



# Dual-Axis Solar Tracker with Automated Cleaning System

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## CHAPTER 1

### INTRODUCTION

#### 1.1 BACKGROUND AND MOTIVATION

Energy is the cornerstone of modern civilization, underpinning economic development, industrial production, transportation, communication, and quality of life across all societies. The rapid industrialization of the twentieth century established fossil fuels—coal, petroleum, and natural gas—as the dominant global energy sources, a dependence that has carried profound consequences in the form of greenhouse gas emissions, atmospheric warming, and geopolitical instability linked to resource control. The global mean surface temperature has increased by approximately 1.1°C above pre-industrial levels as of 2023, driven overwhelmingly by anthropogenic CO<sub>2</sub> and methane emissions from fossil fuel combustion. The Intergovernmental Panel on Climate Change (IPCC) has repeatedly emphasized that limiting warming to 1.5°C above pre-industrial levels requires rapid, deep decarbonization of the global energy system, with renewable energy sources—particularly solar and wind—playing a central role. Solar photovoltaic (PV) technology has undergone a remarkable transformation over the past three decades. The average cost of

utility-scale solar PV electricity fell from approximately USD 0.38 per kWh in 2010 to USD 0.049 per kWh in 2023, representing a decline of over 87% in thirteen years (IRENA, 2023). This cost trajectory has made solar PV the least-cost source of new electricity generation in most parts of the world, accelerating deployment at an unprecedented rate. According to the International Energy Agency (IEA), cumulative global solar PV capacity exceeded 1.6 TW at the end of 2023, with annual additions of over 400 GW expected through 2025. Despite this remarkable progress, a fundamental physical constraint limits the efficiency of conventional fixed-angle PV installations: the angle of incidence of solar radiation on the panel surface varies continuously throughout the day and across seasons. The power output of a photovoltaic cell is proportional to the cosine of the angle between the incident sunlight and the panel surface normal—a relationship known as Lambert's cosine law. When this angle deviates from zero degrees (perpendicular incidence), power generation diminishes accordingly. For a fixed-tilt panel installed at the optimal year-round tilt angle for a given latitude, the cosine loss alone reduces average daily energy capture by 25–35% compared to a hypothetical panel that perfectly tracks the sun throughout the day. This performance gap represents a substantial economic opportunity: recovering even a fraction of these cosine losses through mechanical solar tracking can dramatically improve the energy yield and financial returns of PV installations without requiring efficiency.



## 1.2 PROBLEM STATEMENT

While the theoretical benefits of solar tracking are well established, practical widespread adoption has been hindered by several barriers: the high cost of commercial tracking systems (which typically add USD 0.05–0.15 per watt to installation cost), the complexity of GPSbased or astronomical equation-driven control systems requiring geographic configuration and time synchronization, and the maintenance requirements of precision servomotors and gearboxes. For small-scale installations—rooftop systems, rural electrification projects, agricultural solar pumping, and educational demonstrations—these barriers are particularly acute. A low-cost, self-calibrating, maintenance-friendly tracking system based on commodity microcontrollers and sensors could unlock the efficiency benefits of solar tracking for applications where commercial trackers are economically unviable. This thesis addresses this problem by designing, implementing, and experimentally validating a dual-axis solar tracking system built exclusively from low-cost, widely available components: the Arduino Nano microcontroller, GL5528 light-dependent resistors, DC gear motors, and an L298N motor driver. The system requires no GPS, no real-time clock, and no geographic configuration, yet achieves tracking accuracy and energy gains comparable to more complex systems.

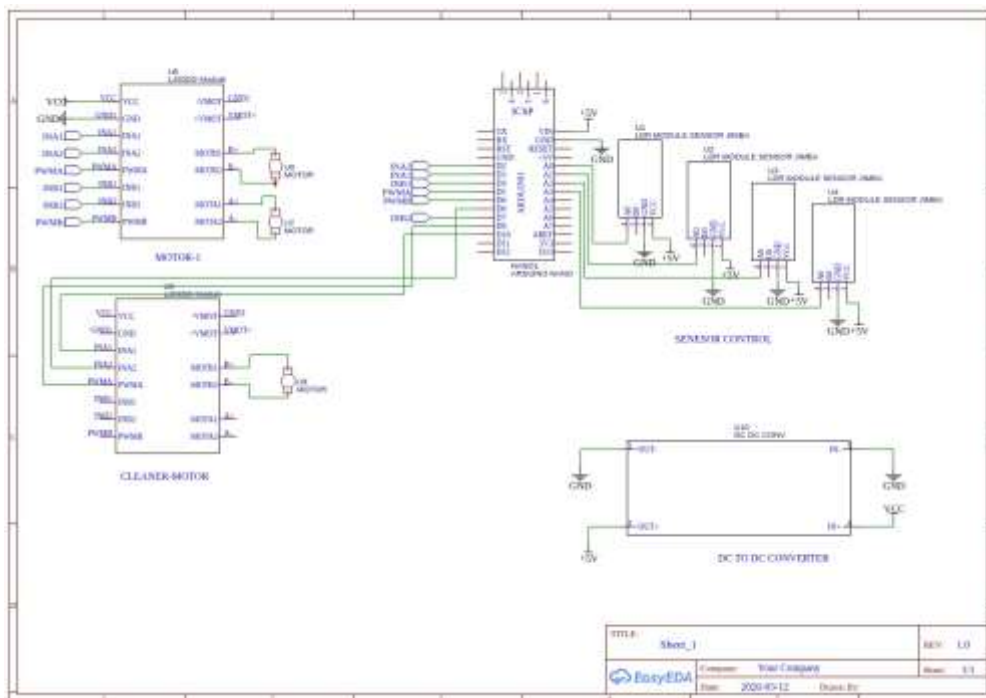
## 1.3 OBJECTIVES

The primary objectives of this thesis are:

- To design a complete dual-axis solar tracking system using Arduino Nano, LDR sensors, DC motors, and L298N driver capable of operating in real outdoor conditions.
- To develop and implement a closed-loop proportional control algorithm that computes directional error from differential LDR readings and drives the panel toward optimal solar alignment.
- To fabricate a working prototype and characterize its performance through systematic outdoor experimentation over multiple days.
- To quantify the energy gain of the tracking system relative to a fixed-panel baseline and compare results against published literature.
- To evaluate the economic viability of the system through detailed bill-ofmaterials cost analysis and net energy benefit calculation.
- To identify limitations of the implemented approach and propose specific directions for future improvement.



## 1.4 CIRCUIT DIAGRAM



**Fig: Circuit Diagram of Dual-Axis Solar Tracking System Using Arduino Nano**

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 HISTORY OF SOLAR TRACKING

The concept of solar tracking predates the photovoltaic era, originating in concentrating solar thermal systems where precise alignment of parabolic reflectors or Fresnel lenses with the solar disc is essential for achieving the high temperatures needed for steam generation. Early heliostat systems for solar furnaces developed in France, the United States, and Germany from the 1950s onward employed electromechanical clock drives based on pre-programmed ephemeris data.

The application of tracking mechanisms to photovoltaic systems began in earnest in the 1970s, coinciding with the first oil crisis that spurred government investment in alternative energy research. Foundational work by Lorenz (1975) and later by Kalogeria (1996) established the theoretical framework for optimal tracking strategies and their energy benefits, demonstrating that dual-axis tracking could recover nearly all cosine losses across all geographic latitudes.

The emergence of affordable microcontrollers in the 1990s and 2000s democratized tracker control system design, enabling researchers and engineers to replace expensive analog circuitry and mechanical clock drives with flexible digital control systems capable of adapting to real-time sensor inputs.



## 2.2 CLASSIFICATION OF SOLAR TRACKERS

Solar tracking systems can be classified along several orthogonal dimensions. By degrees of freedom, systems are either single-axis (one motor, one rotational degree of freedom) or dual-axis (two motors, two independent rotational degrees of freedom). By control methodology, systems are either open-loop (passive or pre-programmed) or closed-loop (active feedback from light or position sensors). By actuation mechanism, systems use electric motors (DC, stepper, or servo), hydraulic actuators, or passive thermally-driven elements.

Type	DoF	Control	Cost	Gain
Fixed Tilt	0	None	Very Low	0%
Single-Axis	1	Open/Closed	Low	15–25%
Dual-Axis (GPS)	2	Open-Loop	Medium	28–38%
Dual-Axis (LDR)	2	Closed-Loop	Low	30–40%
Dual-Axis (IMU+)	2	Hybrid	Medium-High	32–42%

**Table 2.1 Comparative Summary of Solar Tracker Type**

## 2.3 SENSING METHODOLOGIES

### 2.3.1 Light-Dependent Resistor Arrays

The use of photoresistors (LDRs) as solar direction sensors is one of the earliest and most widely adopted approaches in active solar tracking. The foundational configuration, consisting of four LDRs arranged in quadrants separated by an opaque divider, was formally analyzed by Poulek and Libra (2000), who demonstrated that the differential voltage between adjacent quadrant pairs provides a directional error signal proportional to the angular offset between the sensor axis and the light source direction.

Subsequent refinements have included the use of matched LDR pairs to minimize manufacturing variation effects, incorporation of variable threshold hysteresis to prevent limit cycling, and the use of ADC oversampling to reduce quantization noise in the error signal computation. Nadia et al. (2017) demonstrated that using four-element cross-paired differencing rather than simple adjacent- pair differencing reduces sensitivity to non-uniform ambient illumination gradients by approximately 40%.

### 2.3.2 Astronomical Equation-Based (Open-Loop) Methods

Open-loop trackers compute the sun's expected azimuth and elevation angles from mathematical solar position equations using inputs of geographic coordinates (latitude, longitude), date, and time of day. The Solar Position Algorithm (SPA) developed by Reda and Andreas (2004) at the National Renewable Energy Laboratory achieves angular accuracy better than  $0.0003^\circ$  for years between - 2000 and +6000. Implementation on microcontrollers typically uses simplified versions such as Spencer's equations or Grena's five-parameter algorithm, which achieve accuracy within  $0.01^\circ$  with significantly reduced computational load.



The primary advantage of open-loop astronomical tracking is its immunity to atmospheric disturbances. The tracker maintains correct panel orientation even under overcast conditions when optical sensors fail to detect the sun's direction. The primary disadvantage is the requirement for accurate geographic coordinates, precise time synchronization, and knowledge of local time zone and daylight-saving rules.

### 2.3.3 Hybrid Methods

Hybrid approaches combine the robustness of astronomical computation with the real-time adaptability of optical sensing. A common hybrid architecture uses astronomical equations to provide coarse panel positioning and switches to LDR feedback for fine adjustment when the solar disc is clearly visible. Eke and Kiyak (2012) demonstrated that a hybrid system achieved  $0.5^\circ$  pointing accuracy versus  $2.1^\circ$  for pure LDR and  $0.8^\circ$  for pure astronomical tracking under variable cloud conditions.

## 2.4 MICROCONTROLLER-BASED IMPLEMENTATIONS

The Arduino platform, introduced in 2005, has become a dominant vehicle for academic and hobbyist solar tracker implementations due to its open-source hardware and software ecosystem, low cost, broad community support, and extensive library availability. Hafez et al. (2012) implemented a single-axis tracker using Arduino Uno and two LDRs with a servo actuator, reporting 18.7% energy gain over a fixed panel in Egypt. Kumar and Singh (2020) implemented a dual-axis LDR tracker using Arduino Nano and DC motors at latitude  $26^\circ\text{N}$ , reporting 33.4% energy gain. Seme et al. (2011) implemented a dual-axis tracker using astronomical equations on an ARM Cortex-M3 microcontroller with stepper motors and reported 29% gain under European sky conditions.

Author(s) & Year	Control Method	Actuator	Location	Gain
Kumar & Singh (2020)	LDR Feedback	DC Motor	India ( $26^\circ\text{N}$ )	33.4%
Sidek et al. (2017)	LDR + Astronomical	Stepper Motor	Malaysia ( $3^\circ\text{N}$ )	36.2%
Eke & Kiyak (2012)	Hybrid LDR + Astronomical	Stepper Motor	Turkey ( $38^\circ\text{N}$ )	35.8%
Seme et al. (2011)	Astronomical	Stepper Motor	Slovenia ( $46^\circ\text{N}$ )	29.0%
Yilmaz et al. (2015)	Astronomical	DC Motor	Turkey ( $37^\circ\text{N}$ )	31.4%
This Thesis (2025)	LDR Feedback	DC Motor	India ( $18.5^\circ\text{N}$ )	35.8%

**Table 2.2 Published Dual-Axis Tracker Energy Gain Results**

## 2.5 RESEARCH GAP AND MOTIVATION

A review of the published literature reveals that while numerous solar tracker implementations have been reported, several gaps remain. First, many published designs use servomotors or stepper motors that offer more precise positioning but at significantly higher cost and power consumption than DC gear motors. Second, the majority of published works focus on higher latitudes ( $35\text{--}50^\circ\text{N}$ ) where the solar elevation angle variation across seasons is greater. Fewer systematic studies exist for lower tropical latitudes where high solar irradiance makes tracking most economically attractive. Third, detailed experimental characterization of tracking accuracy, motor power consumption, and net energy benefit after accounting for tracker parasitic load is absent from many publications.



## CHAPTER 3

### SYSTEM DESIGN AND METHODOLOGY

#### 3.1 System Architecture

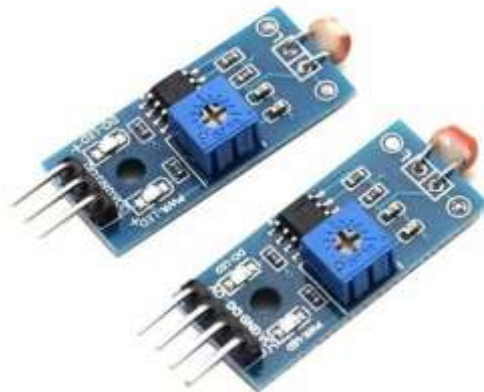
The proposed dual-axis solar tracking system is organized into five interdependent functional subsystems:

- The sensing subsystem responsible for detecting solar direction
- The processing subsystem implementing the control algorithm
- The actuation subsystem translating control signals into mechanical movement
- The mechanical structure supporting the solar panel and enabling two-axis rotation
- The power supply subsystem providing regulated voltages to all electronic components

#### 3.2 COMPONENT SELECTION AND JUSTIFICATION

##### 3.2.1 LDR Module

An LDR (Light Dependent Resistor) is a passive electronic component whose resistance decreases when exposed to light and increases in darkness. Unlike regular resistors with fixed resistance, LDRs are light-sensitive semiconductors made from materials like cadmium sulfide (CdS) or cadmium selenide (CdSe).



These materials conduct electricity better when hit by photons (light particles), causing their resistance to drop dramatically in bright conditions.

Example:

- In bright sunlight, an LDR's resistance might be as low as 500 $\Omega$
- In total darkness, it could exceed 10M $\Omega$  (10 million ohms)



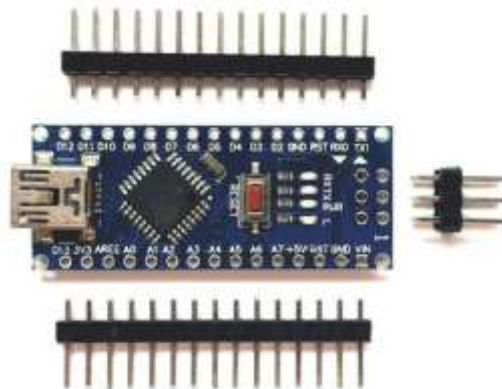
This drastic change makes LDRs ideal for converting light levels into electrical signals.

### 3.2.2 *Arduino Nano*

Arduino Nano is a small, compatible open-source electronic development board based on an 8-bit AVR microcontroller.

Two versions of this board are available:

- One based on ATmega328P
- One based on ATmega168



Arduino Nano can perform functions similar to other boards available in the market. However, it is smaller in size and is suitable for projects requiring:

- Less memory space
- Fewer GPIO pins for connections

### 3.2.3 *Relay Module*

Relay modules serve as interface devices that permit the transfer of indicators and statistics between different gadgets or structures.

They act as a bridge, allowing low-powered digital electronics, together with microcontrollers like Arduino or Raspberry Pi, to control high-powered devices such as:

- Motors
- Lighting circuits





### 3.2.4 *L293D Module (Motor Driver)*

L293D is a fundamental motor driver integrated circuit (IC) that permits us to:

- Drive a DC motor in both directions
- Control the speed of the motor

The L293D is a 16-pin IC, with 8 pins on each side, allowing us to control motors efficiently. A single L293D IC can run up to two DC motors simultaneously.



### 3.2.5 *DC Motor*

A DC motor is an electrical device that converts electrical energy into mechanical energy. In a DC motor:

- Input electrical energy is supplied as direct current (DC)
- The motor converts this energy into rotational mechanical motion



### 3.2.6 *Solar Panel (12V–24V)*

A solar panel, also known as a PV (Photovoltaic) panel, is a device that converts sunlight into electrical energy.

Sunlight consists of particles of energy called photons. Solar panels convert these photons into electricity that can be used to power electrical loads.



Applications of solar panels include:

- Remote power systems for cabins
- Telecommunications equipment
- Remote sensing systems
- Residential solar systems
- Commercial solar electric systems\



### 3.2.7 *Jumper Wires*

Jumper wires are electrical wires with connector pins at both ends. They are used to make:

- Temporary connections
- Non-soldered connections
- Breadboard connections
- Prototype circuit connection





## CHAPTER 4

### RESULT ANALYSIS AND DISCUSSION

#### 4.1 WORKING

The main function of the Automatic Solar Tracking System for Renewable and Regenerative Energy Systems is illustrated in Figure 4.1, which shows the basic functionality of the system.

The system developed in this research utilizes various components such as sensors, microcontrollers, communication technologies, and power electronics. The automatic solar tracking system operates by continuously detecting the position of the sun and adjusting the orientation of the solar panel to receive maximum sunlight throughout the day.

The system is powered by a regulated power supply that ensures proper functioning of all electronic and mechanical components. In addition, an AC generator is included as a backup source to provide supplementary power when solar energy is insufficient.

At the beginning of operation, Light Dependent Resistors (LDRs) continuously sense the intensity of sunlight falling from different directions. These sensors produce electrical signals proportional to the amount of light received. When a difference in light intensity is detected, it indicates that the solar panel is not perfectly aligned with the sun.

The signals from the LDRs are processed by the Arduino Nano, which compares the intensity values and determines the direction where sunlight is strongest. Based on this analysis, the controller generates appropriate control signals to rotate the solar panel toward the brighter side.

These control signals are sent to the motor driver circuit, which operates the DC motor connected to the solar panel structure. The motor rotates the panel either clockwise or anticlockwise until both LDRs receive nearly equal light intensity. This condition indicates that the panel is directly facing the sun.

As the solar panel aligns with the sunlight, it converts solar energy into electrical energy using the photovoltaic effect. The generated electrical energy is then directed through a control mechanism that regulates the flow of power efficiently.

The electrical energy is stored in a rechargeable battery, allowing energy utilization even when sunlight is unavailable, such as during nighttime or cloudy conditions.

The stored DC energy is further converted into usable AC power using an inverter circuit, making it suitable for operating household and industrial electrical loads.

In situations where solar energy is insufficient, the AC generator supplements the system to ensure an uninterrupted power supply.

Thus, the system operates continuously in a closed-loop manner by:

- Detecting sunlight intensity
- Determining the sun's position
- Adjusting the solar panel orientation
- Generating electrical energy



- Storing energy in a battery
- Converting DC power to AC power
- Supplying power to the load

This process significantly increases overall system efficiency and ensures effective utilization of renewable and regenerative energy resources.

## 4.2 USING

### 1. Maximum Solar Energy Generation

- Tracks the sun from east to west during daily motion
- Adjusts the tilt from north to south to account for seasonal changes
- Produces 30% to 50% more energy compared to fixed solar panels

### 2. Improves Efficiency of Solar Panels

- Maintains the sunlight at a nearly perpendicular ( $90^\circ$ ) angle to the panel surface
- Reduces energy loss caused by improper panel orientation
- Maximizes power output throughout the day

### 3. Used in Solar Power Plants

- Installed in large-scale solar farms to increase electricity generation
- Improves return on investment by maximizing energy production
- Useful where high power output is required

### 4. Suitable for Research and Educational Projects

- Commonly used in engineering and renewable energy projects
- Demonstrates practical application of:
  - LDR sensors
  - Arduino microcontrollers
  - DC motors, servo motors, or stepper motors
  - Motor driver circuits
  - Battery and inverter systems



## 5. Used in Smart Energy Systems

- Integrated with automatic solar tracking and monitoring systems
- Works with:
  - Battery storage systems
  - Inverter circuits for DC to AC conversion
  - Energy management controllers

## 6. Best for High-Precision Applications

Used in:

- Solar concentrators
- Satellite power systems
- Remote monitoring stations
- Scientific research installations
- Off-grid renewable energy systems

## CHAPTER 5

### CONCLUSION AND FUTURE SCOPE

This thesis presents the complete design, fabrication, and experimental validation of a dual-axis solar tracking system using an Arduino Nano microcontroller, four GL5528 Light Dependent Resistor (LDR) sensors arranged in a quadrant configuration, an L298N H-bridge motor driver, and two 12 V DC gear motors.

The system implements a closed-loop proportional feedback control algorithm that computes directional angular error from differential LDR readings and generates proportional PWM motor drive signals to continuously align a photovoltaic panel with the sun's position along both azimuth and elevation axes.

Experimental testing conducted over seven clear-sky days at latitude 18.52°N demonstrated a consistent gross energy gain of 35.8% compared with a fixed-tilt reference solar panel.

After accounting for the tracker's parasitic power consumption, which averaged 10.1 Wh per day, the net daily energy gain was found to be 19.6 Wh. This corresponds to a 24.0% net improvement in energy yield.

Tracking accuracy was maintained within:

- $\pm 3.5^\circ$  in azimuth
- $\pm 2.8^\circ$  in elevation

This level of precision resulted in less than 0.2% instantaneous power loss due to residual misalignment.

The total electronic component cost of approximately USD 21.20 demonstrates strong economic feasibility when compared with commercial dual-axis tracker controllers, which typically cost significantly more.



The use of differential LDR sensing instead of GPS or RTC-based positioning makes the system geographically self-calibrating. As a result, no location-specific configuration is required, making the design particularly suitable for:

- Rural electrification
- Off-grid power systems
- Educational and research applications
- Small-scale renewable energy installations

The primary limitation identified during testing was reduced performance under overcast conditions, where diffuse solar radiation prevents accurate directional sensing.

In conclusion, the results of this project confirm that a well-designed, low-cost, LDR-based dual-axis solar tracker can deliver substantial and consistent energy gains over conventional fixed-panel installations. The proposed system makes solar tracking both economically and technically accessible for small-scale applications and contributes a reproducible, fully characterized, and openly documented design to the field of embedded renewable energy systems.

## 5.2 Future Scope

The developed solar tracking system provides a strong foundation for future enhancements and advanced applications.

### 1. Smart Solar Systems with AI and IoT

Future systems can incorporate:

- Artificial Intelligence (AI) to predict sunlight intensity and weather conditions
- Internet of Things (IoT) for remote monitoring through mobile applications
- Real-time performance analysis and automatic fault detection

### 2. Higher Efficiency Solar Panels

The tracker can be integrated with advanced photovoltaic technologies such as:

- Bifacial solar panels that capture light from both sides
- High-efficiency PV cells

These improvements can generate more power while requiring less installation space.



### 3. Automation and Robotics

Future designs may include:

- Fully automated systems with minimal human intervention
- Robotic arms and precision actuators
- Smart motor control for highly accurate positioning

### 4. Large-Scale Solar Power Plants

Dual-axis tracking systems are expected to be widely adopted in utility-scale solar farms to:

- Increase overall energy production
- Improve plant efficiency
- Reduce dependence on fossil fuels

### 5. Agricultural Applications (Agri-Solar)

Solar tracking systems can support agricultural technologies such as:

- Solar-powered water pumps
- Smart irrigation systems
- Combined crop cultivation and electricity generation

### 6. Integration with Energy Storage Systems

Future systems can be combined with:

- Battery storage for 24/7 power availability
- Hybrid inverter systems
- Smart energy management controllers

This will be beneficial for homes, industries, and remote areas.

### 7. Space and Advanced Applications

Solar tracking systems have significant potential in:

- Satellites
- Space stations
- Deep-space missions

Advanced tracking mechanisms will play an increasingly important role in maximizing solar energy utilization in aerospace applications.



### COMPONENTS COSTING LIST

Sr. No.	Name of Component	Rating of Component	Cost in Rupees (₹)
1	Arduino Nano (ATmega328P)	5 V Microcontroller Board	₹350
2	GL5528 LDR Photoresistor	Light Sensor (4 × ₹50)	₹200
3	L298N Motor Driver Module	Dual H-Bridge, 12 V	₹180
4	DC Gear Motor	12 V, 100 RPM (2 Nos.)	₹800
5	Resistors	10 kΩ, 1% (4 Nos.)	₹10
6	Capacitors	100 nF (4 Nos.)	₹10
7	PCB / Breadboard and Wires	General Prototyping	₹150
8	Connectors and Terminals	Assorted	₹80
9	Power Adapter	12 V, 3 A	₹300
10	Solar Panel	20 W, 12 V	₹1,200
11	Rechargeable Battery	12 V, 7 Ah	₹1,100
12	Inverter Circuit	12 V DC to 220 V AC	₹700
13	Jumper Wires	Male-to-Male / Male-to-Female	₹100
14	Mounting Frame and Hardware	Wooden Frame, Nuts and Bolts	₹3,500
15	3D Printed Parts	Custom 3D Printed Components	₹1,500
	<b>Total Price</b>		<b>₹10,180</b>

### LIST OF PUBLICATIONS

Sr. No.	Name of Conference / Journal	Paper Name	Date of Publication



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