

University of Wales Trinity Saint David
School of Engineering



Mechanical Engineering

IMechE Repeatable Vehicle Design
Challenge

Group Project

30/03/2025

Table of Contents

1	Introduction	5
1.1	Project Objectives	5
1.2	Project Scope	6
2	Project Organisation (roles/tasks).....	6
2.1	Initial Planning and Scheduling	8
2.2	Research:.....	10
3	Vehicle Design (James).....	14
3.1	Stage 1 ideas:	14
3.2	Stage 2 Prototype Designs:	15
3.3	Stage 3 Rough CAD Design:	19
3.4	Stage 4 Axle Bracket Designs:	20
3.5	Stage 5 Motor mount design:	24
3.6	Stage 6 Lifting mechanism:	26
3.7	Stage 7 Up CAD Design:	28
3.8	Improving the Design	30
4	Wheel Design And Theoretical Analysis (TJ)	31
4.1	Wheel research	31
4.2	Wheel design	33
4.3	Theoretical minimum value calculations	40
4.4	Current Vehicle Specification Theory	43
4.5	Bill of materials	51
5	Electronics And Code (Ziki)	53
5.1	Introduction – Electrical & Programming Of The Repeatable Vehicle	53
5.2	Component Selection & Justification	53
5.3	Circuit Design and Wiring.....	59

5.3.1	Wiring Diagram	59
5.3.2	Testing And Debugging.....	61
5.3.3	Challenges And Solutions.....	61
5.4	Programming & Software Development.....	62
5.4.1	Code Structure & Implementation.....	62
5.4.2	Stepper Motor Control (NEMA 17 with A4988 stepper driver)	63
5.4.3	Ultrasonic Sensor Integration	63
5.4.4	Ultrasonic Sensor Integration	63
5.4.5	Colour Sensor Integration	64
5.4.6	Problem Solving	65
5.5	Testing And Performance	66
5.5.1	Testing Methodology	66
5.5.2	Stepper Motor Performance Test	66
5.5.3	Ultrasonic Accuracy Testing	67
5.5.4	Colour Sensor Testing.....	68
5.5.5	Power Supply Testing	68
5.5.6	Track Run Test	69
5.5.7	Conclusion.....	70
5.6	Challenges And Problem Solving.....	70
5.6.1	Stepper Motor Stalling And Movement Inconsistencies	70
5.6.2	Ultrasonic Sensor Not Giving Accurate Readings.....	71
5.6.3	Colour Sensor Misreading.....	72
5.6.4	Power Fluctuations	72
5.7	Conclusion.....	73
6	Project Review.....	74
6.1	Summary Of Key Achievements.....	74

6.2	Key Adjustments and Lessons Learned.....	74
7	Conclusion.....	76
8	References.....	77

1 Introduction

This report will look at the designing and developing of an autonomous vehicle for the IMechE Design challenge with a budget of £90. This will require parts to be sourced and created via methods such as 3D printing. The design challenge requires the autonomous vehicle to navigate down a track and simulate charging at a docking station in under 3 minutes. The vehicle is designed to operate without any human intervention (e.g. wireless control). This can be done by using sensors, motors, and decision-making algorithms.

The vehicle will integrate structural design, motion control, sensor technology, and programming to create a functional vehicle. The chassis and mechanical framework of the vehicle were carefully designed to ensure stability and durability. The motion system is derived of several components such as a stepper motor, ultrasonic sensor, colour sensor, and a stepper motor driver.

The success of this project relied on team collaboration across different disciplines such as mechanical design and testing, electrical integration, programming and theoretical analysis. Through careful planning, structured development, and iterative testing, the vehicle was built to function autonomously while demonstrating key engineering principles.

1.1 Project Objectives

The primary objective of this project is to develop a functional autonomous vehicle that can perform the following tasks:

- Navigate independently along the predefined track path.
- Detect the wall and engage the docking lifting mechanism.
- Recognise the colour yellow on the target located on the floor of the track test.
- Complete the challenge in 3 minutes.
- Integrate all hardware components to work seamlessly using code.

1.2 Project Scope

This project will cover the following:

In scope:

- **Hardware development:** Designing and implementing the electrical and mechanical systems required for the autonomous vehicle to function.
- **Software development:** Developing code for the Arduino to process the sensor inputs and motor movement.
- **Testing and optimization:** Ensuring that the vehicle functions accurately and efficiently.

Out of scope:

- **Wireless communication** (e.g. remote control with Wi-Fi or Bluetooth) will not be covered in this project.

2 Project Organisation (roles/tasks)

Roles:

CAD Designer: James

The CAD designer is responsible for overall the design process of the vehicle, ensuring all the components are integrated efficiently and effectively into the vehicle's design. This role also includes the responsibility of creating and refining different custom components that will be used in the vehicle to meet the requirements of the IMechE challenge.

CAD designer tasks:

1. **Mind map/brainstorming:** This involves a brainstorming session to make a list of the different components that could potentially be used to make a prototype layout of the vehicle.
2. **Prototype designs:** The task should be used to compile the different design layouts of the vehicle and how the power will be delivered to the driven wheels.
3. **Rough CAD Model:** This CAD model would be used as a foundation to visualise how the overall would look and to find the most efficient placement of key components.

4. **Axle designs:** Exploring different axle CAD designs to find the most effective options at aligning the axle with the chassis as well as eliminating any additional movement.
5. **Motor mount designs:** Creating different motor mount CAD design to detect the most effective CAD design for holding the motor to the chassis of the vehicle.
6. **Lifting mechanism designs:** To research different types of lifting mechanisms then CAD a final design that will be used on the vehicle to simulate the charging portion of the design challenge.

Electrical & programming: Ziki

This role is responsible for the following tasks:

1. Designing and implementing the electrical system, this includes wiring, power distribution, and energy management.
2. Developing the control software/code: programming the Arduino Uno to be able to execute the autonomous movement.
3. Integrating and calibrating the ultrasonic sensor and colour sensor for obstacle detection and environmental awareness.
4. Programming timed interval actions: ensuring that the vehicle executes tasks in a structured sequence.
5. Implementing reactive reasoning algorithms: allowing the vehicle to dynamically adjust its movement based on the sensor inputs.
6. Improving power usage and energy rationing by ensuring efficient power distribution between the motors, sensors, and the microcontroller.
7. Debugging and testing the electrical and control systems: the refinement of performance for stability and accuracy.

Theory analysis: TJ

This role is responsible for the following tasks:

1. Researching and developing methods and solutions to problems.
2. Mathematically find base mechanical system minimums to begin designing and sourcing components from.

3. Theory trialling the system to discover problems before physical implementation of the system.
4. Make the vehicle mathematically work and complete the competition task in the given time.
5. Research wheels and methods of increasing traction and accuracy.
6. Designing the wheels and creating and implementing methods of increasing traction.
7. Using theoretical analysis to find errors before they arise.
8. Create the bill of materials and ensure the team is following the rules of the competition.

2.1 Initial Planning and Scheduling

The autonomous vehicle required a structured plan to ensure that time and resources were used efficiently. A clear schedule was made to guide the design, implementation, and testing phases. This was to ensure that there was a smooth and easy collaboration between all the members of the team. The planning phase focused on defining clear objectives and milestones using the assigned roles mentioned above to help track the groups progress.

Milestones:

The team made a few milestones for that project that we aimed to achieve within a set time. Figure 1 below shows the milestones the team set out to achieve:

Milestones		
Position	Date	Milestone
1	08/10/2024	Start (08/10/24)
-2	24/10/2024	Prototype Designs (24/10/24)
1	28/10/2024	Rough CAD Design(28/10/24)
-1	10/11/2024	Detailed CAD Design(10/11/24)
-1	28/11/2024	CAD Base/Wheels/Brackets(28/11/24)
1	02/12/2024	3D Print Components(02/12/24)
1	09/12/2024	Presentation(09/12/24)
-1	18/12/2024	Programme Sensors(18/12/24)
1	09/01/2025	Assembly(09/01/25)
-2	10/01/2025	Mock Test 1(10/01/25)
3	16/01/2025	Mock Test 2(16/01/25)
-2	30/03/2025	Viva(30/03/25)
-1	04/04/2025	Internal UWTSD Heats(04/04/25)
1	04/05/2025	South Wales Reginal Heats(04/05/25)
-3	04/11/2025	National Finals London(04/11/25)

Figure 1: Image showing the teams set milestones.

Milestones:

All the important tasks, their estimated duration, start and end dates, and milestones are listed in the Gantt chart. This will aid in team management by ensuring that important tasks are handled so that everyone can devote enough attention to them.

Key milestones and objectives:

- The project planning process is finished.
- Detailed CAD drawings.
- First Viva
- Testing the electrical control system's functionality.
- Completion of prototype.
- Completion of testing and evaluation.
- Final report updates.
- Second Viva.

The group's overall tasks, their start and end dates, and the overall progress of the tasks that have been initiated are all displayed in the Gantt chart below:

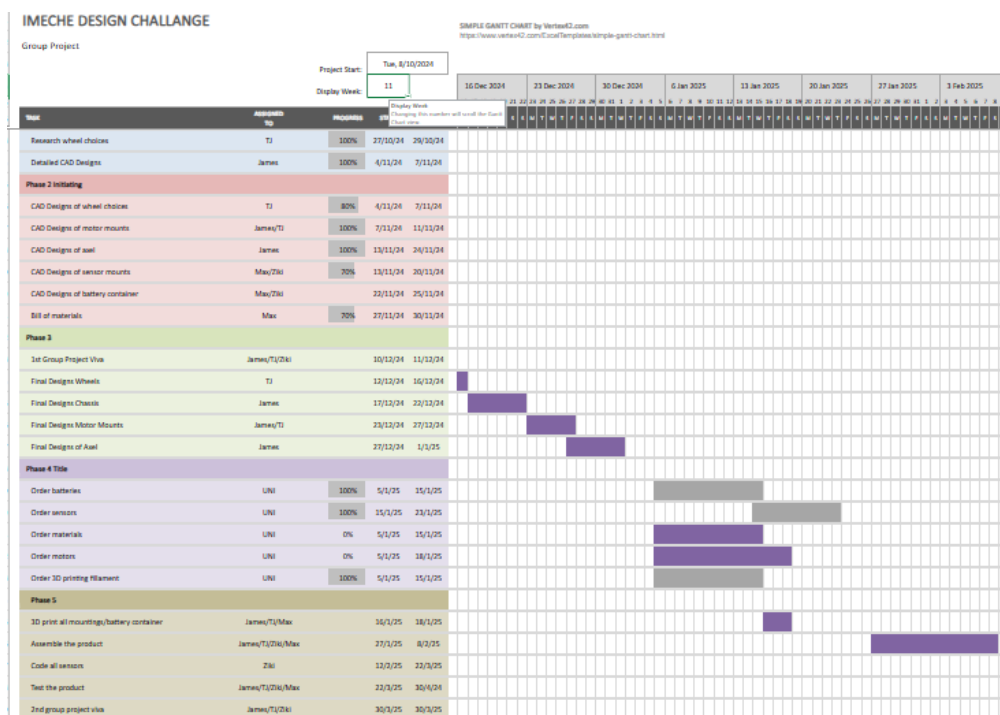


Figure 2: Image showing the Gantt chart for the group.

Link to the full Progress Gantt chart:

[updated Gantt chart.xlsx](#)

2.2 Research:

Common materials seen: Acrylic and laser cut plywood

Acrylic

Acrylic plastic is a lightweight, shatter-resistant material made from polymers of acrylic acid or related compounds. It is known for its clarity, strength, and resistance to UV light, commonly used in products like windows, signs, and lenses.

Advantages:

- **Lightweight:** Acrylic is light, making the model easy to handle and transport.
- **Durability:** It is shatter-resistant and can withstand impacts, making the model more resilient.
- **Easy to shape:** It can be easily cut, moulded, and shaped to create detailed parts of the model.
- **Smooth finish:** It provides a polished and professional appearance when properly finished.

Disadvantages:

- **Brittleness:** Acrylic is prone to cracking under heavy loads or impact, making it less ideal for vehicles that might experience stress or vibration during repeated use.
- **Limited Flexibility:** Acrylic lacks flexibility and can fracture under bending or flexing forces, which are common in vehicle structures that need to absorb shocks or movement.
- **Stress Cracking:** Acrylic is susceptible to stress cracking, especially at drilled holes or sharp edges, which can compromise the structural integrity of a repeatable vehicle.
- **Cost:** Acrylic will have a higher processing cost compared to laser cut plywood.

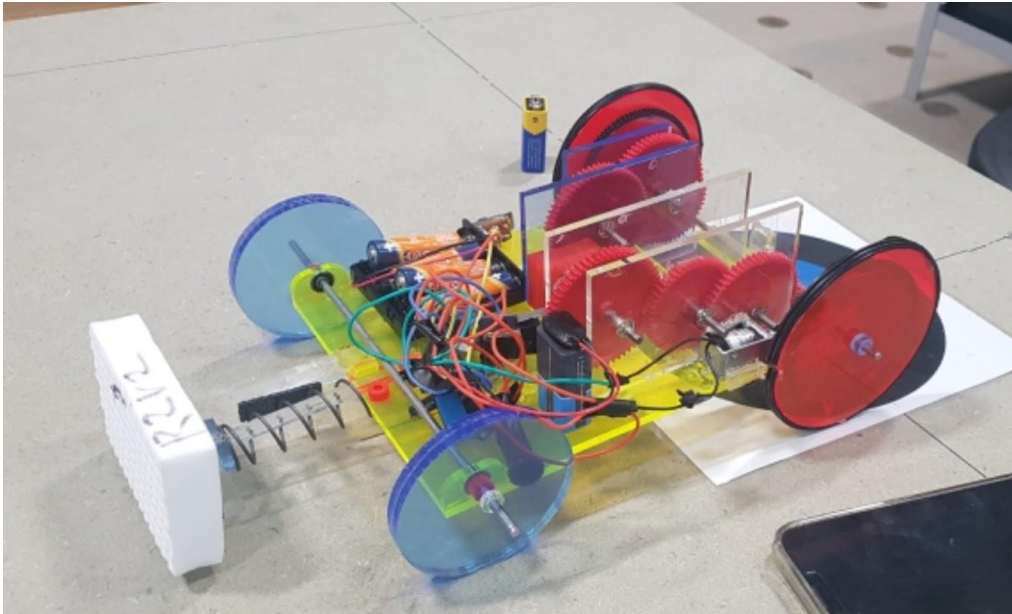


Figure 3: Image showing a repeatable vehicle made from acrylic.

Laser cut plywood

Laser-cut plywood is plywood that has been cut using a high-powered laser. The laser precisely burns sections of the plywood to create detailed shapes, patterns, or designs. This technique allows for intricate and accurate cutting, often used in woodworking, model making, furniture design, and various craft projects. The laser can handle thin to moderately thick plywood, producing smooth, clean edges without the need for traditional cutting tools.

Advantages:

- Precision: Laser cutting offers highly accurate and detailed cuts, ideal for intricate designs and complex shapes.
- Smooth Edges: The laser burns through the wood, creating clean, smooth edges without the need for additional sanding.
- Speed: Laser cutting is a fast process, allowing for quick production, especially for repeatable designs.

- Minimal Waste: The precision of laser cutting reduces material waste, making it more efficient than traditional cutting methods.
- Versatility: Laser cutting can handle various thicknesses and types of plywood, offering flexibility in design.
- Consistency: It provides consistent results, ensuring uniformity across multiple pieces for mass production.
- Low cost: Laser cutting plywood has a very low to no processing cost.

Disadvantages:

- Burn Marks: Laser cutting can leave scorch marks on the edges or surface, requiring post-processing if a clean finish is desired.
- Limited Thickness: Laser cutters can struggle with very thick plywood, limiting the size or robustness of certain designs.
- Material Sensitivity: Plywood with glue layers or certain treatments might not cut cleanly or could release harmful fumes when lasered.
- Structural Weakness: The heat from the laser can weaken the edges, particularly on thinner or lower-quality plywood, affecting the durability of the cut pieces.

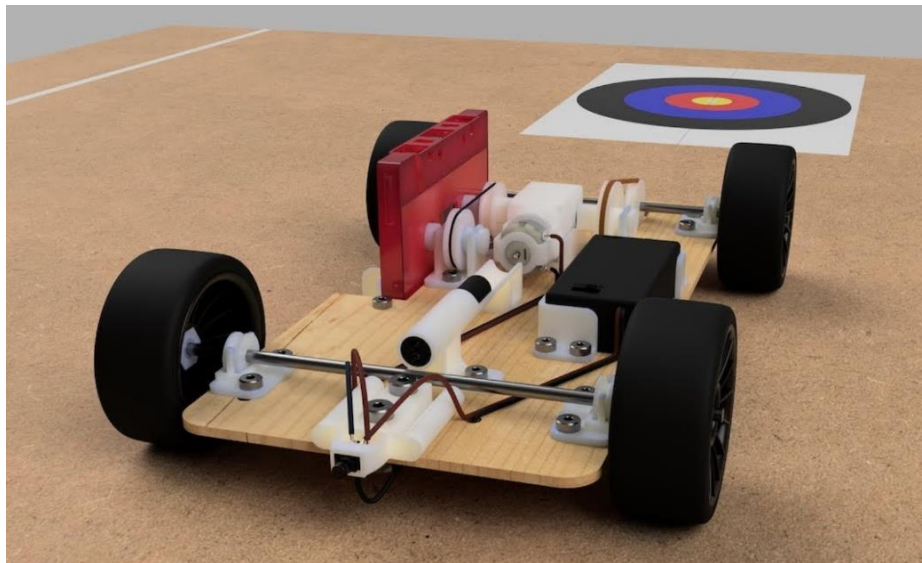


Figure 4: Image showing a repeatable vehicle made from plywood.

Drivetrain and wheels:

Wheels

From research the main set of wheels that I come across from past winners are either 3d Printed wheels, wheels made from main body material (acrylic or plywood), and store-bought toy car wheels.

All of them have advantages and disadvantages but the main disadvantage to consider with the plywood/acrylic wheels is:

- Traction (if car does not have enough weight traction can be a problem).
- Will need a full proof joining method.

The main disadvantage of the toy car wheels and 3D printed wheels:

- Cost of these could be high.
- If they break, they will have to be replaced which will be an additional cost.

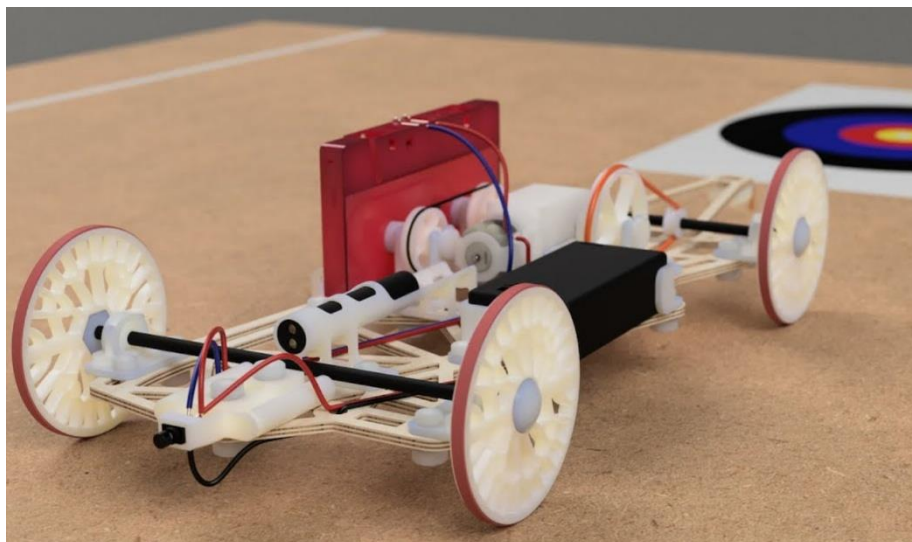


Figure 5: Image showing a repeatable vehicle with 3D printed wheels.

Drive chain

Some past winners use the following:

- RVFM dual output motor which was used to drive the rear wheels utilising a pulley system.
- They said it provided a close output rating for their desired values with minimal gearing required.

- This is a type of stepper motor which have seemed to be easier to work with than other motors.

Material Comparison Table:

material	Material Specifications								
	strength to weight ratio	Machinability	Cost	Environmental impact	stiffness	Aesthetic	waste		
Plywood	4	4	5	2	2	3	3	Key:	
MDF	2	4	5	2	4	3	3	1	Very bad
3D printed filament	4	4	2	3	3	4	5	2	Bad
Carbon Fiber	3	3	1	2	3	5	3	3	Moderate
Sheet metal (Mild Steel)	4	4	3	3	3	1	3	4	Good
Acrylic	4	3	2	2	4	4	3	5	Very good

3 Vehicle Design (James)

3.1 Stage 1 ideas:

Stage 1 of the vehicle design process involved brainstorming and creating a comprehensive mind map to explore various possibilities for the vehicle's overall layout, another crucial factor was the wheel layout, which involved evaluating different drivetrain configurations, including front-wheel drive (FWD), rear-wheel drive (RWD), all-wheel drive (AWD), and four-wheel drive (4WD). By mapping out all these possibilities, the team could identify potential design directions that balanced performance and efficiency. Different electronics were also gathered to find the most practical way of monitoring the overall vehicle performance. Material was another large factor to consider for this project as a set budget was given, the materials needed to have a good strength to weight ratio without increasing the cost.

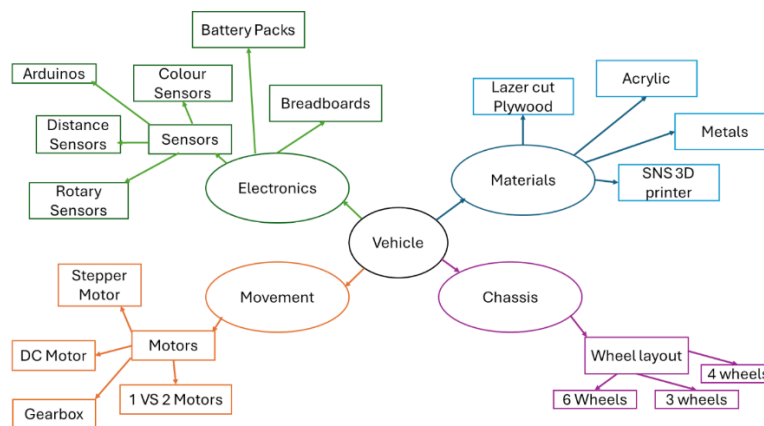


Figure 6: Image showing the mind map for the project.

3.2 Stage 2 Prototype Designs:

Stage 2 of the design phase involved developing and evaluating multiple chassis layouts for the vehicle while considering different methods of delivering power to the driving wheels. This stage was critical in determining how the power generated by the electric motor would be efficiently transmitted to the wheels while maintaining optimal performance, stability, and durability.

Final Drive Layout:

One of the drivetrain configurations considered was a motor with a gear that runs directly to the axle gear. This design is widely used in many competing vehicles due to its simplicity, cost-effectiveness, and proven reliability. By eliminating complex intermediate components, this direct-drive system ensures a more straightforward power transfer mechanism. However, despite its advantages, the design comes with a few challenges. One of the primary concerns is ensuring proper alignment between the motor gear and the axle gear, as misalignment can lead to inefficiencies, excessive wear, and mechanical failures. Additionally, another issue that needs to be addressed is backlash—the small gap between meshing gears—which, if excessive, can result in unwanted play, reduced power transfer efficiency, and potential mechanical noise. To mitigate these issues, precision manufacturing techniques, high-quality materials, and proper gear engagement tolerances must be employed during the design and production process.

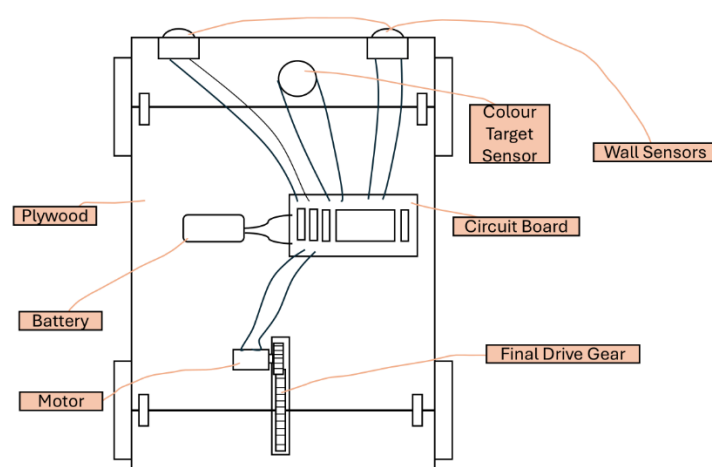


Figure 7: Image showing the final drive layout.

Pulley Drive Layout:

This design uses a motor equipped with a pulley system, where a pulley device is securely attached to the motor, and another corresponding pulley is mounted onto the axle. These two pulleys are connected through a pulley drive or belt, which facilitates the transfer of power from the motor to the axle, ultimately driving the wheels. One of the key advantages of this design is that it creates additional space on the chassis, allowing for the integration of larger and more complex components, such as an Arduino microcontroller, breadboards, sensors, and other electronic systems essential for vehicle operation and control. This additional space can be particularly beneficial in prototype development, where adaptability and flexibility in component placement are crucial.

However, despite its advantages, this design also presents some notable drawbacks. One of the primary concerns is the potential for belt slippage, which can occur when the pulley drive system is subjected to high loads or rapid acceleration. If the belt slips, it can lead to inefficient power transfer, resulting in inconsistent and unreliable power delivery to the wheels. This could negatively impact the vehicle's performance, reducing acceleration, speed, and overall efficiency. Additionally, belt-driven systems require regular maintenance and proper tensioning to prevent excessive wear and premature failure. Over time, the belt may stretch or degrade, necessitating periodic adjustments or replacements to maintain optimal performance. To mitigate these issues, selecting a high-quality belt material with sufficient grip, using a tensioning mechanism, and ensuring precise alignment of the pulleys are critical factors in improving the reliability and efficiency of this power transmission method.

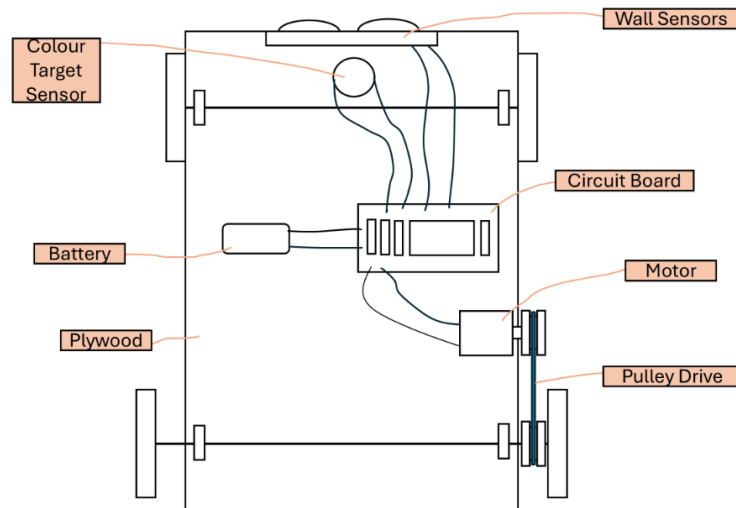


Figure 8: Image showing a pulley drive system.

Two separate motor power delivery:

This design is by far the most advanced and technically sophisticated among the three prototype configurations. Unlike the previous setups, this system offers a significant advantage in terms of precision and control by enabling independent power delivery to both rear wheels. This independent control allows the vehicle to correct straight-line errors dynamically, ensuring a more stable and accurate trajectory. Additionally, by distributing power separately to each rear wheel, the vehicle gains the ability to execute more controlled left and right turns while compensating for any directional inaccuracies that may arise during movement. This level of control is particularly beneficial for autonomous or remotely operated vehicles, as it enhances manoeuvrability and adaptability to different terrains.

Another notable advantage of this design is its impact on weight distribution. By positioning the powertrain components toward the rear of the chassis, a greater proportion of the vehicle's weight is shifted to the rear axle. This redistribution increases the normal force acting on the rear wheels, thereby enhancing traction and improving overall stability, especially during acceleration. The additional frictional force generated at the rear wheels reduces the likelihood of wheel slippage and enhances the vehicle's ability to maintain consistent contact with the ground, leading to improved performance and handling characteristics.

However, despite its numerous advantages, this design also presents significant challenges. One of the primary drawbacks is the increased complexity associated with managing two separate power delivery systems that function independently. Unlike the simpler single-motor configurations, this setup requires each motor to operate with its own control logic, necessitating the use of separate code and independent feedback loops to ensure synchronised and efficient performance. The added computational demand increases the complexity of programming and calibration, requiring more sophisticated algorithms to manage power distribution effectively.

Additionally, the overall cost of the vehicle is considerably higher due to the need for double the number of motors compared to the previous designs. With two motors instead of one, there is also an increased requirement for supporting components, such as motor controllers, sensors, and power management systems, all of which contribute to the total production cost. Furthermore, maintenance and troubleshooting become more intricate, as any issue affecting one motor or its control system could impact the overall functionality of the vehicle. Despite these challenges, this setup remains a highly advanced and promising approach, offering superior control, performance, and adaptability in exchange for its higher complexity and cost.

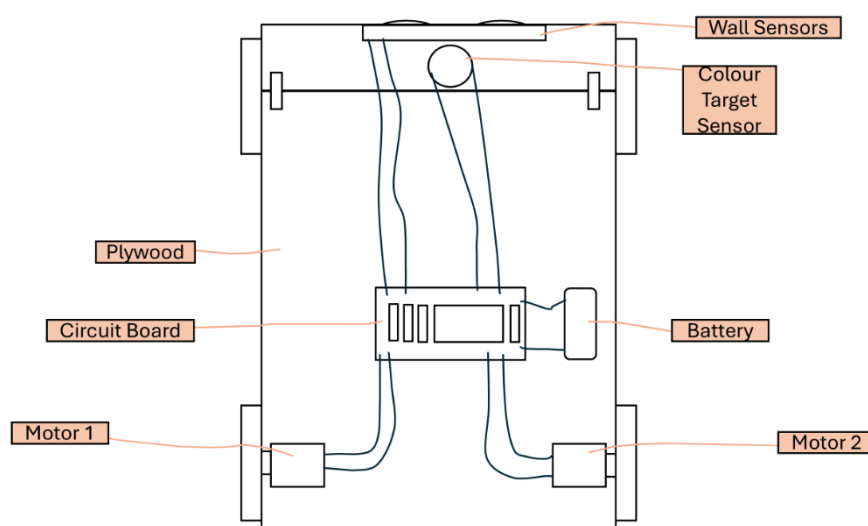


Figure 9: Image showing a dual motor setup.

Chosen layout:

After thorough analysis and careful consideration of all available drivetrain configurations, it was ultimately decided that the final drive design would be the most suitable choice for this project. This decision was based on several key factors, including reliability, ease of manufacturing, and overall efficiency. The final drive system has already been extensively tested and proven to be a dependable solution in a variety of real-world applications, making it a well-established and trusted design. Its widespread use in numerous vehicles and mechanical systems demonstrates its durability and effectiveness under different operating conditions.

Additionally, the simplicity of the final drive system makes it significantly easier to produce and implement, reducing both manufacturing complexity and associated costs. Unlike more intricate setups that require multiple independent power delivery mechanisms or specialised components, the final drive configuration uses a straightforward and well-understood method of power transmission. This ease of production ensures that it can be effectively assembled and maintained without requiring excessive resources or highly specialised expertise.

Another major advantage of this design choice is its adaptability to different circumstances and operating environments. Whether used in high-torque applications, high-speed scenarios, or challenging terrains, the final drive system can be customized to meet performance requirements without sacrificing reliability. Its robust construction and proven track record in the automotive and engineering industries further reinforce its suitability as the preferred drivetrain configuration for this project.

By selecting this design, the project benefits from a balance of efficiency, cost-effectiveness, and mechanical dependability, ensuring that the final product meets the necessary performance standards while remaining practical for production and long-term use.

3.3 Stage 3 Rough CAD Design:

Now that a prototype design had been carefully selected, the next crucial step in the development process was to create a rough Computer-Aided Design (CAD) model. This initial CAD model served as a foundational blueprint to visualise the overall structure of the vehicle

and to determine the most efficient placement of key components. The primary purpose of generating this digital representation was to gain a better understanding of how various essential elements, such as the axle gear, wheels, and ultrasonic sensor, would be positioned within the overall chassis.

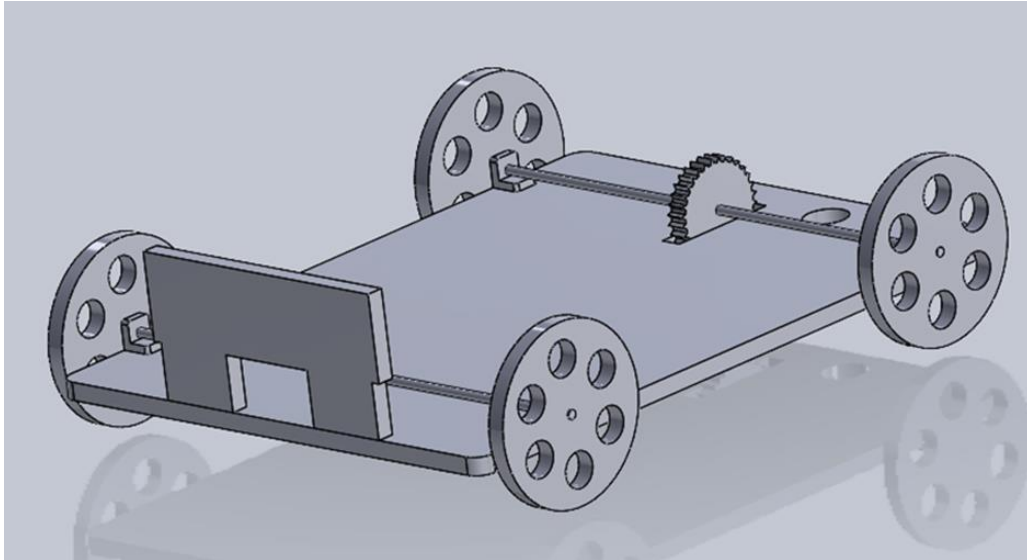


Figure 10: Image showing the first CAD prototype design.

3.4 Stage 4 Axle Bracket Designs:

Axle bracket design 1:

Axle Design 1 was conceptualised as a straightforward and efficient design that aimed to minimise material usage while still fulfilling the necessary functional requirements. This design approach prioritised simplicity, making it relatively easy to manufacture and assemble while also keeping production costs low. One of the primary advantages of this design was its ability to reduce material wastage, ensuring that excess raw materials were not unnecessarily used in the construction process. By refining the shape and structure of the axle, this design contributed to a more cost-effective and environmentally friendly approach to production.

However, despite these benefits, Axle Design 1 also had some significant drawbacks that needed to be carefully considered. One of the main concerns was the potential for axle misalignment, which could arise due to the high degree of movement associated with this design.

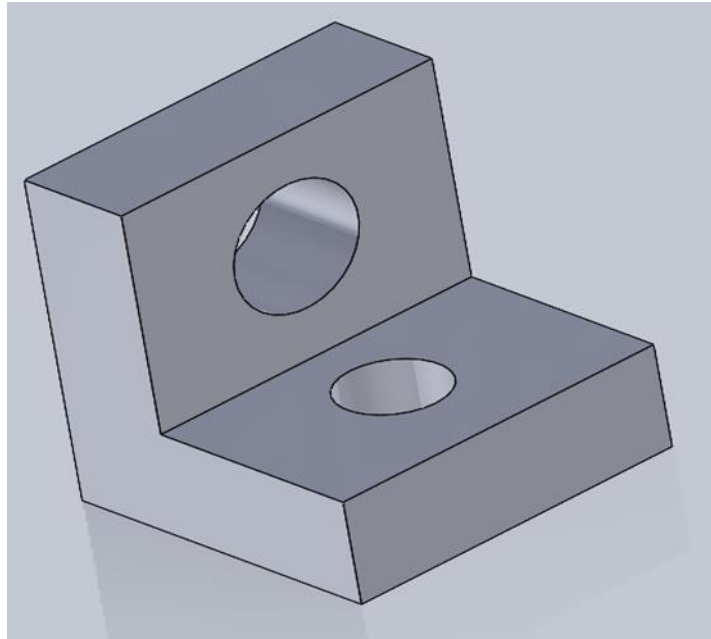


Figure 11: Image showing the 1st axle bracket prototype design.

Axle bracket design 2:

This design represents a significant leap forward in the evolution of the bracket system, incorporating key improvements that enhance both stability and alignment. Unlike previous iterations, these two brackets are specifically engineered to provide self-aligning capabilities, ensuring that the axle remains properly positioned throughout operation. The first bracket achieves this by using a long, continuous piece of material that extends from the centre of one bracket to the other. This structural reinforcement helps maintain the axle's alignment, preventing any deviations or misalignment that could negatively impact performance. Additionally, an under-over clamping mechanism is incorporated into the design, effectively reducing any unwanted movement and further securing the axle in place.

The rear brackets, positioned at the end of the chassis at a precise 90-degree angle, also play a crucial role in maintaining axle alignment. Their perpendicular orientation ensures that the axle runs true, minimising the risk of lateral shifts or rotational inconsistencies. Like the front bracket, the rear brackets also feature the under-over clamping mechanism, which serves as an additional safeguard against any unwanted displacement or instability. This level of precision in the bracket design significantly enhances the overall structural integrity of the

vehicle, leading to improved handling, smoother power transmission, and greater durability over extended periods of use.

Despite its numerous advantages, this design is not without its drawbacks. One of the most notable disadvantages is the considerable amount of material required for its construction. The extended structural elements and additional clamping mechanisms result in increased material consumption, which can lead to higher production costs and potential material wastage. Furthermore, the brackets occupy a significant amount of space on the top of the chassis. This reduction in available surface area may limit the placement of essential electrical components such as microcontrollers, wiring, sensors, and power management systems.

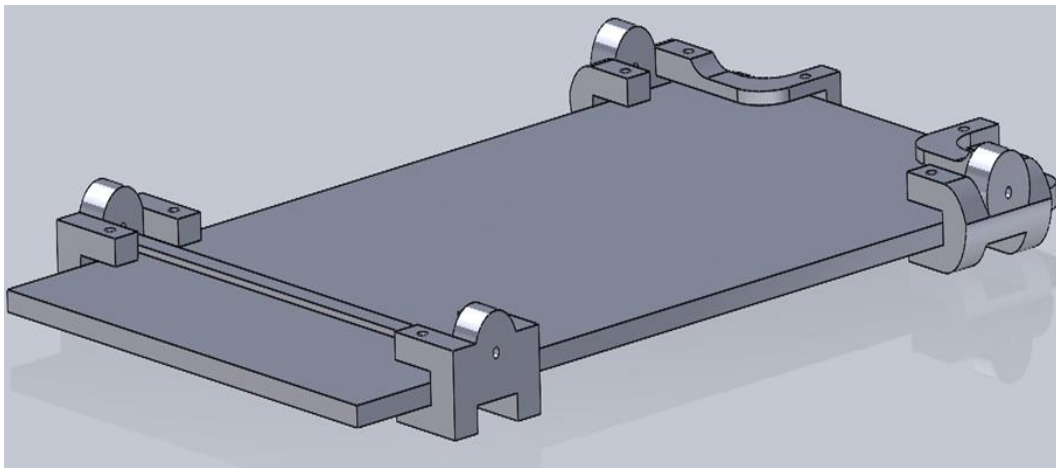


Figure 12: Image showing the 2nd axle bracket prototype design.

Axle bracket design 3:

The final design incorporates key elements from the previous iteration, carefully retaining the advantages while addressing and eliminating the disadvantages observed in earlier versions. By building upon the strengths of the previous design, this improved configuration maintains the essential self-aligning capability that ensures the axle remains properly positioned throughout operation. This self-aligning feature plays a crucial role in enhancing the vehicle's stability and performance, reducing the risk of axle misalignment, and ensuring a smoother and more efficient power transfer.

One of the most significant improvements in this final design is its overall simplification. Unlike the previous version, which featured a more complex structure with extended

components, this iteration streamlines the design, making it easier to manufacture, assemble, and maintain. By reducing unnecessary structural elements, the design not only minimises material usage but also enhances production efficiency. This reduction in material wastage is a major advantage, as it helps lower costs while also promoting a more sustainable and resource-efficient manufacturing process.

Another notable improvement is the optimised use of space on the chassis. The previous design occupied a considerable amount of surface area, which limited the available space for essential electrical components such as microcontrollers, sensors, and wiring systems. In contrast, the final design significantly reduces the amount of surface area taken up by the brackets, creating more room for critical components without compromising structural integrity. This allows for a more compact and efficient layout, ensuring that all necessary electronic and mechanical systems can be accommodated without interference.

Additionally, this refined design enables the axle to run closer to the chassis, which further contributes to improved performance and stability. A lower axle positioning helps lower the vehicle's centre of gravity, enhancing balance and reducing the likelihood of excessive vibrations or instability during operation. This adjustment not only improves handling and control but also enhances the overall durability of the system, ensuring that the axle remains secure and properly aligned even under varying loads and conditions.

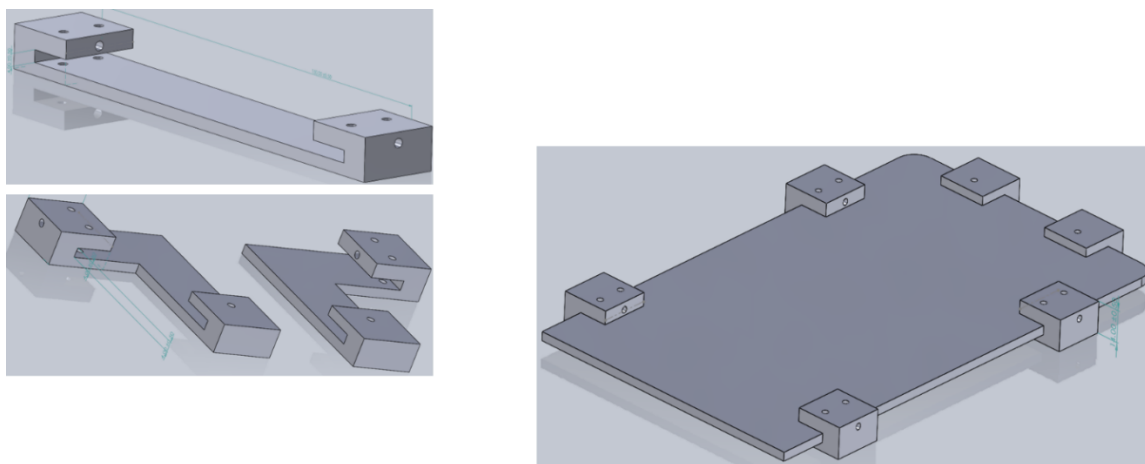


Figure 13: Image showing the 3rd and final axle bracket prototype design.

Axle Bracket choice:

Ultimately, after thorough evaluation and comparison of all proposed bracket designs, it was determined that Design 3 would be the most suitable choice for implementation. This decision was based on a combination of factors, including performance, efficiency, and practicality in real-world applications. Design 3 successfully retains all the key advantages of Design 2 while also introducing several additional benefits that make it a superior choice, effectively rendering Design 2 obsolete.

3.5 Stage 5 Motor mount design:

Motor mount design 1:

Motor Mount Design 1 offers a lightweight, simple, and cost-effective solution, but its potential for motor displacement under certain conditions raises concerns. While it may be suitable for applications where weight and space efficiency are paramount, further design modifications would be necessary to ensure the motor remains securely mounted and the system operates safely and reliably.

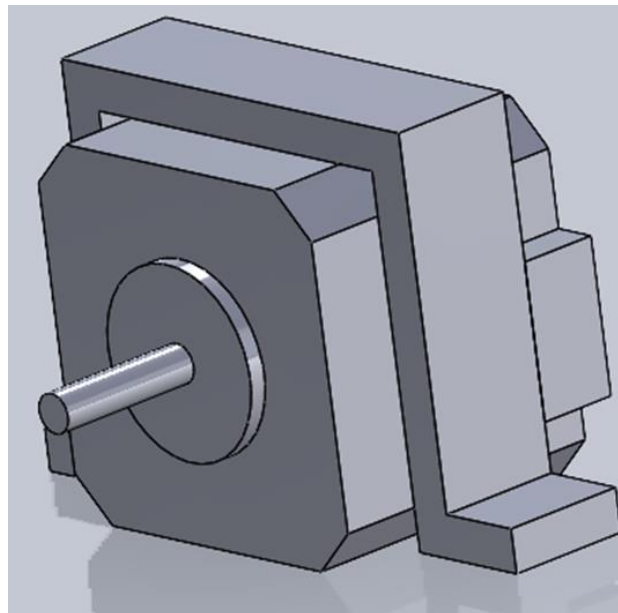


Figure 14: Image showing the 1st motor mount prototype design.

Motor mount design 2:

Design 2 offers a significant improvement over earlier versions by eliminating motor movement and ensuring a more stable and efficient system. The top-down assembly style ensures proper alignment between the motor and mount, leading to better overall performance. However, the trade-off is that this design takes up more surface area and is limited in terms of where it can be positioned within the chassis.

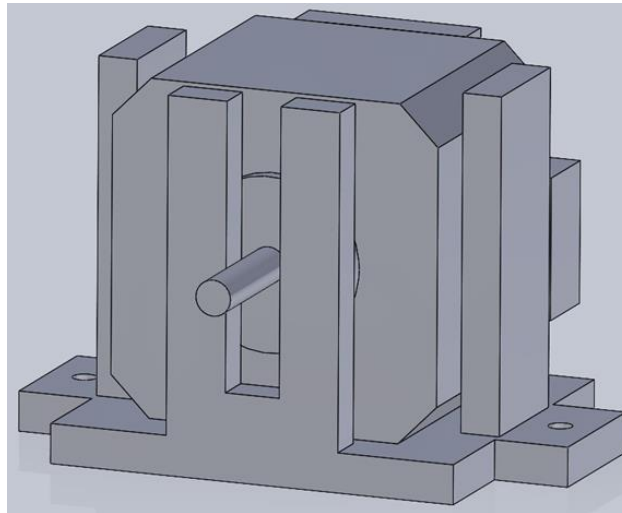


Figure 14: Image showing the 2nd motor mount prototype design.

Motor mount design 3:

Design 3 offers an impressive combination of the best features from previous designs, while successfully eliminating the disadvantage of occupying excessive space. By lifting the motor and placing it above the axle gear, this design maximises the use of available space and optimizes the overall layout.

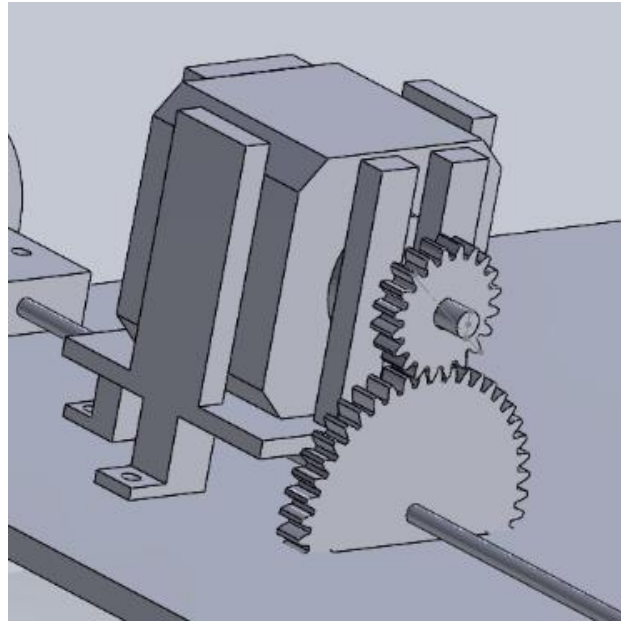


Figure 15: Image showing the 3rd and final motor mount prototype design.

Motor mount outcome:

the decision to choose Design 3 was influenced by the critical need for more space to accommodate essential components such as breadboards and circuit boards. By refining the motor placement and freeing up space within the chassis, this design allowed for a more efficient and organised system layout.

3.6 Stage 6 Lifting mechanism:

Lifting mechanism design 1:

Design 1's rack and pinion lifting mechanism offers several advantages, including simplicity, cost-effectiveness, and space efficiency. Its fewer parts make it easier to produce and maintain, while its compact design helps refine the available space on the chassis. However, the design is not without its potential drawbacks, particularly the risk of gear teeth skipping due to misalignment.

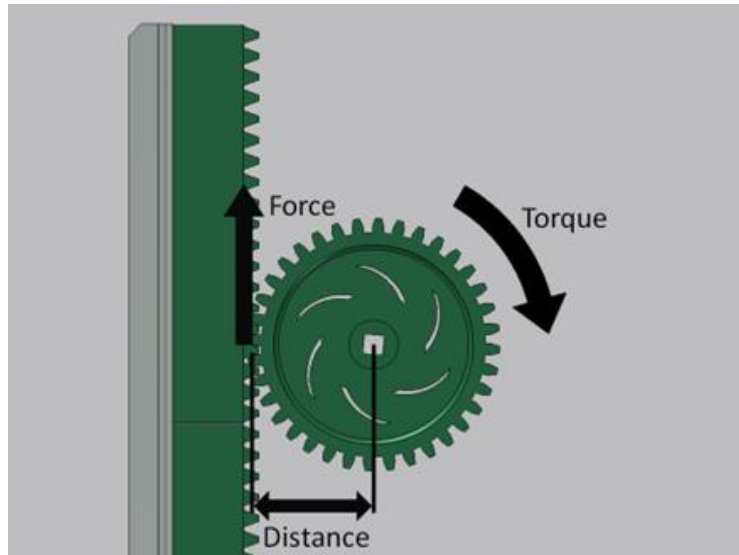


Figure 16: Image showing the 1st lifting mechanism idea.

Lifting mechanism design 2:

Design 2, with its scissor lift mechanism, offers a smooth and controlled lifting action that is highly desirable for applications requiring precision and stability. The system's ability to handle heavy loads with minimal strain on individual components ensures a longer lifespan and reliable performance. However, the primary drawback of this design is its considerable surface area requirement, which could limit space for other essential components and complicate the overall layout of the chassis. While the scissor lift design provides superior motion control, its size and complexity may make it less suitable for systems with limited available space



Figure 17: Image showing the 2nd lifting mechanism idea.

Chosen lifting mechanism:

Design 1, the rack and pinion system, was chosen as the final design due to its simplicity, cost-effectiveness, and space efficiency. The fewer components involved in its assembly, combined with the reduced surface area it occupies on the chassis, made it the most suitable option for the final design. By choosing this design, the team was able to create a more compact, lightweight, and easily assembled system that left plenty of room for other critical components. The benefits of the rack and pinion system far outweighed its potential disadvantages.

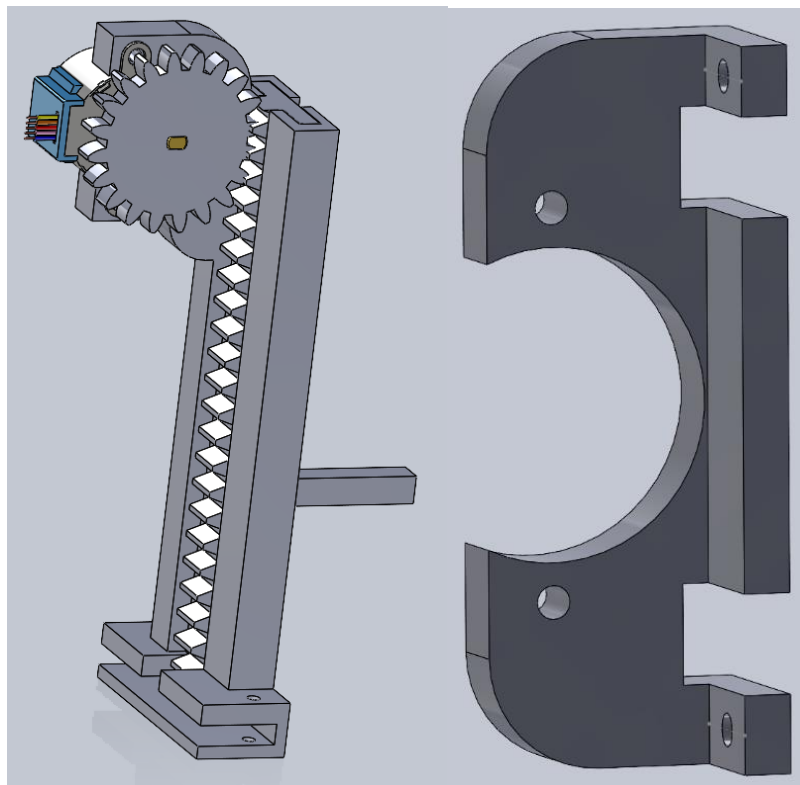


Figure 18: Image showing the final lifting mechanism design.

(Side note the motor mount for the lifting mechanism was incorporated into the design for the lifting mechanism making it a single component.)

3.7 Stage 7 Up Dated CAD Design:

Below is a version of the CAD design, which has been thoroughly revised to incorporate all the selected design components. This CAD model reflects the culmination of various stages

of the design process, integrating all the key elements that have been carefully considered and chosen for the project, as well as all the material and electrical components be represented in the CAD model giving a clearer picture of what the vehicle will look like.

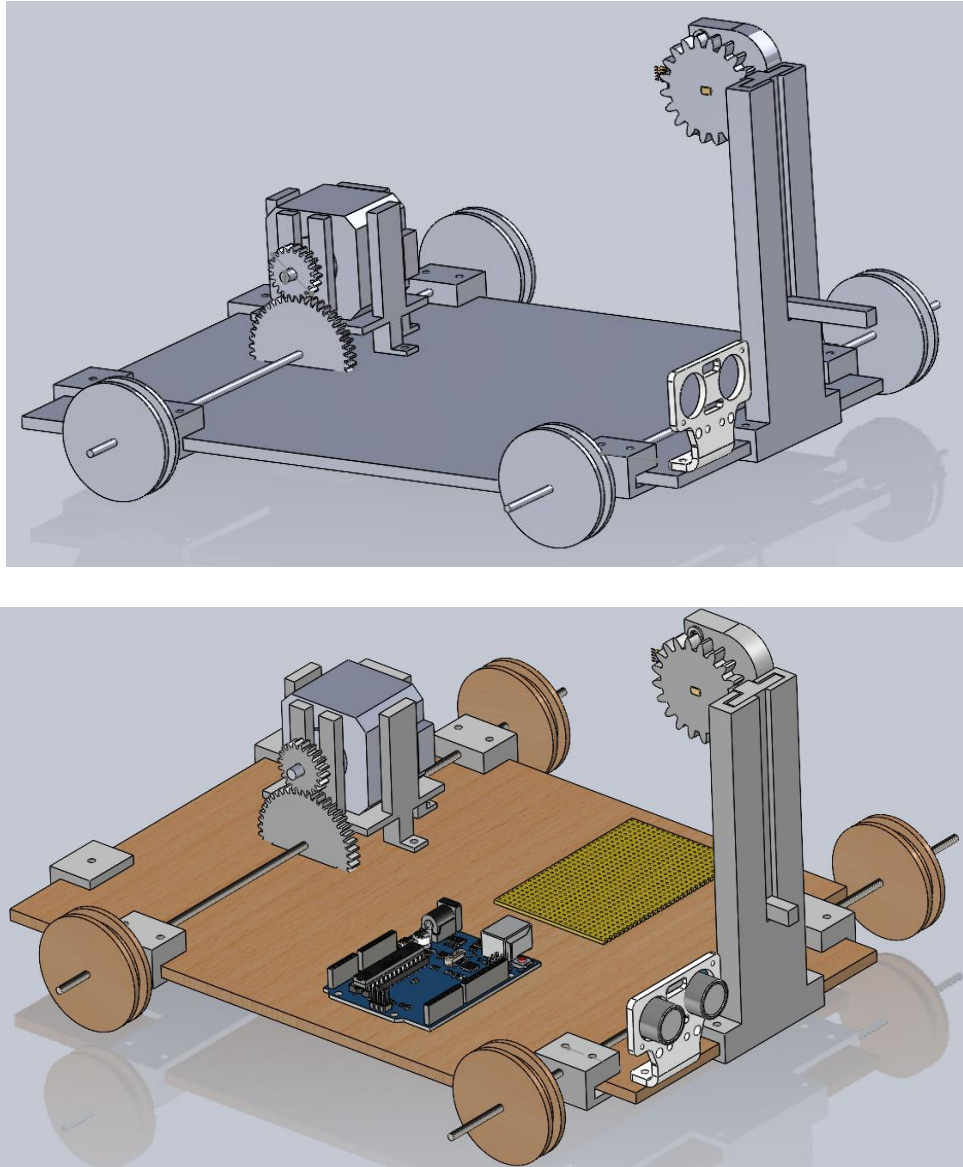


Figure 19: Images showing CAD model of repeatable vehicle.

3.8 Improving the Design

As seen from the previous section the vehicle had an abundance of unnecessary space, it was decided that a redesign of the chassis of the vehicle would be needed to decrease the size of the vehicle to have the components allocated more closely together.

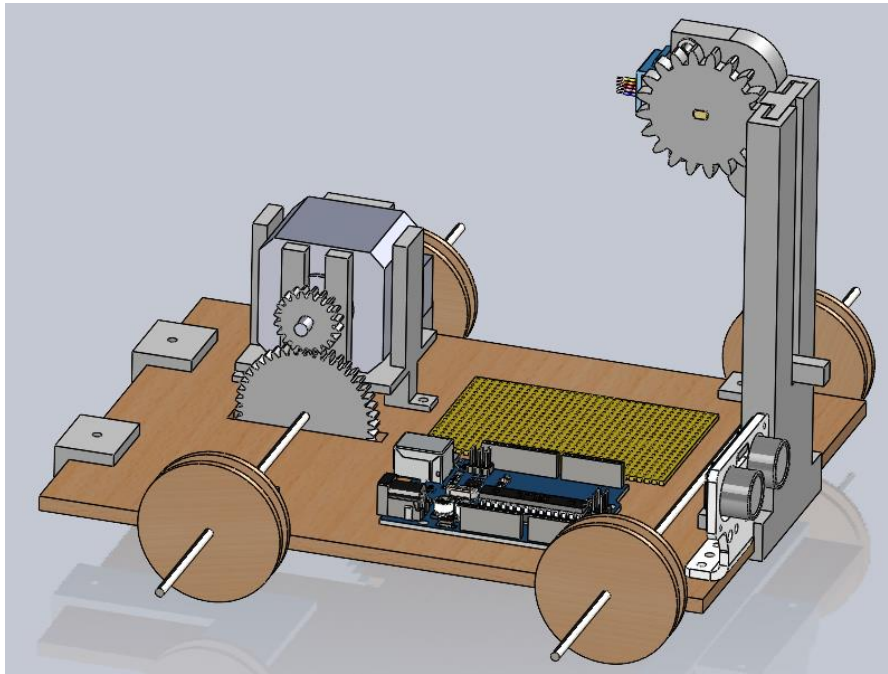


Figure 20: Image showing CAD model of reduced size of the repeatable vehicle.

4 Wheel Design and Theoretical Analysis (TJ)

4.1 Wheel research

During the early stages of development, research was conducted into previous competition winners and general wheel factors and considerations. From the research, size was a large factor in design decisions, having pros and cons for smaller wheels and larger wheels. It can be seen listed in the tables below.

Small wheels	
Pros	Cons
Compact and lightweight – small wheels reduce the overall size and weight of a vehicle	Less stable at high speeds – more prone to vibrations and bumps, leading to accuracy losses
Better acceleration – due to lower rotational mass, smaller wheels can provide quicker acceleration	Poor traction and grip – smaller contact surface area may reduce grip
Lower centre of gravity – improves stability and accuracy	Higher rolling resistance – smaller wheels require more torque to maintain speed
Cost effective – typically cheaper to manufacture or replace	Component damage – small wheels transfer vibrations more easily throughout the vehicle which could damage components or loosen them.
Agile movements – smaller wheels allow for more agile turning	

Table 1: Table showing pros and cons of small wheels.

Large wheels	
Pros	Cons
Better stability at high speeds – larger wheels maintain momentum more efficiently, offering smoother operation	Heavier and slower acceleration – increased rotational requires more energy to start moving
Improved traction and grip – a larger contact surface with the ground enhances grip	Reduced manoeuvrability – harder to turn quickly
Absorbs vibrations – reduces wear and tear on components from vehicle operation	
Lower rolling resistance – once moving, larger wheels require less torque to maintain speed	

Table2: Table showing pros and cons of larger wheels.

From the pros and cons lists, initially and currently designs for the wheels lean more towards being larger than smaller for being more stable, having larger traction and grip and most importantly being able to withstand and minimise vibrations to the other components. From a few submitted presentations from past competitors, they highlighted the accuracy loss from smaller wheels causing issues like making components move when they shouldn't, to avoid any possibility of this happening in the competition, wheels will be on the larger side.

Some methods for adding traction to the vehicle was considered, these don't necessarily have lists of pros and cons but were considerations for when entering the design stage of development. The methods considered for the design stage are as follows:

Choosing material with a high friction – this could be beneficial and save time developing a method to add traction, however material cost and manufacturing costs for that material would likely result in this option being continued with.

Grip tape – this would obviously add traction to the wheels but collects dirt and debris easily causing the lots of wear and tear to the tape, likely resulting in needing replacing, the grip tape would also cause the motion of the vehicle to be a lot less smooth adding more vibration.

Rubber toy tires – this would work well but runs the risk of deformation on under consistent load, such as during vehicle storage, costs would also potentially be high and with each design iteration, sourcing a new tire may prove difficult, however does provide good traction for indoor use.

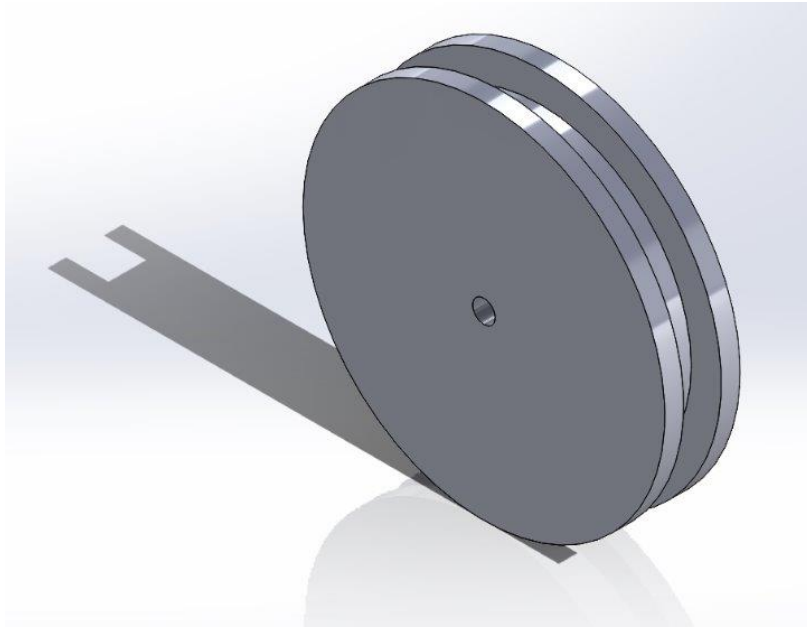
Rubber O-rings – have a low cost and easy to resource in a variety of sizes and provide good traction on smooth surfaces however can deform under load and if too thin can stretch at high rotational speeds.

For material choices there was only ever two options, laser cut plywood or 3D printed plastic as these provide by far the cheapest and strongest wheels. According to the rules laser cut plywood has zero manufacturing cost, and 3D printer filament is quite inexpensive, and the manufacturing cost is on a per gram basis, so very cheap considering 3D printed parts weigh very little.

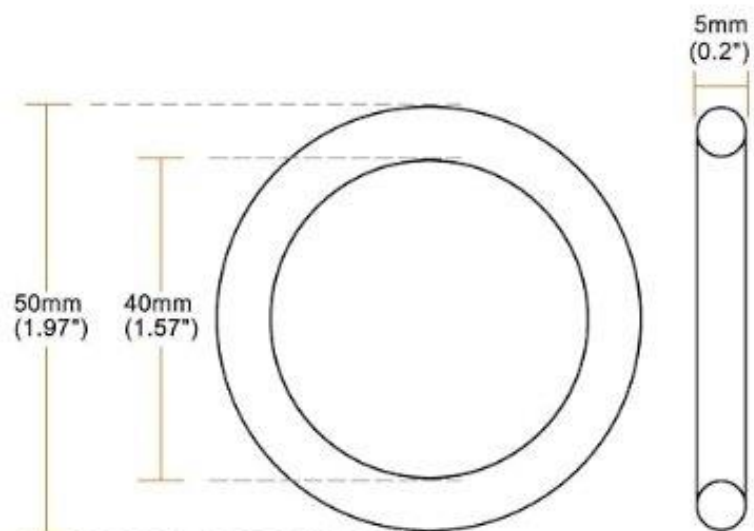
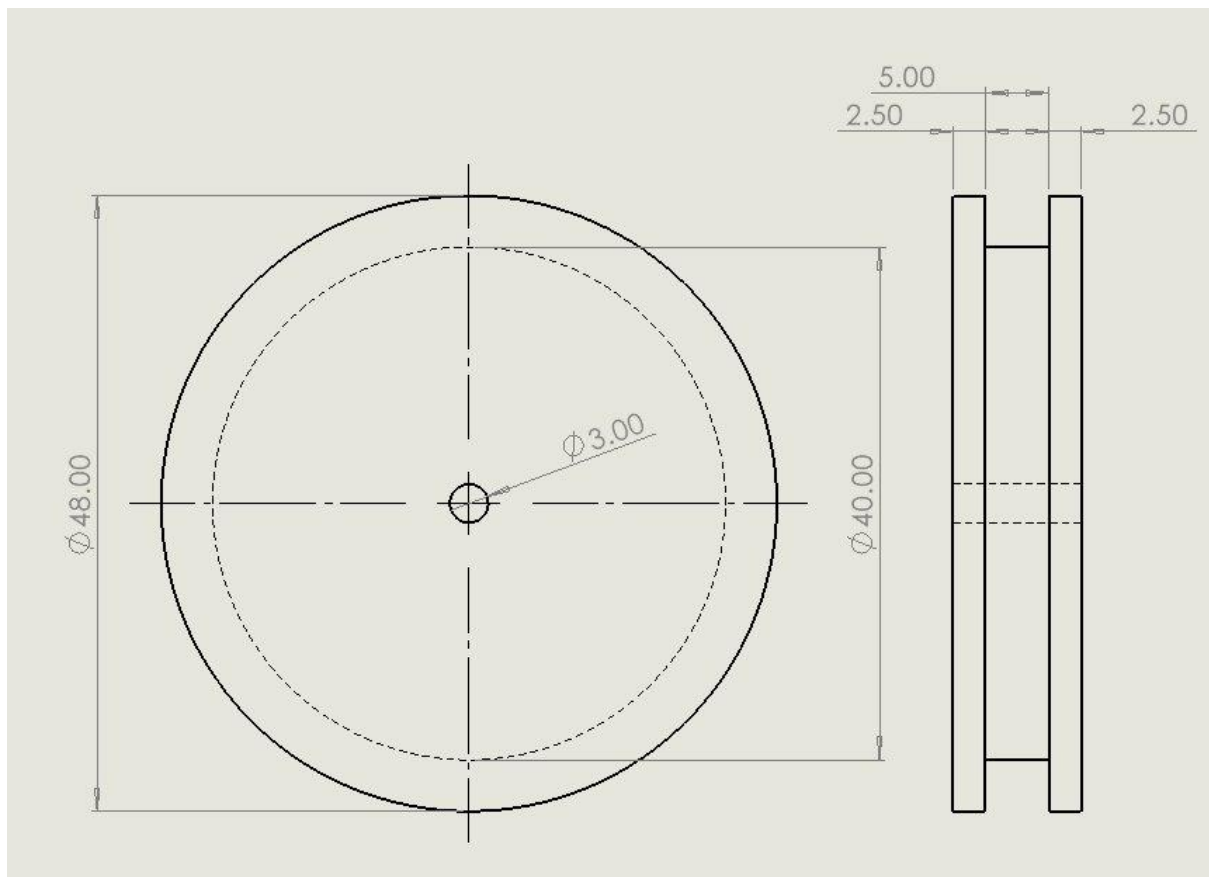
4.2 Wheel design

During development there has been three iterations of design on the wheels. There have been no major changes to the wheel design, mostly just accounting for changes needed throughout development.

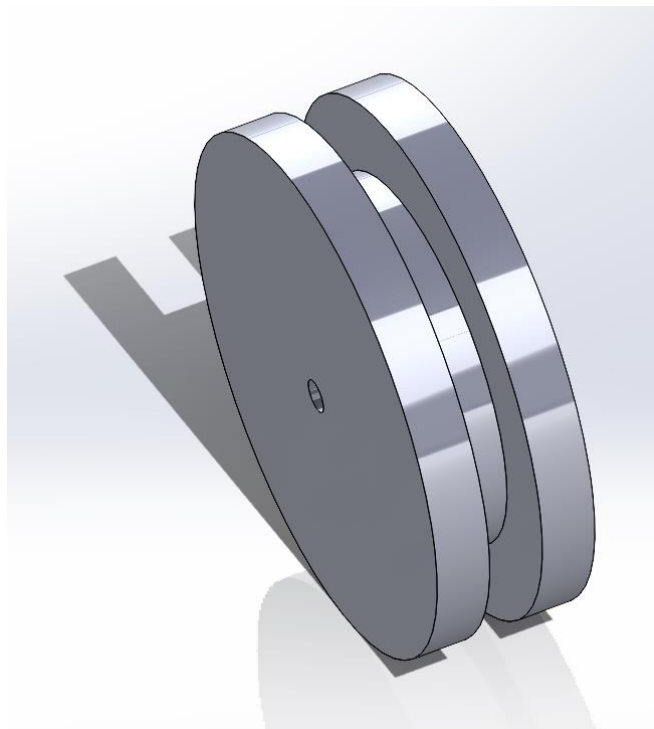
Wheel design 1 is the initial wheel design made prior to any physical parts had been made and acted more as a good starting reference point. The wheel would be made from some common 3D printing materials, whatever was available during that stage of development. This wheel design would be accompanied by a rubber O-ring within the groove to add traction to the vehicle. Choosing a thick O-ring and giving it a deep groove to rest within should counteract majority of the negatives of using an O-ring such as potential deformation under load.



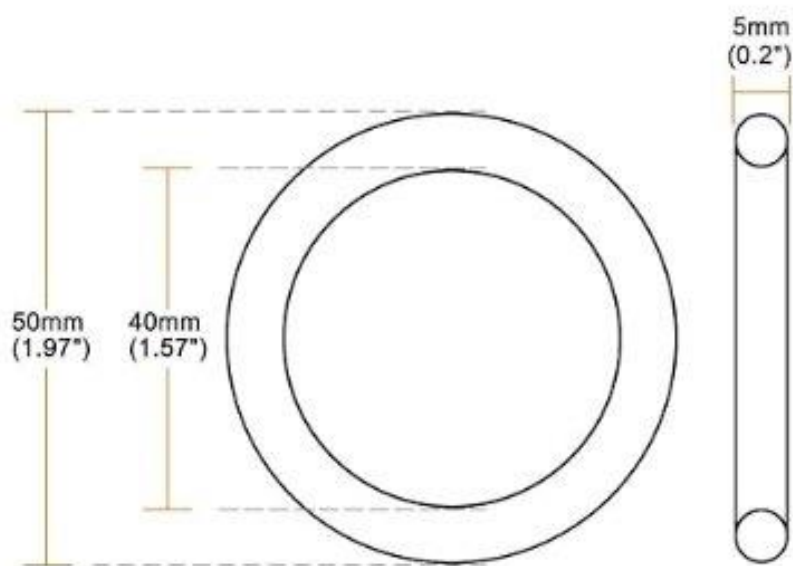
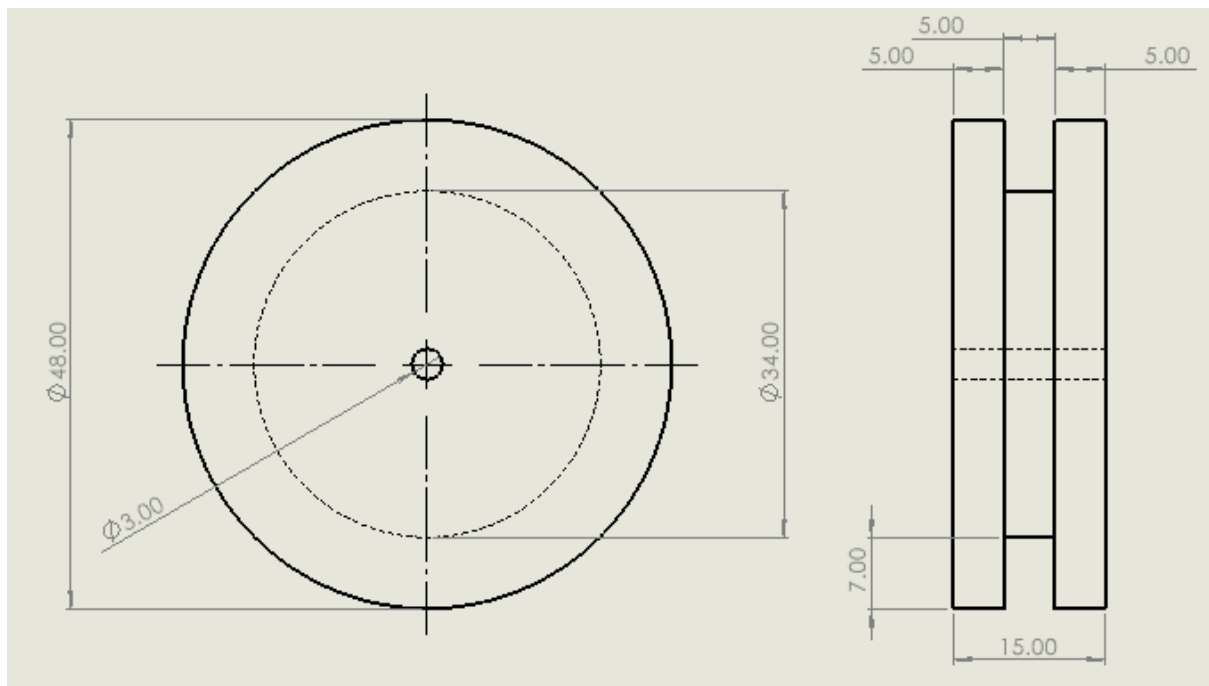
The dimensions for the wheel and O-ring for design 1 are below:



Wheel design 2 was needed due to material limitations at the time. It was advised to not 3D printing the wheels due to potential warping on the printing bed, therefore laser cut plywood was chosen. There were design limitations when it came to using plywood because the thickness of the plywood sheet would limit the dimensions used for the wheel. For the base, 5mm thick plywood was sourced, so to limit waste, it was more efficient to design the wheels around using 5mm thick plywood to save ordering more sheets of potentially varying sizes. To accomplish this, design 1 was broken into 3 parts, one inner part that the O-ring would wrap around and then two larger outer parts to surround the inner part, all being 5mm thick each.



The dimensions for the wheel and O-ring for design 2 are below:



The third design iteration and the most recent was to combat the gearing being too large and scraping along the floor during testing. This simply just required increasing the wheel radius however there was a challenge in find another O-ring that had a width of 5mm and inner thickness of 10mm. So first this design required sourcing an O-ring that fit the required needs and then design around the base dimensions of that O-ring. This resulted in design 3, a much larger version of design 2.

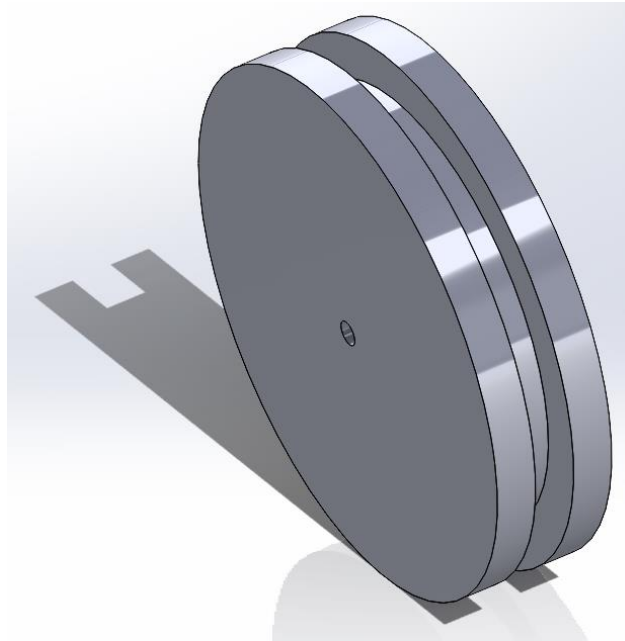


Figure 21: Image showing CAD design of the wheel.



Figure 22: Image showing O-ring to be paired with the wheel.

The dimensions for the wheel and O-ring for design 3 are below:

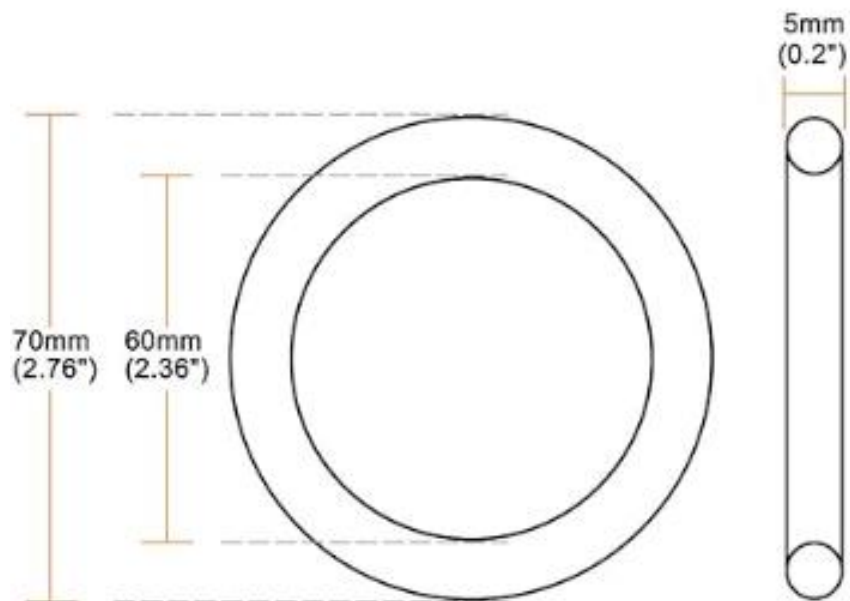
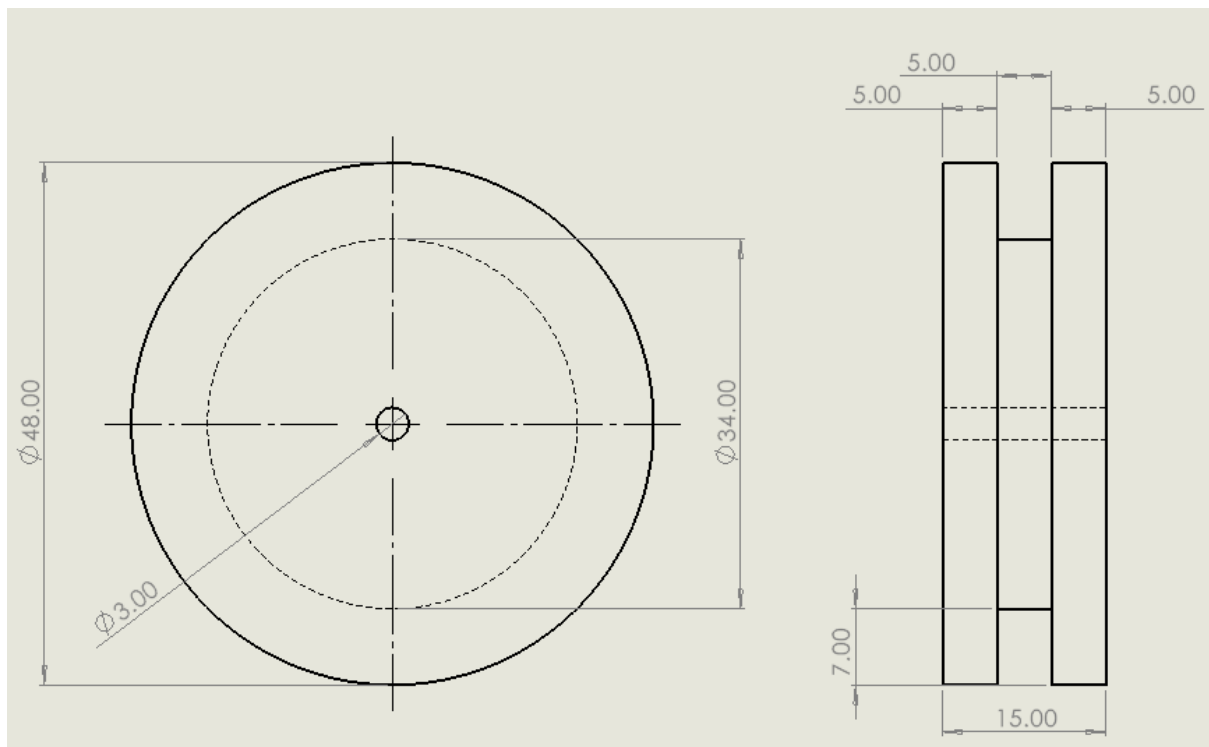


Figure 23: Image showing O-ring dimensions.

4.3 Theoretical minimum value calculations

Using control conditions based off the competition ruling, a theoretical test would help determine useful values for our variable measurements. Most important values to find at the start of the development phase would be the torque. However, during the initial development phase, a few considerations and values were not calculated and if they were, it would have likely saved some time, but due to the unfamiliarity of some aspects of the work needed to be done, some things cannot be perfect on the first attempt.

From the competition brief, it states that the set distances between the targets and from the wall to the targets is to some degree random, providing minimum and maximum values for these distances. Regardless of the distance, the time limit of 3 minutes remains the same. So, the vehicle must be able to complete the task within the time frame using the maximum possible distance to travel as the main reference when conducting tests. This will be to ensure that regardless of the competition set up, as long as the competition runners set up correctly and follow the rules, given the institutions reputation and prestige it is unlikely for an issue such as this to occur, the vehicle will be able to complete the task hopefully with time to spare.

From the brief, the maximum distance the wall can be from target 2 is 4000mm or 4m, so to have the most the distance to travel the distance between target 1 and 2 should be at its minimum of 500mm. This would create the largest distance between target 1 and the wall, which is most of the travelling takes place.

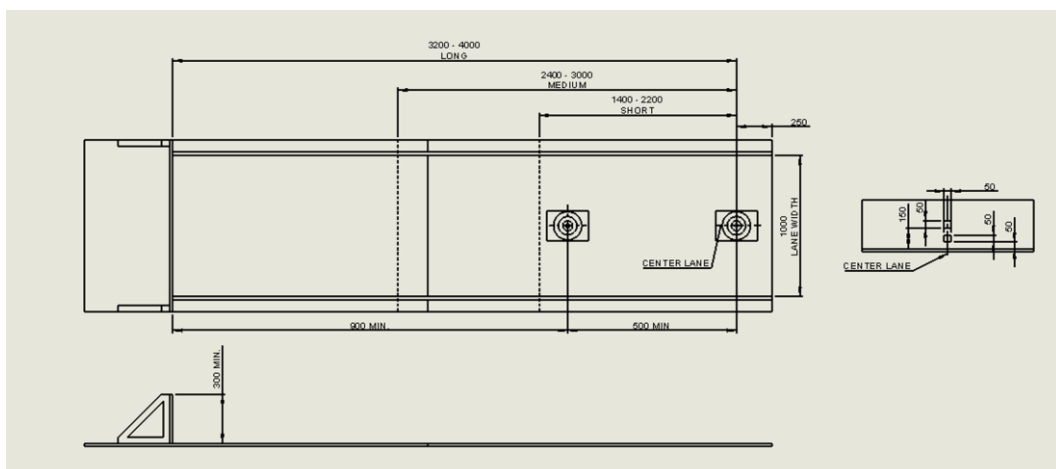


Figure 24: Image showing coarse layout and dimensions.

To calculate the minimum values needed for our vehicle to complete the task, the following control and variable measures were used.

The sum of the following distances would result in the longest possible course the vehicle could encounter in competition.

Target 1 to wall: 3500mm

Wall to target 1: 3500mm

Target 1 to wall: 3500mm

Wall to target 2: 4000mm

Total distance to travel: $(3500 \times 3) + 4000 = 11000\text{mm}$

Time:

Time allowed: 180 seconds

Time required for charging each time: 15 seconds, more would result in 0 points

Max allowed time for travel: $180 - (15 \times 2) = 150\text{ seconds}$

The following are variables that we can change with different components and/or design iterations of components. The competition flooring is expected to be wood, nitrile rubber against wood has a friction coefficient of 0.8.

Coefficient of friction (μ) = 0.8

Wheel diameter: 50mm

Max mass estimate: 2kg

Theory

Minimum speed = $d / t = 11000 / 150 = 73.4\text{mm/s}$ or 0.0734m/s

Friction force = $\mu \times m \times g = 0.8 \times 2 \times 9.81 = 15.696\text{N}$

Since we are using an electric motor and the total weight of the vehicle is so low, it is assumed to reach max velocity from acceleration in 1 second or less.

Acceleration force = $ma = 2 \times 0.074 = 0.148$

$$Total\ force\ required = 15.696 + 0.148 = 15.844N$$

$$Torque\ required = r \times F = 0.05 \times 15.844 = 0.7922Nm$$

Based off researched motors within our budget, multiple had a torque of 0.4Nm, including the ones used in the final design. So, to make these motors usable, the torque would require increasing, the simplest method for this is using gearing between the motor and the axle.

Using 0.4Nm as a reference torque for the motor, the following equation can be used to calculate the required gear ratio to allow the motor to work with the current control measures.

$$Gear\ ratio = output\ torque / input\ torque = 0.7922 / 0.4 = 1.9805$$

With a gear ratio as low as this, it would not be difficult to accommodate this in the vehicles design as it would take such a low amount of additional space. However, these are the bare minimum values required to complete it in the exact time frame which is obviously unrealistic as it would be ideal to have time spare to account for any unforeseen circumstances.

A disputable comfortable time frame to be able to complete the task would be somewhere near 110 seconds, allowing for 20 seconds spare.

The speed required to achieve this time would be as follows:

$$v = 11000 / 110 = 0.1m/s$$

The following equations change due to the speed change:

$$Acceleration\ force = ma = 2 \times 0.1 = 0.2N$$

$$Total\ force = 15.896N$$

$$Torque = rF = 0.05 \times 0.7948$$

$$Gear\ ratio = output\ torque / input\ torque = 0.7948 / 0.4 = 1.987$$

To gain 20 seconds on the longest possible course for the competition, it only required a gear ratio increase of 0.0065, which is an increase of 0.328%, incredibly minimal. This proves that as long the minimum gear ratio is met; any gear ratio should be viable and allows for the speed to be easily regulated. With such a high frictional force, there should be little worry of a potential accuracy loss with increasing the speed even further.

4.4 Current Vehicle Specification Theory

Based off the current measurements of the vehicle, the following theory was carried out to determine whether the vehicle will be able to complete the task in the allotted time along the longest possible track. The calculations show the development of understanding the required mathematics and physics and shows the process of coming to a solution for when the values fail causing the vehicle to be unable to complete the task in the allotted time.

The following is a list of all measured and sourced values, whether that is from measuring the parts of the vehicle, sourcing the information from manufacturers/retailers or setting the values in the design process.

Mass (m): 1.1kg

Motor torque (T): 0.4Nm

Max motor power (P): = 5220W

Gear ratio (GR): 2.25

Wheel radius (r): 35.5mm

Calculated values:

First it is necessary to check whether the torque is low enough to not cause the wheels to slip on the surface during the task, for this the traction force and the friction force will need to be compared.

Wheel torque:

$$\tau_{wheel} = \tau_{motor} \times GR = 0.4 \times 2.25 = 0.9Nm$$

Tractive force:

$$F_{tractive} = \frac{\tau_{wheel}}{r} = \frac{0.9}{0.0355} = 25.5N$$

Friction force:

$$F_{friction} = \mu \times m \times g = 0.8 \times 1.1 \times 9.81 = 8.64N$$

Result:

$$F_{friction}(8.64N) < F_{traction}(25.35N) \rightarrow \text{Wheels will slip}$$

The wheels under these conditions, the wheels in theory will slip, so to alleviate the issue, the torque will need to be reduced, this can be adjusted using the stepper driver by adjusting the motor speed and/or power input into the motor. To successfully do this, the max usable torque will be needed.

Max usable torque without slipping:

$$\tau_{wheelmax} = F_{friction} \times r = 8.64 \times 0.0355 = 0.307Nm$$

$$\tau_{motormax} = \frac{\tau_{wheelmax}}{GR} = \frac{0.307}{2.25} = 0.136Nm$$

Assuming the motor runs at the maximum non-slip torque of 0.136Nm, it can determine the vehicles speed. To determine this, the speed of the motor at this torque will first need to be determined and whether the input power will need to be decreased.

Motor speed:

$$P = \tau \times \omega \rightarrow \omega = \frac{P}{\tau}$$

$$\omega = \frac{5220}{0.136} = 38382\text{rad/s} = 366521\text{RPM}$$

This value is incredibly unrealistic and is likely due to high power, sourced from the amazon listing of the product which likely incorrect, however at this point in the development, there was some misunderstanding with the electrical aspects of the calculations.

Therefore, at this point, after some research, a more realistic motor speed was chosen to attempt to create some starting point for the rest of the calculations, 6000RPM was chosen as a common RPM for most small motors.

$$\omega_o = 6000RPM$$

To determine the motor speed under the torque load, it would require the stall torque of the motor. Specific technical details of this motor proved to be difficult to obtain but the stall torque according to the data sheet is the following. This is not super relevant to the final outcome but at this point in the development it was considered.

$$Stall\ torque\ (\tau_s) = 0.1568Nm$$

Motor speed with a torque of 0.136Nm:

$$\omega = \omega_o \left(1 - \frac{\tau}{\tau_s}\right) = 6000 \left(1 - \frac{0.136}{0.1568}\right) = 795.9RPM$$

Wheel RPM:

$$Wheel\ RPM = \frac{\omega}{GR} = \frac{795.9}{2.25} = 353.7RPM$$

Therefore, the vehicle speed should be the following:

Wheel circumference (C):

$$C = 2\pi r = 2\pi \times 0.0355 = 0.223m$$

Vehicle speed (v):

$$v = Wheel\ RPM \times C \times \frac{1}{60} = 353.7 \times 0.223 \times \frac{1}{60} = 1.315m/s$$

Drag forces at this low of a speed won't be impactful at all to overcome the traction of the vehicle, so no calculations are necessary.

At this speed, the vehicle would complete the longest possible course in roughly 33 seconds, including 11-12 seconds to charge two times. This is quite unrealistic and completing the course in the time would only cause more problems such as losing accuracy and therefore losing points. It would also be harder to program the exact timing of when to stop on the targets when the colour sensor detects the colours for maximum points. A more reliable and workable speed would be around 0.5m/s.

Completion time at 0.5m/s on the longest possible course:

$$2 \times 11 + 12 + 12 = 46\ seconds$$

To calculate this, it would be necessary to work backwards through the previous calculations, which is as follows.

Motor and wheel RPM calculation:

$$Wheel\ RPM = \frac{v}{C \times 0.0167} = \frac{0.5}{0.223 \times 0.0167} = 134.5RPM$$

$$\omega = Wheel\ RPM \times GR = 134.5 \times 2.25 = 302.6RPM$$

$$\omega_0 = \frac{\omega}{1 - \frac{\tau}{\tau_s}} = \frac{302.6}{1 - \frac{0.136}{0.1568}} = 2281.1RPM$$

Once the motor speed and torque requirements are discovered, all that was left to do was determine the required power input for the motor which will be regulated by the stepper driver and calculate the steps for the coding for the motor speed.

$$P = \tau \times \omega_0 = 0.136 \times \left(2281.1 \times \frac{2\pi}{60}\right) = 32.5W$$

$$2281.1 \times 200 = 456220PPS$$

The current requirement for the motor to run with these values, assuming no losses would be:

$$I = \frac{P}{V} = \frac{32.5}{7.3} = 5.56A$$

A 5.56 amp battery would cause more issues for the vehicle, such as needing to include heat sinks for safety. A much simpler solution would be to reduce the vehicles speed, especially since there is an abundance of time spare with the current theoretical parameters. If a 2.1A battery, which would be within the budget, were to be connected in series to the motor and assuming no losses, the max possible speed attainable would be as follows.

$$P_{max} = V \times I = 7.3 \times 2.1 = 15.33W$$

$$\omega_0 = \frac{P}{\tau} = \frac{15.33}{0.136} = 112.72\ radians = 1076.5RPM$$

$$\omega = \omega_0 \left(1 - \frac{\tau}{\tau_s}\right) = 1076.5 \left(1 - \frac{0.136}{0.1568}\right) = 142.8RPM$$

$$Wheel\ RPM = \frac{\omega}{GR} = \frac{142.8}{2.25} = 63.5RPM$$

$$v = Wheel\ RPM \times C \times \frac{1}{60} = 63.5 \times 0.223 \times \frac{1}{60} = 0.236m/s$$

Completion time at 0.236m/s on the longest possible course:

$$\frac{11}{0.236} + 12 + 12 = 70.61\ seconds$$

This result is favourable, completing it with time to spare to allow for power losses in the system and other potential unforeseen circumstances. A comparable battery is currently installed on the vehicle, it has 2.4 amps, slightly above what was previously theoretically tested, it should provide similar results to the previous test including power losses. To best estimate a maximum speed based off losses in just the motor and stepper the following was conducted.

Typically, stepper drivers have an efficiency estimate of 85-95%, leading to a loss of 5-15% of current being lost to heat dissipation. The motor used has estimate of 1 ohm resistance per winding at over 2 amps and has a total of two windings leading to power loss from resistance, therefore the actual current being used by the motor is the following.

$$Stepper\ efficiency\ assumption = 90\%$$

$$Current\ being\ supplied\ to\ the\ motor = 2.4 \times 0.9 = 2.16A$$

$$Resistance\ per\ winding = 1\Omega$$

$$Power\ loss\ per\ winding = I^2 \times R = 2.16^2 \times 1 = 4.6656W$$

$$P_{max} = V \times I - (4.6656 \times 2) = 7.3 \times 2.16 - (4.6656 \times 2) = 6.4368W$$

Due to losses, there is a lot less power to work with in the motor and to maintain the motor torque needed for the vehicle to move, the motor speed and therefore the vehicles speed will have to decrease. The calculations to determine the max speed of the vehicle with the new parameters is the following.

$$\omega_0 = \frac{P}{\tau} = \frac{6.4368}{0.136} = 47.329 \text{ radians} = 4.9RPM$$

$$\omega = \omega_0 \left(1 - \frac{\tau}{\tau_s}\right) = 4.9 \left(1 - \frac{0.136}{0.1568}\right) = 0.65RPM$$

$$Wheel \text{ RPM} = \frac{\omega}{GR} = \frac{0.65}{2.25} = 0.28RPM$$

$$v = Wheel \text{ RPM} \times C \times \frac{1}{60} = 0.28 \times 0.223 \times \frac{1}{60} = 0.001m/s = 1.074mm/s$$

$$\frac{11}{0.001} + 12 + 12 = 11024 \text{ seconds}$$

This is unacceptable as a completion time. To combat this, assume the stall torque is negligible due to the load torque being smaller than the stall torque of the motor.

$$\omega = \omega_0 = 4.9RPM$$

$$Wheel \text{ RPM} = \frac{\omega}{GR} = \frac{4.9}{2.25} = 2.17RPM$$

$$v = Wheel \text{ RPM} \times C \times \frac{1}{60} = 2.17 \times 0.223 \times \frac{1}{60} = 0.008m/s = 8.094mm/s$$

$$\frac{11}{0.008} + 12 + 12 = 1399 \text{ seconds}$$

Even under the assumption that the stall torque is negligible, the vehicle still is not reaching speeds that can complete the competition task within the time limit.

After researching the topic more, a NEMA 17 (the current motor driving the vehicle) data sheet was found, providing a torque vs speed graph for the motor running at 24 volts half step at 1.2 amps constant current.

● Pull out torque curve:

VOLTAGE: 24VDC, CONSTANT CURRENT: 1.2A, HALF STEP

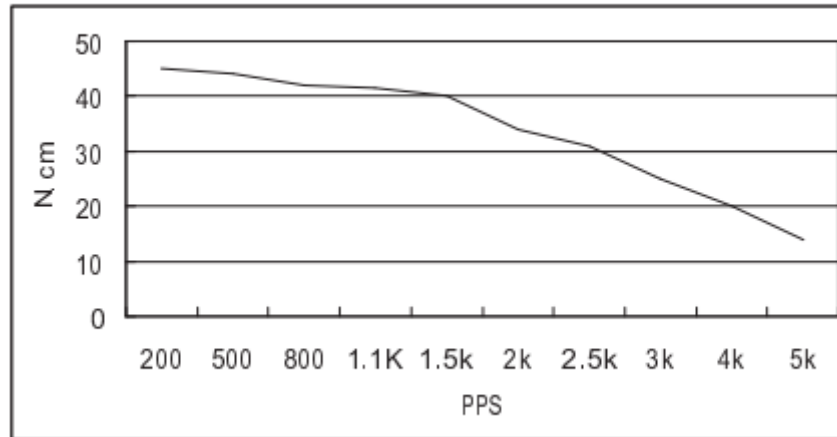


Figure 24: Image showing motor output torque curve.

However, due to minor lack of understanding, the use of the graph proved to be useless in determining a solution to the problem. As a next step, it was worth testing whether having no gear increase will help the speed output.

$$F_{friction} = \mu \times m \times g = 0.8 \times 1.1 \times 9.81 = 8.64N$$

$$\tau_{wheelmax} = F_{friction} \times r = 8.64 \times 0.0355 = 0.307Nm$$

With no gear increase:

$$\tau_{motormax} = \tau_{wheelmax}$$

Then with a new minimum torque requirement, the speed would be as follows:

$$P_{max} = V \times I - (4.6656 \times 2) = 7.3 \times 2.16 - (4.6656 \times 2) = 6.4368W$$

$$\omega = \frac{P}{\tau} = \frac{6.4368}{0.307} = 20.9668 \text{ radians} = 2.1RPM = \text{Wheel RPM}$$

$$v = \text{Wheel RPM} \times C \times \frac{1}{60} = 2.1 \times 0.223 \times \frac{1}{60} = 0.007m/s = 7.805mm/s$$

To avoid wasting more time writing out calculations for each minor change, it was more time efficient to create a spreadsheet on excel, making all the formulas used in the calculations, functions in the cells. This allows for minor changes to be automatically calculated, saving large amounts of time in troubleshooting the calculations to find an optimal solution.

After arduous testing, making small changes to many different values shown in the below spreadsheet, the only way to make this design work and complete the competition task in the allotted time is with the following changes to system.

Gear ratio: 1:5 decrease

Voltage to the motor: 12V

With these changes, the vehicle would move at 0.08m/s, resulting in a completion time of 160 seconds, allowing 20 seconds to account for an issues and unforeseen circumstances.

The only design change would be to change the gearing between the motor and wheels, which should prove to be quite simple.

Mass	Motor torque	Wheel torque	Wheel radius	Tractive force	Friction coefficient	Friction	Slip check	Max wheel torque	Gear ratio	Max motor torque	Voltage	Current
1.1	0.4	0.9	0.0355	25.35211268	0.8	8.6328	Fail	0.3064644	2.25	0.1362064	7.3	2.4
1.1	0.4	0.4	0.0355	11.26760563	0.8	8.6328	Fail	0.3064644	1	0.3064644	7.3	2.4
1.1	0.4	0.08	0.0355	2.253521127	0.8	8.6328	Pass	0.3064644	0.20	0.4	12	2.4
1.1	0.4	20.88	0.0355	588.1690141	0.8	8.6328	Fail	0.3064644	52.2	0.005870966	12	2.4
1.1	0.4	0.9	0.0355	25.35211268	0.8	8.6328	Fail	0.3064644	2.25	0.1362064	24	2.4
1.1	0.4	0.2	0.0355	5.633802817	0.8	8.6328	Pass	0.3064644	0.50	0.4	12	2.4
1.1	0.4	0.2	0.0355	5.633802817	0.8	8.6328	Pass	0.3064644	0.5	0.6129288	7.3	2.4
1.1	0.4	0.4	0.0355	11.26760563	0.8	8.6328	Fail	0.3064644	1	0.3064644	24	2.4
1.1	0.4	0.9	0.0355	25.35211268	0.8	8.6328	Fail	0.3064644	2.25	0.6895449	7.3	2.4
1.1	0.4	0.9	0.0355	25.35211268	0.8	8.6328	Fail	0.3064644	2.25	0.1362064	12	2.4
1.1	0.4	0.9	0.0355	25.35211268	0.8	8.6328	Fail	0.3064644	2.25	0.1362064	24	2.4
1.1	0.4	0.9	0.0355	25.35211268	0.8	8.6328	Fail	0.3064644	2.25	0.6895449	7.3	2.4

Stepper efficiency	Current to the motor	Motor resistance	Power loss	Power	Max power	Motor angular velocity	Motor RPM	Wheel RPM	Velocity	Completion time	Remaining time
0.9	2.16	1	9.3312	17.52	6.4368	47.25769127	4.946305	2.1983578	0.00817	1370.296437	Fail
0.9	2.16	1	9.3312	17.52	6.4368	21.00341834	2.1983578	2.1983578	0.00817	1370.296437	Fail
0.9	2.16	1	9.3312	28.8	16.5888	41.472	4.340736	21.70368	0.08067	160.3658723	19.63412769
0.9	2.16	1	9.3312	28.8	16.5888	2825.565906	295.74256	5.6655664	0.02106	546.3910655	Fail
0.9	2.16	1	9.3312	57.6	42.5088	312.0910618	32.665531	14.518014	0.05396	227.859928	Fail
0.9	2.16	1	9.3312	28.8	16.5888	41.472	4.340736	8.681472	0.03227	364.9146808	Fail
0.9	2.16	1	9.3312	17.52	6.4368	10.50170917	1.0991789	2.1983578	0.00817	1370.296437	Fail
0.95	2.28	1	10.3968	57.6	44.3232	144.6275652	15.137685	15.137685	0.05626	219.5147847	Fail
0.9	2.16	1	9.3312	17.52	6.4368	9.334852596	0.9770479	0.4342435	0.00161	6839.625713	Fail
0.9	2.16	1	9.3312	28.8	16.5888	121.7916339	12.747524	5.6655664	0.02106	546.3910655	Fail
0.95	2.28	1	10.3968	57.6	44.3232	325.4120218	34.059792	15.137685	0.05626	219.5147847	Fail
0.9	2.16	1	9.3312	17.52	6.4368	9.334852596	0.9770479	0.4342435	0.00161	6839.625713	Fail

Figure 26: Image showing theoretical analysis for the vehicle.

For coding the motor, 4340 steps will be needed to achieve the angular velocity required for the motor.

$$200 \times 21.7 = 4340$$

The spread sheet also acts as an easy method test any future changes to the vehicle, due the functions used in each of the cells, any one change would change any and all values that it effects.

4.5 Bill of materials

A mandatory part to enter the competition is submit a bill of materials to the IMechE, this is to ensure the vehicle and other competitor's vehicles are strictly following the rules of the competition in terms of cost. This has to be incredibly accurate to ensure that the vehicle and team are not disqualified from the competition. The following spreadsheet is the teams bill of materials for the vehicle, so far it is unfinished due timing issues and waiting on invoices for the materials and components, it is expected to be completed by the time it is requested by the IMechE.

Bill of materials								
Device Area	Bom item line	Part Number	Design iteration/revision	Part Name	Quantity (units/g/mm)	Unit Cost (£/unit; £/g; £/mm - VAT inc.)	Total Cost (£ - VAT inc.)	IMechE BoM Cost (£ - VAT inc.)
Mechanical structure	1	M001	N/A	Axle	2	£1.20	£2.40	£2.40
	2	M002		Axle Gear	1	£0.06	£0.06	£0.00
	3	M003		Rear motor gear	1	£0.01	£0.01	£0.00
	4	M004		Rear motor mount	1	£0.18	£0.18	£0.00
	5	M005	2	Base	1	£2.70	£2.70	£2.70
	6	M006	3	Wheel	4	£2.70	£2.70	£2.70
	7	M007	N/A	Nitrile Rubber O-Rings	4	£0.98	£3.91	£3.91
	8	M008		Lifting mechanism case	1	£0.46	£0.46	£0.46
	9	M009		Lifting mechanism spine	1	£0.19	£0.19	£0.00
	10	M010		Lifting mechanism gear	1	£0.13	£0.13	£0.00
	11	M011		Ultrasonic sensor mount	1	£0.01	£0.01	£0.00
	12	M013		Rear support bracket	2	£0.14	£0.28	£0.28
	13	M014		Front support bracket	1	£0.19	£0.19	£0.00
	14	M015	1	Battery holder	1	£0.00	£0.00	£0.00
	Mechanical structure IMechE BoM - Partial (£)							£12.17
Electrical components	14	E001	N/A	NEMA 17 Stepper Motor	1	£10.50	£10.50	£10.50
	15	E002	N/A	28BYJ-48 Stepper Motor	1	£4.00	£4.00	£4.00
	16	E003	N/A	Elgoo Uno R3	1	£12.75	£12.75	£12.75
	17	E004	N/A	TCS32725 Colour Sensor	1	£4.99	£4.99	£4.99
	18	E005	N/A	HC-SR04 Ultrasonic Sensor	1	£3.99	£3.99	£3.99
	19	E006	N/A	12V 2.4Ah Ni-MH Battery	1	£19.99	£19.99	£19.99
	20	E007	N/A	??Charging LED??	1			£0.00
	21	E008	N/A	Stepper driver 1	1			£0.00
	22	E009	N/A	Stepper driver 2	1			£0.00
	23	E010	N/A	Breadboard	1	£3.99	£3.99	£3.99
	Electrical components IMechE BoM - Partial (£)							£60.21
Consumables	23	C001	N/A	3mm screw				
	24	C002	N/A	3mm bolt				
	25	C003	N/A					
	26	C004	N/A					
	27	C005	N/A					
	Consumables IMechE BoM - Partial (£)							

Material	Density (kg/m)	Mass (g)	Total Mass (g)	Manufacturing technique / purchased item	Supplier	Hyperlink	Invoice
Steel		0.017	0.034	COtS	Amazon	Item purchase link	
Polyatic acid		0.005	0.005	3D printed	Amazon	Material purchase link	
Polyatic acid		0.001	0.001	3D printed	Amazon	Material purchase link	
Polyatic acid		0.014	0.014	3D printed	Amazon	Material purchase link	
Plywood		0.15	0.15	Laser Cut	Amazon	Material purchase link	
Plywood		0.029	0.116	Laser Cut	Amazon	Material purchase link	
Nitrile Rubber			0	COtS	Amazon	Item purchase link	
Polyatic acid		0.036	0.036	3D printed	Amazon	Material purchase link	
Polyatic acid		0.015	0.015	3D printed	Amazon	Material purchase link	
Polyatic acid		0.01	0.01	3D printed	Amazon	Material purchase link	
Polyatic acid		0.001	0.001	3D printed	Amazon	Material purchase link	
Polyatic acid		0.011	0.022	3D printed	Amazon	Material purchase link	
Polyatic acid		0.015	0.015	3D printed	Amazon	Material purchase link	
Polyatic acid			0	3D printed	Amazon	Material purchase link	
N/A	N/A	0.224	0.224	COtS	Amazon	Item purchase link	
N/A	N/A	0.032	0.032	COtS			
N/A	N/A	0.037	0.037	COtS	Amazon	Item purchase link	
N/A	N/A	0.001	0.001	COtS			
N/A	N/A	0.008	0.008	COtS			
N/A	N/A	0.225	0.225	COtS			
N/A	N/A		0	COtS			
N/A	N/A	0.003	0.003	COtS			
N/A	N/A	0.012	0.012	COtS			
N/A	N/A	0.039	0.039	COtS			

Figure 27: Image showing bill of materials for the project.

According to the rules of the competition, any cost under 20p is negligible towards the total cost of the vehicle.

5 Electronics And Code (Ziki)

5.1 Introduction – Electrical & Programming Of The Repeatable Vehicle

In this project, I was responsible for the electrical design and programming of the repeatable vehicle. My role included selecting and integrating key electrical components, developing the control algorithms, and ensuring the vehicle integrates all the sensors and actuators to run smoothly. The electrical and control systems play a pivotal role to the project, as they ensure autonomous navigation of the test track, wall detection, and decision machining such as stopping the vehicle and controlling the charging mechanism.

The electrical system consists of a NEMA 17 stepper motor, which is controlled by an A4988 stepper driver, HC-SR04 ultrasonic sensor for wall detection, and a TCS34725 colour sensor for floor target detection. These components will be controlled using the Arduino Uno, which uses the data that it gets from the sensors to achieve autonomous movement.

This section of the report will mainly look at the selection and justification of components, the circuit design and wiring process, the development of the vehicle's control software, and the testing and troubleshooting undertaken. It will also cover the challenges faced such as motor control, sensor accuracy problems, software debugging, and the solutions to these challenges faced. It will also evaluate the systems overall performance and suggest potential improvements for future development.

5.2 Component Selection & Justification

The selection of the components for the repeatable vehicle was based on factors such as performance, compatibility, power efficiency, and ease of integration. Below is a detailed justification for each component used in the system:

1. **Microcontroller: Arduino Uno**

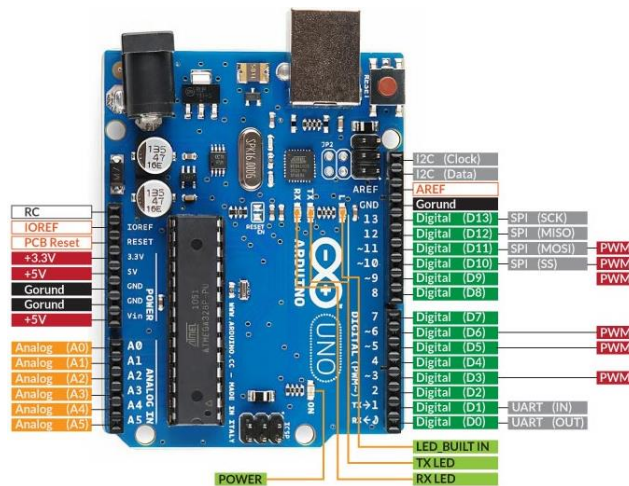


Figure 28: Image showing Arduino Uno and pin locations.

Justification:

The Arduino uno is the microcontroller of chose for the autonomous vehicle due to the following reasons:

- **Easy to use:** The Arduino IDE provides an intuitive programming environment, and the Uno has a very large support community making troubleshooting easy.
- **Sufficient I/O pins:** The Uno has a set of 14 digital pins and 6 analog pins as shown in figure 1, allowing it to interface with multiple sensors and motor drivers.
- **Compatibility:** Support multiple protocols such as I2C, SPI, and UART, making it suitable for interacting with the TCS34725 colour sensor and HC-SR04 ultrasonic sensor.
- **Reliable power management:** It can be powered via 5V USB or an external 5-12V power supply using the barrel jack as shown in figure 1. This provides flexibility in system power design.
- **Processing capability:** The ATmega328P microcontroller operates at 16MHz, which is enough for real time sensor monitoring and motor control.

Alternative considerations:

- **Raspberry Pi** – Is more powerful but requires an additional motor controller and is more power hungry.

- **ESP32** – Has built in Wi-Fi/Bluetooth but was unnecessary for this project and could be on the verge of breaking the rules on wireless control.

2. Motor: NEMA 17 stepper motor

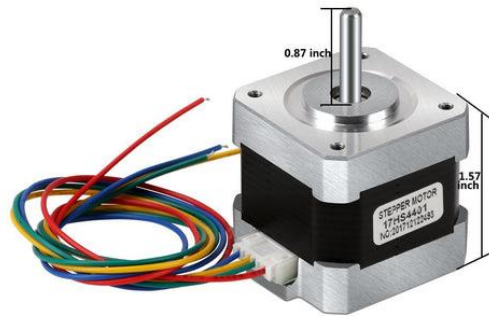


Figure 29: Image showing NEMA 17 stepper motor.

Justification:

The actuator responsible for the repeatable vehicle's motion control is the NEMA 17 motor due to having the following attributes:

- **Precise motor control:** The NEMA 17 moves in discrete steps at 1.8 degrees per step and 200 steps per revolution, allowing for higher accuracy movement.
- **Torque & load capacity:** Has sufficient torque to move the vehicle while maintaining an impressive level of stability.
- **Feedback not required:** Unlike DC motors, stepper motors can operate in an open loop, which simplifies the control without needing an encoder.
- **Micro stepping support:** can have smoother motion when driven by the A4988 driver.

Alternative considerations:

- **DC motor with encoder** – does not allow for precise movement control.
- **Servo motor** – Limited to specific angles and unsuitable for continuous rotation.

3. Motor Driver: A4988 Stepper Motor

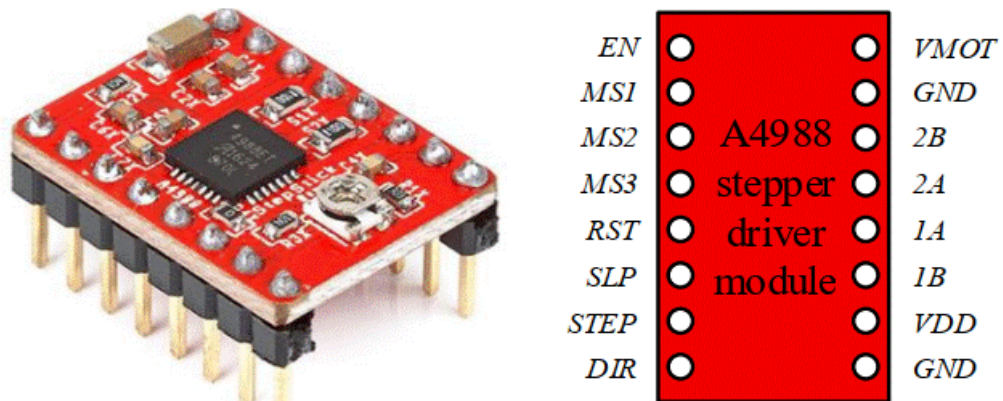


Figure 30: Image showing A4988 stepper driver and pin locations.

Justification:

The A4988 driver was paired with the NEMA17 stepper motor due to:

- **Micro-stepping capability:** it can improve the motors smoothness by choosing between full-step, half-step, $\frac{1}{4}$ step, $\frac{1}{8}$ step, and $\frac{1}{16}$ step micro-stepping.
- **Built-in current limiting:** Can protect the motor and prevent it from overheating.
- **Compact size:** Can be integrated with the vehicles other electronics without taking up too much space.
- **Easy to control:** Requires only two input signals from the Arduino (STEP & DIR pins).

Alternative considerations:

- **DRV8825** – Offers $\frac{1}{32}$ micro-stepping but is more expensive and would take us out of budget.
- **L298N H-Bridge** – not designed for stepper motors and is more suited for DC motors.

4. Ultrasonic Sensor: HC-SR04

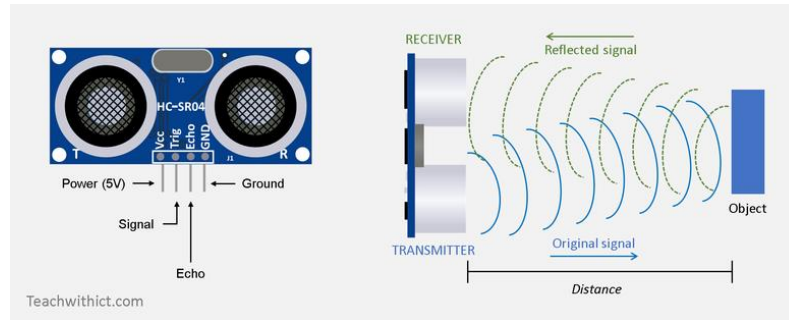


Figure 31: Image showing HC-SR04 ultrasonic sensor and pin locations.

Justification:

To detect the wall the HC-SR04 ultrasonic sensor was chosen due to the following attributes:

- **Accurate distance measurement:** Measures the distance from 2cm to 400cm with an accuracy of $\pm 3\text{mm}$.
- **Low cost:** It is cost effective and readily available compared to alternatives such as LiDAR.
- **Simple integration:** Uses two pins which are the trigger and echo pins for easy integration with the Arduino.
- **Non-contact sensing:** Does not require any physical contact with the wall, which helps with the autonomous navigation.

Alternative considerations:

- **LiDAR (Light Detection and Ranging)** – It is more accurate but very expensive and requires a lot of power to run.
- **Infrared sensors** – Less accurate and affected by any ambient light.

5. Colour Sensor: TCS34725



Figure 32: Image showing TCS34725 colour sensor and pin locations.

Justification:

The TCS34725 colour sensor was chosen for detecting the coloured targets on the track because of their ability to:

- **High sensitivity:** It can detect RGB colour values with a 16-bit accuracy.
- **Built-in IR filter:** Can improve accuracy by reducing interference from ambient infrared light.
- **Compact & lightweight:** Ideal for mounting on the vehicle allowing for space saving.

Alternative considerations:

- **TCS3200** – Older and less accurate than the TCS34725.
- **Camera-based detection** – More powerful but requires image processing, making it out of budget.

6. Power supply: 12V NI-MH 2400mAh battery

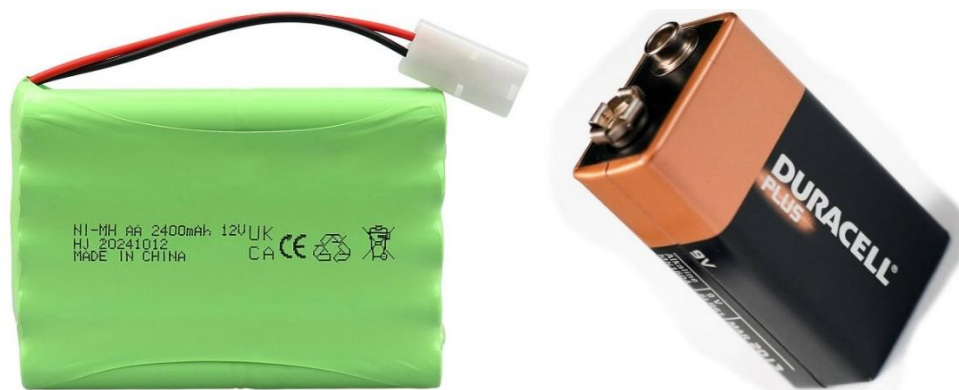


Figure 33: Image showing 12V NI-MH and 9V battery .

Justification:

The power supply design ensures that there is a stable operation of all the components:

- **Battery:** 12V NI-MH 2400mAh powers the stepper motor and Arduino.
- **Battery:** 9V battery powers the Arduino.

Alternative considerations:

- **Direct USB power** – limited current supply, unsuitable for driving the motors.

5.3 Circuit Design and Wiring

The foundation of the repeatable vehicle is formed by the circuit design and wiring as it ensures that the vehicle functions well by integrating all the components together. The goals for the electrical system are to provide stable power, precise motor control, and accurate sensor data processing. This chapter will look at the circuit layout and design considerations for the repeatable vehicle.

5.3.1 Wiring Diagram

The repeatable vehicle's electrical system consists of the following components:

1. Arduino Uno
2. NEMA 17 stepper motor paired with A4988 stepper driver
3. HC-SR04 ultrasonic sensor
4. TCS34725 Colour sensor
5. 12V NI-MH battery pack for stepper motor and 9V battery for Arduino Uno

Below is a wiring schematic that illustrates how each of the components are connected to make the repeatable vehicle function as intended.

NEMA17

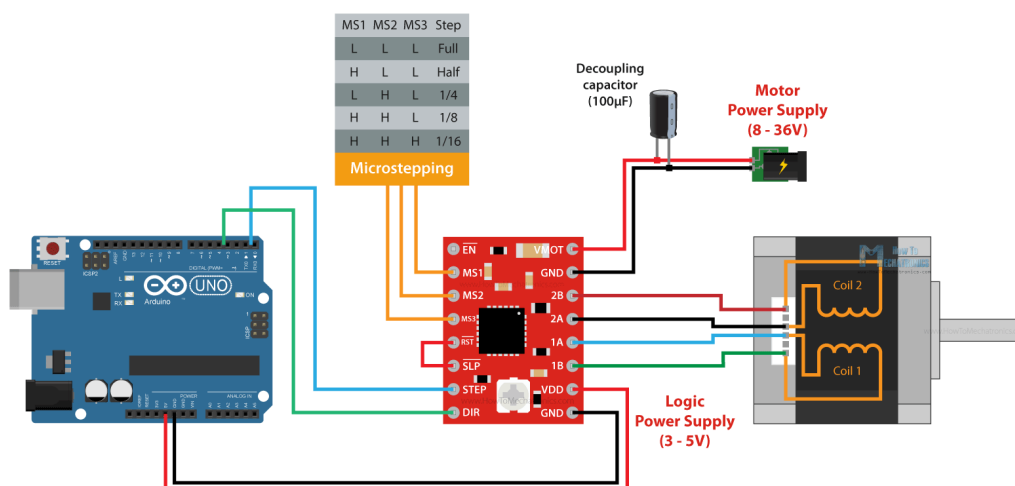


Figure 34: Image showing motor wiring diagram.

Ultrasonic sensor

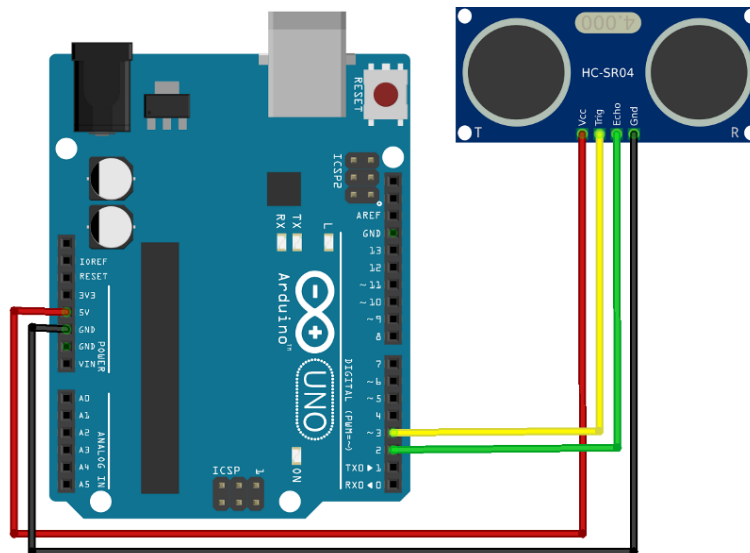


Figure 35: Image showing ultrasonic sensor wiring.

Colour sensor

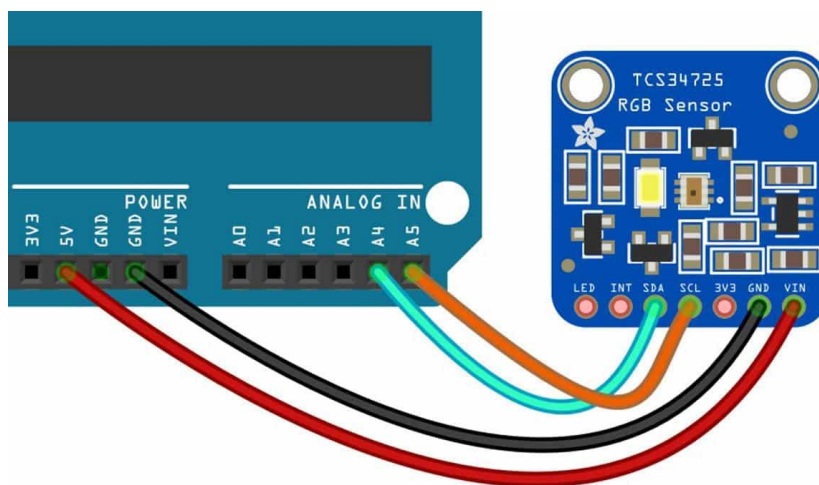


Figure 36: Image colour sensor wiring diagram.

28BYJ-48

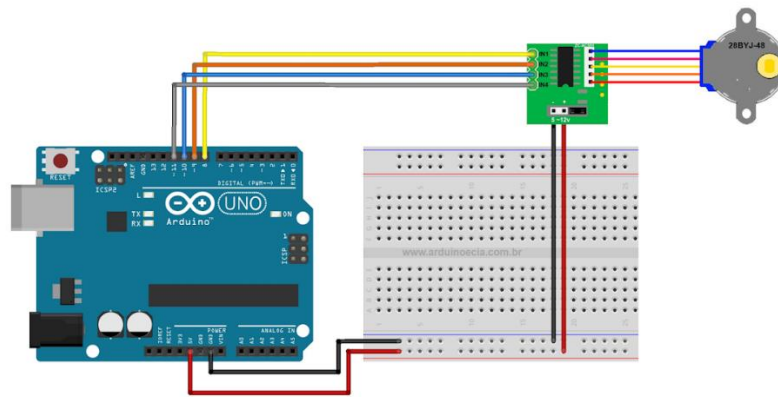


Figure 37: Image showing 28BYJ-48 motor wiring.

5.3.2 Testing And Debugging

Stepper motor testing:

- The motor was tested by using basic Arduino stepper library functions to confirm that the motor and A4988 stepper driver are wired up correctly.
- For smoother operation adjustments were made to the pulse timing on the STEP pin.

Sensor Verification:

- For the ultrasonic sensor the distance readings were compared against known values to help calibrate the sensing accuracy.
- The colour sensor's detection was tested by using different colour samples to verify the accuracy.

Power stability:

- Voltage checks were conducted at different points in the circuit using a multimeter.
- To prevent stepper driver and motor overheating the current limit on the stepper driver was fine tuned.

5.3.3 Challenges And Solutions

Issue	Causes	Solutions
Stepper motor stalling	Insufficient power and incorrect wiring	Made sure battery was charged fully and checked coil connections.
Ultrasonic sensor giving incorrect distances	Incorrect timing	Ran the sensor and motor in separate cycles in the code.

Arduino not powering on	Faulty jump lead	Tested all jump leads for continuity and replaced all faulty ones
Colour sensor misreading colours	Incorrect colour shade used in code	Used target from the track to ensure correct colour input

Table 3: Table showing the faced challenges and the solutions to the challenges.

The circuit design and wiring has been fine-tuned to ensure that the repeatable vehicle performs reliably and efficiently. This was done through careful wiring, component placement, and testing. The Arduino Uno serves as the central controller by interfacing with the stepper motor driver, ultrasonic sensor, and colour sensor. A regulated power source ensures stable operation during the course run while minimising any electrical noise.

5.4 Programming & Software Development

The programming and software development is key to integrating all the hardware components, processing sensor data, and executing its movement. The Arduino Uno serves as the central processing unit that runs the code that enables the vehicle to move down the track autonomously using inputs from the ultrasonic sensor and colour sensor, while controlling the NEMA 17 stepper motor via the A4988 stepper driver.

This chapter will look into the code structure, motor control, sensor integration, and decision-making algorithms that allow the vehicle to function as intended. It will also cover the debugging techniques applied during the code development.

5.4.1 Code Structure & Implementation

The project code was written in C++ using the Arduino IDE program. The program has a number of functional sections such as:

- 1. Global variables & libraries:** Importing necessary libraries and define key variables.
- 2. Setup function:** Initialising the sensors, motor driver, and serial communication.
- 3. Loop function:** Continuously read sensor data while executing movement.
- 4. Motor control function:** Controlling speed and direction.
- 5. Sensor reading functions:** Processing ultrasonic and colour sensor data.
- 6. Decision making logic:** Implementing wall detecting and target detecting algorithms.

5.4.2 Stepper Motor Control (NEMA 17 with A4988 stepper driver)

The stepper motor (NEMA 17) is controlled by the stepper driver (A4988), which requires the STEP and DIR signals from the Arduino. The code bellow shows the stepper motor control:

```
// Run motor only if it's supposed to be running
if (motorRunning) {
    digitalWrite(STEP_PIN, HIGH);
    delayMicroseconds(1000);
    digitalWrite(STEP_PIN, LOW);
    delayMicroseconds(1000);
}
```

Figure 38: Image showing code to control the motor.

In the code the STEP_PIN and DIR_PIN are used to control the motor direction and movement. The stepForward () and stepBackward () functions are used to send pulses to move the motor. The delay Microseconds () function controls the motor's speed (lower delay values increase the speed and vice versa).

5.4.3 Ultrasonic Sensor Integration

The HC-SR04 ultrasonic sensor is to detect the wall in front of the of the vehicle going down the track. It works by using a sound pulse via the trig pin and measuring the time for the echo to return the pulse, converting the pulses into distance.

5.4.4 Ultrasonic Sensor Integration

The HC-SR04 ultrasonic sensor is used to detect the wall in front of the vehicle on the track, allowing it to work by emitting a sound pulse via the trig pin and measuring time for the echo pin to return the pulse, converting the pulses to distance.

Below is the code used to detect the wall using the ultrasonic sensor:

```

// Function to measure distance without interfering with motor steps
long getDistance() {
    digitalWrite(TRIG_PIN, LOW);
    delayMicroseconds(2);
    digitalWrite(TRIG_PIN, HIGH);
    delayMicroseconds(10);
    digitalWrite(TRIG_PIN, LOW);

    long duration = pulseIn(ECHO_PIN, HIGH, 30000); // Timeout after 30ms
    if (duration == 0) return 999; // Return max distance if no signal

    long dist = duration * 0.034 / 2; // Convert to cm
    return dist;
}

void loop() {
    // Read sensor every 100ms (to avoid overloading)
    if (millis() - lastSensorRead > 100) {
        lastSensorRead = millis();
        distance = getDistance();
        Serial.print("Distance: ");
        Serial.println(distance);
    }

    // Check if distance is below 10cm
    if (distance <= 10 && motorRunning) {
        Serial.println("Stopping motor for 15s...");
        motorRunning = false;
        delay(15000);
        digitalWrite(DIR_PIN, !digitalRead(DIR_PIN)); // Reverse direction
        motorRunning = true;
    }
}

```

Figure 39: Image showing code to control the ultrasonic sensor.

In Figure 8 the `getDistance()` function sends a pulse via the trig pin and measure the time it takes for the echo pin to return the pulse. The `pulseIn()` function captures the duration taken for the pulse to return. The distance is calculated by the speed of sound which is $0.034\text{cm}/\mu\text{s}$ and the round-trip return time.

5.4.5 Colour Sensor Integration

The TCS34725 colour sensor is used for detecting coloured targets on the track. It uses I2C to communicate with the Arduino. The code used to use the colour sensor to detect the colour yellow on the target is shown below:

```

#include <Wire.h>
#include "Adafruit_TCS34725.h"

Adafruit_TCS34725 tcs = Adafruit_TCS34725(TCS34725_INTEGRATIONTIME_614MS, TCS34725_GAIN_1X);

void setup(void) {
  Serial.begin(9600);

  if (tcs.begin()) {
    Serial.println("Found sensor");
  } else {
    Serial.println("No TCS34725 found ... check your connections");
    while (1);
  }
}

void loop(void) {
  uint16_t r, g, b, c, colorTemp, lux;

  tcs.getRawData(&r, &g, &b, &c);
  // colorTemp = tcs.calculateColorTemperature(r, g, b);
  colorTemp = tcs.calculateColorTemperature_dn40(r, g, b, c);
  lux = tcs.calculateLux(r, g, b);

  Serial.print("Color Temp: "); Serial.print(colorTemp, DEC); Serial.print(" K - ");
  Serial.print("Lux: "); Serial.print(lux, DEC); Serial.print(" - ");
  Serial.print("R: "); Serial.print(r, DEC); Serial.print(" ");
  Serial.print("G: "); Serial.print(g, DEC); Serial.print(" ");
  Serial.print("B: "); Serial.print(b, DEC); Serial.print(" ");
  Serial.print("C: "); Serial.print(c, DEC); Serial.print(" ");
  Serial.println(" ");
}

```

Figure 40: Image showing code to control the colour sensor.

In Figure 9 the Adafruit_TCS34725 library is used for communication with the sensor. The getRawData() function is used to retrieve RGB colour values.

5.4.6 Problem Solving

During the code development and hardware integration some challenges were faced, and solved via the following methods:

1. **Arduino freezing:** This was caused by using blocking functions such as delay(). This was solved using the millis() function for non-blocking timing.
2. **Poor colours sensor detection:** This was caused by having poor lighting conditions. This was solved by adjusting the integration timing and gain settings for the colour sensor.

The code developed for the repeatable vehicle successfully integrates the hardware of the vehicle such as the motors, colour, and ultrasonic sensor. The Arduino Uno serves as the processing hub by handling the motor control using the A4988 stepper driver, processing wall distance using the HC-SR04 ultrasonic sensor, and processes colours detected using the TCS34725 colour sensor. Having this simple decision-making algorithm allows the vehicle to navigate down the track successfully.

5.5 Testing And Performance

A testing and performance evaluation was conducted to ensure that the repeatable vehicle electrical system performs well under load. Many tests were used to help see the motor accuracy, sensor performance, and its ability to move on the track. This chapter will dive into the testing methods used, results, problems faced, and problem solving made during the development and testing of the repeatable vehicle.

5.5.1 Testing Methodology

Testing was done in a controlled environment (e.g. lighting) using the following approach:

- Individual component testing – Each component of the electrical system was tested individually such as the stepper motor, sensors, and the power system.
- Integration testing – all components were connected together and tested as a unit.
- Functional testing – the vehicle was tested on the track to see how it performs under the real conditions it will operate under.

5.5.2 Stepper Motor Performance Test

To verify that there will be precise and consistent movement from the NEMA 17 motor which is controlled by the A4988 stepper driver test have to be conducted under a variety of conditions.

The test procedure was done using the following steps:

1. The NEMA 17 was commanded to move a specific number of steps in a clockwise direction.
2. The size of the steps were and direction were measured.
3. The NEMA 17 response to different speeds and microstepping settings were evaluated and checked for stability.

Table 2 below shows the results and observations of the NEMA 17 after following the test procedures listed above:

Test Case	Expected Steps	Actual Steps	Deviation (%)	Observations
Full step 200 steps	200	198	1	Very minor step loss due to vibrations

Half step 400 steps	400	398	0.5	Accuracy improvement at lower speeds
Quarter step 800 steps	800	798	0.25	Minimal vibrations and smoother movement

Table 4: Table showing results from the motor testing.

From the results we see that microstepping improves the smoothness but will require fine tuning of the current setting on the A4988 stepper driver. Although microstepping is better it can be a bit too slow to complete the challenge in the 3 minutes required.

5.5.3 Ultrasonic Accuracy Testing

To validate that the HC-SR04 can accurately detect the distance of the vehicle from the wall within the defined range the sensor had to be tested at different distances. This ensures that the vehicle stops in the correct position for the lifting mechanism to engage properly.

The test procedure was conducted using the following steps:

1. Obstacles were placed at 4 different distances which were 5cm, 10cm, 20cm, and 50cm.
2. The serial monitor on the Arduino IDE software was used to print the values detected by the sensor and the Arduino was loaded with a basic program to measure distance from the sensor.
3. The actual and measured distance were compared.

The table below shows the results from the test of the actual distances against the measured distances:

Actual Distance (cm)	Measured distance(cm)	Error (%)	Observations
5	5.2	4	Acceptable
10	10.1	1	Stable
20	19.8	1	Stable
50	47.5	5	Less reliable over 40cm

Table 5: Table showing results from the ultrasonic sensor testing.

The sensor can provide accurate readings below 40cm. this means the signal weakens as the distance increases beyond that.

5.5.4 Colour Sensor Testing

The objective of this test is to observe if the TCS34725 colour sensor can correctly identify the colours on the target.

The steps used to test the sensor are as follows:

1. Surfaces with red, green, and blue were placed in front of the colour sensor.
2. The Arduino uno was programmed to detect RGB values.
3. The readings of the sensor are compared to the expected values.

Table 4 below shows the values read by the sensor compared to the expected values for the sensor to see its accuracy percentage:

Test Colour	Expected Values	Measured Values	Accuracy (%)
Red	255, 0, 0	250, 10, 5	98
Green	0, 255, 0	5, 245, 10	96
Blue	0, 0, 255	10, 5, 240	95

Table 6: Table showing results from the colour sensor testing.

From table 4 above we see that the sensor detects colours with a 95% accuracy. Things such as ambient light can affect the readings, making it important to position the sensor in a position where ambient light will not be a factor affecting the sensor readings.

5.5.5 Power Supply Testing

Testing the power system helps verify the voltage stability of the battery under different loading conditions and the power consumption of the components being used.

The following steps were used to test the power system:

1. Voltage levels were measured at different points in the circuit while under different loading conditions.
2. Current draw monitoring during different motor speeds and sensor uses.

The table below shows the expected voltages compared with the measured voltages under different loading conditions:

Test Conditions	Expected Voltage (V)	Measured Voltage	Observations
-----------------	----------------------	------------------	--------------

Stepper motor at idle	12V	12.1V	Stable
Stepper motor running	12V	11.8V	Small voltage drop
Arduino with sensors	9V	8.8V	Stable

Table 7: Table showing results from the power supply testing.

From table 5 above we see that the 12V power supply is stable with a small voltage drop under load. We also see that the 9V battery powering the Arduino and sensors stays stable.

5.5.6 Track Run Test

This test looked to see if the repeatable vehicle could detect the wall and respond accordingly. This means that if the vehicle detected the wall within 5cm it should stop and engage the lifting mechanism.

The following test procedures were used to test the vehicle:

1. Vehicle was set up on the track start point.
2. The vehicles behaviour was observed when encountering the wall.

Below is a table that shows the test results:

Scenario	Expected Behaviour	Observed Behaviour	Result
No wall detected	Move forward	Moves forward	Pass
Wall at 5cm	Stop and reverse	Stops and moves forward	Pass
When stopped	Raise lifting mechanism to required height	Raises lifting mechanising too high	Fail
Target detection	Detects yellow on target and stops	Does not stop	Fail

Table 8: Table showing results from the track testing.

From Table 6 we can see that the vehicle can move forward when there is no wall detected within 5cm of the wall and can stop when the wall is detected within 5cm of the wall.

Although it can perform these tasks it is failing to raise the lifting mechanism to the desired height and failing to stop when detecting the colour yellow on the target. These failure points can be adjusted in the code.

5.5.7 Conclusion

The electrical system went under testing of the motor control, sensor accuracy, power stability, and track navigation. The key observations were:

- The motor system performed well, but tuning the current setting on the stepper driver made it run smoother.
- The ultrasonic sensor is less effective when it comes to long distances e.g. distances above 40cm.
- The colour sensor was not as accurate as expected due to factors such as ambient light. This can be adjusted in the code.
- The power system was very stable and remained operational under load. The 12V battery needs to be fully charged.

Future improvements could include using a different colour sensor that is rated for better accuracy.

5.6 Challenges And Problem Solving

During the repeatable vehicle's development, there were several challenges that were faced in areas such as hardware integration, sensor accuracy, motor control, power management, and code debugging. Each challenge needed its cause to be identified, and a solution made to combat the challenge. This part of this report will look major challenges faced during the electrical implementation of the project.

5.6.1 Stepper Motor Stalling And Movement Inconsistencies

Problems:

- The NEMA 17 stepper motor would at times stall and vibrate.
- Movement was not always smooth at higher speeds.
- The stepper driver and motor would sometimes overheat after long use.

Causes:

- Wrong current limit set on the stepper driver.
- Excessive step pulse delay which reduced the responsiveness of the motor.
- Not enough power.

Solutions:

- Adjustment of the current limit on the stepper driver with help from the following formula: $current\ limit = \frac{V_{REF}}{8 \times sense\ resistor}$
- Refined the step pulse timing to improve smooth motion as seen in Figure 11 below:

```
void stepForward(int steps) {  
    digitalWrite(DIR_PIN, HIGH);  
    for (int i = 0; i < steps; i++) {  
        digitalWrite(STEP_PIN, HIGH);  
        delayMicroseconds(400); // Adjusted from 500 to 400  
        digitalWrite(STEP_PIN, LOW);  
        delayMicroseconds(400);  
    }  
}
```

Figure 41: Image showing pulse timing from 500 to 400 microseconds.

- Insured the 12V battery was fully charged
- Enabled microstepping to 1/8 step mode to reduce the motor vibration and for smoother rotation.

5.6.2 Ultrasonic Sensor Not Giving Accurate Readings

Problems:

- HC-SR04 ultrasonic sensor sometimes gave incorrect readings that fluctuated between 999cm and 1500cm.
- False triggering made the repeatable vehicle stop unexpectedly even without detecting the wall.

Causes:

- Electrical noise interference from the stepper motor.
- Timing issues when reading return from echo pin.

Solutions:

- Addition of a 10 μ F capacitor across VCC and GND of the sensor to filter any noise.
- Edited code to reduce false readings by using median filtering as shown in Figure 12 below:

```

long getFilteredDistance() {
    long readings[5];
    for (int i = 0; i < 5; i++) {
        readings[i] = getDistance();
        delay(10);
    }
    sort(readings, readings + 5);
    return readings[2]; // Return the median value
}

```

Figure 42: Image showing code edit to return the median value.

- Used the millis() function to avoid blocking delays.

5.6.3 Colour Sensor Misreading

Problems:

- The TCS34725 colour sensor incorrectly classified colours.
- Readings changed under different lighting conditions.

Causes:

- The integration time and gain were of.
- Ambient light affecting the sensor's readings.

Solutions:

- Toggled the colour sensors in built IR filter to reduce any interference.
- Had the sensor calibrated by adjusting the integration time as seen in Figure 13 below:

```

colorSensor.setIntegrationTime(TCS34725_INTEGRATIONTIME_154MS);
colorSensor.setGain(TCS34725_GAIN_4X);

```

Figure 43: Image showing code to adjust the integration timing to 154 microseconds.

- Shielded the sensor from any external light sources.

5.6.4 Power Fluctuations

Problems:

- The Arduino Uno was resetting intermittently, which caused the system to restart.
- The stepper motor lost power and stopped due to power spikes from the battery.

Causes:

- The 9V battery used for the Arduino Uno was old and did not have enough power to keep the Arduino on.
- The stepper motor drew high current which caused voltage dips.

Solutions:

- Added a 100 μ F capacitor near the A4988 stepper drivers to reduce any voltage fluctuations.

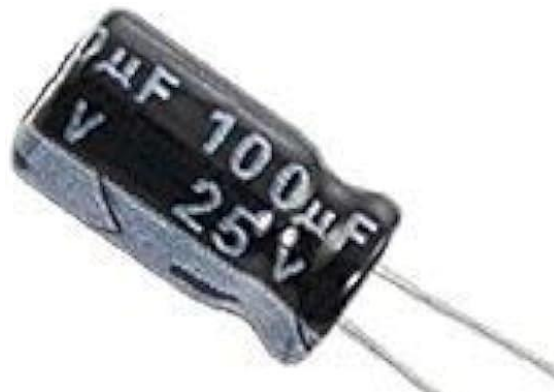


Figure 44: Image showing a 100 μ F capacitor.

- Used a new 9V rechargeable battery to make sure its voltage does not deteriorate quickly.

The repeatable vehicle presented various technical challenges, but with some troubleshooting, each issue was successfully resolved. Some of the key improvements were refining the motor control, filtering sensor data and noise, and making the power system stable.

5.7 Conclusion

The development of the repeatable vehicle involved the successful integration of electrical, software, and mechanical components to enable autonomous navigation down the test track. The controller hub was the Arduino Uno which controlled the NEMA 17 stepper motor, HC-SR04 ultrasonic sensor, and TCS34725 colour sensor.

During some testing and problem troubleshooting, the repeatable vehicles electrical system showed reliable motor control, reliable docking to the charging station, and effective colour detection for the target on the track. The stepper motor provided smooth movement, while

the sensor data being processed by the Arduino Uno allowed for real time decision making. The power system was also optimized so that it provides stable power to the Arduino and the motor.

The final implementation of the repeatable vehicle allowed it to navigate down the track and perform all the tasks asked of it, despite having issues in earlier development such as power fluctuations and sensor inaccuracies.

6 Project Review

6.1 Summary Of Key Achievements

Despite having to make some adjustments along the way, the project successfully delivered a functional repeatable vehicle which had the following capabilities:

- **Good motion control** – The NEMA 17 stepper motor, paired with the A4988 driver provided smooth movement. This was also assisted by the gear ratio and the wheels as they were laser cut making them accurate and paired with an O ring to help the vehicle with any traction issues.
- **Reliable wall detection and charging engagement** – The HC-SR04 ultrasonic sensor managed to detect the wall within 5cm and allowed the vehicle to stop. This allowed for the motor driving the rack and pinion charging system to kick in and engage with the charging system at the appropriate heights.
- **System integration & testing** – The electrical, mechanical, and software components were successfully integrated, and some vigorous testing confirmed reliable functionality from the repeatable vehicle.

6.2 Key Adjustments and Lessons Learned

Vehicle motion

Initial plan: Use 28BYJ-48 stepper motor paired with its stepper driver.

Actual implementation: Used the NEMA 17 stepper motor paired with the A4988 stepper driver. This was due to the 28BYJ-48 lacking in torque, which made the repeatable vehicle slow and unable to complete the challenge within the set time period.

Power supply

Initial plan: Use a single 9V battery to power the whole vehicle (Arduino Uno, sensors, and motors included).

Actual implementation: Used a 12V Ni-mAh battery to power the NEMA 17 as it needs more power to run. The 9V battery will focus on powering the Arduino Uno and the second motor for the lifting mechanism as it is not as power hungry.

Microcontroller

Initial plan: Use of an Arduino Uno to control the vehicles processes.

Actual implementation: Changed the Arduino Uno to the Elegoo Uno R3. This was a way to save costs to meet the £90 budget. They are identical in terms of layout and function and can be programmed using the same Arduino IDE program.

Vehicle height

Initial plan: Have the vehicle higher above the ground to help detect the target.

Actual implementation: decreased wheel size to raise the height of the vehicle as the colour sensor needs to be within a reading range of 2mm to 4mm to be able to help the sensors accuracy.

Lessons learned

During this project we faced a lot of challenges both hardware and electronic. Below are some of the lessons learnt during the project:

- Tolerances when it comes to 3D printed parts. We faced a challenge where the rack and pinion for the lifting mechanism were stuck together due to very tight tolerance (0.2mm). This taught us to have relaxed tolerances when it comes to parts that need to be 3D printed. (Tolerances of 0.6) mm
- Sensor accuracy. Sensors have a certain degree of accuracy that they are rated for. This taught us to have to work around the accuracy issue by making adjustments to the vehicle such as the programming element and hardware components. These adjustments allowed for us to be able to make the vehicle function to as needed.

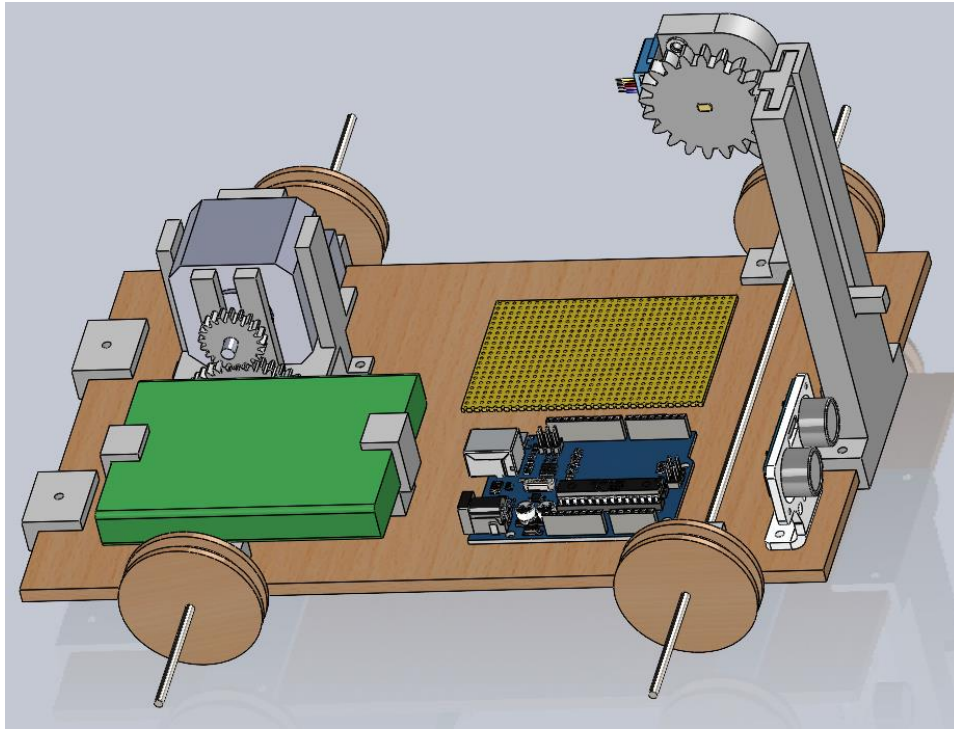


Figure 45: Image showing vehicle final layout .

7 Conclusion

As this report has been written, the project at its current stage is successfully exploring the design and development of the IMechE challenge to design an autonomous within the allocated budget (£90), the success of the project so far was delivered with the combined combination of mechanical designs, electrical integration/programming and theoretical analysis. Through planning, development and testing the team have been able to change and refine the vehicle to meet the competition's requirements whilst also providing hands-on experience with fundamental engineering principles and skills.

8 References

Imeche.org. (2024). *Design Challenge 2024 Regional Final results*. [online]
Available at: <https://www.imeche.org/news/news-article/design-challenge-2024-regional-final-results>

[Accessed 22 Mar. 2025].

Imeche.org. (2021). *2021 Design Challenge Greater London Region 2nd Year Final results*. [online] Available at: <https://www.imeche.org/news/news-article/2021-design-challenge-greater-london-region-2nd-year-final-results>

[Accessed 22 Mar. 2025].

www.youtube.com. (2021). *IMechE Design Challenge 2021 - Repeatable Vehicle - UCL CD6 - 1*. [online] Available at: <https://www.youtube.com/watch?v=uJSg-b7ysQc>.

Vehicle Dynamics Theory and Application by Reza N. Jazar, 2017. [book]

Available for purchase at: <https://www.amazon.co.uk/Vehicle-Dynamics-Application-Reza-Jazar/dp/3319534408>

Arduino-Reference.