System Dynamics & Control Components

CSE 271s - Fall 2024

Project Report

Team **#36**

Ammar Ahmed Wahidi	**2200360**
Amr Ahmed Wahidi	**2200429**
Omar Mohamed Hassan	**2200294**
Abdullah Moataz Mahmoud Mahanny Elshafai	**2200216**
Youssef Maged Noshy Rezk	**2201325**
Youssef Mohamed Shalaby	**2201332**
AbdElRahman ElSaeed Ramadan	**2200657**
Mohamed Elsayed Moustafa	**2200095**
Ali Ahmed Mohamed Abdelmaboud	**2200927**
Sobhey Mohamed Osman	**2200477**
Ammar Mohamed Abdelghany	**2200707**
Mohamed Yehia Saeed	**2200918**

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1.Introduction

The primary objective of this project is to design, simulate, and implement a single-axis solar tracker system capable of maximizing solar energy collection by dynamically aligning a solar panel with the direction of sunlight by using mixed signal circuit and control components.

A solar tracker is a device that orients a payload toward the Sun. Payloads are usually solar panels, parabolic troughs, Fresnel reflectors, lenses, or the mirrors of a heliostat.

For flat-panel photovoltaic systems, trackers are used to minimize the angle of incidence between the incoming sunlight and a photovoltaic panel, sometimes known as the cosine error. Reducing this angle increases the amount of energy produced from a fixed amount of installed power generating capacity.

- Angle of Incidence: This is the angle between the incoming sunlight and the perpendicular (normal) line to the panel's surface. When this angle is small (close to 0°), sunlight hits the panel more directly, allowing it to capture the maximum possible energy.
- Cosine Error: When sunlight strikes at an angle, the effective area of the panel exposed to sunlight decreases. The amount of sunlight captured is proportional to the cosine of the angle of incidence.
  For example:
  --At 0° (sunlight is perpendicular to the panel), the panel receives 100% of the sunlight.
  --At 60° (sunlight strikes at an angle), the panel receives only 50% (cosine of 60° = 0.5) of the sunlight.

The significance of this project lies in its potential to assist communities with limited access to electricity and fewer solar panels, by optimizing the efficiency of solar energy conversion. By minimizing the angle of incidence, the solar panels will be able to capture more sunlight and generate greater power. This project is particularly meaningful in regions under occupation, such as Gaza, where the ongoing oppression of the Palestinian people has led to the cutting of essential services like electricity and water. During times of conflict, such as when The Israeli occupation imposes blockades or restricts access to resources, the lack of reliable energy sources exacerbates the suffering of the population. This solar tracker system could provide a sustainable and independent source of energy, helping to mitigate the impact of these restrictions. By harnessing solar energy more effectively, this system can offer a degree of autonomy, enabling the affected communities to generate power and improve their quality of life despite the oppressive circumstances.

2.Block Diagram

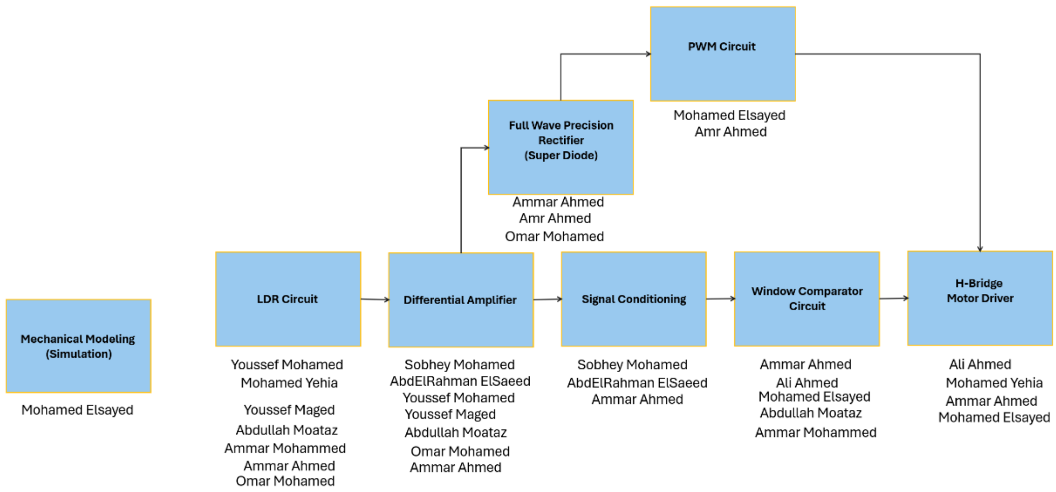


Figure 1

3.Electronic circuit diagram

Overview of the electronic circuit diagrams for the key components of project:

1) LDR Voltage Divider Circuit

The LDR (Light Dependent Resistor) is part of a voltage divider to sense light intensity.

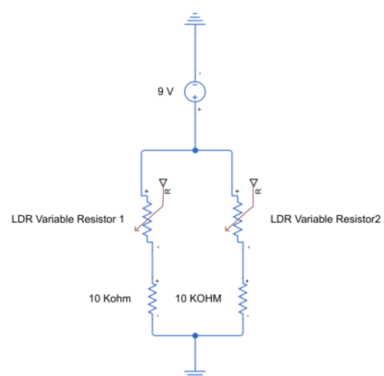


Figure 2

- LDR changes resistance based on light intensity.
- R(10Kohm) is a fixed resistor to create a voltage divider that varies with light intensity, providing an analog signal to control the motor.
- Works like bridge, but we divided them in real life.

2) Differential Amplifier

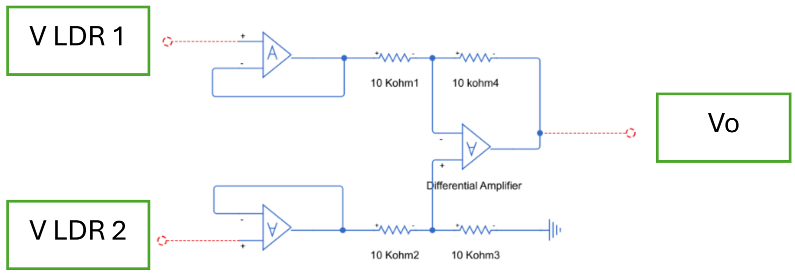
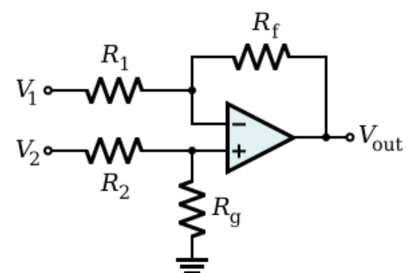


Figure 3

A differential amplifier is an electronic circuit designed to amplify the difference between two input signals while suppressing any signals that are common to both inputs. It is widely used in analog electronics, particularly in signal processing, as the first stage in operational amplifiers, and in communication systems for noise rejection.



General formula >> $(\frac{Rg}{Rg+R2} * \frac{R1+Rf}{R1} * v2) - (\frac{Rf}{R1} * v1)$

In case of (R1 = R2 , R_g=R_f)

V_{out} = $\frac{Rf}{R1}(v2 - v1)$ and this is the case we use in our project

We made $R_f = R_1 = 10\ Kohm\ to\ make\ the\ gain = 1$

For our simple LDR type, we don't need to amplify the signal in the signal conditioning stage, as both theoretical and real-world tests confirm that the voltage range of the output signal is between -5V and 5V approximately. However, for other LDR types, signal conditioning would be necessary to adjust the voltage range accordingly.

The Common Mode Rejection Ratio(CMRR) of a Differential Amplifier is mathematically given as the ratio of Differential Voltage gain (A_D) of the Differential Amplifier to its Common Mode gain (A_C).

- A differential amplifier is a combination of both inverting and non-inverting amplifiers. It uses a negative feedback connection to control the differential voltage gain.
- The common mode gain of an ideal differential amplifier is zero. But due to mismatch in the practical resistor values, there will be a very small common mode voltage and a finite common mode gain.

To reject common mode gain, one could consider using an Instrumentation Amplifier, which is designed for this purpose. However, due to its high cost, we opted for an alternative approach using two operational amplifiers configured as buffers. This configuration allows us to achieve similar results without the expense of an instrumentation amplifier.

In addition, voltage followers (or buffers) were used before the differential amplifier circuit to prevent any loading effect that could distort the signal. Instrumentation amplifiers inherently include internal buffers, which perform the same function as voltage followers in the circuit. Therefore, while we could have used an instrumentation amplifier for its built-in buffering, we chose to manually implement buffers with operational amplifiers to reduce costs, achieving effective common mode rejection.

3) Window Comparator

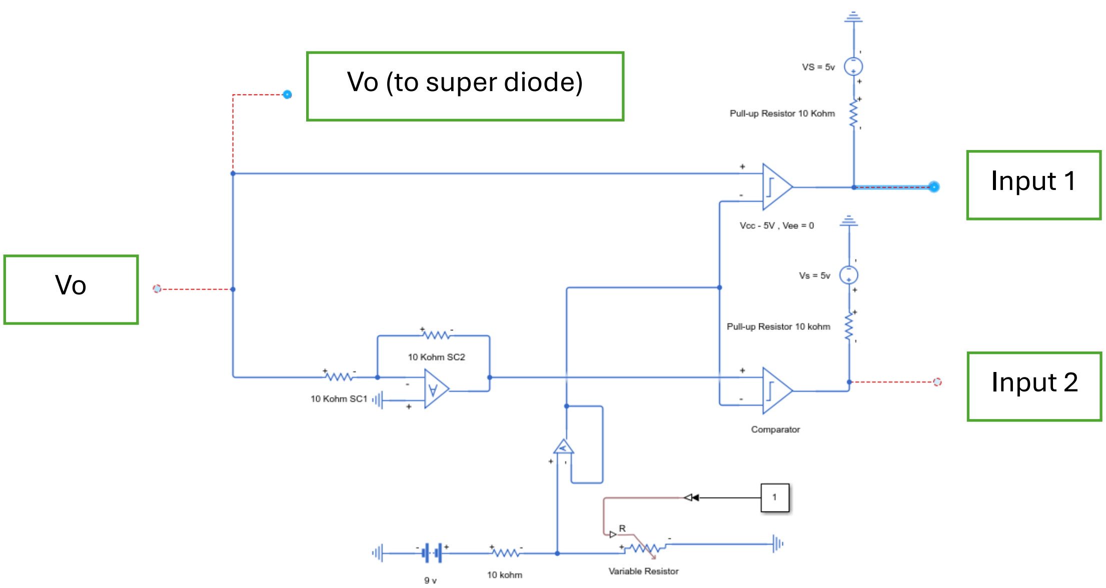


Figure 4

4) Full Wave Precision Rectifier (Super Diode)

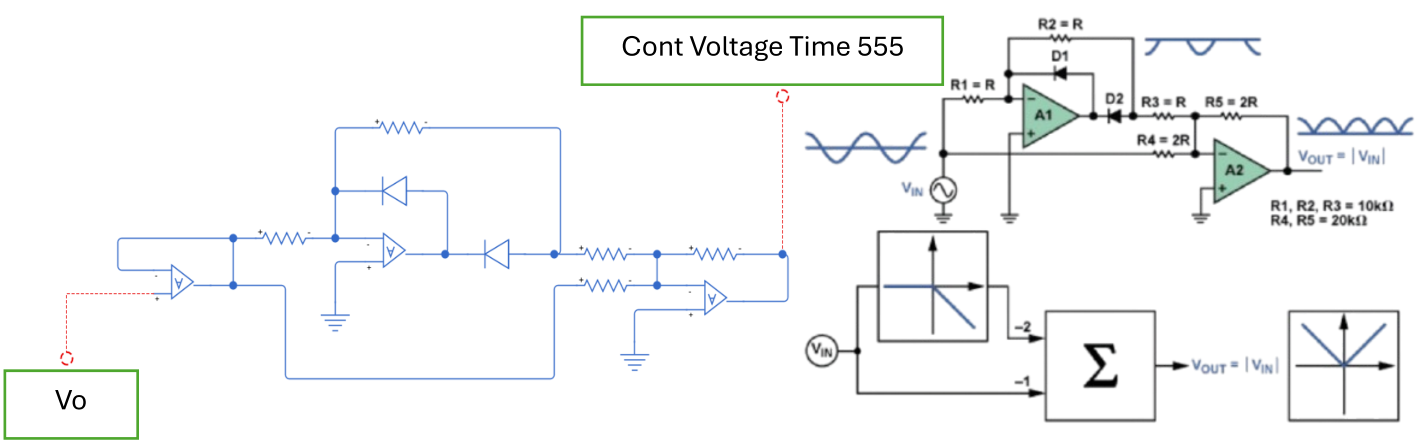


Figure 5

The full-wave precision rectifier, often referred to as a super diode, is employed in the circuit to ensure that only the positive portion of the signal generated by the differential amplifier is passed to the next stage, the 555 timer. This rectifier is essential in converting the alternating output signal from the differential amplifier into a unidirectional (positive-only) signal, which is suitable for further processing.

Unlike traditional rectifiers that rely on diodes and are prone to voltage drops, the precision rectifier uses operational amplifiers to achieve highly accurate rectification with minimal loss, even for low-amplitude signals. This feature is crucial for maintaining signal integrity and ensuring that the 555 timer operates correctly, generating a stable and reliable pulse-width modulation (PWM) signal.

By allowing only the positive signal to pass, the full-wave precision rectifier plays a vital role in ensuring smooth and efficient operation of the overall system, enabling precise motor control in the solar tracker project.

5) PWM Generation Circuit

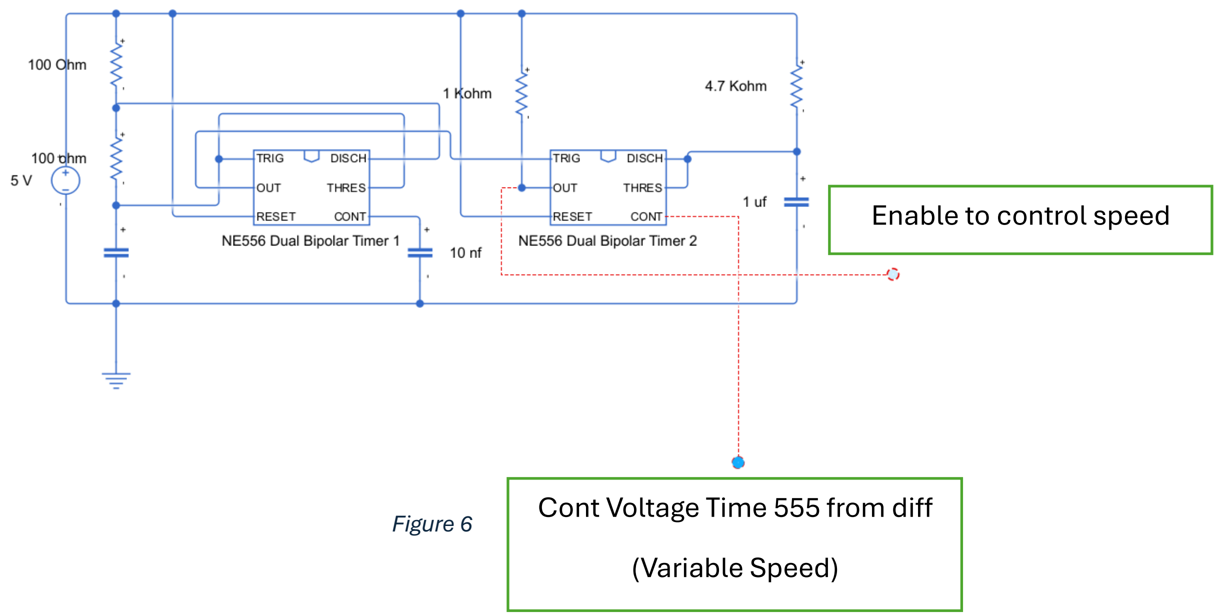


Figure 6

The 555 timer can be configured in astable mode to generate a Pulse Width Modulation (PWM) signal, which is essential for motor speed control in your application. Below are the steps and considerations for implementing this:

Circuit Configuration

1. **Astable Mode Setup:**
   - Connect the 555 timer in astable mode to generate a PWM signal.
   - Use a variable resistor (R2) to control the duty cycle of the output waveform.
   - The PWM frequency is determined using the formula:

$$f = \frac{1}{\ln(2) \times (R_1 + R_2)C}$$

   - The duty cycle can be adjusted by varying R_2 allowing for precise motor speed control.
2. **Signal Conditioning:**
   - To create a smoother PWM signal, a low-pass RC filter can be added at the output. This converts the high-frequency PWM signal into a proportional DC voltage.

6) H-Bridge Motor Driver

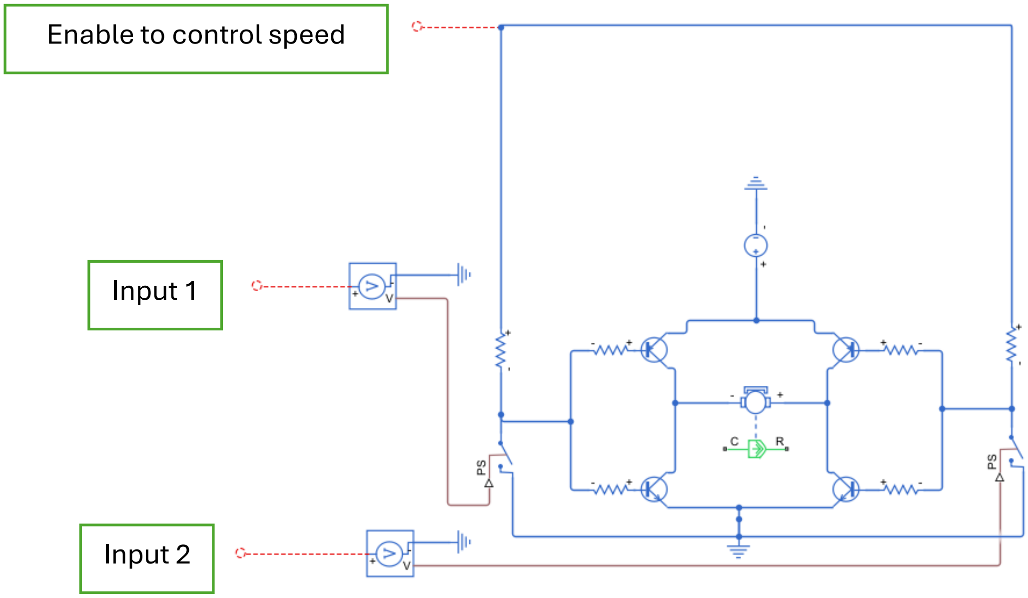
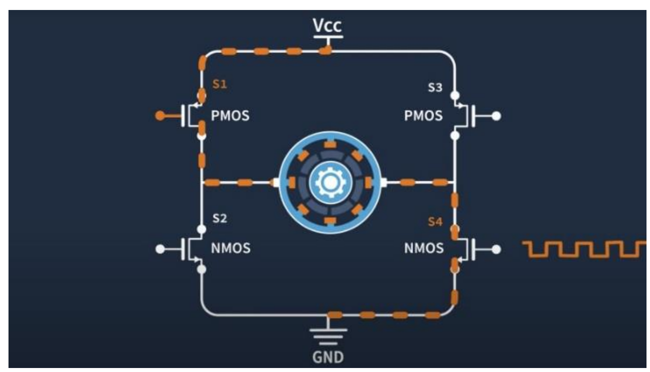


Figure 7

1) What is an H-bridge?

An H-Bridge is a circuit that controls the direction of a DC motor. It has four switches arranged in an "H" shape, which allows current to flow in both directions, making the motor rotate forward or backward



2) Working Principle of H-Bridge:

The basic operation of an H-Bridge is determined by the arrangement of. The four switches are arranged in two pairs, with each pair controlling the current flow in one direction.

To control the motor:

- **Forward Rotation:** Turn on switches S1 and S4. This allows current to flow from the power supply through the motor in one direction, causing it to rotate in the desired direction.

- **Reverse Rotation:** Turn on switches S2 and S3. This causes the current to flow through the motor in the opposite direction, reversing its motion.

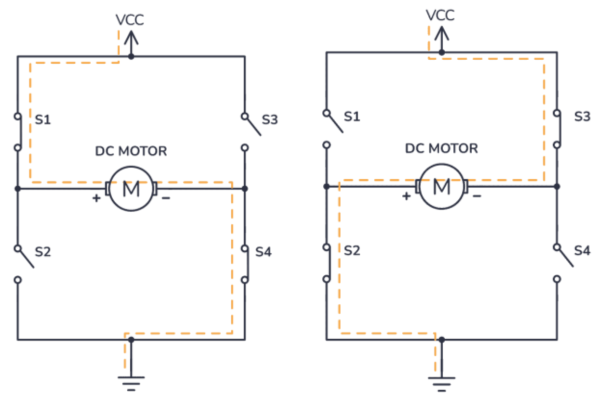


Figure 8

- **Stop or Brake**: Both pairs of switches (S1 & S3 or S2 & S4) can be turned on simultaneously to provide braking, causing the motor to stop abruptly.

3) Control Signals:

We control the speed of the motor in our tracker by connecting a Pulse Width Modulation (PWM) signal, generated by a **555 timer**, to the H-Bridge. The PWM signal adjusts how fast the motor turns. By varying the PWM signal, we can change the speed at which the motor rotates.

4) L298 Motor Driver

In our project, **the L298** is used as the H-Bridge it's a dual H-Bridge motor driver IC.

It allows us to control the direction and speed of the DC motor by providing bidirectional control through PWM signals. The L298 can handle high currents and voltages, making it suitable for driving motors in applications like solar trackers.

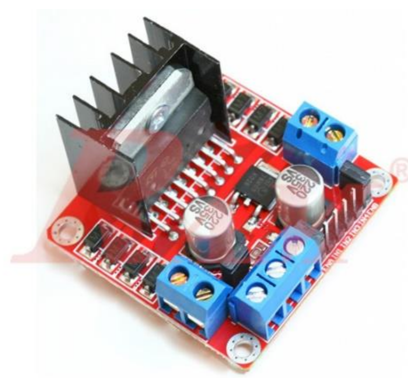


Figure 9

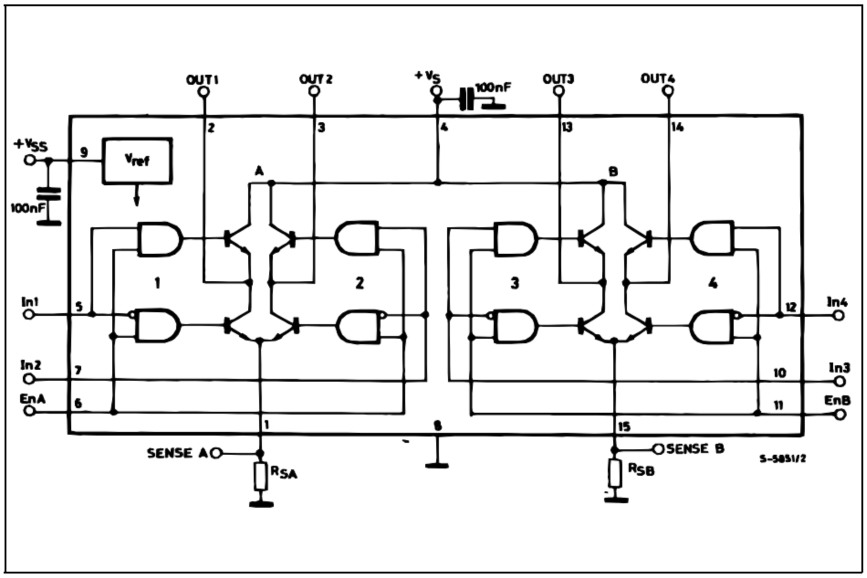


Figure 10

We connect IN1 and IN2 to the comparator output, ENA to the PWM, and OUT1 and OUT2 to the motor to control its direction and speed by the mechanism mentioned previously.

7) Power Supply

Figure 11

In our project, we initially faced challenges using a 24V adapter and dividing the voltage with a voltage divider, which proved inefficient for consistent operation. Normal batteries discharged quickly, leading us to explore more reliable options. Eventually, we adopted a lithium battery setup providing ±7V (Vcc = 7V and Vee = -7V) for the circuit. Additionally, we utilized a stable 5V supply (Vs = 5V) sourced from the H-bridge motor driver, ensuring consistent performance for the motor and other components.

4.Mechanical Modelling

Objective: To simulate a mechanical system representing a light-dependent resistor (LDR) mechanism using MATLAB and Simulink and evaluate its behavior when connected to an electrical circuit driving a DC motor.

System Design:

1. LDR Representation:
   - Two small balls (representing LDRs) are modeled in the mechanical system.
   - They are connected to a shared rotation axis using a revolute joint.
2. Light Source Representation:
   - A larger ball represents the light source, positioned 0.5 meters away from the smaller balls.
3. Distance Measurement:
   - Two distance measurement blocks are used to measure the distance between the light source (large ball) and each of the LDR representations (small balls).
4. Distance-to-Resistance Conversion:
   - A sigmoid function is applied to convert the measured distance into resistance values ranging from 1 $k\Omega$ to 10 $k\Omega$, depending on the distance (from 0.01 m to 1 m).

MATLAB Connections:

1. Input Signal:
   - A motion signal is applied to the light source (large ball) as the system input.
2. Electrical Circuit:
   - A DC motor is connected to the system and controlled using the designed electrical circuit.
   - The output signal from the DC motor drives the revolute joint, causing the rotation of the small balls (LDR representations).

Figure 12

Simulation Objective:

- To validate the mechanical movement of the LDR representations in response to light source displacement and evaluate the impact of varying resistance on the system.

If you'd like, I can also create a visual representation or refine the MATLAB code explanation further!

Conclusion:

The simulation successfully demonstrated the interaction between the mechanical and electrical systems in modeling the behavior of light-dependent resistors (LDRs). By converting the measured distance between the light source and the LDR representations into varying resistances using a sigmoid function, we achieved a realistic emulation of LDR functionality.

The system verified the following key points:

1. The mechanical movement of the LDR representations accurately followed the light source's displacement, driven by the DC motor.
2. The electrical circuit responded dynamically to the changing resistances, showcasing the practical relationship between light intensity (distance) and resistance.
3. The integrated MATLAB-Simulink environment allowed for seamless connection between the mechanical and electrical domains, enabling precise simulation of real-world behaviors.

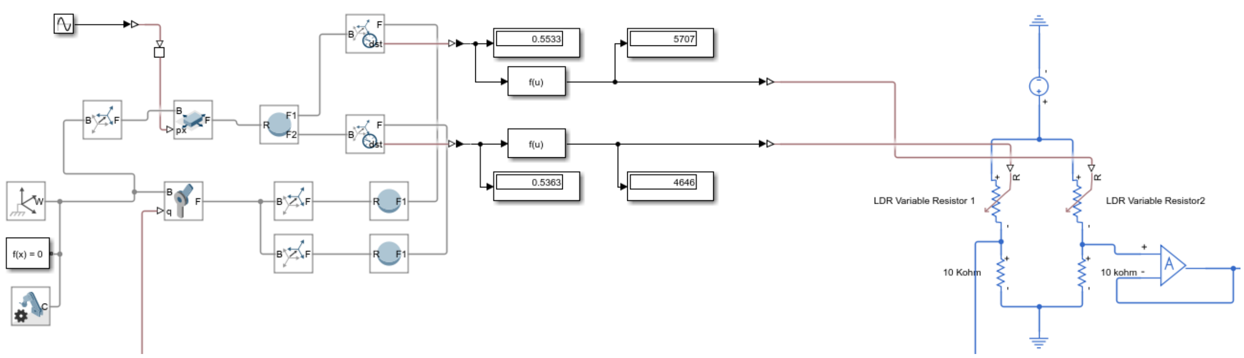


Figure 13

This approach can be extended to more complex systems, providing a valuable framework for studying LDR-based control mechanisms in robotics, automation, and sensor networks.

5. Simulation

I)Variable Speed Control:

In this section, we conducted a simulation to analyze the behavior of the system under varying motor speeds, which directly affects the alignment of the solar panel with the sunlight. The primary objective was to validate the performance of the Pulse Width Modulation (PWM) control circuit and its ability to dynamically adjust the motor speed based on the input signal from the differential amplifier and signal conditioning stages.

System Design:

1. **PWM Control**:
   The PWM signal generated by the 555 timer was simulated under different duty cycle configurations. The duty cycle varied proportionally to the voltage difference detected by the differential amplifier, which represents the light intensity difference between the two Light Dependent Resistors (LDRs).

2. **Motor Model**:
   A DC motor model was integrated into the simulation. The motor's speed was controlled by the PWM signal, where higher duty cycles corresponded to increased motor speed and quicker panel adjustments.

3. **Dynamic Load Conditions**:
   The simulation accounted for the impact of external factors such as wind resistance and panel inertia. These factors were modeled to assess the system's ability to adapt to changing environmental conditions while maintaining alignment accuracy.

Simulation Results:

1. **PWM Signal Variation**:
   The PWM signal exhibited smooth transitions across varying duty cycles, with a frequency of 144 Hz. As the light intensity difference increased, the duty cycle expanded, resulting in a faster motor response to realign the panel.

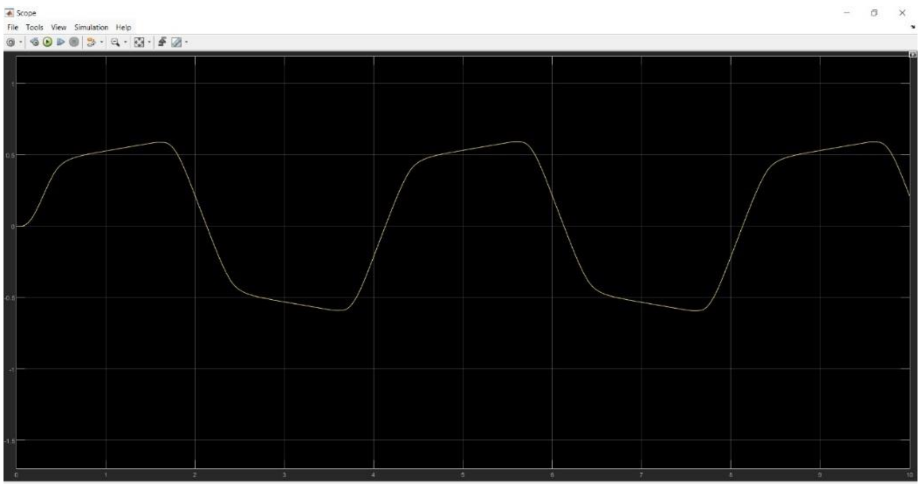
2. **Motor Response**:
   The motor demonstrated precise and proportional speed adjustments based on the PWM input. At low light intensity differences, the motor operated at reduced speeds to avoid unnecessary movements. Conversely, at higher differences, the motor responded with increased speed, ensuring timely panel adjustments.

3. **System Stability**:
   The simulation verified the system's stability across a range of light intensity variations. The panel alignment process occurred seamlessly, without oscillations or excessive overshooting, demonstrating effective control by the feedback mechanism.

4. **Energy Efficiency**:
   The variable-speed operation optimized energy usage by ensuring the motor only consumed power proportional to the required adjustment. This feature is critical for maintaining the system's efficiency, particularly in low-resource environments.

Observations:

- The simulation confirmed the successful integration of electrical and mechanical components in achieving variable-speed control.
- The PWM-based speed control system effectively minimized response time while conserving energy.
- The system-maintained accuracy and stability under dynamic conditions, including variations in light intensity and external disturbances.



This simulation highlights the robustness and adaptability of the designed solar tracker system, demonstrating its potential for practical deployment in real-world scenarios. The variable-speed feature ensures optimal performance while enhancing the system's overall efficiency and reliability.

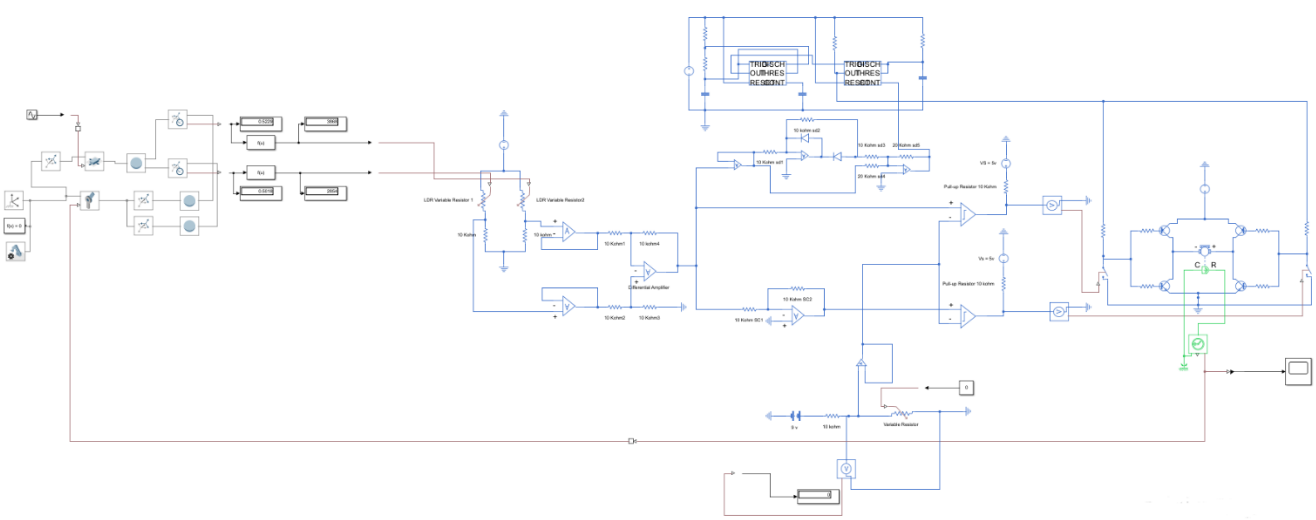


Figure 14

II)Constant Speed Control:

In this section, we detail the simulation of constant speed control for the solar tracker system. The aim of this simulation is to ensure that the motor rotates at a constant speed regardless of variations in light intensity. Unlike the variable speed control setup, we eliminated the **Super Diode** from the circuit and directly set the control voltage for the second 555 timer to a fixed value of 5V. This modification simplifies the system while achieving steady motor operation.

Simulation Objectives

- To achieve a constant motor speed irrespective of external light variations.
- To validate the stability and functionality of the system under fixed PWM control.

Simulation Design

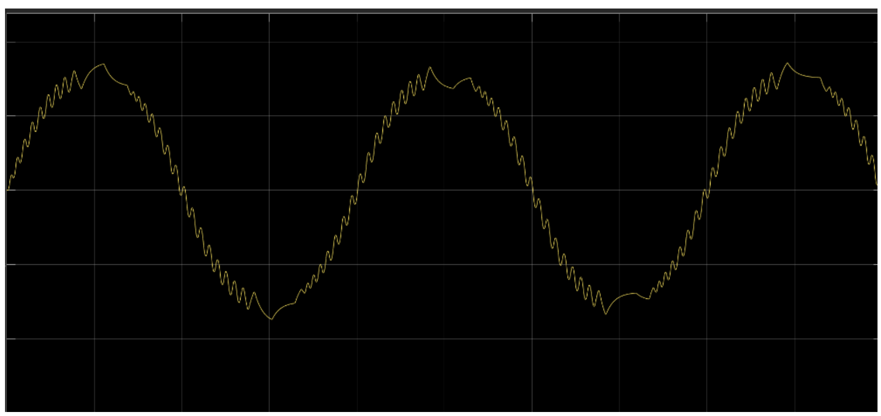
1. **PWM Generation Circuit**:
    - The second **555 timer** was configured in astable mode, with its control voltage fixed at **5V**.
    - The fixed control voltage ensures a consistent duty cycle for the generated PWM signal.
    - The circuit was designed with appropriate resistor and capacitor values to ensure stable operation and consistent output frequency.
2. **H-Bridge Motor Driver**:
    - The generated PWM signal was fed into the **L298 H-Bridge Motor Driver**, which controls the motor.
    - The motor received a stable PWM signal, ensuring constant rotation speed.
3. **Testing Parameters**:
    - The circuit was connected to a DC motor, and the rotational speed was observed using an oscilloscope.
    - Voltage at the motor terminals and the PWM signal waveform were analyzed for stability and consistency.

Results

During the simulation, the motor operated at a constant speed. The oscilloscope captured the following key results:

- The PWM waveform maintained a steady duty cycle, confirming the fixed 5V control voltage to the timer.
- The motor received a uniform voltage signal, resulting in smooth and constant rotational motion.

The results demonstrate the effectiveness of this simplified design for maintaining constant speed control.



Circuit Diagram

Below is the complete circuit used for the constant speed simulation:

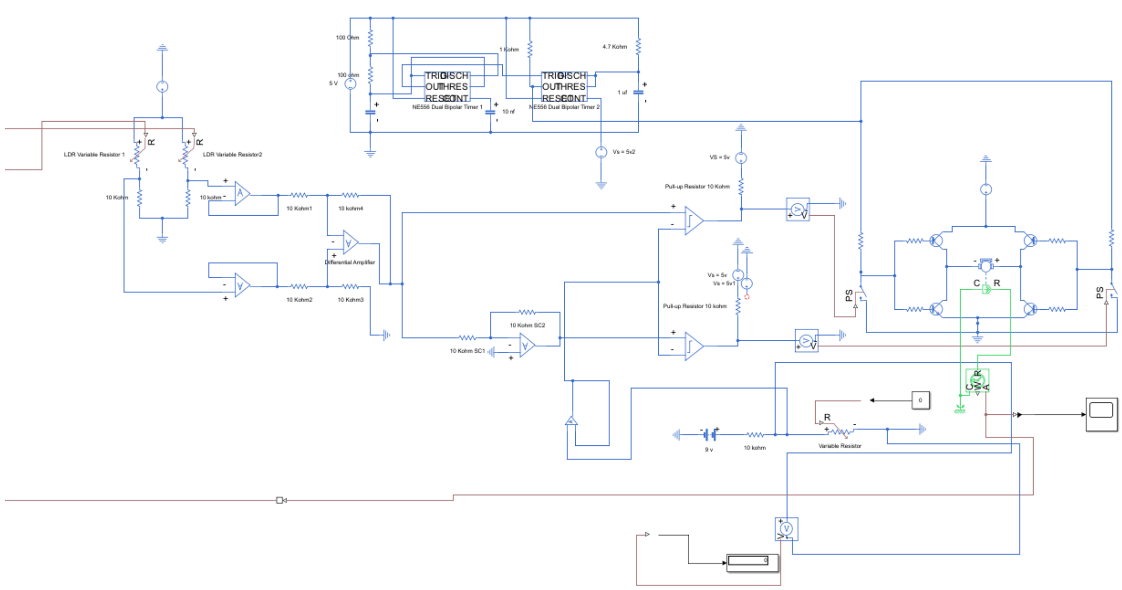


Figure 15

6.Testing and Results

1) **LDR Circuit:** The oscilloscope was placed at the output of the voltage divider, with additional placement at the two LDR points. The results obtained from these measurements are as follows (figure below).

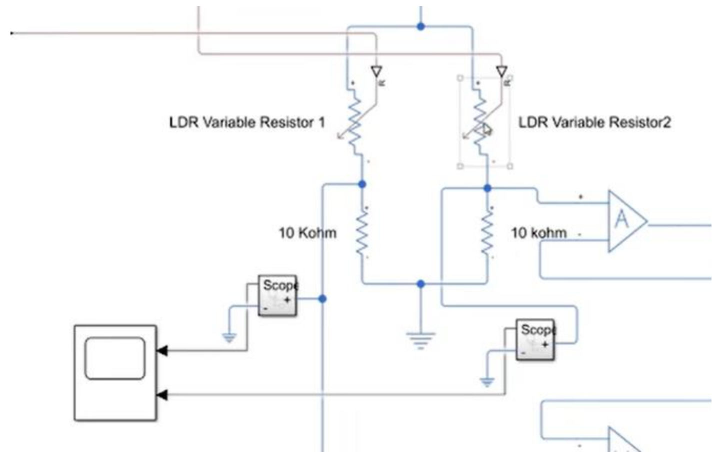


Figure 16

- **LDR Circuit & Signal Conditioning:** The voltage-divider principle was studied and implemented to measure light intensity. Potentiometers were integrated to adjust sensitivity based on ambient light conditions. The circuit was designed to ensure smooth output voltage variation from the LDRs under varying sunlight conditions.
- **LDR Voltage Divider Circuit:** A voltage divider was designed using LDRs to measure sunlight intensity, with potentiometers or resistors used for sensitivity adjustments.

2) Differential Amplifier:

Two oscilloscopes were used to measure the output voltage of the differential amplifier: one for the output and another for the inverting amplifier. The output gain was set at 1, with an inversion factor of -1.

The differential amplifier successfully processed the signals from the two LDRs, amplifying the light intensity difference. The output of the differential amplifier was fed into the comparator.

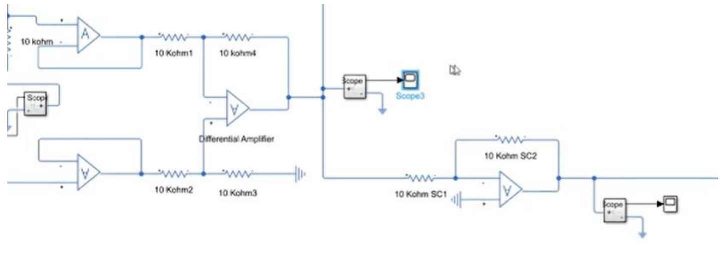
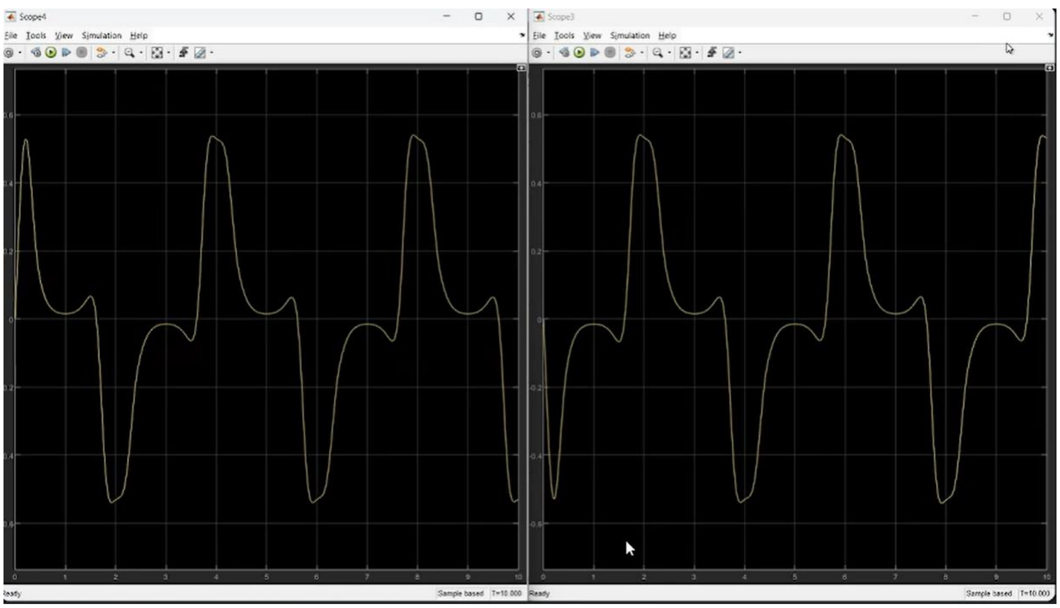


Figure 17

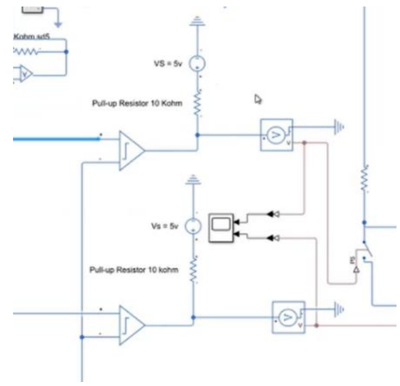
The photo below explains the setup and the results observed during testing.



3) Comparator with Hysteresis:

Two oscilloscopes were used to measure the output voltage of the two comparators. The input to one comparator was the output of the differential amplifier, while the input to the other was the output of the inverting amplifier, which in turn received its input from the differential amplifier.

The photo below explains the setup and the results observed during testing.



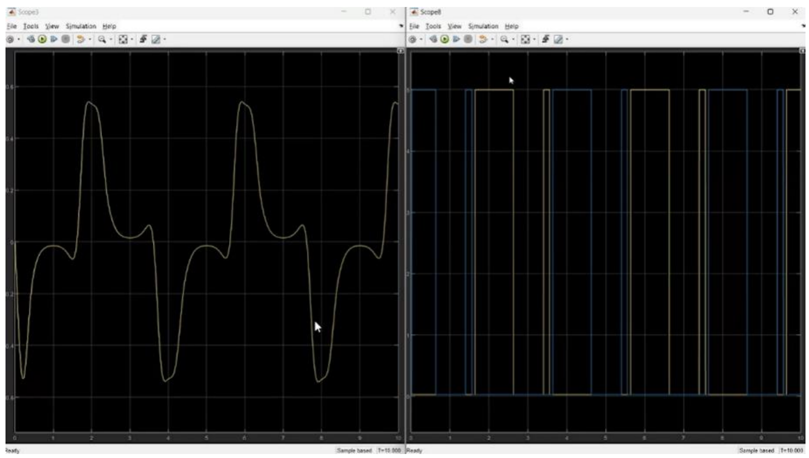


Figure 18

4) Super Diode:

The super diode circuit was used with the output of the differential amplifier as its input. A super diode is a configuration that combines a diode with an operational amplifier to create a circuit that allows current to flow in one direction only, essentially "clipping" the signal to prevent negative voltages. It helps in ensuring that only positive signals are passed through while blocking the negative part of the waveform.

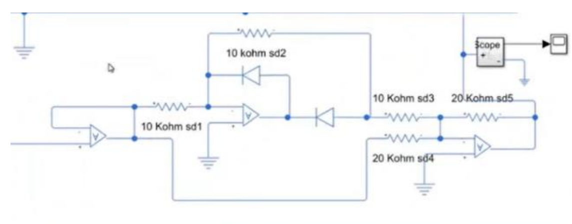
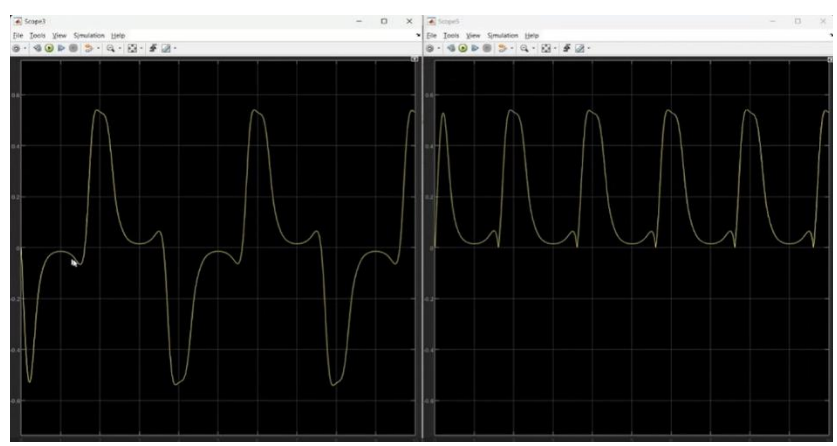


Figure 19

The photo below explains the setup and the results observed during testing.



5) PWM Generation with 555 Timer:

PWM signals were generated using two 555 timers configured in A stable mode. The input (control) to the PWM circuit was the output of the super diode. The frequency of the PWM signal was set to 144 Hz, with the following component values:

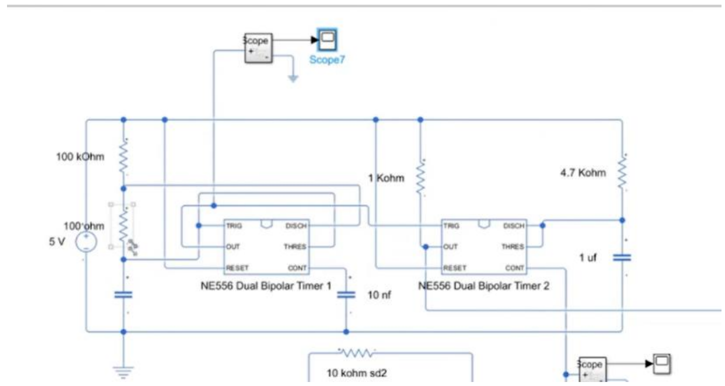


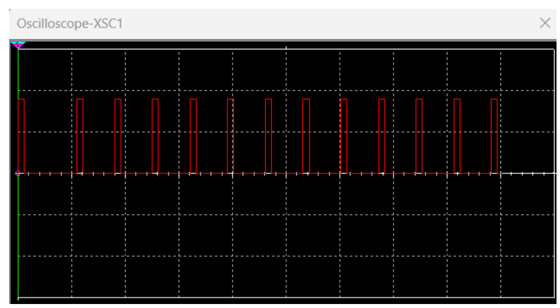
Figure 20

- R1 = 100,000 Ω
- R2 = 100 Ω
- C = 10 nF

The function for the frequency of the PWM signal is given by:

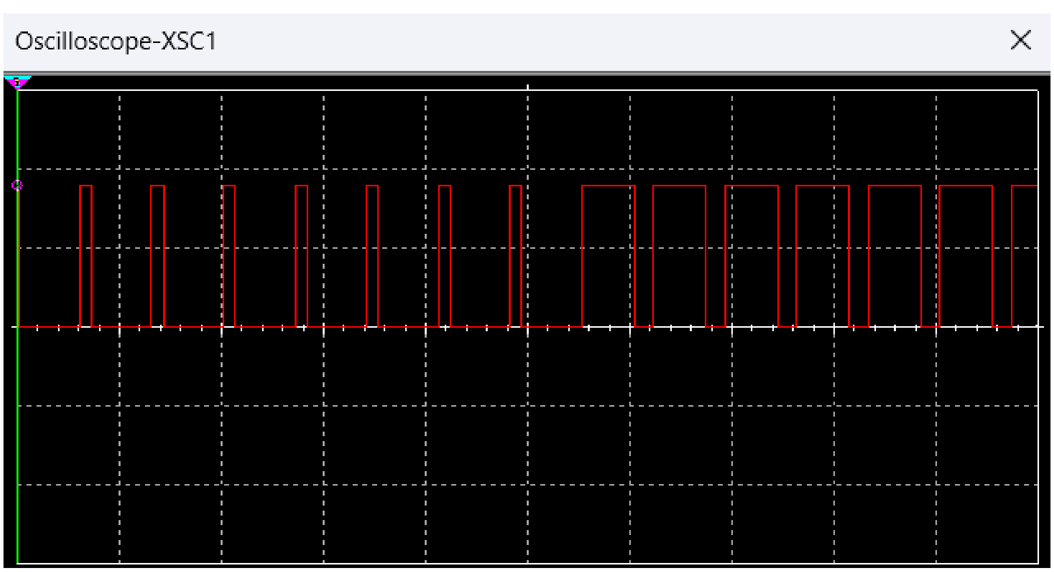
$$f = \frac{1.44}{(R1 + R2) * C}$$

The PWM signal's duty cycle was dynamically adjusted by modifying the input voltage to the timer, which was based on the amplified signal from the differential amplifier. This adjustment allowed for control of motor speed based on the light intensity difference.



The photo below explains the setup and the results observed during testing.

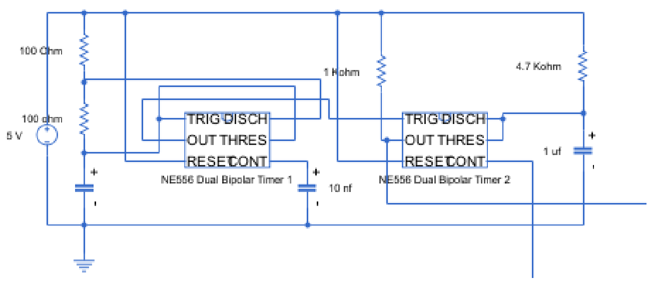
As the control (input) voltage from the super diode changes, the duty cycle of the PWM signal also changes



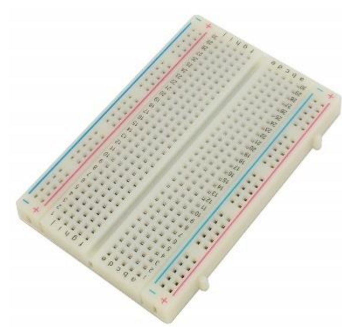
7.Cost Analysis

I) Components:

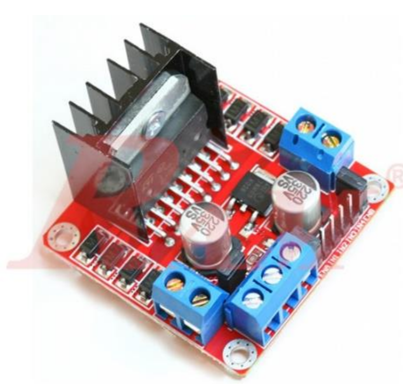
1) **Timer 555:** integrated circuit used for timing and oscillator applications.



2) **Breadboards:** Used for prototyping circuits without the need for soldering.



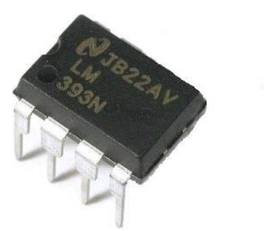
3) **H-Bridge (Driver_L298)**



4) Light Dependent Resistors (LDR)

5) DC Geared Motor

6) LM358 (Operational Amplifier)
7) LM393 (Comparator IC)



8) Potentiometer

9) Lithium Batteries

10) Adapter + DC Power Connector

11) 7805 Regulator
12) 7912 Regulator

II) Costs:

To evaluate the financial feasibility of our project, we have conducted a detailed cost analysis. Below is a breakdown of all the components and supplies purchased, along with their respective costs:

Component	Quantity	Unit Cost (EGP)	Total Cost (EGP)
Timer 555	2	4	8
Breadboards	2	38	76
H-Bridge (Driver_L298)	1	80	80
Light Dependent Resistors (LDR)	2	17	34
DC Geared Motor	1	35	35
LM358 (Operational Amplifier)	5	6	30
LM393 (Comparator IC)	1	8	8
Potentiometer	-	-	-
Resistors and Capacitors	-	-	-
Lithium Batteries	4	40	160
Adapter + DC Power Connector	1	100+7	107
7805 Regulator	1	6	6
7912 Regulator	1	7	7
Team Maquette & Supplies	1	80	80

Total Project Cost: The total cost of the project, including electronics components and mechanical supplies, is:

551 + 80 = 631 EGP

8.Discussion

During this project, we encountered several challenges that required careful adjustments and solutions.

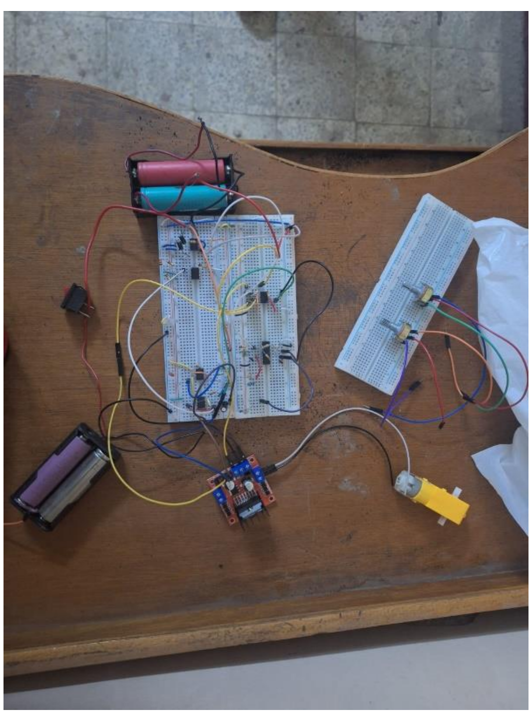
One of the primary issues we faced was with the comparator. We observed that the comparator could not process negative voltages correctly. To address this, we implemented signal inversion. For one comparator, we fed the signal as it was, while for the second comparator, we inverted the signal to ensure proper functionality.

Another issue we encountered was related to resistance values. The resistors used were not ideal or identical, which led to slight variations in the expected results. To solve this, we adjusted the reference voltage to a higher value, ensuring that the comparator's behavior remained stable and unaffected by these resistor variations.

Additionally, we faced a problem with generating the negative voltage required for the operational amplifier (OP-AMP). The solution involved connecting two power sources in series, with the negative terminal of the second battery connected to the VEE and the positive terminal of the first battery connected to the VCC. This arrangement provided the necessary negative voltage for the system to operate as intended.

Despite these challenges, we were able to find effective solutions and continue with the project. These adjustments ensured that the circuit operated smoothly and met the design specifications

Implementation :



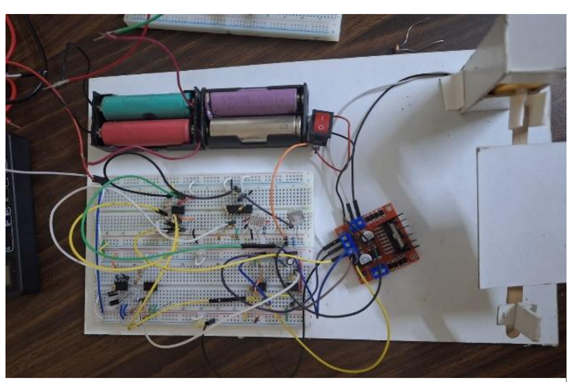


Figure 21

9.Conclusion

In conclusion, this project successfully demonstrated the design, simulation, and implementation of a single-axis solar tracker system capable of enhancing solar energy collection efficiency. Through the integration of mixed-signal circuitry, control components, and precise mechanical modeling, we developed a system that dynamically aligns a solar panel with sunlight, reducing the angle of incidence and maximizing energy capture.

The project validated the use of various electronic circuits, including LDR-based voltage dividers, differential amplifiers, comparators, precision rectifiers, PWM generation circuits, and H-bridge motor drivers, all working in unison to achieve the desired functionality. The integration of mechanical and electrical systems, simulated in MATLAB and Simulink, effectively emulated real-world behaviors and provided insights into optimizing light-dependent resistor mechanisms.

Despite encountering challenges, such as handling negative voltages in comparators, addressing non-ideal resistance values, and generating the necessary negative voltage for operational amplifiers, the team overcame these issues through innovative problem-solving and adjustments. These efforts ensured the system's stability, efficiency, and adherence to design specifications.

This project highlights the potential of solar tracker systems in regions with limited access to energy resources. By optimizing solar energy conversion, such systems can play a vital role in improving the quality of life for communities facing energy scarcity, particularly in conflict-affected areas. The knowledge and experience gained through this project provides a foundation for future advancements in renewable energy systems, fostering sustainability and self-reliance in underserved regions.

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