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Analog Project
Automatic Solar Tracker

Group Members:

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Abstract

Design and implementation of a **single-axis automatic solar tracker** aimed at maximizing photovoltaic energy generation using optimized panel orientation. Due to maximum electrical output of a solar panel depending heavily on the angle of incidence and intensity of sunlight, a dynamic tracking system is required to maintain high efficiency under varying environmental conditions. This system fully employs a purely analog PID control circuit, made using OPAMPs and discrete electronic components to continuously observe the sunlight and change the direction and rotate the solar panel accordingly. All circuitry was simulated using **LT-Spice** and subsequently validated using breadboard testing as well. A complete PCB design was done using **Altium Designer** following JLCPCB's manufacturing guidelines, and mechanical integration is done using 3D printing using models done on **SOLIDWORKS**. The final implementation demonstrates a reliable and responsive analog system for enhanced solar energy harvesting.

Contents

1. Introduction and Functionality

1.1 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.

1.2 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.

1.2.1 Error Generation

Our system uses two Light-Dependent-Resistors (LDRs) paired with a voltage divider to generate output voltage proportional to the light intensity, which acts as the base of error generation. We feed both output of the voltage divider through buffers to eliminate necessary current draw, then we use a differential amplifier made of OPAMPs to find the voltage difference. Afterwards, using a variable-resistor and an inverting amplifier setup we modify the gain given to the voltage difference. This processed signal represents the deviation of the solar panel's alignment from the optimal position.

1.2.2 Triangular Wave Generation

We generate a Square Wave using a symmetric Astable Multivibrator circuit which consists of an OPAMP, a capacitor and resistors.Afterwards we integrate the generated square wave using an OPAMP integrator, which results in a triangular wave.

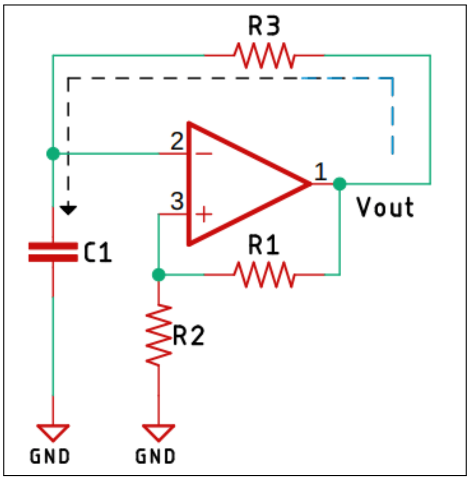

Figure 1: Astable Multivibrator Circuit

1.2.3 PID generation

We are using a PID controller, which 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 by controlling the externally connected variable resistors. The output of error generation is fed into the PID controller.

1.2.4 PWM Wave Generation

The generated Triangular Wave and the PID signal are first rectified using two full wave precision rectifier circuit made using OP-AMPs. The triangular wave and PID output are 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, which controls the motor's rotating speed. This PWM wave is fed into L298N Motor Driver module's ENA pin which in return controls the motor's rotating speed.

1.2.5 Switching

Using 2 MOSFETs and the generated PID signal, we have created a circuit which outputs the direction in which the motor should rotate. Then the output of 2 MOSFET voltages are fed into the L298N Motor Driver module's IN1 and IN2 port which will then be used to control the motor direction according to the light intensity.

1.2.6 Phyiscal Implementation

The system is built on a compact, four-layer printed circuit board (PCB) that integrates all electronic components. The solar panels are mounted on a frame designed using SolidWorks and 3D-printed with PLA and PETG 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.

2 System Architecture

2.1 Block Diagram

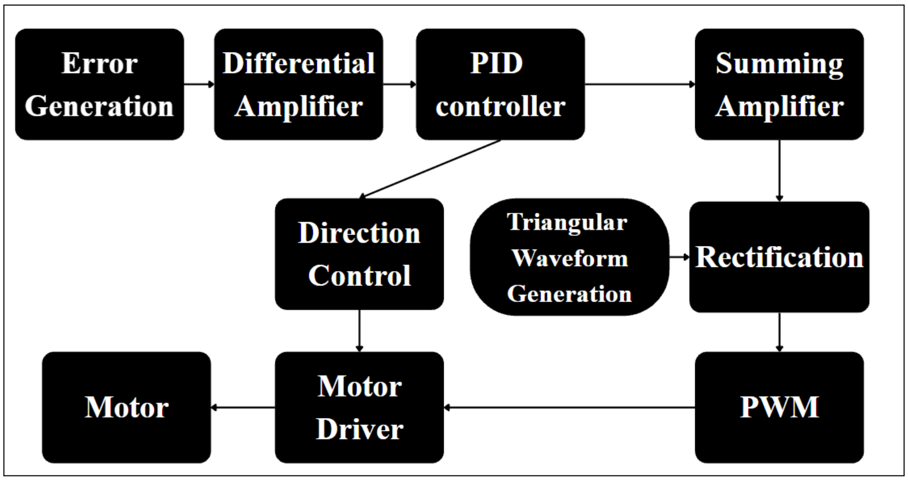

Figure 2: Block Diagram

2.2 Design Parameters

The following key parameters were kept in mind to ensure optimal performance and efficiency:

2.2.1 Objective and Specifications

- **Objective:** Develop a single-axis solar tracker system to enhance photovoltaic efficiency by maintaining optimal alignment with the sun
- **Control Mechanism:** Analog PID controller implemented using OPAMPs.
- **Power Supply:** Dual supply of ±12 V for circuit operation
- **Motor Control:** Pulse Width Modulation based motor driver with directional control.

2.2.2 Error Generation

Obtained differential voltages via the voltage divider with fixed resistors and LDRs are buffered and amplified using OPAMPs.

- **Light Dependent Resistors (LDR):**
  - Light Resistance : <5kΩ
  - Dark Resistance : 1MΩ

2.2.3 PID Generation

- **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.

Each part of PID is amplified using inverting OPAMP amplifiers with adjustable gains through variable resistors, then all three of them are added using an OPAMP adder configuration.

2.2.4 PWM Generation

- **Motor Driver:** L298N dual H-bridge IC for directional control
- **PWM Signal:** OPAMP comparator compares PID and triangle wave and creates PWM with duty cycle modulation.
- **Direction Control:** Two MOSFETs are paired with the PID gives the directional control to the L298N Motor Driver.

2.2.5 PCB

- Compact 4-layer PCB with dimensions of 225mm x 85mm
- Manufactured by **JLCPCB**.

2.2.6 Enclosure Design

- Battery Enclosure made with PETG material.
- Other parts of the enclosure made with PLA material for environment friendliness.

3. Component Selection

OP-AMPs

1. For the Error generation stage and the triangular wave generation stage we used a μ**A**741 **general-purpose OP-AMP**. Reasons include:
   - High input impedance ($2M\Omega$) prevents loading of the feedback and error signals.
   - Good CMRR (70dB–90dB) for error sensing.
   - Slew rate ($0.5\,\mathrm{V}/\mu\mathrm{s}$) is suitable for our application.
   - Low cost and availability.
   - The LM741 is designed to operate cleanly in integrator configurations.
   - Output swing is stable on dual supply.
2. The **LM358AP OP-AMP** was used for the PID stage and the precision full wave rectification stage. Reasons include:
   - Better input offset voltage than 741 $\rightarrow$ less drift in the integrator.
   - Slew rate is adequate for use in our control loop since response time of the sun is very slow. (Higher slew rate than the μA741 OP-AMP.)
   - Output can swing close to ground.
   - Low power consumption.
   - Low cost.
3. For the comparators used to change the direction of rotation of the motor, we used the **LM318 OP-AMP**. Reasons include:
   - Very High Slew Rate ($50\,\mathrm{V}/\mu\mathrm{s}$).
   - Wide bandwidth.
   - High open loop gain improves the comparators sensitivity to small differences between input signals.
   - Low input offset voltage (Typical 4mV) ensures less error in threshold detection.

Power Regulators

Initially, we decided to use 4 3.7V 1000mAh batteries in series and use two LT8331 converters to obtain the necessary +12V and -12V necessary for the operation of the OP-AMPs. But due to the high cost of the converters we decided to use 8 batteries to obtain separate +14.8V and -14.8V and then convert them to +12V and -12V respectively.

1. +14.8V to +12V
   - L7812ABD2T-TR
   - Low noise and ripple. Can handle the current requirment for the OP-AMPs' and high tourque motor.
   - Low cost
2. -14.8V to -12V
   - LM7912CT
   - Low noise, low ripple
   - Low cost

3. +12V to +5V
    - LM2596S-5.0/NOPB
    - High efficiency ($\sim 80\%$).
    - Low cost

Transistor

IRF3205STRLPBF. This is an n-channel mosfet with a protection diode.

- Low RDS - Low power loss.
- Fast switching. (Needed for the PWM generation and motor direction control.)

4. PCB Design

The circuit was implemented on a compact four-layer PCB.

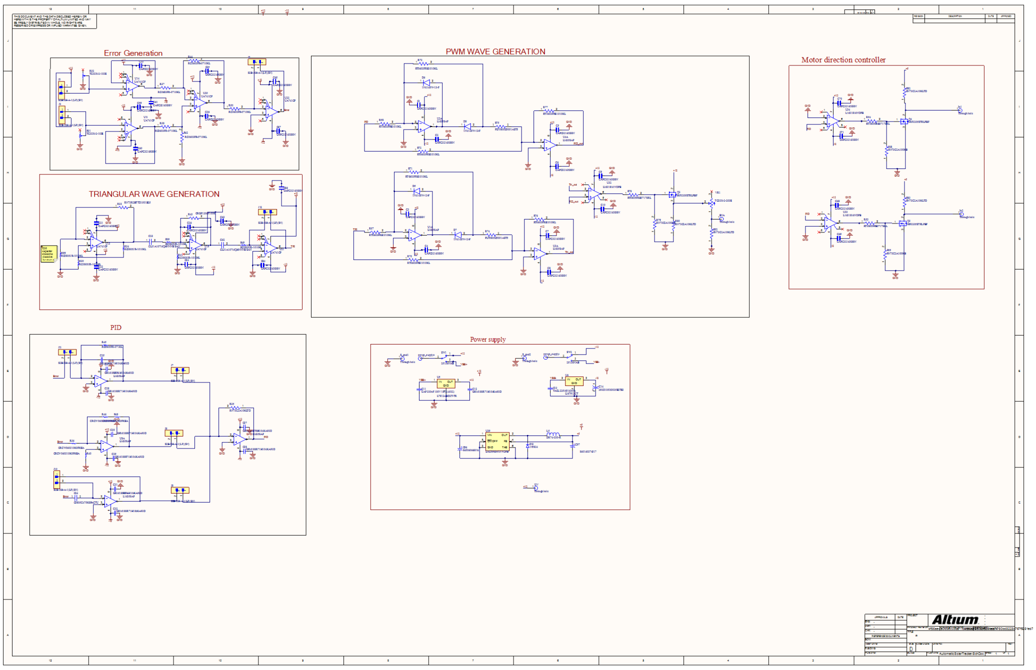

Figure 3: Schematic

The layout of the PCB follows a logical flow as shown below.

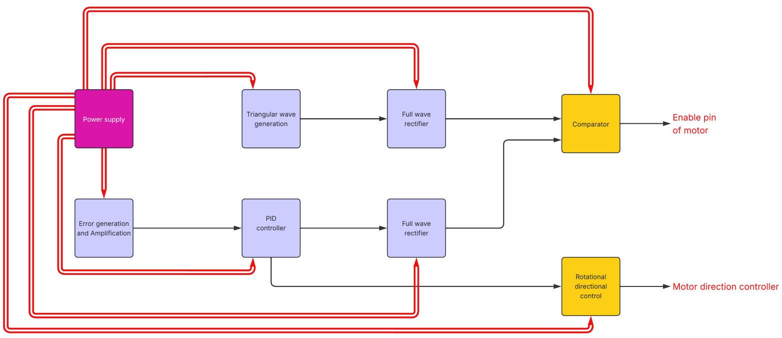

Figure 4: PCB Flow

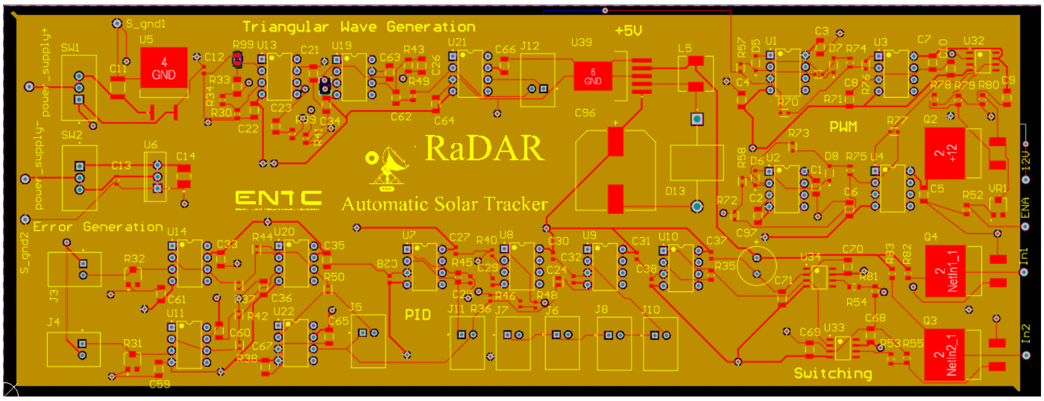

Figure 5: PCB layout

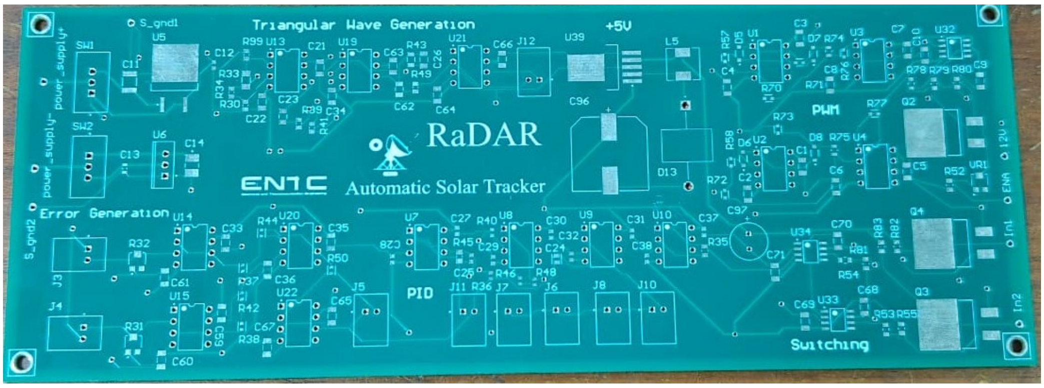

Figure 6: PCB before component placement.

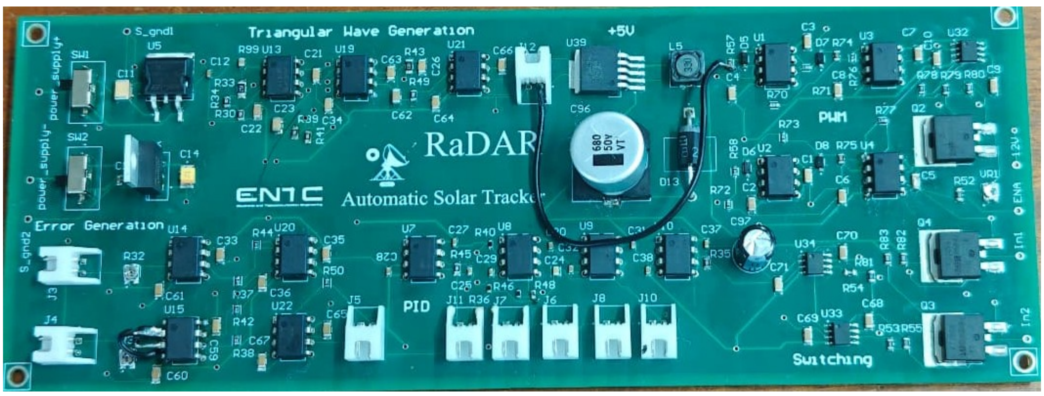

Figure 7: PCB after component placement and troubleshooting.

5 Enclosure Design

5.1 Mechanical Enclosure and Assembly Description:

The mechanical design comprises a modular enclosure and a rotating solar panel mounting system, modelled and assembled using SolidWorks. The enclosure is divided into functional sections to improve accessibility and ease of maintenance. The bottom section houses the battery enclosure with a removable lower lid for battery replacement. Due to 3D printing constraints and thermal considerations, the battery enclosure components were fabricated using **PETG**, while all other enclosure components were fabricated using **PLA**. Above the battery enclosure is the PCB enclosure, consisting of a base and removable lid to house and protect the control electronics.

Mounted on the top right of the PCB enclosure is a motor enclosure that secures the DC motor and motor driver, with a removable lid to allow component replacement. On the opposite side, a support stand with an integrated ball bearing supports the horizontal rotating shaft, ensuring smooth motion with reduced friction. The shaft carries the solar panel holder, which is designed to accommodate two solar panels and includes two symmetrically placed LDR mounting holes. This arrangement provides sufficient separation between the LDRs to generate an effective error signal for accurate solar tracking.

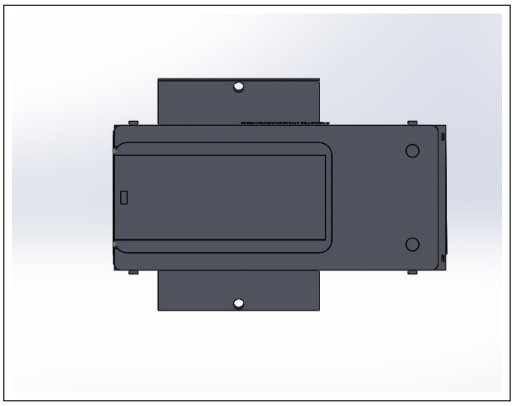

Figure 8: Bottom View

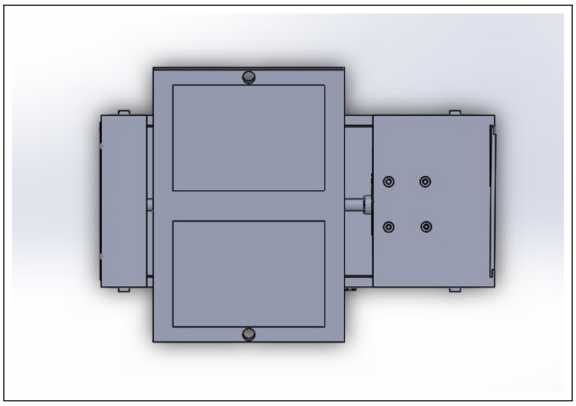

Figure 9: Top View

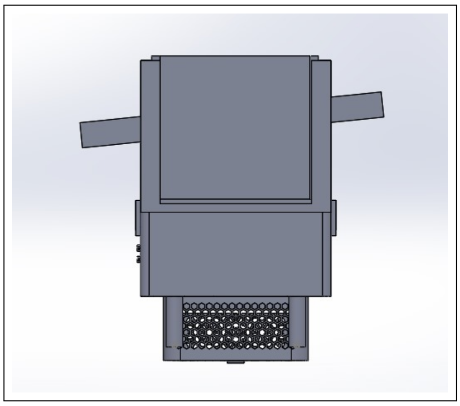

Figure 10: Side View

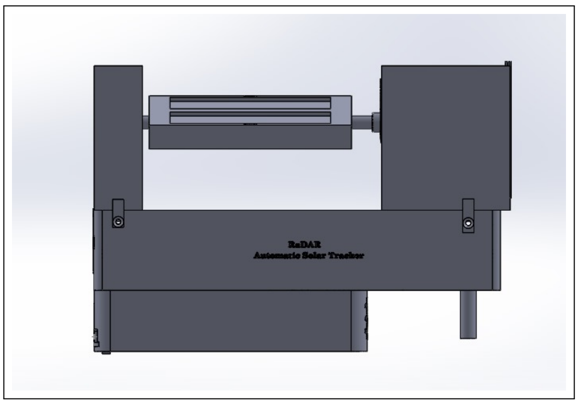

Figure 11: Front View

6. Software Simulation and Hardware Testing

6.1 Software simulation

All simulations were performed using LTspice. The entire circuit was separated into stages to make simulation easier.

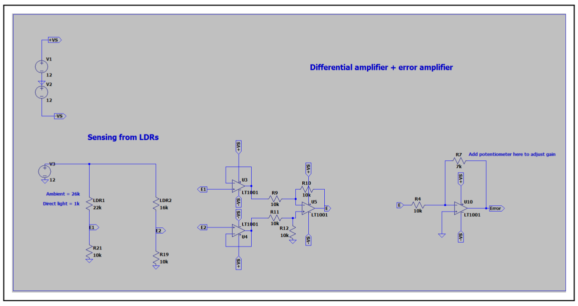

Figure 12: Light intensity sensing stage.

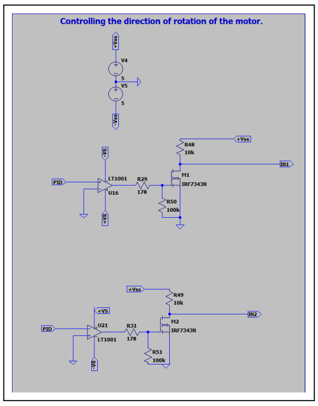

Figure 13: Rotational direction changing stage.

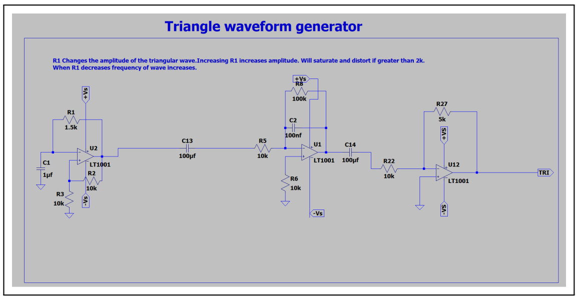

Figure 14: Triangle wave generation stage.

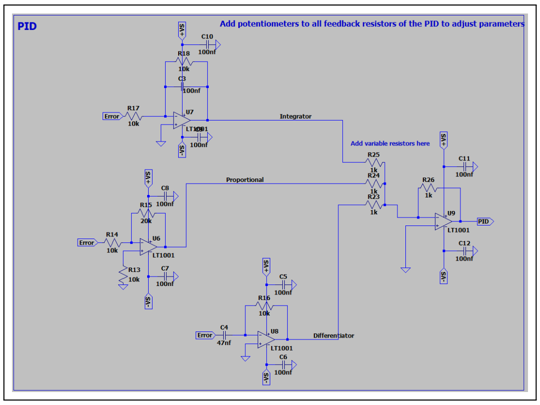

Figure 15: PID control stage.

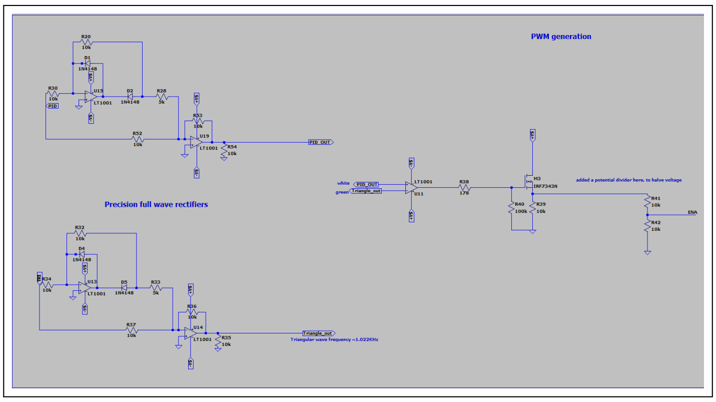

Figure 16: PWM generation stage.

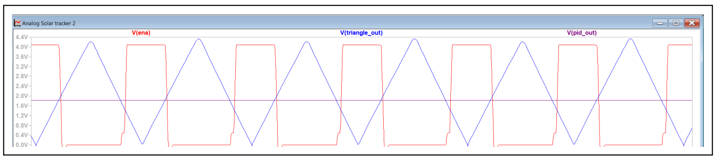

Figure 17: The PWM signal is generated using the PID stage and the Triangular wave generation stage.

5.2 Hardware testing

Initial testing was performed on a breadboard using a dual power supply. LM741 OP-AMPs were used for all stages.

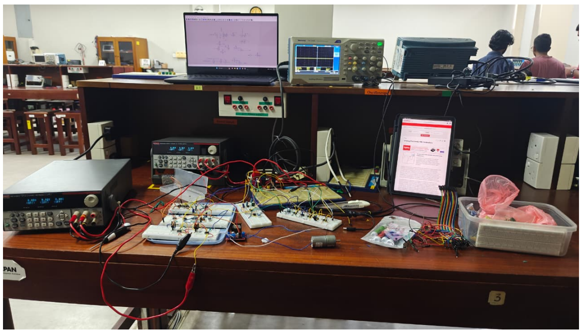

Figure 18: The setup

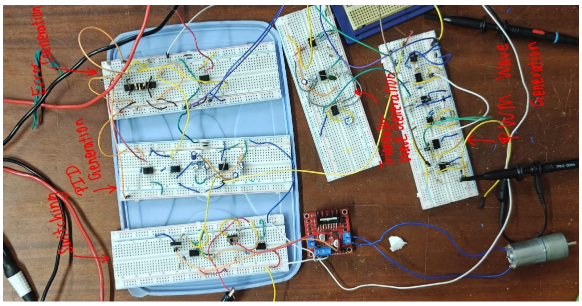

Figure 19: The setup

7. Conclusion and Future Works

7.1 Conclusion

The implementation of a solar tracker to increase the efficiency of a solar panel is increasingly beneficial in this time and age, especially when most countries opt for a greener footprint through the use of renewable energy sources. This model serves as a prototype for a much larger solar tracker that has the capability to carry a higher wattage solar panel.

7.2 Future Works

Notes for improvement and optimization of PCB design.

1. The input to the PWM enable pin could be modified as such, to get rid of the negative voltage ripple.

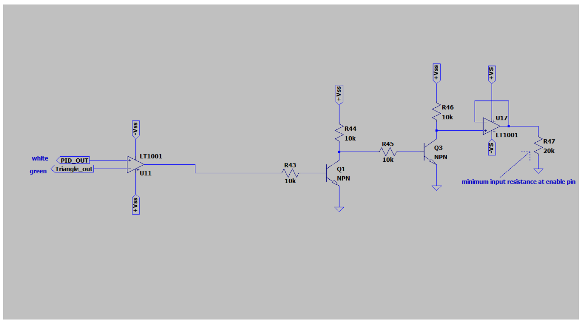

Figure 20: LTspice circuit schematic

2. Integrate a dual-axis tracking system to improve precision.
3. Include real-time data logging of sunlight intensity and power output.
4. Add low-power standby mode and automatic night reset to reduce power consumption.
5. Design a weather-proof enclosure for outdoor deployment and long-term stability.

8. Contribution of Group Members

Member	Contribution
De Mel D.J	Circuit Design, Software simulation, Soldering
RAHMAN M F A	Enclosure using SOLIDWORKS, Soldering
RAHUL B	Circuit Designing, Testing, Soldering
RATHEESHAN A R	PCB Designing, Assembling, Soldering

Table 1: Member Contribution