



DESIGN AND IMPLEMENTATION OF AUTOMATIC SOLAR PANEL CLEANING SYSTEM WITH IOT INTEGRATION

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Abstract:

This project presents the design and development of an automated solar panel cleaning system integrated with IoT-based monitoring for real-time performance evaluation. The study demonstrates that dust accumulation can significantly reduce the voltage output of solar panels, resulting in an efficiency reduction of approximately 10–30%. Experimental results indicate that following the cleaning process, the panel voltage is restored to nearly 99–100% of its efficiency, highlighting the immediate benefits of effective dust removal. Solar irradiance measurements recorded at 10-minute intervals showed that the panel voltage falls below the predefined threshold only once during the day. This enables the system to perform cleaning approximately 1–2 times per day, thereby minimizing power consumption and mechanical wear. The proposed cleaning mechanism effectively removes dust, bird droppings, and other surface contaminants while helping to prevent thermal hotspots. Consequently, it improves energy generation, contributes to longer panel lifespan, and reduces maintenance requirements. The proposed automated solution enhances the reliability and operational efficiency of solar power systems, making it suitable for long-term and large-scale applications.

1. INTRODUCTION

In recent years, solar panels have emerged as a preferred source of power in various sectors, including electricity generation, agriculture, and industrial applications, thereby reducing



dependence on conventional generators and traditional energy systems. Solar panels play an important role by converting solar radiation into usable thermal or electrical energy according to the intended application. However, in regions with high levels of dust concentration, the performance of solar panels is significantly affected by dust accumulation on their surfaces, which reduces the transmittance of the glass covering. This problem is particularly evident in solar desalination plants located in Middle Eastern countries such as Abu Dhabi, where dust deposition can considerably reduce system efficiency. Although modifying the tilt angle of solar panels can help minimize dust accumulation by changing their exposure to sunlight, this approach cannot completely eliminate the problem. Therefore, regular cleaning is necessary; however, conventional cleaning methods are time-consuming, labor-intensive, and costly, particularly when frequent cleaning is required. To address these challenges, this study proposes an innovative automated solar panel cleaning system that aims to maintain panel efficiency while minimizing manual effort and operating costs. Various techniques are commonly employed for cleaning solar panels, including mechanical vibration, ultrasonic cleaning, scrubbing, and mopping. Among these, brushing is one of the widely used methods, in which a brush or scrubber is moved across the panel surface using a mechanism similar to automobile windshield wipers. However, this method may not effectively remove fine or strongly adhered dust particles. Furthermore, the harsh environmental conditions encountered at solar farms can increase the challenges associated with maintaining cleaning equipment. Since solar installations generally cover large areas, the use of such cleaning methods can become expensive and less efficient. Air-blowing methods can also be utilized for dust removal; however, they have certain limitations, including relatively low cleaning effectiveness, high energy consumption, and complex maintenance requirements associated with blower systems. Mechanical cleaning approaches also include techniques such as ultrasonic cleaning and vibration-based dust removal. These methods depend on parameters such as vibration frequency, vibration amplitude, and the type of actuation mechanism employed. Williams R. Brett demonstrated the application of piezoelectric and piezoceramic actuators for developing a self-cleaning solar panel system based on controlled vibrations. Such systems utilize vibration principles to detach and remove dust particles accumulated on the panel surface. Several environmental parameters, including wind speed, humidity, ambient temperature, solar radiation intensity, atmospheric dust concentration, and wind direction, have a significant influence on the power output of photovoltaic modules. Dust accumulation on the panel surface is a major concern, particularly in desert regions where occasional or frequent dust storms can occur. When dust particles settle on the glass surface, the transmittance of the cover is reduced, allowing less solar radiation to reach the photovoltaic cells and consequently decreasing electrical power generation. The magnitude of this reduction depends on several factors, including dust density on the surface, panel orientation, tilt angle, exposure duration, prevailing wind direction, and climatic conditions at the installation site. In addition, the physical characteristics of dust, such as particle size distribution, composition, and mass density, play an important role in determining its impact on module power generation and current–voltage (I–V) characteristics. When photovoltaic modules



operate outdoors for extended periods, their performance gradually decreases due to continuous dust accumulation unless the deposited dust is removed naturally by rainfall or through manual cleaning. Studies have reported that the power output of solar panels can decrease by more than 50% when they remain uncleaned for a period exceeding six months. The extent of performance degradation is affected not only by the duration of dust exposure but also by the frequency and intensity of dust events. Therefore, regular cleaning of PV modules, at least once every two weeks, is recommended to maintain their performance under normal operating conditions. During periods of sandstorms or significant dust accumulation, immediate cleaning may be required to minimize power losses. Although rainfall can temporarily improve the performance of dust-covered panels, it cannot be considered a reliable cleaning method because its occurrence is irregular and unpredictable.

2. LITERATURE SURVEY

1. Ghafoor et al. [1] (2024) - Ghafoor et al. presented an IoT-based solar array cleaning system aimed at improving the performance and efficiency of photovoltaic panels. The system integrates automated cleaning with monitoring capabilities, allowing the operating condition of the solar array to be observed more effectively. Their work demonstrates the potential of IoT technology for improving solar-panel maintenance and reducing the impact of dust accumulation on energy generation.
2. Prastomo and Budiman [2] (2023) - Prastomo and Budiman developed an automatic dust cleaning system using a wiper and sprinkler mechanism for solar panels. The proposed approach combines mechanical wiping with water spraying to remove dust deposited on the panel surface. Their study demonstrates that an automated cleaning mechanism can reduce the need for manual maintenance and help maintain the operating performance of solar panels.
3. Dahlioui et al. [3] (2023) - Dahlioui et al. investigated a waterless cleaning technique for photovoltaic panels installed on a dual-axis tracker. The study focused on removing accumulated dust without relying on water, which is particularly beneficial in regions where water availability is limited. Their work highlights the importance of water-free cleaning approaches for improving the sustainability and maintenance of PV systems.
4. Olorunfemi et al. [4] (2023) - Olorunfemi et al. proposed an Arduino-based approach for detecting and removing dirt from solar panel surfaces using color recognition. The system identifies surface contamination and supports automated removal based on the detected condition. This work demonstrates the application of low-cost embedded systems for intelligent detection and cleaning of solar panels.
5. Gochhait et al. [5] (2022) - Gochhait et al. studied the application of IoT in automated solar panel cleaning systems. Their work explored the use of IoT technology to improve automation and monitoring during the cleaning process. The study emphasizes that connected monitoring and



automated operation can reduce human intervention and support more effective solar-panel maintenance.

6. Gupta et al. [6] (2022) - Gupta et al. investigated the performance enhancement of solar photovoltaic systems using a waterless cleaning system. Their study examined the effect of cleaning on PV performance and demonstrated the importance of removing accumulated contaminants from the panel surface. The research supports the use of waterless cleaning techniques as an alternative for maintaining PV efficiency while reducing water consumption.

7. Habib et al. [7] (2021) - Habib et al. developed an Arduino-based automatic solar panel cleaning system for dust removal. The proposed system automates the cleaning operation to reduce the effect of dust accumulation on the panel. Their work demonstrates the feasibility of using an Arduino-controlled mechanism for automatic dust removal and improving the operational performance of solar panels.

8. Roy et al. [8] (2021) - Roy et al. proposed a programmable logic controller (PLC)-based robust automatic solar-panel cleaning system for efficiency improvement. The use of PLC technology provides controlled and automated operation of the cleaning mechanism. Their study highlights the suitability of industrial control technology for developing reliable automated cleaning systems for photovoltaic installations.

Table 1 A Comprehensive Review

Ref.	Authors	Year	Research Focus / Method	Key Contribution / Findings
[1]	Ghafoor, M., Amin, A. A., & Khalid, M. S.	2024	IoT-based solar array cleaning system	Developed an IoT-enabled cleaning system for solar arrays to improve panel performance and efficiency through automated cleaning and monitoring.
[2]	Prastomo, N., & Budiman, W.	2023	Wiper and sprinkler-based cleaning	Proposed an automatic cleaning system combining a wiper and sprinkler to remove dust from solar panels and reduce manual maintenance.
[3]	Dahlioui, D., Alaoui, S. M., Laarabi, B., & Barhdadi, A.	2023	Waterless cleaning for dual-axis PV trackers	Investigated a water-free cleaning technique for photovoltaic panels, providing a suitable approach for locations where water availability is limited.
[4]	Olorunfemi, B. O., Nwulu, N. I., & Ogbolumani, O. A.	2023	Arduino-based dirt detection and removal	Developed a system using Arduino and color recognition to detect surface dirt and support automated solar-panel cleaning.
[5]	Gochhait, S., Asodiya, R., Hasarmani, T., Patin, V., & Maslova, O.	2022	IoT-based automated cleaning	Studied the application of IoT technology in automated solar-panel cleaning, emphasizing remote monitoring and reduced human intervention.



[6]	Gupta, V., Sharma, M., Pachauri, R., & Babu, K. D.	2022	Waterless cleaning system	Investigated waterless cleaning techniques and their effect on PV performance, highlighting the benefits of cleaning without significant water consumption.
[7]	Habib, M. R., Tanvir, M. S., Suhan, A. Y., et al.	2021	Arduino-based automatic cleaning	Developed an Arduino-controlled automatic cleaning system for removing dust from solar panels and maintaining their operating performance.
[8]	Roy, S., Mandal, M., Jena, C., Sinha, P., & Jena, T.	2021	PLC-based automatic cleaning	Proposed a PLC-controlled robust cleaning system designed to automate panel cleaning and improve photovoltaic efficiency.
[9]	Zatsarinnaya, Y., Amirov, D., & Elaev, M.	2020	Arduino-based cleaning system	Designed a solar-panel cleaning system based on an Arduino microcontroller, demonstrating the application of low-cost embedded control for automated cleaning.
[10]	Noh, F. H. M., Yaakub, M. F., Nordin, I. N. A. M., et al.	2020	Solar-panel cleaning robot	Developed an Arduino-based cleaning robot capable of performing automated cleaning operations on solar-panel surfaces.
[11]	Sugiartha, N., Ardana, I. G. N., Sugina, I. M., et al.	2020	Water-spray cleaning system	Presented and tested a preliminary water-spray cleaning system for solar panels to remove accumulated dust and improve panel cleanliness.
[12]	Vaghani, M., Magtarpara, J., Vahani, K., et al.	2019	IoT-based automated cleaning	Developed an automated solar-panel cleaning system incorporating IoT technology for improved monitoring and control of the cleaning process.
[13]	Zainuddin, N. F., Mohammed, M. N., Al-Zubaidi, S., & Khogali, S. I.	2019	Smart self-cleaning system	Designed a smart self-cleaning solar-panel system aimed at automatically removing surface contaminants and reducing maintenance requirements.
[14]	Manju, B., Bari, A., & Pavan, C. M.	2018	Automatic cleaning mechanism	Developed an automatic solar-panel cleaning system to reduce the effect of dust accumulation and minimize manual cleaning effort.
[15]	Rao, A., & Kumar, S. S.	2018	Smart IoT-based cleaning	Proposed a smart IoT-based solar-panel cleaning system integrating automated cleaning with monitoring and control capabilities.
[16]	Deb, D., & Brahmabhatt, N. L.	2018	Soiling prevention and water-free cleaning	Reviewed methods for preventing solar-panel soiling and proposed a water-free automated cleaning approach to improve PV energy yield.
[17]	Patil, P. A., Bagi, J. S., & Wagh, M. M.	2017	Review of PV cleaning mechanisms	Reviewed different solar photovoltaic cleaning mechanisms and discussed their approaches, advantages, and limitations.
[18]	Mondal, A. K., & Bansal, K.	2015	History and future of automatic cleaning	Reviewed the development of automatic PV cleaning systems and discussed future possibilities for automated solar-panel maintenance.



[19]	Moharram, K. A., Abd-Elhady, M. S., Kandil, H. A., & El-Sherif, H.	2013	Water and surfactant cleaning	Investigated the effect of cleaning PV panels using water and surfactants and demonstrated the importance of cleaning for maintaining panel performance.
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3. PROPOSED METHODOLOGY

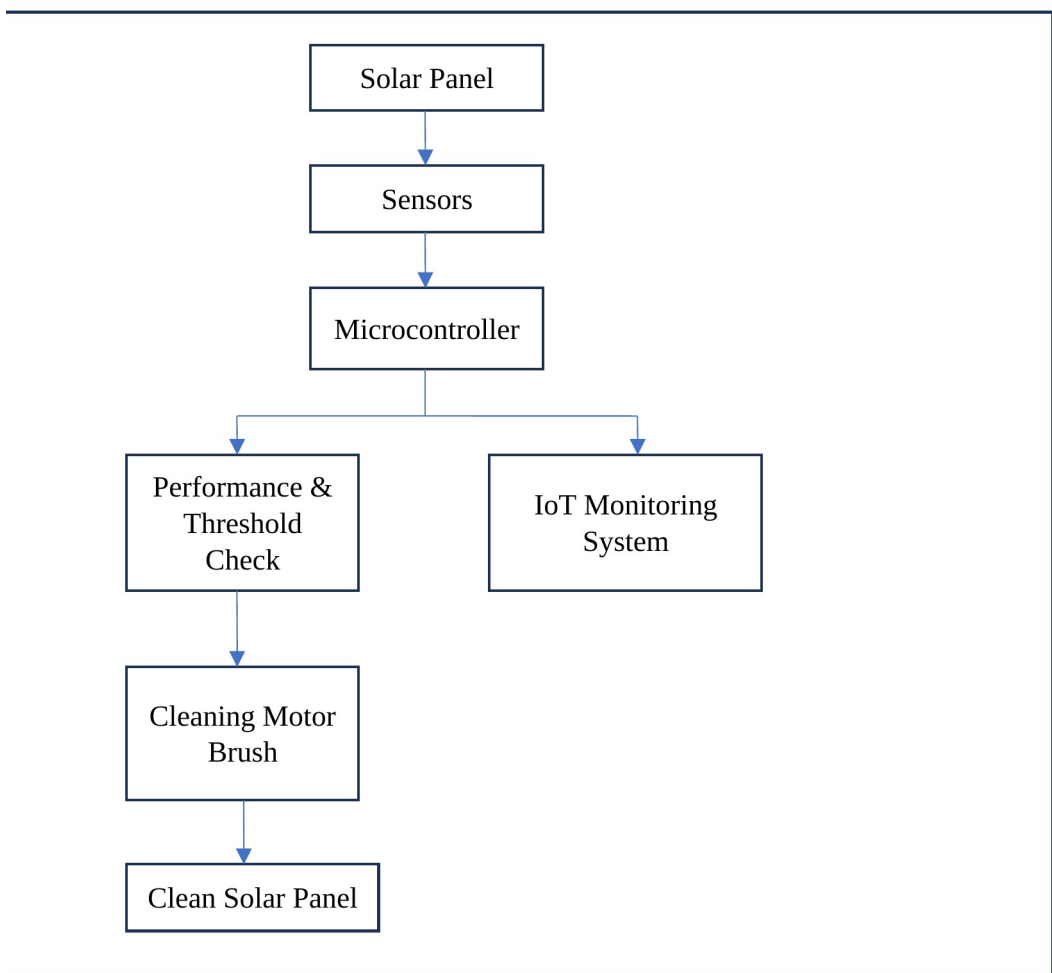


Figure 1 Block Diagram of Proposed System

The proposed system consists of an automated solar-panel cleaning mechanism integrated with an IoT-based monitoring system. The methodology is designed to continuously monitor the operating condition of the solar panel and initiate the cleaning process when the measured performance falls below a predefined threshold.

1. Solar Panel and Sensor Data Acquisition

The solar panel is operated under outdoor conditions where dust and other contaminants accumulate on its surface. Sensors are used to measure important parameters such as solar



irradiance, panel voltage, current, and temperature at regular intervals. These measurements are continuously acquired by the microcontroller for evaluating the operating condition of the panel.

2. Performance Monitoring

The collected voltage and current values are processed by the controller to determine the instantaneous performance of the solar panel. Solar irradiance is also considered because the generated voltage and power naturally vary with changes in sunlight intensity. Data are recorded at a fixed interval, such as every 10 minutes, to observe changes in panel performance throughout the day.

3. Threshold-Based Cleaning Decision

A predefined performance threshold is established for the solar panel. The controller compares the measured operating parameters with the reference/threshold values. If the panel performance decreases beyond the specified limit, indicating possible dust accumulation or surface contamination, the controller generates a cleaning command.

This condition-based approach avoids unnecessary cleaning when the panel is already operating satisfactorily.

4. Automatic Cleaning Mechanism

When the cleaning condition is satisfied, the controller activates the cleaning mechanism. A motor-driven wiper/brush mechanism moves across the panel surface to remove accumulated dust, bird droppings, and other contaminants. The mechanism is designed to cover the required panel area while minimizing mechanical stress and energy consumption.

5. Cleaning Completion and Performance Verification

After completion of the cleaning cycle, the system again measures the panel parameters. The post-cleaning voltage and power output are compared with the values obtained before cleaning. This provides a direct method for evaluating the effectiveness of the cleaning operation.

The system can therefore determine whether the cleaning operation has successfully restored the panel performance.

6. IoT-Based Monitoring

The measured parameters and system status are transmitted to an IoT-based monitoring platform. The user can observe parameters such as:

- Solar irradiance
- Panel voltage
- Panel current
- Power output
- Panel temperature

- Cleaning status
- Cleaning frequency
- Pre-cleaning and post-cleaning performance

This enables real-time monitoring and provides historical data for performance analysis.

4. RESULT AND DISCUSSION

Result

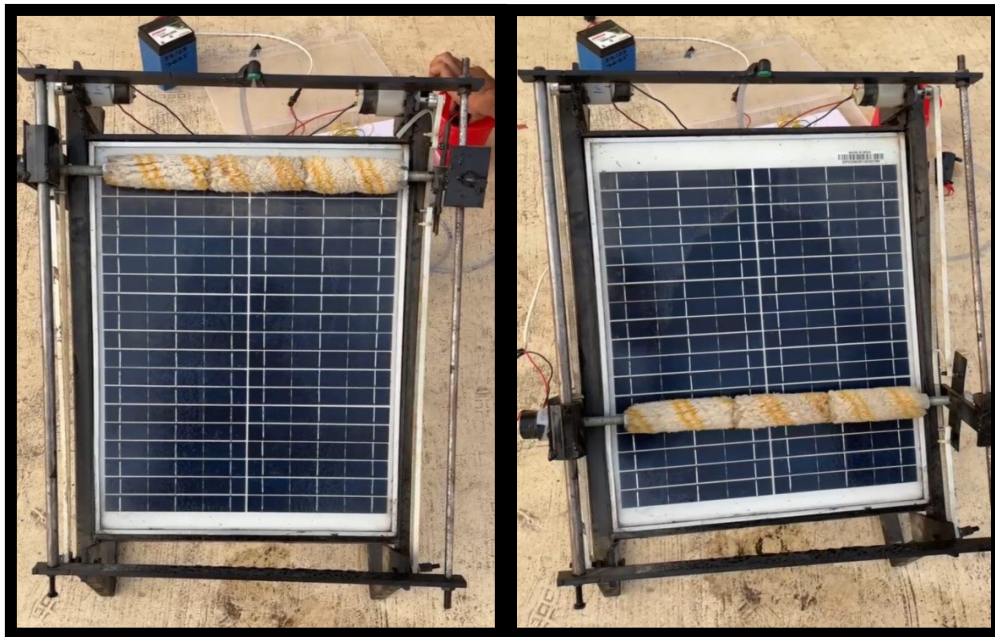


Figure 2 Hardware Design

Discussion

The developed automated solar panel cleaning system demonstrates the importance of maintaining a clean photovoltaic surface for efficient power generation. Dust and other contaminants deposited on the panel reduce the amount of solar radiation reaching the photovoltaic cells, which directly affects the electrical output of the panel. The experimental observations indicate that the panel voltage decreases as dust accumulates on the surface. After the cleaning operation, the voltage improves significantly and approaches the normal operating level. This confirms that automatic cleaning can effectively reduce the performance losses caused by surface contamination. The proposed threshold-based cleaning approach also helps avoid unnecessary cleaning operations. Instead of cleaning the panel at fixed time intervals, the system activates the cleaning mechanism when the monitored panel performance falls below the predefined threshold. This can reduce the number of cleaning cycles, power consumption, and mechanical wear of the cleaning mechanism. The integration of IoT-based monitoring further improves the system by allowing parameters such



as voltage, current, temperature, irradiance, power output, and cleaning status to be monitored in real time. The collected data can also be used to compare panel performance before and after cleaning and to evaluate the effectiveness of the cleaning mechanism. Overall, the results indicate that the proposed system provides an effective approach for automated solar-panel maintenance, performance monitoring, and reduction of manual cleaning requirements. The system can be further improved for large-scale solar installations by incorporating advanced soiling detection, optimized cleaning mechanisms, and long-term performance analysis.

5. CONCLUSION

The proposed automated solar panel cleaning system provides an effective solution for reducing the performance losses caused by dust accumulation on photovoltaic panels. The system combines automatic cleaning with real-time monitoring of important parameters such as voltage, current, solar irradiance, and temperature. The experimental results demonstrate that cleaning the panel can significantly improve its output performance. The threshold-based cleaning approach also helps avoid unnecessary cleaning operations, thereby reducing energy consumption and mechanical wear. The integration of IoT-based monitoring enables continuous observation of panel performance and cleaning status. Overall, the proposed system can reduce manual maintenance requirements, improve solar-panel efficiency, and provide a reliable approach for long-term photovoltaic system operation.

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