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Analog Line Following Robot

Team Outlaws

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Abstract

This project presents a fully analog line-following robot designed to detect and track a path using real-time analog signal processing. Unlike conventional designs that rely on microcontrollers and digital algorithms, our approach implements every control function—sensing, error generation, and motor control using purely analog circuitry. An IR sensor array measures the robot's deviation from the line, producing continuous analog outputs that are conditioned and processed through an operational amplifier based PID controller. The proportional, integral, and derivative components are combined to generate a smooth corrective signal, which is subsequently fed through adders and subtractors to produce differential control signals for the left and right motors. To interface with the motor driver, the analog control signal is converted into a Pulse Width Modulated (PWM) signal using a comparator and triangular-wave generator. Additional features such as speed selection and adjustable PID gains were incorporated to enhance flexibility. A compact PCB using Surface Mount Device (SMD) components was developed to implement the circuit efficiently, and a 3D-printed enclosure was designed to provide mechanical stability and support. This project demonstrates the effectiveness of analog methods in achieving precise, low-latency line following without digital computation.

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Chapter 1

Introduction

Line-following robots are widely used in autonomous navigation, typically relying on digital microcontrollers for sensor processing and control. In this project, however, a fully analog approach is employed to achieve line following without any digital computation. The robot detects line position using an eight-sensor IR array that outputs analog voltages based on reflected light intensity. To ensure clean and stable signals, each sensor output is passed through a buffer stage before being processed.

The buffered signals are fed into weighted scaling adders that compute left and right positional values. A differential amplifier then generates an error signal representing the robot's deviation from the line. This error is corrected through a complete analog PID controller, implemented using LM324 op-amps, resistors, capacitors, and variable resistors. The proportional, integral, and derivative components are computed in real time to provide smooth and accurate control.

The resulting PID output is converted into PWM using an analog triangular-wave generator and comparator, which then drive the DC motors through transistor switches. A regulated ± 5 V power supply, custom PCB, and 3D-printed enclosure ensure stable and compact system operation. This project demonstrates the effectiveness of analog control in achieving precise, low-latency line following.

Every functionality is implemented using analog circuits, divided into functional blocks:

1. IR Sensor Array: Detects the position of the black line by producing analog voltages proportional to reflected light intensity.
2. Buffer Circuit: Isolates the sensor outputs and prevents loading to ensure clean, stable analog signals for further processing.
3. Scaling Adders (Weighted Sum Calculators): Computes weighted left-side and right-side position values by giving different importance to each sensor.
4. Subtractor / Differential Amplifier: Generates the line error signal by subtracting the right-side weighted sum from the left-side weighted sum.
5. Proportional Block (P): Provides an immediate correction by amplifying the error signal proportionally to the deviation.

6. Integral Block (I): Accumulates the error over time to eliminate steady-state offset and improve long-term accuracy.
7. Derivative Block (D): Predicts rapid changes in the error to reduce overshoot and produce smoother responses.
8. Analog PID Controller: Combines the P, I, and D components to generate a stable and corrective control signal for line tracking.
9. Triangular Wave Generator: Produces a continuous triangular waveform required for analog PWM generation.
10. Comparator (PWM Generator): Compares the PID output with the triangular wave to generate a PWM signal with a duty cycle proportional to the correction.
11. Transistor Motor Driver: Uses MOSFET switches to drive the DC motors efficiently based on the PWM control signals.
12. DC Motors: Execute movement and adjust speed to correct the robot's position on the line.
13. Voltage Regulators / Power Management: Provide stable ± 5 V regulated supplies to ensure reliable analog circuit operation.

Chapter 2

Component Selection

2.1 IR Sensors

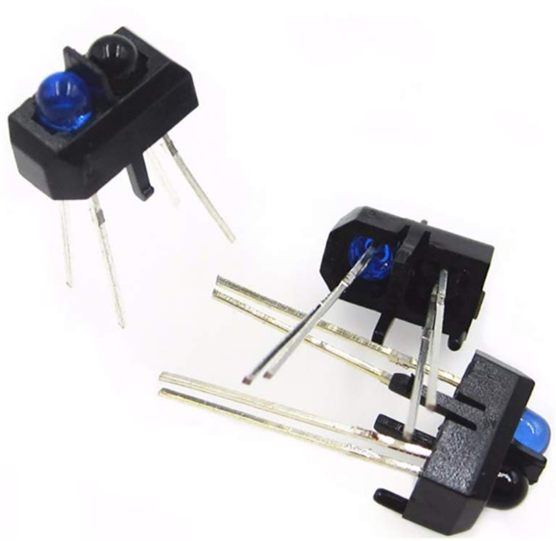


Figure 2.1: TCRT5000 IR Sensors

The TCRT5000 IR sensor array consists of eight infrared emitter–receiver pairs that detect the presence of a black line on a reflective white surface. Each module emits infrared light and measures the amount of light reflected back, producing an analog voltage proportional to surface reflectivity. Black surfaces absorb more IR light and generate lower output voltages, while white surfaces reflect more light and produce higher outputs. This continuous analog response makes the TCRT5000 array ideal for precise line detection and smooth analog signal processing in the PID control system.

2.2 LM324 Op-Amp IC

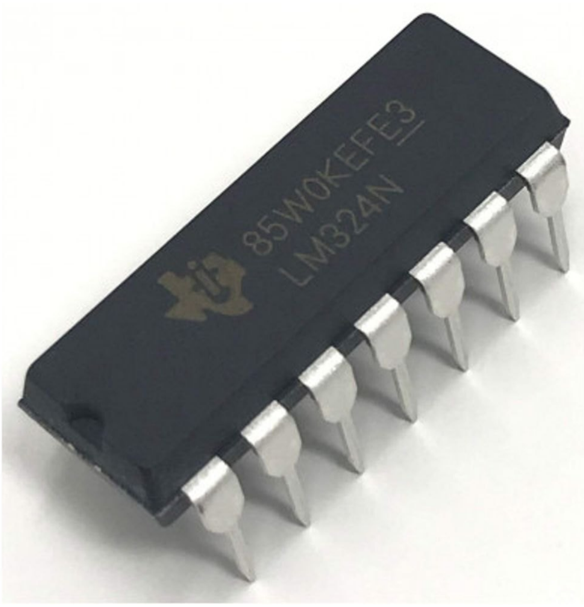


Figure 2.2: LM324 Op-Amp IC

The LM324 is a quad operational amplifier IC containing four independent op-amps in a single package, making it highly suitable for compact analog circuit design. It operates reliably on a single supply, supports low-frequency applications, and offers sufficient slew rate for PID, filtering, and signal conditioning tasks in a line-following robot. The LM324 was chosen for this project because it is cost-effective, power-efficient, and capable of handling the multiple amplification, integration, differentiation, and buffering stages required. Its ability to operate from a 5V supply and provide stable performance in analog control circuits makes it an ideal choice for implementing the fully analog PID controller and supporting signal-processing blocks.

2.3 Li-Ion-Rechargeable-Batteries

Figure 2.3: Li-Ion-Rechargeable-Battery

Used as the main power source. Two 3.7V Li-Ion batteries connected in series supply sufficient voltage for both regulators to produce ± 5 V.

2.4 Voltage Regulators

Figure 2.4: 7905 and 7805 Voltage Regulators

The analog line following robot uses a carefully designed voltage regulation system to power both its analog control circuitry and motor drivers. Four 3.7 V Li-ion batteries connected in series form the main supply, providing approximately 14.8 V. From this input, a dual ±5 V regulated supply is generated using 7805 (positive) and 7905 (negative) voltage regulators to ensure stable and noise-free operation of the LM324 op-amp–based analog circuits.

2.5 Buck Converter

Figure 2.5: Buck Converter

To power the DC motors, the robot uses an MP1584-based DC-DC buck converter module, capable of stepping down voltages from 4.5–28 V to an adjustable range of 0.8–18 V with up to 3 A output current. This compact and highly efficient switching regulator provides a stable 6 V supply for the motors while minimizing heat generation and power loss compared to linear regulators. Its adjustable output and high current capability make it ideal for handling the dynamic load changes of DC gear motors, ensuring reliable torque and preventing fluctuations that could interfere with the robot's analog control circuitry.

2.6 N20 300RPM DC Motor

Figure 2.6: N20 300RPM Gear Motor

The robot uses compact N20 300 RPM DC gear motors to drive the wheels and perform precise movement during line following. These motors feature a small cylindrical metal housing with an integrated gearbox, providing high torque at low speed, making them ideal for accurate and smooth navigation. Operating efficiently at 6 V, the N20 motors deliver consistent rotational speed and reliable response to the PWM-based control signals generated by the analog circuitry. Their lightweight design, low power consumption, and stable performance make them well suited for compact mobile robots requiring fine control and quick directional adjustments.

Chapter 3

System Architecture

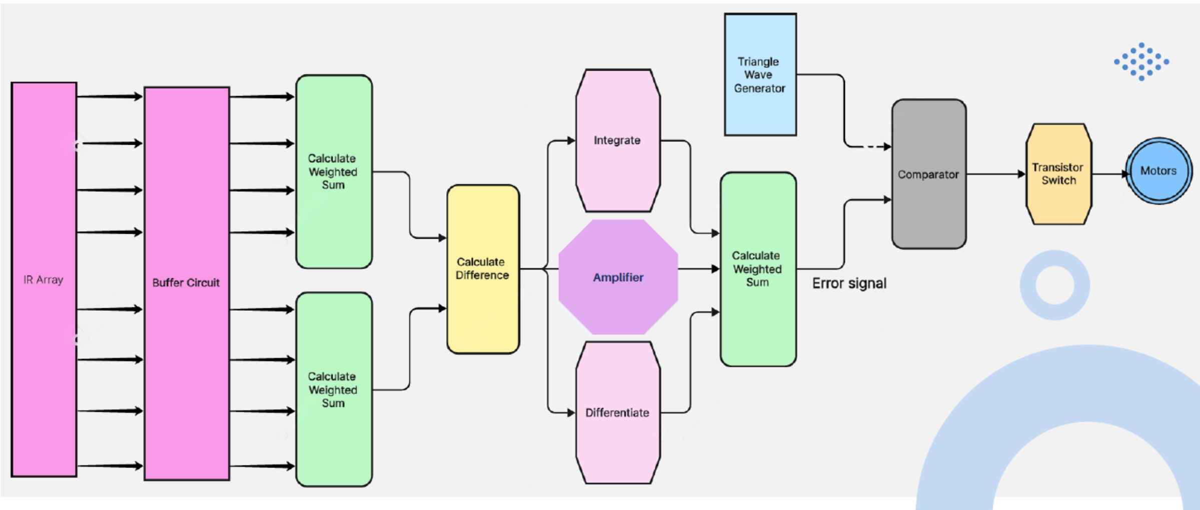


Figure 3.1: System Architecture

Chapter 4

Functionality and Parameters

4.1 Input IR sensors and buffer circuit

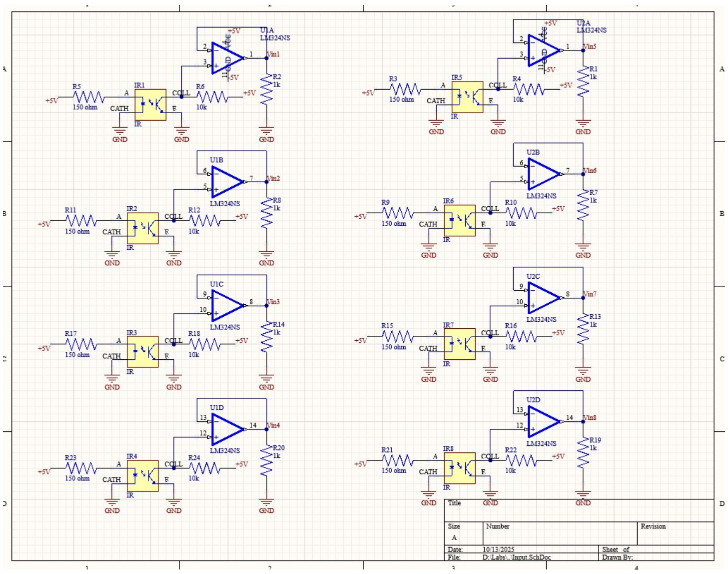


Figure 4.1: Input IR sensors and buffers

IR Sensor Array Functionality: The IR sensor array detects the position of the black line by emitting infrared light and measuring the reflected intensity from the surface. Each TCRT5000 sensor produces an analog voltage that varies depending on whether it is over a black or white region, allowing the robot to determine line position and deviation accurately across all eight sensors.

Buffer Circuit Functionality: The buffer circuit, implemented using op-amps in voltage follower mode, isolates the sensor outputs from subsequent processing stages and prevents signal distortion due to loading effects. It ensures that each sensor's analog signal is delivered cleanly, preserving accuracy before entering the weighted sum and error-generation circuits.

4.1.1 Output of the Input IR sensors and buffer circuit

1. Sensor model (single sensor)

$$V_s = V_{CC} - I_c R_L.$$

- V_s: The analog output voltage delivered to your circuit
- V_{CC}: Supply voltage (typically +5V)
- I_c: Phototransistor collector current (increases when more IR light is detected)
- R_L: Load resistor (pull-up resistor connected between supply and collector)

2. Buffer Output (Voltage Follower)

Each sensor output passes through a buffer:

$$V_b = V_s$$

The buffer gives:

- unity gain
- high input impedance
- clean, isolated sensor signals

4.2 Scaling adders and Subtractor

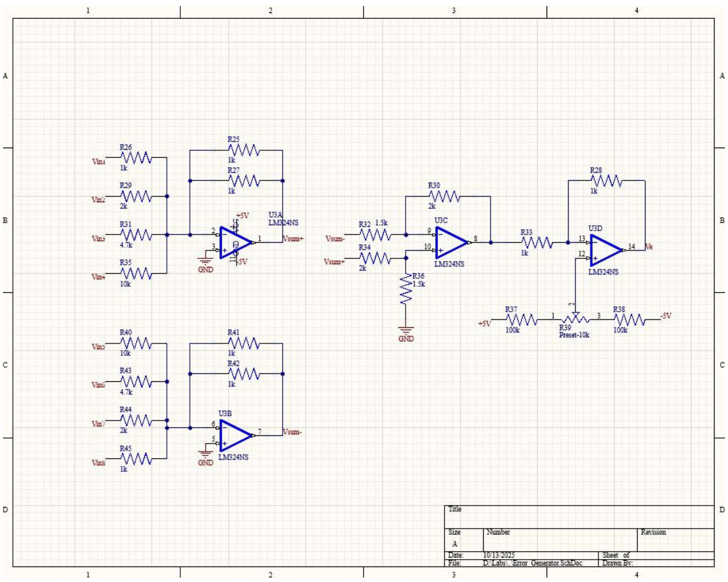


Figure 4.2: Scaling adders and Subtractor

Weighted Sum Calculation (Scaling Adders)

The scaling adder circuits compute the robot's position by assigning different weights to each sensor in the IR array, ensuring sensors closer to the center have a higher influence. Each sensor's buffered analog voltage is multiplied by a resistor-defined weight, and the resulting currents are summed to produce two analog values—one representing the left side of the line and the other the right side. This converts raw sensor readings into meaningful positional information for accurate line tracking.

Difference Calculation (Subtractor / Differential Amplifier)

The subtractor circuit compares the left and right weighted sums to generate the line error signal. By computing the difference between these two values, the circuit determines the direction and magnitude of deviation from the center of the line. A positive output indicates drifting toward one side, while a negative output indicates drifting toward the other, providing the essential input for the PID controller.

4.2.1 Scaling Adder Output

The weighted sum output is:

$$V_{sum+} = -\frac{R_{25}R_{27}}{R_{25}+R_{27}}\left(\frac{V_{in1}}{R_{26}} + \frac{V_{in2}}{R_{29}} + \frac{V_{in3}}{R_{31}} + \frac{V_{in4}}{R_{35}}\right)$$

$$V_{sum-} = -\frac{R_{41}R_{42}}{R_{41}+R_{42}}\left(\frac{V_{in5}}{R_{40}} + \frac{V_{in6}}{R_{43}} + \frac{V_{in7}}{R_{44}} + \frac{V_{in8}}{R_{45}}\right)$$

4.2.2 Subtractor Output

$$V_e = -\frac{R_{30}}{R_{32}}(V_{sum+} - V_{sum-})$$

4.3 PID Controll

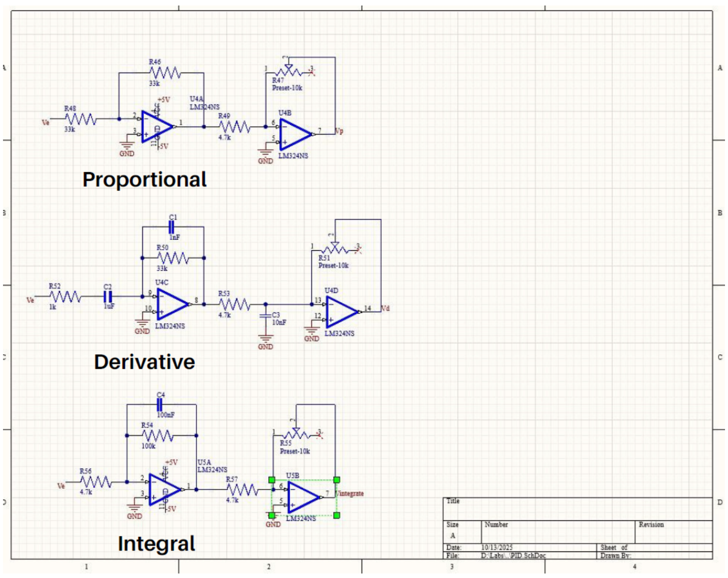


Figure 4.3: PID Controll

The PID controller processes the line error signal and generates a smooth correction to keep the robot accurately aligned with the path. The Proportional (P) stage amplifies the instantaneous error to provide an immediate corrective response. The Integral (I) stage accumulates past error over time, eliminating steady-state offset and helping the robot remain centered even when sensor outputs drift. The Derivative (D) stage predicts future changes by responding to the rate of error variation, reducing overshoot and stabilizing rapid turns. Implemented entirely using LM324 op-amps, resistors, capacitors, and potentiometers, the analog PID controller continuously combines these three components into a single control voltage that ensures fast, stable, and real-time line following without any digital computation.

4.3.1 Proportionality of PID

The proportional block generates an output that is directly proportional to the instantaneous line error, providing an immediate corrective response to keep the robot aligned with the path.

$$V_P = K_P\, e(t)$$

where the proportional gain is given by

$$K_P = \frac{R_f}{R_{\text{in}}}.$$

4.3.2 Differentiation of PID

The differentiator responds to the rate of change of the error signal, predicting rapid deviations and reducing overshoot during fast movements.

$$V_D = K_D\, \frac{de(t)}{dt}$$

where the analog differentiator gain is defined as

$$K_D = \frac{R_f\, C}{R_{\text{in}}}.$$

4.3.3 Integrator of PID

The integrator accumulates the error over time, eliminating steady-state offset and improving long-term accuracy in line tracking.

$$V_I = K_I \int_0^t e(\tau)\, d\tau$$

with the analog integrator gain given by

$$K_I = \frac{1}{R_{\text{in}}\, C}.$$

4.4 Motor controlling circuit

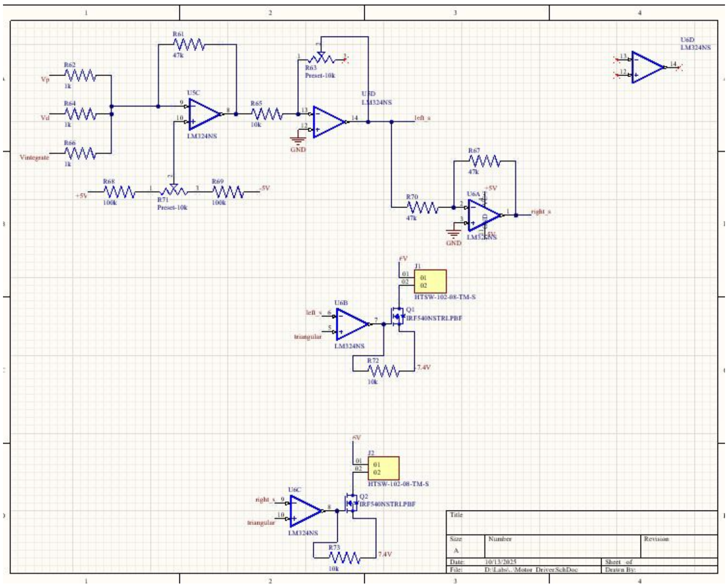


Figure 4.4: Motor Controlling Circuit

The motor controlling circuit converts the PID controller's analog correction signal into actual motor movement using an analog PWM-based drive stage. The PWM signal generated from the comparator is fed into a series of power transistors configured as switching elements, allowing efficient control of motor speed through duty-cycle variation. Each motor has its own transistor switch that amplifies the low-power PWM signal into a high-current output capable of driving DC gear motors. This design ensures smooth acceleration, precise speed control, and responsive turning based on the error signal from the PID block. By combining analog PWM generation with transistor-based power stages, the circuit provides reliable and low-latency motor control without requiring any microcontroller or digital processing.

4.5 PWM Generator

The PWM generator converts the analog output of the PID controller into a Pulse Width Modulated signal suitable for driving the DC motors. It operates by first producing a stable triangular waveform using an analog integrator–comparator oscillator. This triangular wave is then fed into a comparator along with the PID output voltage. When the PID signal is higher than the triangular waveform, the comparator output goes high; otherwise, it goes low, creating a PWM signal whose duty cycle is directly proportional to the required correction. A higher PID voltage results in a wider duty cycle, increasing motor speed, while a lower PID voltage reduces the duty cycle, slowing the motor. This analog PWM mechanism enables smooth and real-time speed control without the need for any digital circuitry, ensuring accurate response to line deviations.

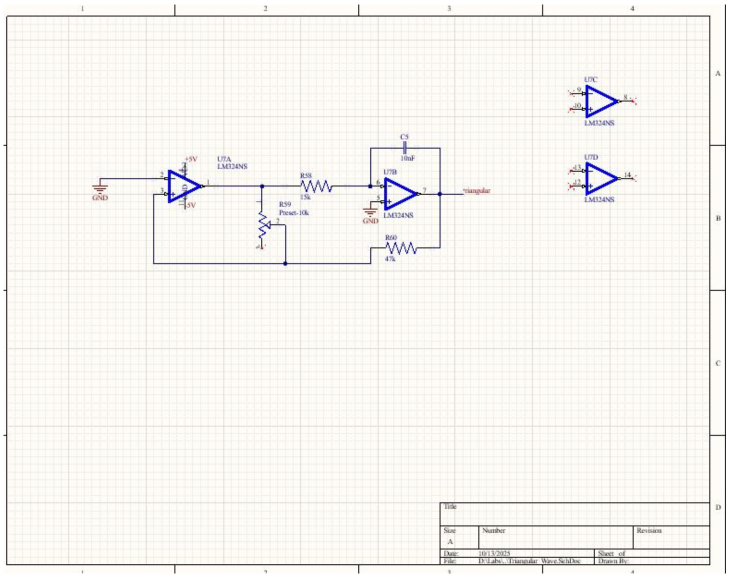


Figure 4.5: Triangular Wave Generator

4.5.1 PWM Generator - Equations

Let $v_{\text{pid}}(t)$ denote the analog PID output voltage, and let $v_{\text{tri}}(t)$ denote the triangular carrier waveform of amplitude A and frequency f. A common analytic expression for a symmetric triangular wave is

$$v_{\text{tri}}(t) = \frac{2A}{\pi} \arcsin\Big(\sin(2\pi f t) \Big).$$

The comparator generates a PWM signal by comparing the PID voltage with the triangular carrier. The instantaneous PWM output $V_{\text{pwm}}(t)$ is therefore

$$V_{\text{pwm}}(t) = \begin{cases} V_{CC}, & v_{\text{pid}}(t) > v_{\text{tri}}(t), \\ 0, & v_{\text{pid}}(t) \leq v_{\text{tri}}(t), \end{cases}$$

which can be written compactly using the Heaviside step function $H(\cdot)$ as

$$V_{\text{pwm}}(t) = V_{CC}\, H\Big(v_{\text{pid}}(t) - v_{\text{tri}}(t)\Big).$$

If the PID voltage is approximately constant during a carrier period and the triangle spans $[-A, +A]$, the duty cycle D (fraction of period where the PWM is high) is

$$D = \frac{1}{2}\left(1 + \frac{v_{\text{pid}}}{A}\right),$$

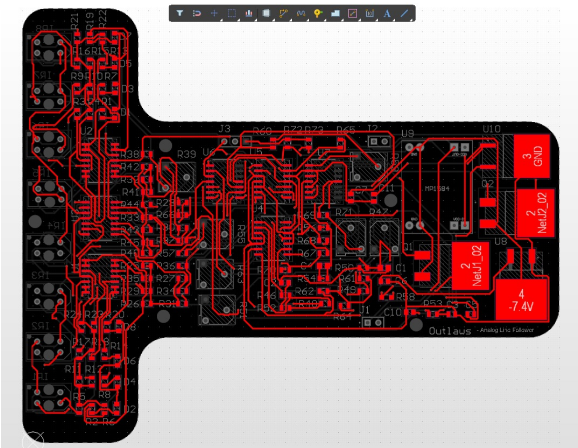
with clipping to the range $0 \leq D \leq 1$. More generally, for a triangle varying between $V_{\min}$ and $V_{\max}$,

$$D = \frac{v_{\text{pid}} - V_{\min}}{V_{\max} - V_{\min}},$$

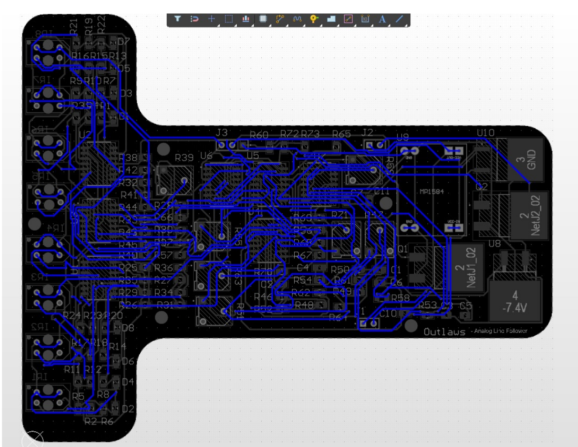
again clipped to $[0, 1]$.

Chapter 5

PCB Design



(a) Top Layer



(b) Bottom Layer

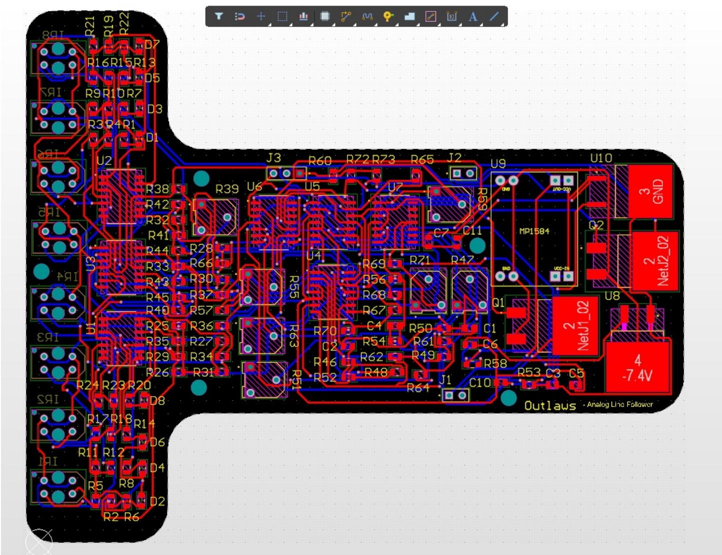
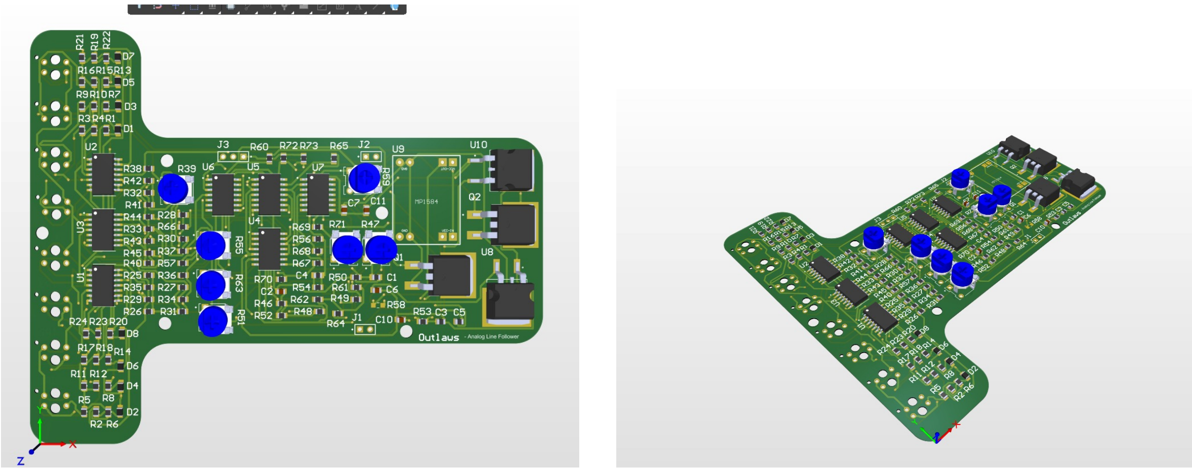


Figure 5.2: PCB Design

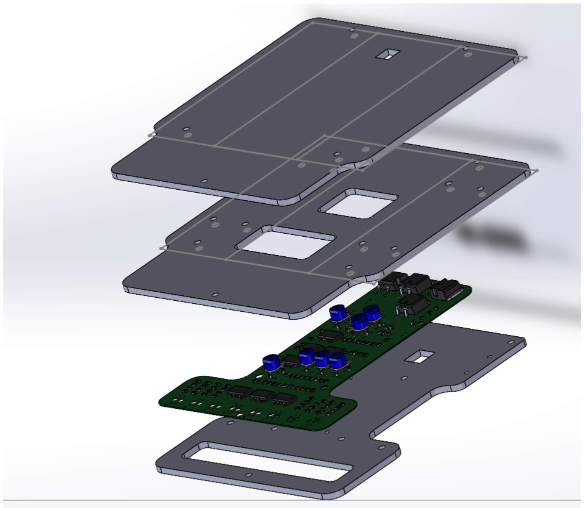


(a) 3D Top View (b) 3D View

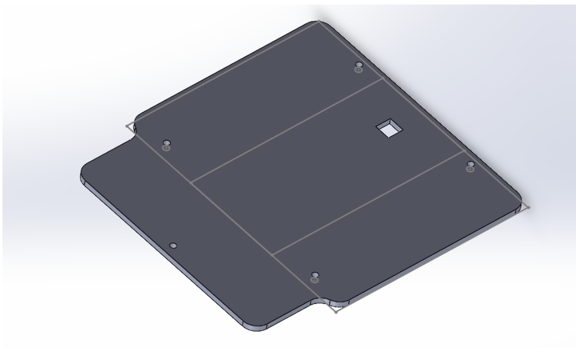
The PCB for the analog line-following robot was designed using Altium Designer, integrating all functional blocks—including the IR sensor interface, weighted sum circuits, PID controller, PWM generator, and motor driver—into a compact and efficient layout. A two-layer board was used, with the top layer primarily carrying signal traces and the bottom layer allocated for ground planes and power distribution to minimize noise and improve signal integrity. Surface Mount Device (SMD) components were selected to reduce board size and enhance routing density, allowing more than fifty analog components and multiple op-amp stages to be fitted within a small footprint. Special attention was given to separating sensitive analog sections from high-current motor paths to avoid interference. The final 3D-rendered PCB provides a clear visualization of component placement and mechanical fit, ensuring compatibility with the custom 3D-printed enclosure. Overall, the PCB design enables stable analog operation, clean signal flow, and reliable performance in real-time line-following tasks.

Chapter 6

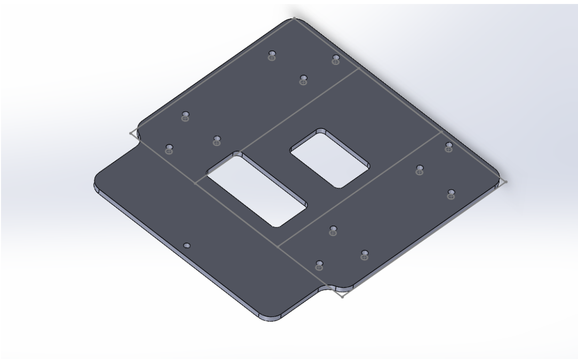
Enclosure Design



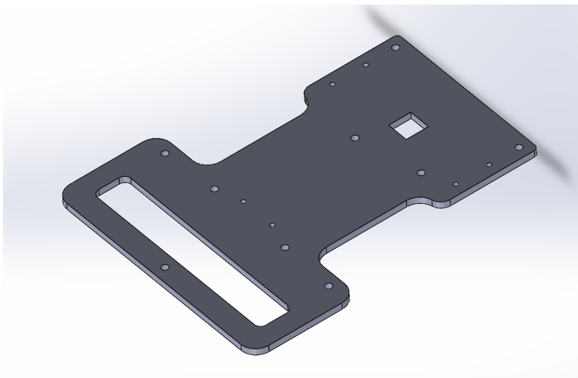
(a) Enclosure Assembly



(b) Upper Top Layer



(c) Upper Layer

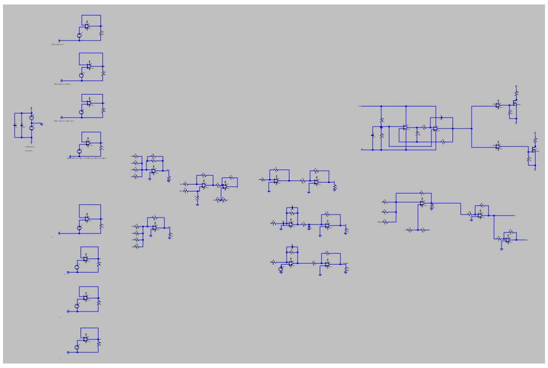


(d) Bottom Layer

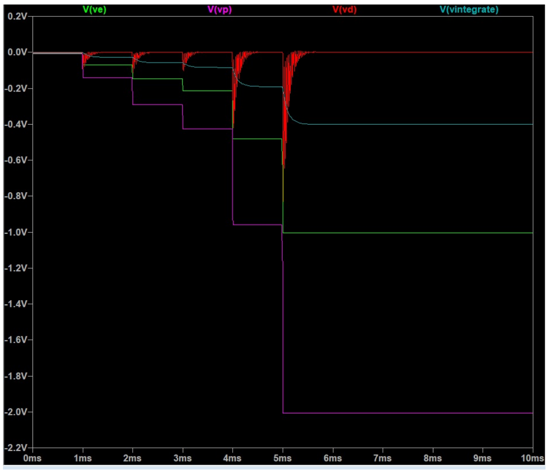
The enclosure for the analog line following robot was designed using SolidWorks, consisting of a layered structure that securely houses the custom PCB and provides mechanical protection during operation. The design includes precisely aligned mounting holes, cutouts for component access, and adequate spacing for heat dissipation and wiring. Each layer is engineered to fit tightly around the PCB, ensuring stability while keeping the overall form factor compact and lightweight. This modular design also simplifies assembly and maintenance, allowing easy access to internal components without compromising structural rigidity.

Chapter 7

Software Simulation and Hardware Testing

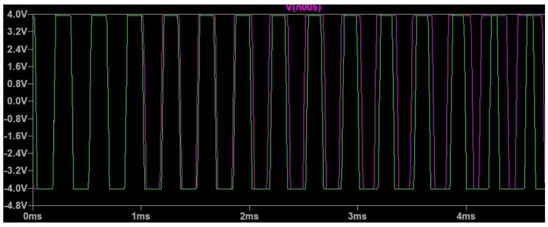


(a) Circuit Simulation

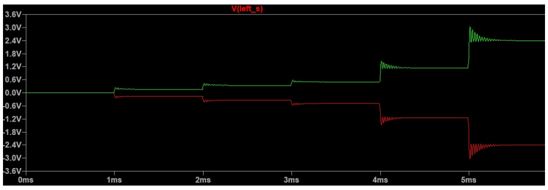


(b) PID Response

Figure 7.1: Software simulation results

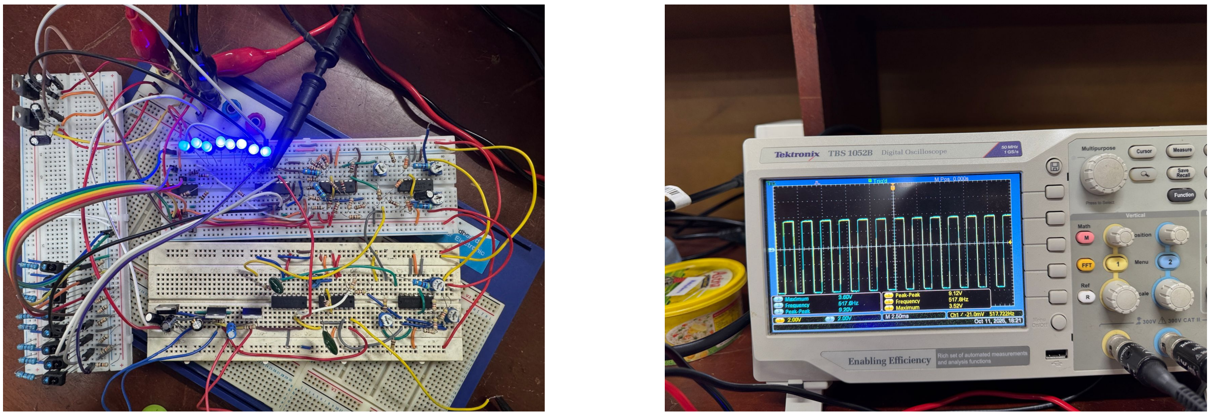


(a) PWM Signal (Simulation)



(b) Correction Signal

Figure 7.2: Control signal analysis



(a) Hardware Circuit Testing (b) PWM Signal (Hardware)

Figure 7.3: Hardware testing results

Chapter 8

Contribution of Group Members

Index Number	Contribution
230687P	Circuit analysis and debugging , Circuit Designing & Simulation
230525U	Circuit analysis and debugging , Enclosure Designing
230355X	Circuit analysis and debugging, PCB Designing
230248X	Circuit analysis and debugging , Soldering & Testing

Chapter 9

Conclusion

The development of the analog line following robot successfully demonstrated that precise and reliable control can be achieved using purely analog circuitry without relying on microcontrollers or digital processing. By integrating an IR sensor array, weighted-sum processing, and a fully analog PID controller built with LM324 operational amplifiers, the robot was able to detect line deviations and respond with smooth and stable corrections in real time. The implementation of an analog PWM generator and an efficient multi-stage power regulation system ensured clean signal operation and consistent motor performance, while the custom-designed PCB and 3D-printed enclosure resulted in a compact, robust, and well-integrated final product.

Beyond achieving these technical outcomes, this project provided valuable hands-on learning experiences. We gained a deep understanding of analog signal processing, operational amplifier behavior, noise management, and the practical challenges of implementing theoretical PID control in real hardware. Designing and tuning the system taught us the importance of precise component selection, proper grounding techniques, and systematic testing using simulations, breadboards, and oscilloscopes. The PCB design process improved our skills in layout optimization, routing, and EMI minimization, while working with real sensors and motors strengthened our understanding of calibration, power management, and physical constraints. Overall, this project not only demonstrated the capabilities of analog control systems but also significantly enhanced our practical engineering skills, teamwork, and problem-solving abilities, preparing us for more advanced embedded systems and robotics work in the future.

References

- PID-Theory: `https://www.ni.com/en/shop/labview/pid-theory-explained.html`
- DIY Circuit Design - PWM: `https://www.engineersgarage.com/diy-circuit-design-pulse-`
- PID Controller: `https://www.elprocus.com/the-working-of-a-pid-controller/`
- Practical Integrator: `https://www.electronics-tutorial.net/analog-integrated-circuits` `op-amp-integrator/practical-integrator/`
- Vishay Semiconductors. (2017). TCRT5000 Reflective Optical Sensor – Datasheet. – Reference for IR sensor characteristics, output behavior, and application guidelines used in the sensor array.