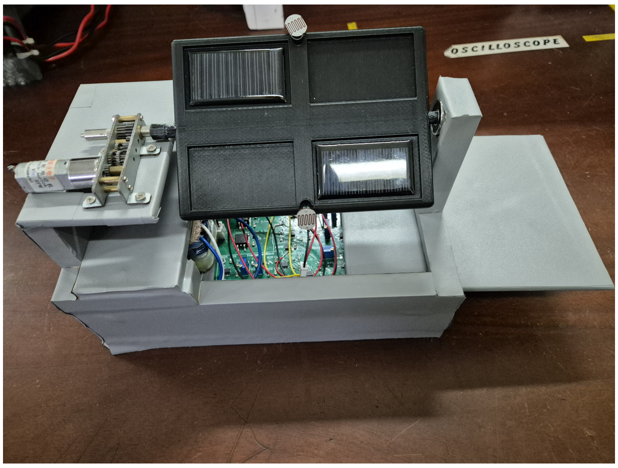
DEPARTMENT OF ELECTRONIC & TELECOMMUNICATION ENGINEERING
UNIVERSITY OF MORATUWA

EN-2091 Laboratory Practice and Projects

Automatic Solar Tracker



Socket Burners

MANAWADU D.N. 220380J

MANAWADU M.D. 220381M

MUFTEE M. M. M. 220399B

NADHA M.I. 220409J

Contents

1 Abstract

This project presents the development of an automatic solar tracker system designed to maximize the efficiency of photovoltaic (PV) systems by maintaining an optimal alignment between solar panels and the sun throughout the day. The proposed system employs a single-axis tracking mechanism controlled by an analog Proportional-Integral-Derivative (PID) controller, implemented using operational amplifiers. Key components include light-dependent resistors (LDRs) for sunlight sensing, a motor driver for panel movement, and a pulse-width modulation (PWM) circuit for motor control.

The design process encompasses system modeling, circuit design, simulation, and implementation. A compact two-layer printed circuit board (PCB) was developed to integrate the system's electronic components. The enclosure was crafted from environmentally friendly materials, combining wood and 3D-printed PLA for durability and cost-effectiveness. Multisim simulations validated the functionality of the PID controller and PWM generation, while testing confirmed the system's ability to optimize solar energy capture.

This project demonstrates the potential of analog control systems in achieving cost-effective and reliable solutions for solar energy applications, contributing to the ongoing efforts in sustainable energy development.

2 Introduction

The growing demand for sustainable energy solutions, coupled with rising energy costs, has propelled solar power to the forefront as a reliable and eco-friendly alternative. Solar energy, abundant in regions like Sri Lanka due to its proximity to the equator, can be harnessed effectively through photovoltaic (PV) systems. However, the efficiency of these systems is highly dependent on the angle at which sunlight strikes the panels. A fixed solar panel often fails to capture the maximum solar energy throughout the day due to the sun's changing position. To address this limitation, an automatic solar tracker system has been developed, designed to dynamically adjust the orientation of solar panels and ensure that sunlight is consistently perpendicular to their surface. By integrating a single-axis tracking mechanism with an analog Proportional-Integral-Derivative (PID) controller, this system optimizes energy generation, paving the way for more efficient and sustainable solar power utilization.

3 Functionality Description

The automatic solar tracker system is designed to optimize the efficiency of photovoltaic (PV) systems by dynamically aligning solar panels with the sun's position throughout the day. The system operates through a series of integrated components that detect sunlight intensity, compute the error in alignment, and adjust the orientation of the solar panels accordingly.

3.1 Sunlight Sensing

The system uses two light-dependent resistors (LDRs) arranged in a differential configuration to measure the intensity of sunlight incident on each sensor. These LDRs are paired with fixed resistors to form a voltage divider circuit, generating voltage outputs proportional to the light intensity. Any imbalance in sunlight exposure between the sensors creates a voltage difference, which serves as the error signal.

3.2 Error Signal Processing

The error signal is buffered using an operational amplifier to prevent current draw from the voltage divider, ensuring signal integrity. The buffered signal is then passed through a differential amplifier to enhance the accuracy of the error calculation. This processed signal represents the deviation of the solar panel's alignment from the optimal position.

3.3 PID Controller

The error signal is sent to an analog Proportional-Integral-Derivative (PID) controller implemented with operational amplifiers. The PID controller calculates the corrective action required to realign the solar panels by balancing three components:

- **Proportional (P):** Corrects the error based on its current magnitude.
- **Integral (I):** Addresses cumulative errors over time for precise alignment.
- **Derivative (D):** Predicts and minimizes future errors by considering the rate of change.

The outputs of the P, I, and D components are combined using a weighted summing amplifier, allowing fine-tuning of the controller's performance.

3.4 Pulse-Width Modulation (PWM) Generation

The output of the PID controller is used to generate a PWM signal. A triangular wave is generated by passing a square wave through an integrator circuit. The triangular wave and the PID output are then compared using a precision comparator to produce a PWM signal whose duty cycle varies according to the error magnitude. The PWM signal serves as the input to the motor driver circuit.

3.5 Motor Control

The motor driver, powered by the PWM signal, controls the orientation of the solar panel by adjusting the speed and direction of the motor. Comparators within the motor control circuit determine the motor's rotational direction based on the polarity of the PID signal, ensuring precise alignment with the sun.

3.6 Physical Implementation

The system is built on a compact, two-layer printed circuit board (PCB) that integrates all electronic components. The solar panels are mounted on a frame designed using SolidWorks and fabricated with wood and 3D-printed PLA for cost-effectiveness and durability. The frame houses the motor, sensors, and electronic circuitry, ensuring reliable operation in outdoor conditions.

Through this integrated functionality, the solar tracker dynamically adjusts the solar panel's orientation to maximize energy capture, significantly improving the efficiency of PV systems. The design emphasizes cost-effectiveness, reliability, and ease of implementation, making it a practical solution for sustainable energy generation.

4 System Model

4.1 Block Diagram

Figure 1: Block diagram

4.2 Design Parameters

The design of the automatic solar tracker was guided by the following key parameters to ensure optimal performance and efficiency:

1. Objective and Specifications

- **Objective:** To develop a single-axis solar tracker system to enhance photovoltaic (PV) efficiency by maintaining optimal alignment with sunlight.
- **Control Mechanism:** Analog PID controller implemented using operational amplifiers.

- **Power Supply:** Dual supply of ±12V for the circuit operation.
- **Motor Control:** Pulse Width Modulation (PWM)-based motor driver for directional control.

2. **Sunlight Sensing**

- **Sensors Used:**
  - Light Dependent Resistors (LDR) (Advanced Photonix NSL-4960).
  - **Light Resistance:** $< 5\text{k}\Omega$.
  - **Dark Resistance:** $1\text{M}\Omega$.
- **Error Signal Generation:**
  - Differential voltage obtained via a voltage divider with fixed resistors and LDRs.
  - Buffered and amplified using an operational amplifier.

3. **PID Controller Design**

- **Implementation:**
  - Proportional (P): Inverting amplifier for error proportional gain adjustment.
  - Integral (I): Op-amp integrator for cumulative error compensation.
  - Derivative (D): Op-amp differentiator for error rate anticipation.
- **Gain Adjustment:**
  - Inverting amplifiers for independent tuning of K_p, K_i, and K_d parameters.
- **Output Combination:** Weighted summation of P, I, and D components via an op-amp adder.

4. **Motor Driver and PWM Generation**

- **Motor Driver:** L293DD dual H-bridge IC for directional control.
- **PWM Signal Generation:**
  - Triangle wave derived from differentiated square wave.
  - Comparator circuit for PWM signal creation with duty cycle modulation based on PID output.
- **Direction Control:**
  - Comparators determine motor spin direction based on PID output polarity.

5. **Circuit Design**

- **Active Components:**
  - Operational Amplifiers: Texas Instruments TLV-9352.
- **Passive Components:**
  - Resistors, capacitors, and biasing components for stability and error compensation.

6. **PCB and Enclosure**
   - **PCB Design:**
     - Compact 2-layer PCB with dimensions of 123 mm × 82 mm.
     - Top and bottom layers with ground reference planes.
     - Manufactured by JLCPCB, China.
   - **Enclosure Design:**
     - Frame: PLA for environmentally friendliness and easy to 3D print.
     - Wood for low cost and durability.
     - Dimensions: 25 cm × 15 cm × 10 cm for the base; 15 cm × 10 cm for the solar panel holder.
7. **Environmental and Practical Considerations**
   - **Temperature Range:** Designed to operate in typical outdoor conditions.
   - **Scalability:** Configured to support up to four small-sized solar panels (5.8 cm × 3.5 cm each).

These parameters were crucial to achieving the desired performance in aligning the solar panels accurately with the sunlight and improving the efficiency of solar energy harvesting.

5 Specifications

- **Dual Op Amp**: TLV9352IDR with a slew rate of 20 V/µs
- **Motor Driver**: L293DD
- **Motor**: High torque 12V 10RPM open gearbox electric motor
- **BJT**: BC53PAS-QX
- **+12V Regulator**: L7812ABD2T-TR
- **-12V Regulator**: L7912CD2T-TR
- **5V Regulator**: L78L05ACUTR
- **Small Signal Switching Diodes**: 1N4148WT-76K
- **SMD Capacitors**: (1206)
- **SMD Resistors**: (1206)

6 Description of individual circuits

6.1 Error Signal Generation

The first stage of the solar tracker circuit focuses on **error signal generation**. This is achieved using a **voltage divider** formed by fixed resistors and **Light Dependent Resistors (LDRs)**. The LDRs detect the intensity of sunlight falling on the solar panel. When the light intensities on both LDRs are equal, the voltage outputs from the voltage divider are balanced. However, any misalignment causes a difference in the light intensity, resulting in an imbalance in the voltage levels.

To ensure that this signal is stable and prevents any current draw from the voltage divider, the outputs are fed to an **operational amplifier (Op-Amp)** configured as a **buffer**. The buffer maintains the voltage output equal to the input while protecting the voltage divider from any loading effects due to the high input impedance of the Op-Amp.

This buffered signal is then passed to a **differential amplifier**. The differential amplifier calculates the difference between the two buffered signals (V_1 and V_2) generated by the LDRs. The output voltage of the differential amplifier is given by:

$$V_0 = \frac{R_5}{R_4 + R_5} \times \left(\frac{R_3 + R_6}{R_3} \times V_2 - \frac{R_6}{R_3} \times V_1 \right)$$

By choosing equal resistor values, the equation simplifies, and the output becomes:

$$V_0 = V_2 - V_1$$

This voltage difference ($V_2 - V_1$) serves as the **error signal**, which indicates the degree of misalignment of the solar panel.

6.2 Error Gain Adjustment

The next stage of the circuit involves **error gain adjustment** using an **inverting amplifier**. This amplifier adjusts the gain of the error signal to a desired level. The output voltage of the inverting amplifier is given by:

$$V_0 = -\frac{VR_2}{R_7} \times V_{in}$$

Here, V_{in} is the input error signal, and VR_2 and R_7 determine the gain.

Additionally, the circuit includes features for **input bias current compensation** and **input offset voltage compensation**. These features ensure that any errors due to input bias current or offset voltages of the operational amplifier do not affect the accuracy or final operation of the solar tracker.

In summary, this stage produces a clean and amplified error signal, which is essential for determining the corrective action required to align the solar panel optimally with the sun.

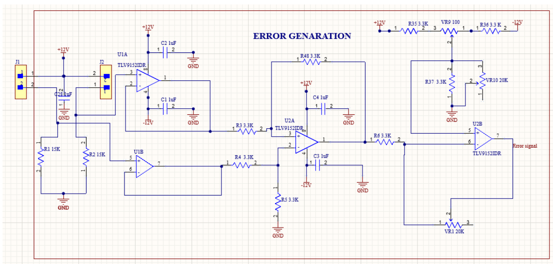


Figure 2: Error signal generation

6.3 PID Generation

A PID (Proportional-Integral-Derivative) controller is a control system mechanism designed to maintain a desired output by minimizing the error between a setpoint and the actual value. The PID control action is mathematically given by:

$$V(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt}$$

Where:

- $V(t)$: Output of the PID controller
- $e(t)$: Error signal (difference between setpoint and actual value)
- K_p, K_i, K_d: Proportional, Integral, and Derivative gains, respectively

1. Proportional (P) Component

The proportional component is implemented as an inverting amplifier. The output voltage is given by:

$$V_o = -\frac{R_9}{R_7} V_i$$

Where:

- R_9: Feedback resistor
- R_7: Input resistor
- V_i: Input error signal

2. Integral (I) Component

An op-amp integrator is used to implement the integral component. The output voltage is given by:

$$V_o = -\frac{1}{R_{10}C_{11}} \int_0^t V_i \, dt$$

Where:

- R_{10}: Input resistor
- C_{11}: Feedback capacitor
- V_i: Input error signal

An additional resistor R_{22} is added to improve the performance at low frequencies.

3. Derivative (D) Component

The derivative component is implemented using an op-amp differentiator. The output voltage is given by:

$$V_o = -R_{14}C_{12}\frac{dV_{in}}{dt}$$

Where:

- R_{14}: Input resistor
- C_{12}: Input capacitor
- V_{in}: Input error signal

A capacitor C_{13} is included to enhance stability at lower frequencies.

6.4 Gain Adjustment

To tune the PID controller, inverting amplifiers are added after each component.

6.5 Weighted Adder

The outputs of the proportional, integral, and derivative components are summed using a weighted adder circuit. The output is given by:

$$V_o = -R_{21}\left(\frac{K_{p_{\text{out}}}}{R_{15}} + \frac{K_{i_{\text{out}}}}{R_{19}} + \frac{K_{d_{\text{out}}}}{R_{20}}\right)$$

Where:

- R_{21}: Feedback resistor
- R_{15}, R_{19}, R_{20}: Input resistors for P, I, and D outputs, respectively
- $K_{p_{\text{out}}}, K_{i_{\text{out}}}, K_{d_{\text{out}}}$: Outputs of the P, I, and D controllers

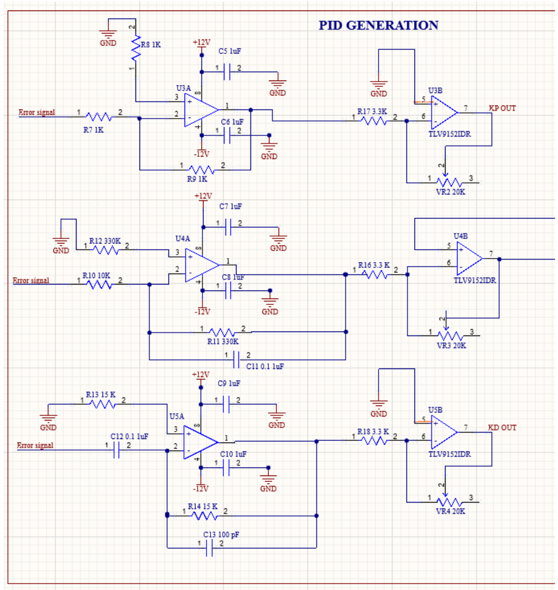


Figure 3: Generation of PID signal

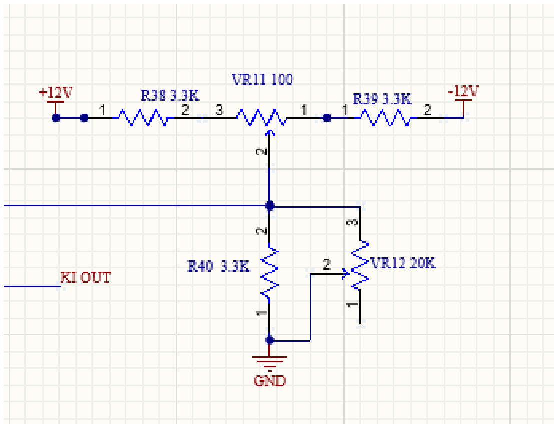


Figure 4: Gain Adjustment

6.6 PWM Generation

The PWM generation begins with the creation of a square wave signal. This is achieved using an astable multivibrator circuit. The astable multivibrator is a type of oscillator that generates a continuous square wave without requiring any external triggering. The frequency of the square wave is determined by the resistors and capacitors in the circuit. Variable resistors are used to fine-tune the frequency to the desired value, ensuring compatibility with the requirements of the PWM signal. The generated square wave is then converted into a triangular waveform. This is done by passing the square wave through an integrator circuit. An integrator circuit, typically implemented using an operational amplifier, integrates the square wave signal over time, resulting in a triangular waveform with a frequency matching that of the square wave input. To improve the signal quality and eliminate noise, the triangular wave is passed through a precision rectifier. A precision rectifier ensures accurate rectification of low-amplitude signals without introducing significant distortion.

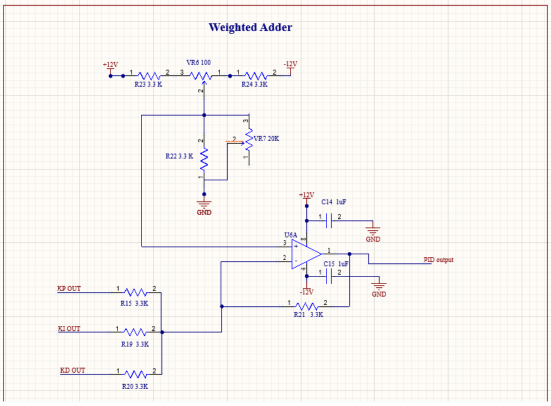


Figure 5: Adder

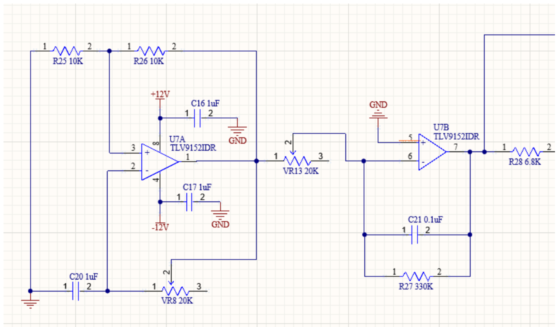


Figure 6: Triangular wave generation

Parallel to the triangular wave processing, the output from the PID controller is also rectified. The rectification ensures that the PID output is in a suitable format for direct comparison with the triangular waveform.

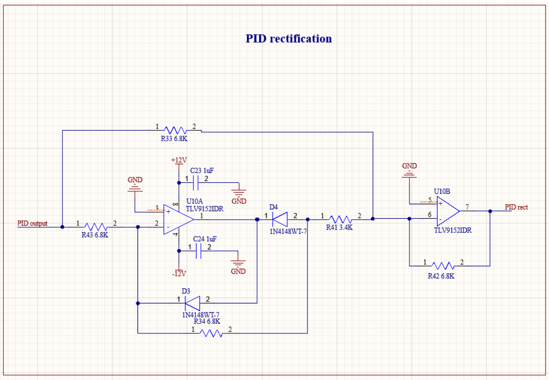


Figure 7: Rectification

The rectified triangular waveform and the rectified PID output are fed into a comparator circuit implemented using an op-amp. The comparator compares the two signals at any given instant. When the amplitude of the PID signal exceeds that of the triangular waveform, the output of the comparator switches states, generating a PWM signal.

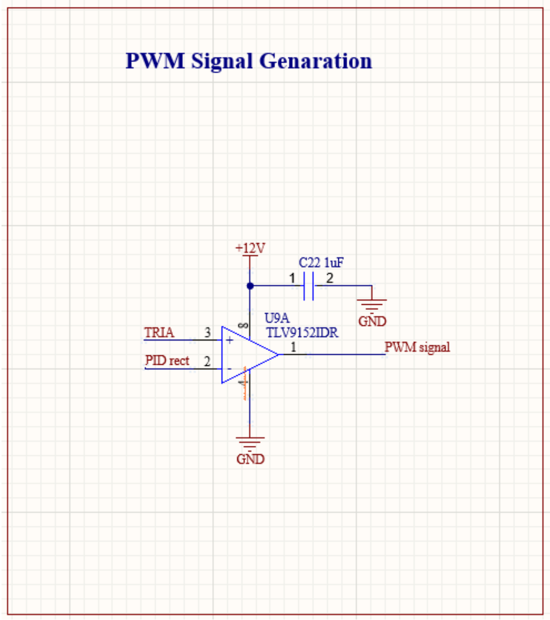


Figure 8: PWM generation

6.7 Motor Control

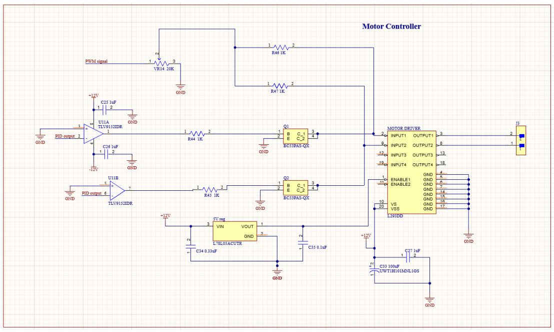


Figure 9: Motor Control

In this motor controller circuit, the BC53PAS-QX transistors are utilized as switches operating in saturation mode. Their primary role is to condition and transmit the control signals generated by the preceding stages, such as the comparator circuit, to the L293DD motor driver IC. When the transistors are driven into saturation, they act like closed switches, allowing current to flow with minimal voltage drop across the collector-emitter terminals. This ensures that clean, full logic-level signals are sent to the input pins of the motor driver, enabling reliable control of the motor.
The L293DD motor driver IC is responsible for controlling both the speed and direction of the motor. It achieves direction control by adjusting the polarity of the voltage applied across the motor terminals based on the logic states of its input pins. For instance, setting one input high and the other low drives the motor in one direction, while reversing these inputs changes the direction of rotation. The transistors serve as intermediaries, ensuring seamless interfacing between the low-power control signals and the motor driver. This design enables efficient and precise motor control, which is essential for the solar tracker's ability to adjust its position for optimal sunlight capture.

7 Simulation

Simulations were done using Multisim software to verify the circuit design and functionality before proceeding to the breadboard implementation. The simulations provided valuable insights into the behavior of the circuit, allowing us to fine-tune the parameters for optimal performance. The results from the simulations were favorable, confirming the feasibility of the design. With the confidence gained from these results, we proceeded to build the circuit on a breadboard for further testing and validation.
The simulation results show the successful generation of a PWM signal through a series of stages:
Square-wave generation: An astable multivibrator circuit produced a stable square wave with adjustable frequency, controlled by variable resistors.

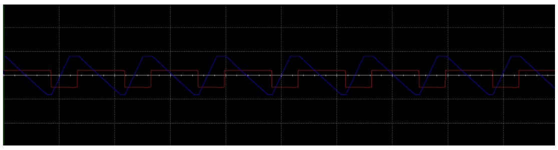


Figure 10: Square waveform

Triangular Wave Conversion: The square wave was integrated using an operational amplifier, resulting in a smooth triangular waveform with the same frequency.
Rectification and Filtering: The triangular wave was passed through a precision rectifier, which ensured accurate rectification without distortion, improving signal quality.

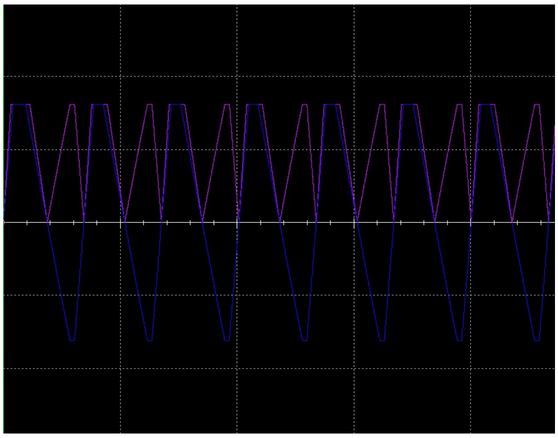


Figure 11: Triangular waveform

Final PWM Signal: The rectified triangular waveform was compared with the rectified PID output, generating a clean PWM signal with a stable frequency and varying duty cycle, suitable for motor control.

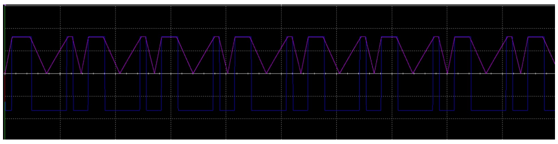


Figure 12: PWM signal

Overall, the simulation confirmed the successful generation of a clean, stable PWM signal for motor control in the solar tracker system.

8 PCB Design

To enhance the circuit's performance and ensure compactness, a 2-layer PCB was designed. The design incorporates both surface-mount devices (SMD) and a few through-hole components, providing a balance between modern assembly techniques and adjustability for tuning. The following details describe the PCB design and manufacturing:

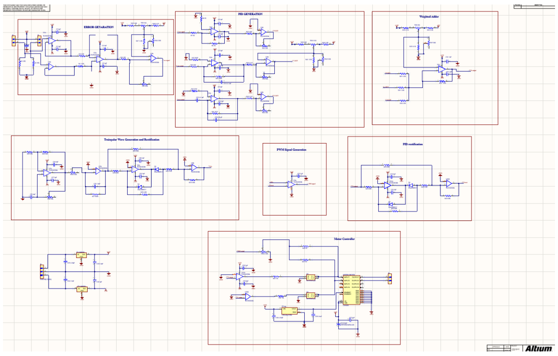


Figure 13: PCB Schematic

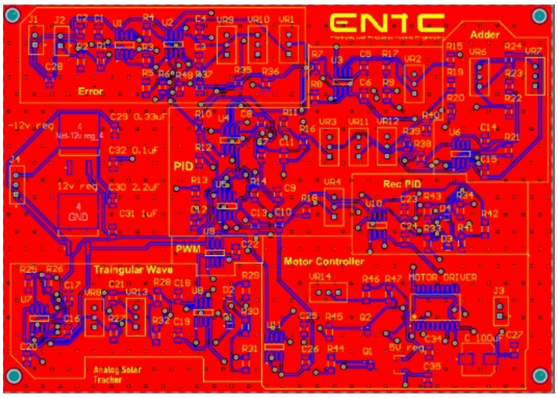


Figure 14: Top layer

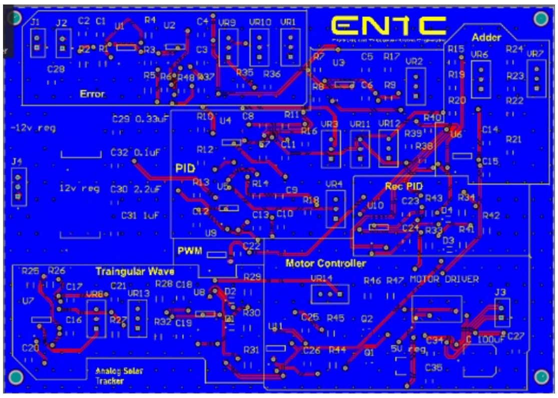


Figure 15: Bottom layer

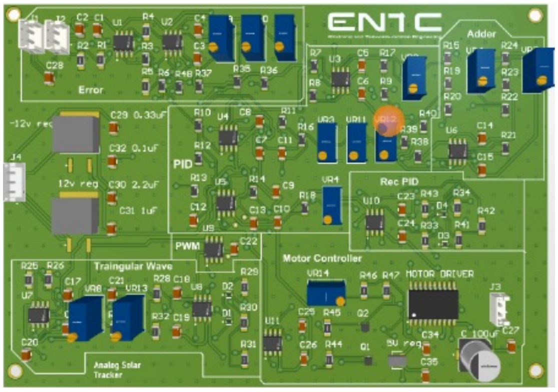


Figure 16: 3D layout

8.1 Components and Layout

- **SMD Components:** Most of the resistors and capacitors on the PCB are 1206 package SMD components, chosen for their compact size and ease of assembly.
- **Through-Hole Components:** Through-hole components include variable resistors and JST headers, which are essential for adjustability and reliable connections.
- **Dimensions:** The PCB measures 150 mm in length and 100 mm in width, providing sufficient space for component placement while maintaining a compact design.

8.2 Ground Reference Plane

Both the top and bottom layers of the PCB serve as common ground reference planes. This design ensures improved signal integrity, reduces noise, and enhances the overall performance of the circuit.

8.3 Manufacturing

The PCB was manufactured by **JLCPCB** in China. Their high-quality fabrication processes ensured precision and reliability, meeting the required design specifications.

9 Enclosure

The enclosure for the solar tracker system was designed using SolidWorks, allowing for precise modeling and optimization of space for all components. The design focused on ensuring that all electronics, such as the motor driver and motor, were securely housed and easily accessible for maintenance. To keep costs to a minimum, the enclosure was made from wood, a cost-effective material that also provided the necessary durability and protection for the system's components.

The wooden enclosure was fabricated based on the SolidWorks model, ensuring that the dimensions and structural integrity matched the design specifications. The design also included ventilation features to prevent overheating of the electronics. By using wood, the project kept material costs low while maintaining an effective and practical enclosure for outdoor use.

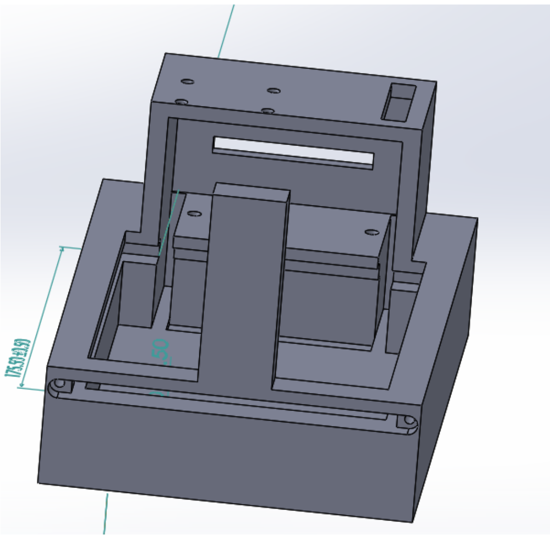


Figure 17: Base

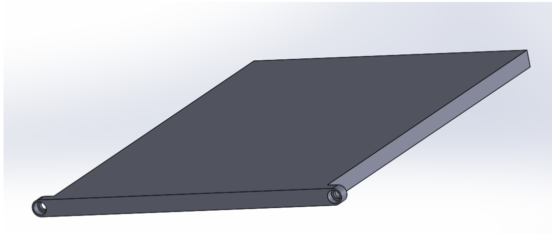


Figure 18: Lid

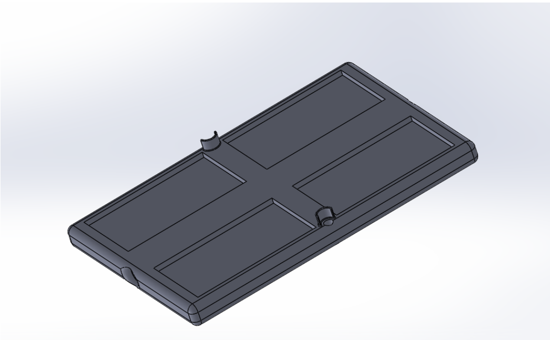


Figure 19: Panel Holder

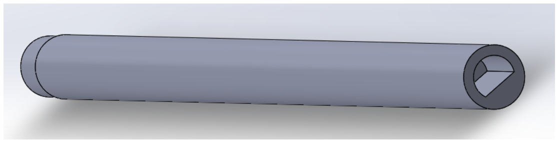


Figure 20: Rod

10 Assembly

The final assembly of the solar tracker system's enclosure involved installing the components into the wooden casing, which was designed in SolidWorks. The motor and circuitry were carefully placed to ensure proper alignment and spacing for efficient operation. Wiring was routed neatly to prevent interference with moving parts, while ventilation openings, as designed, were incorporated to prevent overheating.

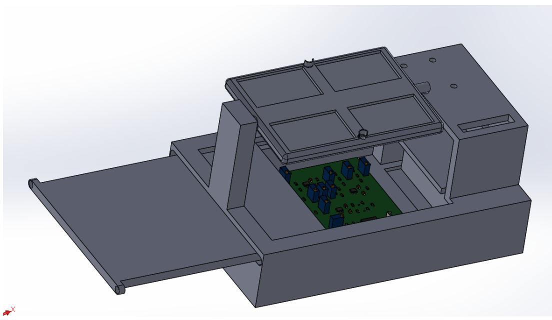


Figure 21: Assembly

Figure 22: Wood Assembly

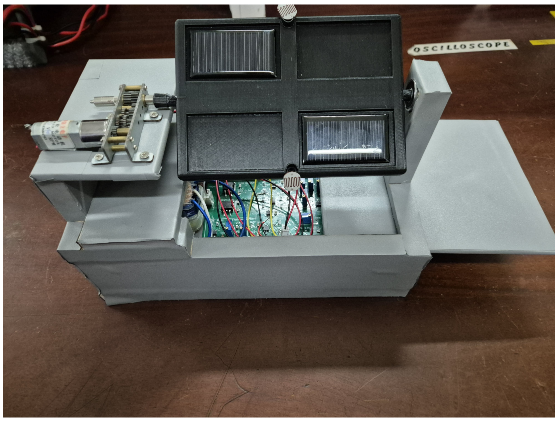
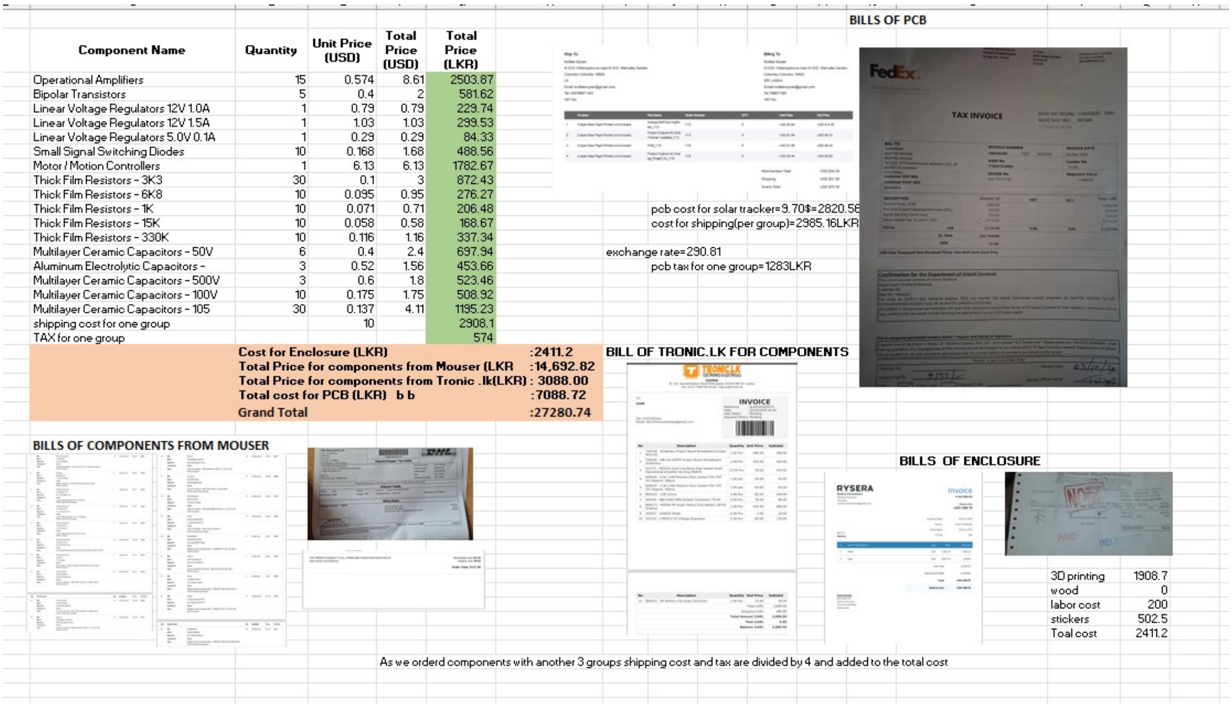


Figure 23: Final Assembly

11 Bill of Materials



Component Name	Quantity	Unit Price (USD)	Total Price (USD)	Total Price (LKR)
Operational Amplifiers	15	0.574	8.61	2503.87
Bipolar Transistors	5	0.4	2	581.62
Linear Voltage Regulators 12V 1.0A	1	0.79	0.79	229.74
Linear Voltage Regulators 12V 1.5A	1	1.03	1.03	299.53
Linear Voltage Regulators 5.0V 0.1A	1	0.29	0.29	84.33
Small Signal Switching Diodes	10	0.168	1.68	488.56
Motor / Motion Controllers	1	6.13	6.13	1782.67
Thick Film Resistors - 3K3	30	0.1	3	872.43
Thick Film Resistors - 6K8	10	0.095	0.95	276.27
Thick Film Resistors - 1K	10	0.071	0.71	206.48
Thick Film Resistors - 15K	10	0.058	0.58	168.67
Thick Film Resistors - 330K	10	0.116	1.16	337.34
Multilayer Ceramic Capacitors - 50V	6	0.4	2.4	697.94
Aluminum Electrolytic Capacitors -	3	0.52	1.56	453.66
Multilayer Ceramic Capacitors - 500V	3	0.6	1.8	523.46
Multilayer Ceramic Capacitors - 100V	10	0.175	1.75	508.92
Multilayer Ceramic Capacitors - 105	30	0.137	4.11	1195.23
shipping cost for one group		10		2908.1
TAX for one group				574

Cost for Enclosure (LKR) :2411.2
Total Price for components from Mouser (LKR :14,692.82
Total Price for components from Tronic .lk(LKR) : 3088.00
Total cost for PCB (LKR) b b :7088.72
Grand Total :27280.74

3D printing	1908.7
wood	0
labor cost	200
stickers	502.5
Toal cost	2411.2

As we orderd components with another 3 groups shipping cost and tax are divided by 4 and added to the total cost

Figure 24: BoM

12 Future Improvements

Future improvements for the solar tracker system can enhance both its functionality and ease of use. One key improvement would be to integrate a solar power harvesting system, allowing the tracker to use the power generated by the solar panel itself to run all its components. This would reduce reliance on external power sources and eliminate the need for additional wires, making the system more self-sufficient and efficient. The tracker could operate even in remote locations or during power outages, ensuring continuous functionality.

Another important improvement would be the design of mounting solutions specifically tailored for rooftop installations. By developing customizable and easy-to-install mounts, the tracker could be securely placed on various roof types, ensuring stability and optimal orientation for solar panel positioning. These mounts could be adjustable, allowing for quick setup and alignment of the tracker, further enhancing its usability and practicality for residential or commercial solar installations.

Additionally, improvements in weatherproofing and durability of the enclosure could be made to ensure the system performs optimally in harsh outdoor conditions, extending its lifespan. Advanced tracking algorithms could also be implemented to improve the accuracy and efficiency of the solar tracking system, ensuring maximum solar energy capture throughout the day.

13 Task Allocation

Name	Index Number	Tasks Assigned
MANAWADU D.N.	220380J	• Simulations using Multisim. • Enclosure design using SolidWorks.
MANAWADU M.D.	220381M	• PCB design using Altium. • Enclosure assembly and building using wood in the wood workshop at the Mechanical Department.
MUFTEE M. M. M.	220399B	• Enclosure design using SolidWorks. • Enclosure assembly and building using wood in the wood workshop at the Mechanical Department.
NADHA M.I.	220409J	• Simulations using Multisim. • PCB design using Altium.
Common Tasks (Performed by All Members):		
• Circuit design. • Testing, prototyping, and breadboard implementation. • Soldering and PCB testing. • Report writing.		

Table 1: Task Allocation Among Team Members

14 Conclusion

In conclusion, the designed solar tracker offers significant benefits in addressing the growing energy demands and the rising costs of traditional energy sources. By maximizing solar power generation through precise tracking, the system enhances the efficiency of solar panels, ensuring optimal energy capture throughout the day. As the world shifts toward more sustainable energy solutions, this solar tracker plays a crucial role in improving the effectiveness of solar power systems, making them more reliable and cost-efficient for future use. With continued improvements and integration of additional features, the solar tracker has the potential to become a vital component in the global transition to renewable energy.

15 References

- Warren, S. J. (2024). *Solar Tracker*. GitHub repository. Available at: https://github.com/Warren-SJ/Solar_Tracker

16 Acknowledgements

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