Fall 2023

MEMS 411: Mini-Golf Robot Vehicle

Catherine Huang
Washington University in St. Louis

Shicheng Li
Washington University in St. Louis

Colin Chen
Washington University in St. Louis

Maximilian Li
Washington University in St. Louis

Recommended Citation

Huang, Catherine; Li, Shicheng; Chen, Colin; and Li, Maximilian, "MEMS 411: Mini-Golf Robot Vehicle" (2023). *Mechanical Engineering Design Project Class*. 209.
https://openscholarship.wustl.edu/mems411/209

Washington University in St. Louis
JAMES MCKELVEY SCHOOL OF ENGINEERING

Mechanical Engineering Design Project
MEMS 411, Fall 2023

Mini-Golf Robot Vehicle

The project focused on developing a remote-controlled mini-golf robot for the ASME Student Design Competition. Due to the complexity of the project, our group aims to design and construct the vehicle base for navigating the mini-golf course with various obstacles. The project demands a comprehensive understanding of customer needs, mechanical design, control systems, and strategic planning to ensure optimal performance.

Our project involved detailed research into existing devices and patents to guide our design process. We undertook a comprehensive user needs assessment and generated multiple concepts, evaluating them based on cost, fabrication difficulty, and usability. The most viable design, a tank-style model, was further refined and prototyped. We utilized 3D printing for the main structure, ensuring a direct translation of our SolidWorks designs into physical form. The electronic system was designed for remote control via a smartphone app. Assembling the 3D-printed parts, which took over two weeks, involved numerous minor design tweaks to enhance performance. The final prototype demonstrated excellent mobility, capable of moving smoothly in all directions and overcoming obstacles like a 1.5-inch thick and 3.5-inch tall wooden board.

Throughout this process, we focused on ensuring that our design was safe, manufacturable, and user-friendly. These principles were pivotal in transforming our initial ideas into a functional prototype capable of completing our performance goals.

HUANG, Catherine
CHEN, Colin
LI, Maximilian
LI, Shicheng

Contents

List of Figures

List of Tables

1 Introduction

The primary objective of the project is to develop a remote-controlled vehicle capable of completing a round of mini golf as part of the ASME Student Design Competition. The vehicle's functionalities are categorized into driving and golf-ball striking. Our group is specifically responsible for the former aspect.

The remote-controlled vehicle is expected to traverse through the designated competition field and exhibit the ability to maneuver between and over obstacles, including a high wall and a low platform. Our design should adhere to the competition regulations set forth by ASME SDC, which include specific criteria for the vehicle such as size limitations, battery restrictions, and the prescribed method of remote control [1]. Successful completion of this project also necessitates collaboration with a striking group. This collaborative effort is crucial for the development of a multifunctional vehicle capable of accomplishing a wide range of tasks as demanded.

2 Problem Understanding

2.1 Existing Devices

There are existing devices that are already able to complete our tasks, below are examples of two golf robots and one climbing vehicle.

2.1.1 Existing Device #1: Golfi

Figure 1: Golfi (Source: Website)

Link: https://spectrum.ieee.org/golf-robot-putts-like-pro

Description: The Golf Robot, also called a Golfi, developed at Paderborn University in Germany, uses a 3D camera to take a snapshot of the green, which it then feeds into a physics-based model to simulate thousands of random shots from different positions. These are used to train a neural network that can then predict exactly how hard and in what direction to hit a ball to get it in the hole, from anywhere on the green. Researchers at Paderborn University in Germany report that Golfi makes 70 percent of its putts but didn't specify how long the putts were.

2.1.2 Existing Device #2: Rob-OT

Figure 2: Rob-OT (Source: Website)

Link: https://rob-ot.com/
Description: The Rob-OT is the first Robot Golfer to become a member of a country club at Fairbanks Ranch. It aces hole 16 at the Phoenix Open. It can strike and put golf balls, and it also has four wheels to move with the ball. Rob-OT can play from tee to green and also become a golf educator at Fairbanks Ranch.

2.1.3 Existing Device #3: B2P2 UVG

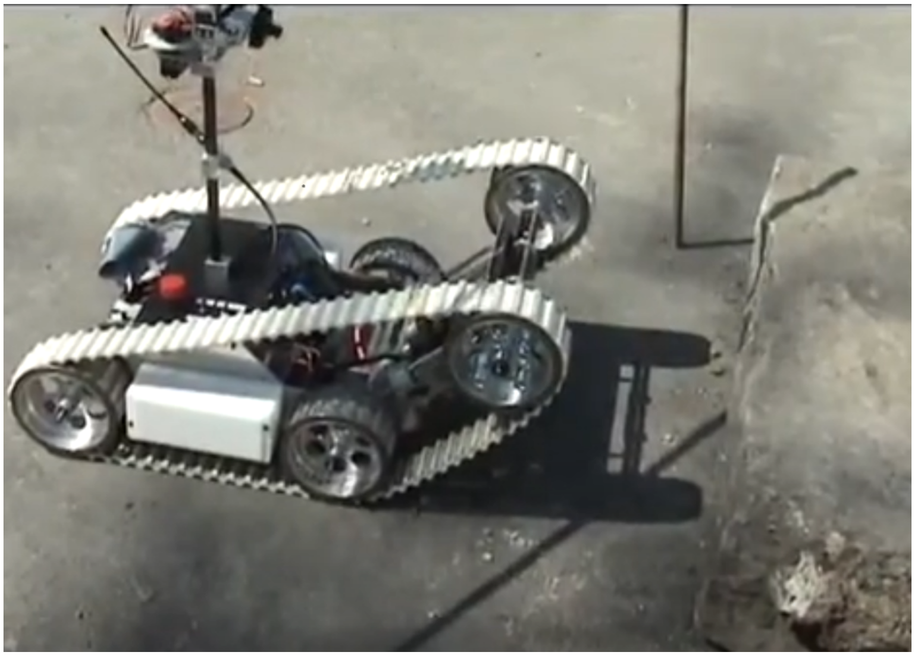


Figure 3: B2P2 UVG (Source: Website)

Link: https://lucidar.me/en/projects/b2p2-variable-geometry-unmanned-vehicle/
Description: The B2P2 is an Unmanned Ground Vehicle (UVG) and is based on an original mechanical architecture: it can change its shape according to the obstacle it has to pass through. This UVG has been designed to increase its clearing capabilities. It is able to pass through a wide range of obstacles like stairs, ramps, bumps, and curbs. It can also explore buildings in order to ensure some recognition. It is equipped with a video camera, and a 2.4 GHz wireless transmission allows one to visualize the pictures captured by the UVG from afar. A compass and a GPS sensor are embedded in order to obtain positive information. Sensors are used to control the robot's posture and provide useful information to the operator. Computer PC 104 is embedded to supervise control and communication. Microcontrollers are used to locally control the DC motor.

2.2 Patents

2.2.1 Variable configuration articulated tracked vehicle (US7600592B2)

This patent uses a tracked vehicle with a configurable arm mechanism. On both sides of the chassis, the drive pully is rotatably attached to the chassis, and a planetary wheel is attached to the chassis through the rotatable arm mechanism. The track extends around the pully and the planetary wheel. The arm is connected to the chassis through a camshaft to ensure the track length of the planetary wheel is constant. Power to the track is provided through pully motors on both sides. The center of gravity of the vehicle should be monitored by an inclinometer and adjusted accordingly. [2]

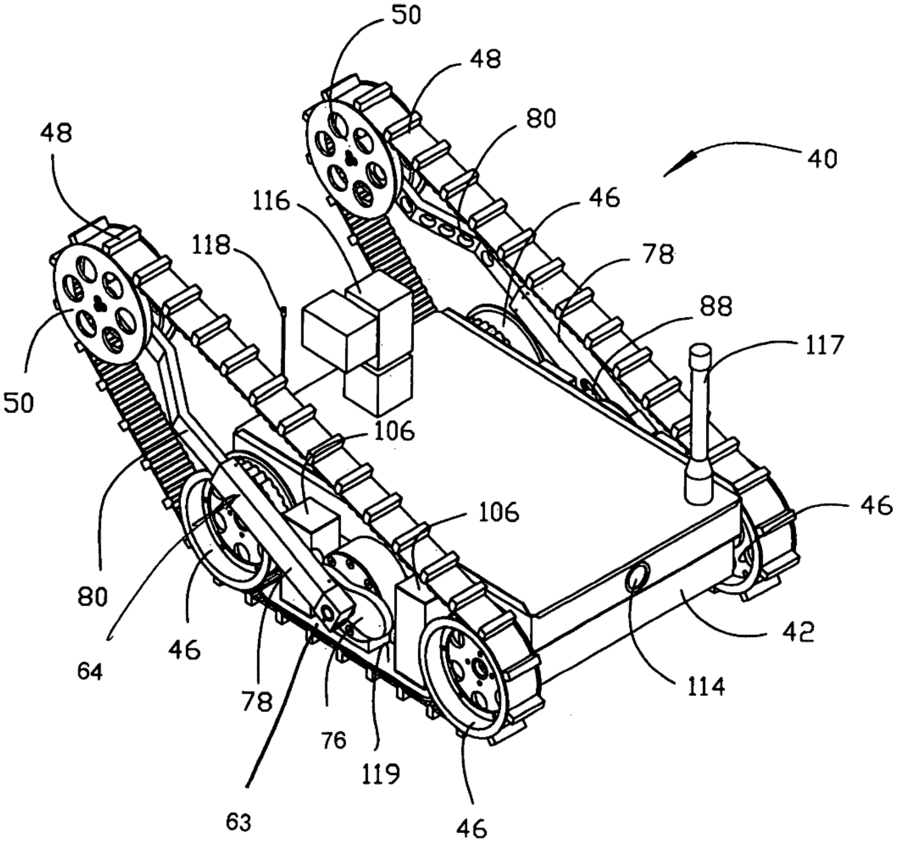


Figure 4: Patent Images for variable config. tracked vehicle

2.2.2 Suspension system for track vehicle (US7552785B2)

The patent describes a tracked system with a plurality of suspension modules which forced the contact of the track and the ground. Two idler wheels expand the track and may be in contact with the ground when during selected conditions. The suspension module consists of a wheel and a leaf spring, which is rigidly connected to the frame. [3]

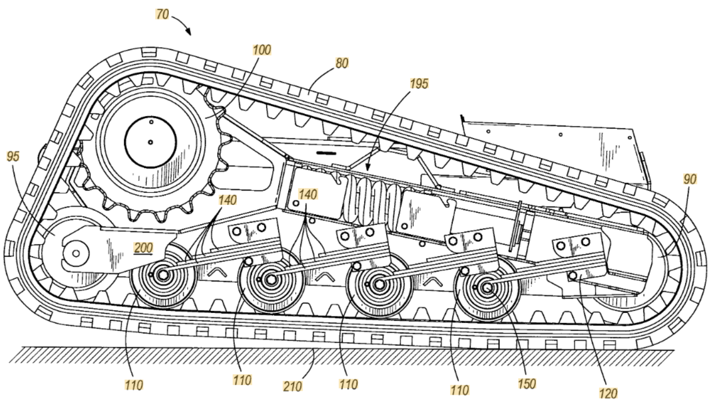


Figure 5: Suspension system for track vehicle

2.3 Codes & Standards

2.3.1 Children's Product Safety Standard (ASTM F963-17)

ASTM F963-17 is a safety standard for toys, providing guidelines for mechanical, electrical, and material safety. If an electric vehicle is used for recreations, such as mini-golf, it should comply with this standard. This ensures the safety of the vehicle's design, components, and materials, as well as age-appropriate labeling and warnings. Compliance with ASTM F963-17 helps minimize potential hazards and risks associated with the use of the electric vehicle as a toy.

2.3.2 Standard Test Method for Navigation: Defined Area (ASTM F3244-21)

The standard defines the test method for evaluating an autonomous unmanned ground vehicle's (A-UGV) capability to traverse through a 2D terrain representative of the common working conditions of such vehicles. The vehicle should exhibit the capability of navigation, object avoidance, and precision. The test can be scaled and adapted for vehicles of different sizes and tasks.

The test standard could provide a helpful framework for us to evaluate how our RC vehicle could efficiently move across the competition terrain. The precision testing aspect also allows us to assess the accuracy of the vehicle movement.

2.4 User Needs

The following rules from the competition rules brochure are selected and demonstrated here as the "requests from customers"

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Hillman 60, Washington University in St. Louis, Danforth Campus
Date: September 08th, 2023
Setting: The interview was conducted in the lecture hall with all groups with the intent of completing the same project present. True-scale models of game elements were shown. Tasks were categorized into driving and striking. We decided on whether to form a "supergroup" or reconvene later in the semester. Due to the need for coordination between different groups, we were given some instructions on how to make sure our product could be compatible with each other.

Interview Notes:

- There is a board over the top of the 2in x 4in wall, and it is unrealistic to go under the board because the vehicle would be too small
- One possible design is that the striker is designed such that it can be inserted to the front of the vehicle. If collaborating with a striker design group which favors this design, the designed vehicle of our team need to stay tuned to this design as well.

2.4.2 Interpreted User Needs

The target customer for this product is mainly the judges and spectators of 2023-2024 ASME Student Design Competition. Subsequently, the following rules from the competition rules brochure are selected and demonstrated here as the "requests from customers" [1]. The number at the end of each sentence represent the importance of each need:

a. Sizing

1. The device (vehicle + striker) should be as small as possible, fitting within a rigid sizing box with maximum internal measurements of 50cm by 50cm by 50cm (a Sizing Box bonus is awarded). [5]
2. Devices may expand beyond their initial size after being taken from the sizing box, but may not at any time become larger than 100cm in any orientation when operating at full reach. [2]

b. Device Details

1. Once an obstacle has been completed, the device must navigate the field and align itself with the golf ball at the next tee. [3]
2. The rules were developed with the spirit of the game in mind, which 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. [1]
3. The vehicle must be able to pass a leveled obstacle (see Figure 4 [1]) [4]
4. The vehicle must be able to climb over a 4" wall. [4]

c. Control Details

1. If device operation is powered by batteries, the batteries must be rechargeable. [3]
2. Only one team member can be allowed to control the device when the clock is started. [1]
3. The devices must be controlled either via remote control through a transmitter/receiver radio link or through an umbilical cord (tether). [2]

2.5 Design Metrics

Following the user needs that we derived from the customer interview, we compiled a list of target specifications that we consider vital in the completion of the project.

Table 1: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	a.1	Total volume	cm^3	<50x50x50	<50x50x20
2	a.2	Total extended length	cm	<100	<100
3	b.3, 4	Maximum obstacle height	in	>3.5	4
4	b.1	Operating time	min	<10	>10
5	c.1	Number of battery	#	No limit	1

2.6 Project Management

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

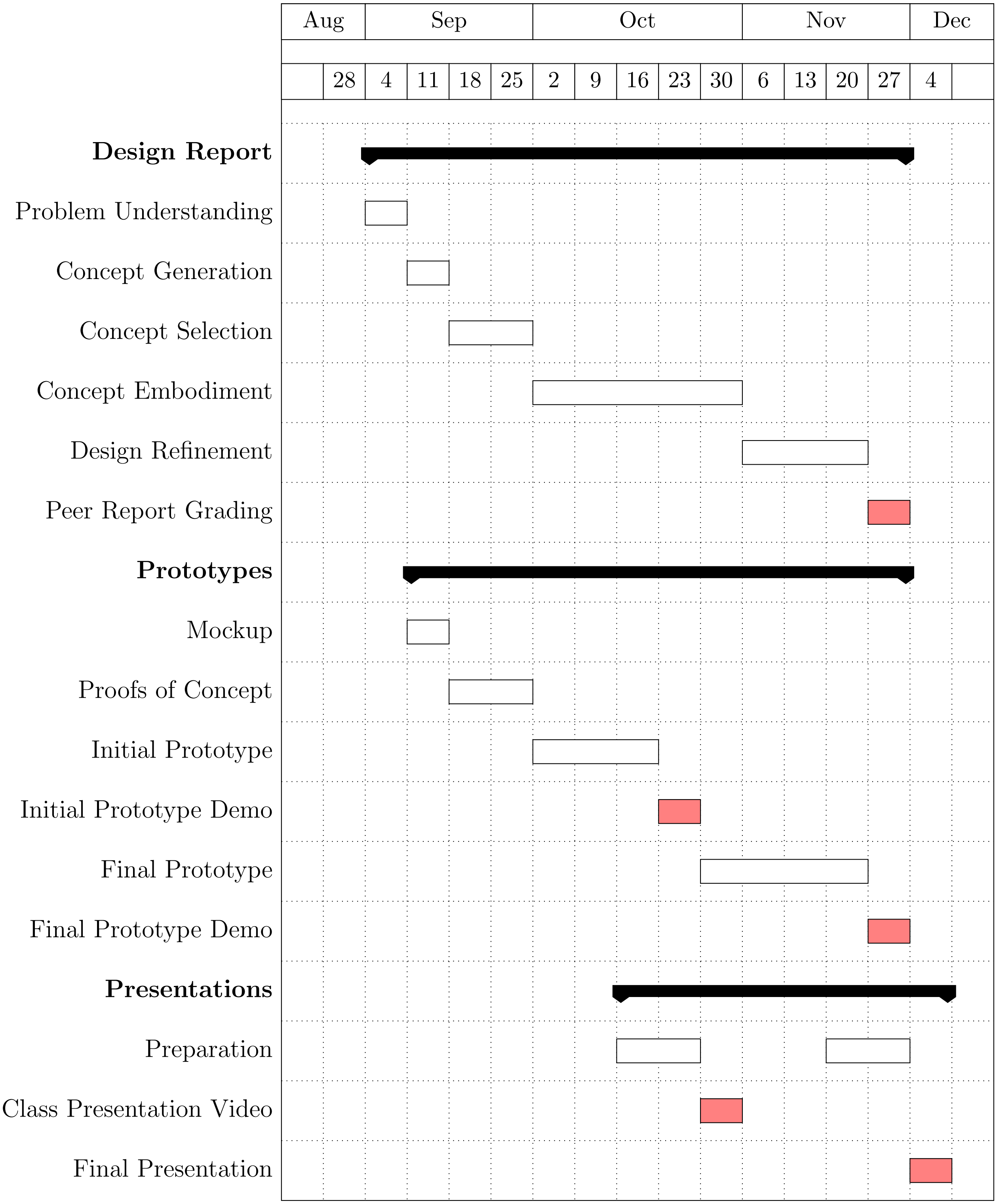
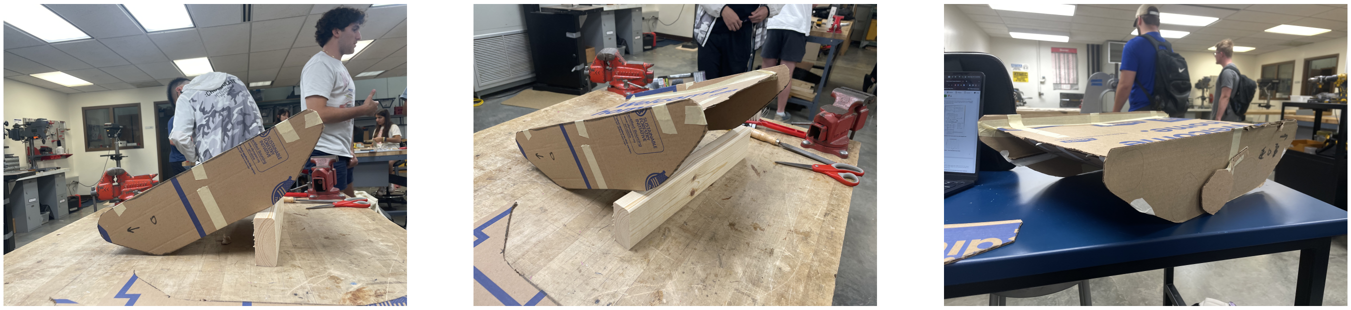


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype



(a) Side view

(b) On the wall

(c) Mock suspension wheel

Figure 7: Cardboard Mock-up of Mini Golf Robot Chassis

We constructed a 1:1 mock-up of the mini golf robot chassis. A rough outline of the side profile of the tank chassis is drawn out on the cardboard with a length measured to be about 50 cm. The shape is cut out and duplicated. The two sides of the chassis are connected with a 40x50 rectangular cardboard. The mockup helps us to understand the dimension relations between our robot and field elements. The position of the front driving wheel would affect the ease at which the track could catch onto the wall/platform. The angle between the back of the chassis and the ground would heavily determine if the robot would tip over when climbing, thus lowering this angle becomes one of our priorities. We also find that reducing the thickness of the chassis would also reduce the moment arm of the center of gravity. Considering that the front wheels still need to be positioned at a relatively high position, we would approach thickness reduction by adding suspensions to the middle support wheels.

3.2 Functional Decomposition

Figure 8 shows the function decomposition of the mini golf robot chassis. We considered the mobility of the car and the ability to complete game tasks to be vital functions of the vehicle chassis.

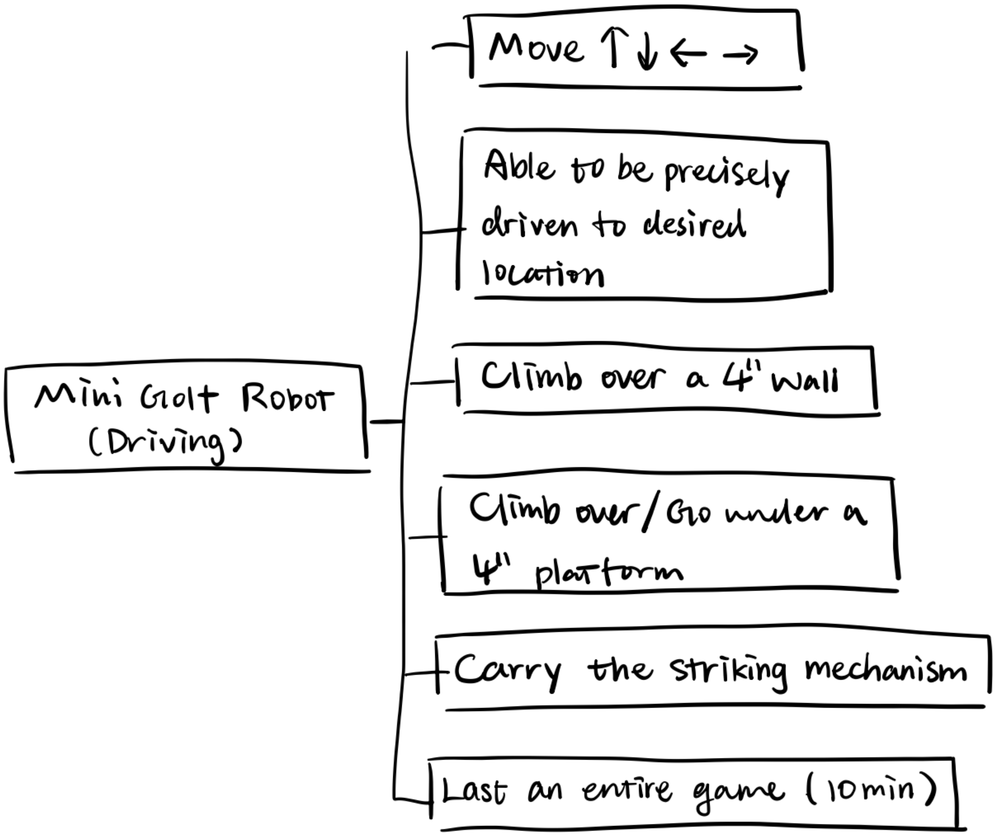


Figure 8: Function tree for Mini Golf Robot Chassis

3.3 Morphological Chart

Figure 9 is the morphological chart derived from the corresponding function tree. The morph chart includes 2-4 designs for each function to be realized.

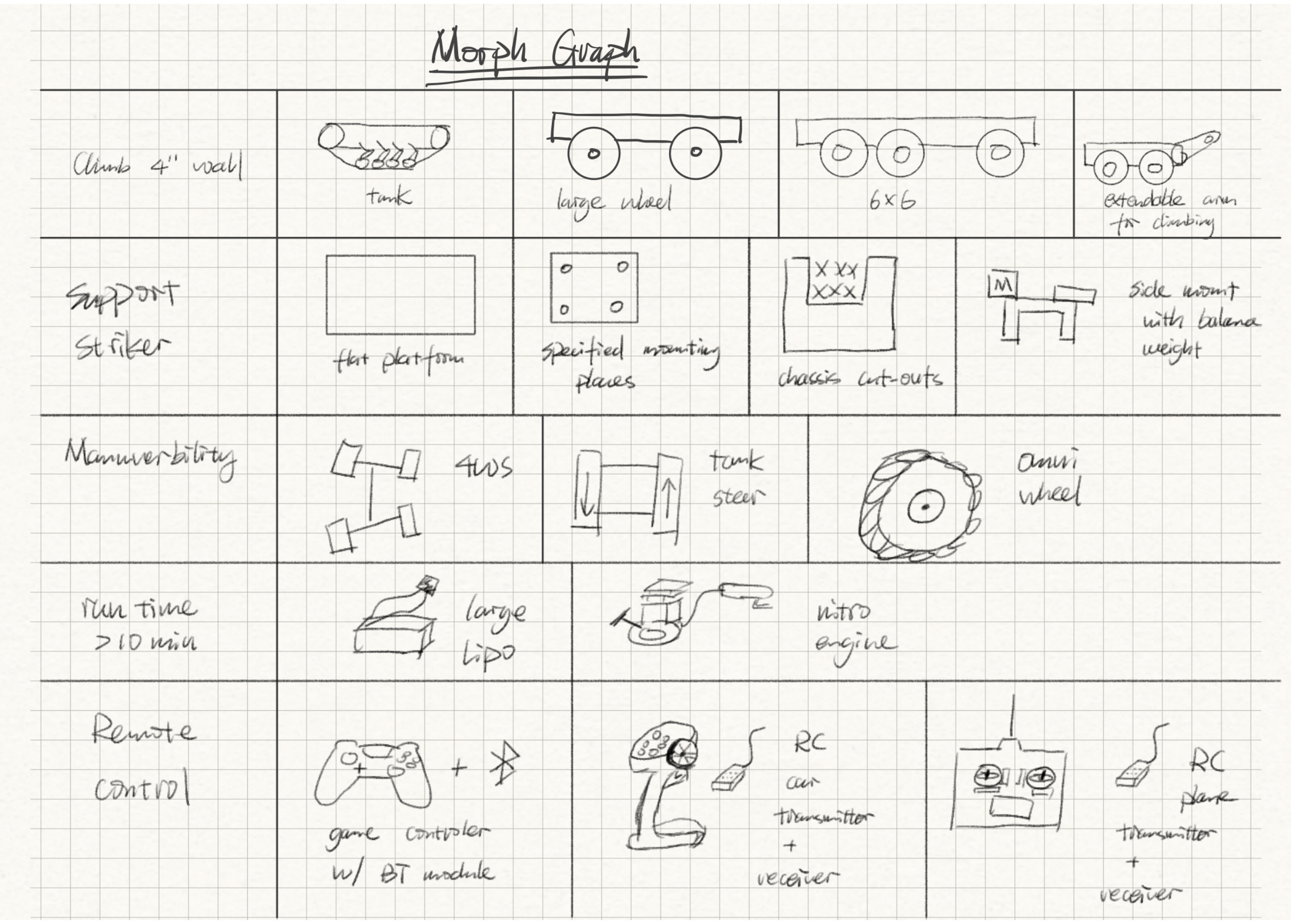


Figure 9: Morphological Chart for Mini Golf Robot Chassis

3.4 Alternative Design Concepts

The following are four full concepts for the mini golf robot chassis, with functions labeled and brief descriptions.

3.4.1 Concept #1: Triangle Wheel

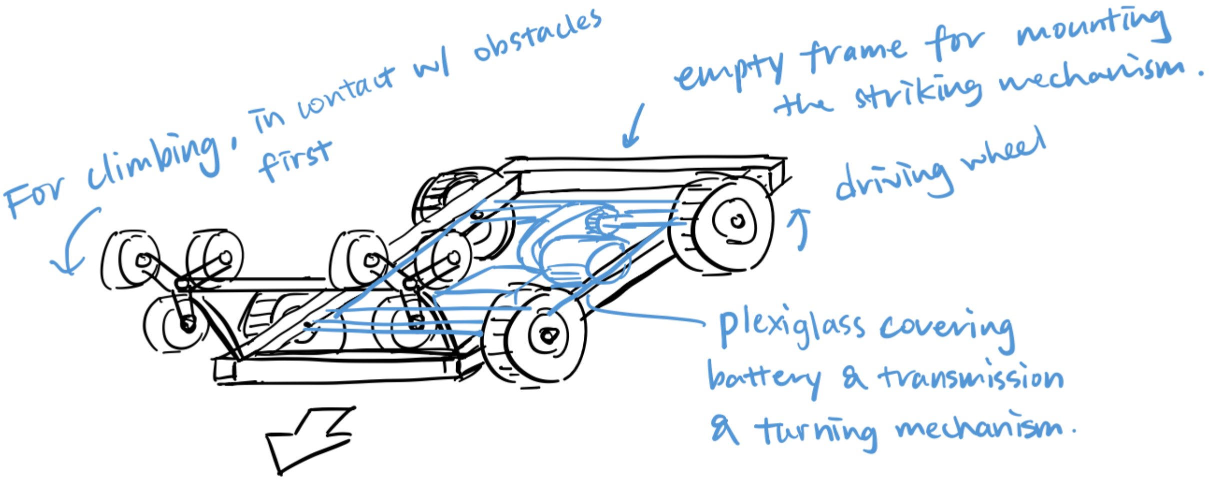


Figure 10: Sketches of Triangle Wheel Chassis Concept

Description: Four moderately sized wheels are mounted to an aluminum frame, which has multiple holes in it for mounting of the striking mechanism. Power will be provided by a motor to the back wheels, and a turning mechanism and a servo motor determine the angle of the front wheel. A piece of plexiglass or acrylic plate covers the middle of the frame with the battery, motors, and radio receiver attached to the bottom, as well as provides partial support for the striking mechanism. Two triangular wheelsets are attached to the front of the car at an angle, which will be able to "catch" onto the edge of the platform and wall, thus climbing over the obstacles with a decent amount of driving power.

3.4.2 Concept #2: Bisected Chassis

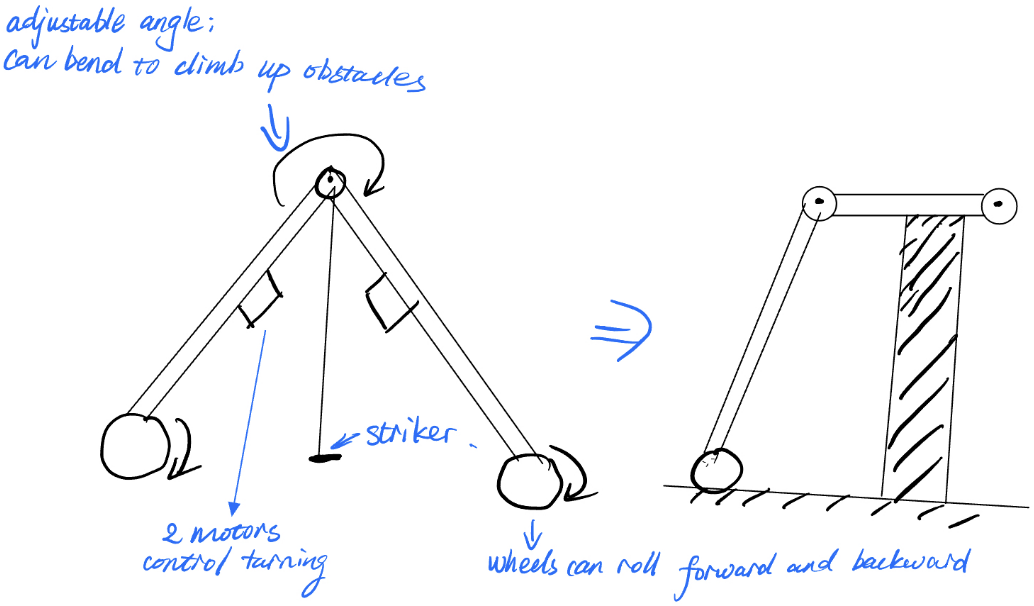


Figure 11: Sketches of Bisected Chassis

Description: Four wheels are placed to a frame which is bisected into two parts, connected by a joint. The power will be provided by two motors to facilitate the movement of the front and back wheels (4 in total). The joint will be controlled by another servo motor. All three motors were powered by a battery(not in the side view) in on the other side of the vehicle. When met with obstacles, the motor can open the angle of the joint, such that the front arm can climb up the obstacle. After climbing over the obstacle, the motor can control to shrink the angle, such that the vehicle can move forward normally using its four wheels. The joint also holds the striker, potentially, so that the striker will move along with the vehicle in the same direction of displacement.

3.4.3 Concept #3: Battle of Hillman

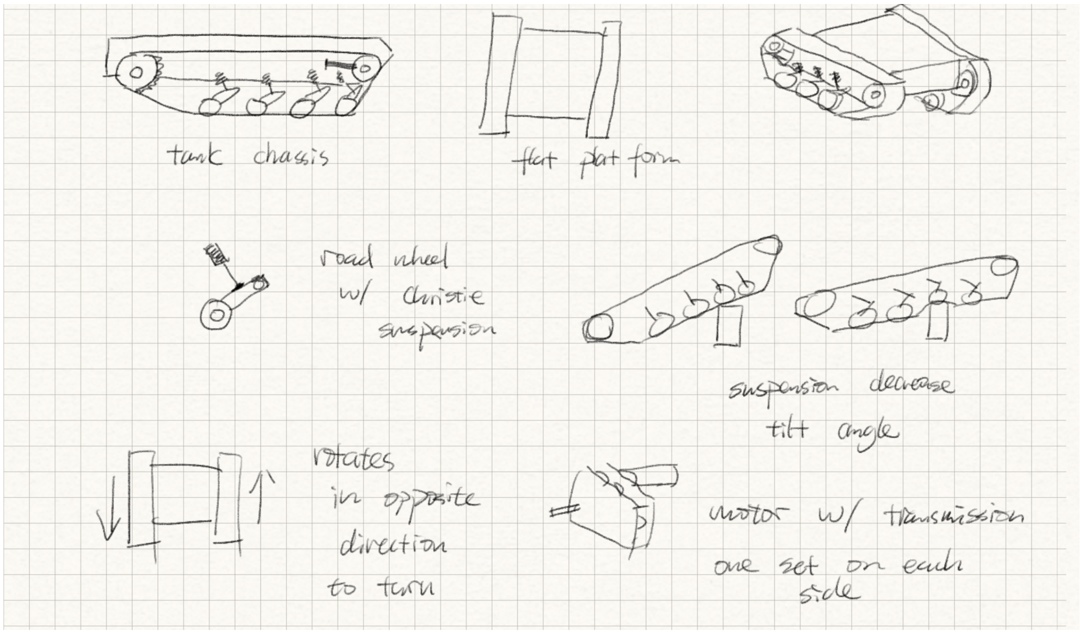


Figure 12: Sketches of “Battle of Hillman” Chassis

Description: This design is a design of tank chassis. The tank body containing motor, transmission, battery, and other electronics will be integrated into the chassis to leave a flat plate on top for the striker team to install their device. The powertrain of the chassis consists of two sets of motor and transmission, each having an output sprocket that connects to the track. Four to five road wheel is designed for better stability and off-roadability. A tension idler wheel at the front is designed to adjust the tension of the track as needed. The Christie suspension is chosen because of the ease of manufacture and installation.

3.4.4 Concept #4: Monster Jam

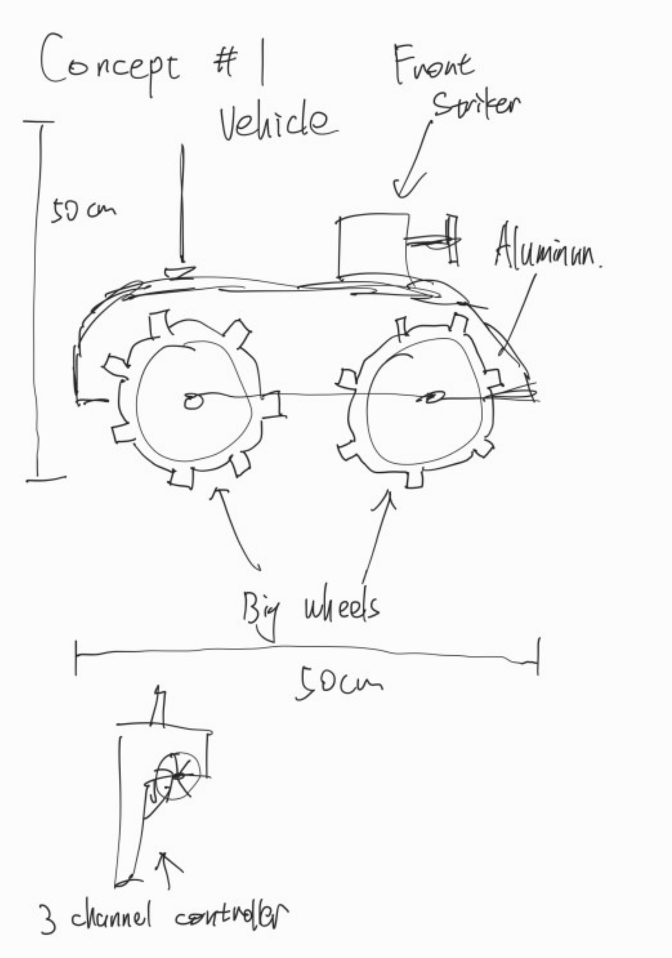


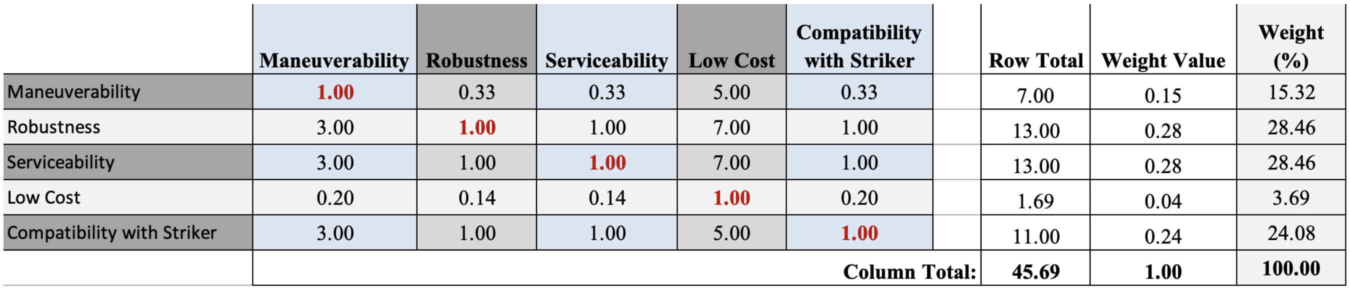
Figure 13: Sketches of "Monster Jam" Chassis

Description: This vehicle has four monster truck wheels that help it for better climbing, with aluminum materials covering the side body of the vehicle. Big wheels can provide better traction for vehicles because they convert more surface area on the road. These wheels are connected by transmission shafts. The aluminum frame helps reduce the weight of the vehicle which allows for more portability. The motor is installed on the back of the vehicle to support the power. Batteries are installed adjacent to the motor. The radio receiver is attached to the top of the frame. The striker mount is placed on the top front of the vehicle. At least a 3-channel remote controller is needed to control the vehicle driving, turning, and hitting the ball. The size of the vehicle is about 50x50 cm so it can be kept in the box. Also, suspensions are recommended for better climbing performance.

4 Concept Selection

4.1 Selection Criteria

The selected criteria that are used to evaluate each model are shown below. Maneuverability measures how quickly the vehicle can be controlled. Robustness evaluates how the vehicle would be unaffected by the perturbation from the external environment. Serviceability is the measure of and the set of features that support the ease and speed at which corrective maintenance and preventive maintenance can be conducted on a system. Low cost measures the estimated price of the vehicle. Finally, the vehicle will also be rated on its compatibility with the striker.

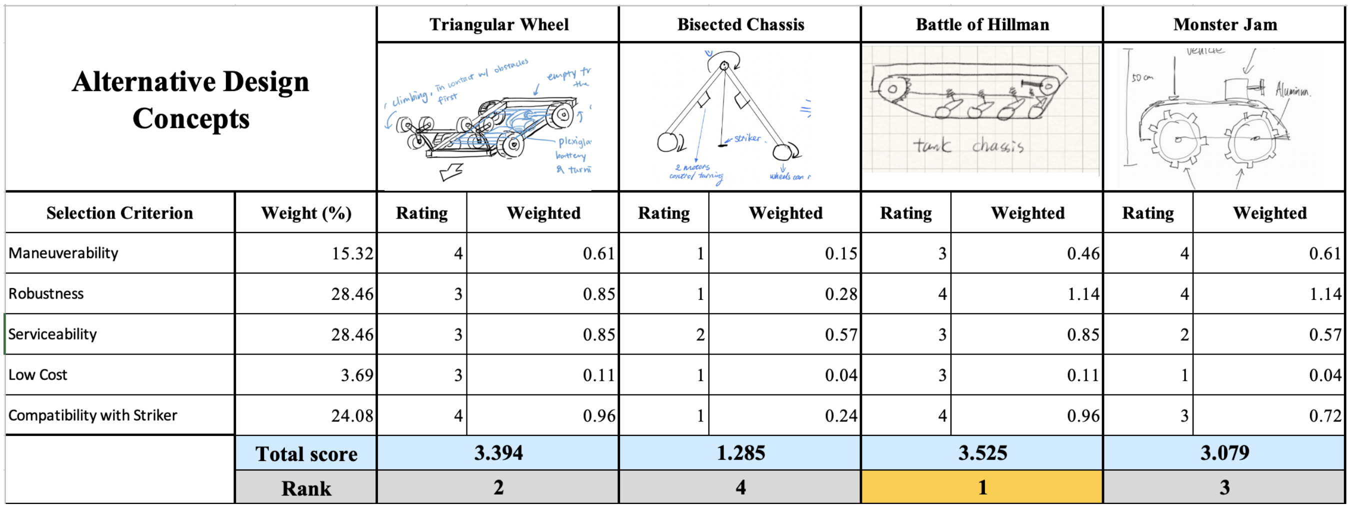


	Maneuverability	Robustness	Serviceability	Low Cost	Compatibility with Striker		Row Total	Weight Value	Weight (%)
Maneuverability	1.00	0.33	0.33	5.00	0.33		7.00	0.15	15.32
Robustness	3.00	1.00	1.00	7.00	1.00		13.00	0.28	28.46
Serviceability	3.00	1.00	1.00	7.00	1.00		13.00	0.28	28.46
Low Cost	0.20	0.14	0.14	1.00	0.20		1.69	0.04	3.69
Compatibility with Striker	3.00	1.00	1.00	5.00	1.00		11.00	0.24	24.08
						Column Total:	45.69	1.00	100.00

Figure 14: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

According to the AHP, each vehicle is rated regarding their maneuverability, robustness, serviceability, cost, and compatibility with the striker. The results are shown below:



Alternative Design Concepts		Triangular Wheel		Bisected Chassis		Battle of Hillman		Monster Jam	
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Maneuverability	15.32	4	0.61	1	0.15	3	0.46	4	0.61
Robustness	28.46	3	0.85	1	0.28	4	1.14	4	1.14
Serviceability	28.46	3	0.85	2	0.57	3	0.85	2	0.57
Low Cost	3.69	3	0.11	1	0.04	3	0.11	1	0.04
Compatibility with Striker	24.08	4	0.96	1	0.24	4	0.96	3	0.72
	Total score	**3.394**		**1.285**		**3.525**		**3.079**	
	Rank	**2**		**4**		**1**		**3**	

Figure 15: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

According to the WSM chart, the Battle of Hillman idea holds the top position among all four ideas. The team assigned a weight of 15.32% to maneuverability, with the Triangular Wheel and Monster Jam receiving a rating of 4, while the Battle of Hillman received a rating of 3. The Bisected

Chassis, on the other hand, received a rating of only 1 in this category. In terms of robustness, which was weighted at 28.46%, both the Battle of Hillman and Monster Jam received the highest rating of 4, while the Bisected Chassis received the lowest rating of 1. Serviceability was also weighted at 28.46%. For this criterion, the Triangular Wheel and Battle of Hillman both received a rating of 3, which is the highest among the four ideas. The Bisected Chassis and Monster Jam, however, received a rating of 2. Low cost was given a weight of only 3.69%. The Triangular Wheel and Battle of Hillman both received a rating of 3 in this category, whereas the Bisected Chassis and the Monster Jam only received a rating of 1. Lastly, the compatibility of the striker was weighted at 24.08%. The Triangular Wheel and Battle of Hillman received a rating of 4, while the Monster Jam received a rating of 3, and the Bisected Chassis only received a rating of 1. Considering the weight percentages and ratings, the Battle of Hillman emerges as the top choice and is therefore our final decision.

4.4 Engineering Models/Relationships

4.4.1 Mass-Spring-Damper System

Each of the idler wheels at the bottom of the tank is a mass-spring damper system. A similar schematic of the idler wheels is shown below [4]:

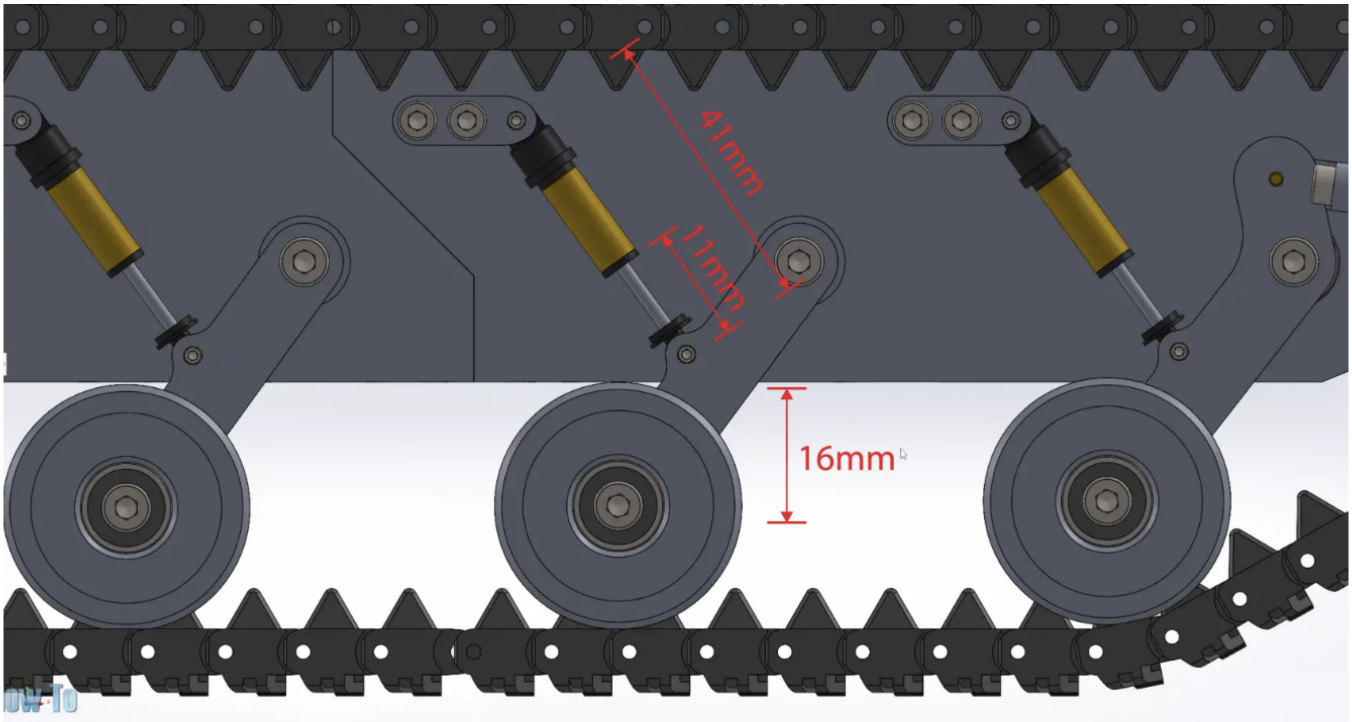


Figure 16: Engineering Model 1: Mass-Spring-Damper System

The motion of the mass-spring-damper system can be modeled with the following differential equation:

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = \omega_n^2 f(t) \tag{1}$$

where $2\zeta\omega_n = c/m$, $\omega_n^2 = k/m$, and $f(t) = F(t)/k$. In the equation, x denotes the vertical displacement [m], c is the damping coefficient $[N \cdot s/m]$, k is the stiffness of spring [N/m], and F(t) is the external perturbation. The suspension or shock absorber for a vehicle can be modeled as a spring and a damper in parallel. Assuming the external force F(t) is constant (equal to a fraction of the weight of the vehicle), the motion of the wheels attached to the suspension will be determined by the properties of the spring and damper (k and c). Thus, having a rough estimation of the vehicle weight and ideal configuration (x(t)) will help us locate a range of acceptable suspension systems. Alternatively, we can use the equation to check if the suspension (given k and c) will provide the performance we need.

4.4.2 Transmission Gearing

The figure below shows the model for determining the gearing of the tank transmission to be able to provide enough torque to climb over obstacles with the striker mechanism on board.

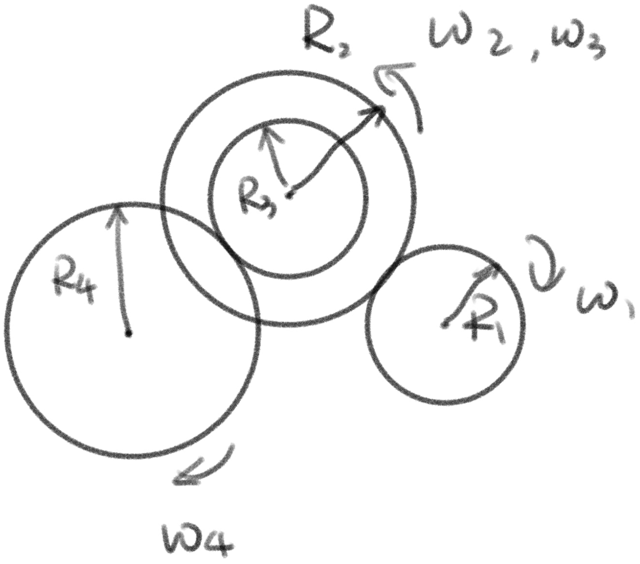


Figure 17: Engineering Model 2: Transmission Gearing Model

The governing equations of gear speed and torque are $\omega_1 R_1 = -\omega_2 R_2$ and $T_1 R_2 = T_2 R_1$, where ω is the angular velocity of the gear, T is the torque transmitted, and R is the radius of the gear. For gears of the same pitch, the number of teeth N is proportional to the radius R, thus the R in the equation above can be replaced by N. This would lead to the final equations for the angular velocity and torque of the four-gear system shown above as:

$$\omega_4 = \omega_1 \frac{N_1 N_3}{N_2 N_4} \tag{2}$$

$$T_4 = T_1 \frac{N_2 N_4}{N_1 N_3} \tag{3}$$

For systems with more gear counts, one can simply add the corresponding number of teeth N_n into the equations.

4.4.3 Fracture Toughness

The materials of the tank need to be strong enough to hold the weights of the striker and the tank itself. Eq. 4 is the fracture toughness equation for typical materials used on a beam. The chassis of the tank can then be determined by how much stress can be put onto.

$$K = Y\sigma\sqrt{\pi a} \tag{4}$$

where K is fracture toughness, a measure of a material's resistance to brittle fracture when a crack is present. Y is a dimensionless parameter or function that depends on both crack and specimen sizes and geometries, as well as on the manner of load application. For Figure 18, Y is about 1.1. σ is the applied stress on the materials and a is the length of the edge crack [5].

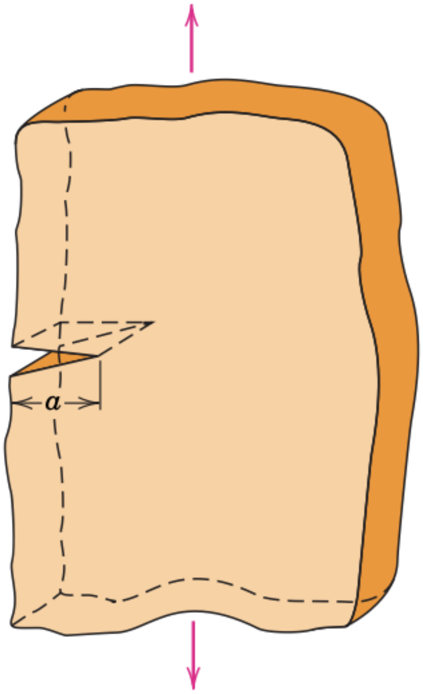


Figure 18: An edge crack in a plate of semi-infinite width.

With Eq. 4, we can calculate the edge crack of length a by knowing the chosen material's K, Y, and the stress we applied on σ.

5 Concept Embodiment

5.1 Initial Embodiment

Our initial prototype is based on design concept #3. The group was going to build a 50 cm-long tank-shaped vehicle. The body, wheels, and tank tracks were planned to be 3D printed, and parts like screws, springs, motors, batteries, and control systems were bought online. Five panels were used to build the body: the front left panel, front right panel, back panel, front panel, and lid. The front panel is designed to mount the striker. Eight eccentric wheels, four on each side, were assembled as idle wheels. They are connected to the wheel linkage using M4 Head screws with the suspension system on. One motor is placed on each side of the body back panel to power the car. One sprocket wheel is attached to the motor shaft on each side to make the chassis move. The motors are connected to the Arduino, which allows the team members to control the motor rotation by using an Android phone through Bluetooth signals. The Electronic speed controllers(ESCs) are built in to inform the speed of rotation.

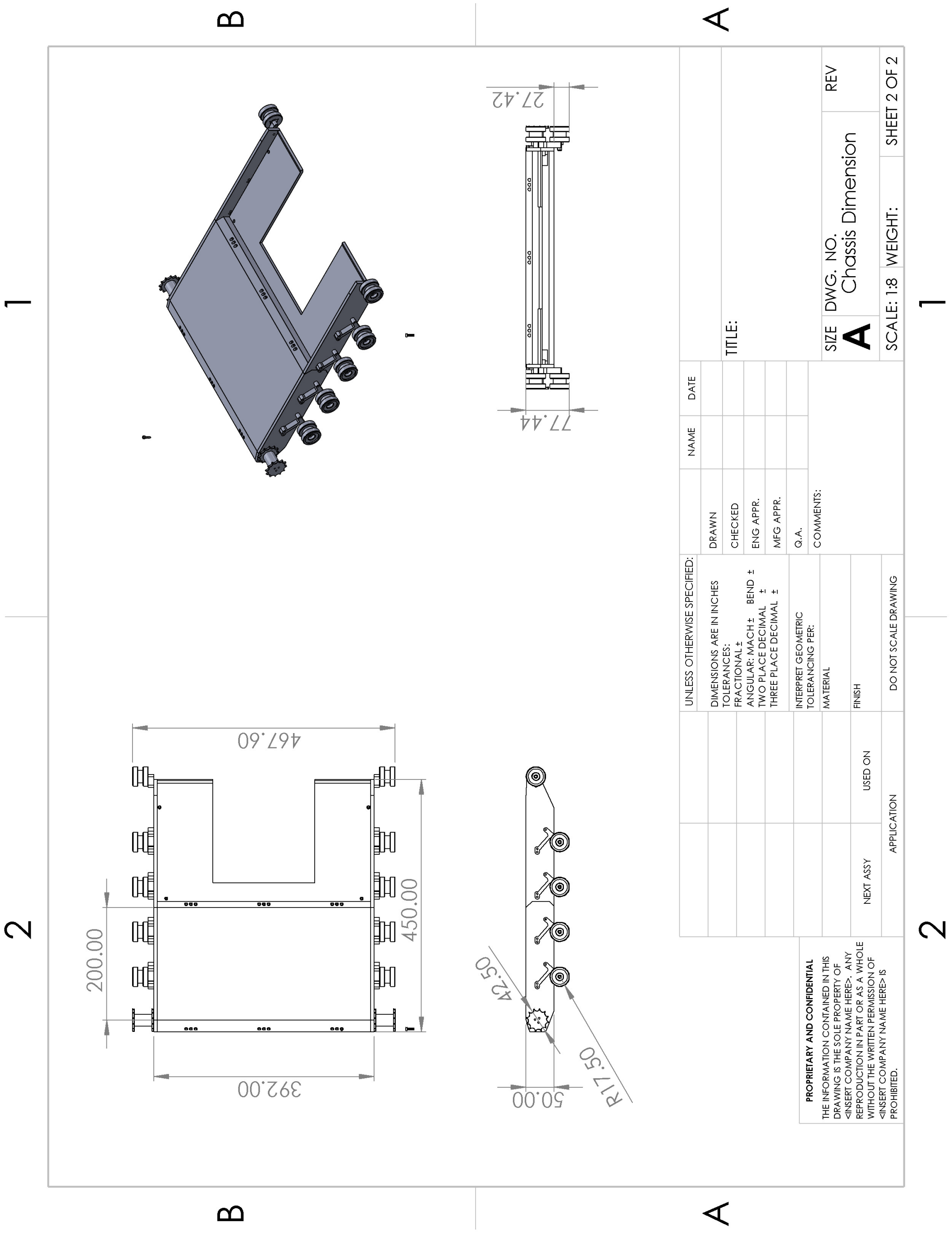
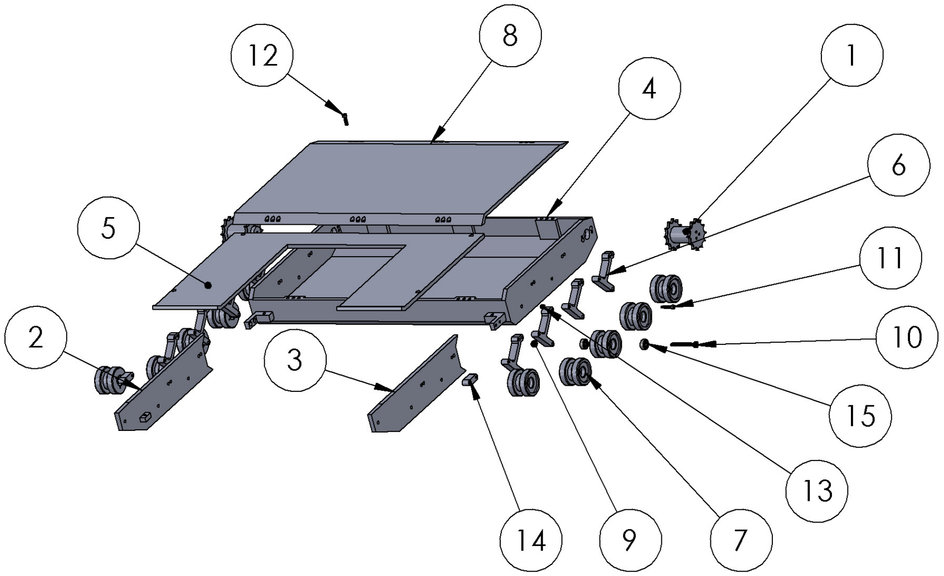


Figure 19: Assembled projected views with overall dimensions

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Sprocket Assembly		2
2	Body Front Left		1
3	Body Front Right		1
4	Body Back		1
5	Front Panel		1
6	Wheel Linkage		8
7	Road wheel Assembly		10
8	Lid		1
9	M4, locknut	High-Strength Steel Nylon-Insert Locknut	10
10	M4, 35mm	Alloy Steel Socket Head Screw	10
11	M3, 16mm	Alloy Steel Socket Head Screw	/
12	M3, 12mm	Alloy Steel Socket Head Screw	/
13	M3 Heat Insert		/
14	Tension Arm		2
15	13mm Ball Bearing	Precision Ball Bearing	10



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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: 1:8
WEIGHT:
SHEET 1 OF 1

Figure 20: Exploded view with callouts to Bill of Materials BOM

Our design goals are:

1. While carrying an extra weight of a striker, the device can climb over a long wooden board that is 3.5” tall and 1.5” thick.
2. While carrying an extra weight of a striker, the device can climb onto, over, and back down from a sheet of 1/2”-thick plywood whose bottom surface is 3.5” above the ground.
3. While carrying an extra weight of a striker, the device can 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.

We have already taken these goals into accounts when making the CAD model for the vehicle. For goals 1 and 2, we have designed the tracks of our vehicle such that it can provide sufficient traction to the vehicle due to the mechanical advantages of the patterns on the tracks. As a result, when connected to motors with sufficiently large motor speeds, the vehicle can climb over the 2” by 4” obstacles with ease. For goal 3, we have set two motors to each track on the vehicle, and we control them using a Bluetooth module, two electronic speed controllers(ESCs), and an Arduino, so that motors can respond differently to different commands from users. When the vehicle needs to readjust its orientations, the command from users can render it turn left or right, for which the motors will rotate in opposite directions, creating rotations of the vehicle.

5.2 Proofs-of-Concept

Incidents happening during the construction of the initial prototype slightly modified our design procedure. The modification is divided into three cases: modeling, 3D printing, and electronics.

5.2.1 Modeling

We were thinking about building a vehicle that is 50cm long. However, we have been informed that the 3D printers could not print such long components. We previously designed the body of our vehicle as a whole, but currently, we have to seek other solutions. Specifically, we designed parts that can be connected to constitute the entire body, with the consideration that the connecting joints do not collide with the joint where the motor is put. The re-designed body parts are yet to be printed, but we believe that they should work.

5.2.2 3D Printing

To self-make the tracks for the vehicle, we designed 200 small identical components to be assembled. When printed out, however, the 200 small identical materials were attached to small but significantly obstructive supporting materials, so it cost 2 days of work to totally remove the supporting materials. Additionally, it was discovered that 3D printing is not consistent in printing parts with holes, as the sizes of the holes did not usually match. To solve this issue, we utilized drills to clear out all holes. We would like to find out future plans for printing materials in a way that requires less supporting materials in order to reduce our work.

5.2.3 Motors in the Vehicle

To make the vehicle move forward and backward smoothly, we attached two motors, one on each side, and used ESCs to inform the motor speed. While the circuit has been successfully built in

Arduino and the motors have been rotating according to Bluetooth signals from the Android phone, the speed output from each gear is not consistent. With the same signal sent from two ESCs, two motors responded with different motor speeds. This might be due to a slight difference in the manufacturing of the two motors. To solve this issue. We would like to allow the vehicle to perform more self-adjusting actions, such as a left turn and a right turn so that we can adjust its orientation when remotely controlling it for a desired position in the field.

5.3 Design Changes

The major design change is the deletion of shocks. After we received the 1/24 scale RC shocks, the spring stiffness was determined to be not sufficient for supporting both the vehicle and the striker mechanism. An online overview showed us no better options to install well-functioning springs onto the vehicle. Thus, the damping system was replaced by a rigid structure connecting the road wheels to the chassis.

Additionally, the tensioner wheel has been changed for the vehicle. The original design was an eccentric wheel. However, it was too time-consuming to calculate the diameter and location of the circle. Instead, a fixed tension rod will be designed and printed to provide tension in tank tracks. To work with the rod, multiple mounting holes will be drilled in different locations on the chassis to provide different tension settings.

6 Design Refinement

6.1 Model-Based Design Decisions

6.1.1 Tank Speed Estimation

In our real design, the sprocket wheel will be connected directly to the track to induce traction. The motor will be providing the torque to the track, which moves the vehicle forward. At the same time, the friction caused by the ground to the track will constrain the speed at which the motor rotates. A simplified diagram, on which the free body diagrams for the vehicle as well as for the motor, is shown below:

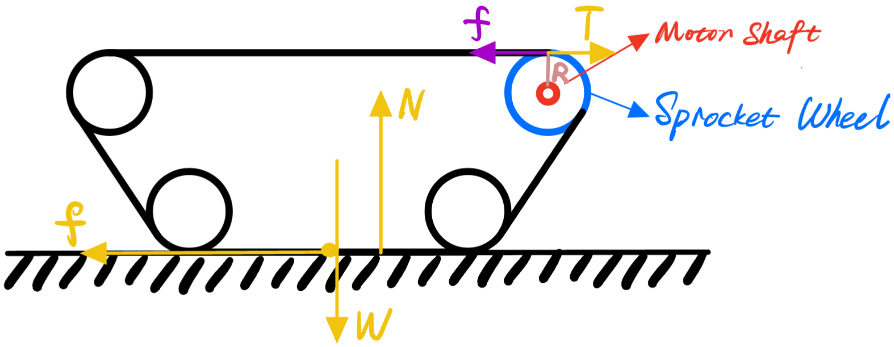


Figure 21: Free Body Diagram for the Tank in Force Balance

In Fig.21, yellow arrows represent the forces on the tank, and the purple arrow refers to the friction exerted on the motor. The force-moment balance calculation is done below to calculate the terminal speed of the vehicle on flat ground.

Known Variables

$m \approx 5kg$: mass of the tank
$\mu \approx 0.5$: coefficient of friction between the tank and the ground
$\omega_{max} \approx 580rad/s$: maximum angular speed of the motor
$\tau_{max} \approx 15N \cdot m$: maximum torque exerted by the motor
$R \approx 0.02m$: radius of the sprocket wheel

Assumptions

1. The tank moves to the right on the figure, and the friction does not change
2. The torque and angular speed of the motor is a linear projection between the maximum angular speed and the angular torque. In other words, $\omega = \omega_{max} - \frac{\omega_{max}}{\tau_{max}}\tau$
3. Force is balanced, and the tank will not accelerate

Unknown (Want to Find)

ω: angular velocity of the motor
τ: torque exerted by the motor during the motion
v: speed of the tank

Calculations

$$F_x = T - f = 0 \Rightarrow \frac{\tau}{R} - \mu mg = 0 \Rightarrow \tau = \mu mgR = 0.5 \times 5kg \times 9.81m/s^2 \times 0.02m = 0.49N \cdot m$$

$$\omega = omega_{max} - \frac{\omega_{max}}{\tau_{max}}\tau = 580rad/s - \frac{580rad/s}{15N \cdot m}0.49N \cdot m = 562rad/s$$

$$v = \omega R = 562rad/s \times 0.02m = 11.2m/s$$

Our calculations show that the vehicle can travel at 11m/s in force and moment balance mode. In real situations, power width modulation might be playing a role, and we will not use the maximum voltage exerted on the tank all the time, so the real velocity will be lower than the calculation.

6.1.2 Suspension Failure Analysis

We used a self-designed suspension(linkage) part to connect the body of the vehicle to the wheels. A comprehensive side view of the linkage is shown below:

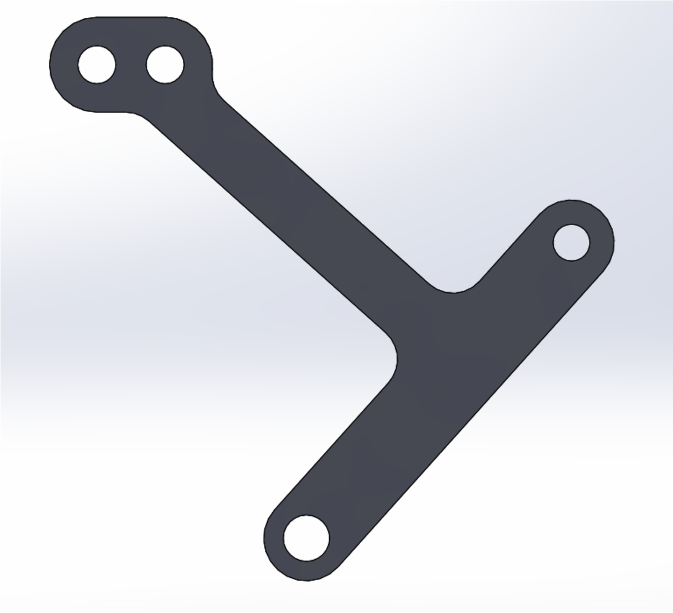


Figure 22: Side View of the Linkage

During the motion, it is important that the linkage is not subject to failure. To ensure that the linkage will not break, we performed a force analysis on the linkage to predict whether the linkage will fail.

It is known that for a Euler-Bernoulli cantilever beam, the normal stressed caused by bending can be calculated using the following equation:

$$\sigma = -\frac{My}{I}$$

where σ is normal stress [Pa], M is moment $[N \cdot m]$, y is the distance from the neutral axis [m], and I is area moment of inertia $[m^4]$. The shear stress of the beam can be represented as:

$$\tau = \frac{VQ}{Ib} \tag{5}$$

where τ is shear stress $[Pa]$, V is the shear force $[N]$, Q is first moment of area $[m^3]$, and b is the thickness of the beam $[m]$. Due to the complexity of the linkage, the calculation cannot be done in algebraic computation. Therefore, we set up a computational model that calculates the stress on the linkage. In the simulation, the fixture is shown below:

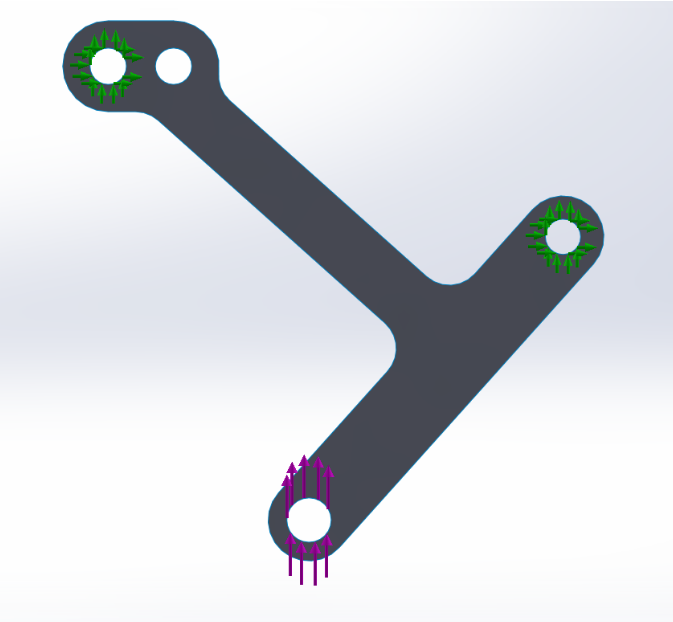


Figure 23: Linkage Fixture

One of the upper hole and the right hole is fixed, while the bottom hole, which contains the wheel and will support the weight of the tank, bears a force that directs upward. The magnitude of the force is an eighth of the tank's weight, because there are 8 identical wheels distributing the weight. The force exerted on a single linkage would be approximately 6N. The mesh feature of the linkage is shown below:

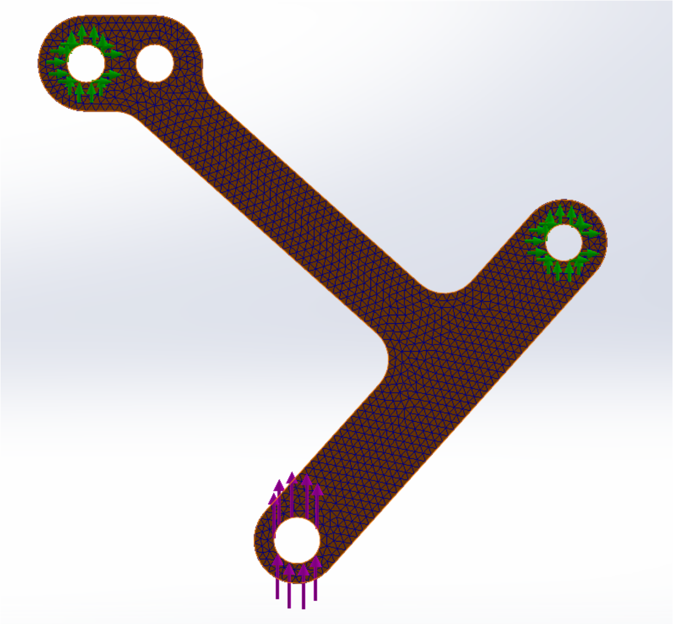


Figure 24: Mesh Feature

The study was run, and the result of the stress distribution on the linkage is shown below:

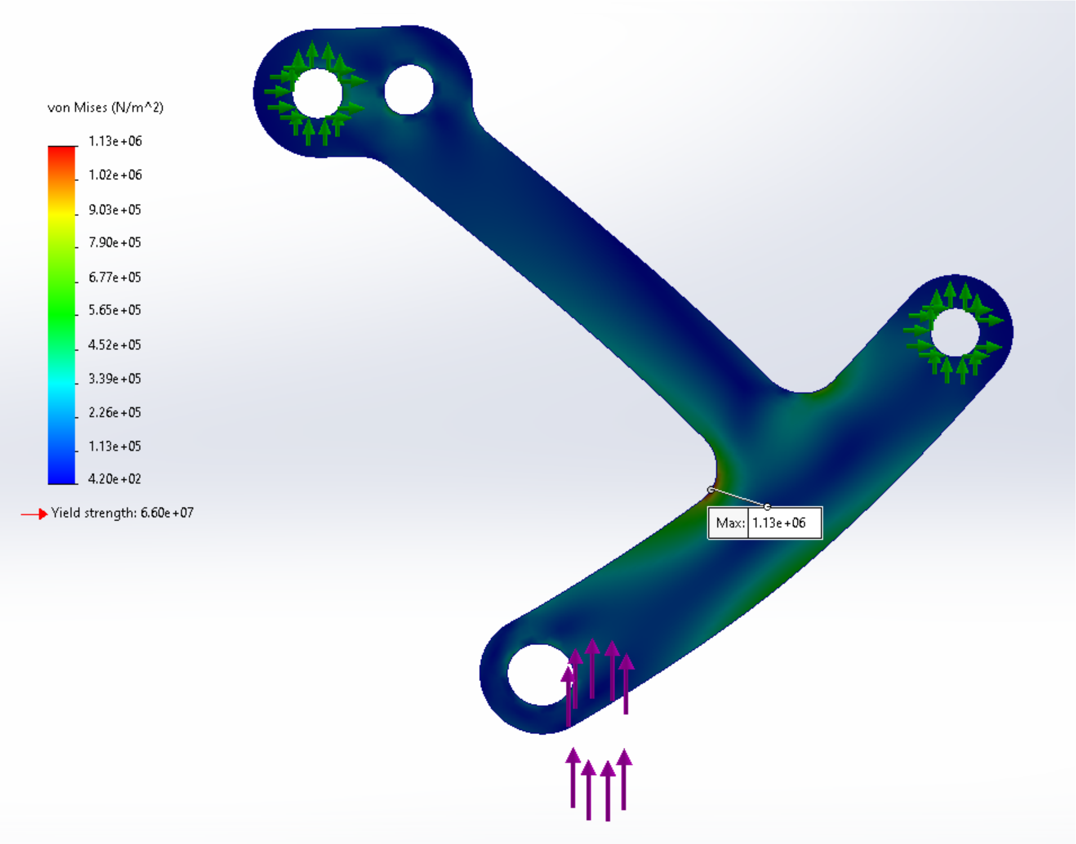


Figure 25: Von Mises Stress

The result shows that the stress is mild throughout the entire linkage except for a stress concentration at the intersection of two "beams." Although the stress is as high as 1.13MPa, it is lower than the yield strength of the 3D printed material, whose yield strength is 66MPa. Therefore, the linkage is strong enough to hold the vehicle during motion.

6.2 Design for Safety

Risks may happen during the competition. Below are the potential risks.

6.2.1 Risk #1: Electronics Overheating

Description: Overheating or malfunction of batteries, Arduino, or motors is likely to occur when running for a long period of time or when the torque load is high. This could cause heat damage to the chassis and damage the electronic components themselves. The melted plastic could also cause pollution to the environment.

Severity: Critical

Probability: Seldom

Mitigating Steps: Heat dissipation for the electronic components needs to be taken into account. More space and cutouts should be incorporated to the design of the vehicle during modeling.

6.2.2 Risk #2: Loss of Control

Description: The remote control could be improperly set up, causing the vehicle to move in an undesired direction. This will probably cause damage to the vehicle as well as the objects hit by the vehicle.
Severity: Marginal
Probability: Likely
Mitigating Steps: To prevent the risk, pre-testing of the control system needs to be performed. The motor specification needs to be double-checked to ensure that the connection is stable. The control system for the connection between the vehicle and the striker should also be considered.

6.2.3 Risk #3: Damage field

Description: A large weight of the vehicle might damage the field on which the vehicle is moving.
Severity: Marginal
Probability: Occasional
Mitigating Steps: Lighter motor/parts will be used to construct the vehicle.

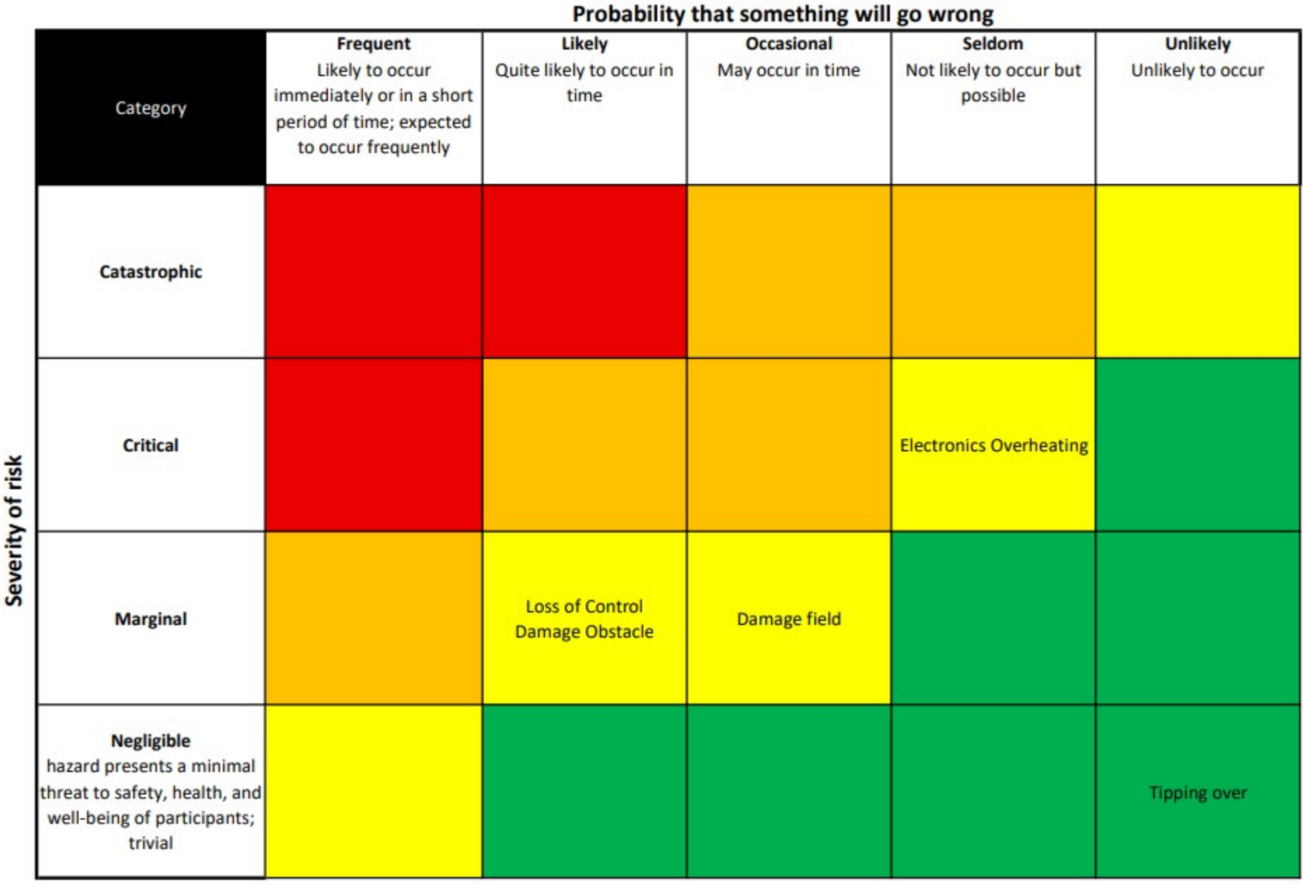
6.2.4 Risk #4: Damage obstacle

Description: When climbing on the obstacle designated by the competition, the movement of the vehicle might be too fierce that it moves the obstacle. This is not allowed by the competition.
Severity: Marginal
Probability: Likely
Mitigating Steps: The vehicle operation needs to be careful. The kinetic energy of the vehicle shouldn't be too large which limits the power output and vehicle mass.

6.2.5 Risk #5 Tipping over

Description: Tipping over the car during the operation might cause damage to parts or spectators.
Severity: Negligible
Probability: Unlikely
Mitigating Steps: The center of mass of the vehicle should be close to the ground to avoid tipping, even during climbing. This requires careful designation of component position.

6.2.6 Heat Map



Probability that something will go wrong

Severity of risk

Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Catastrophic	🟥	🟥	🟧	🟧	🟨
Critical	🟥	🟧	🟧	🟨 Electronics Overheating	🟩
Marginal	🟧	🟨 Loss of Control Damage Obstacle	🟨 Damage field	🟩	🟩
Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial	🟨	🟩	🟩	🟩	🟩 Tipping over

Figure 26: Heat Map

According to Figure 26, none of the risks are located in red and orange blocks. Our highest priority is **Electronics Overheating** with ”Critical” severity and ”Seldom” likelihood. The second priorities are **Loss of Control** and **Damage obstacle**. They both fill in the ”Marginal” severity and ”Likely” probability. The next priority is **Damage field** with ”Marginal” severity and ”Occasional” probability. The least priority is **Tipping over** with ”Negligible” severity and ”Unlikely” probability. In general, this design is fairly safe and most of the risks won’t happen under proper operation.

6.3 Design for Manufacturing

The table below shows the individual components and their amounts in the real assembly. The parts marked with an asterisk are 3-D printed in two symmetrical sections due to the printer’s size constraint.

Table 2: Parts Listing

No.	**Part**	**Amount**
1	Body *	2
2	Body Front Panel *	2
3	Body Front Side Panel	2
4	Lid *	2
5	Sprocket Assembly	2
6	Tension Arm	2
7	Tread	2
8	Wheel Assembly	10
9	Wheel Linkage	8
10	Electrical Components	/

In addition, the sprocket assembly, wheel assembly, and electrical components are each composed of individual parts as listed in the table below:

Table 3: Individual Components in the Sub-Assemblies

Assembly	**Individual Components**
Sprocket Assembly	Shaft
	Gear
	Socket
Wheel Assembly	Outer piece
	Inner Piece
	Ball Bearing
Electrical Components	Arduino
	Electronic Speed Controller
	Brushed Motors
	Wire, resistors, other connections

The assembly's initial design requires 10 5cm-long M4 screws and bolts, about 30 M3 screws of various sizes, and about 30 M3 heat inserts. Due to the splicing of the chassis body, lid, and body front panel, 20 additional screws and bolts are needed.

The assembly's Theoretically Necessary Components (THC), defined by congregating parts with no relative motion and of the same materials, are listed below:

- Body; Body Front Side Panels; Wheel Linkages; Tension Arms
- Lid: Necessary to be a separate piece from the body for easy removal and access to the components inside the body as well as securing them when the chassis is in motion.
- Body Front Panel: Separated from the body to allow for modification to its size and shape in order to cooperate with the design of the striker.
- Tread: To fulfill its function, the tread needs to move separately from the body and other components to propel the chassis.
- Wheel Assembly: Same reasoning as the tread.

- Sprocket Assembly: Same reasoning as the tread.

Note that sub-assemblies are considered as joined individual parts, and material differences within the sub-assemblies do not qualify as separate components.

The chassis body and front side panels should ideally be fabricated as one piece so that the chassis could have higher structural integrity and fewer stress concentrations induced by fasteners. However, wheel linkages and tension arms should still remain separate from the body, as they undergo more stress and are prone to failure. Keeping them separate from the body would allow for maintenance and swapping.

The illustration below shows the ideal necessary components that enable ease of repair and structural stability.

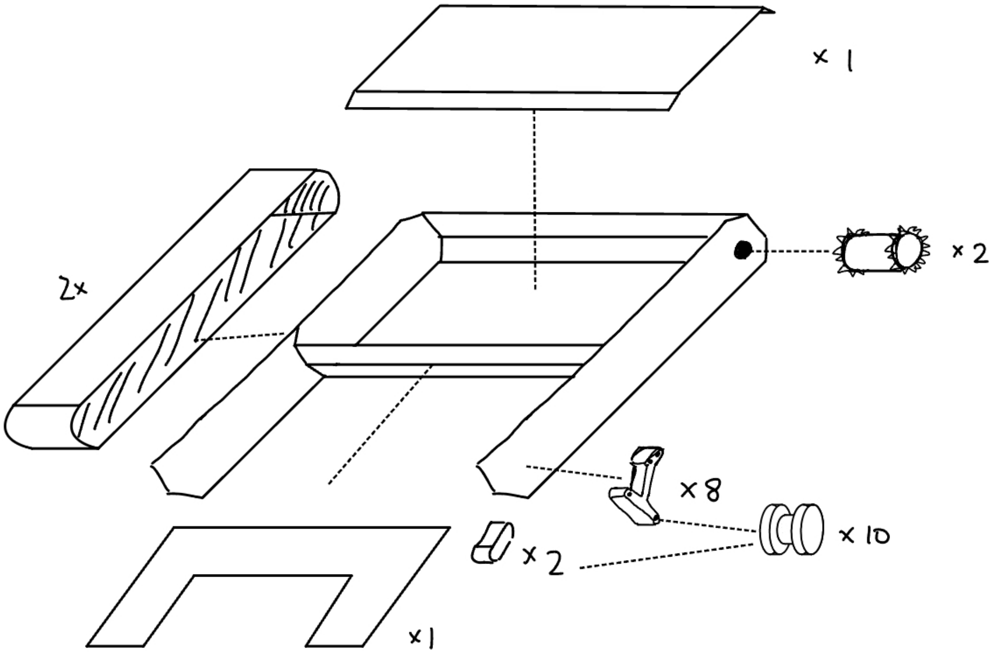


Figure 27: Illustration of Ideal Necessary Components

6.4 Design for Usability

6.4.1 Vision Impairment

The usability of our device will not be influenced by color blindness because the controller app configures the control of the vehicle to buttons of different shapes rather than colors. Admittedly, people with vision impairment like presbyopia will find it hard to control the vehicle because of the lack of haptic feedback from the controller. To improve the usability, physical controller buttons are recommended.

6.4.2 Hearing Impairment

Hearing impairment (such as presbycutia) will not influence the usability of our device. The operation of our vehicle does not require audio feedback. However, hearing impairment may raise some safety concerns, as sound and noise generated during vehicle operation can be a good indication of whether the vehicle is running properly.

6.4.3 Physical Impairment

Certain physical impairments such as limb immobilization may influence the usability of our vehicle. The control of the vehicle requires the movement of fingers to activate. Other physical impairments may not influence the usability of our vehicle because the operation of the vehicle requires little to no physical movement. One possible improvement that can be made is designing a control system based on motion-capturing technology.

6.4.4 Control Impairment

Our vehicle requires minimum skill to operate. The controller is simple and intuitive. There are four buttons controlling four functions of the vehicle: drive, reverse, turn left, and turn right. However, control impairment may raise some safety concerns, as the vehicle requires attention when operating. Precise control of the vehicle also requires focus from the operator.

6.5 Design Considerations

Table 4: 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 5: Contexts considered for ethical judgments

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

7 Final Prototype

We made minute adjustments to the vehicle during the construction to better the performance. The batteries were fixed to the very front of the vehicle so that they balanced out the weight of the motors, and the vehicle could climb over the 2x4 more easily. The configuration of the roadwheels was also adjusted to change the angle of approach and departure. The figure below shows our final prototype.

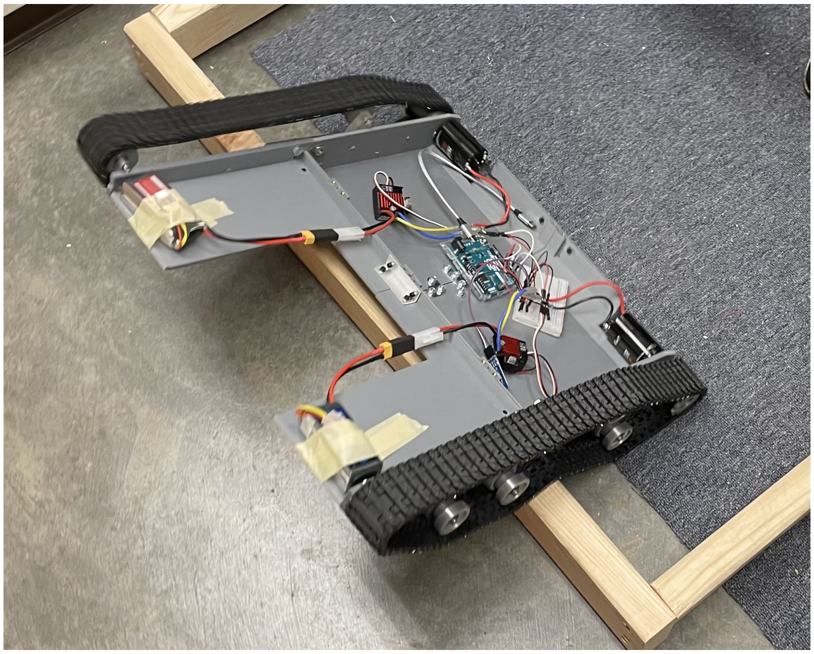


Figure 28: Final Prototype

As we did not collaborate with striker teams during our design process, the final prototype did not take the weight of the striker into consideration when attempting to complete the performance goals. In all, the vehicle completed 2/3 goals, and should theoretically complete the rest after improving the transmission. The following figure is a screenshot taken from a video documenting the vehicle climbing over the wooden board.

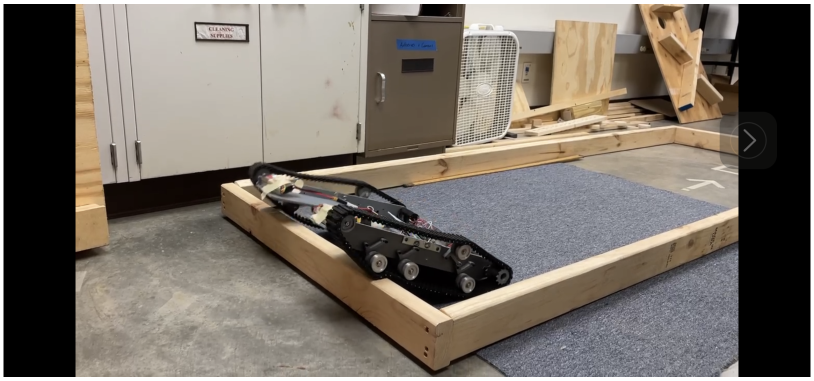


Figure 29: Screen Shot during Testing

The vehicle was able to move with agility and speed to the desired location without disturbing any surrounding objects. The vehicle could also successfully climb over a 2x4 wooden board. While we did not test its ability to climb onto a platform, we had good faith in its ability to complete this task with adjustment to its transmission system and modification to body height. We also look forward to collaborating with the striker team to fabricate a fully functioning robot capable of playing the round of mini-golf on the designated course.

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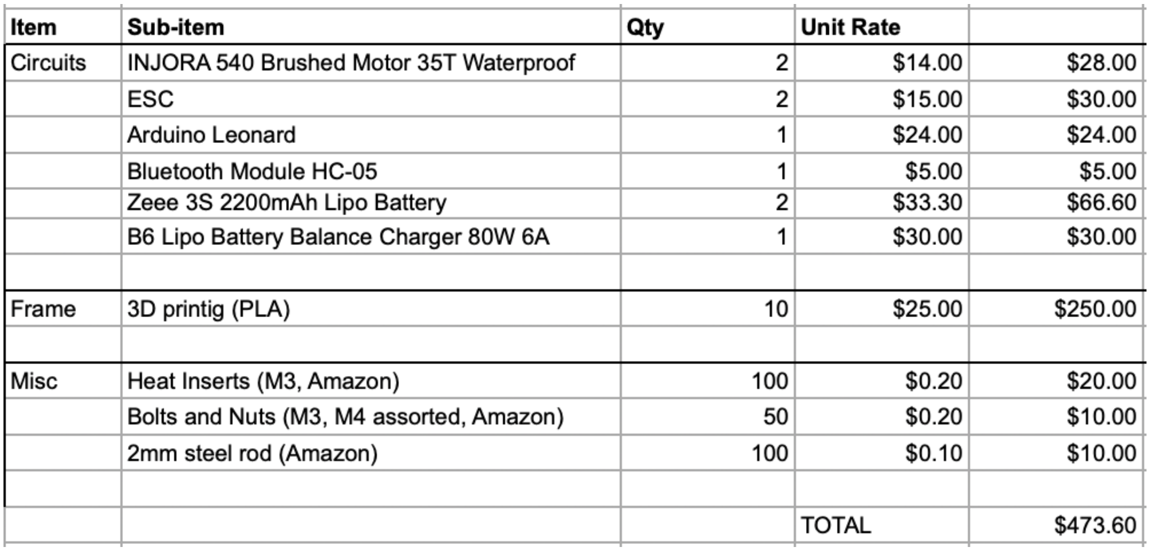
[5] D Callister W & Rethwisch. Wiley.

A Parts List



Item	Sub-item	Qty	Unit Rate	
Circuits	INJORA 540 Brushed Motor 35T Waterproof	2	$14.00	$28.00
	ESC	2	$15.00	$30.00
	Arduino Leonard	1	$24.00	$24.00
	Bluetooth Module HC-05	1	$5.00	$5.00
	Zeee 3S 2200mAh Lipo Battery	2	$33.30	$66.60
	B6 Lipo Battery Balance Charger 80W 6A	1	$30.00	$30.00
Frame	3D printig (PLA)	10	$25.00	$250.00
Misc	Heat Inserts (M3, Amazon)	100	$0.20	$20.00
	Bolts and Nuts (M3, M4 assorted, Amazon)	50	$0.20	$10.00
	2mm steel rod (Amazon)	100	$0.10	$10.00
			TOTAL	$473.60