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**International Journal on Advanced Computer Engineering and Communication Technology**

ISSN: 2278-5140
Volume 14 Issue 01, 2025

# Advanced Solar Panel Cleaning Robot with IoT-Based Automation

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**Peer Review Information**

*Submission: 05 Feb 2025*
*Revision: 17 Mar 2025*
*Acceptance: 18 April 2025*

**Keywords**

*Solar Panel Efficiency*
*IoT-Based Cleaning Robot*
*Renewable Energy*

**Abstract**

Solar energy, which is one of the renewable energy sources, has an important role in meeting the increasing electrical energy demand of our globe. In recent years, many countries have established their energy policies based on solar energy, and researchers have been working on solar panel efficiency, maximum energy extraction from the sun, control and power electronics. The energy extracting from the sun is converted into electrical energy via solar panels. To extract continuously maximum energy level from the sun reduces installation costs and makes it easier to meet the demanded peak electrical power. Physical conditions such as muddy rain, snow and dusting place between the solar panel and the sun. This situation results the reduced electrical power extraction level which can be technically produced with clean solar panel surface. Therefore, it is also very important to keep the solar panels clean as well as the maximum power point tracking devices. In this study, a solar panel cleaning robot (SPCR) has been designed and tested in real time. The designed dual-motor and crawler robot moves horizontally and the cleaning brush runs on the vertical axis. In addition, the length of the solar panel array can be detected by position switches to keep the SPCR in desired working area.

## INTRODUCTION

Solar energy is a crucial renewable energy source, offering a sustainable alternative to fossil fuels. However, solar panels' efficiency can be significantly reduced due to the accumulation of dust, dirt, and other environmental contaminants, forming a barrier between the panel surface and sunlight. This obstruction results in lower power output, ultimately affecting overall energy generation.

To mitigate this issue, regular cleaning of solar panels is essential to ensure optimal energy production. Manual cleaning methods pose challenges such as labor costs, safety risks, and inefficiency in large-scale installations. The IoT-based Solar Panel Cleaning Robot (SPCR) addresses these limitations by offering an autonomous, cost-effective, and scheduled cleaning mechanism. Equipped with an Arduino microcontroller, motor-driven navigation, and a roller brush system, the SPCR ensures continuous and efficient panel cleaning while integrating IoT functionalities for remote monitoring and automation. The research aims to enhance energy extraction efficiency while reducing maintenance efforts and costs

## Literature Survey

Several studies have explored automated cleaning solutions for solar panels, integrating IoT and robotics to enhance efficiency. Kumar & Murthy (2020) developed an autonomous cleaning robot with air blowing and liquid spraying mechanisms controlled via IoT, reducing manual intervention and increasing energy efficiency. Singarapu et al. (2023) introduced a cost-effective IoT-integrated solar panel cleaning system, achieving a 32% power output improvement through scheduled cleaning operations. Bedge et al. (2022) designed an Arduino-based automatic cleaning robot with dust density sensors, optimizing cleaning intervals and reducing energy losses caused by dust accumulation.

Other studies highlight the advantages of automation in solar maintenance. Gochhait et al. (2022) analyzed the impact of robotic cleaning systems on energy efficiency, demonstrating a 1.6% to 2.2% improvement over manual cleaning. Kumar (2022) proposed a Bluetooth-controlled solar panel cleaning robot, showcasing its ability to enhance PV panel efficiency while minimizing operational costs. Khairul & Rahman (2021) emphasized the environmental benefits of automated cleaning systems, highlighting water conservation and reduced chemical runoff. Zhao et al. (2023) explored self-cleaning coatings and hydrophobic surfaces to minimize dirt adhesion, further enhancing solar panel maintenance strategies. These studies support the development of IoT-driven autonomous cleaning solutions to improve solar energy generation.

## AIM & OBJECTIVES

The aim of this study is to develop an IoT-enabled solar panel cleaning robot that improves panel efficiency by ensuring regular and effective cleaning. The objectives include:

- Designing an autonomous solar panel cleaning system using IoT-based scheduling.
- Increasing solar energy efficiency by maintaining clean panel surfaces.
- Reducing labor dependency and operational costs for solar farm maintenance.
- Ensuring real-time monitoring and control using a cloud-based IoT interface.
- Enhancing safety by eliminating the need for manual panel cleaning.

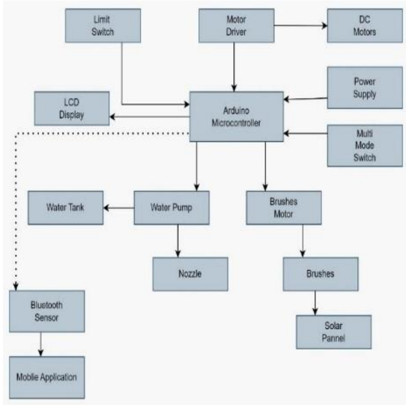


*Fig 1: Block Diagram*

The First Phase: Data Collection and Processing

- Sensors detect dust accumulation and environmental conditions affecting panel performance.
- The Arduino microcontroller processes real-time sensor data and activates the cleaning mechanism when required.
- The system operates on a predefined schedule while allowing manual intervention through IoT control.

The Second Phase: Cleaning Mechanism and Navigation

- The SPCR utilizes a dual-motor and roller brush system for panel cleaning.
- The cleaning mechanism includes a water sprayer and rotating brush to remove dust and grime effectively.
- Position switches detect the panel array length, ensuring precise navigation within the designated area.

The Final Phase: IoT-Based Monitoring and Automation

- A cloud-based IoT system enables remote monitoring and scheduling of cleaning cycles.
- Users can access real-time performance data via a mobile application or web dashboard.
- Alerts and maintenance logs are generated for proactive troubleshooting and system optimization.

## Project Requirements

### Hardware Components:

A. Arduino Microcontroller

The Arduino microcontroller serves as the central processing unit, coordinating all components by executing programmed logic. It controls motor movement, processes sensor data, and manages the cleaning mechanism. Using PWM (Pulse Width Modulation), it regulates motor speed and communicates with various components through input and output pins. Additionally, it enables cloud connectivity via IoT modules for remote monitoring and control.

B. Motor Driver Circuit

The motor driver circuit acts as an interface between the Arduino and motors, ensuring stable power distribution. It controls motor speed, direction, and torque using H-Bridge circuits or dedicated driver ICs like L298N. By supplying stable voltage and current, it prevents motor damage while supporting bidirectional movement for precise navigation.

C. Motors and Wheels Assembly

The movement of the SPCR is facilitated by DC or stepper motors, which are coupled with rubber or silicone-coated wheels for proper traction on solar panels. Geared motors provide the necessary torque for smooth operation on inclined surfaces, while encoders may be integrated to track movement and enhance navigation accuracy.

D. Sensor Subsystem

The sensor subsystem is equipped with multiple sensors for efficient operation. Optical or infrared sensors detect dust accumulation, while environmental sensors measure temperature, humidity, and light intensity to optimize cleaning schedules. Proximity sensors prevent collisions and detect panel edges, while positioning sensors track the robot's location for efficient coverage. A water level sensor ensures sufficient availability of cleaning fluid.

E. Cleaning Mechanism

The cleaning mechanism consists of a rotating roller brush that dislodges dust and dirt from the solar panel surface. A water spray system dispenses water or cleaning fluid to enhance debris removal, while a wiper or squeegee ensures the panels are left dry and streak-free. Actuators may be used to adjust brush pressure, ensuring optimal cleaning performance without causing damage to the panels.

*Software Components:*

Arduino IDE: An open-source integrated development environment (IDE) used for writing, compiling, and uploading code to the Arduino microcontroller. It supports the C/C++ programming language, providing a user-friendly interface for sensor integration and data processing. The IDE includes built-in libraries for communication protocols such as I2C, SPI, and UART, allowing seamless interaction between sensors and peripheral devices.

**Cloud Server:**

The cloud server stores and processes data collected from the robot, including cleaning logs and environmental readings. It enables remote access to system performance and supports predictive maintenance by analyzing sensor trends and failure patterns.

**IoT Integration:**

IoT integration allows real-time monitoring and scheduling of cleaning operations through a web-based or mobile interface. Using Wi-Fi or cellular modules like ESP8266 or SIM800, the system can operate efficiently based on weather conditions and dust levels, enhancing automation and user control.

**Data Encryption Protocols:**

To ensure secure data transmission, encryption protocols such as AES (Advanced Encryption Standard) and TLS (Transport Layer Security) are implemented. These measures prevent unauthorized access and protect system data from potential cyber threats

**Result And Discussion**

The SPCR was tested in real-time conditions on solar panels affected by dust and debris accumulation. The system successfully maintained panel cleanliness, resulting in an increased power output of up to 30% compared to uncleaned panels. IoT-based scheduling allowed optimized cleaning cycles based on real-time dust accumulation, reducing unnecessary water usage and extending system longevity. The automated system eliminated the need for manual labor, making solar farm maintenance more cost-effective and sustainable. Future improvements may include AI-driven cleaning predictions, enhanced mobility for different panel configurations, and integration with weather forecasting systems to optimize cleaning schedules further.

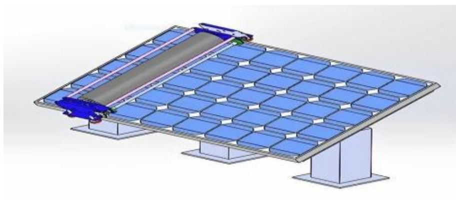

*Fig 2: Cleaning Robot*

**Conclusion**

The IoT-based Advanced Solar Panel Cleaning Robot provides an effective solution to maintaining solar panel efficiency by automating the cleaning process. The integration of IoT enables real-time monitoring and scheduling, reducing energy losses caused by dirt accumulation while minimizing labour costs. With continued advancements, the system can be expanded for larger solar farms, improving overall energy production and supporting sustainable energy initiatives. Future research will focus on AI-based decision-making, adaptive cleaning techniques, and enhanced autonomous navigation for complex solar installations.

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