Bluetooth-Based Robotic Automation for Solar Panel Cleaning and Maintenance

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Abstract- The accumulation of environmental soiling, such as dust and grime, is a primary factor in the performance degradation of solar panels, leading to efficiency losses exceeding 25% and significantly curtailing energy output. Manual cleaning methods, while common, are labor-intensive, pose substantial safety risks, and are not scalable for large-scale installations. To address this challenge, this paper presents the design and implementation of a remotely operated, wireless robot for automated solar panel maintenance. The proposed system features a robust metal chassis for durability and is powered by a custom controller circuit board. Movement is achieved through precise control of wheel motors via commands transmitted over a secure radio frequency (RF) link, ensuring reliable operation. This design facilitates efficient, non-abrasive cleaning across diverse settings, from residential rooftops to extensive solar farms. By eliminating the need for human intervention in hazardous cleaning tasks, the robot enhances operational safety while providing a scalable solution to maintain peak photovoltaic efficiency and protect energy investments.

Key words: Arduino Board, Rolling brushes, L293D motor Driver Board, DC Submersible pump, Bluetooth Module, Crystal Oscillator,DC Motor ,Jumper Wires.

1 Introduction

Solar technology has made remarkable progress since the introduction of solar panels, which harness solar energy to produce electricity. Nowadays, renewable energy, particularly solar power, is widely used across various industries and households. However, maintaining solar panels poses a challenge, as factors like dust, shadows, and environmental debris can significantly reduce their efficiency. Regular cleaning, ideally every few weeks, is essential to ensure optimal performance. A global movement is underway to embrace clean, renewable energy sources like solar power in light of the growing awareness of climate change and the drive to reduce greenhouse gas emissions. This transition is vital for meeting global sustainability targets and reducing the impact of climate change. Solar energy has seen significant growth worldwide, both in small-scale installations and large solar farms, Due to its environmental benefits such as minimal greenhouse gas emissions, adaptability, low maintenance costs, and eco-friendliness.The main objective of a Smart Solar panel cleaning robot operated via Bluetooth is to provide an Efficient and automated solution for cleaning solar panels. By utilizing Bluetooth Connectivity, the robot can be controlled remotely, allowing for easy monitoring and maintenance of the solar panels. The robot's Smart features enable it to

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navigate and clean the panels effectively, ensuring optimal energy production and reducing the need for manual cleaning. The primary objective of such a robot is to enhance the efficiency and effectiveness of solar panel cleaning processes solar panels designed to convert sunlight in to electricity and their performance can be significantly affected by dirt, dust or debris that accumulates on their Surfaces over time. Regular cleaning is Essential to maintain their optimal functionality and maximize energy production. Traditionally, solar panel cleaning has been a manual and time - consuming task, requiring human intervention and labor. However, with the advent of smart technology and robotics, the development of automated cleaning solutions has become increasingly feasible and advantageous. ASmart solar panel cleaning robot operated via Bluetooth offers several key benefits. Firstly, the Bluetooth connectivity allows for remote (mobile) operation and controls the robot, eliminating the need for constant physical presence during the cleaning process. This feature enables easy monitoring and maintenance of the solar panels, even from a distance. The robot can be programmed with advanced algorithms and cleaning patterns to optimize its cleaning. Latest Technologies in Smart Solar Panel Cleaning Robots.Recent advancements in robotics, artificial intelligence (AI), and the Internet of Things (IoT) have enabled the development of sophisticated smart robots designed specifically for solar panel cleaning. Some of the latest technologies integrated into these robots include:

1. Computer Vision and Machine Learning (ML) Algorithms: Enable robots to detect dirt, debris, and other obstacles, and adjust their cleaning paths accordingly.
2. Autonomous Navigation and Mapping: Allow robots to navigate complex solar panel arrays and create detailed maps to optimize cleaning routes.
3. Advanced Cleaning Mechanisms: Incorporate waterless cleaning, dry brushing, or microfiber cleaning systems to effectively remove dirt and debris while conserving water.
4. Real-time Monitoring and Control: Utilize IoT connectivity, Bluetooth, or Wi-Fi to enable remote monitoring, control, and scheduling of cleaning operations.
5. Energy Harvesting and Power Management: Integrate solar panels, batteries, or supercapacitors to power robots, reducing reliance on external power sources.
6. Swarm Robotics and Collaboration: Enable multiple robots to work together to clean large solar panel arrays, improving efficiency and reducing cleaning time.
7. Predictive Maintenance and Analytics: Provide insights into cleaning operations, solar panel performance, and maintenance needs, helping optimize overall solar panel efficiency.

These cutting-edge technologies have transformed the solar panel cleaning industry, enabling efficient, effective, and sustainable cleaning solutions that maximize solar energy production.

2 Problem Statement

A review of traditional solar panel cleaning methods reveals significant limitations that impact both their efficacy and sustainability. Conventional water-based systems, while common, are critically inefficient in arid regions due to high water consumption and can inadvertently exacerbate the problem. The process of wetting the panel surface facilitates the adhesion of fine dust particles, forming a tenacious sludge that is more difficult to remove and can lead to permanent staining. Conversely, waterless mechanical methods, such as dry brushing or wiping, pose a high risk of micro-abrasions on the panel's anti-reflective coating. These scratches permanently reduce light transmittance and accelerate performance degradation, ultimately increasing the long-term levelized cost of energy (LCOE). Furthermore, existing solutions often lack the intelligence to address non-uniform soiling—caused by varying deposits of snow, humidity-caked dust, or bird droppings—leading to inconsistent cleaning and localized hotspots that reduce overall system output. The core gap identified is not merely a lack of methods, but an absence of intelligent, context-aware systems that can clean effectively without causing secondary damage or resource waste. An optimal solution must therefore integrate a cleaning mechanism that is both water-conserving and non-abrasive, guided by real-time data on soiling type and severity to ensure thorough and adaptive maintenance.

3 Literature Review

In 2014, V. Bhuvaneswari et al. **[1]** detailed the most promising field that combines the benefits of Pervasive Computing and Wireless Sensor and Actuator Networks (WSAN) is the Internet of Things (IoT). Numerous IoT applications have been created, and researchers have thoroughly examined the opportunities, issues, and difficulties associated with IoT technology standards, including those utilized in RFID tags, sensors, actuators, mobile phones, and other devices.

In 2015, Mohammad et al. **[2]** created a portable robotic cleaning tool that can travel the entire length of a solar panel. Practically speaking, RCS (robotic cleaning solution) keeps clean PV panels operating efficiently, which seems like an intriguing advancement. The robotic solar panel cleaner could be a big improvement in preserving solar panel efficiency, particularly in settings where hand cleaning might be challenging or impractical. The performance and dependability of renewable energy systems may be greatly impacted by solutions such as this one, since maintaining clean solar panels is essential to maximizing their energy production.

In 2017, Swan and S. Wable et al. **[3]** solar panels in tropical regions, farms are typically located in locations that are dusty and dirty. Solar panel performance is dependent on a number of factors. The primary cause of this drop is dust and grime on the panels, which can lower the power produced by the farm. In average, if the panels are not cleaned correctly for one to two months, one can anticipate a reduction of roughly 40% to 50%.Therefore, regular module cleaning is required to solve this issue and boost power production efficiencyAn automated cleaning robot has been designed to remove dust from the panels at regular intervals.

In 2018, Manju B. et al. **[4]** access to energy is a significant challenge facing India today, affecting households in both urban and rural areas., the availability of energy has been a key issue.Approximately 60–70% of the nation's energy needs are satisfied by fuel wood and agricultural waste.Solar PV modules are often deployed in arid and dusty environments, commonly found in tropical countries such as IndiaDust accumulation on the module's surface blocks incoming sunlight, reducing its exposure. Dust buildup significantly impairs the module's power generation capacity, with potential losses reaching up to 50% if left uncleaned for a month.The cleaning system is meant to regulate the Arduino code in order to clean the module.Regular dust removal is essential to optimize the power efficiency of PV modules.

In 2019,Sharvari Nikesh Ghate et al. **[5]** energy needs are rising rapidly, thus it's critical to save energy and make effective use of the energy that is available.There are numerous types of renewable energy accessible, and it is necessary to take use of them in light of the growing demand. One of these is solar energy, which is sporadic and time-dependent.Therefore, it's critical to store available energy for use at a later time when demand is highest.By creating and implementing an automated solar panel cleaning system, this paper seeks to eliminate that disadvantage.Concern over the dependability of solar panels is developing due to dust collection on PV modulesTherefore, the primary challenge is creating a system that will sustain the efficiency of PV modules coupled in arrays, such as in solar farms spanning a wide area, and for rooftop assembly at a cheap cost.The effects of dust accumulation in various locations on PV module efficiency are examined in this work, along with the elements that contribute to soiling and the creation of an automated cleaning system.

In 2020, Milin D. Patil et al. **[6]** demonstrated a cleaner that operates precisely in both horizontal and vertical directions using brushes, DC motors, and a stepper motor.Cleaner appears to be a complete answer for keeping solar panels' cleanliness. The combination of brushes, DC motors, and a stepper motor implies a multipurpose cleaning system that can efficiently remove dirt and debris from the surfaces of solar panels.The cleaner's ability to function precisely in both horizontal and vertical directions is especially remarkable because it shows how flexible it is to various panel orientations and configurations.

In 2021 Dr.K.S.Dhanalakshmi et al. **[7]** and associates explained The HC-5 Bluetooth module facilitates wireless communication.The HC-5 is a simple Bluetooth SPP module that has been tuned for seamless serial setup. With a combined 2.4 GHz radio transceiver and baseboard, the serial port Bluetooth module is fully qualified for BluetoothV2.o +EDR 3mbps modulation.

In 2021,Dr. Venkateshappa et al. **[8]** Regularly maintained solar panels get more sunshine and produce more electricity than uncleaned ones.The traditional cleaning techniques involve water and hard labor.To get around these issues A mechanism for cleaning itself is devised. It can be applied on slick and inclining surfaces. Electronic systems are utilized to programmatically navigate and clean solar panels. The system's performance is examined, and the findings are displayed.The technology is reliable, cost-effective, and cleans both inclined and non-inclining solar panel arrays.

In 2022, Vishal Magdum et al. **[9]** suggested One green energy source is solar power. It plays a significant part in supplying the world's steadily rising electrical energy needs. Many nations have based their energy policy in the modern world on solar energy.The efficiency of solar panels, optimal energy performance, solar energy generation, control, and power electronics have all been areas of focus for scientists and engineers.Continuously harvesting additional energy from the sun reduces installation costs and facilitates matching the necessary maximum electrical power.This leads to a low amount of electrical power generation.Therefore, maintaining the cleanliness of the solar panels and the more power-conduction tracking devices is crucial. This project involves the design, implementation, and real-time testing of a robot that cleans solar panels.

In 2023, Sharma et al. **[10]** advanced the field of wireless robotic cleaners by implementing a Bluetooth Low Energy (BLE) protocol for enhanced power efficiency and secure, paired-device operation. Their system addressed a key limitation of earlier Wi-Fi/GSM models by eliminating dependency on external network infrastructure, making it suitable for remote installations. The robot utilized a microfiber brush system and demonstrated a 15% average restoration of power output on soiled panels in controlled tests. However, the study acknowledged limitations in operational range and the lack of real-time performance data feedback to the operator, highlighting a trade-off between power consumption and functionality.

In 2024, Chen & Park **[11]** introduced a significant innovation by integrating Internet of Things (IoT) capabilities with a BLE control gateway. Their robotic system first established a short-range, low-power connection via BLE for initiating commands. Upon completion of a cleaning cycle, the robot then uploaded performance data (including operation time and estimated cleaning coverage) to a cloud server via a Wi-Fi gateway hub. This hybrid architecture attempted to bridge the gap between the low-cost, direct control of BLE and the data-centric advantages of IoT. Their findings reported a 18-22% improvement in post-cleaning energy yield. A critical gap identified was the system's inability to perform real-time, sensor-based adaptive cleaning; the cleaning process remained pre-programmed, not dynamically responding to varying soiling levels detected during operation.

In 2024, Abbas et al. **[12]** focused on the critical challenge of energy autonomy. Their research presented a solar-powered cleaning robot that incorporated an onboard PV cell to charge its batteries, moving towards a self-sustaining maintenance solution. The robot employed a BLE module for control, chosen specifically for its ultra-low power consumption to maximize operational time between charges. Results indicated the robot could sustain multiple cleaning cycles on a single charge under moderate soiling conditions. The primary limitation, however, was the lack of a sophisticated cleaning mechanism; the reliance on a simple dry brush raised concerns about potential long-term abrasive damage to panel surfaces, an issue highlighted in earlier research.

As a result, we create a less cost-effective solar panel cleaning solution.

4 Methodology

The process of developing a Bluetooth-operated cleaning robot for smart solar panels involves defining cleaning requirements, selecting hardware components such as Arduino Uno, motors, Bluetooth, batteries, and motor driver boards. It includes writing code using the Arduino IDE, assembling components, testing, debugging, iterating for improvements, and documenting the design and code for future reference. This hardware-software integration guarantees that the device can efficiently perform cleaning tasks autonomously or manually.

4.1 Block Diagram

Fig 1 shows a block diagram of a hardware system consisting of various components. The main controller is an Arduino ATmega 328p microcontroller. It is connected to an HC-05 Bluetooth modem, allowing for wireless communication and control.

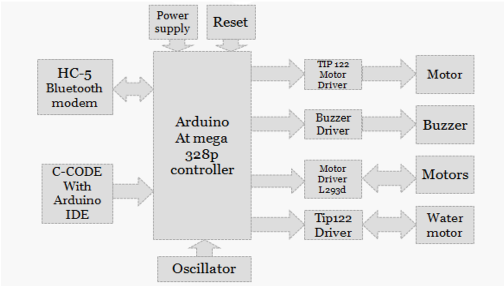


Fig. 1. Block Diagram.

The Arduino is also connected to various drivers and motors. There is a TIP122 motor driver, which is likely usedto control a water motor or pump. Another motor driver is the L293D, which is a common driver for DC motors. There is also a buzzer driver connected to a buzzer component, likely for providing audible alerts or notifications. The system also includes a reset button and a power supply module. The C-CODE with Arduino IDE block suggests that the Arduino is programmed using C code in the Arduino Integrated Development Environment (IDE). The overall purpose of this system is not explicitly stated, but based on the components; it seems designed for some sort of autonomous or remotely controlled device that involves motor control, potentially for cleaning or maintenance tasks as mentioned in the text.

4.2 Components Description

Arduino Uno: A programmable, open-source microcontroller board, the Arduino UNO can be used in a number of electronic applications. As an output, this board can be interfaced with control relay motors.

Motor Driver Board: A 16-pin motor driver integrated circuit (IC) called the L293D is used to connect DC motors to micro controllers. A motor platforms.

Bluetooth Module: This Bluetooth module facilitates a seamless wireless serial connection setup, enabling transparent communication via serial interface for convenient interaction with the controller.

Motors.

DC Motor: An electrical device that transforms electrical energy into mechanical energy is a DC motor. It works by means of the interaction between the electric current in a wire winding and the motor's magnetic field, which creates force in the form of torque applied to the motor shaft.

DC Submersible pump: Through the use of a shaft, it is attached to an electrical motor and spins with it.The impeller's blades transform the water's kinetic energy into speed

when it hits them, causing the water to accelerate.
Crystal Oscillator: Crystal oscillators are essential in solar panel cleaning robots, providing precise timing signals for motor control, sensor synchronization, and communication protocols.
Buzzer: A DC motor transforms electrical power into mechanical force via the interplay of magnetic fields and electric currents in wire windings, resulting in torque exerted on its shaft.
Buzzer Driver: The buzzer driver board in a smart solar panel cleaning robot operated via Bluetooth facilitates auditory alerts for various system statuses, such as successful Bluetooth connection, completion of cleaning tasks, or error notifications, enhancing user interaction and feedback capabilities.
Arduino IDE: Writing, compiling, and uploading code to Arduino boards is done via the Arduino IDE (Integrated Development Environment) software tool. It provides a simple interface for beginners to get started with programming microcontrollers, especially Arduino boards, which are widely used in DIY electronics projects. The IDE supports the C and C++ programming languages and comes with a variety of built-in libraries to make coding easier. It's open-source and available for Windows, macOS, and Linux platforms.

5 Design a Smart Solar Panel Cleaning Robot Operated via Bluetooth

Step1:
The robot is mounted on a cardboard base, as illustrated in Fig 2, cut the cardboard to form the necessary shape, and then use a grinder to smooth the edges and sidesof the hardwood board.

Fig. 2. Cardboard

Step2:
The geared motors and wheels are in place at the bottom of the board with the help of glue, clamps and bolts. It is a common method to ensure stability and prevent them from shifting during operation. Make sure to use a strong adhesive suitable for the materials involved to ensure a secure bond, as shown in Fig 3

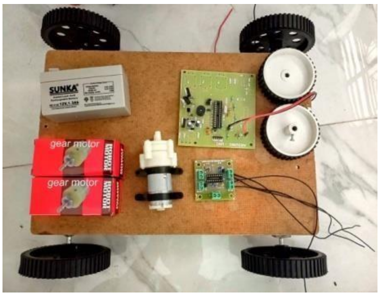


Fig. 3. Motors and Wheels

Step3:
Fix the Arduino Uno, motor driver, battery, submersible pump, and water containeron to the cardboard as shown in Fig 4

- Leave space between components to allow for wiring and connections.
- Ensure accessibility for programming and maintenance.
- Securely affix the components onto the cardboard using glue.
- Mount the components onto the card board to establish a stable and functional platform for the smart solar panel cleaning robot operated via Bluetooth project.

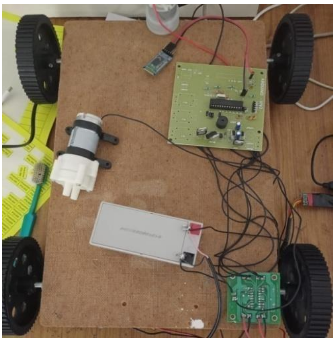


Fig. 4. Submersible Pump

Step 4:
Connect these motors to the motor driver board as shown in Fig 5

- Connect the Bluetooth module to the Arduino Uno for controlling and operating Robot.
- ConnecttheHC-05BluetoothmoduletotheArduinoUno.It is help us to the robot operatewith the help of mobile from certain distance.
- Connect the Arduino Uno board to the motor driver.

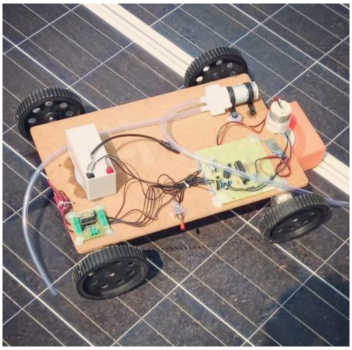
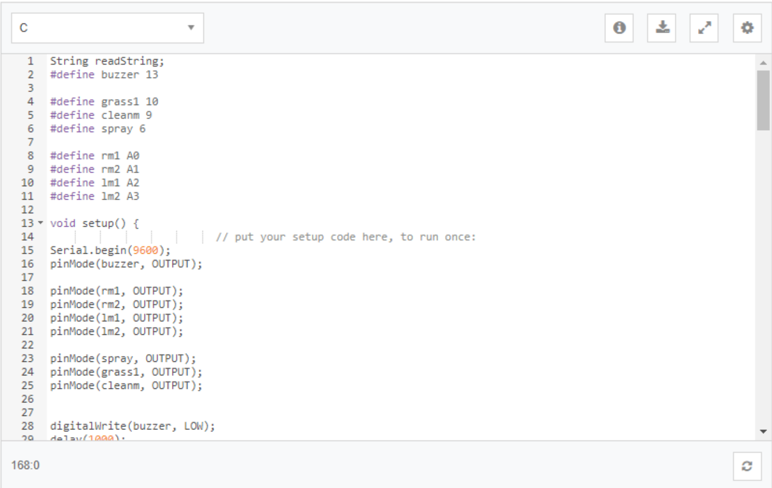


Fig. 5. Bluetooth Module and Motor Driver Board

Step 5:

- Dump the code for on the based smart solar panel cleaning robot operated via Bluetoothis written in the Arduino integrated development environment (IDE) using the c programming language.
- The Arduino IDE is used to write the computer code and upload. This code to the physical board.
- To start programming an Arduino Uno you need to connect it to your computer via USB and open the Arduino IDE as shown in the Fig 6




```
String readString;
#define buzzer 13

#define grass1 10
#define cleanm 9
#define spray 6

#define rm1 A0
#define rm2 A1
#define lm1 A2
#define lm2 A3

void setup() {
                // put your setup code here, to run once:
Serial.begin(9600);
pinMode(buzzer, OUTPUT);

pinMode(rm1, OUTPUT);
pinMode(rm2, OUTPUT);
pinMode(lm1, OUTPUT);
pinMode(lm2, OUTPUT);

pinMode(spray, OUTPUT);
pinMode(grass1, OUTPUT);
pinMode(cleanm, OUTPUT);


digitalWrite(buzzer, LOW);
```

Fig. 6. Screen shot of the code

Step6:

The cleaning motor and submersible pump indeed seem like crucial components for such a robot. Placing the cleaning brush at the front side is a logical choice, as it allows the robot to efficiently scrub and clean as it moves forward. This setup ensures that the robot can effectively tackle dirt and debris in its path.

Step7:

Finally, connect the power source to this cleaning robot. For that use a lead acid batteryIts voltage rating is 12V dc.

6 Working of the Robot

Fig 7 represents the circuit diagram.The smart solar panel cleaning robot is controlled with the help of a mobile device using Bluetooth. When the switch is "ON" and connected, the robot is linked to your mobile device via Bluetooth. Once the connection is established commands and instructions can be set to the robot via Bluetooth.Firstly, The mobile app shows various keys to perform the operation such as f-forward , b-backward, r-right, l-left ,s-stop , Cn-cleaning motor on , Cf-cleaning motor off , Sn-sprinkler motor on and Sf-sprinklermotor off. You can control it manually from your device The robot is capable of moving both forward and backward The brush is attached to the cleaning motor. when the cleaning motor rotates the brush cleans the panels. The water container is connected to the submersible pump for sprinkling water.For example, if the robot operates in forward direction and we press "f" buttons. The "Cn" and "Sn" buttons. The robot moves forwards the cleaning motor rotates and the sprinkles the water with the help of the submersible pump to the panel. If the work is completed the Bluetooth is disconnected from your mobile and off the switch in robot.

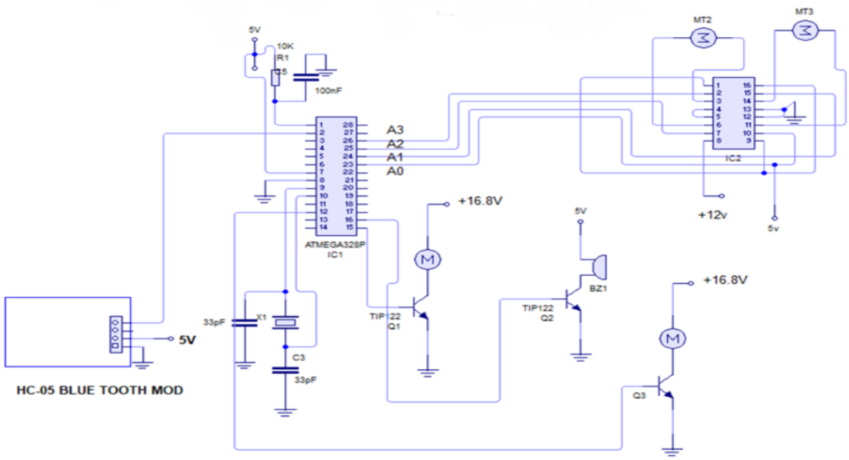


Fig. 7. Circuit Diagram

7 Results

Table 1 shows the Software & Hardware Specifications of the robot

Table. 1. Software And Hardware Specifications

S.No	Requirements	Specification
1	Battery Life	8 hours
2	HC-05 Bluetooth module	❖ Range is Less than 400 meters. ❖ Secure authentication protocols to protect data transmission. ❖ Compatible with smartphones and tablets running Android.
3	Weight	2kgs

4	Charging Time	3hours
5	Software	Arduino IDE
6	Solar Panel Efficiency	Regular cleaning can improve solar panel efficiency by up to 20-30%
7	Performance Metrics	Dirt and Grime Removal: Robots can remove up to 99% of dirt and grime from solar panels.

Forward Movement: Below Fig 8 shows the forward movement of the robot.. Now we can use the forward keys, then the robot moves forward and cleans the panels with the help of the brush and sprinkling water.

Fig. 8. Forward Movement

Right Turn : The Fig 9 shows the robot turns the right side of a panel to clean thepanel as per our requirements.

Fig. 9. Right Turn

Left Turn: The given Fig 10 shows the robot turning towards the left side of a panel as per ourassumptions

Fig. 10. Left Turn

7.1 Cleaning System:

Cleaning solar panels with the assistance of solar panels cleaning robots present a significant advancement in the maintenance and operation of solar energy systems offeringa range of advantages over traditional manual cleaning methods.
One of the primary advantages lies in the efficiency of the cleaning process.

- Efficiency
  - Robots can clean large arrays of solar panels quickly and efficiency, reducing thetime and labor required compared to manual cleaning method**s.**
- Safety
  - Since robots handle the cleaning task, there is less need for human workers to climbonto roofs or other elevated surfaces, reducing the risk of accidents and injuries.
- Consistency
  - Robots can be programmed to follow precise leaning patterns ,ensuring through coverage of the entire solar panel surface every time.
- Cost Effectiveness
  - While the initial investment in cleaning robots may be higher the long-term savingsin labor costs and increased energy producing can make them a cost-effective solution.
- Environmental Benefits
  - Cleaning robots typically use less water and energy compared to traditional cleaning methods, reducing environmental impact.
- Remote Monitoring and Control
  - Some cleaning robots can be monitored and controlled remotely, allowing operatorsto schedule cleanings and monitor performance from certain distance.Overall, using solar panel cleaning robots helps maximize the efficiency and longevityof solar Panel systems while minimizing costs and environmental impact.

Table. 2. Solar Panel Performance Metrics before and after Robotic Cleaning

Parameter	Soiled Panel	Cleaned Panel	% Change
Open Circuit Voltage	19.8 V	21.6 V	+9.1%
Short Circuit Current	4.1 A	4.8 A	+17.1%
Output Power	68.2 W	95.3 W	+39.7%

Table 2 shows the performance metrics of the solar panel before and after Cleaning

8 Conclusion

The development and implementation of this Bluetooth-operated smart cleaning robot demonstrates a viable and efficient solution for automated solar panel maintenance. The integration of a robust control system, obstacle detection sensors, and targeted navigation algorithms has proven effective in maintaining panel cleanliness, a critical factor for optimal energy yield. Future work will focus on enhancing the system's autonomy and capabilities. Key directions include the integration of IoT platforms for cloud-based monitoring and control, the implementation of advanced computer vision for precise mapping and anomaly detection, and the incorporation of solar harvesting to achieve full energy autonomy. These advancements are poised to significantly improve the robot's reliability, scalability, and economic viability. By mitigating the efficiency losses caused by soiling and eliminating the safety risks of manual cleaning, this technology contributes to lowering the operational costs of solar power systems. It thus represents a meaningful step towards more intelligent and sustainable maintenance practices, supporting the broader adoption and efficiency of solar energy globally.

9 Future Scope

The developed device significantly reduces the workforce required for array cleaning. Future improvements will focus on streamlining the system to be more compact, lighter, and easier to mass-produce while enhancing user-friendliness.The next stage will involve expanding the robot's capabilities to include automatic inspection, communication, and self-diagnostic functions. Additionally, integrating a thermal camera module will enable panel inspection, detecting any uncleaned areas by identifying cold spots beneath the glass surface, and prompting additional cleaning passes if necessary. Solar panel energy can replace individual batteries, and wireless cameras can be incorporated for seamless wireless operation. Smart Solar Panel Cleaning Robot Operated Via Bluetooth as shown in Fig 11

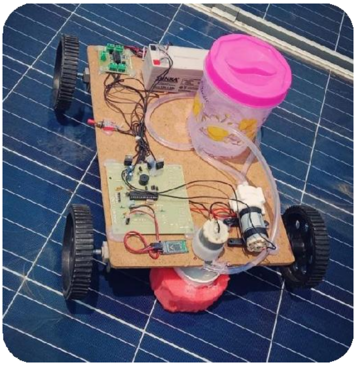


Fig. 11. Smart Solar Panel Cleaning Robot Operated Via Bluetooth

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