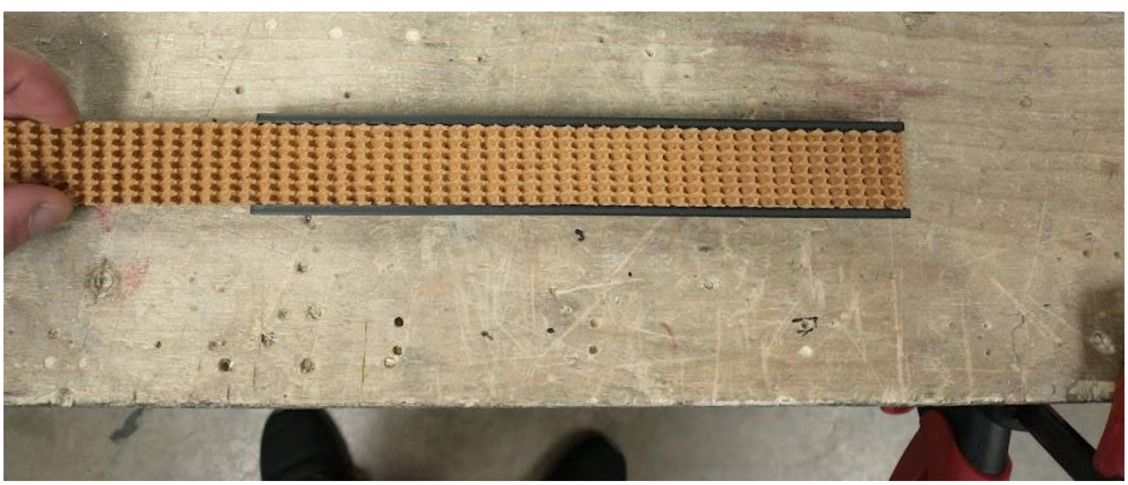


Figure 33: Wheel Tread Jig

The next step is to cut the tread (item 3) to length and drill the fastening holes. This is done by using the tread jig that measures the tread to the exact length needed for the wheel.

Figure 34: Cutting Wheel Tread

Once the tread is properly placed into the jig, it is clamped to the table. The tread is cut to length and the 8x holes are drilled into the back of it.


Figure 35: Complete Wheel Hub Assembly

Then the tread is wrapped around the wheel assembly and fastened using the 8x button head screws (item 7).

1-03-PULLEY ASM

1-03-PULLEY ASM	
ITEM NO.	PART NUMBER
1	#8, FLATWASHER
2	1-01-403-BEARING, FLANGED 10.25MM ID X 0.875IN OD X 0.280IN WD STEEL, PART NO. 217-5829, VEX
3	1-03-101-SHAFT, HEX 0.375IN, DRIVE, ALUMINUM, PART NO. 217-2754, VEX
4	1-03-102-MOUNT A, WHEEL, ONYX
5	1-03-103-PULLEY, HTD-5M, 50T, ONYX
6	1-03-104-BEARING, RADIAL 8MM ID X 16MM OD X 5MM WD STEEL, PART NO. MR688-ZZ, VXB
7	1-03-106-SHAFT, HEX 0.375IN, DRIVE, ALUMINUM, PART NO. 217-2754, VEX
8	1-03-108-SPACER, HEX, 0.375IN ID X 0.6IN OD X 0.135IN LG, ONYX
9	1-03-109-SPACER, THUNDER HEX, 0.375IN ID X 14MM OD X 0.425IN LG, ONYX
10	1-03-110-GEAR, SPUR, 34T, 20 DP, ENCODER, ONYX
11	1-03-111-SPACER, 3.8MM ID X 0.375IN OD X 0.575IN LG, ALUMINUM
12	1-03-112-MOUNT B, WHEEL, ONYX
13	1-03-113-SPACER, 0.201IN ID X 0.375IN OD X 1.650IN LG, ALUMINUM
14	1-03-114-SPACER, 0.375 ID X 16MM OD X 0.152IN LG, ABS
15	1-03-115-SPACER, 0.375 ID X 0.500 OD X 0.152IN LG, ABS
16	1-03-116-SPACER, HEX, 0.375IN ID X 0.6IN OD X 18.15MM LG,ABS
17	1-03-401-GEAR, BEVEL, 15T, PART NO. 1-25MOD_TTB-S-015, THRIFTY BOT
18	1-03-402-GEAR, SPUR, 20T, 20DP, 0.375IN HEX, ALUMINUM, PART NO. 217-2701, VEX
19	1-03-403-GEAR, SPUR, 16T, 20 DP, 0.375IN HEX, ALUMINUM, PART NO. 217-5450, VEX
20	1-03-404-BEARING, 3IN ID X 3.5IN OD X 0.25IN WD, PART NO. WCP-0357, WCP
21	1-03-405-INSERT, 10-32 BRASS HEAT SET, PART NO. 97171A200, MCMASTER-CARR
22	1-03-704-SCREW, SOCKET HEAD, 10-32, 3IN LG, PART NO. 91251A360, MCMASTER CARR
23	1-03-705-SCREW, BUTTON HEAD 6-32 X 0.500 LONG, PART NO. 91306A324, MCMASTER-CARR
24	1-03-707-SCREW, FLATHEAD, 6-32 X 0.375 LONG, PART NO. 91263A514, MCMASTER CARR
25	1-03-708-SCREW,SCOKET HEAD, 10-32 X 1.75IN, PART NO. 91251A352, MCMASTER CARR
26	1-03-709-SCREW,BUTTON HEAD 10-32 X 0.375 LONG, PART NO. 91306A354, MCMASTER CARR
27	#10 FLATWASHER
28	8-32 X 0.375 LONG, BUTTON HEAD SCREW

Figure 36: Lower Plate Bearing Components

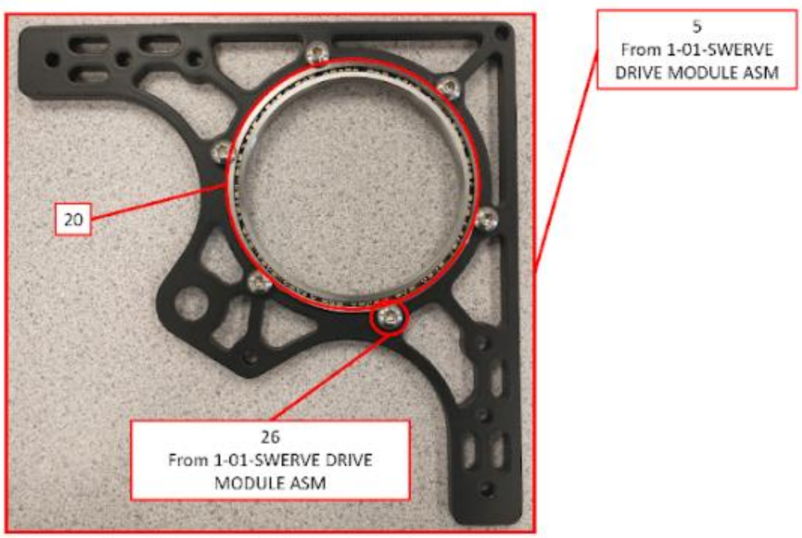


Figure 37: Lower Plate Assembled

The first step is to press fit the bearing (item 20) into the lower plate from 1-01 assembly (item 5). Then to secure the bearing in place, the button head screws from 1-01 assembly (item 26) are installed into the lower plate.

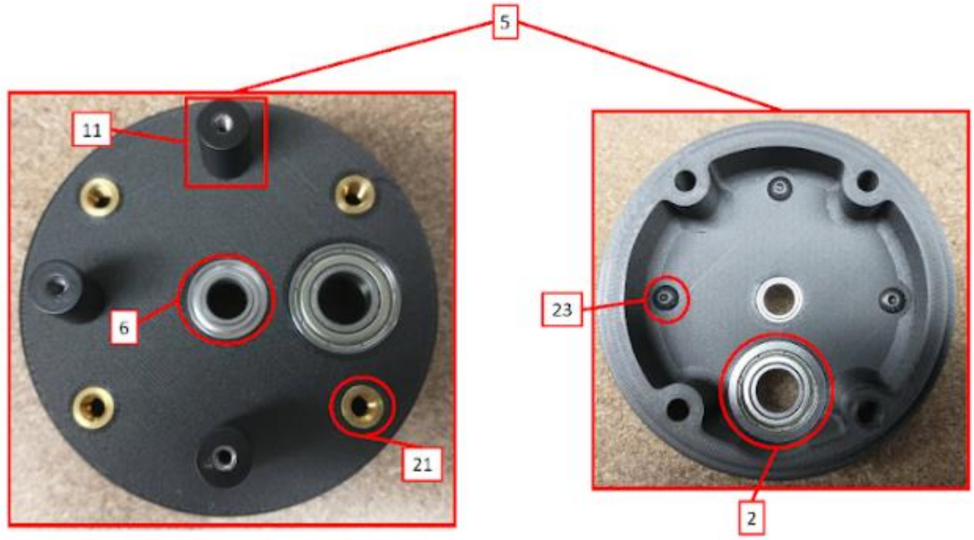


Figure 38: Pulley Assembly

The next step is to install the 4x heat set inserts (item 21) into the top of the pulley (item 5). then press fit the bearing (item 6) into the top of the pulley. Then the pulley is flipped over to press fit the other bearing (item 2) into it. The 3x spacers (item 11) are installed on the top of the pulley, and are fastened using the 3x button head screws (item 23) from the back of the pulley.

Figure 39: Wheel Mount Assembly

Next, the bearing (item 6) is installed into wheel mount A (item 4). In wheel mount B (item 12), a brass heat set insert (item 21) is installed into the side.

Figure 40: Drive Shaft Assembly

On the hex drive shaft (item 3), a spacer (item 8) is added 0.73 inches from the bottom of the shaft. Then the bevel gear (item 17) is added on top spacer, item 8. Lastly, a spacer (item 9) is added above the bevel gear (item 17), leaving 0.2 inches from the top of the shaft.

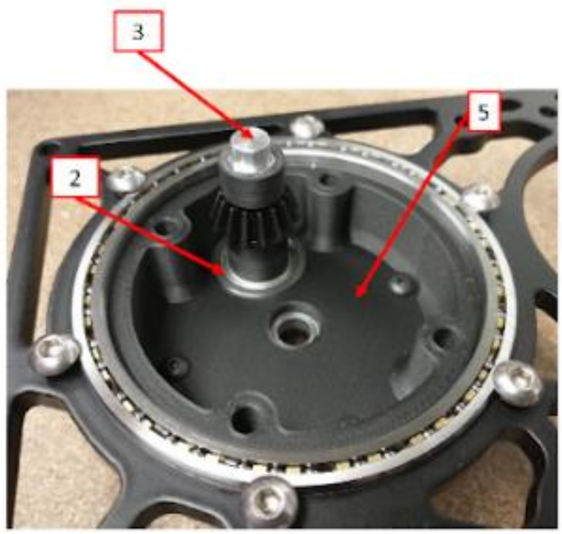


Figure 41: Drive Shaft Installed into Pulley

The shaft (item 3) is then installed into the bearing (item 2) on the back side of the pulley (item 5).

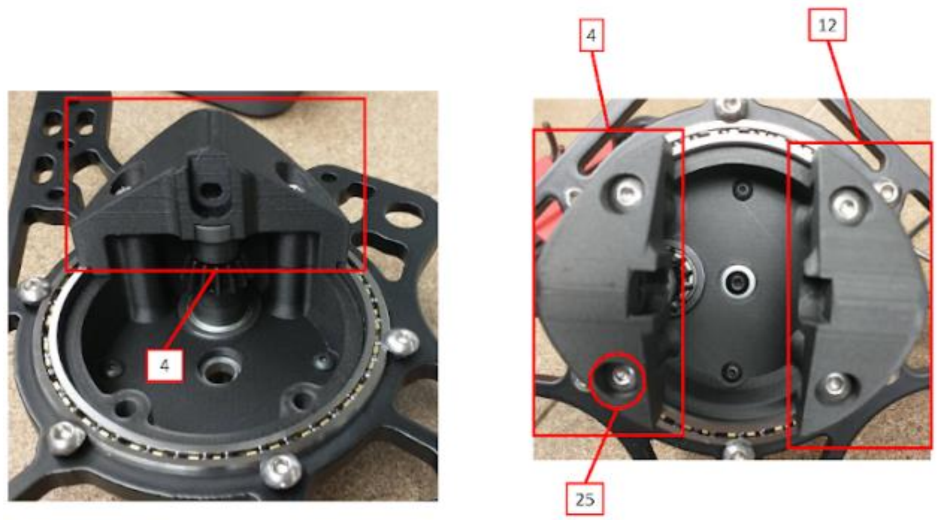


Figure 42*:* Wheel Hubs Installed onto Pulley

Wheel mount A (item 4) was then placed on top of the drive shaft (item 3), aligning with the mounting holes on the pulley (item 5). Then wheel mount B (item 12) was placed on top of the other set of mounting holes on the pulley. Both wheel mounts were fastened to the pulley using socket head screws (item 25).

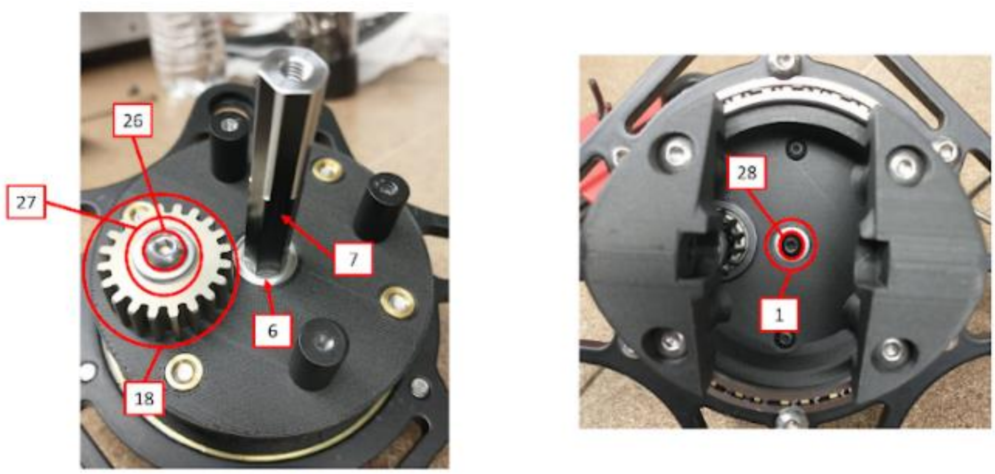
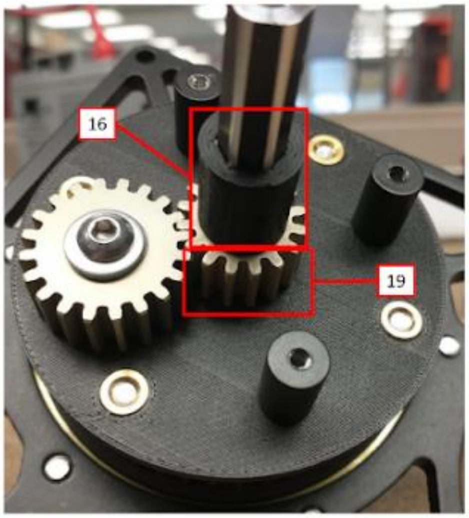


Figure 43: Drive Shaft and Gear Installation

Then the drive shaft (item 7) is inserted into the bearing (item 6) on the top side of the pulley (item 5). The shaft is fastened from the bottom of the pulley using a washer (item 1) and a button head screw (item 28). Next, the spur gear (item 18) is added to the top of the shaft (item 3) and fastened with a washer (item 27) and a button head screw (item 26).



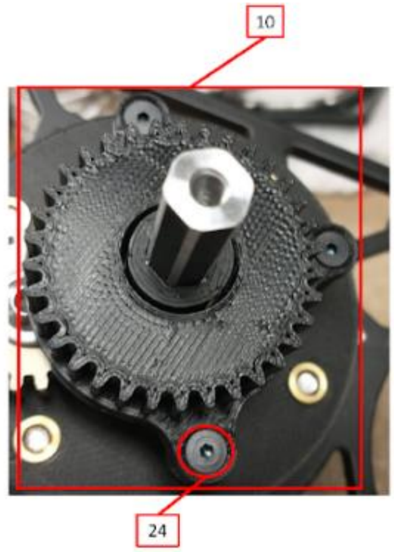
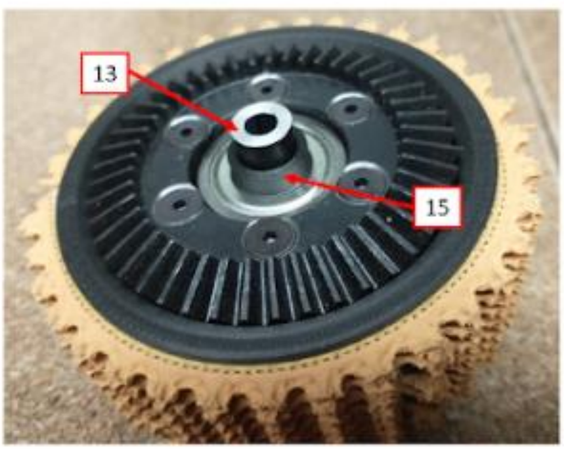


Figure 44: Gears and Spacer Installation

Next the other spur gear (item 19) is added onto the drive shaft (item 7) and interlocks with the other spur gear (item 18). Then a spacer (item 16) is added on top of the spur gear (item 19). Lastly, the 3-D printed spur gear (item 10) is added on top of the 3 spacers (item 11). The gear is then fastened to the spacers using flathead screws (item 24).



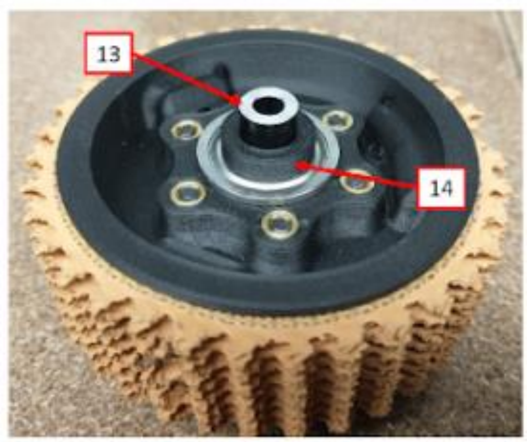


Figure 45: Shaft into Wheel Installation

The aluminum spacer (item 13) is inserted into the wheel assembly with a spacer (item 15) placed on top of item 13 on the side with the bevel gear. On the other side of the wheel assembly, a spacer (item 14) is placed on top of item 13.

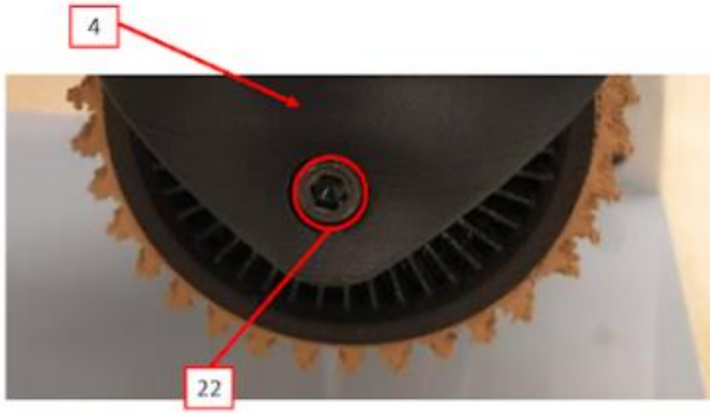


Figure 46: Wheel into Wheel Hub Installation

The last step is to insert the wheel assembly with the spacers into the pulley assembly. The bevel gear on the wheel assembly will face wheel hub A (item 4). Once the hole on the wheel assembly aligns with that of the two wheel hubs, a socket head screw (item 22) is used to attach the wheel assembly to the pulley assembly.

1-05-NUT PLATE ASM

1-05-NUT PLATE ASM	
ITEM NO.	PART NUMBER
1	1-05-100-PLATE, NUT, 10_32, ABS
2	1-05-700-NUT, HEX 10-32

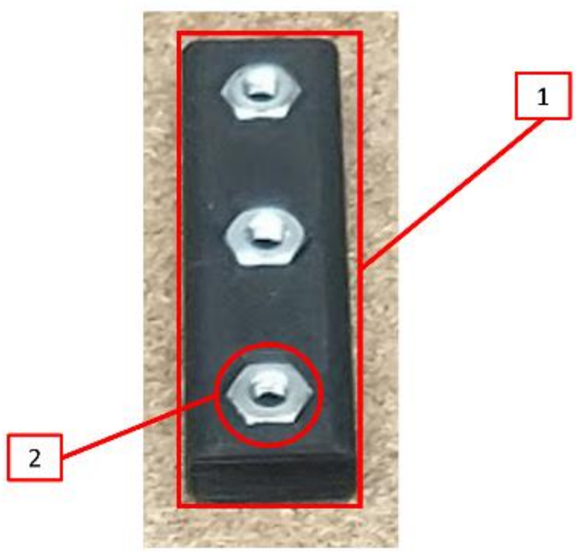


Figure 47: Nut Plate Assembly

For the nut plate, the 3x 10-32 hex nuts (item 2) are inserted into the three slots in the nut plate (item 1). Then the nut plate assembly is set aside until the modules are assembled to the frame.

1-06-FRAME ASM

1-06-FRAME ASM	
ITEM NO.	PART NUMBER
1	0-06-101-TUBE, RECTANGULAR ALUMINUM 6061, 1 X 2 X .100 WALL, PART NO. 217-3453, VEX
2	0-06-102-ANGLE, ALUMINUM 6061, 1.5 X 1.5 X .125 WALL,90 DEG ANGLE, PART NO. 8982K13, MCMASTER-CARR

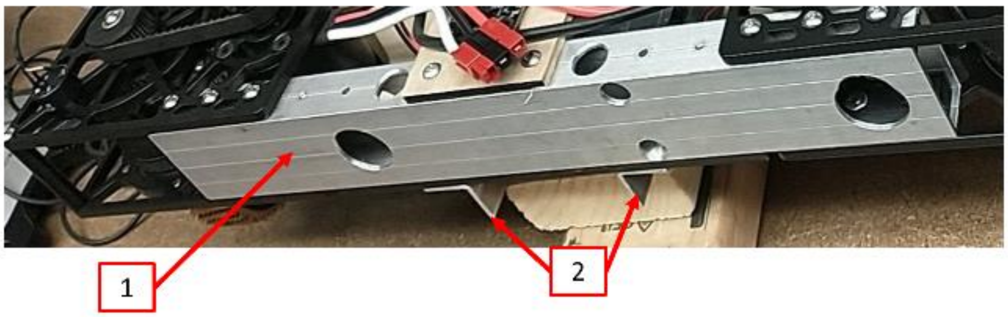


Figure 48: Test Frame Components

The 4x rectangular aluminum extrusion (item 1) are added to the four sides of the wooden electronics board, item 1 in 1-04-Electronics Plate ASM. Then the 2x aluminum angle (item 2) are added to the bottom of the electronics board to add support for the electrical components.

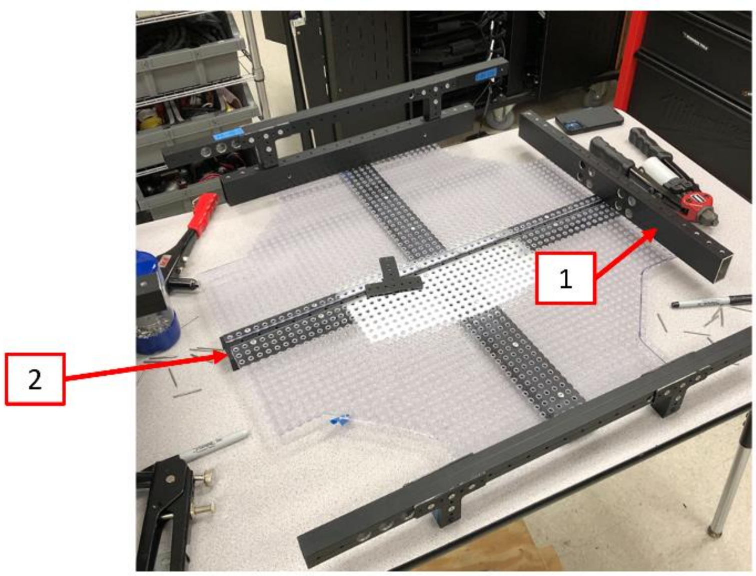


Figure 49: Competition Frame Components

Similar to the test frame, the competition frame uses 4x rectangular aluminum extrusion (item 1) that are riveted to the polycarbonate electronics board. Then for the bottom bracing, 3x aluminum C-channel (item 2) are used to support the entire weight of the competition robot.

1-04-ELECTRONICS PLATE ASM

1-04-ELECTRONICS PLATE ASM	
ITEM NO.	PART NUMBER
1	1-04-100-PLATE, ELECTRONICS, 23IN X 23IN X 0.25IN, Plywood
2	1-04-1000-BATTERY, PART NO AM-3062, ANDYMARK
3	1-04-1001-ROBORIO, PART NO. 783581-01, NATIONAL INSTRUMENTS
4	1-04-1002-POWER DISTRIBUTION PANEL, PART NO. 217-4244, VEX
5	1-04-1003-RADIO, PART NO. AM-3205, ANDYMARK
6	1-04-1004-VOLTAGE REGULATOR MODULE, PART NO. AM-2857, ANDYMARK
7	1-04-1005-CONTROLLER, SPARK MAX MOTOR, PART NO. REV-11-2158, REV ROBOTICS
8	1-04-1006-CIRCUIT BREAKER, PART NO. AM-0282, ANDYMARK
9	1-04-1007- GYRO, GADGETEER PIGEON IMU, PART NO. 16-737785, CTR ELECTRONICS

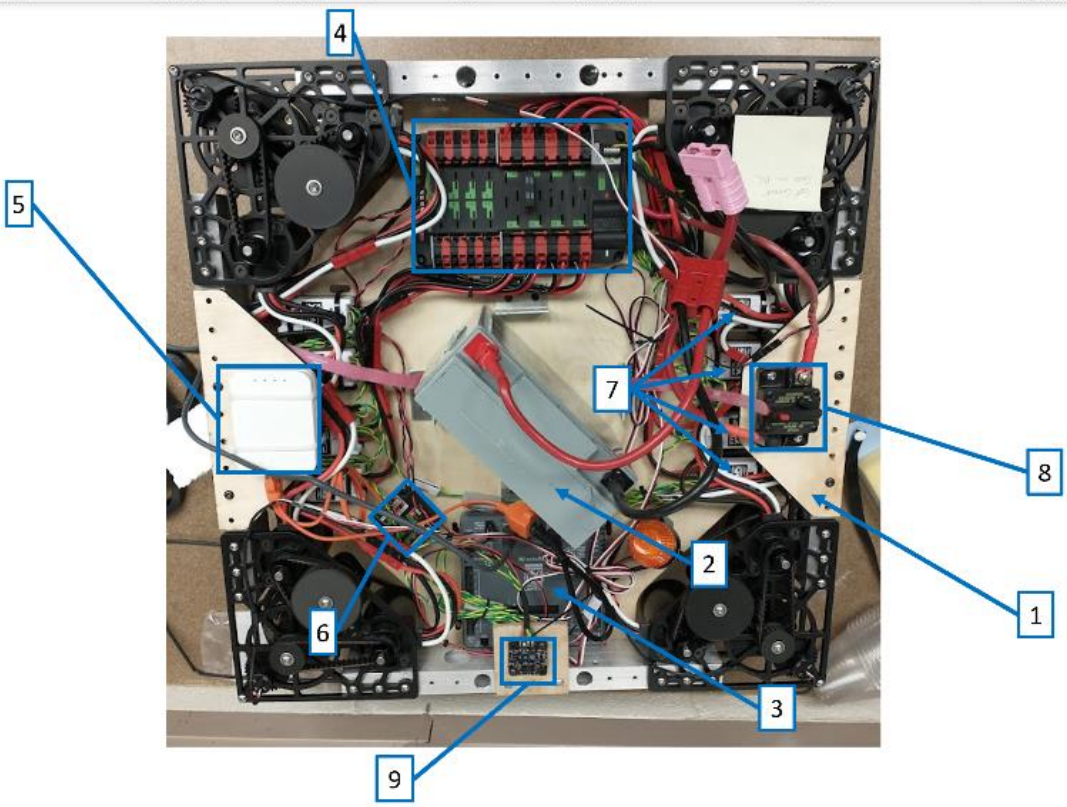


Figure 50: Test Frame Electrical Components

Using the wire schematic in the Wire Schematic section we were able to wire the components and place them accordingly. The electronics are mounted on laser cut wood plates (item 1) for quick fabrication.

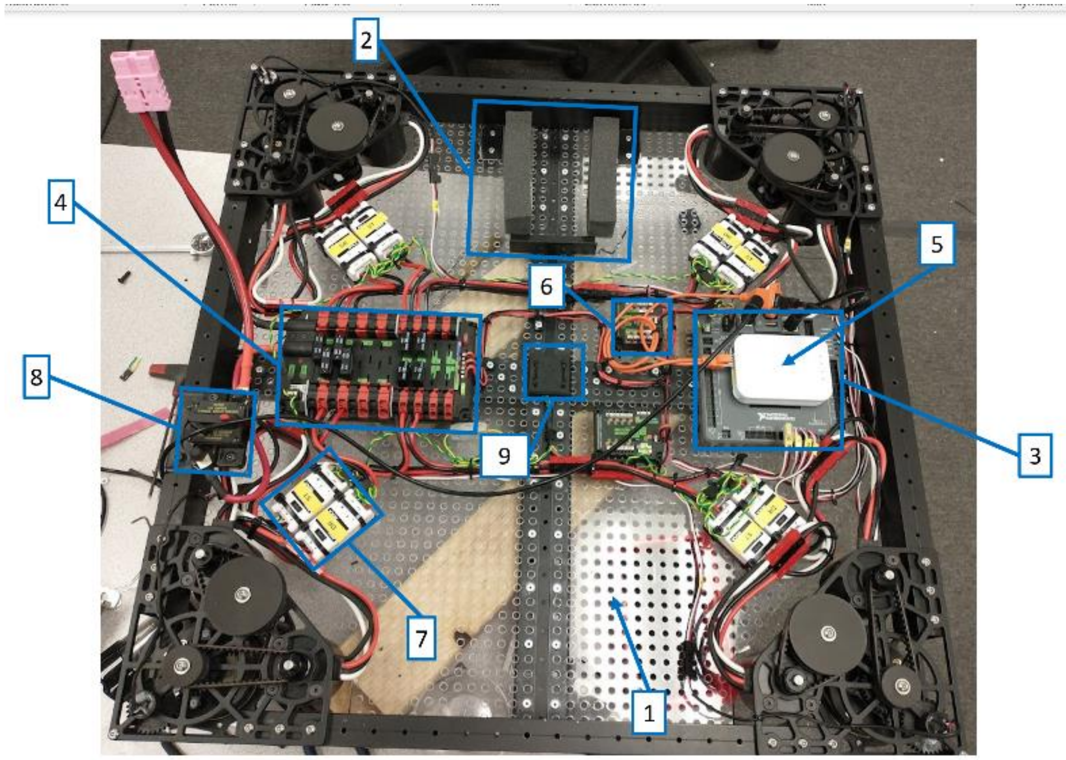


Figure 51: Competition Frame Electrical Components

Using the wire schematic in the Wire Schematic section we were able to wire the components and place them accordingly. The electronics are mounted to perforated polycarbonate (item 1).

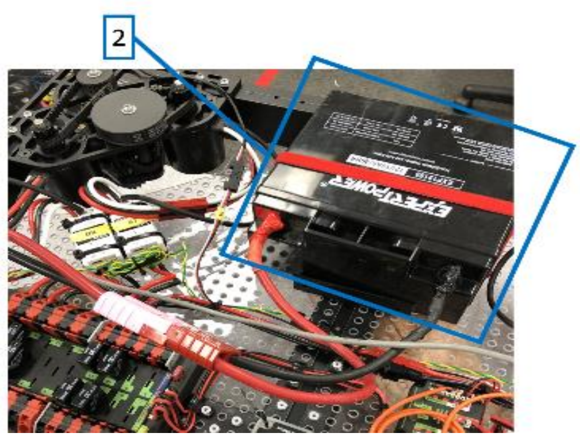


Figure 52: Battery Inserted into the Competition Frame

The FRC SLA battery (item 2) are secured to the front of the base frame using Velcro straps.

1-01-SWERVE DRIVE MODULE ASM

1-01-SWERVE DRIVE MODULE ASM	
ITEM NO.	PART NUMBER
1	#10, FLATWASHER
2	#6, FLATWASHER
3	1-01-1000-MOTOR, NEO BRUSHLESS, PART NO. REV-21-1650, REV
4	1-01-1001-ENCODER, ABSOLUTE 360 DEG CONTINOUS, PART NO. 987-1393-ND, DIGIKEY
5	1-01-101-PLATE, LOWER, ALUMINUM
6	1-01-102-PULLEY, HTD-5M,9MM, 0.375 HEX, 20T, ONYX
7	1-01-103-PLATE, UPPER, ALUMINUM
8	1-01-104-SHAFT, HEX 0.375IN, DRIVE, ALUMINUM, PART NO. 217-2754, VEX
9	1-01-105-PULLEY, HTD-5M, 15MM, 40T, HEX, ONYX
10	1-01-106-SPACER, ROUND 0.375 OD ALUMINUM 6061
11	1-01-112-GEAR, SPUR, 34T, 20 DP, ENCODER, ONYX
12	1-01-116-SPACER, ROUND, 8MM ID, 0.7IN OD, 5.4MM LG, ABS
13	1-01-117-SPACER, HEX, 0.375IN ID X 0.6IN OD X 33.7MM LG, ABS
14	1-01-118-SPACER, HEX, 0.375IN ID X 0.6IN OD X 0.1325in LG, ABS
15	1-01-119-KEY, 2MM X 2MM X 14MM, PART NO. 217-2760, VEX
16	1-01-401-BEARING, RADIAL 8MM ID X 16MM OD X 5MM WD STEEL, PART NO. 688ZZ, SDS
17	1-01-402-PULLEY, 12T 8MM KEYED ALUMINUM 6061, PART NO. WCP-0076, WCP
18	1-01-403-BEARING, FLANGED 10.25MM ID X 0.875IN OD X 0.280IN WD STEEL, PART NO. 217-5829, VEX
19	1-01-413-BELT, 62T 5MM HTD 9MM WIDTH, PART NO. A6R25M062090, SDP-SI
20	1-01-414-BELT, 48T 5MM HTD 9MM WIDTH, PART NO. A6R25M048090, SDP-SI
21	1-01-415-BELT, 52T 5MM HTD 9MM WIDTH, PART NO. A6R25M052090, SDP-SI
22	1-01-418-Collar, SHAFT, 8MM ID ROUND, PART NO. 217-2744, VEX
23	1-01-701-COLLAR, SHAFT,0.25ID X 0.5OD X 0.28125LG, PART NO. 9414T6, MCMASTER CARR
24	10-32 X 0.375 LONG, FLAT HEAD SCREW
25	10-32 X 0.375 LONG, ROUNDED HEAD SCREW
26	10-32 X 0.500 LONG, ROUNDED HEAD SCREW
27	6-32 X 0.250 LONG, BUTTON HEAD SCREW

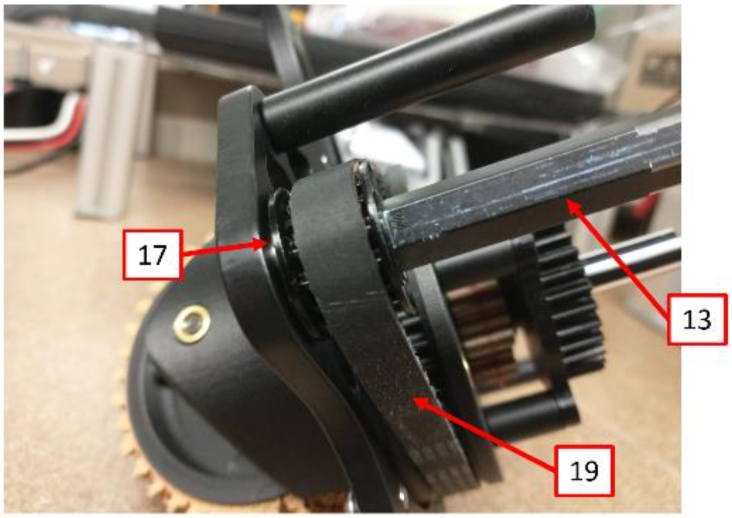


Figure 53: Steer Pulley and Belt

The first step is to insert a key (item 15) into the shaft's (item 13) key slot and then interlock the pulley (item 17) to the shaft using the pulley's key slot.

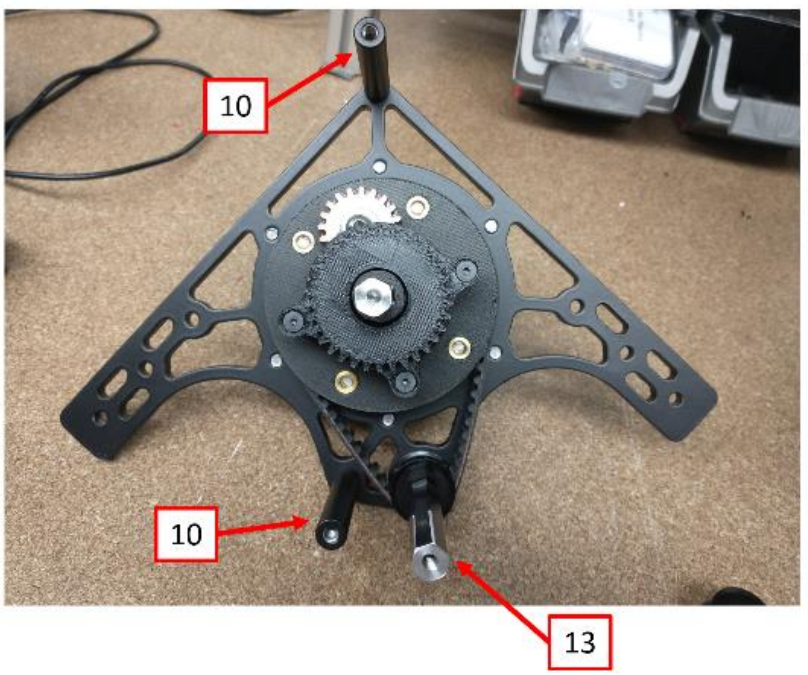


Figure 54: Spacers and Steer Shaft Added to the Bottom Plate

The next step is to insert the hex shaft (item 13) into a bearing (item 16) on the bottom plate and is fastened using a button head screw (item 27) and a washer (item 2). Next, add the 2x spacers (item 10) to the bottom plate using rounded head screws (item 26).

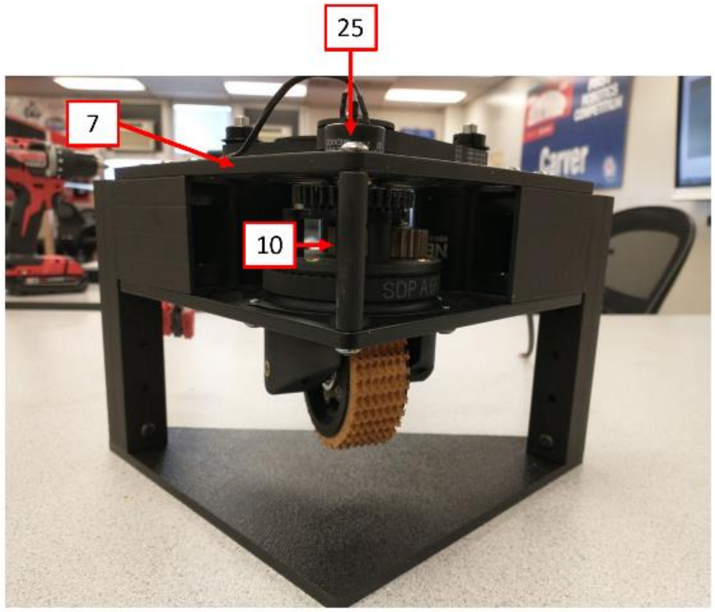


Figure 55: Top Plate Assembled to Spacers

Next the top plate (item 7) is assembled on top of the two spacers (item 10) using a rounded head screw (item 25) for the front spacer and a flat head screw (item 24) for the back spacer so that it does not interfere with steer pulley (item 9).

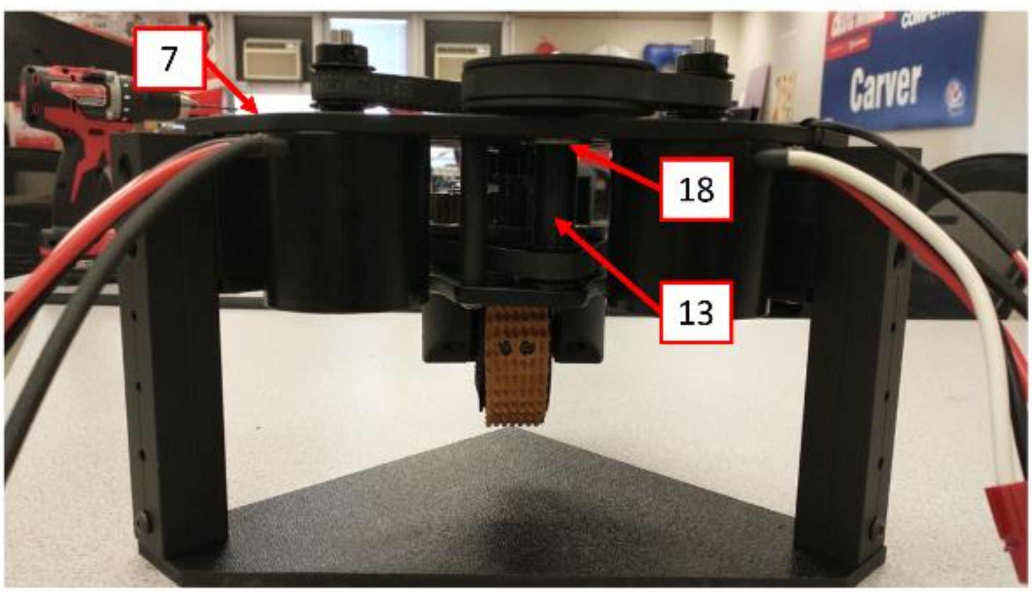


Figure 56: *Steer Shaft Inserted into Top Plate*

When the top plate (item 7) is being assembled, the steer shaft (item 13) is inserted into a bearing (item 18) on the top plate. The drive shaft (item 7 from 1-03-PULLEY ASM) is inserted into a bearing (item 18) underneath the drive pulley (item 6) on the top plate.

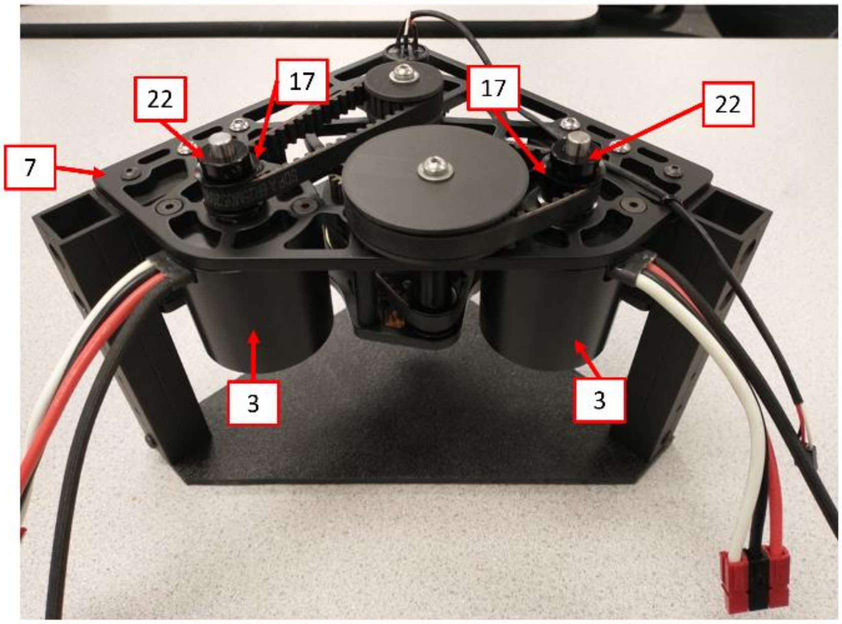


Figure 57: Motors Mounted and Pulley Components

The next step is to insert the motors (item 3) into the top plate. The motors are secured to the top plate using 3x flat head screws (item 24) each. Then a key (item 15) is inserted into the key slot on each motor shaft. Then a pulley (item 17) is added to each motor shaft interlocking with the key. Once the belts are added onto the pulleys (item 17), shaft collars (item 22) are placed on top of each pulley.

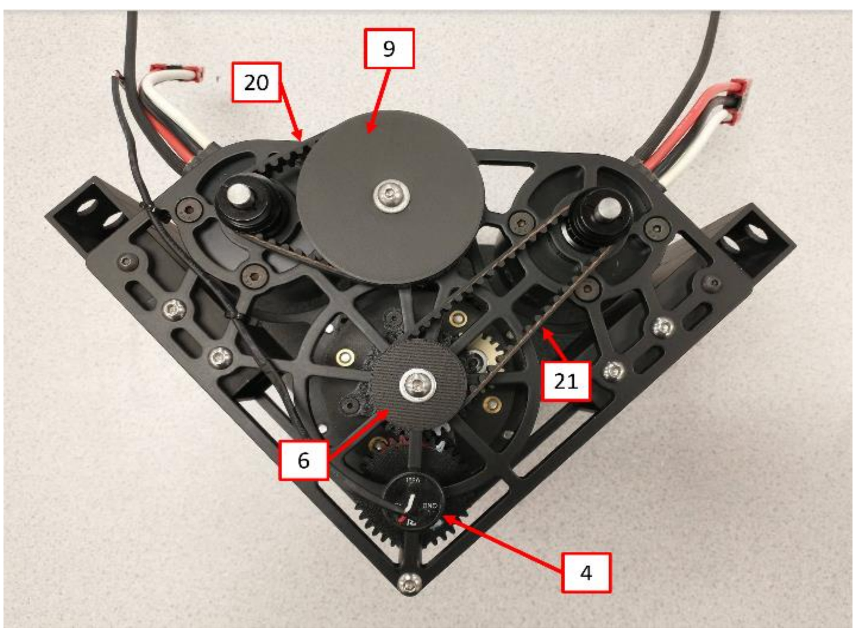


Figure 58: Steer and Drive Pulleys with Absolute Encoder

The next step is to add the belting to the drive and steer motors. When installing the belts to the pulleys, the motors need to be unmounted. The drive belt (item 21) is added to both the pulley (item 6) and motor pulley (item 17) simultaneously. The steering motor needs to have one of the motor mount screws installed before installing the belt (item 20) to the steer pulley (item 9) and motor pulley (item 17) due to the pulley (item 9) covering the mounting hole once assembled.

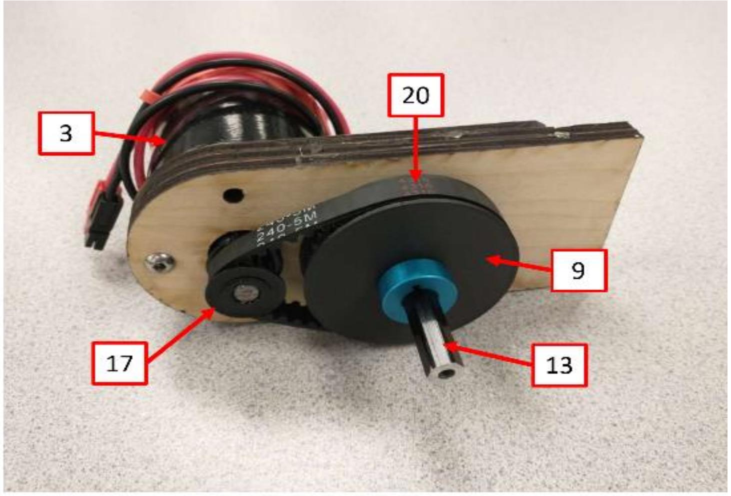


Figure 59: Belting Jig

Using Solidworks, the belting length was able to be determined for each of the belts. To ensure that the belting length was correct, we used this prototype jig. In the jig, it shows the belt for the steering and motor pulleys are properly tensioned.

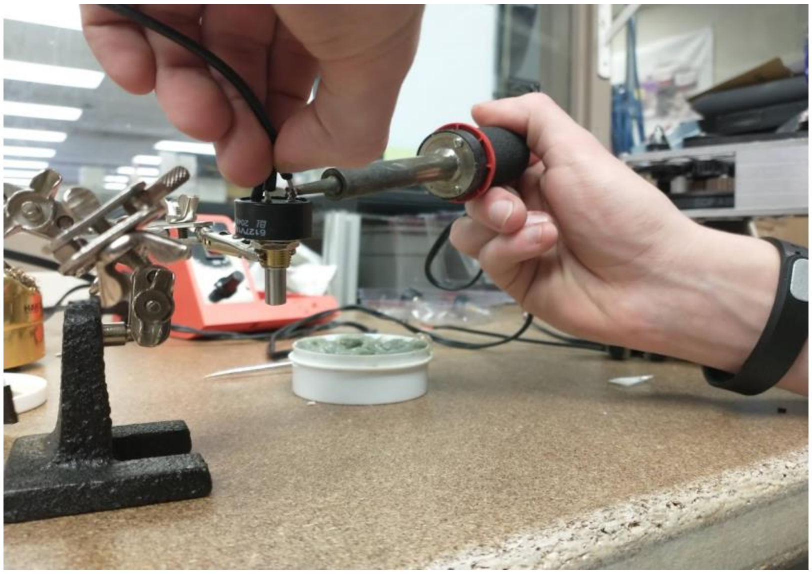


Figure 60: Soldering Encoder Wires

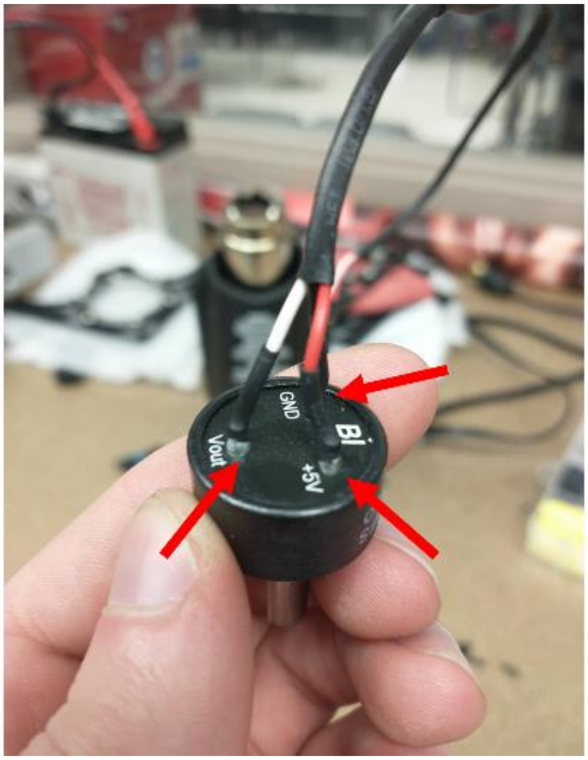


Figure 61: Soldering Wire Locations

For the absolute encoder, we had to solder the 3x wires to each of the 4x encoders (item 4) using a solder iron and stand. Heat shrink tubing was placed over the soldered connections to prevent electrical shorting.

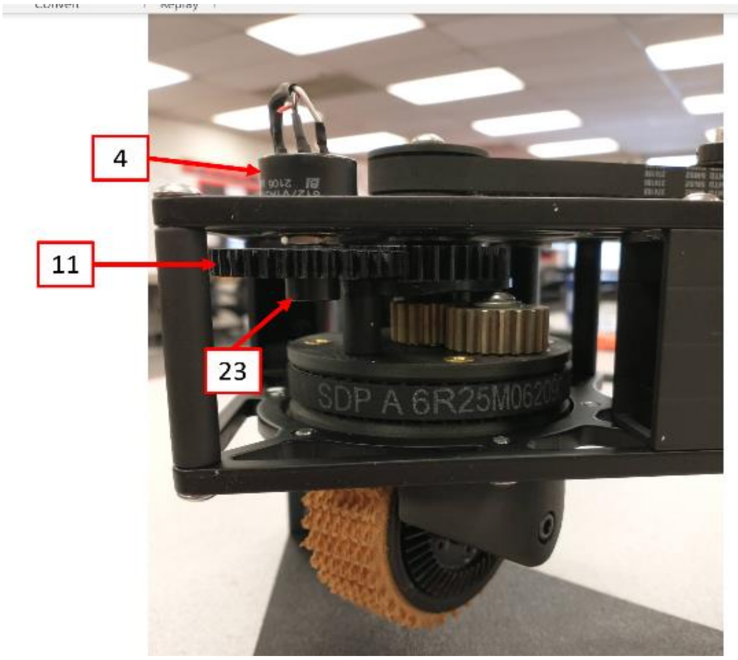


Figure 62: Encoder and Encoder Gear Assembly

The encoder (item 4) is then installed onto the top plate. From the bottom side of the top plate, the encoder gear (item 11) is installed onto the encoder shaft. Then a shaft collar (item 23) is placed at the end of the shaft.

Module Assembled to Frame

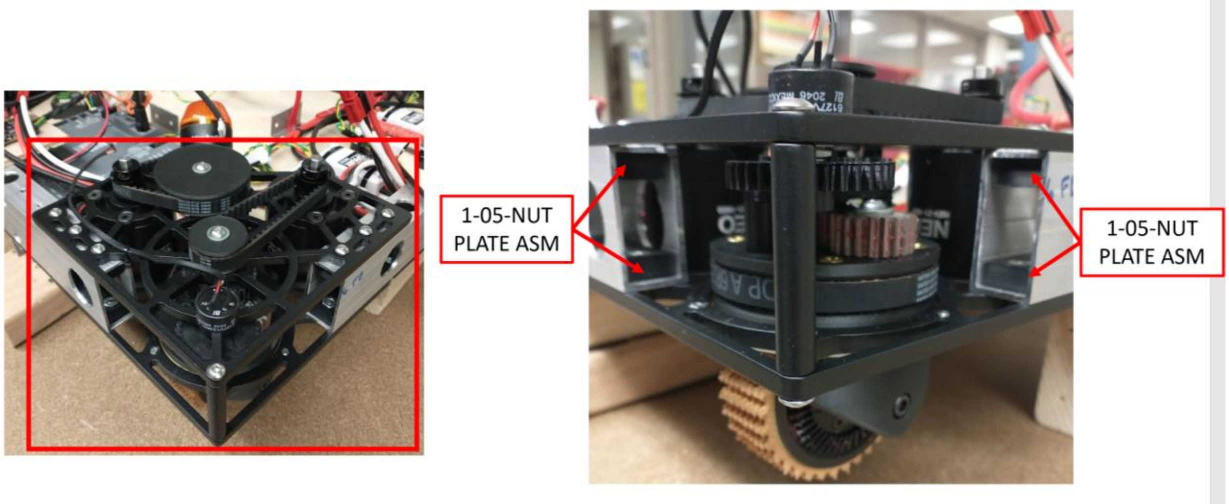


Figure 63: Module Assembled to the Frame

Once the assemblies are completed, it is time to install the modules to the frame. This is done by inserting 2x 1-05-NUT PLATE ASM into the frame tubing per side. One nut plate is placed on the top of the tubing, with the nuts facing down, and the other nut plate is placed on the bottom of the tubing, with the nuts facing up. Then the module is fastened to the frame and nut plates from the top and bottom on both sides using 3x 10-32 button head screws on the top and 3x 10-32 button head screws on the bottom. This is repeated until all four modules are installed to the frame.

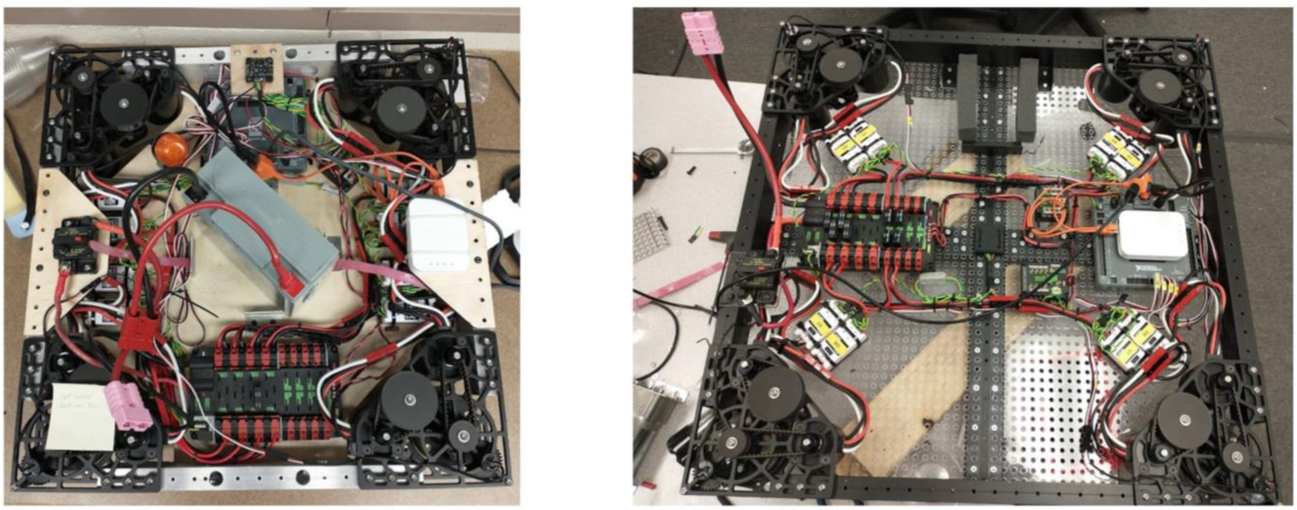


Figure 64: Completed Prototype and Competition Robot Bases

Programming

- Kinematics
  - Complex movement and continuous rotation
  - Each wheel is driven and steered independently
  - Vector addition was used to combine vehicle translation and rotation
  - Robot can rotate while strafing in a desired direction

- Sensors
  - Pigeon IMU Gyroscope
    - Field Centric Control
    - Intuitive driving
    - Accurate autonomous operations
  - Hall Effect Absolute Encoders
    - Output a voltage between 0.25- 4.75Vdc
    - Linear interpolation is used to convert voltage to degrees (-180° to 180°)

- Closed Loop Position Control (PID)
  - 4 independent PID loops (one per wheel)
  - Eliminates error between desired and current position
  - Efficiency logic to determine quickest path of each wheel.
  - Wheel never turns > 90°

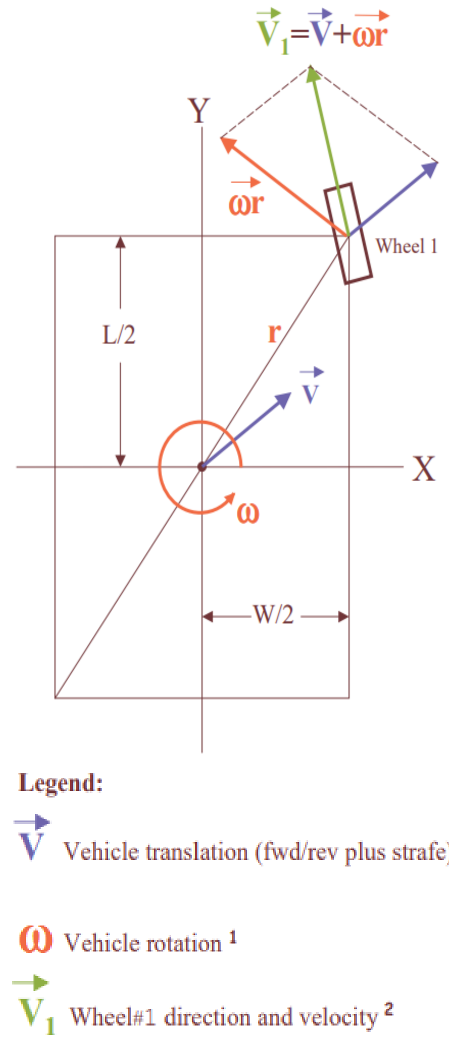


Figure 65: Programming Schematic

- LabVIEW VI
    - A Custom Swerve Drive VI was created to make programming plug and play easy for all teams.
    - Easier for high school students to program
    - FRC team 325 now uses our custom VI

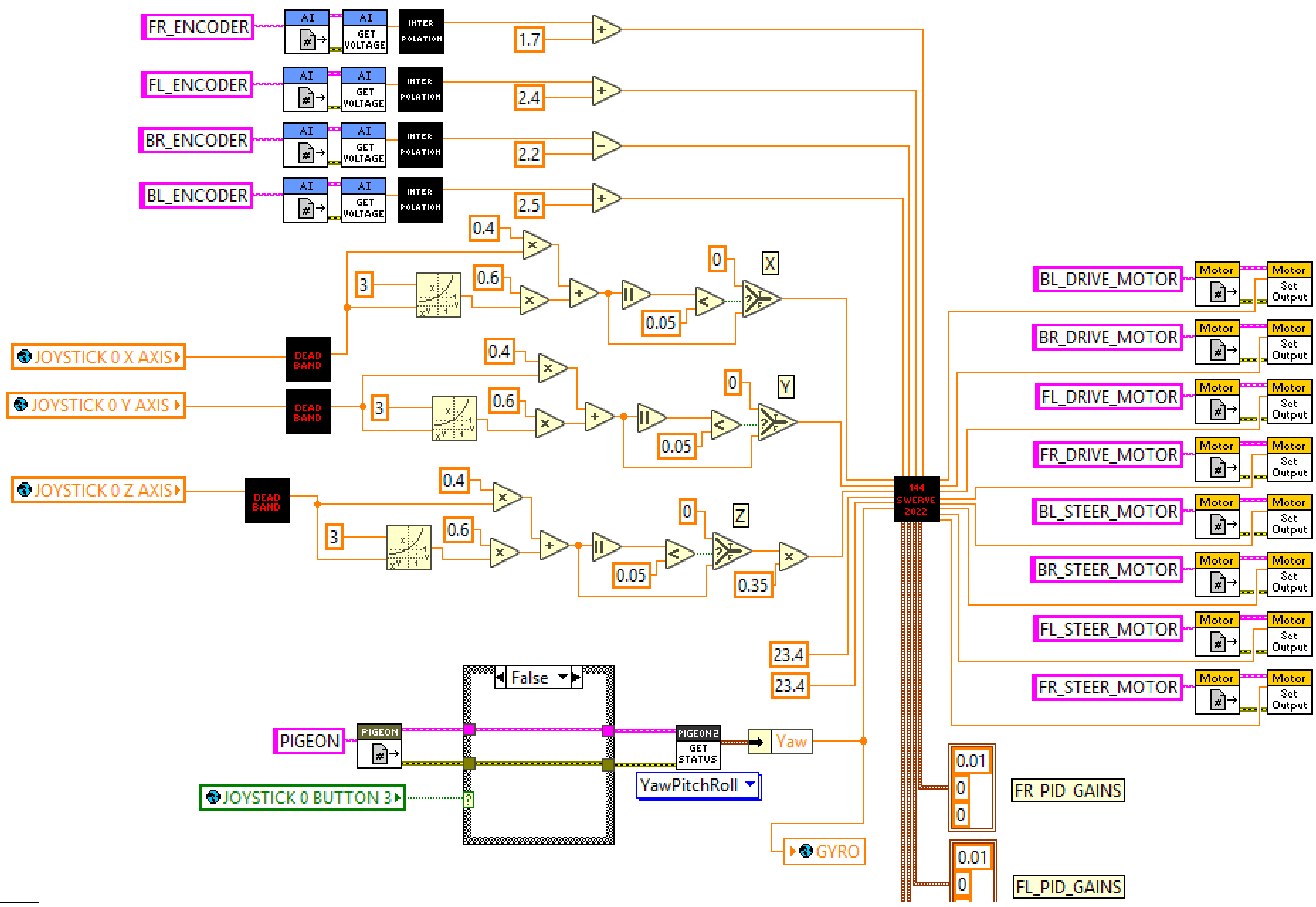


Figure 66: Custom Swerve Drive VI

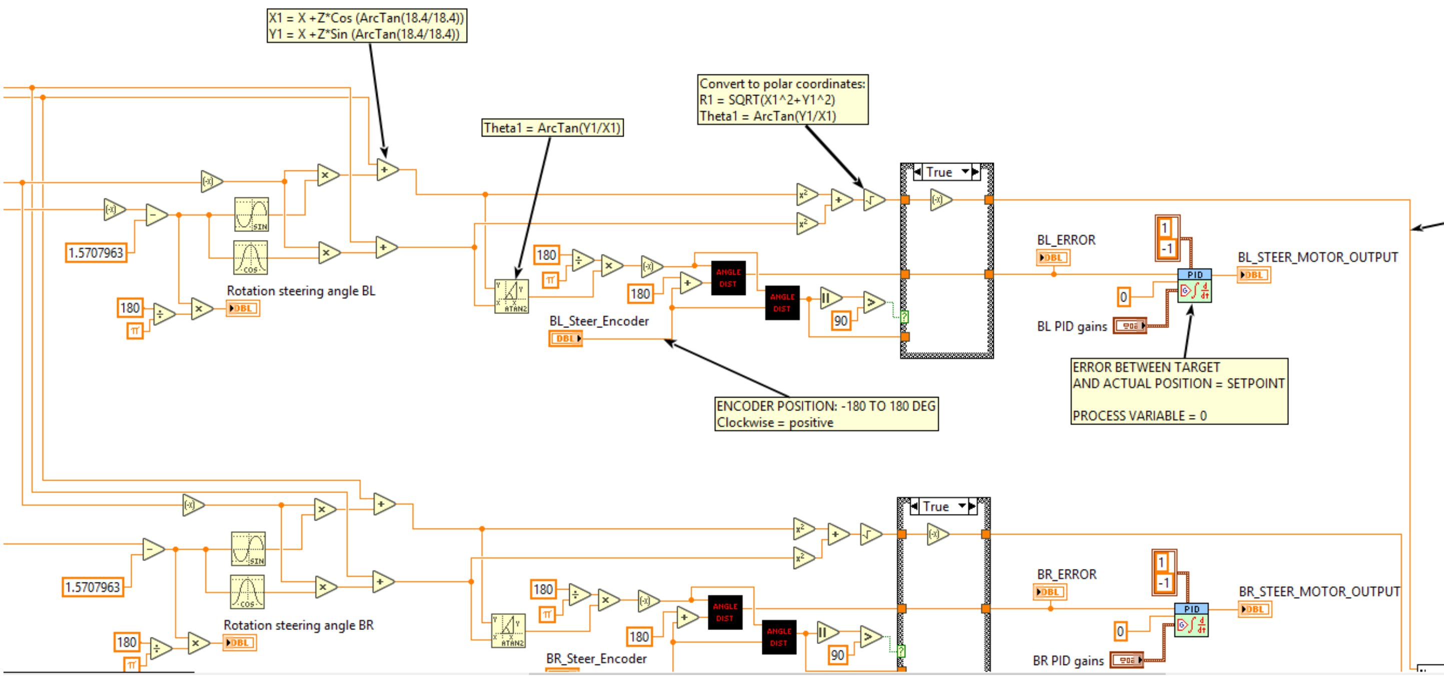


Figure 67: Image inside of the Custom Swerve Drive VI

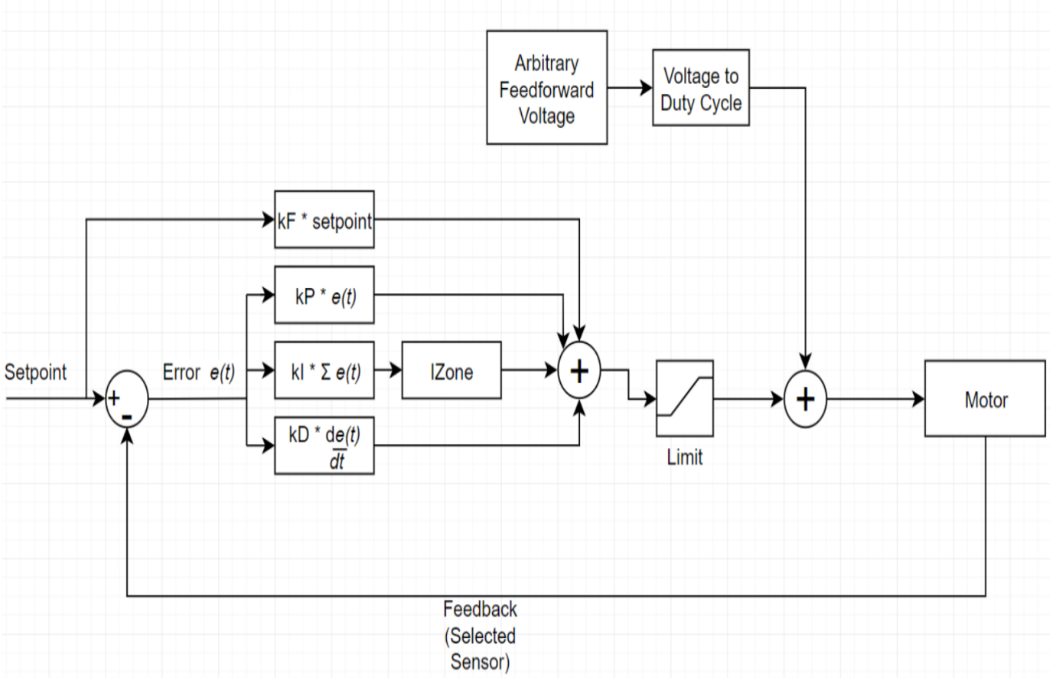


Figure 68: PID Diagram

Proposed Testing

We plan to test our design by driving it across field elements we have encountered in past competitions such as one inch by two-inch bumps, ramps, and a timed obstacle course. We will compare these results to FRC Team 144 previous years robot that used mecanum drive.

If we can complete this design in time, we will use the swerve drive modules in the FIRST competition. The date of the first competition is March 16th through March 19th, 2022, in Pittsburgh, Pennsylvania. Illustrated below is a sample FIRST Robotics course.

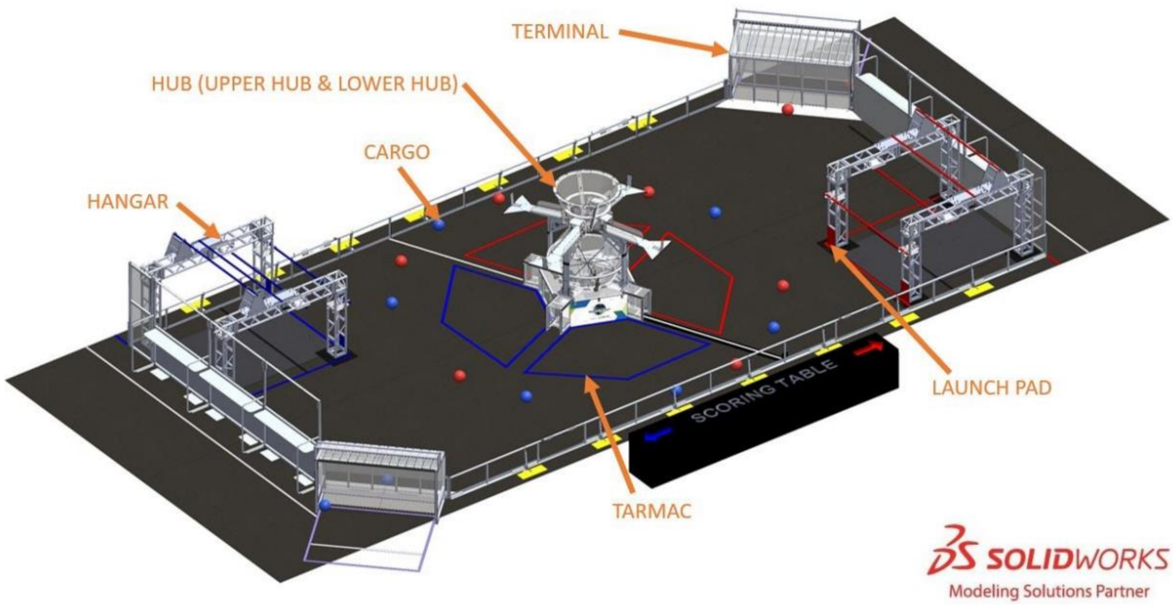


Figure 69: FIRST Robotics Competition Sample Course

Actual Testing

During our initial testing phase of driving the test frame, we noticed after 30 minutes of testing the cheaper tread showed wear after about 30 minutes of testing and thus, we upgraded the tread to blue nitrile tread. The blue nitrile tread was able to stand up to 8 hours of competition before the need to be replaced.

Figure 70: *Tread Wear*

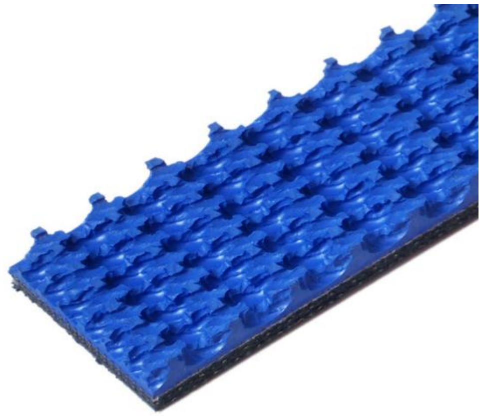


Figure 71: Blue Nitrile Tread

We also ran into issues with screws used to secure the pulleys and shafts. With the quick change of directions, the screws started to back out. To solve this issue, we used lock washers and blue Loctite to secure the screws.

Proof of Design

Our project will be a success if our swerve drive modules are able to operate, pass the initial inspections, reduces the overall weight of the robot, and is able to compete with other FRC team's drive and steer trains.

Competition Results

The Swerve Modules were thoroughly tested at two competitions. The first one in Pittsburgh, Pennsylvania and the second one in Huntsville, Alabama.

During the Pittsburgh competition, no damage or wear was observed on the swerve modules. The robotics team ranked 12th out of 47 teams and became the 8th seed alliance captain to compete in quarterfinals.

During the Huntsville competition minor damage was observed on the main drive pulley that caused loss of drivetrain power. The cause of this was due to slow fatigue of the main 3D printed drive pulley. The internal hex profile of the pulley rounded out which caused the pulley to slip on the drive shaft. To fix the issue, the pulley was broached and a metal ½ in. to ⅜ in. insert was installed.

Figure 72: Rounded Out Drive Pulley

Figure 73: Metal Insert Installed into Drive Pulley

The robotics team ranked 6th out of 49 teams and competed in quarterfinals on the 4th seed alliance. The overall design won the Industrial Design award which celebrates the team that demonstrates industrial design principles, striking a balance between form, function, and aesthetics.

Project Management

Proposed Budget

For our proposed budget, we went with a price per module of $250-$325 as this was the most favorable result from our survey. The overall budget was set at $1,400 for the frame, module components, and hardware. The electrical components, including the motors and controls, were excluded from this budget as they will be donated to us from FRC Team 144. Through the cost breakdown per assembly shown in Appendix C, the estimated price per module came out to be $249.69 and the overall cost for five modules and the frame came out to be $1,367.85. The funding for this project will come from FRC Team 144 and some manufacturing will be supplied by RA Jones.

PROJECT TOTAL	COST PER PART:	COST PER ASSY:	TOTAL COST:	ASSY QTY.	TOTAL QTY.	MATERIAL LENGTH (in)	WEIGHT PER PART (lbs)	WEIGHT PER ASSY (lbs)
	TOTAL:	$249.69	$1,367.85					2.436

Figure 74: Total Cost and Weight Break Down

Actual Budget

By utilizing FRC Team 144's lab and sticking to our design plan, we were able to stick to our initial budget. Our cost per module is $249.69, with a total cost of $1,367.85, for five modules and a test frame. With our initial budget set to $1,400, we were able to be under budget by $32.15.

PROJECT TOTAL	COST PER PART:	COST PER ASSY:	TOTAL COST:	ASSY QTY.	TOTAL QTY.	MATERIAL LENGTH (in)	WEIGHT PER PART (lbs)	WEIGHT PER ASSY (lbs)
	TOTAL:	$249.69	$1,367.85					2.436

Figure 74: Total Cost and Weight Break Down

Proposed Timeline

Below shows our proposed Senior Design 2 schedule, actual Senior Design 2 Schedule, and our proposed Senior Design 3 schedule. Comparing our proposed Senior Design 2 schedule to our actual Senior Design 2 schedule it can be seen that tasks were completed earlier and later than expected. Overall, the project was completed on time, with parts being ordered earlier than expected.

For our proposed Senior Design 3 schedule, the tasks are looking to be complete on time and we are working towards having the modules ready for testing by March 20th. If the modules are ready before March 16th, the modules will be used in the FIRST Robotics Competition March 16th through the 19th in Pittsburg, Pennsylvania.

2021/2022	Milestones	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Proposed Senior Design 2	Concept Designs				5-Nov					
	Weighted Matrix				12-Nov					
	Calculations				12-Nov					
	Budget				15-Nov					
	Final Design				18-Nov					
	Solidworks FEA				21-Nov					
	Senior Design 2 Presentations				30-Nov					
	Senior Design 2 Report					5-Dec				
	Order Parts					7-Dec				
	Fabrication Drawings Complete					10-Dec				
Actual Senior Design 2	Concept Designs				8-Nov					
	Weighted Matrix				9-Nov					
	Calculations				12-Nov					
	Budget				16-Nov					
	Final Design				20-Nov					
	Solidworks FEA				27-Nov					
	Senior Design 2 Presentations				30-Nov					
	Senior Design 2 Report					5-Dec				
	Order Parts					7-Dec				
	Fabrication Drawings Complete					10-Dec				
Senior Design 3	Electrical Diagram					12-Dec				
	Kinematics					20-Dec				
	Fabrication						5-Jan			
	Assembly						17-Jan			
	Wiring						20-Jan			
	Programming							10-Feb		
	Testing								20-Mar	
	Tech Expo									15-Apr

Figure 75: Senior Design Schedule

Actual Timeline

For the most part, we followed our proposed Senior Design 3 schedule. As stated in the Proposed Timeline section, if the modules were ready before March 16th, they would be used in the FIRST Robotics competition. At the start of Senior Design 3, we made it our goal to have the modules ready for the competition dates. The reason for this is that our customer wanted the modules by then and the competitions would be a great environment for testing our design.

This pushed our testing dates back four days from March 20th to March 16th and also added another testing day on April 9th.

2021/2022	Milestones	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Proposed Senior Design 2	Concept Designs				5-Nov					
	Weighted Matrix				12-Nov					
	Calculations				12-Nov					
	Budget				15-Nov					
	Final Design				18-Nov					
	Solidworks FEA				21-Nov					
	Senior Design 2 Presentations				30-Nov					
	Senior Design 2 Report					5-Dec				
	Order Parts					7-Dec				
	Fabrication Drawings Complete					10-Dec				
Actual Senior Design 2	Concept Designs				8-Nov					
	Weighted Matrix				9-Nov					
	Calculations				12-Nov					
	Budget				16-Nov					
	Final Design				20-Nov					
	Solidworks FEA				27-Nov					
	Senior Design 2 Presentations				30-Nov					
	Senior Design 2 Report					5-Dec				
	Order Parts					7-Dec				
	Fabrication Drawings Complete					10-Dec				
Proposed Senior Design 3	Electrical Diagram					12-Dec				
	Kinematics					20-Dec				
	Fabrication						5-Jan			
	Assembly						17-Jan			
	Wiring						20-Jan			
	Programming							10-Feb		
	Testing								20-Mar	
	Tech Expo									14-Apr
Actual Senior Design 3	Electrical Diagram					12-Dec				
	Kinematics					20-Dec				
	Fabrication						5-Jan			
	Assembly						17-Jan			
	Wiring						20-Jan			
	Programming							10-Feb		
	Testing (Competition 1)								16-Mar	
	Testing (Competition 2)									9-Apr
	Tech Expo									14-Apr

Figure 76: *Complete Senior Design Schedule*

Conclusion

Our team was able to design, manufacture, assemble, program, and test a swerve drive module that was competitive with other products on the market. As a team we were able to follow our timeline and budget to have the actual product ready for our customer by the requested date. During the design phase, we were able to catch interference issues that could have caused major issues in the actual assembly. In the testing phase we were able to determine when common wear items, such as tread, would need to be replaced. We also found that the drive pulley wears overtime. This was an easy fix, but something we would not have caught, if it were not for testing the product. Even with these minor issues, our product showed great success. Comparing our module to other modules on the market, we were able to reduce the overall weight by ½ lb, reduce the overall height by 2.53 in. , reduce the overall cost by $60, and we were able to match the performance speed of 10.1 ft/sec. While working on this project, we were able to combine concepts we have learned over the course of our curriculum, like PID closed loop motor control and gear ratios, and apply them to innovate a current product. By following the steps of the design process, we were able to provide a functional product on time that exceeded our own and our customer's expectations.

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Appendices:

Appendix A

American National Standards Institute (ANSI)

- *R15.06*, Industrial Robots and Robot Systems - Safety Requirements. Provides safety requirements for industrial robot manufacture, remanufacture, and rebuild (Part 1); and robot system integration/installation (Part 2). R15.06 (ANSI/RIA R15.06-2012) is the U.S. National Adoption of the ISO 10218-1,2:2011.
    - *RIA TR R15.306 ("TR 306"), Task-Based Risk Assessment Methodology*. Describes one method of risk assessment that would comply with the R15.06 requirements.
    - *RIA TR R15.406 ("TR 406"), Safeguarding*. Explains how to design a system of safeguards to protect human workers in an industrial environment that also contains robot system(s). TR 406 contains greater detail than the 2012 R15.06 standard.
    - *RIA TR R15.506 ("TR 506"), Applicability of R15.06-2012 for Existing Industrial Robot Applications*. The R15.06 standard is forward-looking; that is, its primary topic is the installation of an all-new robot system. TR 506 explains how to take the 2012 R15.06 standard into account for existing robot systems.
    - *RIA TR R15.606 ("TR 606"), Collaborative Robot Safety*. Explains safety requirements specific to collaborative robots and robot systems and is supplemental to the guidance in ANSI/RIA R15.06. TR 606 is the U.S. National Adoption of the ISO/TS 15066:2016.
    - *RIA TR R15.806 ("TR 806"), Testing Methods for Power & Force Limited Collaborative Applications*. Describes methods to test and verify that the forces exerted by a collaborative robot system remain within the allowable limits described in TR 606 (ISO/TS 15066).
- *B11.0, Safety of Machinery – General Requirements and Risk Assessment*. Applies to new, existing, modified, or rebuilt power-driven machines, not portable by hand while working, used to shape and/or form metal or other materials by cutting, impact, pressure, electrical, or other processing techniques, or a combination of these processes. This can be a single machine, a machine tool, or a machine tool system(s), and may include industrial robot(s) and robot system(s). Also contains guidance on performing risk assessments.
- *B11.20, Safety Requirements for Integrated Manufacturing Systems*. Specifies the safety requirements for the design, construction, set-up, operation, and maintenance (including installation, dismantling and transport) of integrated manufacturing systems, which may include industrial robot(s) and robot system(s).

Motors & Actuators

R27. The only motors and actuators permitted on 2021 ROBOTS include the following (in any quantity):

Table 9-1 Motor allowances

Motor Name	Part Numbers Available	
AndyMark 9015	am-0912	AndyMark 9015
AndyMark NeveRest	am-3104	
AndyMark PG	am-2161 (alt. PN am-2765)	am-2194 (alt. PN am-2766)
AndyMark RedLine Motor	am-3775	am-3775a
AndyMark Snow Blower Motor	am-2235	am-2235a
Banebots	am-3830 M7-RS775-18 RS775WC-8514	M5 – RS550-12 RS550VC-7527 RS550
CIM	FR801-001 M4-R0062-12 AM802-001A 217-2000 PM25R-44F-1005	PM25R-45F-1004 PM25R-45F-1003 PMR25R-45F-1003 PMR25R-44F-1005 am-0255
CTR Electronics/VEX Robotics Falcon 500	217-6515 am-6515	19-708850 am-6515_Short
Current/former KOP Automotive motors	Denso AE235100-0160 Denso 5-163800-RC1 Denso 262100-3030	Denso 262100-3040 Bosch 6 004 RA3 194-06 Johnson Electric JE-PLG-149
Nidec Dynamo BLDC Motor	am-3740	DM3012-1063
Playing with Fusion Venom	BDC-10001	
REV Robotics HD Hex Motor	REV-41-1291	
REV Robotics NEO Brushless	REV-21-1650	
REV Robotics NEO 550	REV-21-1651	
VEX BAG	217-3351	
VEX Mini-CIM	217-3371	
West Coast Products RS775 Pro	217-4347	
Electrical solenoid actuators, no greater than 1 in. (nominal) stroke and rated electrical input power no greater than 10 watts (W) continuous duty at 12 volts (VDC)		
Fans, no greater than 120mm (nominal) size and rated electrical input power no greater than 10 watts (W) continuous duty at 12 volts (VDC)		
Hard drive motors part of a legal COTS computing device		
Factory installed vibration and autofocus motors resident in COTS computing devices (e.g. rumble motor in a smartphone).		
PWM COTS servos with a retail cost < $75.		
Motors integral to a COTS sensor (e.g. LIDAR, scanning sonar, etc.), provided the device is not modified except to facilitate mounting		
One (1) compressor compliant with R79 and used to compress air for the ROBOT'S pneumatic system		

R38. Each electrical terminal on the ROBOT battery, main breaker, and their connections (lugs, stripped wire ends, etc.) to the wire must be fully insulated at all times.

R42. All wiring and electrical devices, including all Control System COMPONENTS, shall be electrically isolated from the ROBOT frame. The ROBOT frame must not be used to carry electrical current.

R43. The 120A circuit breaker must be quickly and safely accessible from the exterior of the ROBOT. This is the only 120A circuit breaker allowed on the ROBOT.

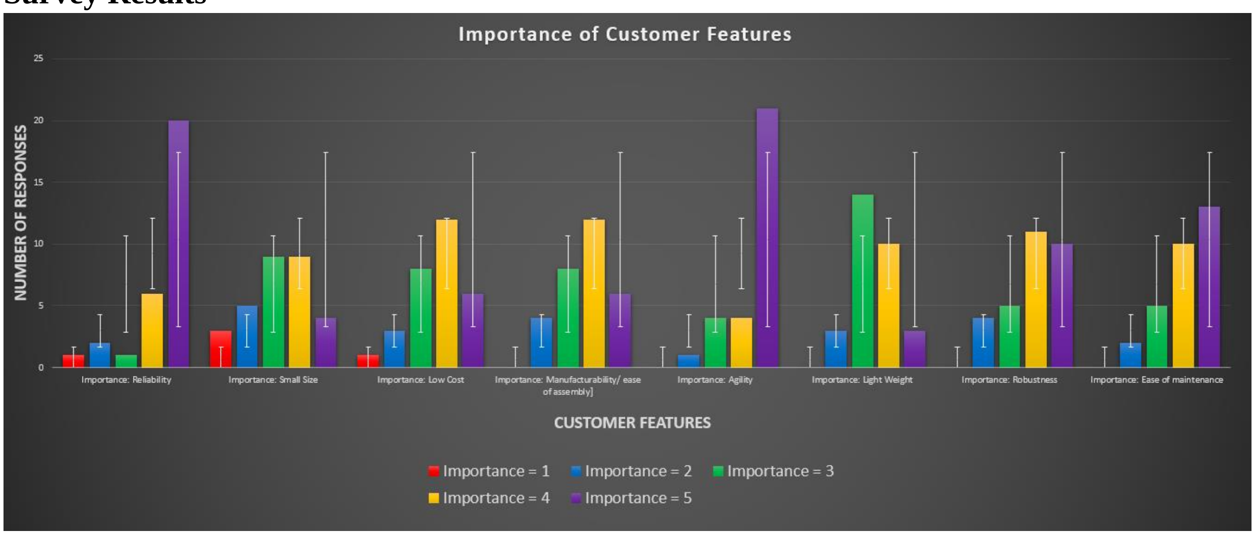
R53. All circuits shall be wired with appropriately sized insulated copper wire (SIGNAL LEVEL cables don't have to be copper):

Table 9-4 Breaker and wire sizing

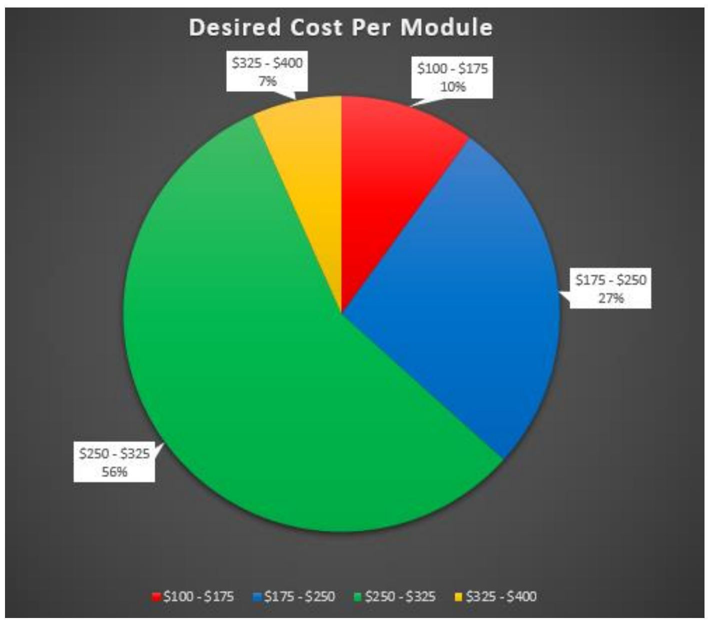
Application	Minimum Wire Size
31 – 40A protected circuit	12 AWG (13 SWG or 4 mm2)
21 – 30A protected circuit	14 AWG (16 SWG or 2.5 mm2)
6 – 20A protected circuit	18 AWG (19 SWG or 1 mm2)
Between the PDP dedicated terminals and the VRM or PCM	
Compressor outputs from the PCM	
Between the PDP and the roboRIO	22 AWG (22 SWG or 0.5 mm2)
≤5A protected circuit	
VRM 2A circuits	24 AWG (24 SWG or .25mm2)
roboRIO PWM port outputs	26 AWG (27 SWG or 0.14 mm2)
SIGNAL LEVEL circuits (i.e. circuits which draw ≤1A continuous and have a source incapable of delivering >1A, including but not limited to roboRIO non-PWM outputs, CAN signals, PCM Solenoid outputs, VRM 500mA outputs and Arduino outputs)	28 AWG (29 SWG or .08 mm2)

Appendix B

Survey Results




Satisfaction of Current Customer Features
NUMBER OF RESPONSES
14
12
10
8
6
4
2
0
Satisfaction: Reliability
Satisfaction: Small Size
Satisfaction: Low Cost
Satisfaction: Manufacturability/ ease of assembly
Satisfaction: Agility
Satisfaction: Light Weight
Satisfaction: Robustness
Satisfaction: Ease of maintenance
CUSTOMER FEATURES
Satifaction = 1
Satifaction = 2
Satifaction = 3
Satifaction = 4
Satifaction = 5


Desired Cost Per Module
$325 - $400
7%
$100 - $175
10%
$175 - $250
27%
$250 - $325
56%
$100 - $175
$175 - $250
$250 - $325
$325 - $400

Appendix C

Budget By Assembly

1-01-SWERVE DRIVE MODULE ASM					ASSY'S NEEDED:		5		
ITEM NO.	PART NUMBER	COST PER PART:	COST PER ASSY:	TOTAL COST:	ASSY QTY.	TOTAL QTY.	MATERIAL LENGTH (in)	WEIGHT PER PART (lbs)	WEIGHT PER ASSY (lbs)
1	#10, FLATWASHER	$0.00	$0.00	$0.00	2	10		0.003	0.006
2	#6, FLATWASHER	$0.00	$0.00	$0.00	1	5		0.003	0.003
3	1-01-1000-MOTOR, NEO BRUSHLESS, PART NO. REV-21-1650, REV	$0.00	$0.00	$0.00	2	10		0.938	1.876
4	1-01-1001-ENCODER, ABSOLUTE 360 DEG CONTINOUS, PART NO. 987-1393-ND, DIGIKEY	$21.29	$21.29	$106.45	1	5		0.04	0.04
5	1-01-101-PLATE, LOWER, ALUMINUM	$0.00	$0.00	$0.00	1	5		0.27	0.27
6	1-01-102-PULLEY, HTD-5M,9MM, 0.375 HEX, 20T, ONYX	$3.79	$3.79	$18.95	1	5		0.028	0.028
7	1-01-103-PLATE, UPPER, ALUMINUM	$0.00	$0.00	$0.00	1	5		0.43	0.43
8	1-01-104-SHAFT, HEX 0.375IN, DRIVE, ALUMINUM, PART NO. 217-2754, VEX	$1.12	$1.12	$12.99	1	5	36	0.03	0.03
9	1-01-105-PULLEY, HTD-5M, 15MM, 40T, HEX, ONYX	$5.53	$5.53	$27.65	1	5		0.078	0.078
10	1-01-106-SPACER, ROUND 0.375 OD ALUMINUM 6061	$0.00	$0.00	$0.00	2	10		0.02	0.04
11	1-01-112-GEAR, SPUR, 34T, 20 DP, ENCODER, ONYX	$0.32	$0.32	$1.60	1	5		0.035	0.035
12	1-01-116-SPACER, ROUND, 8MM ID, 0.7IN OD, 5.4MM LG, ABS	$0.02	$0.04	$0.20	2	10		0.002	0.004
13	1-01-117-SPACER, HEX, 0.375IN ID X 0.6IN OD X 33.7MM LG, ABS	$0.10	$0.10	$0.50	1	5		0.011	0.011
14	1-01-118-SPACER, HEX, 0.375IN ID X 0.6IN OD X 0.1325in LG, ABS	$0.02	$0.04	$0.20	2	10		0.002	0.004
15	1-01-119-KEY, 2MM X 2MM X 14MM, PART NO. 217-2760, VEX	$0.09	$0.27	$1.99	3	15	12	0	0
16	1-01-401-BEARING, RADIAL 8MM ID X 16MM OD X 5MM WD STEEL, PART NO. 688ZZ, SDS	$2.00	$2.00	$10.00	1	5		0.09	0.09
17	1-01-402-PULLEY, 12T 8MM KEYED ALUMINUM 6061, PART NO. WCP-0076, WCP	$9.99	$29.97	$149.85	3	15		0.009	0.027
18	1-01-403-BEARING, FLANGED 10.25MM ID X 0.875IN OD X 0.280IN WD STEEL, PART NO. 217-5829, VEX	$2.99	$5.98	$29.90	2	10		0.04	0.08
19	1-01-413-BELT, 62T 5MM HTD 9MM WIDTH, PART NO. A6R25M062090, SDP-SI	$8.53	$8.53	$42.65	1	5		0.022	0.022
20	1-01-414-BELT, 48T 5MM HTD 9MM WIDTH, PART NO. A6R25M048090, SDP-SI	$7.86	$7.86	$39.30	1	5		0.01	0.01
21	1-01-415-BELT, 52T 5MM HTD 9MM WIDTH, PART NO. A6R25M052090, SDP-SI	$8.01	$8.01	$40.05	1	5		0.01	0.01
22	1-01-417-INSERT, HEAT SET, 4-40, PART NO. 93365A120, MCMASTER-CARR	$0.00	$0.00	$0.00	1	5		0	0
23	1-01-418-Collar, SHAFT, 8MM ID ROUND, PART NO. 217-2744, VEX	$2.99	$5.98	$29.90	2	10		0.012	0.024
24	1-01-700-SCREW, SET, 4-40 X 0.125IN LG, PART NO. 91375A103, MCMASTER-CARR	$0.00	$0.00	$0.00	1	5		0.003	0.003
25	10-32 X 0.375 LONG, FLAT HEAD SCREW	$0.00	$0.00	$0.00	7	35		0.003	0.021
26	10-32 X 0.375 LONG, ROUNDED HEAD SCREW	$0.00	$0.00	$0.00	10	50		0.003	0.03
27	10-32 X 0.500 LONG, ROUNDED HEAD SCREW	$0.00	$0.00	$0.00	1	5		0.003	0.003
28	6-32 X 0.250 LONG, BUTTON HEAD SCREW	$0.00	$0.00	$0.00	1	5		0.003	0.003
		TOTAL:	$100.83	$512.18					3.178

1-02-HUB ASM					ASSY'S NEEDED:		5		
ITEM NO.	PART NUMBER	COST PER PART:	COST PER ASSY:	TOTAL COST:	ASSY QTY.	TOTAL QTY.	MATERIAL LENGTH (in)	WEIGHT PER PART (lbs)	WEIGHT PER ASSY (lbs)
1	1-02-100-HUB, WHEEL, A, 3IN OD, ONYX	$6.04	$6.04	$30.20	1	5		0.06	0.06
2	1-02-101-HUB, WHEEL, B, 3IN OD, ONYX	$6.04	$6.04	$30.20	1	5		0.06	0.06
3	1-02-400-TREAD, NITRILE, 0.28IN THK X 1IN WD, BLUE, PART NO. TTB-0037, THRIFTY BOT	$2.37	$2.37	$29.99	1	5	120	0.091	0.091
4	1-02-401-GEAR, BEVEL, 45T, PART NO. 1-25MOD_TTB-S-016, THRIFTY BOT	$20.00	$20.00	$100.00	1	5		0.14	0.14
5	1-02-402- BEARING, FLANGE, 0.375 ID X 0.875 OD X 0.280 WD, PART NO. 217-2733, VEX	$2.99	$5.98	$29.90	2	10		0.031	0.062
6	1-02-403-INSERT, 6-32 BRASS HEAT SET, PART NO. 93365A130, MCMASTER-CARR	$0.00	$0.00	$0.00	6	30		0.003	0.018
7	6-32 X 0.375 LONG, BUTTON HEAD SCREW	$0.00	$0.00	$0.00	8	40		0.003	0.024
8	6-32 X 1.000 LONG, FLAT HEAD SCREW	$0.00	$0.00	$0.00	6	30		0.003	0.018
9	6-32, HEX NUT	$0.00	$0.00	$0.00	8	40		0.003	0.024
		TOTAL:	$40.43	$220.29					0.497

1-03-PULLEY ASM					ASSY'S NEEDED:		5		
ITEM NO.	PART NUMBER	COST PER PART:	COST PER ASSY:	TOTAL COST:	ASSY QTY.	TOTAL QTY.	MATERIAL LENGTH (in)	WEIGHT PER PART (lbs)	WEIGHT PER ASSY (lbs)
1	#8, FLATWASHER	$0.00	$0.00	$0.00	1	5		0.003	0.003
2	1-01-403-BEARING, FLANGED 10.25MM ID X 0.875IN OD X 0.280IN WD STEEL, PART NO. 217-5829, VEX	$2.99	$2.99	$14.95	1	5		0.04	0.04
3	1-02-403-INSERT, 6-32 BRASS HEAT SET, PART NO. 93365A130, MCMASTER-CARR	$0.00	$0.00	$0.00	3	15		0.003	0.009
4	1-03-101-SHAFT, HEX 0.375IN, DRIVE, ALUMINUM, PART NO. 217-2754, VEX	$0.76	$0.76	$0.00	1	5		0.02	0.02
5	1-03-102-MOUNT A, WHEEL, ONYX	$4.08	$4.08	$20.40	1	5		0.048	0.048
6	1-03-103-PULLEY, HTD-5M, 50T, ONYX	$10.62	$10.62	$53.10	1	5		0.131	0.131
7	1-03-104-BEARING, RADIAL 8MM ID X 16MM OD X 5MM WD STEEL, PART NO. MR688-ZZ, VXB	$2.00	$4.00	$20.00	2	10		0.02	0.04
8	1-03-106-SHAFT, HEX 0.375IN, DRIVE, ALUMINUM, PART NO. 217-2754, VEX	$0.90	$0.90	$0.00	1	5		0.03	0.03
9	1-03-107-SHIM, 8MM ID X 14MM OD X 0.5MM LG, STEEL, PART NO. 98089A336, MCMASTER-CARR	$0.33	$0.33	$8.36	1	5	25 PACK	0	0
10	1-03-108-SPACER, HEX, 0.375IN ID X 0.6IN OD X 0.135IN LG, ONYX	$0.02	$0.02	$0.10	1	5		0.002	0.002
11	1-03-109-SPACER, THUNDER HEX, 0.375IN ID X 14MM OD X 0.425IN LG, ONYX	$0.04	$0.04	$0.20	1	5		0.004	0.004
12	1-03-110-GEAR, SPUR, 34T, 20 DP, ENCODER, ONYX	$0.54	$0.54	$2.70	1	5		0.06	0.06
13	1-03-111-SPACER, 3.8MM ID X 0.375IN OD X 0.575IN LG, ALUMINUM	$0.21	$0.63	$14.99	3	15	36	0.01	0.03
14	1-03-112-MOUNT B, WHEEL, ONYX	$4.08	$4.08	$20.40	1	5		0.048	0.048
15	1-03-113-SPACER, 0.201IN ID X 0.375IN OD X 1.650IN LG, ALUMINUM	$0.69	$0.69	$0.00	1	5		0.01	0.01
16	1-03-114-SPACER, 0.375 ID X 16MM OD X 0.152IN LG, ABS	$0.02	$0.02	$0.10	1	5		0.002	0.002
17	1-03-115-SPACER, 0.375 ID X 0.500 OD X 0.152IN LG, ABS	$0.02	$0.02	$0.10	1	5		0.002	0.002
18	1-03-401-GEAR, BEVEL, 15T, PART NO. 1-25MOD_TTB-S-015, THRIFTY BOT	$20.00	$20.00	$100.00	1	5		0.03	0.03
19	1-03-402-GEAR, SPUR, 20T, 20DP, 0.375IN HEX, ALUMINUM, PART NO. 217-2701, VEX	$9.99	$9.99	$49.95	1	5		0.036	0.036
20	1-03-403-GEAR, SPUR, 16T, 20 DP, 0.375IN HEX, ALUMINUM, PART NO. 217-5450, VEX	$9.99	$9.99	$49.95	1	5		0.02	0.02
21	1-03-404-BEARING, 3IN ID X 3.5IN OD X 0.25IN WD, PART NO. WCP-0357, WCP	$29.99	$29.99	$149.95	1	5		0.135	0.135
22	1-03-405-INSERT, 10-32 BRASS HEAT SET, PART NO. 97171A200, MCMASTER-CARR	$0.32	$1.60	$15.77	5	25	50 PACK	0.003	0.015
24	1-03-700-SCREW, SOCKET HEAD, 10-32, 1.5IN LG, PART NO. 91251A351, MCMASTER CARR	$0.26	$1.04	$12.96	4	20	50 PACK	0.005	0.02
25	1-03-702-10-32 X 0.375 LONG, FLAT HEAD SCREW	$0.00	$0.00	$0.00	1	5		0.003	0.003
26	1-03-703-SCREW, FLATHEAD, 6-32 X 1.25IN LONG, PART NO. 91253A155, MCMASTER CARR	$0.37	$1.12	$9.35	3	15	25 PACK	0.005	0.015
27	1-03-704-SCREW, SOCKET HEAD, 10-32, 3IN LG, PART NO. 91251A360, MCMASTER CARR	$0.58	$0.58	$14.65	1	5	25 PACK	0.005	0.005
28	8-32 X 0.375 LONG, BUTTON HEAD SCREW	$0.00	$0.00	$0.00	1	5		0.003	0.003
		TOTAL:	$104.04	$557.98					0.761

1-04-ELECTRONICS PLATE ASM					ASSY'S NEEDED:		1		
ITEM NO.	PART NUMBER	COST PER PART:	COST PER ASSY:	TOTAL COST:	ASSY QTY.	TOTAL QTY.	MATERIAL LENGTH (in)	WEIGHT PER PART (lbs)	WEIGHT PER ASSY (lbs)
1	1-04-100-PLATE, ELECTRONICS, 23IN X 23IN X 0.25IN, POLYCARBONATE	$0.00	$0.00	$0.00	1	1		N/A	N/A
2	1-04-1000-BATTERY, PART NO AM-3062, ANDYMARK	$0.00	$0.00	$0.00	1	1		N/A	N/A
3	1-04-1001-ROBORIO, PART NO. 783581-01, NATIONAL INSTRUMENTS	$0.00	$0.00	$0.00	1	1		N/A	N/A
4	1-04-1002-POWER DISTRIBUTION PANEL, PART NO. 217-4244, VEX	$0.00	$0.00	$0.00	1	1		N/A	N/A
5	1-04-1003-RADIO, PART NO. AM-3205, ANDYMARK	$0.00	$0.00	$0.00	1	1		N/A	N/A
6	1-04-1004-VOLTAGE REGULATOR MODULE, PART NO. AM-2857, ANDYMARK	$0.00	$0.00	$0.00	1	1		N/A	N/A
7	1-04-1005-CONTROLLER, SPARK MAX MOTOR, PART NO. REV-11-2158, REV ROBOTICS	$0.00	$0.00	$0.00	8	8		N/A	N/A
8	1-04-1006-CIRCUIT BREAKER, PART NO. AM-0282, ANDYMARK	$0.00	$0.00	$0.00	1	1		N/A	N/A
9	1-04-101-PLATE, ELECTRONICS, 23IN X 23IN X 0.25IN, POLYCARBONATE	$0.00	$0.00	$0.00	1	1		N/A	N/A
		TOTAL:	$0.00	$0.00					N/A

1-05-NUT PLATE ASM					ASSY'S NEEDED:		20		
ITEM NO.	PART NUMBER	COST PER PART:	COST PER ASSY:	TOTAL COST:	ASSY QTY.	TOTAL QTY.	MATERIAL LENGTH (in)	WEIGHT PER PART (lbs)	WEIGHT PER ASSY (lbs)
1	1-05-100-PLATE, NUT, 10_32, ABS	$0.38	$0.38	$7.60	1	20		N/A	N/A
2	1-05-700-NUT, HEX 10-32	$0.00	$0.00	$0.00	3	60		N/A	N/A
		TOTAL:	$0.38	$7.60					N/A

1-06-FRAME ASM					ASSY'S NEEDED:		1		
ITEM NO.	PART NUMBER	COST PER PART:	COST PER ASSY:	TOTAL COST:	ASSY QTY.	TOTAL QTY.	MATERIAL LENGTH (in)	WEIGHT PER PART (lbs)	WEIGHT PER ASSY (lbs)
1	0-06-101-TUBE, RECTANGULAR ALUMINUM 6061, 1 X 2 X .100 WALL, PART NO. 217-3453, VEX	$13.80	$13.80	$13.80	1	1	2X 59	N/A	N/A
2	0-06-102-ANGLE, ALUMINUM 6061, 1.5 X 1.5 X .125 WALL,90 DEG ANGLE, PART NO. 8982K13, MCMASTER-CARR	$0.00	$0.00	$0.00	4	4		N/A	N/A
3	0-06-100-TUBE, RECTANGULAR ALUMINUM 6061, 1 X 2 X .100 WALL, PART NO. 217-3453, VEX	$9.00	$36.00	$36.00	4	4		N/A	N/A
		TOTAL:	$49.80	$49.80					N/A