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Introduction and Motivation

In general, the line follower robot is one of the self-operating mobile machines that follows a 'line' or 'path' already predetermined by the user. This line or path may be as simple as a physical white line on the floor or as complex path marking schemes e.g. embedded lines, magnetic markers and laser guide markers. In this project we are using certain number of sensors to detect these specific lines, also outlining the design construction and testing of our line follower robot.

In this project, we used 15 reflective optical sensors (TCRT5000) which include an infrared emitter and phototransistor in a leaded package which blocks visible light. In terms of accuracy, we implement a calibration algorithm to eliminate or minimize factors that cause inaccurate measurements. It is a fundamental aspect of instrumentation design simply by taking the maximum and minimum of the sensors. Due to the limitation of Arduino board, we decided to use two multiplexers in order to reduce the usage of pin.

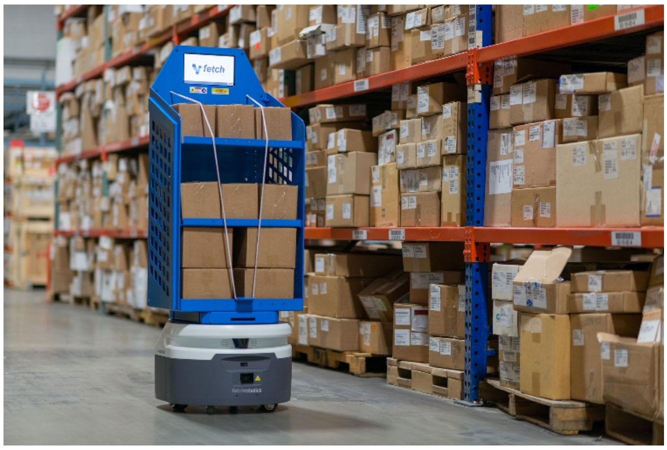
The innovation within the project that are seeking to be acquired and recognized by external parties:

- Engaging way to understand concepts related to sensors, control systems, and autonomous navigation
- Enhance our creativity and problem-solving abilities (e.g. process of designing printed circuit board (PCB), designing a gear box, drafting and producing CAD)
- Further exploration of algorithms for line detection and tracking
- Endeavor to present a fully developed line following system

Relative Work/background

Line-sensing robots, also known as line-following robots, are autonomous robots that use sensors to detect and follow a line on the ground. They are widely used in industrial automation, robotics competitions, and educational projects. Early versions of these robots used simple analog circuits and light sensors to detect the line's position. They typically had wheels or tracks for locomotion. In recent years, with the advancement of technology and the availability of affordable microcontrollers and sensors, line-following robots have become popular educational tools for teaching programming, electronics, and robotics. They provide a hands-on approach to learning about sensors, control systems, and autonomous navigation. Infrared (IR) sensors and proportional-integral-derivative (PID) control are commonly used in these robots.

Line following robot in industrial application:



Rule of competition

2 students in a group, design and make an autonomously guided robot that follows a line drawn on the ground to detect a dark line on a white surface and participate in inter-class competition while the size of robot is limited 200(L)x200(W)mm. There are 3 rounds in the match, each round the robots are able to run 3 loops. The final result is taken the best single loop time.

These are the following violations who commit serious infractions will be disqualified from the competition:

- Intentional damage to the competition area or target objects
- Touching or tampering with other participants' works or target objects without permission from the staff during the competition
- Participating with a work that does not meet the specified requirements

Aim

This project aims to perform an autonomously guided robot with the capability of moving at high speeds while maintaining stability and accuracy. Nevertheless, the robot should be extremely sensitive to the changes of brightness, ensuring that the robot stays on track and avoids deviating from the path.

- Time used to travel a cycle: 10 seconds
- Remote console:
- Weight:
- Dimension:
- Highest speed:
- Wheel:
- Infrared sensor: 15 (tcrt5000)
- Power supply: 11.1V lithium-ion battery (3 cell Li-po Battery)

Bill of materials

i. 3D printed gearbox x2

ii. PCB

iii. carbon fiber base x1

iv. tcrt5000 IR sensor x15

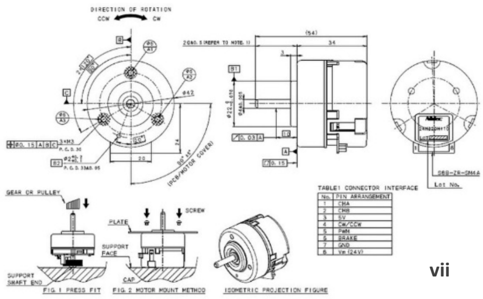
v. Mother board

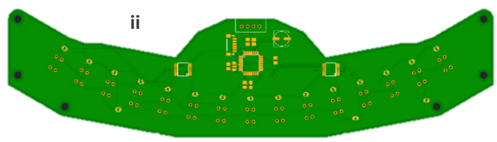
vi. NRF24 x2

vii. Nidec 24h brushless motors x2

viii. Ball caster x2

ix. Washer (multiple)



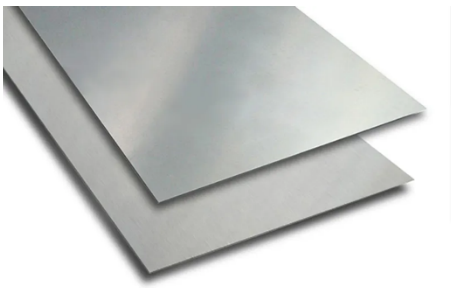
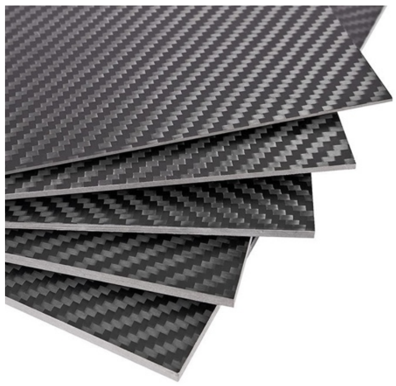
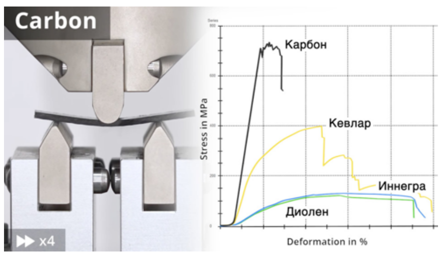


Mechanism

Selection of Materials

An appropriate selection of materials while designing a robot can make a big difference in the performance including durability, stability, weight and cost of your robots

In this project, we undertake a comprehensive analysis from various perspectives as above, and gain a thorough understanding of different subject matter. Through evaluation, we have reached a consensus on choosing “Carbon fiber”.

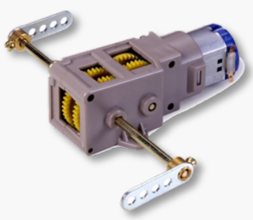
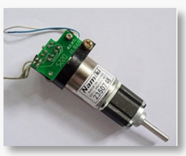
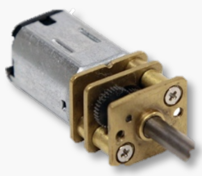
Steel	Acrylic (PMMA)	Carbon Fiber (✓)
		
Advantages: ➢ Strong ➢ Durable ➢ Able to withstand heavy loads ➢ Rigid Drawbacks: ➢ Corrodes easily ➢ Extremely heavy (increase the energy consumption in the motor) ➢ Conducts heat (complicated the cooling effect)	Advantages: ➢ Commonly used ➢ Same qualities as glass without the fragility issue (will no break into piece easily) ➢ Safe material ➢ Lightweight Drawbacks: ➢ Brittle when under load (especially under an impact force) ➢ Low wear resistance (obtain scratches easily)	Advantages: ➢ High mechanical strength ➢ Light weight ➢ Low thermal expansion ➢ Affordable ➢ High stiffness  Drawbacks: ➢ Conduct electricity

➢ Considerably more expensive than other materials	➢ Stiffness (not rigid enough to hold the main body of our robot)	

→ In summary, considering the massive size and weight of our gearboxes and motors, carbon fiber emerges as the most suitable material due to its unique properties.

Selection of motor

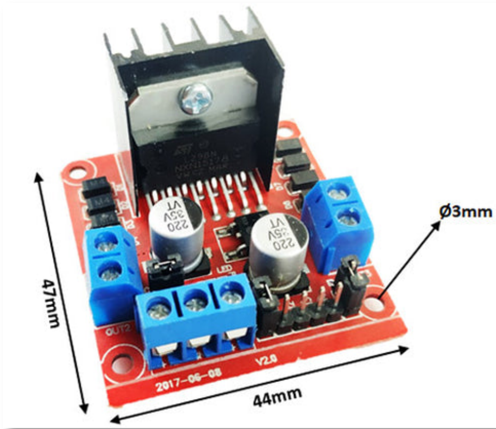
In this project, we have chosen to use “Nidec 24H055M020” (Nidec 24H), a brushless DC motor, as the actuator of the line-following robot. Here are several factors we have considered:

Name	**Tamiya 70093 3-Speed Crank-Axle Gearbox Kit**	**Namiki 22CL-3501PG**	**N20 Motor**	**Nidec 24H055M020**	**RoboMaster M2006 P36**
Category	Brushed			Brushless	
Gear ratio	17:1/58:1/203:1	80:1	298:1	1:1	36:1
Min Speed (rpm)	17:1⇒ 481(2V) 58:1⇒ 141(2V) 203:1⇒ 40(2V)	N/A	100 (6V)	150	N/A
Max Speed (rpm)	17:1⇒ 1202(5V) 58:1⇒ 353(5V) 203:1⇒ 101(5V)	120	200 (12V)	3900	416
Voltage (V)	3 - 6	12	6 - 12	12	12
Driver Required	External H-Bridge DC driver required			Built-in driver	External ESC/FOC driver required
Weight (g)	40	5000	9.5	110	90
Photo					

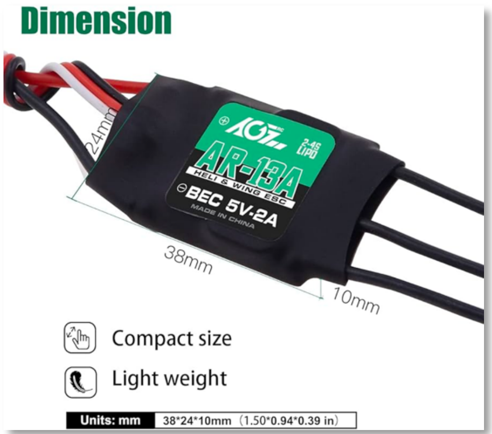
1. Usability

Unlike the Nidec 24H motor, many commercial motors typically require external H-Bridge or Electronic Speed Control (ESC) drivers for operation. This setup required additional space, especially since two drivers are needed to manage both left and right motors.

Therefore, motors with integrated drivers are preferred due to their more compact and efficient design.



L298N H-Bridge Driver



AGFRC 13A ESC

2. Motor Category:

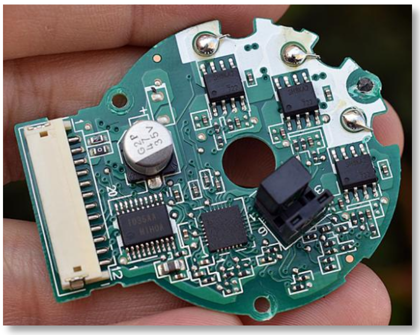
There are two typical types of motor, brushed and brushless.

Comparison of Features between brushed and brushless motor

- <u>Brushless Motor:</u>
  - **Longer Lifespan:** Without brushes, brushless motors experience less wear and tear, resulting in a longer operational life.
  - **Higher Efficiency:** Brushless motors are more efficient, generating less heat and using less energy for the same power output.
  - **Improved Performance:** They offer superior speed control and torque (compared to brushed motor).
  - **Reduced Low-Speed Torque:** BLDC motors can struggle to provide high torque at low speeds, which can be a limitation in applications that require strong torque from a standstill or during slow-speed operations.
- <u>Brushed Motor:</u>

- **Lower Initial Cost:** Brushed motors are generally less expensive upfront than BLDC motors. This is due to their simpler design and fewer component requirements.
- **Simpler Control and Drive Electronics:** They require less complex control and drive electronics, making them easier to integrate and operate in various applications.

Comparing the merits of both types of motor, we consider **brushless DC motor** a suitable actuator for our application because brushless motor offers a handful of merits, including a faster speed, a higher efficiency, and a longer lifespan. Despite the fact that BLDC required a driver (ESC/FOC) to operate, some brushless DC motors, such as Nidec 24H, are integrated with the driver circuits.



Integrated BLDC driver in Nidec 24H

This integration not only simplifies the system design but also enhances overall performance and reliability, making Nidec 24H an ideal choice for our line follower which aims to travel at high speed with a compact body.

3. Weight

The weight of our selected motors directly factors the nimbleness and maximum speed of our application. The Namiki 22CL-3501PG weighs 5kg, which is a considerable factor in determining the overall agility and speed capabilities of our system.

In conclusion, we've chosen the Nidec 24H as the actuator for its numerous advantages: its brushless design ensures a longer lifespan and higher efficiency, reducing wear and energy consumption.

Additionally, the motor offers improved performance with superior speed control and torque. The integration of a driver circuit in the Nidec 24H simplifies system design and boosts performance and reliability, making it perfect for our compact, high-speed line follower, especially when considering the weight and agility factors of our system.

Gear set design

1. *Desired Motor RPM*

We aim to design a follower that travel the entire track within 10 seconds (0.167 minute)

- Track length: 8000mm
- Tire diameter: 65mm

- $Desired\ Motor\ RPM = \frac{TrackLength}{TireCircumference} \div \mathrm{Time}\ (min)$
- $Desired\ Motor\ RPM\ = \frac{8000mm}{65mm \times \pi}\ \div\ 0.167\ min\ =\ \mathbf{234.6rpm}$

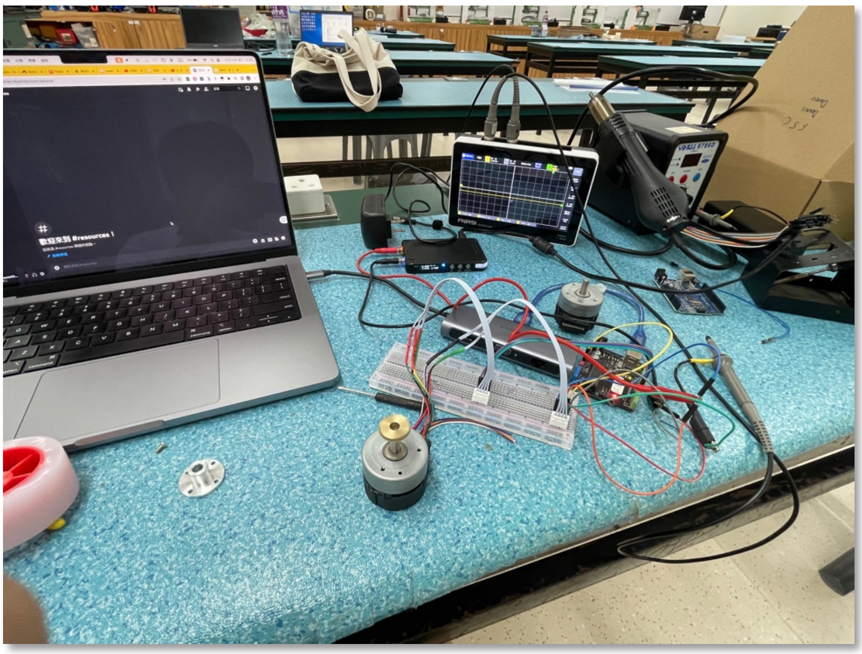
After selecting the ideal motor (Nidec 24H) and evaluating the desired motor speed, we discovered that the Nidec 24H operates at a relatively high-speed range (150 – 3900 rpm). However, it cannot provide sufficient torque during low-speed operations (150 – 500 rpm), a limitation that has been discussed in the "motor selection" section. Furthermore, its maximum speed of 3900 rpm is somewhat excessive for our follower's requirements.

Therefore, a gear set is needed for:

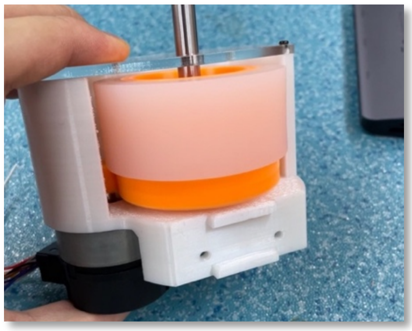
- Speed Reduction
- Torque Enhancement

Nidec 24H motor operation and properties test:

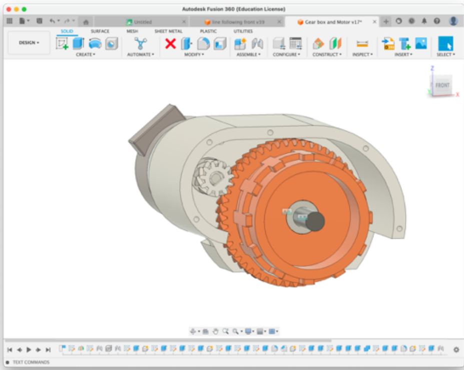
Testing Video **(Click Me!)**



2. *Gear ratio*



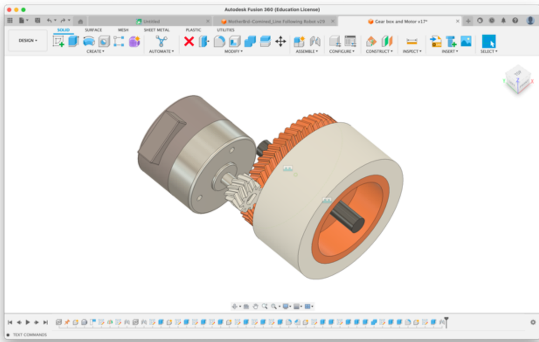
We eventually designed a gearbox with a gear ratio of 4.55:1, featuring an output gear with 50 teeth and an input gear with 11 teeth.



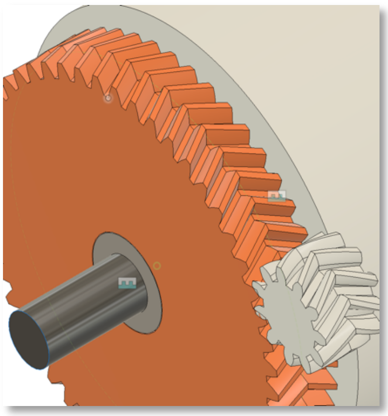
This gear ratio effectively converts the rotational speed of the Nidec 24H motor from 150 – 3900 rpm to an output rotational speed ranging from 33.7 – 876.4 rpm, which matches our desired rotational speed of 234.6 rpm.

Video of motor with gear box equipped: https://photos.app.goo.gl/NPo4kNCyhGdWwo8V7

3. *Design Detail*



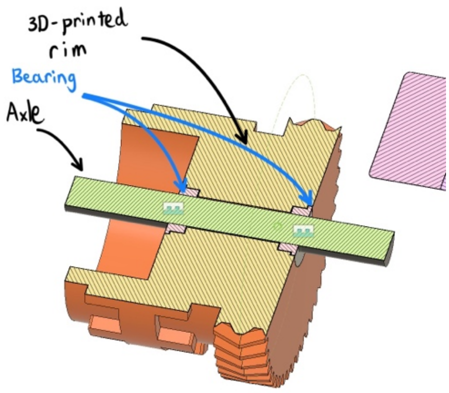
In order to align the input gear and output gear firmly, a pair of herringbone gear is used. Herringbone gears are different from regular spur gears because they have a unique V-shaped double helical design. This design allows for more teeth to be in contact at any given time, providing smoother operation and greater load capacity.



The V-shaped double helical design of a herringbone gear

Additionally, the mirrored helical teeth of herringbone gears effectively cancel out the lateral forces that typically occur in single helical gears. This feature eliminates the need for large thrust bearings, making herringbone gears ideal for high-torque applications in compact spaces, as they can maintain alignment and stability under heavy loads.

Moreover, to hold the wheel in place and aligned with the axle, two flanged ball bearings are mounted on each side of the 3D-printed rim.

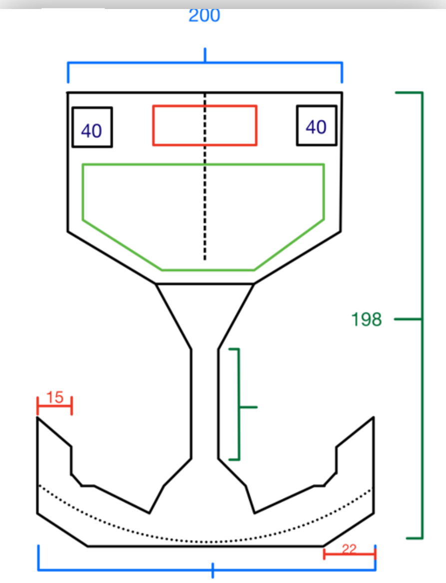


Follower Design

To create a Line Follower capable of efficiently tracking and following a line, we recognized the need to consider several key aspects of the robot's design namely:

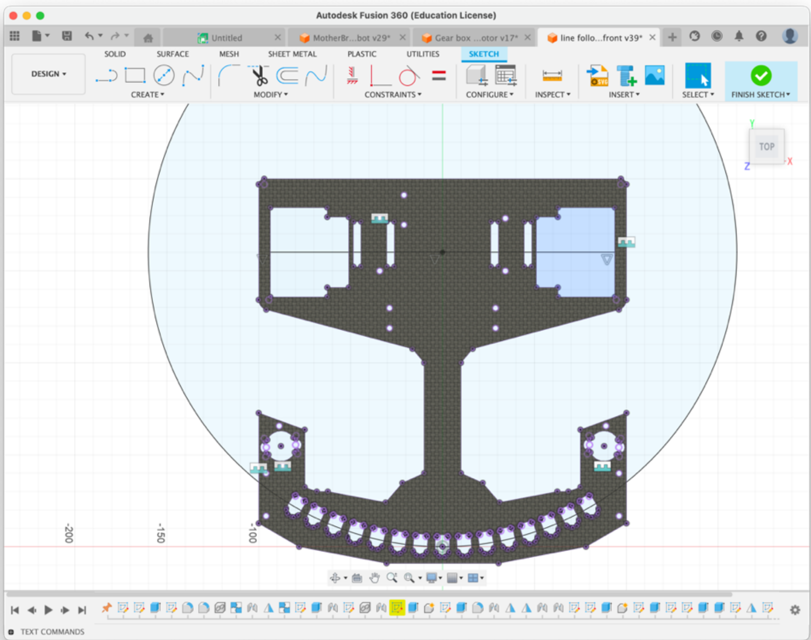
- Width of Robot
- Width of Sensor Array
- Gap Distance between Sensors
- Spacing from Sensors to Motors.

However, constrained by time limitations, we opted to adopt the parameters of a Line Follower design uploaded to GrabCAD by Andri Setiawan. We are grateful to Andri for this valuable resource. 🙏



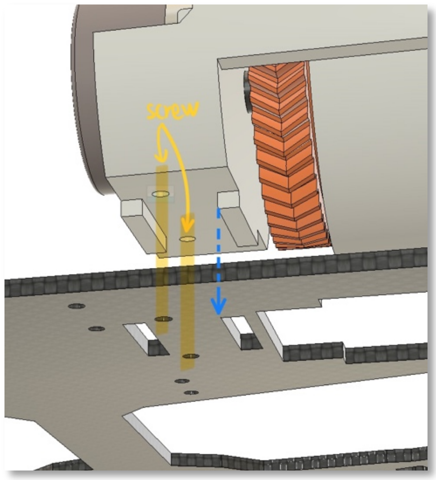
Before moving on to the design and creation of a 3D CAD model for the follower, we engaged in brainstorming and sketched a preliminary draft of the line follower.

We aimed to align the center of the sensor array's curvature with the robot's rotational center, which helps add a degree of linearity to the data captured by the sensors.

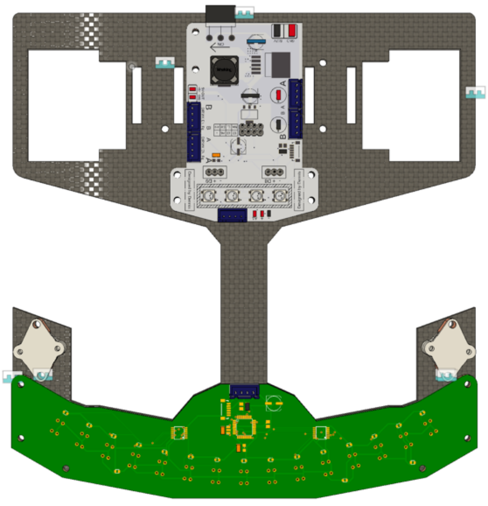


Alignment of the center of rotation and the center of curvature of the sensors

After designing the bottom frame, we implement the gear box into the design. We mount the gear box on the frame with a mortise and tenon joint and two screws.



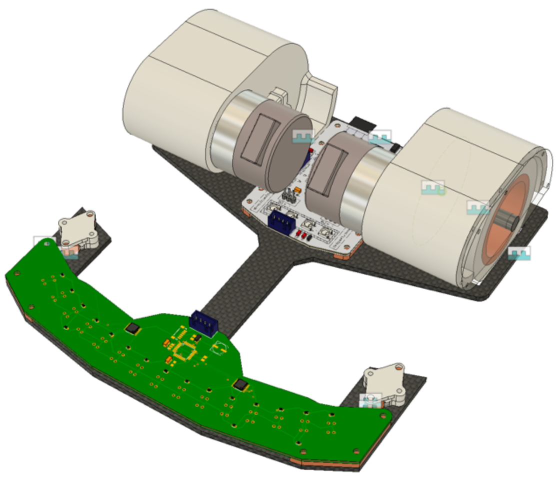
A mortise and tenon joint and screw mount.

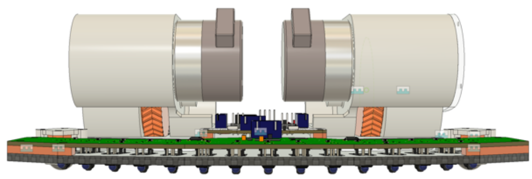


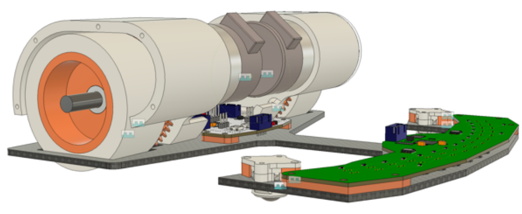
Mother Board (upper part) Sensor Board (bottom part)

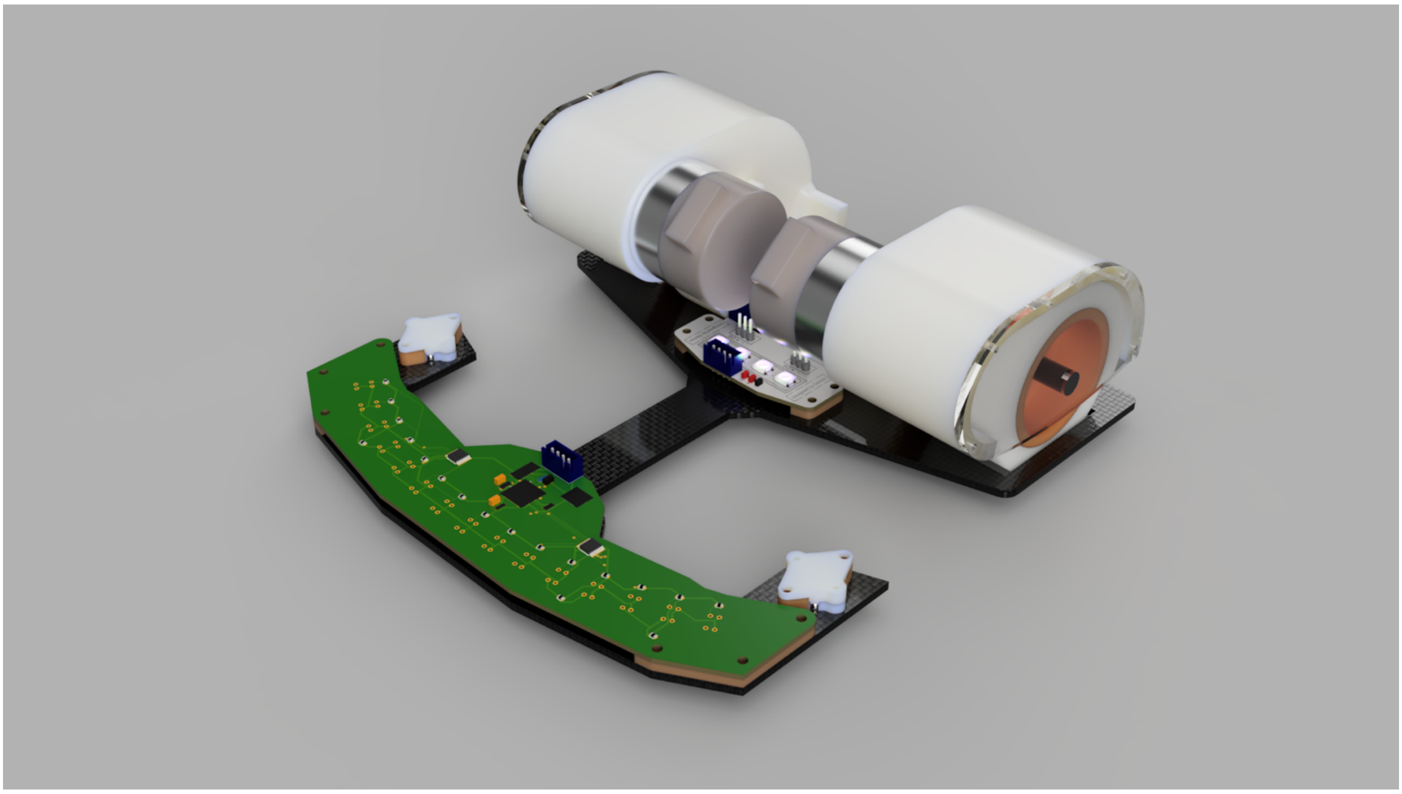
Afterwards, we implement two customized circuit boards, including one sensor array circuit board and one mother circuit board. The electronic design of the boards will be discussed in the upcoming sections.

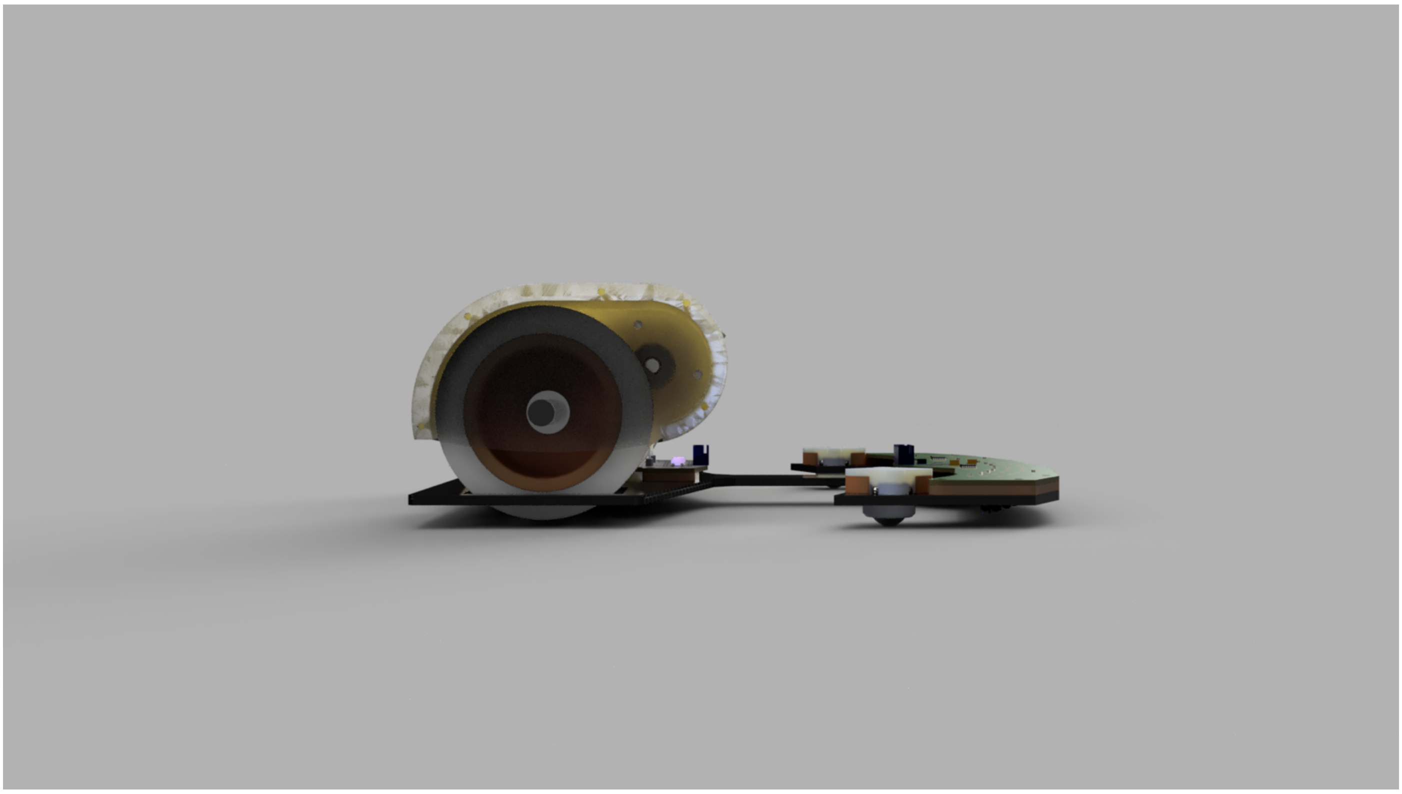
After finalizing the design, including mounting the ball caster, designing spacers for the circuit boards, here is our final design:

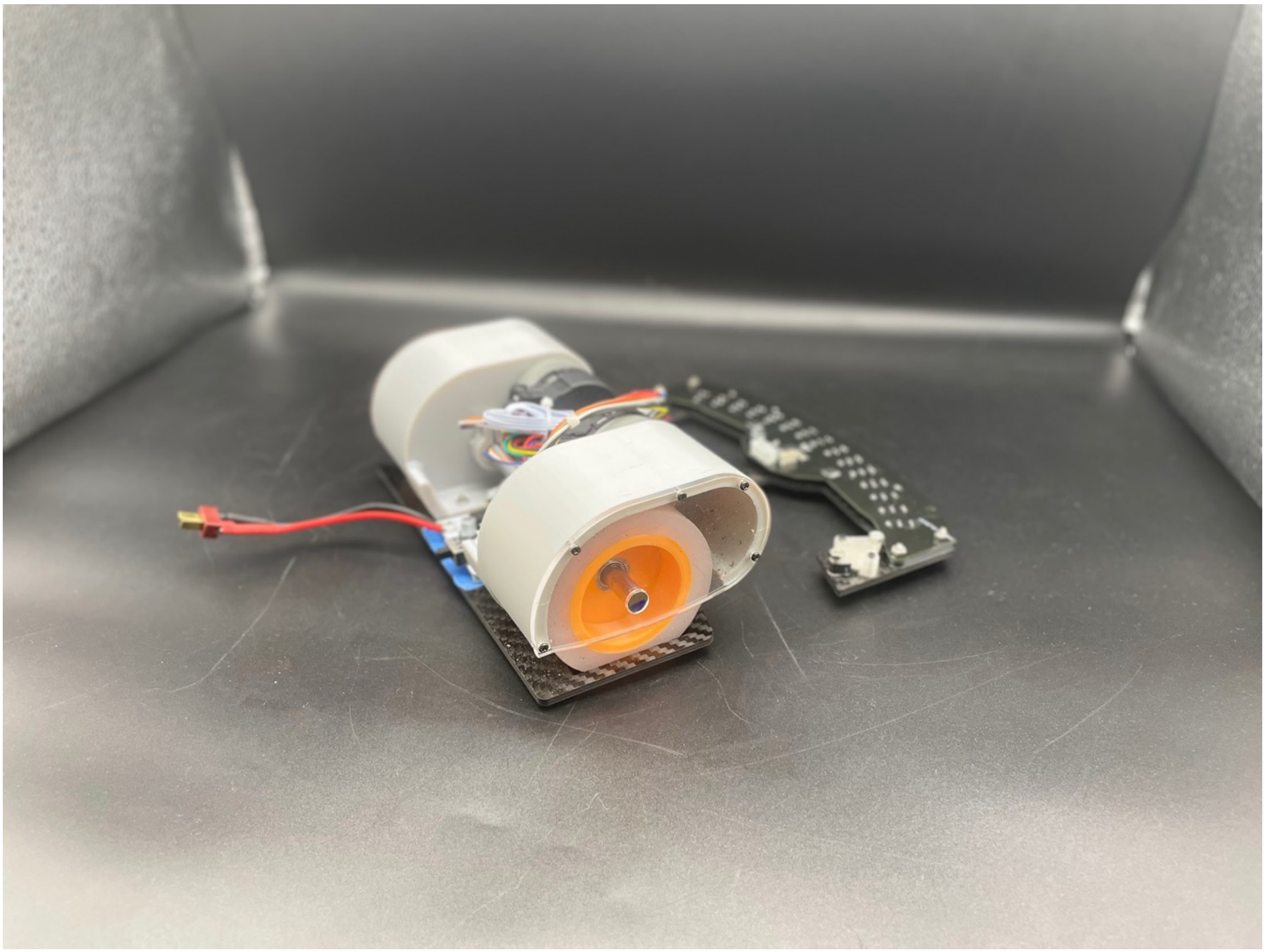


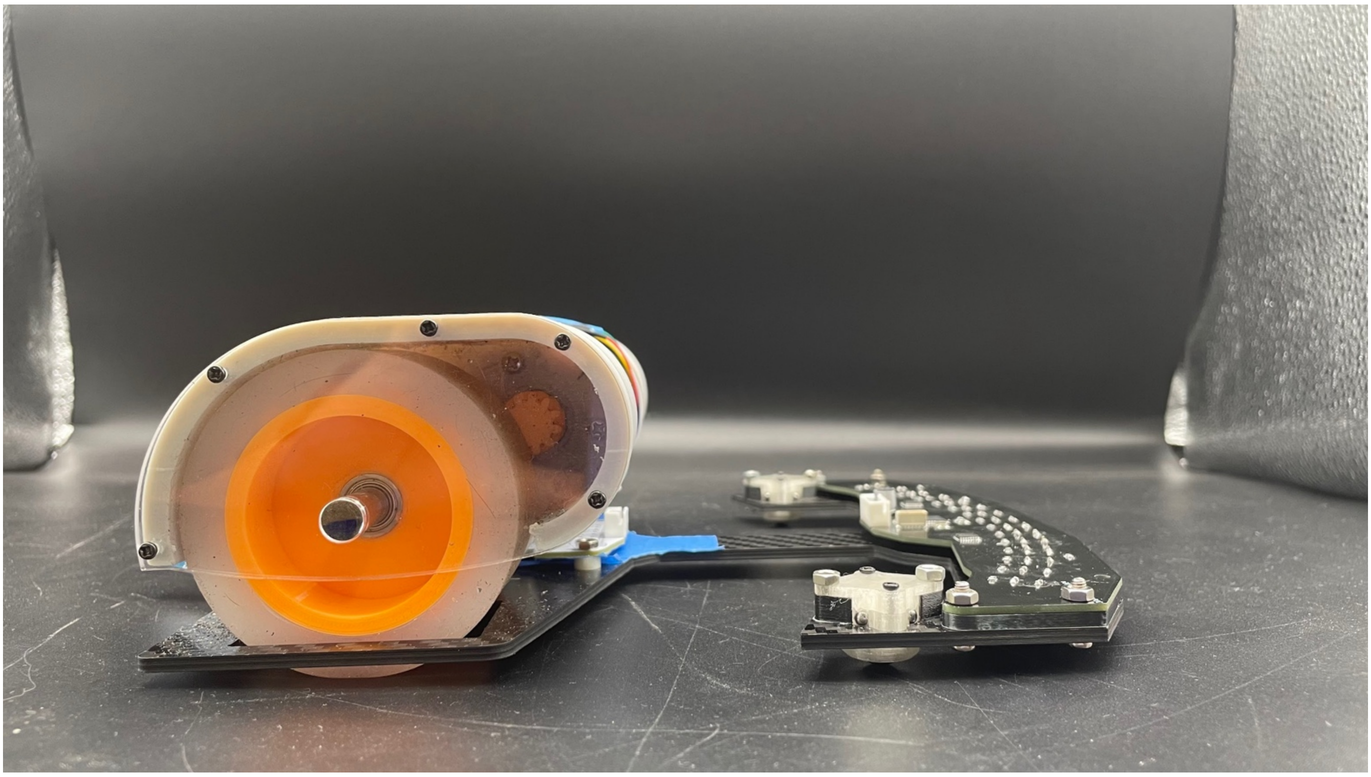










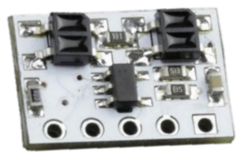


Electronics

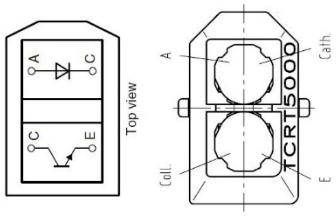
Selection Of Sensor

Sensor Consideration:

- Output signal
- Weight
- Size (is it easy to integrate to our robot)
- Suitability of the competition arena

JSumo Mz80 Infrared Sensor	JSumo Dual Micro Line Sensor ML2
 (1)	 (2)
Features: ● Height: 4.5 cm ● Voltage: 5V ● Weight: 20g ● Widely used in mini sumo robots and sumo robots ● Range can be decreased or increased with trimpot head screw ● 15 ° detection angle Pros: ▫ Digital output (easier to process) ▫ Can be integrated into various robotic projects (sumo robot and line following robot) ▫ Adjustable sensitivity Cons: ▫ Low resolution (comparing to analog signal) ▫ Not convenient ▫ Low accuracy (adjustable)	Feature: ● Dimensions: 9.80 x 14.00 x 3.30 mm ● Weight: 0.4g ● Voltage: 3.3-5V ● Integrated fabrication ● Two separated IR sensor Pros: ▫ Tiny size of the sensor ▫ Easy integration (integrate with various of device) ▫ Consist of two individual sensors (processing more efficient and display of information) Cons: ▫ Limitation of sensor (difficult to track line efficiently in high speed)

Tcrt5000



Feature:

- Dimensions: 10.2 x 5.8 x 7
- Voltage: 5V
- Sensing range: 0.2to 15 mm
- Peak operating distance: 2.5mm
- Typical output current under test: IC = 1 mA

Pros:

- Presence of different physical object
- Clear observation of signal
- Good waveform
- Common

Cons:

- Easily affected by environment conditions (sunlight and lights from surrounding)

In contrast, other groups who use the official line tracking sensor module (fig b), will generates only a digital signal, we have chosen to implement the tcrt5000 directly on our PCB board.

This decision was made to enhance the accuracy of line detection by utilizing the analog signals produced when the sensor receives infrared signals.

By collecting and analyzing different analog readings, it will benefit us from using the calibration command and employ a map function, which will be further discussed in subsequent sections.

fig a

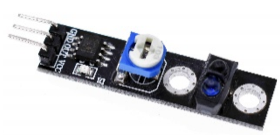
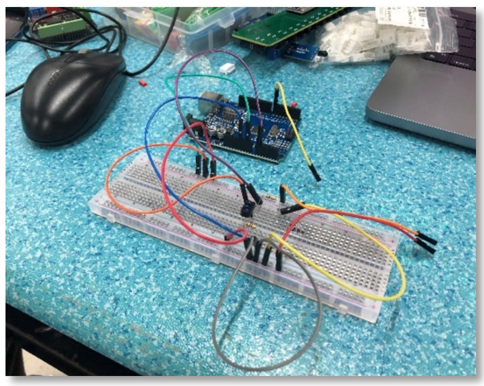


fig b

Process of testing the sensitivity of the TCRT5000 Sensor



To sum up, sensor (1) and (2) can only generate a digital signal. However, in this project we desire to make use of the benefit of analog signal. Furthermore, those sensors (1) are too large in size, so it restricts us from implementing multiple sensors. Regrading sensor (2), considering its performance while following line, it will be more suitable for us to select the tcrt5000 as our line following sensor.

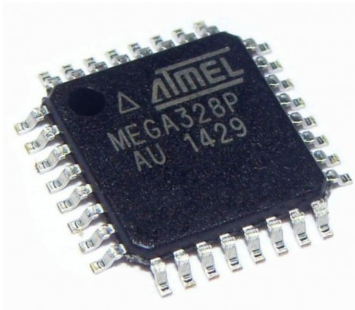
Sensor board

(i) PCB design

- MCU (Marvel Cinematic Universe)

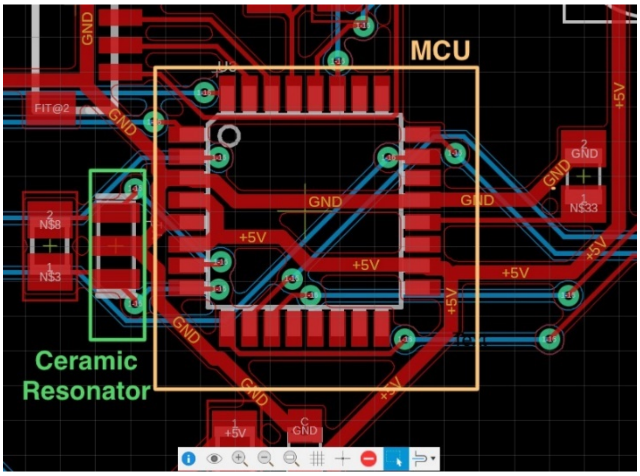
In this project, we pick ATmega328P as our microcontroller unit, it can operate at a clock speed of up to 20 MHz and has 32KB of flash memory for program storage. By executing powerful instructions in a single clock cycle, the device achieves throughputs approaching one MIPS per MHz, balancing power consumption and processing speed.

Reason for selecting this MCU are:



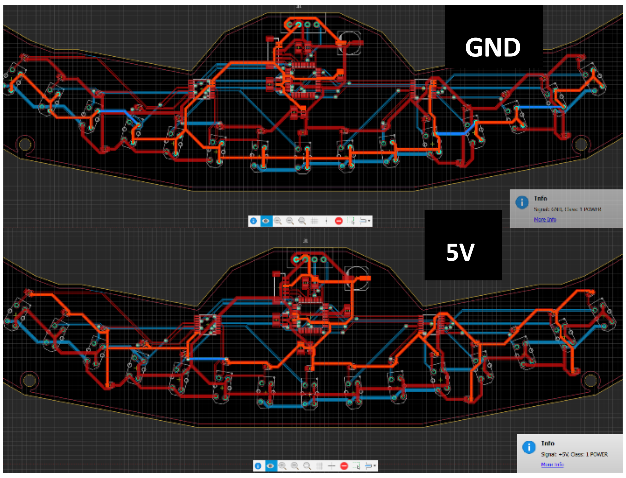
- Obtain 1024B EEPROM
- Easy integration with Arduino boards
- Abundance of libraries (since it supports various functionalities and many pre-written code, such as EasyTransfer)

- Ceramic Resonator



Since the ceramic resonator that provide accurate timing of frequency reference, it can be used as the source of the clock signal for digital circuits such as microprocessors. As such, we did place it extremely close the MCU.

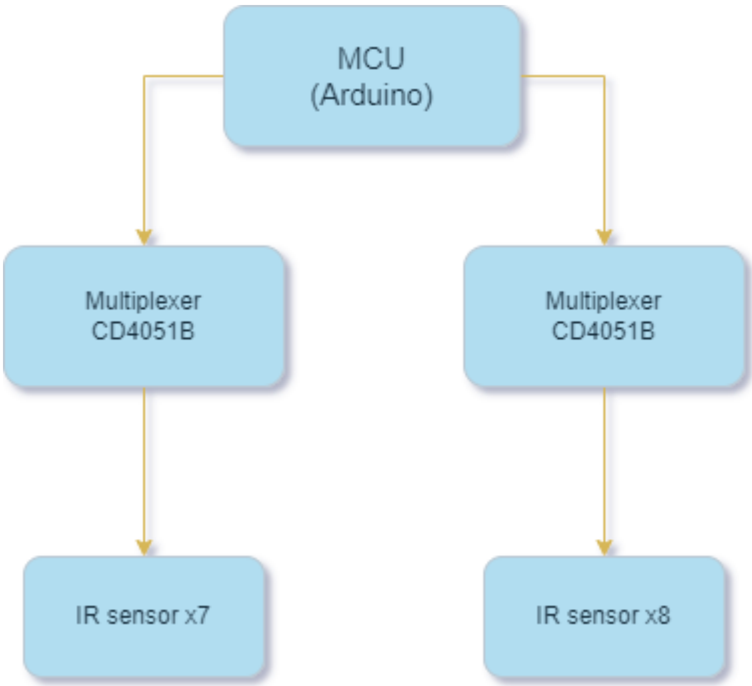
- PCB Layout



Due to the high consumption of current, the 5V and ground circuit is thickened for stability.

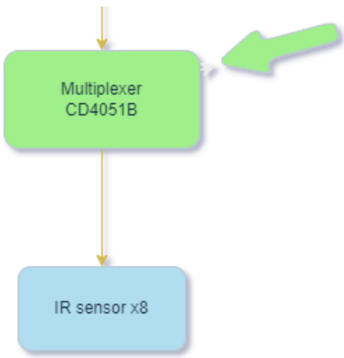
(ii) System

As the diagram below, the MCU (Microcontroller Unit) is sending data to two multiplexers, specifically the CD4051B, which are connected to seven IR sensors each.



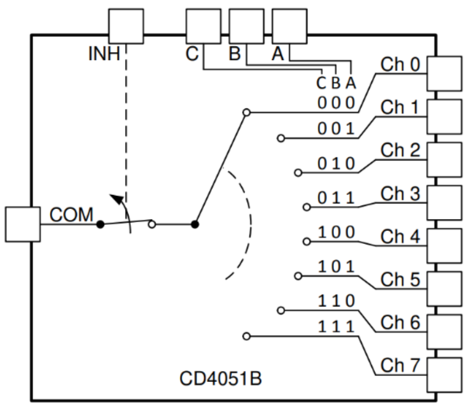
How the "Multiplexer" works

The CD4051B analog multiplexers and demultiplexers are digitally-controlled analog switches having low ON impedance and very low OFF leakage current. These multiplexer circuits dissipate extremely low quiescent power ov er the full VDD – VSS and VDD – VEE supplyvoltage ranges, independent of the logic state of the control signals.

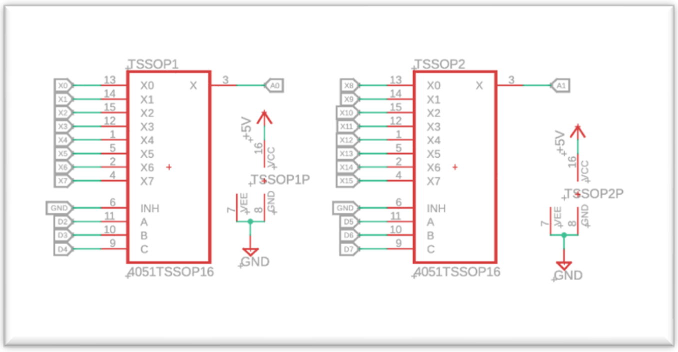


This multiplexer can integrate circuit that operates as an 8 channel snolg switch, it allows one of eght analog input signals to be selected and routed to the output based on control signal (Arduino).

The CD4051B has three control pins (A,B,C), and by setting the approiate combination, the desired input channel can be selected.



In this robot, there are 2 multiplexers as there are 15 IR sensors (fig a). By connecting 7 out of 15 IR sensor to one mutiplexer and the rest to the other one, it will gain the ability to collect the exact number of value of sensors, which the MCU required, by switch different cases and returning the values. Furthermore, due to the limitation of analog pinouts on the Arduino board, which only obtain A0 – A5 in total. This restricts us from navigating various numbers of analog output signal. As a result, applying multiplexers are more suitable for us.

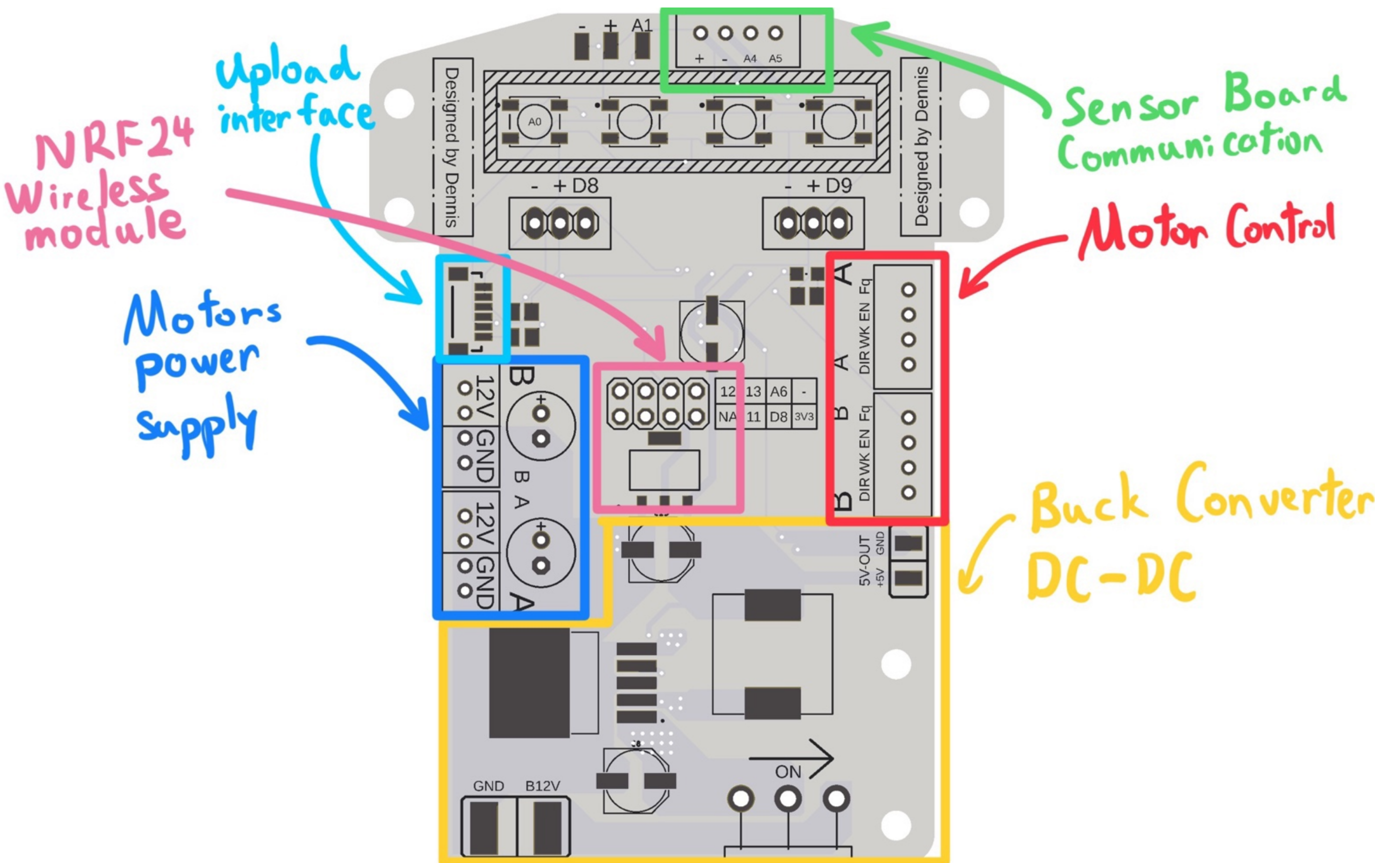


Mother Circuit Board

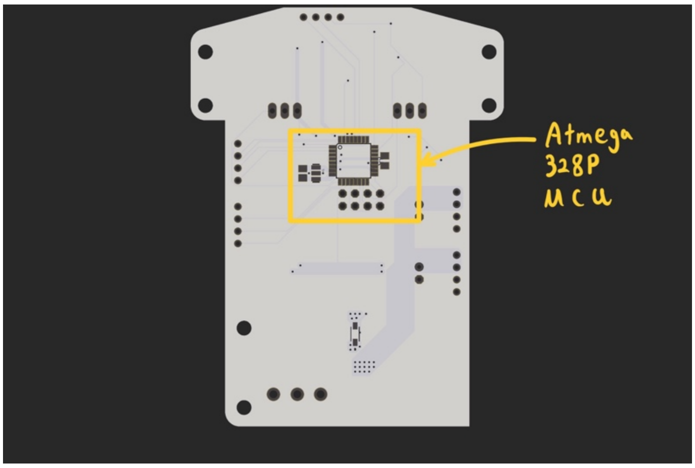
In this project, we have designed and implemented a customized mother board as the robot's brain. Here are the tasks it has to handle:

- Communication with the sensor board using
  - I2C
- Communication with the wireless console using
  - NRF24
- Motor Controlling
  - Two Nidec Motors Speed Tuning
- Power Voltage Converting with
  - LM2596 Buck DC-to-DC converter

The diagram provided illustrates the specific pinouts assigned for these functionalities on the motherboard.



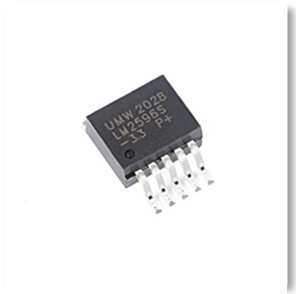
To drive these features, we utilize an ATmega328P microcontroller unit (MCU) due to its ease of programming and the extensive range of available libraries that enhance its usability.



PCB Layout

Maintaining a stable power supply within the 1.8 to 5.5 volts operating range is critical for the reliable functioning of the ATmega328P microcontroller. Power fluctuations can cause erratic behavior, so it's vital to keep the voltage steady to ensure the microcontroller operates correctly and avoid system issues.

With the plan to use a 10v – 12v three-cell battery for the robot, employing a LM2596 buck converter to downscale the voltage to 5V is necessary.



LM2596

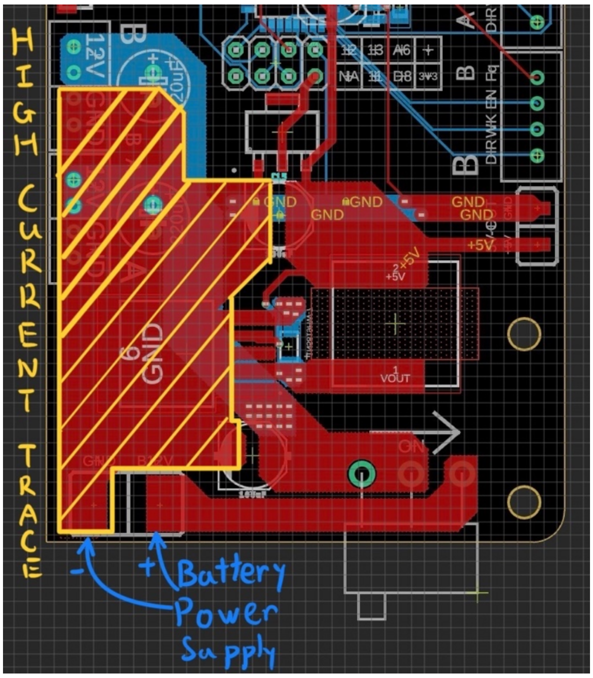
AMS1117-3.3 V

Moreover, the NRF24 wireless radio module runs at a voltage of 3.3V, therefore, an additional 5V to 3V converter is needed. In this case, we decided to implement a small package LDO, AMS1117-3.3 V, to supply a 3.3V power to the NRF24 module.

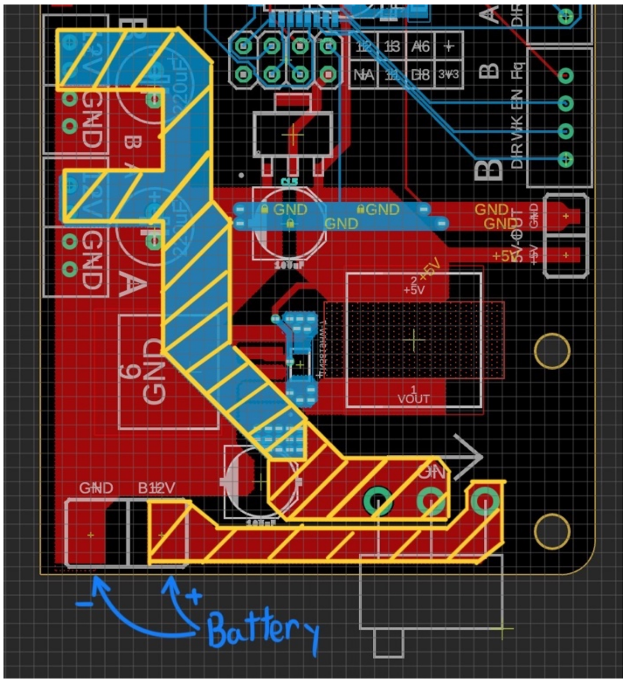
NRF24 Module

Additionally, since the motors draw a large amount of current, designing the circuit with optimized and well-designed high current traces is crucial for delivering robust and stable power to the motors.

The images below show the high current trace designed for the motor ground and the positive.



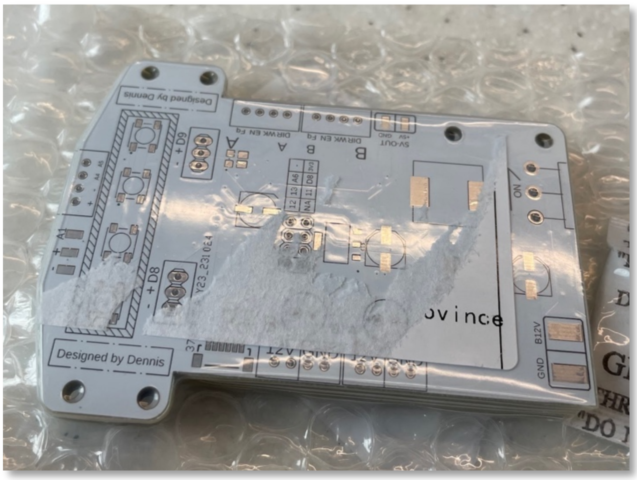
High current trace from battery ground to motor ground.



High current trace from battery positive to motor positive.

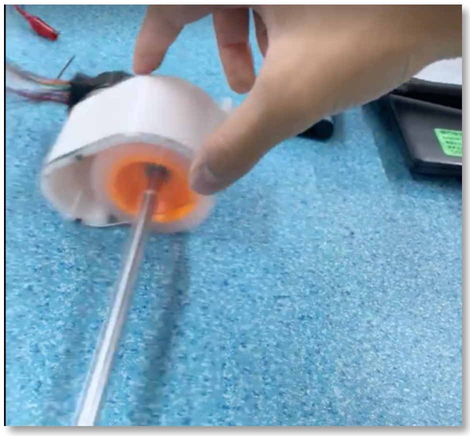
Prototype

After designing our line follower, we tested and build a prototype of our robot.

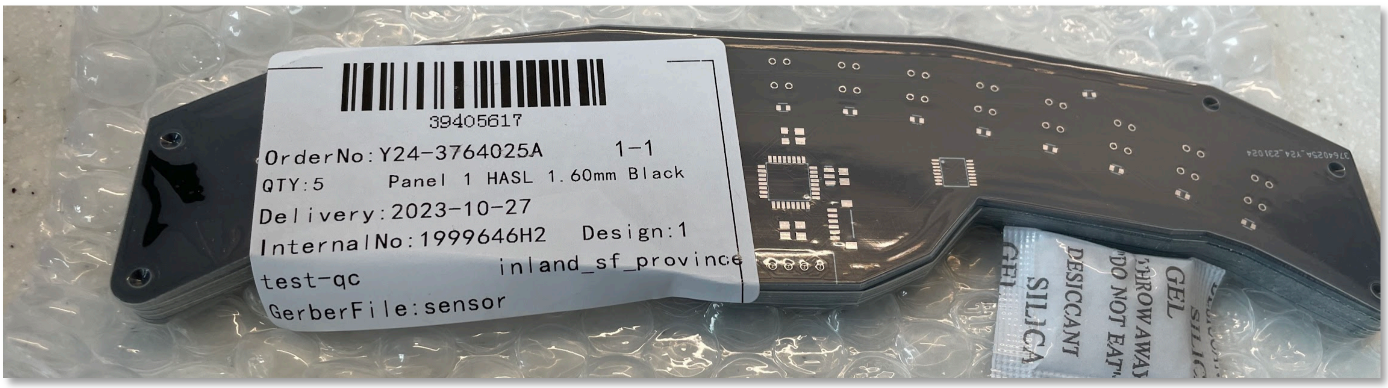


Our very first prototype

Click me!



Click me!



Software Development

After prototyping the follower, we begin to program and develop the firmware of our robot, including the program for the mother board and the sensor board.

Integration

The entire line follower system consists of three major hardware, a mother board, a sensor board and a remote console.

Here is how they collaborate with each other:

The sensor board gathers data from 15 sensors, calculates an “error” value (measure of misalignment of the robot and the line), and transmits it to the motherboard, which uses a PID controller to steer the car, while calibration data is stored in EEPROM; additionally, a remote console with NRF24 allows for wireless control and calibration of the car.

1. Sensor Board

- Get the sensor value from all 15 sensors
    - Calculate an “error” value from those sensors
    - Transmit the calculated “error” value to the mother board
- Calibration
    - Using a min-max calibration algorithm to calibrate each sensor independently
    - Store those calibrated parameters (min and max value) into EEPROM

2. Mother Board

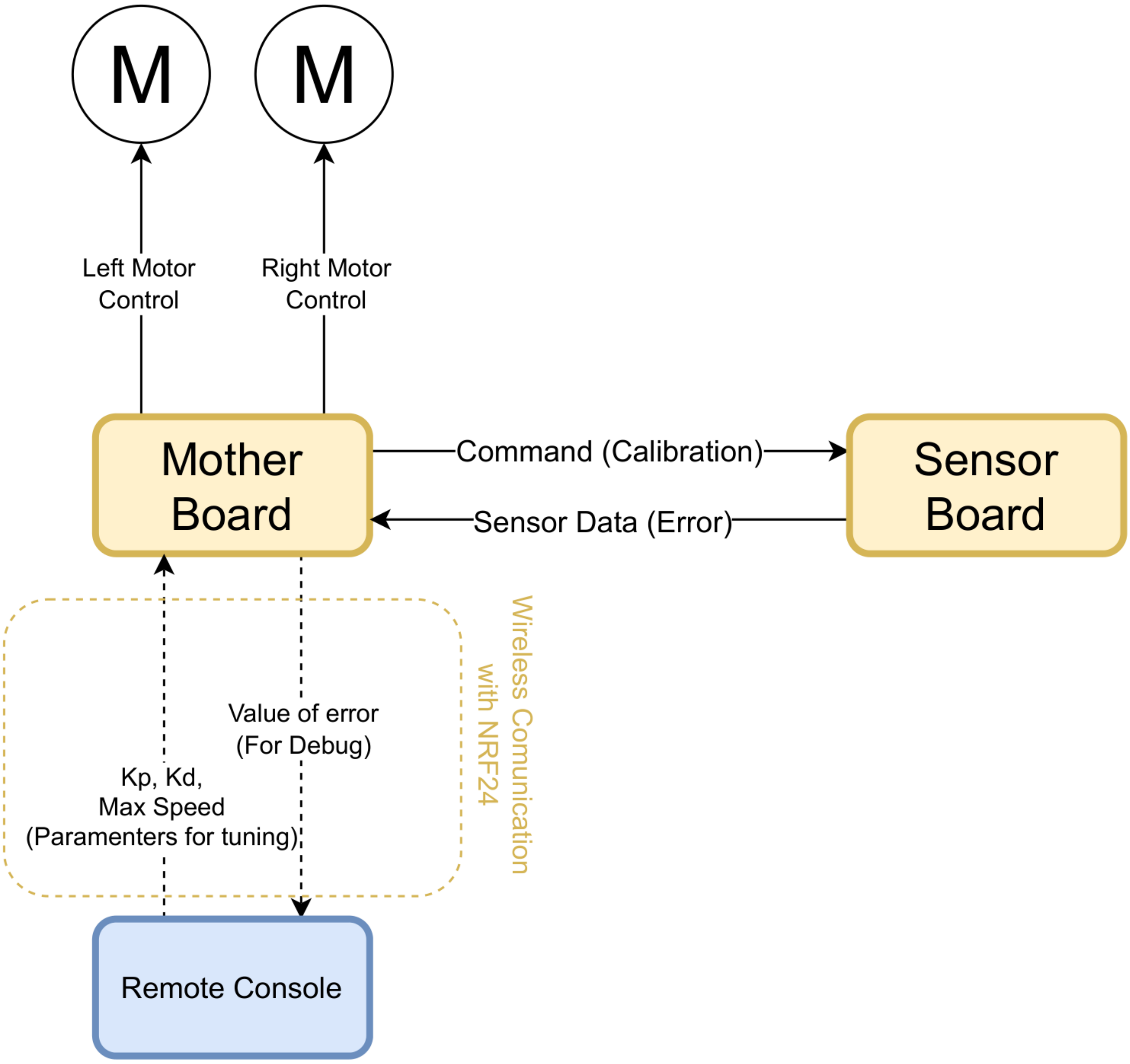
- Receive the “error” value from sensor board
- Use a PID controller to control the movement of the car according to the “error” value
    - In simpler words, track and follow the line
- Rotate the robot during calibration so that sensor board could capture more data to eliminate random error

3. Remote Console

This is a console equipped with NRF24 (a wireless module) to communicate with the mother board wirelessly.

- User can send command to the follower via the remove console to
    - Drive the car wirelessly (Video: Click ME!)
    - Tune the PID controller wirelessly
    - Calibrate the sensor whenever needed

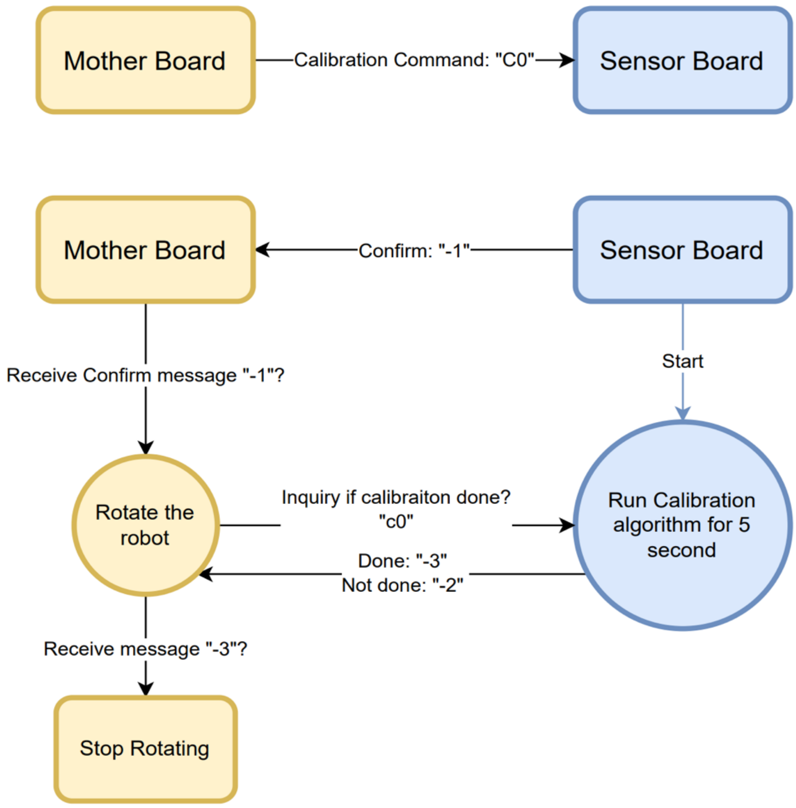
The flowchart below demonstrates the control system of our line follower: The Sensor Board detects the line and sends error data for calibration to the Mother Board, which controls the motors. The Remote Console wirelessly adjusts PID settings and commands calibration.


M
M
Left Motor Control
Right Motor Control
Mother Board
Command (Calibration)
Sensor Board
Sensor Data (Error)
Wireless Comunication with NRF24
Value of error (For Debug)
Kp, Kd, Max Speed (Paramenters for tuning)
Remote Console

Communication between sensor board and mother board:

Calibration

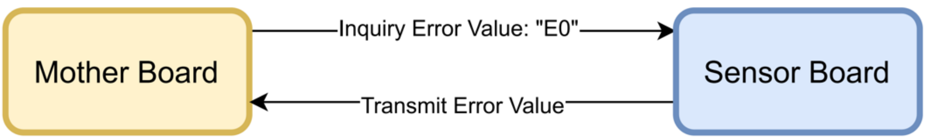
The calibration process for our line follower begins with the Mother Board sending a "C0" command to the Sensor Board. Upon receiving confirmation ("-1"), the robot starts rotating and the Sensor Board runs the calibration algorithm for five seconds. If calibration is complete, indicated by a "-3" message, the robot stops rotating.



Calibration sequence for a line-following robot:

Error Value Transmit

The Mother Board requests an error value with "E0" and the Sensor Board responds by transmitting that value back.



Communication protocol between Mother Board and Sensor Board for error value retrieval.

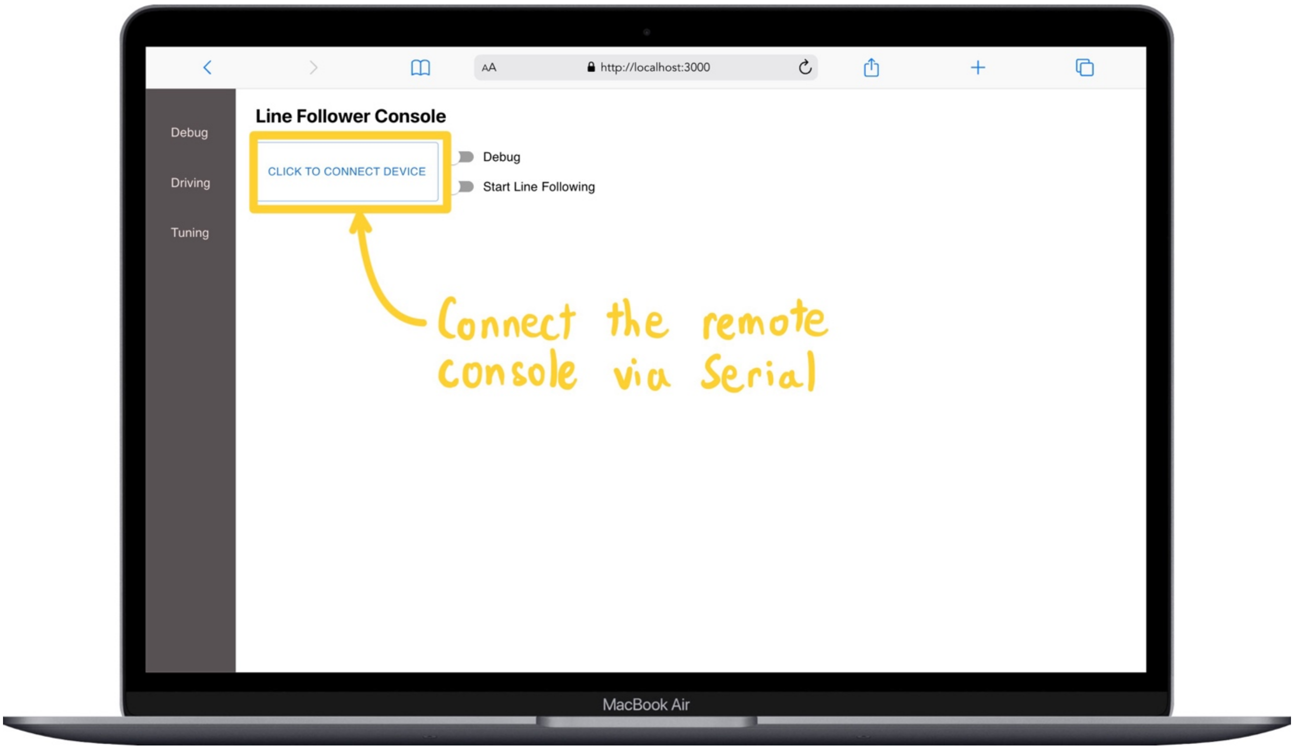
User Interface

To enable user interaction with the line follower, I developed a web-based user interface that simplifies the control of the robot for any user. Utilizing the ReactJS framework along with the Material-UI library, I have designed a responsive and intuitive interface that allows for the navigation and tuning of the robot.

Here are the features:

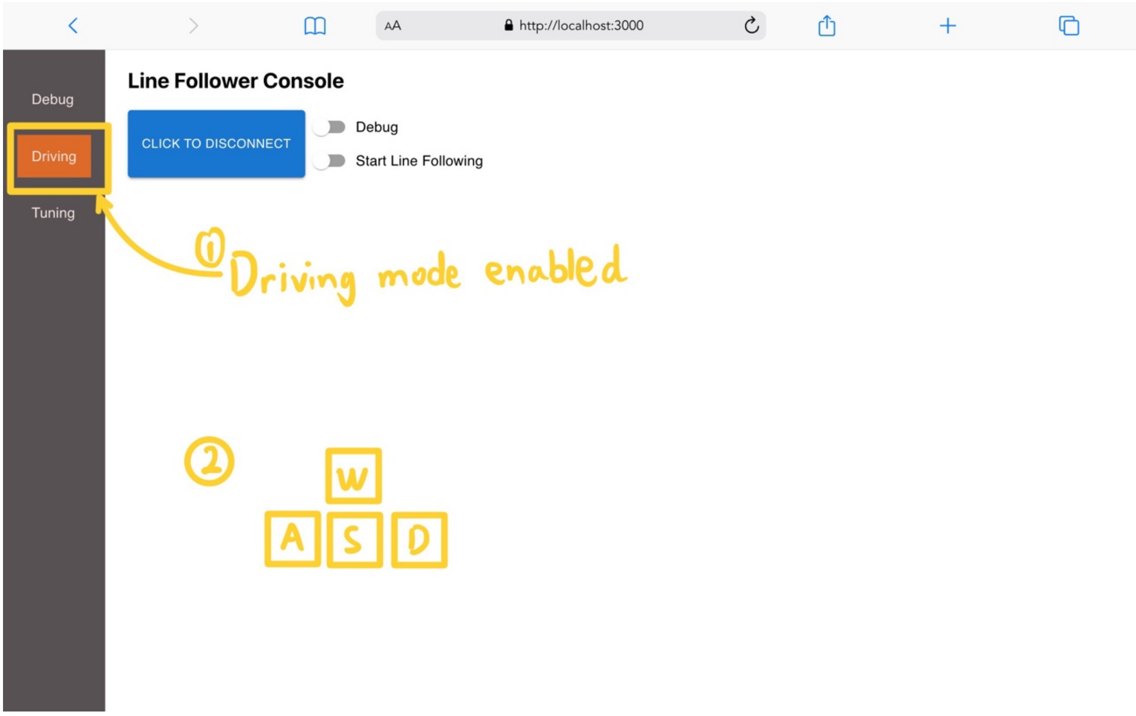
1. Connection

   - Press "Click to connect device" button to connect the hardware remote console via Serial.



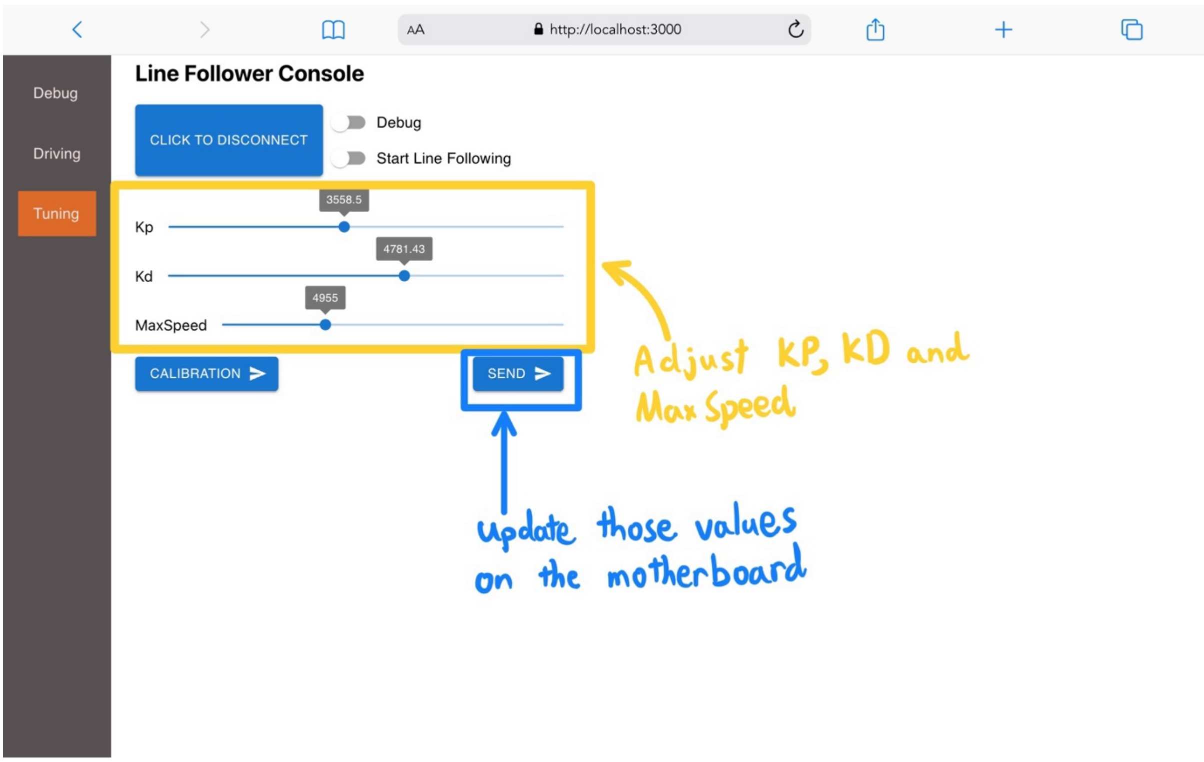
2. Driving

- Press the “Driving” button on the navigator to drive the robot with ‘W’, ‘A’, ‘S’, ‘D



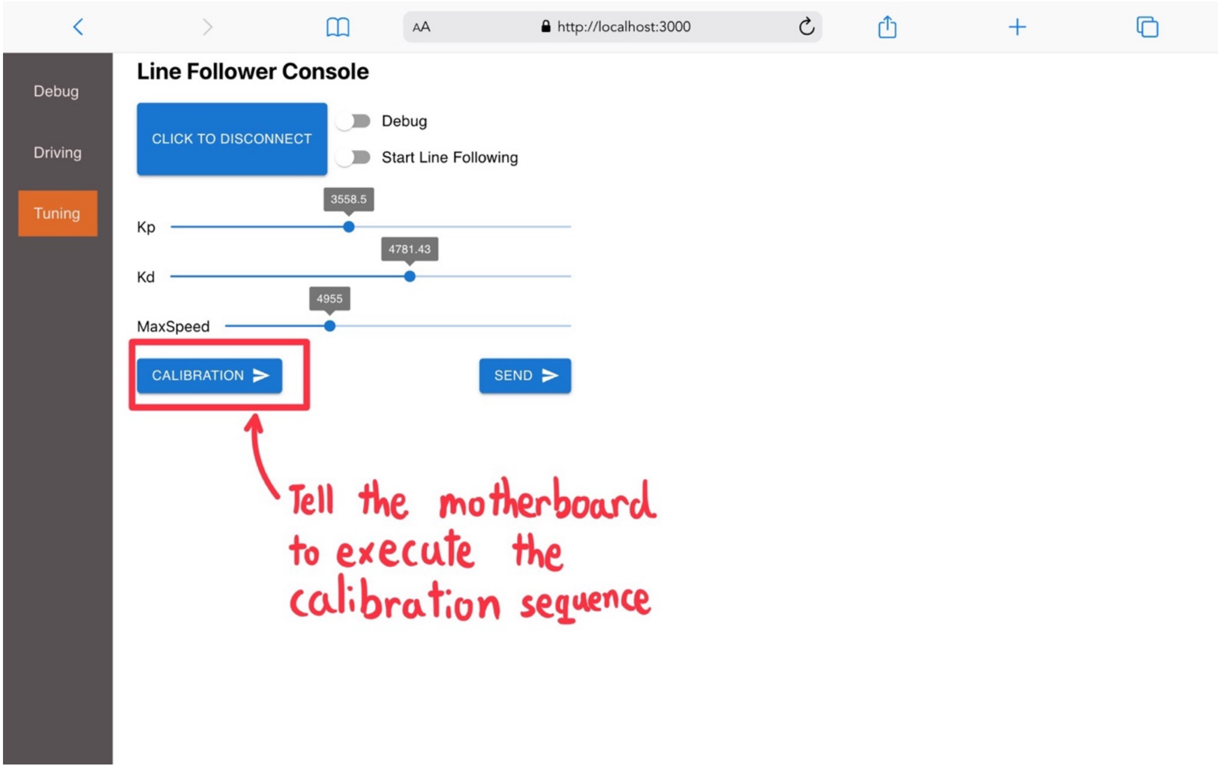
3. Tuning

- By selecting the "Tuning" option, user could modify the Kp, Kd, and MaxSpeed parameters using three interactive sliders. Afterwards, clicking the “Send” button updates those values on the follower.



4. Calibration

- User could send a calibration command to the robot to start a calibration sequence of sensors.



5. Debug

- By toggling the “Debug” switch, a bar is shown to present the current value of “error” (measure of misalignment) of the follower