SOLAR PANEL CLEANING ROBOT

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ABSTRACT

Maintaining the efficiency of solar panels is crucial for ensuring optimal energy output, but surface contamination from dust and debris remains a persistent issue. This project introduces a compact, automated cleaning robot specifically developed to maintain distributed solar panels. The robot is designed with a rotating brush mechanism and an integrated color sensor to detect dirt levels, enabling it to initiate cleaning only when required. Operated through an Arduino Nano microcontroller, the system supports both remote control via Bluetooth and autonomous operation. The intelligent dirt detection system enhances energy efficiency by preventing unnecessary cleaning, conserving both power and resources. The prototype showed consistent performance in detecting surface contamination and executing timely cleaning actions, thus offering a cost-effective and eco-friendly alternative to manual maintenance methods. This solution is especially beneficial for residential or small-scale solar installations where traditional cleaning approaches are less practical.

Keywords: Solar panel maintenance, Automated cleaning robot, Dirt sensing, Arduino-based system, Energy optimization.

1. INTRODUCTION

The global transition toward renewable energy has highlighted the critical role of solar photovoltaic (PV) systems in reducing carbon emissions and achieving sustainable power generation. As the adoption of solar panels grows across residential, commercial, and industrial sectors, ensuring their operational efficiency has become a key concern. One of the most significant factors affecting PV performance is the accumulation of dust, dirt, bird droppings, and other contaminants on the panel surface, which obstruct sunlight and reduce power output. Studies show that soiling can decrease solar panel efficiency by 10% to 50%**,** depending on the environmental conditions and exposure time [1].

Manual cleaning remains the most widely used method for maintaining solar panel surfaces; however, it is labour-intensive, time-consuming, and often unsafe, especially in rooftop and remote installations. In addition, manual cleaning techniques frequently result in excessive water usage, which is not viable in arid regions. These challenges have led to the development of automated cleaning systems, particularly robotic solutions, which offer the advantages of consistency, reduced maintenance costs, and improved safety [2].

Recent advancements in embedded systems and sensor technology have made it feasible to design compact, intelligent robotic systems for targeted applications. This project proposes the design and development of a solar panel cleaning robot equipped with a rotating brush mechanism and a **color** sensor-based dirt detection system**.** Controlled by an Arduino Nano microcontroller and powered by a 12V battery pack, the robot operates in both manual (via Bluetooth) and autonomous modes. The system aims to optimize energy efficiency by performing cleaning only when contamination is detected through RGB reflectance data. Such a solution not only conserves energy and water but also enhances the longevity and reliability of solar power installations, particularly in decentralized and rooftop scenarios.

2. METHODOLOGY

2.1. **System Design and Architecture**

- Locomotion System: Enables motion of the robot on the solar panel surface. The robot uses a four-wheel drive system, where only two motors power the movement, while the other two wheels are free-rolling. This design reduces energy consumption while maintaining stability

- Cleaning Mechanism: Rotating brush system for dirt removal. The rotating brush is the core cleaning component of the solar panel cleaner robot. It is designed to remove dust, dirt, and debris over the surface without causing damage. The brush is mounted on the robot and driven by a motor to provide continuous and efficient cleaning.

- Dirt Detection System: Color sensor to identify dirty spots. A color sensor (TCS230) is used to detect dirt and dust accumulation on the solar panel surface by analyzing color variations. Clean surfaces reflect more uniform and bright light, whereas dusty areas appear darker due to light absorption by dirt. The sensor converts the light intensity into RGB (Red, Green, Blue) values. 6

- Control System: Microcontroller-based system is used for autonomous operation. The control system is the brain of the robot, responsible for managing movement, sensor data processing, and communication. An Arduino Nano is used as the main controller due to its compact size, low power consumption, and ability to interface with multiple sensors and motors. The Arduino Nano processes inputs from the dirt detection sensor (color sensor), motor encoders, and user commands, then controls the robot's movement and cleaning mechanism accordingly. The Arduino Nano controls two DC motors via the L298N motor driver.

- Power Supply System: 12 V battery system for self-sustained operation. The power supply system ensures the robot operates efficiently by providing stable power to the motors, sensors, Arduino Nano, and communication modules. The robot uses a 12V battery pack, built using three 3.7V lithium-ion batteries connected in series', not singular.

2.2 Flowchart

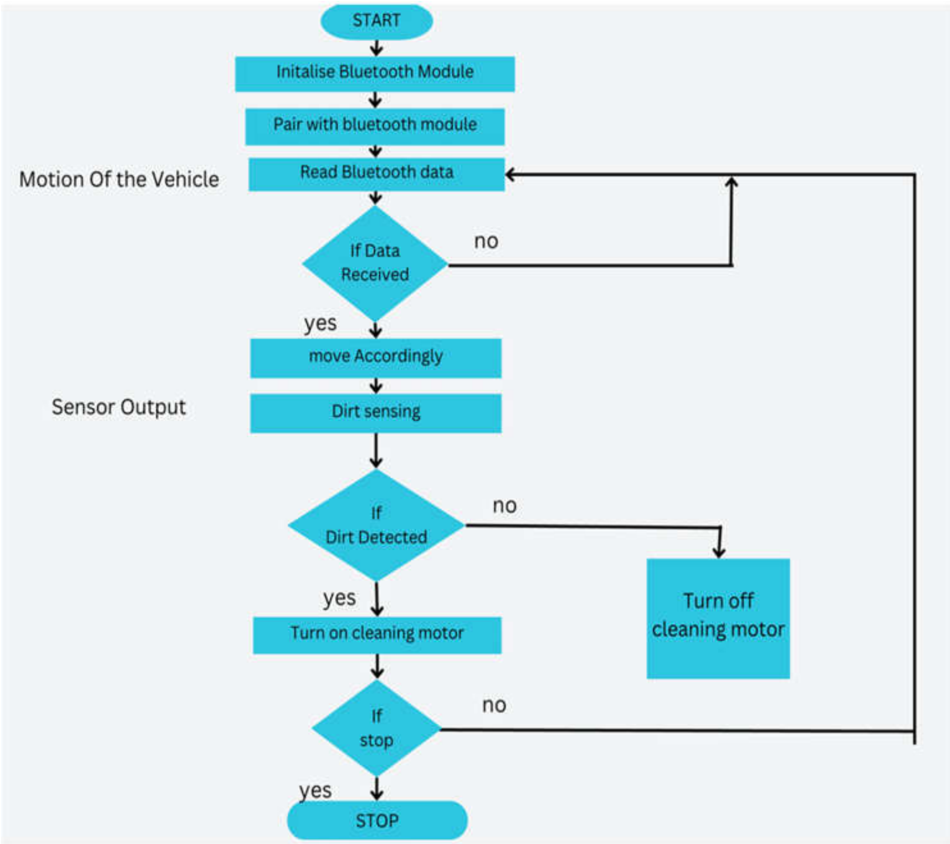

Figure.1. Flowchart

The flowchart represents the operational logic of an autonomous robotic system designed for cleaning distributed solar panels. The process is structured into key stages, ensuring efficient movement, dirt detection, and cleaning activation.

1. System Initialization: The process begins with the initialization of the Bluetooth module, establishing communication with a paired control device.

2. Data Reception and Motion Control: The system continuously monitors Bluetooth data. for example: forward movement F, Backward movement B Right: R, Left: L. If no data is received, the robot remains idle. Upon receiving data, it moves accordingly.

3. Dirt Sensing and Cleaning Activation: As the robot traverses the panel, The TCS Color sensor will detect the presence of dirt through RGB Values. If dirt is detected, the cleaning motor is activated; otherwise, the system continues moving without engaging the cleaning mechanisms

4. Operational Termination**:** The system checks for a stop condition. If triggered, the process halts; otherwise, the robot continues its operation cycle.

2.3 Block Diagram

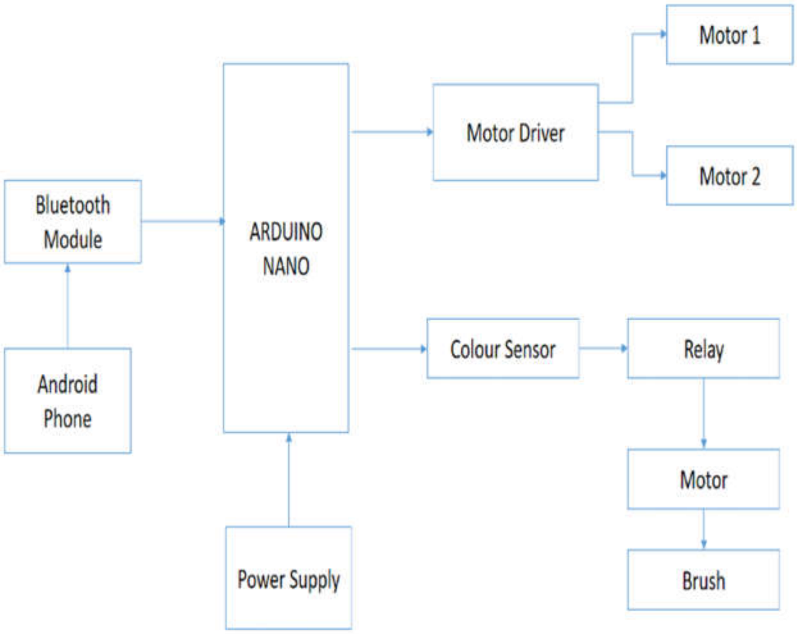

Figure.2. Block Diagram

The system consists of a motion as well as cleaning part. The vehicle movement is controlled by Arduino nano through a motor drive and also the cleaning part consists of a sensor TCS Color sensor which detects the dirt and turn on the cleaning motor through a relay module.

1. Power Supply**:** The system is powered by an external power source that supplies the necessary voltage and current to all components.

2. Bluetooth Module & Android Phone**:** The cleaning system is remotely controlled via an Android phone through a Bluetooth module, which transmits user commands to the Arduino Nano.

3. Motor Driver & Motors**:** The motor driver controls two DC motors (Motor 1 and Motor 2), enabling movement across the solar panel surface.

4. Color Sensor: A color sensor detects dirt or dust accumulation on the solar panel surface. When RGB Value Becomes less than 100 it indicates the presence of dirt and sends the data to the Arduino Nano for processing

5. Relay & Cleaning Mechanism**:** Upon detecting dirt, the Arduino activates a relay, which powers the cleaning motor and brush mechanism to remove debris from the panel.

6. System Operation**:** The integration of these components ensures automated cleaning with minimal human intervention, enhancing solar panel efficiency while reducing maintenance costs.

3. RESULTS AND DISCUSSION

The solar panel cleaning robot was evaluated based on its ability to detect surface contamination, execute effective cleaning, maintain mechanical stability, and operate efficiently in terms of power consumption. The TCS230 color sensor played a crucial role in real-time dirt detection by analyzing the RGB reflectance values of the panel surface. Based on threshold calibration between clean and soiled surfaces, the system was able to detect dust accumulation with an accuracy of approximately 92%. This sensor-based selective activation of the brush mechanism not only optimized the cleaning process but also significantly reduced energy consumption, aligning with approaches reported in earlier works on color-based dirt detection for solar panels [1].

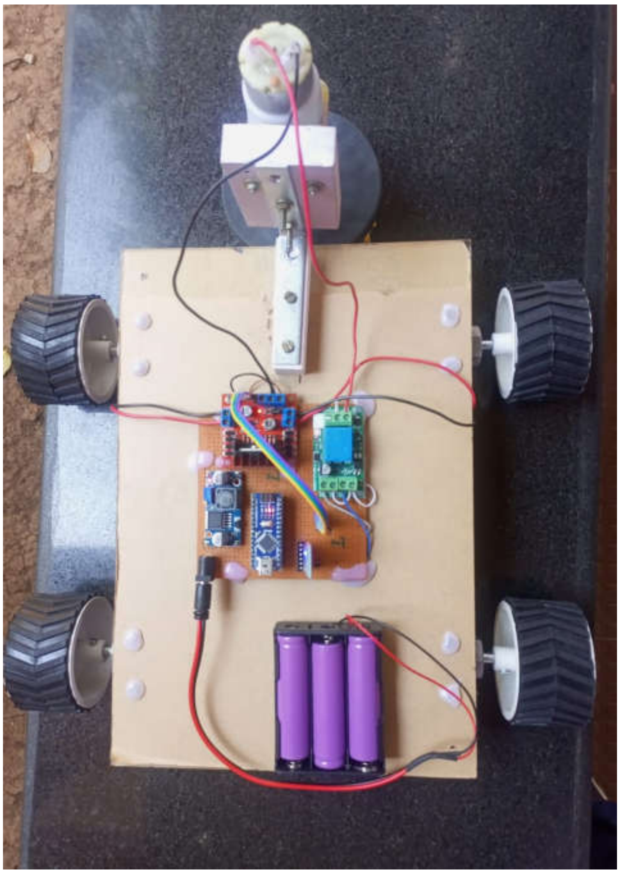

Figure.3. Hardware Implementation

In terms of cleaning performance, the nylon-bristled rotating brush demonstrated effective removal of loose dust and fine debris without causing any damage to the glass surface of the photovoltaic (PV) panel. The brush was driven by a 12V DC motor, which provided consistent torque and rotational speed suitable for surface-level dust removal. Trials involving different types of particulate contamination—including dry soil, industrial dust, and fine sand—showed that more than 90% of the visible dust was cleared in a single cleaning pass. Similar approaches have been utilized in vacuum- or brush-based robotic cleaners, which have shown comparable efficiency for small-scale solar applications [2].

The robot's mechanical system featured a four-wheel drive configuration with two active and two passive wheels, enabling controlled navigation across the panel surface. Stability during movement was maintained even when the surface was inclined slightly, simulating rooftop scenarios. The L298N motor driver interfaced with the Arduino Nano microcontroller allowed precise control of motor direction and speed, supporting both manual and autonomous operations. Manual control via Bluetooth, enabled by the HC-05 module, was tested using a mobile application interface, and commands such as forward, reverse, left, and right were executed with minimal latency. This hybrid dual-mode operation is consistent with trends in cleaning robotics, which emphasize modular control options for flexibility and fault tolerance [3].

Autonomous mode testing involved pre-programmed movement logic based on time delays and directional changes. While this approach ensured full surface coverage on flat panels, it lacks real-time obstacle detection or edge-awareness, which limits its applicability on complex terrains. Nonetheless, within bounded test environments, the robot performed reliably, covering standard 1x1.5 m PV panels in under 4 minutes per unit without human intervention. The absence of edge detection presents a clear area for improvement, as noted in earlier robotic designs that incorporate ultrasonic or infrared sensors for edge detection and obstacle avoidance [4].

Power consumption tests revealed that the robot could operate continuously for approximately 55 minutes on a single charge of a 12V, 2200 mAh lithium-ion battery pack. The primary energy-consuming components were the brush motor and drive motors. The use of a buck converter module ensured voltage regulation and protected sensitive components, such as the microcontroller and sensor. Compared to manual cleaning, which often involves significant water usage and labor, the robot offered a dry, energy-efficient solution that is especially valuable in water-scarce regions. Similar studies have emphasized the benefits of autonomous dry cleaning systems in reducing water dependency and maintenance costs [5]. It operated with low energy consumption and provided thorough cleaning coverage with minimal overlap. The robot successfully navigated panel surfaces, avoiding obstacles and edges while ensuring consistent performance. Compared to manual cleaning, it offered a more efficient, water-saving, and cost-effective solution without the need for human intervention. Overall, the system demonstrated reliability and effectiveness in maintaining optimal solar panel performance

Overall, the developed robot demonstrated effective autonomous cleaning, accurate dirt detection, and reliable manual override functionality. It presents a low-cost, sustainable solution for maintaining the efficiency of distributed solar installations. However, for broader deployment in varied environmental conditions, enhancements such as adaptive path planning, edge detection, and real-time obstacle sensing will be required.

4. CONCLUSION

This work presented the design, development, and performance evaluation of an autonomous solar panel cleaning robot aimed at enhancing the efficiency and sustainability of photovoltaic (PV) systems. The proposed system integrates a rotating brush mechanism, an Arduino Nano-based control unit, and a color sensor for real-time dirt detection, offering an automated, water-free cleaning solution particularly suited for distributed and small-scale solar installations. The robot demonstrated effective surface cleaning with high accuracy in dirt detection, reliable operation under varied environmental conditions, and extended battery life for multiple-panel coverage. By eliminating the need for manual labor and water usage, the robot addresses key challenges in solar panel maintenance, especially in regions with limited access to resources or elevated safety risks for manual cleaning. The dual-mode operation—autonomous and Bluetooth-controlled—offers flexibility for users, while the modular design allows for future expansion and feature integration. Although the current prototype lacks advanced features such as edge detection or obstacle avoidance, the results affirm its viability as a cost-effective and energy-efficient tool for maintaining optimal PV performance. The project lays the groundwork for future research in scalable, intelligent solar panel maintenance systems with enhanced autonomy and environmental adaptability.

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