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

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Abstract :

Solar energy is an important renewable power source; however, its performance is greatly affected by environmental conditions such as the buildup of dust, mud, and other debris on solar panels. This research introduces an IoT-based Advanced Solar Panel Cleaning Robot (SPCR) developed to automatically maintain panel cleanliness. The robot works in a scheduled mode and moves using a dual-motor drive system combined with a roller brush mechanism to perform efficient cleaning. By removing dirt deposits, the system helps in maintaining maximum power output and avoids efficiency loss. The IoT integration enables remote monitoring, scheduling, and real-time data tracking, thereby enhancing energy efficiency and reducing maintenance expenses and dependence on manual labor. The SPCR was evaluated in real-time conditions and showed better solar energy absorption along with improved cleaning effectiveness.

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

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I. INTRODUCTION

Solar energy is an essential renewable power source that provides a sustainable alternative to conventional fossil fuels. However, the efficiency of solar panels can be greatly affected by the accumulation of dust, dirt, and other environmental pollutants, which create a layer between the panel surface and incoming sunlight. This blockage decreases the power output and negatively impacts the total energy generation.

To overcome this problem, periodic cleaning of solar panels is necessary to maintain proper energy production. Manual cleaning methods create difficulties such as high labour expenses, safety concerns, and low effectiveness in large-scale installations. The IoT-based Solar Panel Cleaning

Robot (SPCR) solves these issues by providing an automatic, economical, and scheduled cleaning system. Using an Arduino microcontroller, motor-based movement, and a roller brush mechanism, the SPCR performs continuous and reliable cleaning while also incorporating IoT features for remote monitoring and automation. The study focuses on improving energy harvesting efficiency while minimizing maintenance effort and cost.

II. LITERATURE SURVEY

Various research works have investigated automated cleaning approaches for solar panels by combining IoT technology and robotics to improve system performance. Kumar & Murthy (2020) created an autonomous cleaning robot using air blowing and liquid spraying methods operated through IoT, which lowered manual effort and enhanced energy efficiency. Singarapu et al. (2023) proposed a low-cost IoT-based solar panel cleaning system and reported a 32% increase in power output through scheduled cleaning activities. Bedge et al. (2022) developed an Arduino-based automatic cleaning robot equipped with dust density sensors, allowing optimized cleaning timing and reducing energy loss due to dust buildup.

Additional studies demonstrate the benefits of automation in solar panel maintenance. Gochhait et al. (2022) examined robotic cleaning systems and observed a 1.6% to 2.2% efficiency improvement compared to manual cleaning methods. Kumar (2022) designed a Bluetooth-operated solar panel cleaning robot that improved photovoltaic panel performance while decreasing operating expenses. Khairul & Rahman (2021) discussed the environmental advantages of automated cleaning, including water savings and less chemical discharge. Zhao et al. (2023) investigated self-cleaning coatings and hydrophobic surfaces to reduce dirt adhesion, thereby supporting improved solar panel upkeep. These findings encourage the adoption of IoT-based autonomous cleaning systems to enhance solar energy production.

III. Aim & Objectives

The purpose of this research is to design an IoT-enabled solar panel cleaning robot that enhances panel performance by providing consistent and efficient cleaning. The objectives are:

- Developing an autonomous solar panel cleaning system with IoT-based scheduling.
- Improving solar energy output by keeping the panel surface clean.
- Minimizing labour involvement and lowering maintenance expenses in solar installations.
- Providing real-time monitoring and control through a cloud-supported IoT platform.
- Improving safety by removing the need for manual cleaning of panels.

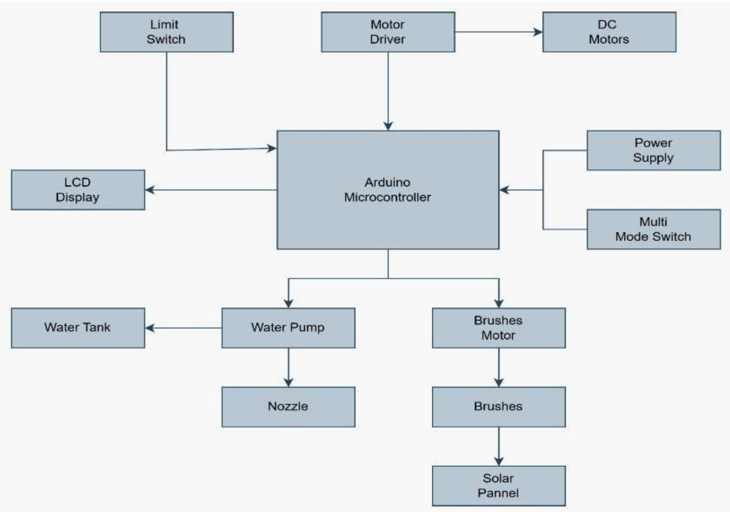

Figure 1: Block Diagram

The First Phase : Data Collection and Processing

- Sensors identify dust buildup and surrounding conditions that influence panel efficiency.
- The Arduino microcontroller analyses real-time sensor readings and triggers the cleaning system when necessary.
- The system follows a preset schedule while also permitting manual control through IoT access.

The Second Phase : Cleaning Mechanism and Navigation

- The SPCR uses a dual-motor drive along with a roller brush arrangement for cleaning the panels.
- The mechanism incorporates a water spraying unit and a rotating brush to effectively remove dust and dirt.
- Limit switches sense the length of the panel array to ensure accurate movement within the defined area.

The Final Phase : IoT-Based Monitoring and Automation

- A cloud-connected IoT platform allows remote observation and scheduling of cleaning operations.
- Users can view real-time performance information through a mobile app or web dashboard.
- Notifications and maintenance records are created to support early fault detection and system improvement.

V.PROJECT REQUIREMENTS:

Hardware Components:

A. *Arduino Microcontroller*

The Arduino microcontroller functions as the main control unit, coordinating all connected components by running the programmed instructions. It manages motor operation, reads sensor inputs, and controls the cleaning system. Through PWM (Pulse Width Modulation), it adjusts motor speed and communicates with different modules using input and output pins. It also supports cloud connectivity using IoT modules for remote access and control.

B. *Motor Driver Circuit*

The motor driver circuit works as an interface between the Arduino and the motors, providing proper power regulation. It manages motor speed, rotation direction, and torque using H-Bridge circuits or driver ICs such as L298N. By delivering stable voltage and current, it protects the motors from damage and enables forward and reverse movement for accurate navigation.

C. *Motors and Wheels Assembly*

The SPCR's motion is achieved using DC or stepper motors connected to rubber or silicone-coated wheels for better grip on the solar panel surface. Geared motors supply sufficient torque for smooth movement on inclined panels, and encoders can be added to monitor motion and improve navigation precision.

D. *Sensor Subsystem*

The sensor unit contains multiple sensors for effective functioning. Optical or infrared sensors identify dust accumulation, while environmental sensors monitor temperature, humidity, and light intensity to determine suitable cleaning intervals. Proximity sensors avoid collisions and detect panel edges, and positioning sensors help track the robot's movement for proper coverage. A water level sensor confirms the availability of cleaning liquid.

E. *Cleaning Mechanism*

The cleaning unit includes a rotating roller brush that removes dust and particles from the panel surface. A water spraying arrangement releases water or cleaning solution to assist debris removal, while a wiper or squeegee leaves the panel clean and dry. Actuators can also regulate brush pressure to ensure efficient cleaning without damaging the panels.

Software Components:

Arduino IDE:

An open-source development environment used to write, compile, and upload programs to the Arduino microcontroller. It uses the C/C++ language and offers a simple interface for integrating sensors and handling data. The IDE also provides built-in libraries for communication methods like I2C, SPI, and UART, enabling smooth interaction with sensors and external devices.

Cloud Server:
The cloud server collects and processes information sent by the robot, including environmental readings and cleaning records. It allows remote monitoring of system performance and supports predictive maintenance by evaluating sensor data and identifying possible faults.

IoT Integration:
IoT connectivity enables real-time observation and scheduling of cleaning tasks through a web or mobile interface. By using Wi-Fi or cellular modules such as ESP8266 or SIM800, the system can operate based on weather conditions and dust presence, improving automation and user management.

Data Encryption Protocols :
For secure communication, encryption methods like AES (Advanced Encryption Standard) and TLS (Transport Layer Security) are applied. These techniques prevent unauthorized access and safeguard system information from cyber risks.

VI. RESULT AND DISCUSSION

The SPCR was evaluated under real-time conditions on solar panels covered with dust and debris. The system effectively preserved panel cleanliness, leading to a power output increase of up to 30% when compared with uncleaned panels. IoT-based scheduling enabled optimized cleaning intervals according to actual dust accumulation, which minimized unnecessary water consumption and improved the overall lifespan of the system. The automated operation removed the requirement for manual labour, making solar plant maintenance more economical and sustainable. Future enhancements can include AI-based cleaning prediction, improved movement capability for various panel layouts, and integration with weather forecasting systems to further refine cleaning schedules. Additionally, the system showed stable performance during continuous operation without major mechanical or electrical failures. The sensors responded accurately to varying environmental conditions and ensured timely activation of the cleaning process. The navigation mechanism covered the panel area properly, preventing untreated sections. Overall, the prototype demonstrated reliable operation and practical suitability for small and medium-scale solar installations.

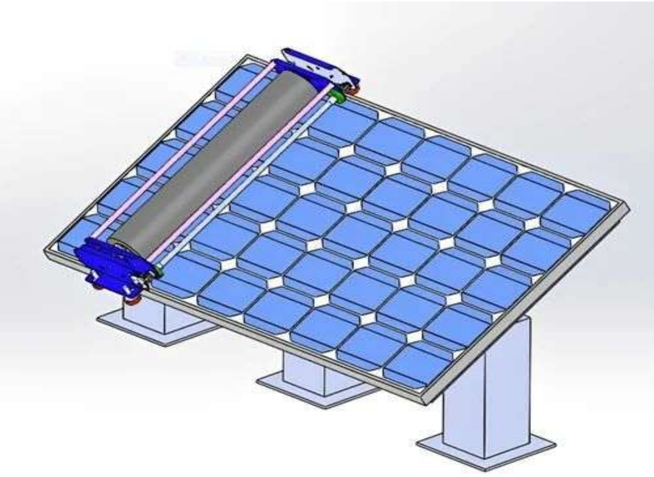

Fig 2: Cleaning Robot

VII.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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