

Smart IoT-Enabled Solar Panel Cleaning Robot with Scheduled and On-Demand Operation

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Abstract :

Solar energy is a key renewable energy source, but its efficiency is significantly influenced by environmental factors such as the accumulation of dust, mud, and other contaminants on solar panels. This study presents an IoT-enabled Advanced Solar Panel Cleaning Robot (SPCR) designed to automatically ensure panel cleanliness. The system operates in a scheduled manner and uses a dual-motor drive mechanism along with a roller brush for effective cleaning. By eliminating dirt and debris, the robot helps maintain optimal power generation and prevents efficiency degradation. The integration of IoT allows remote monitoring, scheduling, and real-time data analysis, which improves overall energy performance while minimizing maintenance costs and reducing reliance on manual labour. The SPCR was tested under real-world conditions and demonstrated enhanced cleaning efficiency along with improved solar energy absorption.

Keywords— Solar panel performance, IoT-enabled cleaning robot, Renewable power, Automated cleaning, Arduino-controlled system.

I. INTRODUCTION

Solar energy is one of the most important renewable energy sources, offering a sustainable replacement for traditional fossil fuels. However, the performance of solar panels is highly influenced by environmental factors such as dust, dirt, and other pollutants that accumulate on their surface. These deposits form a layer that obstructs sunlight from reaching the panel, resulting in reduced power output and overall energy generation. To address this issue, regular cleaning of solar panels is essential to ensure efficient energy production. Conventional manual cleaning methods involve several challenges, including high labour costs, safety risks, and limited efficiency, especially in large-scale solar installations.

The IoT-based Solar Panel Cleaning Robot (SPCR) is designed to overcome these challenges by providing an automated, cost-effective, and scheduled cleaning solution. The system utilizes an Arduino microcontroller, a motor-driven movement mechanism, and a roller brush to perform consistent and reliable cleaning operations. Additionally, IoT integration enables remote monitoring and automated control. This study aims to enhance solar energy efficiency while reducing maintenance effort and operational costs.

II. LITERATURE SURVEY

Several studies have explored automated solar panel cleaning systems by integrating IoT and robotic technologies to enhance overall efficiency. Kumar & Murthy (2020) developed an autonomous cleaning robot that uses air blowing and liquid spraying techniques controlled through IoT, which reduced manual intervention and improved energy output. Singarapu et al. (2023) introduced a cost-effective IoT-based cleaning system and reported an approximate 32% increase in power generation due to regular scheduled cleaning. Similarly, Bedge

et al. (2022) designed an Arduino-based automatic cleaning robot integrated with dust density sensors, enabling optimized cleaning schedules and minimizing energy loss caused by dust accumulation.

Further research highlights the effectiveness of automation in maintaining solar panels. Gochhait et al. (2022) analysed robotic cleaning systems and observed an efficiency improvement ranging from 1.6% to 2.2% compared to traditional manual methods. Kumar (2022) developed a Bluetooth-controlled cleaning robot that enhanced photovoltaic performance while lowering operational costs. Khairul & Rahman (2021) emphasized the environmental benefits of automated cleaning, such as reduced water usage and minimal chemical discharge. Additionally, Zhao et al. (2023) explored the use of self-cleaning coatings and hydrophobic surfaces to prevent dust adhesion, contributing to better maintenance of solar panels.

Overall, these studies support the implementation of IoT-based automated cleaning systems as an effective approach to improving solar energy efficiency and sustainability.

III. Aim & Objectives

The aim of this study is to develop an IoT-enabled solar panel cleaning robot that improves panel efficiency through regular and effective cleaning. The key objectives of the research are:

- To design an autonomous solar panel cleaning system integrated with IoT-based scheduling.
- To enhance solar power generation by maintaining a clean panel surface.
- To reduce human effort and decrease maintenance costs in solar power systems.
- To enable real-time monitoring and control using a cloud-based IoT platform.
- To increase operational safety by eliminating the need for manual panel cleaning.

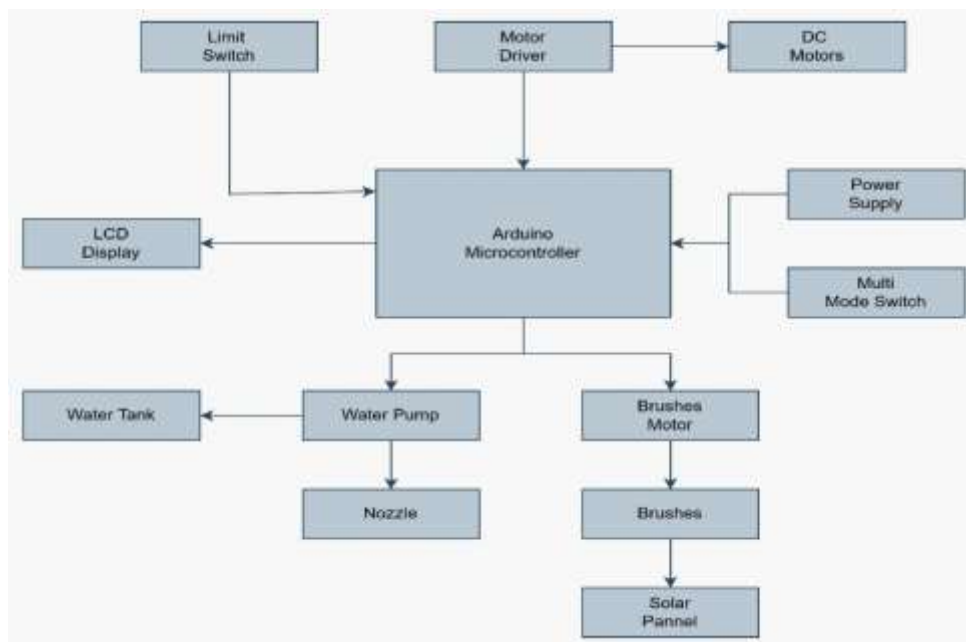


Figure 1: Block Diagram

The First Phase : Data Collection and Processing

- Sensors detect dust accumulation and environmental factors affecting the efficiency of the solar panels.
- The Arduino microcontroller processes real-time sensor data and activates the cleaning mechanism when required.
- The system follows a preset schedule while also permitting manual control through IoT access.

The Second Phase : Cleaning Mechanism and Navigation

- The SPCR is equipped with a dual-motor drive system combined with a roller brush setup for effective panel cleaning.
- It includes a water spraying mechanism along with a rotating brush to efficiently eliminate dust and debris.
- Limit switches are used to detect the boundaries of the panel array, ensuring precise movement within the specified area

The Final Phase : IoT-Based Monitoring and Automation

- A cloud-integrated IoT platform enables remote monitoring and scheduling of cleaning activities.
- Users can access real-time system performance data through a mobile application or web-based dashboard.
- Alerts and maintenance logs are generated to assist in early fault identification and continuous system enhancement.

V.PROJECT REQUIREMENTS:

Hardware Components:

A. *Microcontroller*

The Arduino microcontroller acts as the central control unit of the system, managing and coordinating all connected components by executing programmed instructions. It is responsible for controlling motor operations, processing sensor inputs, and regulating the cleaning mechanism. Using PWM (Pulse Width Modulation), it controls the speed of the motors and communicates with various modules through its input and output pins. Additionally, it enables cloud connectivity through IoT modules, allowing remote monitoring and control of the system.

B. *Motor Driver Circuit*

The motor driver circuit serves as an interface between the Arduino and the motors, ensuring proper power control and regulation. It controls the speed, direction of rotation, and torque of the motors using H-Bridge circuits or driver ICs like L298N. By supplying a stable voltage and current, it safeguards the motors from potential damage while enabling both forward and reverse motion for precise movement.

C. *Motors and Wheels Assembly*

The movement of the SPCR is carried out using DC or stepper motors attached to rubber or silicone-coated wheels, ensuring a firm grip on the solar panel surface. Geared motors provide the required torque for smooth operation, especially on inclined panels. Additionally, encoders can be integrated to track movement and enhance navigation accuracy.

D. *Sensor Subsystem*

The sensor unit is composed of multiple sensors to ensure efficient system operation. Optical or infrared sensors are used to detect dust accumulation on the panel surface, while environmental sensors measure factors such as temperature, humidity, and light intensity to determine appropriate cleaning intervals. Proximity sensors help prevent collisions and identify panel edges, and positioning sensors assist in tracking the robot's movement to ensure complete coverage. Additionally, a water level sensor monitors the availability of cleaning fluid.

E. *Cleaning Mechanism*

The cleaning unit consists of a rotating roller brush that effectively removes dust and debris from the panel surface. A water spraying system is included to apply water or a cleaning solution, helping to loosen and wash away dirt particles. Additionally, a wiper or squeegee ensures the panel surface is left clean and dry after the process. Actuators may also be used to control the pressure applied by the brush, allowing efficient cleaning without causing any damage to the panels.

Software Components:

Arduino IDE:

It is an open-source development platform used for writing, compiling, and uploading programs to the Arduino microcontroller. The environment is based on C/C++ and provides a user-friendly interface for integrating sensors and processing data. It also includes built-in libraries that support communication protocols such as I2C, SPI, and UART, ensuring seamless interaction with sensors and other external components.

Cloud Server:

The cloud server gathers and processes data transmitted by the robot, including environmental parameters and cleaning activity records. It enables remote monitoring of system performance and facilitates predictive maintenance by analyzing sensor data to detect potential issues at an early stage.

IoT Integration:

IoT connectivity allows real-time monitoring and scheduling of cleaning operations through a web-based or mobile interface. By utilizing Wi-Fi or cellular modules such as ESP8266 or SIM800, the system can function based on environmental conditions like weather and dust levels, thereby enhancing automation and improving overall user control.

Data Encryption Protocols :

To ensure secure communication, encryption techniques such as AES (Advanced Encryption Standard) and TLS (Transport Layer Security) are implemented. These methods help protect system data from unauthorized access and reduce the risk of cyber threats.

VI. RESULT AND DISCUSSION

The SPCR was tested under real-world conditions on solar panels affected by dust and debris accumulation. The system successfully maintained panel cleanliness, resulting in a power output improvement of up to 30% compared to uncleaned panels. The use of IoT-based scheduling allowed cleaning operations to be optimized based on actual dust levels, reducing unnecessary water usage and extending the system's operational life. Automation eliminated the need for manual labor, making maintenance more cost-effective and sustainable. Future improvements may include AI-based prediction for cleaning cycles, enhanced mobility for different panel configurations, and integration with weather forecasting systems to further optimize performance.

The system also demonstrated consistent and stable performance during continuous operation without significant mechanical or electrical issues. Sensors accurately detected environmental changes and ensured timely activation of the cleaning mechanism. The navigation system effectively covered the entire panel surface, avoiding missed or uncleaned areas. Overall, the prototype proved to be reliable and suitable for practical implementation in small to medium-scale solar installations.

In addition, the system offers scalability and adaptability for larger solar farms with minimal modifications. Its modular design allows easy integration of advanced features such as improved sensors and control algorithms. The use of IoT further enhances system monitoring, making it easier to track performance over time. This adaptability makes the SPCR a promising solution for future smart energy management systems.



Fig 2: Cleaning Robot

VII.CONCLUSION

The IoT-based Advanced Solar Panel Cleaning Robot provides an effective and intelligent solution for maintaining solar panel efficiency through automated cleaning operations. By integrating IoT technology, the system enables real-time monitoring, remote control, and scheduled cleaning, which helps reduce energy losses caused by dust and debris accumulation while also lowering labor and maintenance costs. The automation not only improves operational efficiency but also enhances safety by minimizing the need for manual intervention. Furthermore, the system is designed to be scalable and adaptable, making it suitable for deployment in both small installations and large-scale solar farms. Its ability to optimize cleaning based on environmental conditions contributes to better resource utilization, including reduced water consumption and extended panel lifespan. With continuous technological advancements, the system has strong potential to significantly improve overall energy production and support sustainable and smart energy management practices.

Future developments will focus on integrating AI-based decision-making for predictive cleaning, implementing adaptive cleaning strategies based on real-time environmental analysis, and enhancing autonomous navigation to efficiently handle complex and irregular solar panel layouts. These improvements will further increase the reliability, efficiency, and practicality of the system in modern renewable energy infrastructures.

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