Fall 2023

MEMS 411: Mini-Golf Robot

Matthew J. Sullivan
Washington University in St. Louis

Jack Nanez
Washington University in St. Louis

William Urdahl
Washington University in St. Louis

Eli Cohen
Washington University in St. Louis

Recommended Citation

Sullivan, Matthew J.; Nanez, Jack; Urdahl, William; and Cohen, Eli, "MEMS 411: Mini-Golf Robot" (2023). *Mechanical Engineering Design Project Class*. 208.
https://openscholarship.wustl.edu/mems411/208

Washington University in St. Louis
JAMES MCKELVEY SCHOOL OF ENGINEERING

Mechanical Engineering Design Project
MEMS 411, Fall 2023

Mini-Golf Robot

The following report details the design and construction of a mini-golf robot over three months. The robot was designed under the standards provided by the ASME Fall 2023 Design Challenge. The robot would need to traverse the mini-golf course, completing it in under 10 minutes with the assistance of an attached striker mechanism. It was necessary that the robot could position itself precisely with respect to the goofball, while also staying stationary while striking the object. The robot design timeline followed the guidelines of the engineering design process, with concept generation, concept selection, prototype embodiment and design refinement all playing important roles in ensuring the design of the vehicle was best suited to the goals it was supposed to complete. The final prototype performance goals of the vehicle, determined by our customer, Dr. J. Jackson Potter, were for the device to a) climb over a long wooden board that is 3.5" tall and 1.5" thick, b) climb onto, over, and back down from a sheet of 1/2"-thick plywood whose bottom surface is 3.5" above the ground, and c) position itself next to three golf balls (without disturbing them) and "aim" in a specified direction before removing the ball and continuing to the next ball in ¡ 1 minute, all while carrying extra weight in the shape of a wooden striker template. The group was able to complete prototype goal number 3 successfully but failed to complete prototype goals 1 or 2. This report outlines the full process of the creation and assembly of the vehicle.

SULLIVAN, Matthew
COHEN, Eli
URDAHL, William
NANEZ, Jack

Contents

List of Figures

List of Tables

1 Introduction

This project is part of the ASME Student Design Competition for the 2023-2024 year. The purpose of this project is to satisfy the customer need for a moving robot that can perform minigolf swings and traverse a course with obstacles. Since the breadth of the entire project is too wide to accomplish, we have split up the project into components and will be focusing on the robotic rover and the obstacles that it traverses. As such, this report will document the creation of a robot that can be remote controlled to move throughout a course, position itself with accuracy to complete a swing, and travel over walls.

2 Problem Understanding

2.1 Existing Devices

This section is dedicated to showcasing devices that currently exist and solve problems similar to the project we are working to complete.

2.1.1 Existing Device #1: Sphero RVR

Figure 1: Sphero RVR (Source: Cool Things)

Link: https://www.coolthings.com/sphero-rvr-rover-robot-porgrammable-all-terrain/
Description: The Sphero RVR is a rover designed to transport itself and small objects over various terrains. It is optimized to be able to traverse obstacles with treads as a opposed to wheels. It is equipped with color, light, and IR sensors, as well as has a magnetometer, accelerometer, and gyroscope. The RVR can be programmed and is compatible with a multitude of 3rd party hardware pieces, from board computers to speakers to cameras.

2.1.2 Existing Device #2: Robot Rover

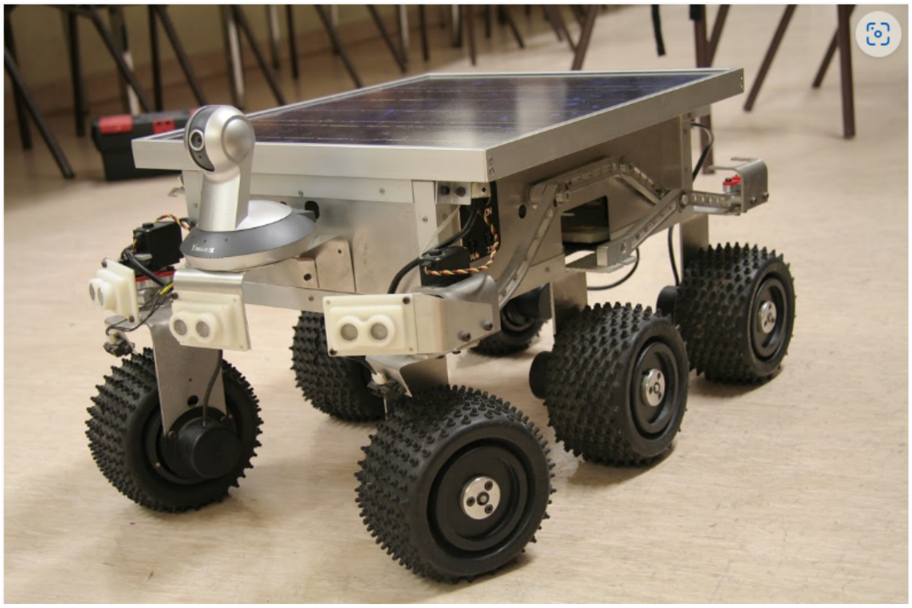


Figure 2: Robot Rover (Source: IEEE Maker Project)

Link: https://transmitter.ieee.org/makerproject/view/dd264
Description: This robot is a sensor-equipped rover designed for autonomous locomotion. It utilizes six wheels, including four that are controlled and powered independently. It can accomplish a wide range of movements and traverse multiple types of terrain and is equipped with wheel support structures that support this function. It also incorporates technology that can sense environmental markers, tell time, and view the environment in real-time.

2.1.3 Existing Device #3: Golfi

Figure 3: Golfi (Source: Paderborn University)

Link: `https://www.engadget.com/golf-robot-putting-golfi-machine-learning-microsoft-kinect-200008516.html`
Description: Golfi stands as a testament to the fusion of robotics and sports and is the first robot to be able to autonomously spot and travel to a golf ball anywhere on a green and sink a putt. The robot takes a snapshot of the green with a Microsoft Kinect 3D camera and it simulates thousands of random shots taken from different positions. It takes factors like the turf's rolling resistance, the ball's weight and the starting velocity into account. Training Golfi on simulated golf shots takes five minutes, compared with 30-40 hours if the team were to feed data from real-life shots into the system. Once Golfi has figured out the shot it should take, it rolls over to the ball and uses a belt-driven gear shaft with a putter attached to make the putt with 60-70% accuracy.

2.2 Patents

2.2.1 Vehicle Toy Mounting Projectile Mechanism (EP0700703A2)

This patent describes a RC Toy Vehicle with a projectile launcher on top. A user uses a remote controller to drive and steer the vehicle. The same controller is also used to launch the projectiles. The launcher can be popped out of the roof of the vehicle using just the controller. The projectile is launched with as a gear rotates with a pin. Each time the pin rotates, it causes the spring in each barrel to release the projectile. Patent Link

EP 0 700 703 A2

FIG. 1

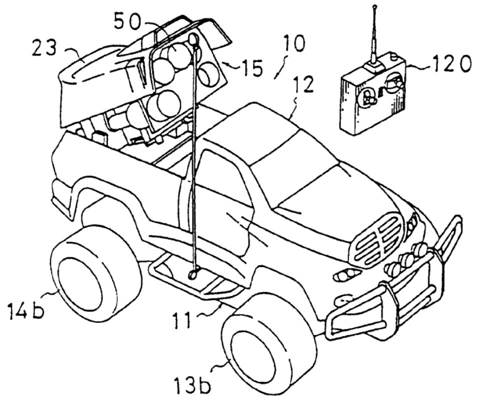


Figure 4: Patent Images for Vehicle Toy with Projectile

2.2.2 Golf Robot Arm (US7775898B1)

This patent outlines the design and circuitry of a golf swing training robot. A servo attached at the elbow is timed with the swing of a golf club to lock the bicep. The robot begins being bent by 80 degrees. Once it detects a swing, the robot determines when to turn the servo to make the arm bent at 10 degrees. This allows the user to have an accurate follow through each golf stroke.

Patent Link

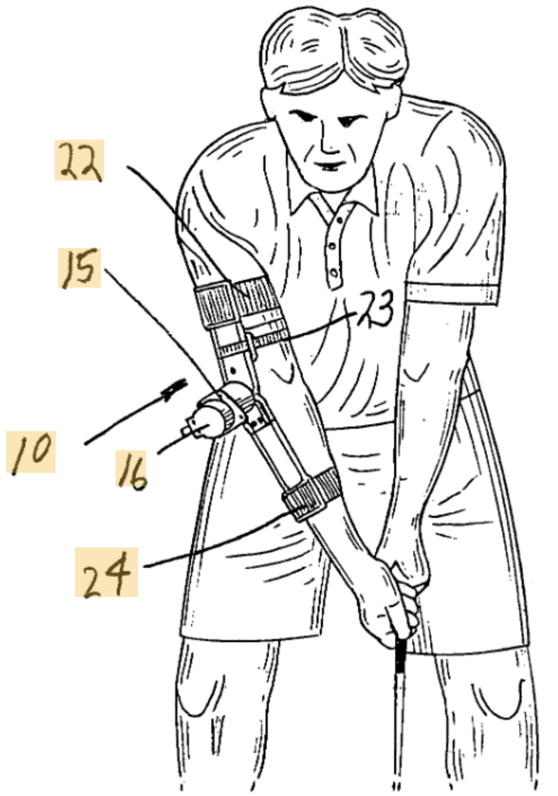


Figure 5: Patent Images for Robot Golfer Arm

2.3 Codes & Standards

2.3.1 Wireless Standards (IEE 802.15)

This is a collection of standards that go over Bluetooth, Low Energy Bluetooth and mesh networks. Bluetooth can be used in our project as an effective way to transmit larger packages of information while also using lower energy amounts than conventional bluetooth.

2.3.2 Lithium-ion batteries and charging systems (IEC 63370:2022)

This International Standard describes charging systems used for rechargeable lithium ion batteries for common tools. This could influence our battery choice and how we recharge the batteries of our mini golf device.

2.4 User Needs

Sed ut perspiciatis unde omnis iste natus error sit voluptatem accusantium doloremque laudantium, totam rem aperiam, eaque ipsa quae ab illo inventore veritatis et quasi architecto beatae vitae dicta sunt explicabo.

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Hillman 70, Washington University in St. Louis, Danforth Campus
Date: September 8th, 2023
Setting: During the friday engineering design lecture, Dr. Potter described the ASME Student Design Competition, which is to design and fabricate a robot that can play a round of mini golf.

Presentation Notes:

The competition design requirements

- The device should be as small as possible, fitting within a rigid sizing box with maximum internal measurements of 50 cm by 50 cm by 50 cm
- If device operation is powered by batteries, the batteries must be rechargeable.
- The device will have 10 minutes to navigate a mini golf course to nine designated tees from which the device will "tee-off". Up to 5 strokes are allowed when attempting to complete a mini golf obstacle. Once an obstacle has been completed, the device must navigate the field and align itself with the golf ball at the next tee.
- Proper design practices and time management for fabrication and testing are valued. A bonus is awarded for optional design and initial operation videos submitted prior to the competition.
- These rules were developed with the spirit of the game in mind. Any necessary judgement not captured explicitly in the rules will rule in favor of the spirit of the game. The spirit of this game is to provide a golf game that is an appropriate challenge for all engineering teams participating. The golf ball is to traverse through a set of obstacles only propelled by the built robot itself.

Splitting of the Project into Rovers and Strikers

- Doing both the rover and golf ball putting is too much work for one group, so the competition is being broken up into 2 parts: the rover and the striker.
- This group has decided on doing the rover part of the competition.
- Dr. Potter has created dummy rovers and strikers that have the same footprint and clearances so that teams can develop their own devices separately.

Dr. Potter's Recommendations

- Don't worry about making it as small as possible. Make it the size where it easiest and fastest to make.
- The area where the striker attaches to the rover should be made out of a material which is easy to attach things to.
- Try to make the device low-cost because of the $400 budget. For a good reason, this amount can be increased.
- The rover doesn't need need to move that fast. Precise positioning is more important
- Very long battery life is not important as long as it can get through the competition.
- It is not important to hit the golf ball far because the course is not that large.

2.4.2 Interpreted User Needs

The following interpreted user needs were determined by combining the information Dr. Potter provided in his presentation and some team derived user needs.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The robot can completely traverse the ASME designed course	5
2	The robot must complete the course in less than 10 minutes	3
3	The robot can not be moving while striking the golf ball	5
4	The robot can support a generic golf ball striker	4
5	The robot must fit inside a 50cm x 50 cm x 50 cm box	5
6	If batteries are used, they must be rechargeable	4
7	The robot should be able to drive around for a minimum of 15 minutes	3
8	The robot should cost less than 400 dollars	2
9	The robot should be able to precisely position the striker in relation to the golf ball	5
10	The striker mounting area should be easily attached to in many different ways	4

Our robot will be designed in accordance to these users needs. We will update this table as new user needs are identified or user need priorities change.

2.5 Design Metrics

Because of the limitations of the size of the mini golf course, and other parameters within the ASME Design Challenge specifications, the following target specifications have been generated from our list of interpreted customer needs.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	2	Time taken to complete course	minutes	< 10	< 7
1	5	Total volume	m^3	< 0.125	0.1
3	7	Length of battery life	minutes	> 15	> 20
4	8	Total cost	dollars	$< \$400$	$< \$400$
5	9	Number of strokes for average-difficulty hole	integer	< 5	3

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

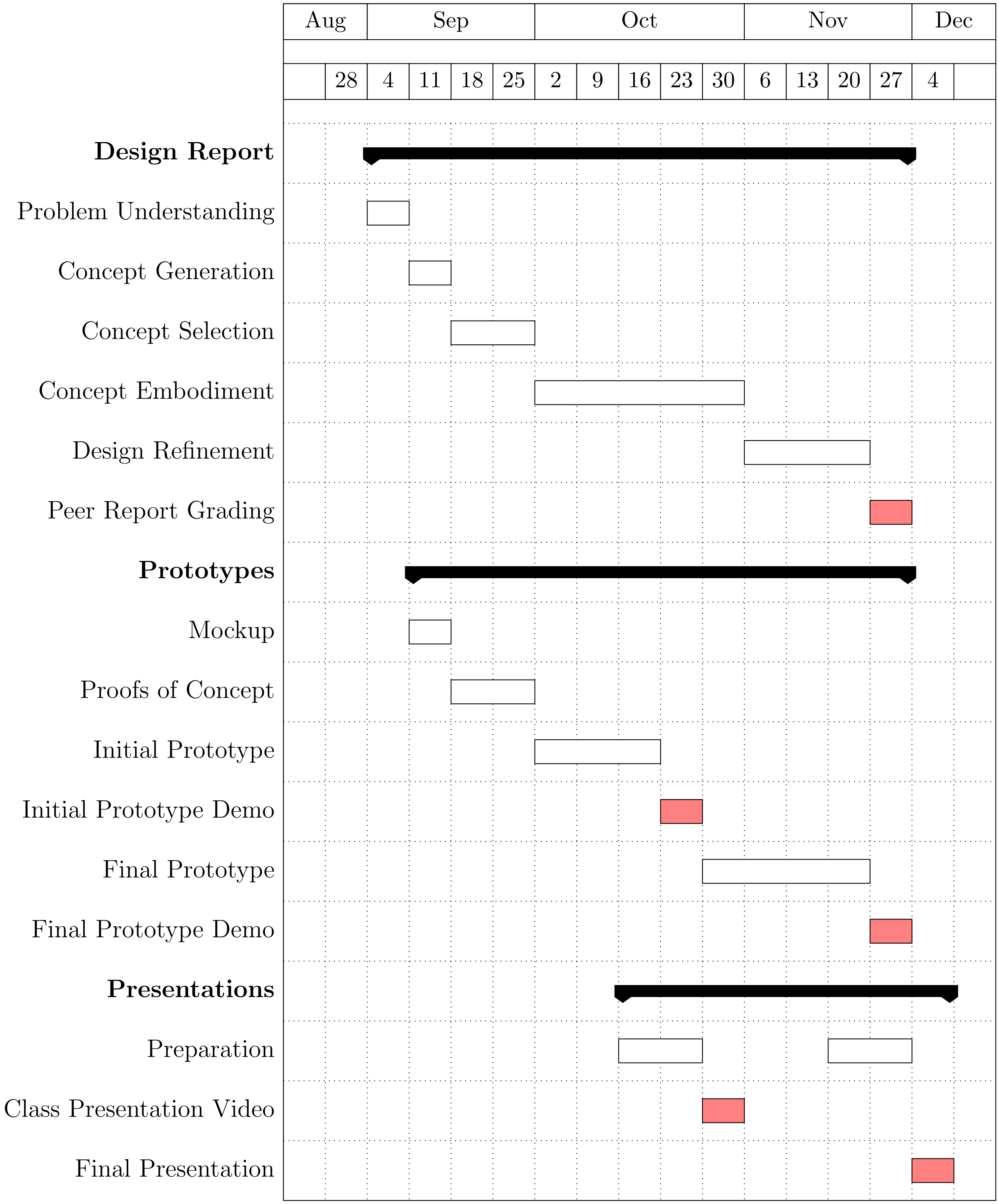


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

Figure 7 shows the mMckup created in studio. The Mockup is named ”Big Wheels” due to having big wheels. This was made with wheels found in the basement, a piece of cardboard folded into a rectangular box, and a dowel rod connecting each set of wheels.

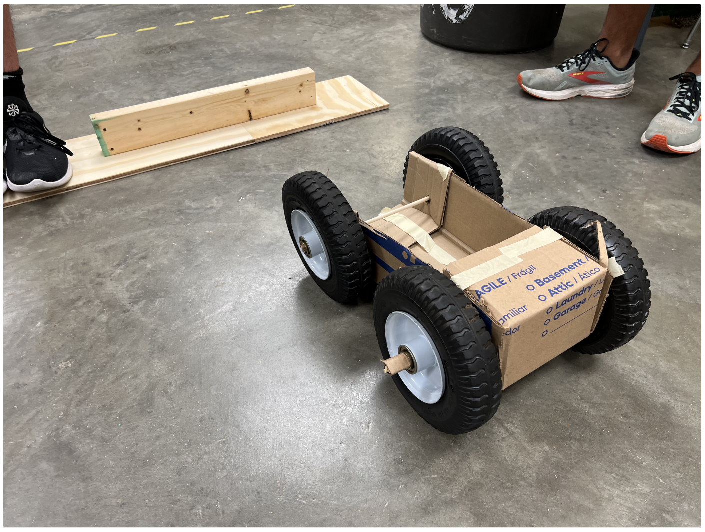


Figure 7: ”Big Wheels” In-Class Mockup

A 2x4” wood plank was used to test effectiveness of the Big Wheels. Testing was done by rolling big wheels over the plank, as shown in Figure 8.

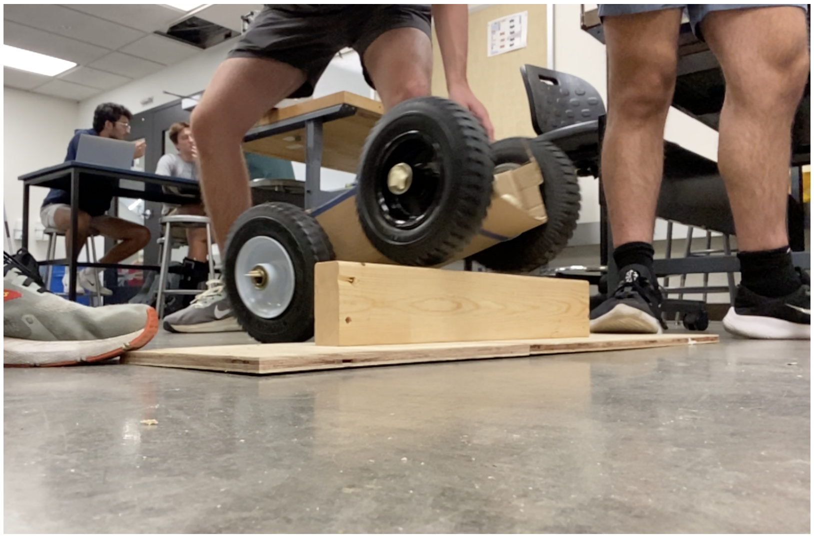


Figure 8: ”Big Wheels” front wheels successfully rolling over the 2x4

The front two wheels successfully rolled over the 2x4 wood plank. Due to the gap between the front and back wheels, Big Wheels bottomed out as shown in Figure 9.

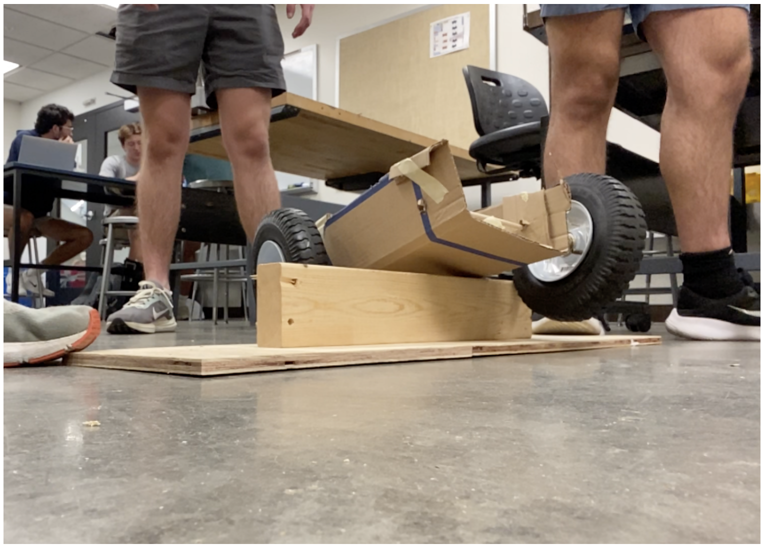


Figure 9: "Big Wheels" bottoming out

Big Wheels had success with it's front wheels rolling over the 2x4. The problem was Big Wheels bottomed out because of the large gap between the set of wheels. Going forward, we will look into either rubber tank treads or position the wheels close enough together such that there is no chance of bottoming out.

3.2 Functional Decomposition

The below function tree demonstrates the goals of our device and preliminary ideas on how we can accomplish those goals.

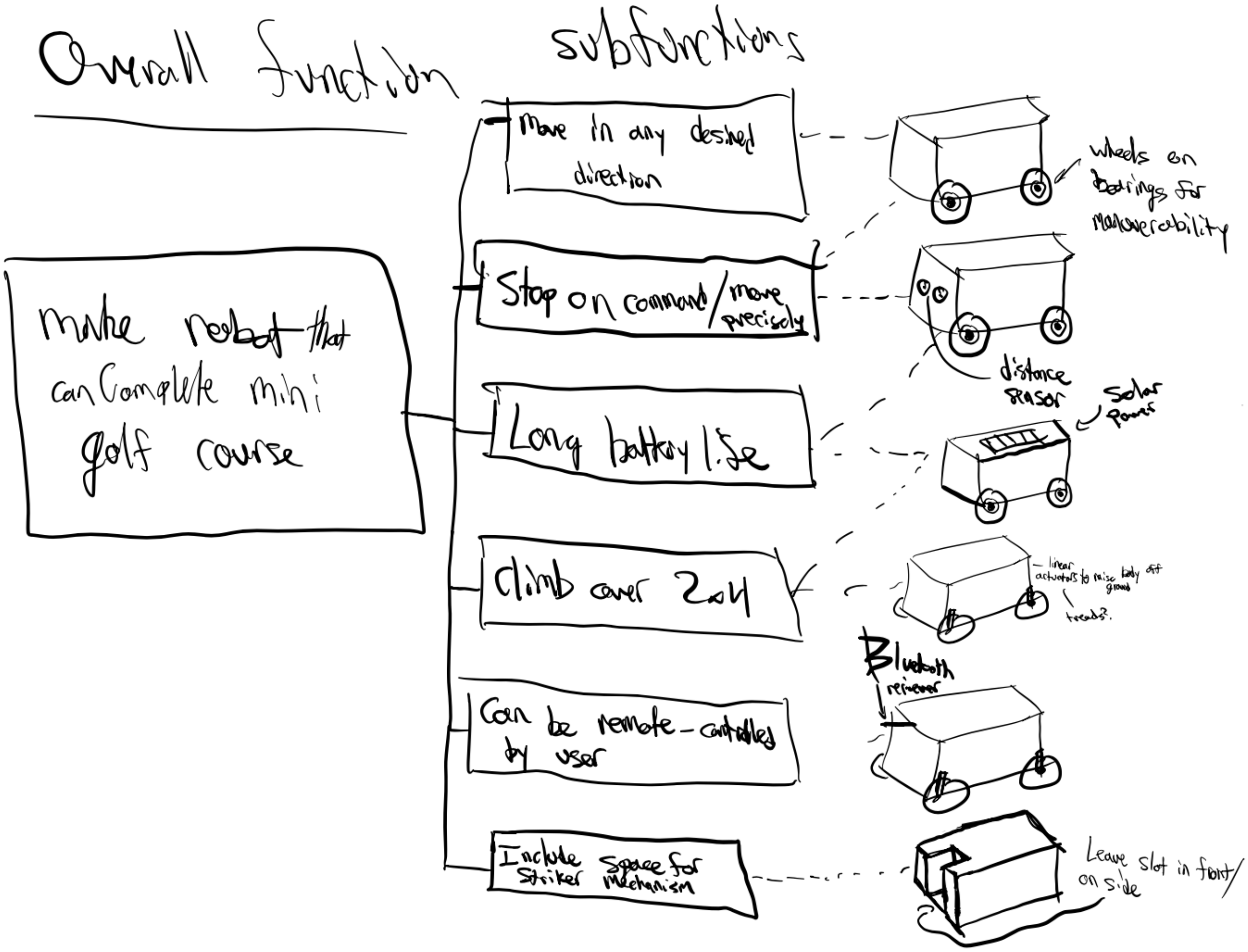


Figure 10: Function tree for the Mini Golf Robot, hand-drawn and screenshotted

3.3 Morphological Chart

Sed ut perspiciatis unde omnis iste natus error sit voluptatem accusantium doloremque laudantium, totam rem aperiam, eaque ipsa quae ab illo inventore veritatis et quasi architecto beatae vitae dicta sunt explicabo.

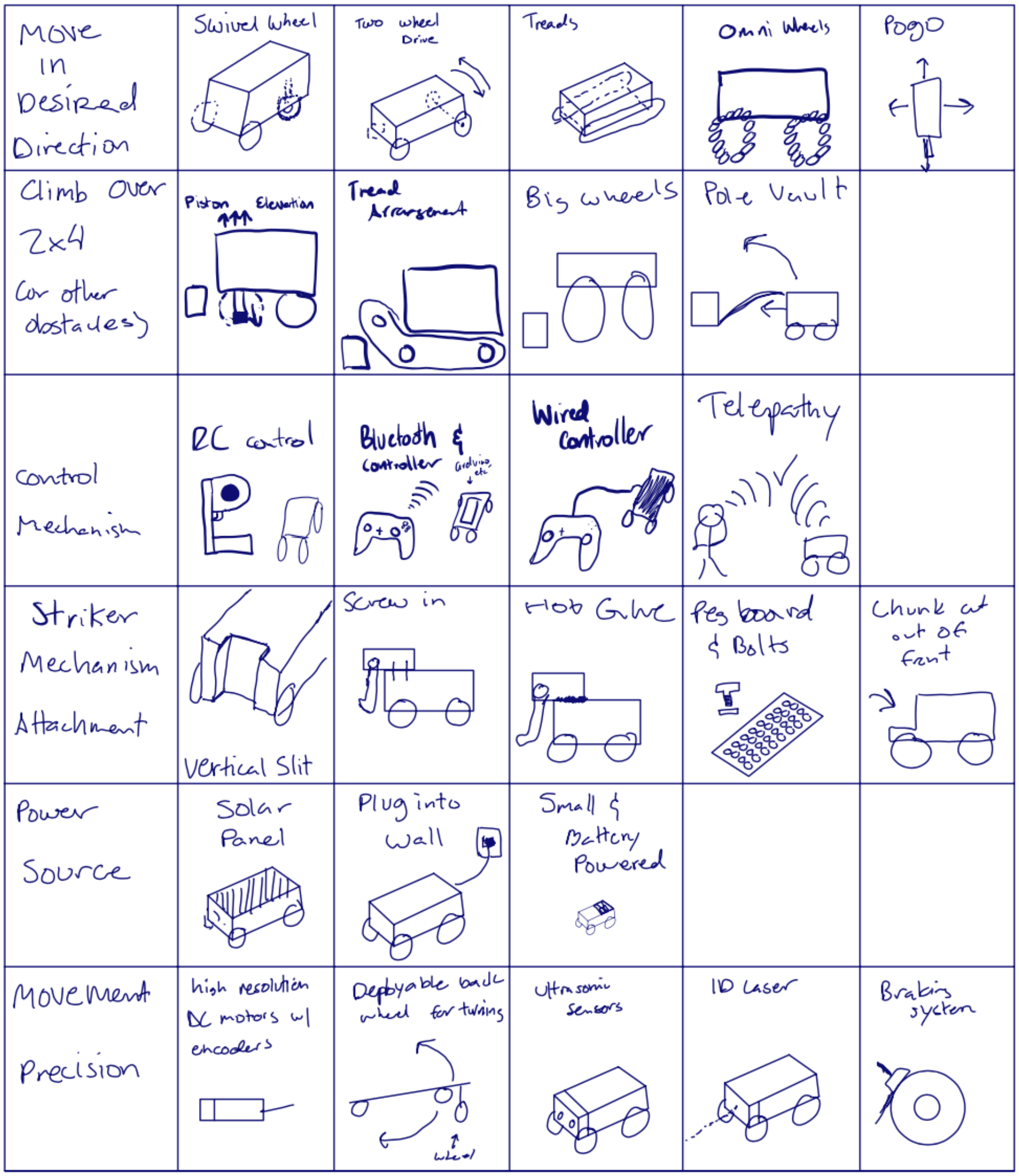


Figure 11: Morphological Chart for Useless Box

3.4 Alternative Design Concepts

3.4.1 Concept #1: Big Wheels

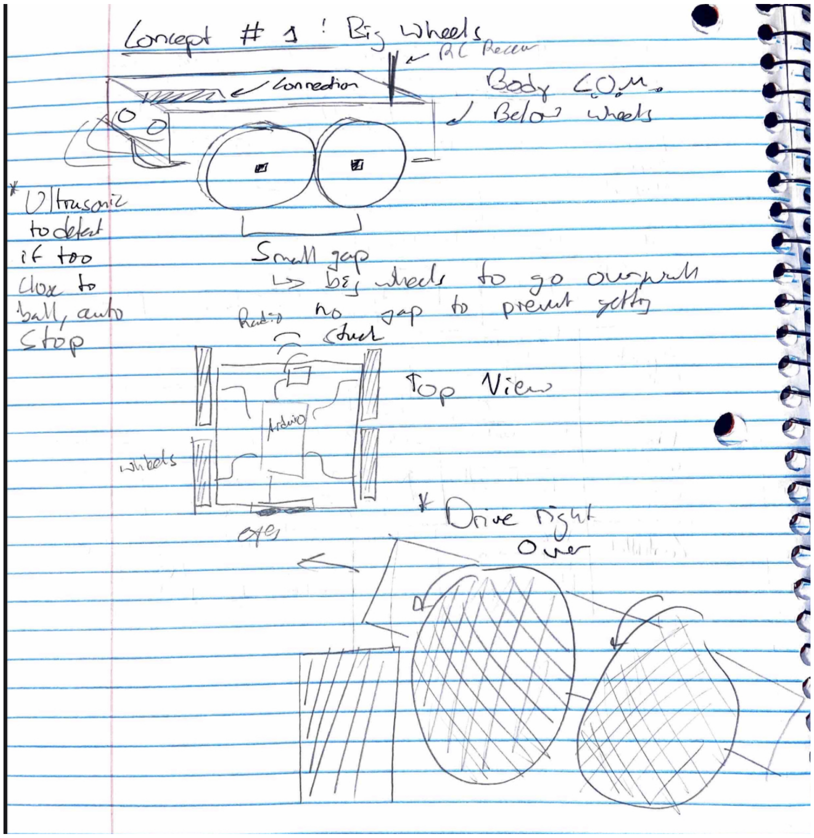


Figure 12: Concept #1

<u>Description</u>: A robot that utilizes large wheels to navigate over the obstacles of the course. The wheels have a very small spacing in between to prevent the bottom of the robot from bottoming out while going over the 2x4. A microcontroller is used to control the robot.

3.4.2 Concept #2: Tank

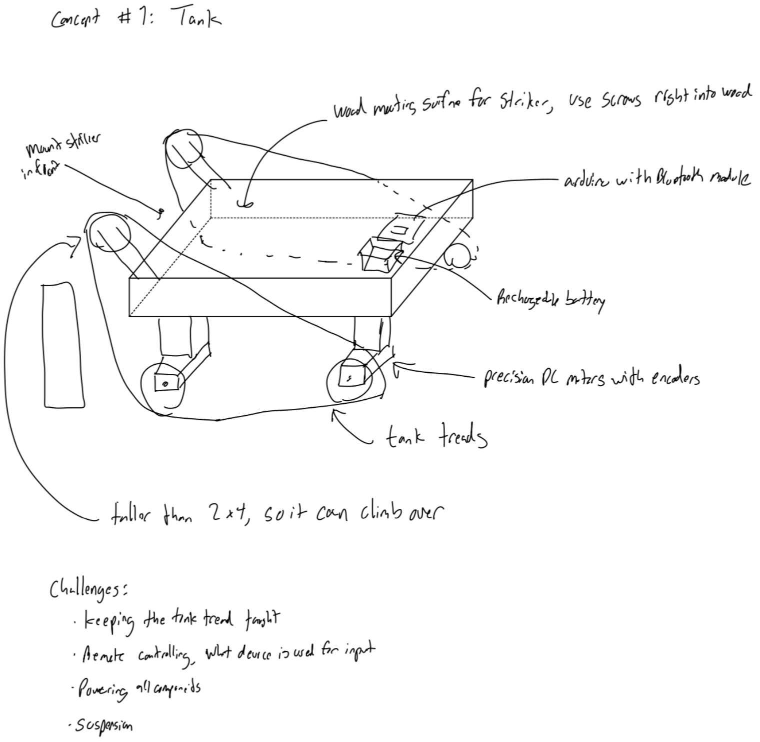


Figure 13: Concept #2

Description: This robot design uses tank treads to pull itself over obstacles and prevent bottoming out while going over the 2x4. A micro-controller is used to control the robot. Also, the ball-striker is mounted at the front of the robot.

3.4.3 Concept #3: Piston Tank

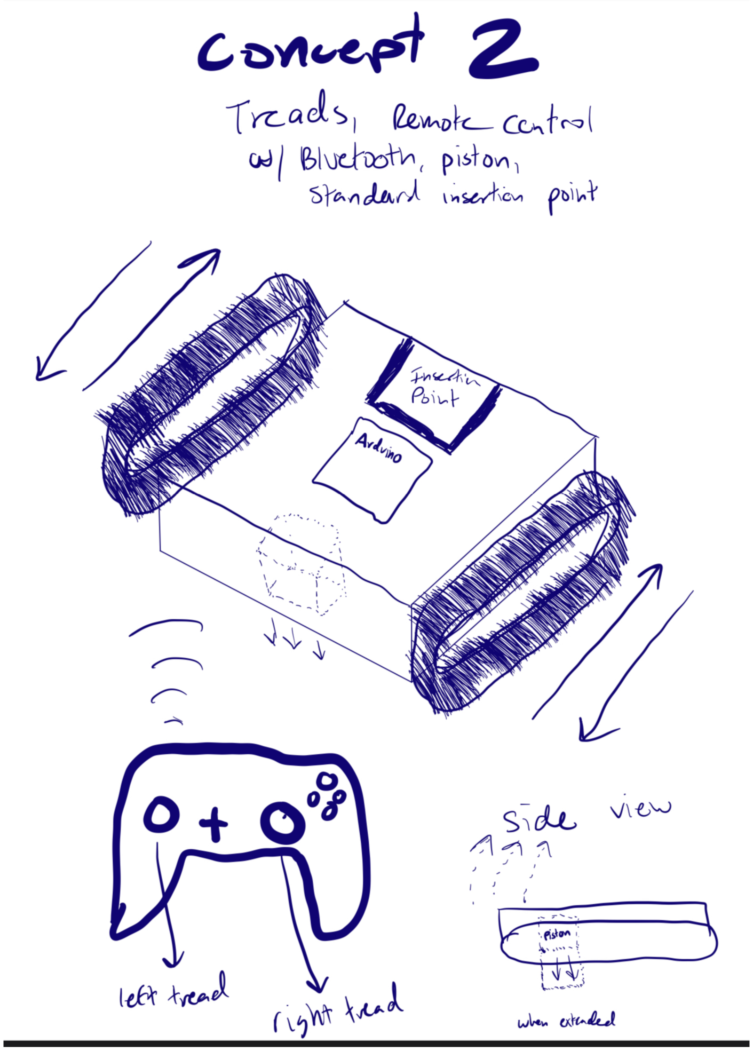


Figure 14: Concept #3

Description: This design uses tank treads to move around the course and employs a piston to lift itself up so that it can navigate over obstacles. This robot is controlled using an Arduino and a gaming controller.

3.4.4 Concept #4: Olympian

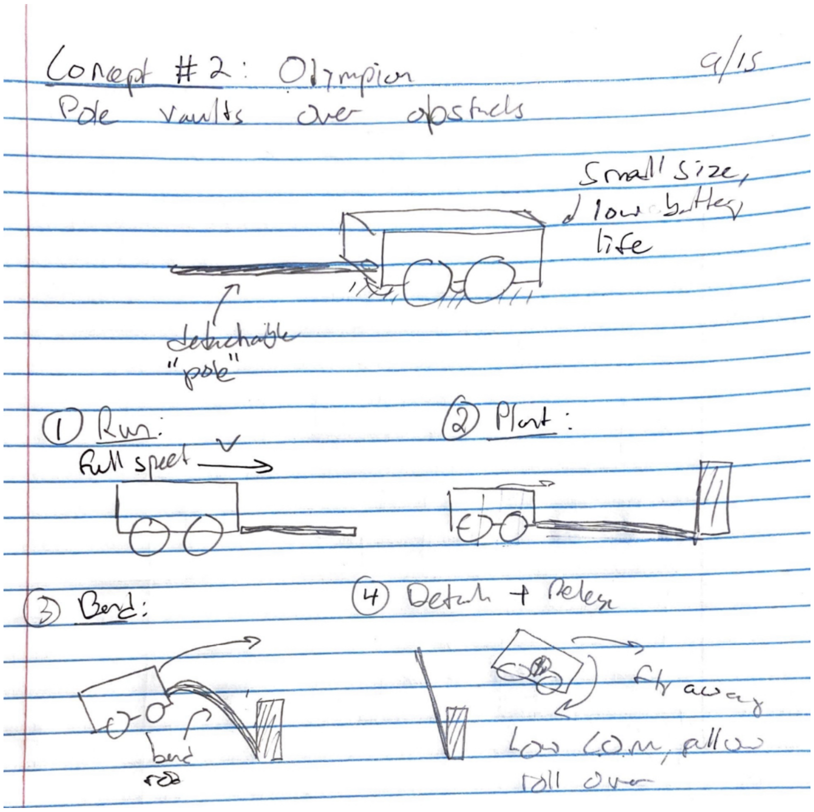


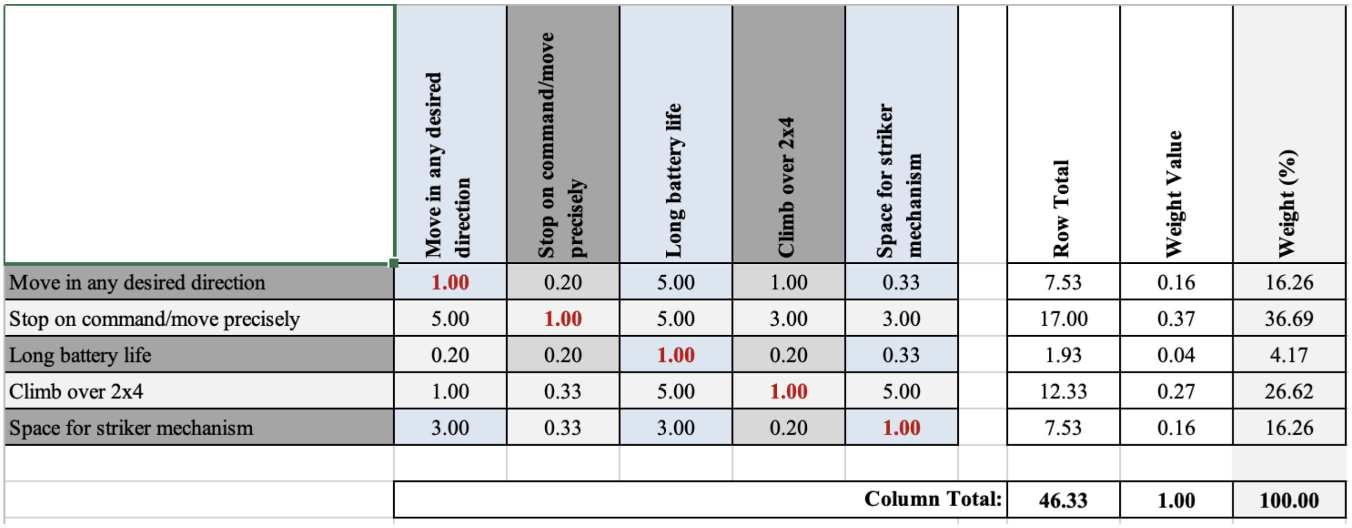
Figure 15: concept #4

Description: This robot uses wheels to navigate the course and pole vaults over obstacles that are too high to navigate with wheels. It is also remotely controlled, and has room for the ball-striker on the main robot body.

4 Concept Selection

4.1 Selection Criteria

The following figure shows our goals for the robot and their relative importance to eachother.

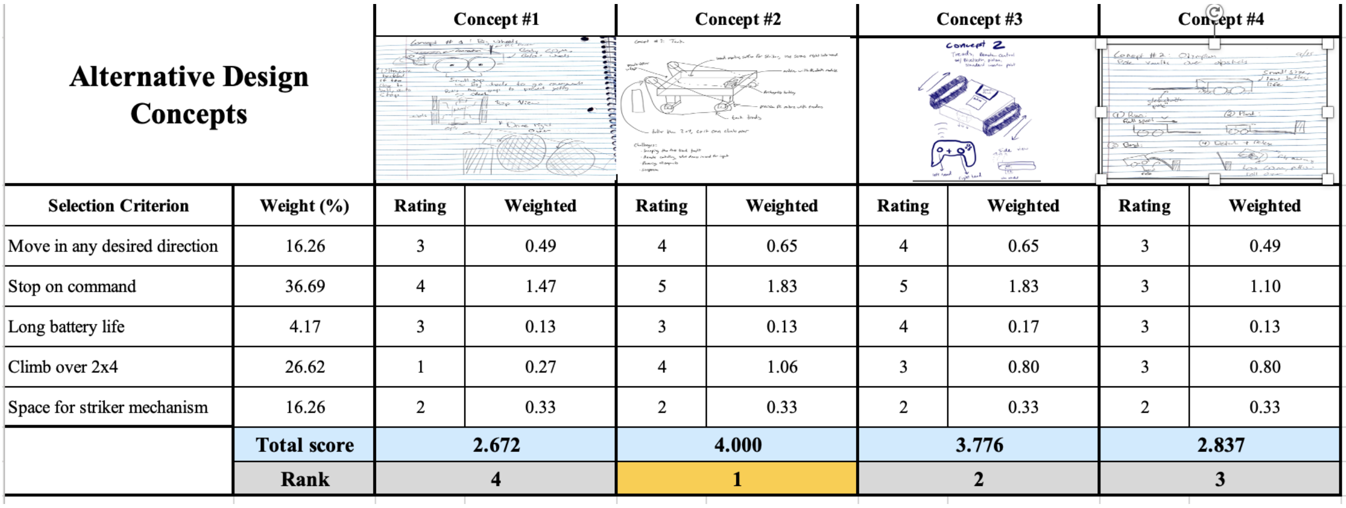


	Move in any desired direction	Stop on command/move precisely	Long battery life	Climb over 2x4	Space for striker mechanism		Row Total	Weight Value	Weight (%)
Move in any desired direction	1.00	0.20	5.00	1.00	0.33		7.53	0.16	16.26
Stop on command/move precisely	5.00	1.00	5.00	3.00	3.00		17.00	0.37	36.69
Long battery life	0.20	0.20	1.00	0.20	0.33		1.93	0.04	4.17
Climb over 2x4	1.00	0.33	5.00	1.00	5.00		12.33	0.27	26.62
Space for striker mechanism	3.00	0.33	3.00	0.20	1.00		7.53	0.16	16.26
						Column Total:	**46.33**	**1.00**	**100.00**

Figure 16: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

The below figure uses the weights from Section 4.1 and puts four of the design choices head to head, ultimately demonstrating that concept 2 does the best job at meeting our teams' needs.



Alternative Design Concepts		**Concept #1**		**Concept #2**		**Concept #3**		**Concept #4**	
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Move in any desired direction	16.26	3	0.49	4	0.65	4	0.65	3	0.49
Stop on command	36.69	4	1.47	5	1.83	5	1.83	3	1.10
Long battery life	4.17	3	0.13	3	0.13	4	0.17	3	0.13
Climb over 2x4	26.62	1	0.27	4	1.06	3	0.80	3	0.80
Space for striker mechanism	16.26	2	0.33	2	0.33	2	0.33	2	0.33
	Total score	**2.672**		**4.000**		**3.776**		**2.837**	
	Rank	**4**		**1**		**2**		**3**	

Figure 17: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

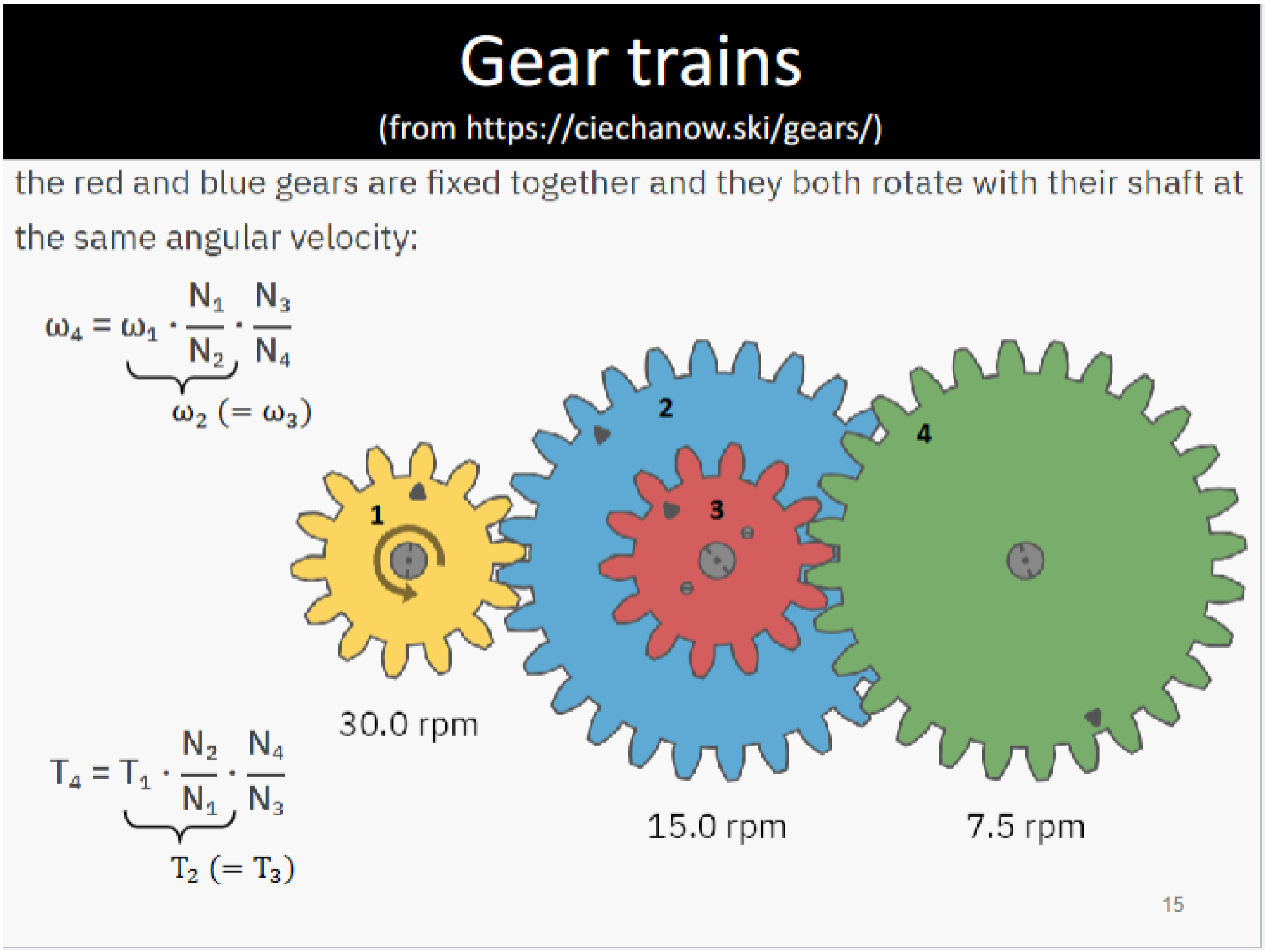
4.3 Evaluation Results

Concept 2 ”Tank” had a 4 for move in any desired direction. To turn left or right, the treads can move at different speeds for accurate turns. The treads can also move in opposite directions to spin the golf robot. Concept 2 can also stop easily and effectively, relying on the weight of the treads to stop movement. Concept 2's battery would not last as long as the other concepts due to the high weight of the system. Concept 2 can effectively climb over the 2x4 by utilizing the elevated and angled tread design at the front. All designs received a 2 for space for striker mechanism due to similar nature of the front of each Concept.

4.4 Engineering Models/Relationships

4.4.1 Engineering Model #1: Gear Ratio Model

The engineering model of gear ratios allows for the purposeful manipulation of both angular speed ω and torque $\mathbf{T}$, using gears with different numbers of teeth $\mathbf{N}$.



Gear trains

(from https://ciechanow.ski/gears/)

the red and blue gears are fixed together and they both rotate with their shaft at the same angular velocity:

$$\omega_4 = \underbrace{\omega_1 \cdot \frac{N_1}{N_2}}_{\omega_2\ (=\ \omega_3)} \cdot \frac{N_3}{N_4}$$

$$T_4 = \underbrace{T_1 \cdot \frac{N_2}{N_1}}_{T_2\ (=\ T_3)} \cdot \frac{N_4}{N_3}$$

Figure 18: Gear Train Model to Determine Angular Speed and Torque

With respect to our project, this model pertains to the speeds and torque needed for our tank treads and how to obtain those values using multiple gears. The illustrated relationships can be used within the context of our project in order to obtain relevant design information to carry out our concepts. Specifically, we can use the known input torque to find the gear ratio and ergo gears needed to facilitate the desired output torque.

4.4.2 Engineering Model #2: Linear Torque/Speed Relationship of Brushed DC Motor

Figure 19 shows the relationship between torque(τ) and speed(ω) of a brushed DC motor.

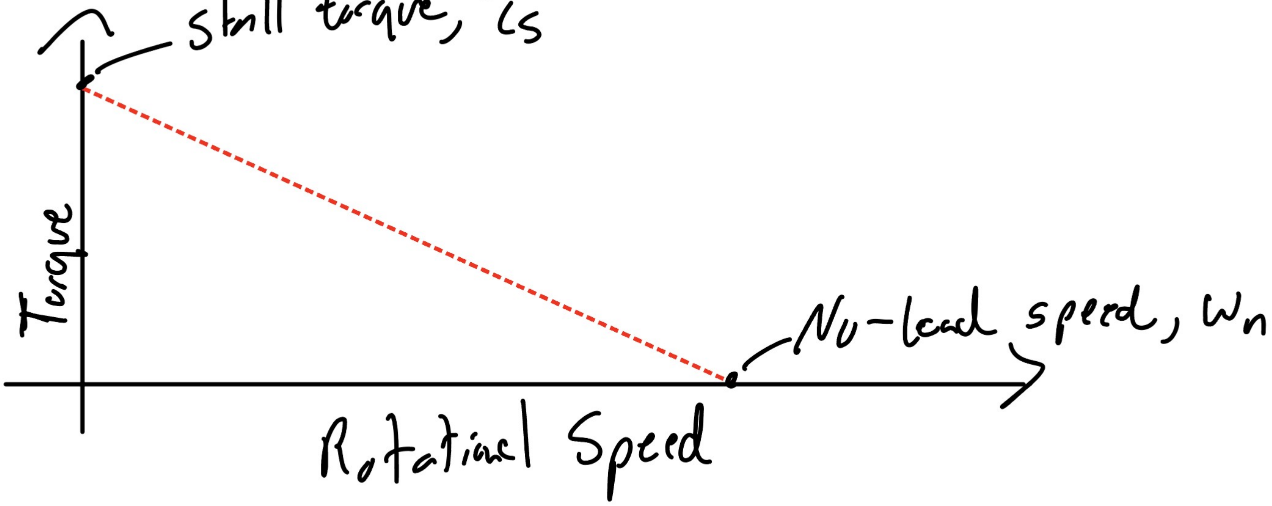


Figure 19: Relationship between Torque and Speed of a Brushed DC Motor

There is a linear relationship between these two variables. When the motor has zero rotational speed, it exerts its maximum torque, the stall torque(τ_s). When there is no load on the motor, the motor spins the fastest at its no-load speed(ω_n). This model pertains to the selection of the DC motors we might use to move our robot. we need to have enough torque to navigate obstacles and be able to move reasonably fast through the course. The stall torque and the no-load speed would likely be listed in the product specifications, and this information will help us compare different DC motor options. We will also use this information to determine the motor speeds we would like to use in order to generate the correct amount of torque in different scenarios.

4.4.3 Engineering Model #3: Flat Belt Pulleys

Below are two equations that relate the tension in pulley belts to the transmitted torque and the effect of the pulley angle of engagement and coefficient of friction to the belt tensions.

$$T_{transmitted} = (P_t - P_s)r \tag{1}$$

$$\frac{P_t - P_c}{Ps - P_c} = e^{\mu\phi} \tag{2}$$

In the first equation, $T_{transmitted}$ is the torque transmitted at the pulley, P_t is the tension in the taught belt, P_s is the tension in the slack belt, and r is the radius of the pulley. In the second equation, P_c is the centrifugal tension in the pulley, μ is the coefficient of friction between the belt and pulley, and ϕ is the angle of engagement of the belt on the pulley. These models are helpful because we are using tank treads on our robot, which can be modelled as a flat belt and pulley. We will be transmitting torque from the motors to the tank tread, and we can use the first equation to determine tensions in the different section of the tread. This will help us make sure we are transmitting enough force to navigate obstacles and make sure that the tread we choose is strong enough. The second equation is important in us deciding which wheel to power. The coefficient of friction will be the same for all wheels on the same tread, so we will select the wheel with the largest angle of engagement to power. The second equation will also help determine at what torques we may begin to see the wheel slip in the tank tread, which would be undesirable.

5 Concept Embodiment

5.1 Initial Embodiment

Figure 20 shows projected views of the robot assembly with some overall dimensions. Figure 21 shows a larger exploded view of the robot from a different angle compared to the first drawing. Figure 28 shows an exploded view of the robot with a bill of materials listing the different components used and their respective quantities. Figure 23 shows additional views of the exploded configuration of the robot assembly. This initial embodiment of the design will help us achieve our prototype performance goals. Our prototype performance goals are for the robot to move in any direction, stop on command, have a long battery life, climb over a wood 2x4, and have space for the striker.

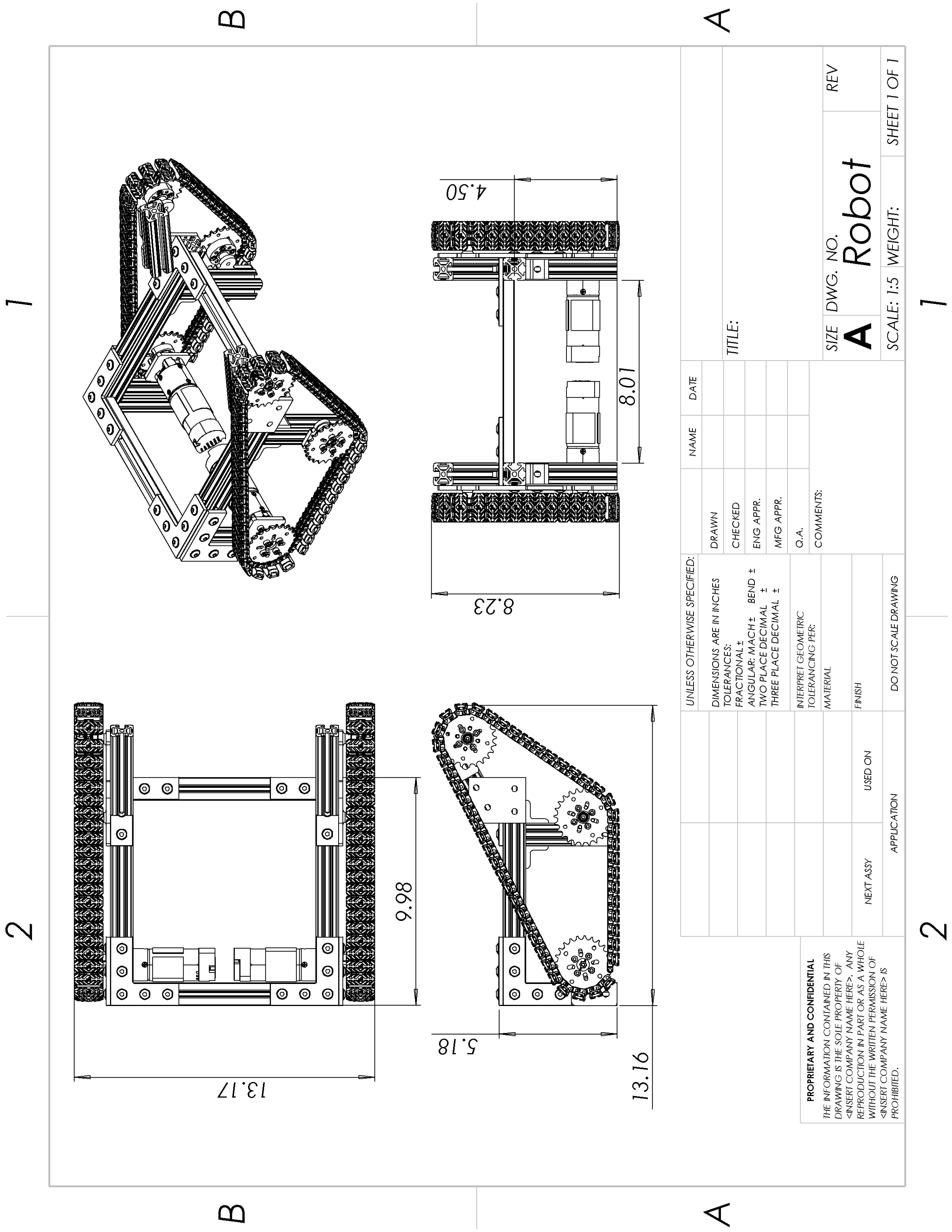


Figure 20: Assembled projected views with overall dimensions (inches)

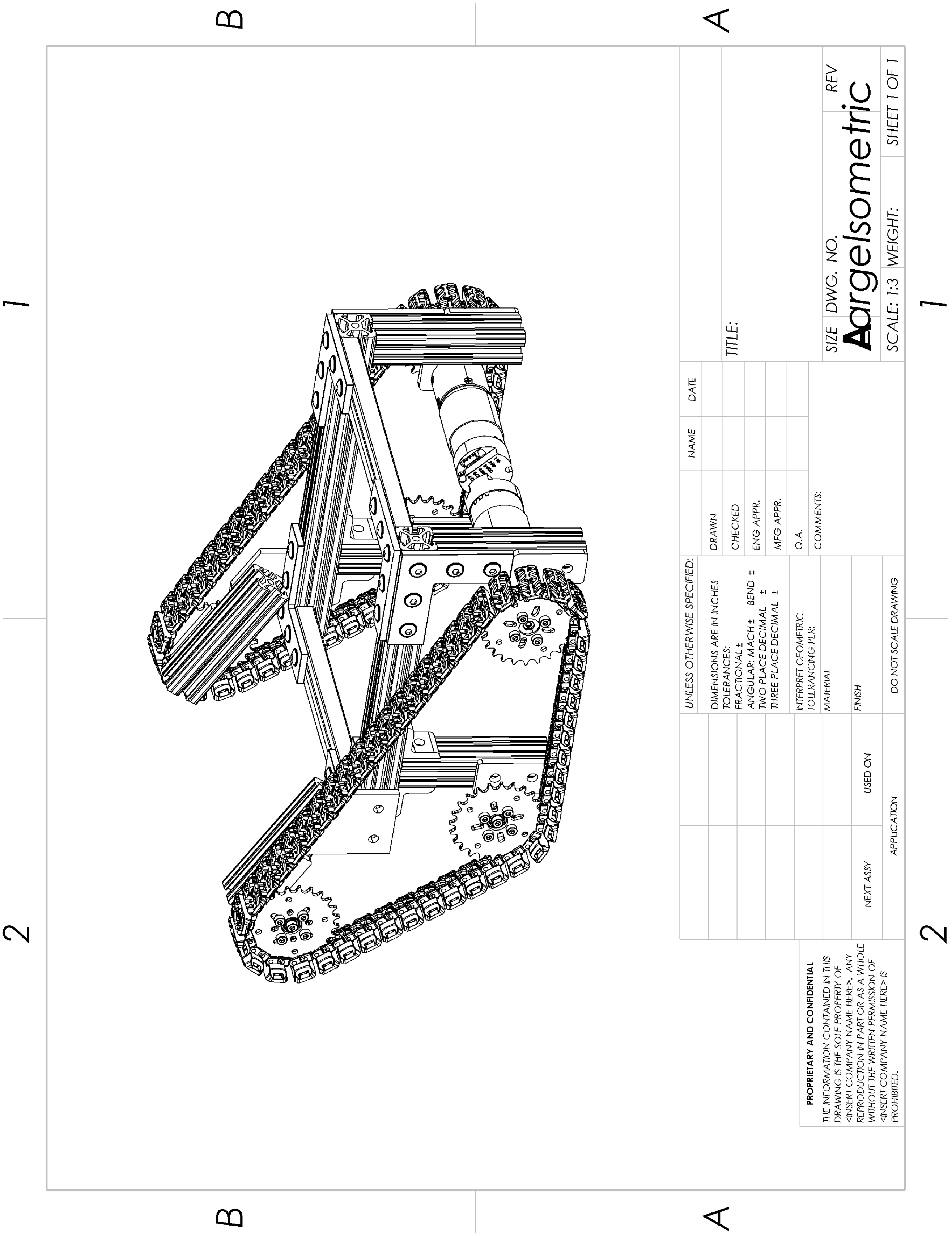
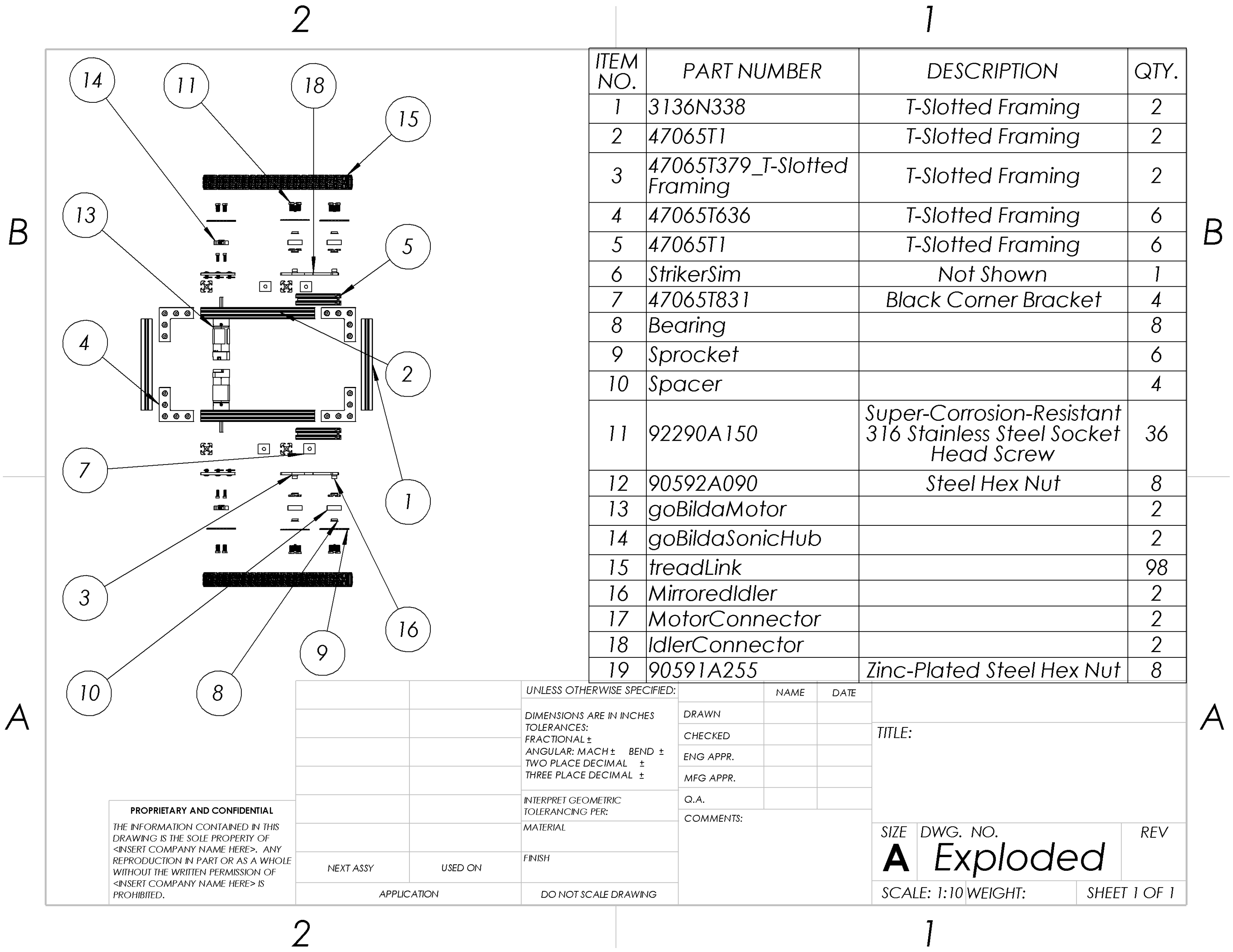


Figure 21: Assembled isometric view from a Different Angle



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	3136N338	T-Slotted Framing	2
2	47065T1	T-Slotted Framing	2
3	47065T379_T-Slotted Framing	T-Slotted Framing	2
4	47065T636	T-Slotted Framing	6
5	47065T1	T-Slotted Framing	6
6	StrikerSim	Not Shown	1
7	47065T831	Black Corner Bracket	4
8	Bearing		8
9	Sprocket		6
10	Spacer		4
11	92290A150	Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw	36
12	90592A090	Steel Hex Nut	8
13	goBildaMotor		2
14	goBildaSonicHub		2
15	treadLink		98
16	MirroredIdler		2
17	MotorConnector		2
18	IdlerConnector		2
19	90591A255	Zinc-Plated Steel Hex Nut	8

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY
USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE A
DWG. NO. Exploded
REV
SCALE: 1:10 WEIGHT: SHEET 1 OF 1

Figure 22: Exploded view with Callout to BOM

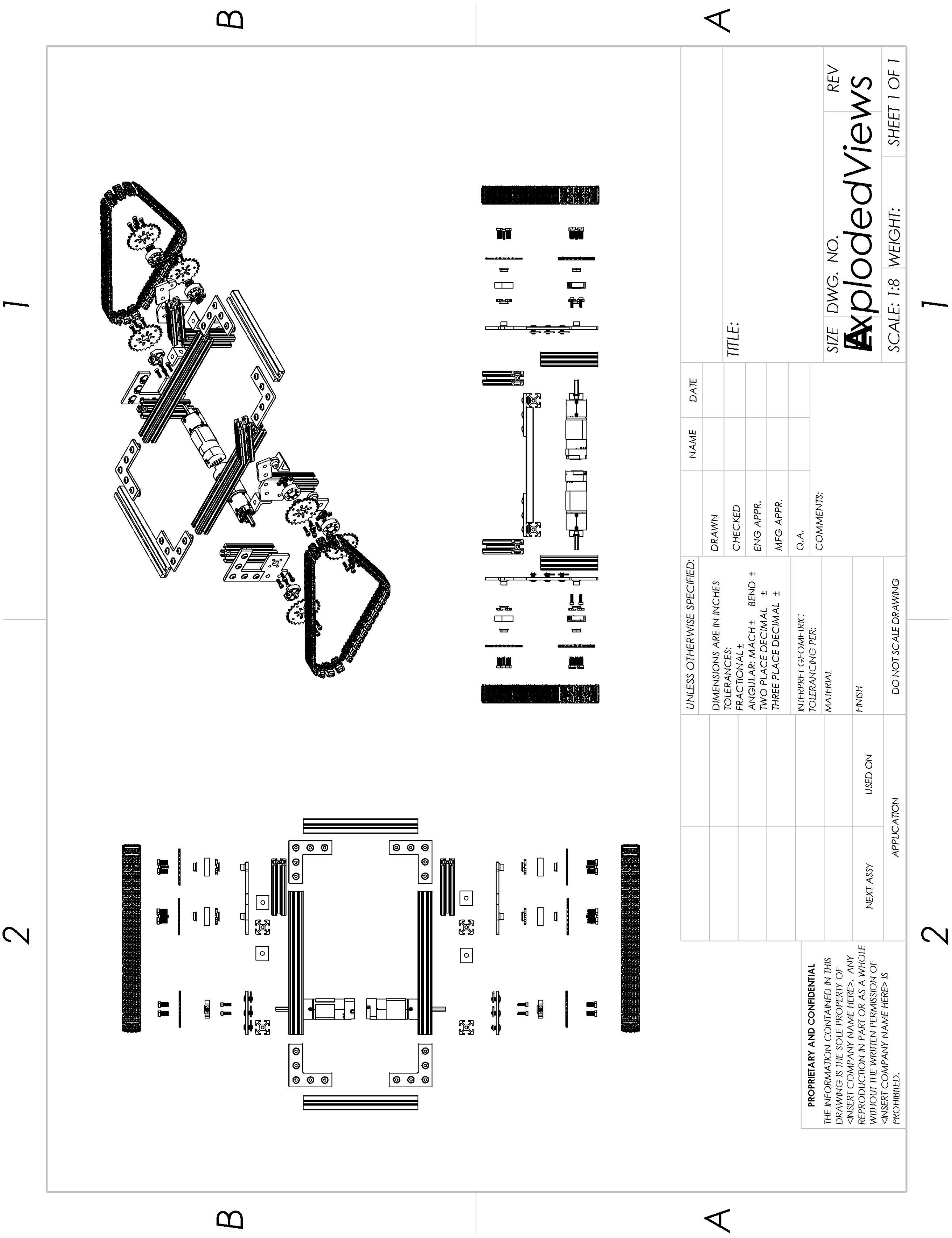


Figure 23: More Exploded Views

5.2 Proofs-of-Concept

On the controller side, our initial plan to use a micro-controller has not been affected through the process. The structure of our rover progressed similarly. The main impact that our proof of concepts had on our initial prototype was the the usage of wheels. When trying to use a wheel based rover to climb over the 2 x 4 obstacle in our initial proof of concept, we failed. This marked a major milestone in which we pivoted away from the usage of wheels and towards the usage of treads. From that point, we used the other prototypes to optimize the tread positioning leading up to the Initial Prototype.

5.3 Design Changes

Overall, our design did not change much compared to the selected concept in section 17. The treads were placed at a smaller angle with respect to the horizontal; this increased the amount of contact that the treads have with the 2x4 and decreased the vertical speed of the robot as it climbs over obstacles. We have also not yet implemented the Bluetooth receiver that will allow the robot to be controlled remotely; we are planning to install a BT-compatible Arduino to provide us with the necessary hardware and software to complete this goal. Additionally, we may change the striker placement from the original design, but this will depend on how we arrange the robot's onboard hardware once all of the components have been added.

6 Design Refinement

6.1 Model-Based Design Decisions

6.1.1 Linear Torque/Speed Relationship of a Brushed DC Motor

From our motor's data sheet, the no-load speed of the motor is 312 RPM and the stall torque of the motor is 24.3 kg-cm. We want to make sure that our robot can lift itself using the torque of the two motors so that the robot can lift itself over the obstacles in the course. The mass of our robot is 3.346 kg and the sprockets have a pitch diameter of 4.1 cm or a radius of 2.05 cm. The required torque is estimated as just the weight of the robot applied at the radius of the driving sprocket. This neglects that the force applied by the robot on the obstacle is not totally in line with the gravitational force on the robot, that there is additional thickness due to the thickness of the treads, and that the robot's weight is also supported at other points while traversing the obstacles. Thus, the required torque is (note that the gravitational constant is elided because of the units of torque used):

$$T_{req} = \frac{1}{2} m_{robot} r_{sprocket}$$

$$\mathrm{T}_{req} = \tfrac{1}{2} 3.346kg \times 2.05cm$$

$\mathrm{T}_{req} = 3.43kg \times cm$ (3)

The equation for the torque speed curve is given by:

$$\omega = \omega_n (1 - \frac{\tau}{\tau_s}) \tag{4}$$

Plugging in the required torque, the stall torque, and the no-load speed:

$$\omega = (312RPM)(1 - \frac{3.43kgcm}{24.3kgcm}) = 268.0RPM \tag{5}$$

Therefore, the robot can lift itself over the obstacles in the track while maintaining a large excess of rotational velocity. This also means it will have a large excess of torque at lower speeds. Thus, this model gives us the confidence that the motors we selected are powerful enough for the robot to navigate the course effectively.

6.1.2 Transmitted Torque within Flat Belt Pulley

The transmitted torque, $T_{transmitted}$, from the pulley is found using the no-load speed of 312 RPM, the known motor torque of 24.3 kg-cm, the motor sprocket diameter of 0.0205, and an estimated coefficient of friction of $\mu = 0.70$ between steel and rubber. Each set of treads has the motor placed where the maximum wrap around angle is, 160°. This is the top sprocket gear. To find the tension in the taught belt, P_T, the given motor torque was converted from 24.3 kg-cm to 0.0238 N-m. Then, it was divided by the sprocket gear radius of 2.05cm to give the tension in the taught belt to be $P_T = 1.161$ N. The centrifugal belt tension was found with the following relationship:

$$P_c = m'V^2 \tag{6}$$

Where m' is the mass per unit length of the tread and V is the velocity of the treads. m' is found by dividing the tread mass of 3.5 grams by tread pitch distance of 8mm to give a $m' = 0.4375kg/m$. V was found by converting 312RPM into a linear velocity of $0.669m/s$. The centrifugal belt tension was found to be $P_c = 0.2930$. The following equation solves for the slack belt tension, P_s

$$\frac{P_t - P_c}{Ps - P_c} = e^{\mu\phi} \tag{7}$$

$$\frac{1.161 - 0.2930}{Ps - 0.2930} = e^{.70*2.79} \tag{8}$$

This returns that slack tension $P_s = 0.425N$. To find transmitted torque, the following equation is used.

$$T_{transmitted} = (P_T - P_s) * r = (1.16 - 0.425) * .0205 = 0.015N \tag{9}$$

Therefore, the torque transmitted from our belt system is 0.015 N and we have a back slack tension of 0.425N.

6.2 Design for Safety

All devices can have risks associated with them, with varying levels of probability and severity. In order to prevent or mitigate these risks within our project, we must first identify and analyze the possible harmful effects of our rovers usage or failure. The following section documents and analyzes five important risks we have identified could appear within our project. These risks and their properties are then transferred over to a heat map that identifies the risks of highest priority. This heat map is included and the implied priority list of risks is enumerated below, concluding this section.

6.2.1 Risk #1: Pinch Points

Description: Due to the space constraints on the rover, the extruded aluminum frame is densely surrounded by brackets, sprockets, motors, and treads. The very tight and specific clearance between all of these parts leads to a lot of crevices in which the user risks being pinched.

Severity: The severity of these pinches is rather low and therefore marginal.

Probability: This risk can occur when any individual who is not familiar with the robot tries to touch it or play around with it, and therefore the likelihood of this happening is likely.

Mitigating Steps: The probability of this risk could be reduced by either including a more spacious frame and robot layout to eradicate all small crevices that could pinch appendages, or by introducing an outer shield around the finished product that blocks all access to any identifiable pinch points.

6.2.2 Risk #2: Robot Crash

Description: If the person driving the rover is doing so incorrectly or commits an error, the robot could run into a physical obstacle and crash.

Severity: Depending on the obstacle, the severity could change. Since the robot will not be moving at extremely fast speeds, and it has no extremely sharp edges, we would argue that the result of a slow blunt crash would be relatively marginal for the majority of the time.

Probability: Since the robot is incredibly receptive to the controller, even slight mistakes could cause crashes. That being said, we would assume those driving the robot would do so with pure intentions and would attempt to avoid crashing it at all costs. Given this, we would rate the likelihood as occasional.

Mitigating Steps: The simplest step we could take to mitigate this risk is reduce the speed of the robot across the board. This would let the driver have more control over the slower robot, and therefore reduce the likelihood of crashing. We could also put a protective foam around the outer border of the robot, to reduce the severity of the crashes.

6.2.3 Risk #3: Wires Short Circuit

Description: The majority of our electronics are coordinated with wires between the batteries, motors, ESP32, and motor shield. If any of the wires were to short within the circuit created, the electronics of the robot would cease to work at best, and could potentially spark or heat up at worst. **Severity:** The severity would be marginal. The electronics run on relatively low power, and the most likely effect of a wire shorting would just be the system failure.

Probability: We were very precise with the placement and wiring of the circuit pieces and would not expect any of the fastenings to come undone unless someone were to provoke it. Therefore the probability of this risk occurring is seldom.

Mitigating Steps: To mitigate the severity, we could implement fuses that break when wires attempt to short circuit or electric overloads occur. This would prevent any major sparks or harm coming from the risk itself. To mitigate the likelihood of the risk, we could solder the wires to their destined locations. This would reduce the frequency with which the wires detach and potentially short circuit.

6.2.4 Risk #4: Over-discharging LiPo Battery

Description: Using the battery too long could lead to voltage decreases below 3.6V which would induce permanant damage to the LiPo battery. Stalling the battery implies drawing more currant than the allowable amount of amp hours, which would kill the battery life.

Severity: The severity of this is negligible, as it would just lead to a dead/obsolete battery.

Probability: With the knowledge of these possible risks, we would avoid practices that would induce these system failures. As such, the likelihood of this risk is unlikely.

Mitigating Steps: To mitigate these risks, we could implement a battery voltage meter to monitor what voltage the battery is outputting. We could identify cutoff voltages to signify when it is time to recharge the battery. We could further mitigate the risks by limiting the functions of the motors (through coding control) such that they are never overdrawing the amperage from the battery.

6.2.5 Risk #5: Getting Digits Stuck in Treads

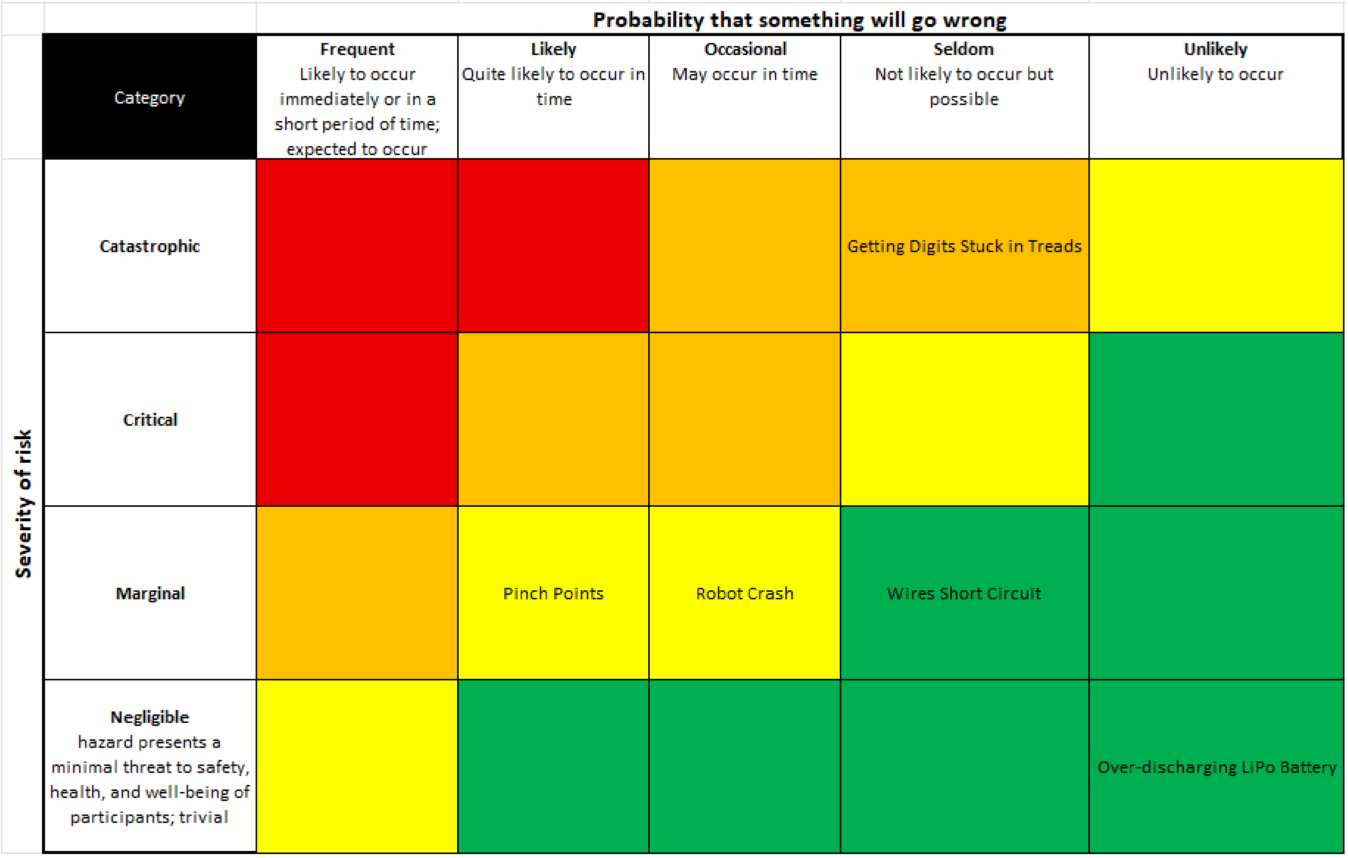
Description: If someone tries to move or touch the rover while it is in movement, their fingers could get caught in the treads and specifically in between the sprockets and treads.

Severity: The severity of this could be catastrophic, as the spinning sprockets could theoretically pin a finger against the tread and cut it open.

Probability: The probability of this is seldom, as most people would know not to touch the robot while it is moving, let alone place their fingers anywhere near the treads and sprockets close enough to get hurt in this manner.

Mitigating Steps: To mitigate the severity of this risk, we could require gloves be worn when physically handling the robot. We could also implement an emergency switch on the robot. Mechanically, we could implement a cutoff that activates when the motor stalls, implying something is caught in its path. To mitigate the likelihood of this risk, we could place shields around the treads and sprockets, or require usage education to all people that are handling our project.

The aforementioned information on potential risks was aggregated and added to an Excel Macro that documents the priority of these risks in the form of a heat map. This map is shown in Figure 24



		Probability that something will go wrong				
	Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Severity of risk	**Catastrophic**	🟥	🟥	🟧	🟧 Getting Digits Stuck in Treads	🟨
	Critical	🟥	🟧	🟧	🟨	🟩
	Marginal	🟧	🟨 Pinch Points	🟨 Robot Crash	🟩 Wires Short Circuit	🟩
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial	🟨	🟩	🟩	🟩	🟩 Over-discharging LiPo Battery

Figure 24: Heat Map of Potential Risks in Project

The heat map distinguishes the risks into 4 different tiers of priority: Red, Orange, Yellow, and Green. Giving this priority tiering, the fifth risk of getting digits suck in treads is the most important. Next on the priority list is the risk of pinch points, which is just as severe but more common than the following risk, crashing the robot. The last risks are both relatively inconsequential, as seen by the green tier in the heat map. They are the wires short circuiting and the LiPo battery being over discharged, in that order. With this heat map in mind, our team can work on risks present in our project in the priority order established here.

6.3 Design for Manufacturing

The current design has 163 components, 98 of which are tread links and 65 of which comprise the body and control system of the robot. The design has approximately 54 threaded fasteners. The theoretically necessary components are as follows: - Motors - The motors are necessary to power the treads and allow the robot to drive in any direction. - Breadboard/Arduino - Motor Driver - The Motor driver allows for a Bluetooth connection between an external remote and the robot, creating instantaneous response time and the ability to drive and control the device on command. - Lipo Battery (for motors) - Lipo Battery Holder - Computer Battery (for logic) - Treads - The treads allow the body of the robot to make contact with the ground and be driven forward. They are made of rubber and are designed to provide high-friction contact with the course surface. - Tensioners - Sprockets - Sprocket Axles

It would be possible to reduce the number of TNCs by creating one solid piece of aluminum to serve as the body; this shape would be a complex geometry and would be difficult to manufacture.

This would also reduce the number of threaded fasteners and 3D-printed connections between pieces of extruded aluminum- these connections between extruded aluminum parts can be clearly seen in the picture below.

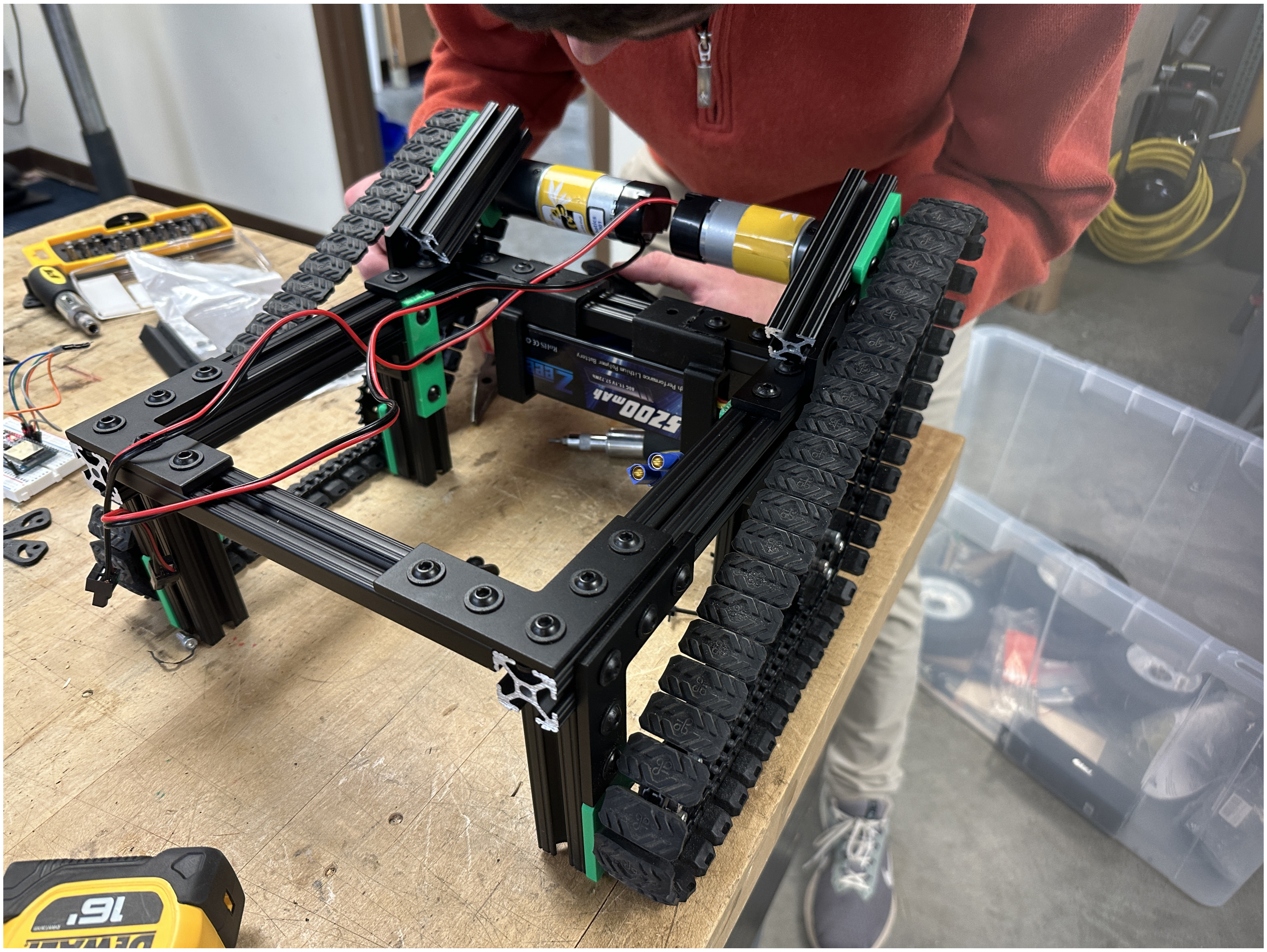


Figure 25: A clear view of the threaded fasteners that connect each piece of extruded aluminum. To reduce the number of TNCs, the entire body of the robot could be manufactured as 1 part.

6.4 Design for Usability

When engineering possible solutions to problems, one must consider who will be implementing the solutions. Furthermore, one must consider how physical differences between individuals could impair the usability for some. In this section, we will cover how some condition affect the usability of our project, and propose modifications that would improve the usability.

Vision Impairment: There are no aspects of the usage of our device that rely on the distinction of colors. For the usage of our rover, the entire setup could essentially be monochrome and none of the functions would be affected. The implementation aspect that vision impairment could affect would be one's ability to drive the rover. For proper controlled use of the rover, the user must have vision to the quality needed for them to confidently drive the rover about the course. Modifying this project to nullify this requirement could involve making the rover movements from position to position autonomous, and having them occur at the click of a button. This would drastically decrease the control an individual has over the rover's movement, but would allow someone with impaired vision to still utilize this rover.

Hearing Impairment: Hearing impairment would not affect the usage of the rover at all. Other than an emergency situation in which alarms are sounded, there are no aspects of rover utilization that involve any hearing. Driving the rover solely involves hand-eye coordination, and deciding where the rover should go solely involves forethought and planning.

Physical Impairment: Physical impairments could have effects on the usage of our project. Since the rover is controlled by the Bluetooth connection to an Xbox Controller, sufficient ability to control the Xbox Controller is needed to move the robot. As such, physical impairments that limit controller usability could affect our project. To design against this impairment, either the sensitivity of the controller could be increased such that less movement (and ergo force) on the controller is necessary to move the rover, or an alternate controller could be used. Since the base movement of the rover simplifies down to 2 treads moving either forwards or backwards, an easier mechanism that can perform these 4 commands would also suffice. An example of this could be 4 buttons, each moving a tread side in a direction at a specific speed.

Control Impairment: Since our rover is relatively small, there is not a huge blunt force damage concern from impaired driving. To design against possible errors resulting from impaired driving, there could be pressure sensors added to the rover's outer frame to track its movement difficulty against any obstacles in its path. Then, any sensing of prolonged movement difficulty (implying a crash, incorrect controlling, or system failures) could signal an emergency stop to prevent further damage. Furthermore, due to the treads and motors, there are a few pinch points on the rover. Thus, impaired setup and touching of the rover could lead to individual injury. To design against this, we could create a frame that surrounds all of the pinch points to prevent an individual's ability to insert any appendages in there.

6.5 Design Considerations

Table 3: Factors considered for design solution

Design Factor	Applicable	Not Applicable
Public Health		X
Safety	X	
Welfare		X
Global		X
Cultural		X
Societal		X
Environmental	X	
Economic	X	

Table 4: Contexts considered for ethical judgments

Situation	**Applicable**	**Not Applicable**
Global context		X
Economic context	X	
Environmental context	X	
Societal context		X

7 Final Prototype

7.1 Overview

After the design refinement stage, the project was further altered to bring the extruded aluminum body up further off the ground. New 3D-printed parts altered the design of the wheel assembly and called for a longer linkage of treads. Unfortunately, although these design changes minorly increased the vehicle's chances of fully traversing the 2x4, the alterations caused an issue where a tread would jump off one of the sprocket teeth and completely come off the device. There are certainly ways to keep improving the design and ensuring that it fully completes each final performance goal to the best of its ability.

7.2 Documentation

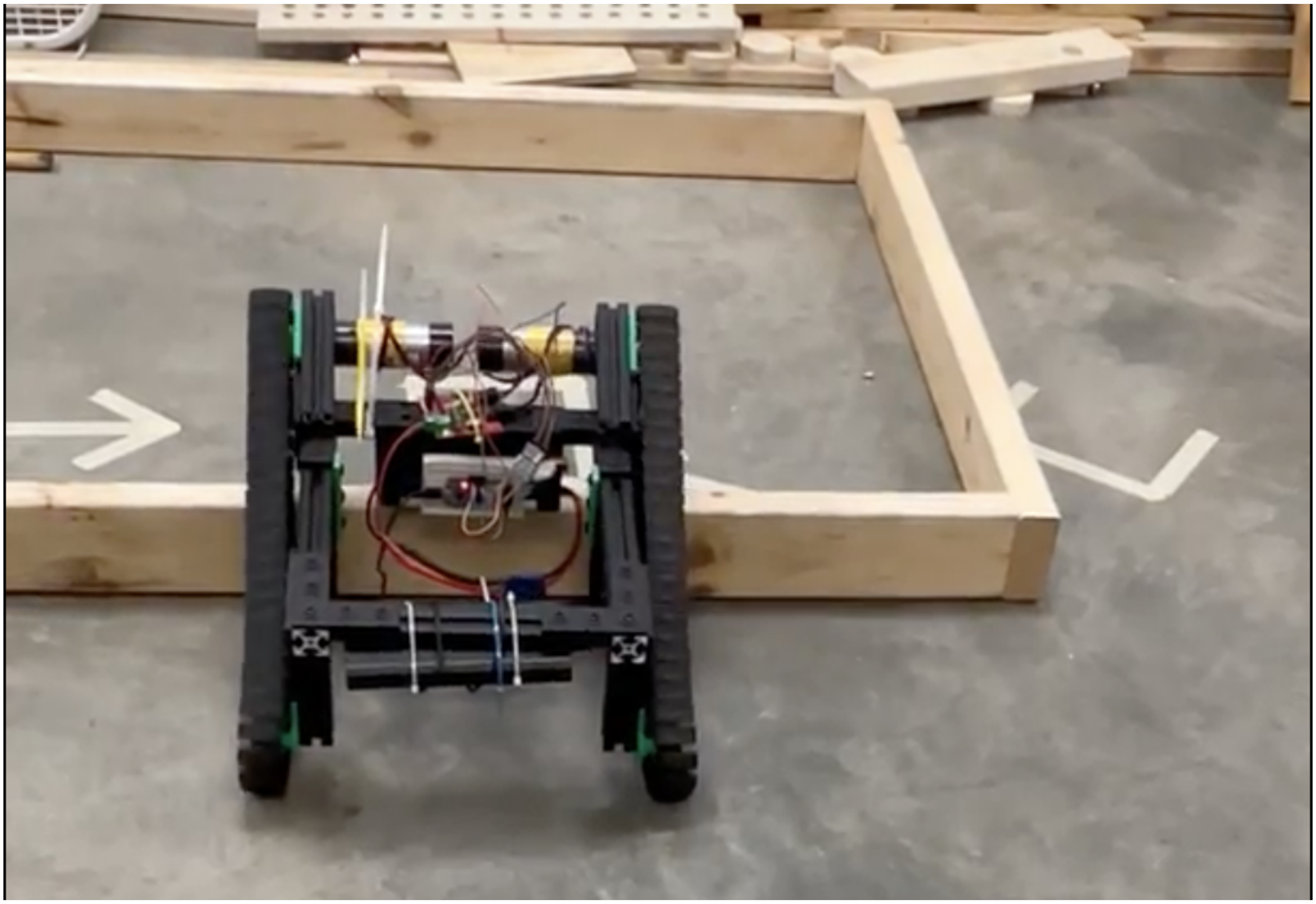


Figure 26: The robot attempting to complete Prototype Performance Goal 1 (traversing a 2x4).

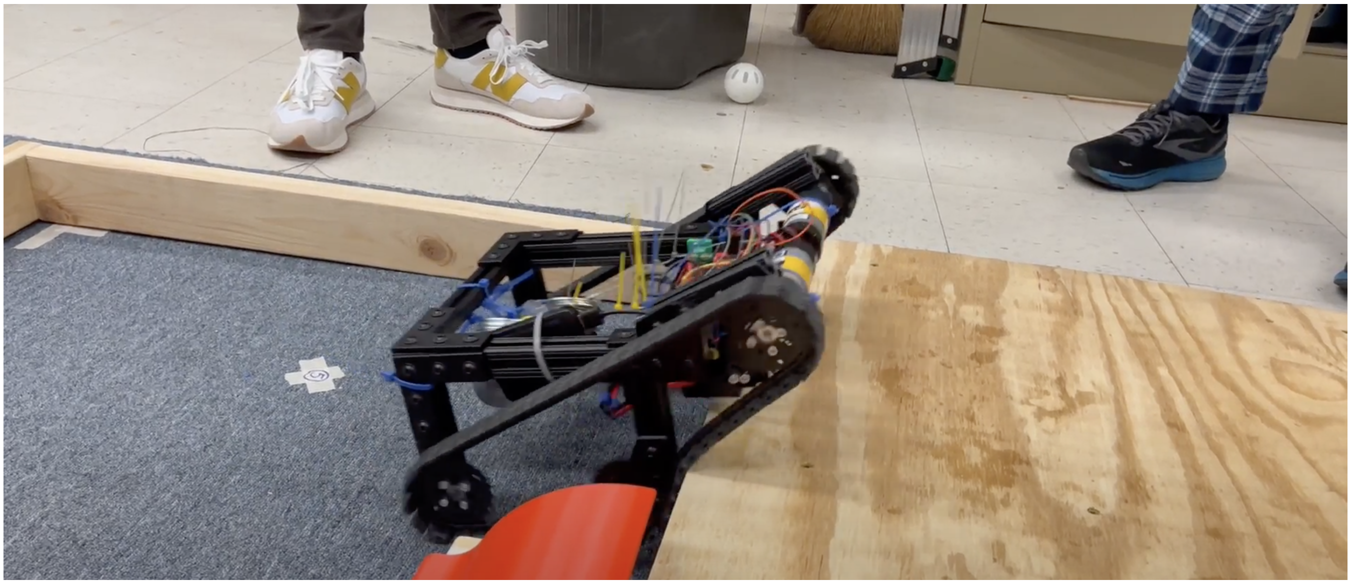


Figure 27: The robot attempting to complete Prototype Performance Goal 2 (traversing a piece of plywood).

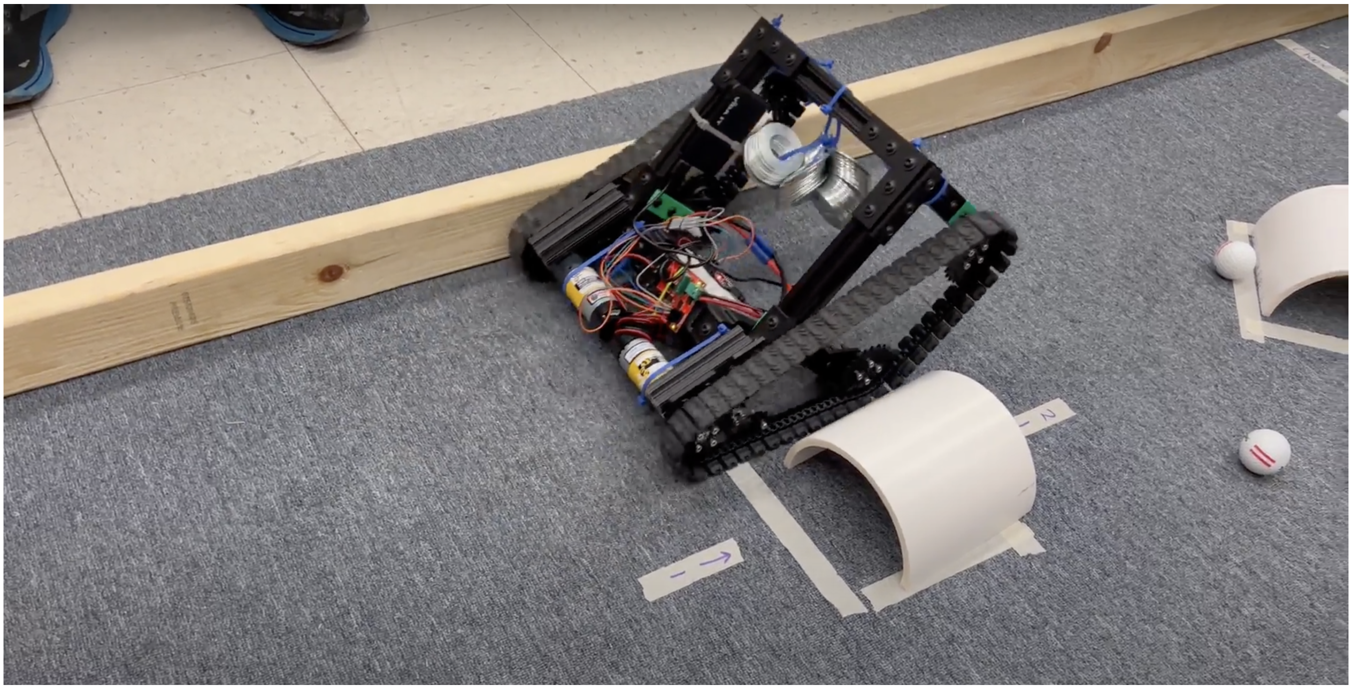


Figure 28: The robot successfully completing Prototype Performance Goal 3 (manuvering around the course).