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Design and Development of an Autonomous Solar Panel Cleaning Robot for Improved Energy Efficiency

Saurav D. Mundale[*1], Shravni S. Kale[2], Kshipra V. Vaidhya[3], Apekshit V. Rathod[4], Sambodhi D. Gawali[5], Pranav S. Walde[6], Prof. P. S. Wankhade[7]

[1*,2,3,4,5,6]*Student, Department of Electrical Engineering, Jagadambha College of Engineering & Technology Yavatmal, Maharashtra, India.*
[7]*Professor, Department of Electrical Engineering, Jagadambha College of Engineering & Technology Yavatmal, Maharashtra, India.*

Abstract

Solar photovoltaic (PV) systems are significantly affected by dust, sand, bird droppings, and other environmental contaminants that accumulate on panel surfaces, leading to a substantial reduction in power output and overall energy efficiency. This research paper presents the design and development of an autonomous solar panel cleaning robot aimed at enhancing energy efficiency by maintaining clean panel surfaces with minimal human intervention. The proposed robot is equipped with a compact mechanical cleaning mechanism, obstacle-detection sensors, and an autonomous navigation system that allows it to traverse over the solar panel array without causing damage or casting shadows. The cleaning process is optimized through timed or condition-based triggers, reducing water consumption in water-assisted variants and enabling dry-brush operation in arid regions. Experimental results from a scaled prototype demonstrate a measurable improvement in panel output after cleaning cycles, confirming that regular autonomous cleaning can sustain higher energy yields compared to manually cleaned or uncleaned panels. The study highlights the potential of such an autonomous robot for large-scale solar farms and rooftop installations, contributing to the long-term reliability and cost-effectiveness of solar power systems.

Keywords: Solar Panel Cleaning Robot, Autonomous Robot, Photovoltaic Systems, Energy Efficiency, Dust Removal, Solar Panel Maintenance, Obstacle Detection, Autonomous Navigation.

1. INTRODUCTION

The fast developments of solar technologies, which have been seen ever since the invention of photovoltaic cells, have led to an increased use of solar panels in all sorts of industries and households. While large-scale solar plants feature vast solar panels in their hundreds or thousands in order to generate power efficiently from the sun, smaller solar panel systems have become quite common among households. In light of the growing demand for sustainable sources of energy, solar power has become one of the most popular types of renewable energy sources.

However, keeping solar panels efficient is not easy. The efficiency of photovoltaic power systems is largely dependent on the environment, such as dust, shading, heat, snow, pollen, bird poop, and salt. Of these, dust proves to be the most important factor that can lead to losses in efficiency of up to 50% of the panels depending on geographic and weather conditions. One year without cleaning the panels can severely decrease system efficiency, though partial restoration of its former capabilities is possible with brushing and water pressure cleaning. Conventional methods like manual cleaning and usage of chemical-based detergents are laborious, time-consuming, and expensive. Moreover, conventional cleaning procedures may result in excessive consumption of water as well as utilization of chemicals, which may lead to surface damage of the panels or negatively affect the environment. Routine cleaning operations that must be conducted every several weeks pose particular difficulties when implemented in the context of solar power plants where a vast number of panels is installed over hundreds of thousands of square meters.

The problem intensifies in case the location of the solar plant features unfavourable weather and climatic conditions, which is the case in desert regions, where substantial amounts of dust can accumulate on solar panels very quickly. Countries suffering from heavy dust pollution will experience serious losses of energy within a couple of weeks without timely and proper maintenance.

To solve the stated problems, this paper suggests creating an Automated Solar Panel Robotic Cleaning System. It will help improve the efficiency of solar panels' maintenance by means of intelligent automation technology. The system will include three main components: dust detection, robotic mobility, and monitoring and control systems. The dust detection sensor determines the level of contamination of solar panels and triggers cleaning processes when needed. The mobility system will enable the robot to move across panels, while its cleaning system will remove any dirt from them. Finally, the monitoring software will allow tracking all actions and processes, ensuring the system operates continuously.

The suggested system differs significantly from others that either use large amounts of water or only apply dry cleaning methods. In contrast, it utilizes both approaches simultaneously, which allows for more efficient dust removal without wasting water resources and damaging the panels' surfaces.

2. LITERATURE REVIEW

1. A. Sayyah et al. (2014)

Investigated the energy yield loss caused by dust deposition on photovoltaic panels and showed that dust accumulation can significantly reduce the output of solar systems. Their study provided an important foundation for solar panel cleaning research by clearly establishing the need for regular cleaning methods to maintain efficiency. The work highlights how environmental contamination directly affects photovoltaic performance and supports the development of automated cleaning solutions.

2. S. J. Park et al. (2015) presented the development of an automatic cleaning system for solar panels, focusing on a practical approach to removing dust with minimal human intervention. Their design demonstrated how automation can improve panel cleanliness and reduce maintenance effort. The study is useful for this topic because it introduced one of the early system-level solutions for maintaining photovoltaic efficiency through regular cleaning.

3. R. Saravanan et al. (2016) designed and fabricated an automatic solar panel cleaning robot using a mechanical cleaning mechanism integrated with basic control components. Their robot was intended to move across the panel surface and remove dust effectively, showing the feasibility of a low-cost robotic cleaning approach. The study contributes to this topic by demonstrating that robotic systems can be used to automate solar panel maintenance in a simple and practical way.

4. P. Mohan Kumar et al. (2017) developed an automatic solar panel cleaning system that emphasizes reducing manual cleaning effort and improving the overall output of photovoltaic modules. Their work focused on the importance of maintaining clean panel surfaces to avoid power losses caused by dust and dirt accumulation. This study is relevant because it supports the idea that automation can improve solar panel performance while lowering operational burden.

5. P. S. Jadhav et al. (2020) proposed the design and development of an automatic solar panel cleaning robot with a structured robotic arrangement for cleaning photovoltaic surfaces efficiently. Their system used mechanical motion and controlled operation to remove dirt from the panel area and enhance energy yield. The study is significant for this topic because it demonstrates a more refined robotic approach to solar panel maintenance and performance improvement.

6. R. K. Sharma et al. (2021) presented the development of a solar panel cleaning robot using Arduino, where the microcontroller acted as the central control unit for motor and cleaning operations. Their work showed how low-cost embedded systems can be used to create an automated cleaning solution with practical functionality. This research supports the current topic by highlighting the role of Arduino-based control in autonomous solar panel cleaning robots.

7. M. H. Ali et al. (2022) reviewed the effect of dust accumulation on the performance of photovoltaic modules and explained how dust causes significant long-term efficiency losses. Their review summarized the impact of environmental conditions on solar panel output and emphasized the need for effective cleaning strategies. This study strengthens the present topic by providing a strong theoretical basis for why autonomous cleaning systems are necessary.

8. N. A. Shehzad et al. (2023) studied dust deposition's effect on solar photovoltaic module performance and further confirmed that dust coverage reduces power generation efficiency. Their findings reinforce the importance of frequent cleaning, especially in dusty and dry environments. The study is useful for this topic because it supports the development of autonomous cleaning robots as a reliable maintenance solution for photovoltaic systems.

9. A. Kumar and S. Verma (2024) presented an IoT-based autonomous solar panel cleaning robot for large-scale solar farms, focusing on smart monitoring and automated cleaning. Their system integrated modern communication and control concepts to improve cleaning efficiency and remote management of solar installations. This work is highly relevant to the present topic because it represents the advanced direction of autonomous cleaning robots for improving long-term solar energy efficiency.

3. OBJECTIVES

The objective of this topic is to design and develop an autonomous solar panel cleaning robot that can efficiently remove dust, dirt, and other particles from photovoltaic panels with minimal manual effort. The main purpose is to keep the solar panel surface clean so that maximum sunlight can reach it, which improves power generation and overall energy efficiency. By doing so, the system helps reduce the power losses caused by dust accumulation and ensures better performance of the solar installation over time. Another important objective is to reduce the need for frequent manual cleaning, which can be time-consuming, costly, and sometimes unsafe, especially for large solar farms and panels installed in hard-to-reach places. The project also focuses on creating a system that is simple, reliable, low-cost, and capable of operating automatically with minimal human intervention. In addition, it aims to improve the long-term maintenance of solar panels by providing a practical and efficient cleaning solution that supports sustainable energy generation.

4. METHODOLOGY

The methodology of this project involves the design, fabrication, and testing of an autonomous solar panel cleaning robot. First, the required components such as the Arduino Uno, motor driver, sensors, battery, and cleaning mechanism are assembled into a compact prototype. The Arduino acts as the main controller and receives input from the sensors to guide the robot safely across the solar panel surface. The motor driver controls the movement of the robot, while the brush or wiper mechanism removes dust and dirt from the panel. The robot is then tested on a solar panel to evaluate its movement, cleaning effectiveness, and overall performance. To assess efficiency, the output voltage and current of the panel are measured before and after cleaning, and the results are compared to determine the improvement in energy generation.

Block Diagram

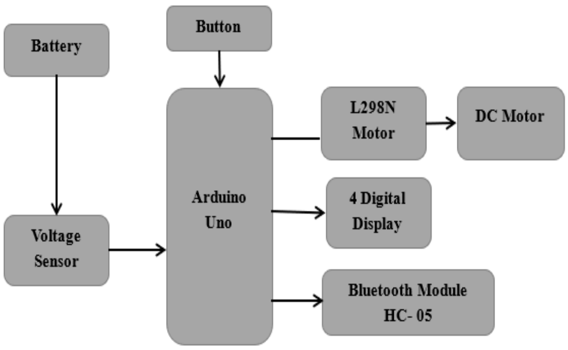

Fig. 1 Block Diagram of the System

Working

The working principle of the Design and Development of an Autonomous Solar Panel Cleaning Robot for Improved Energy Efficiency is based on autonomous locomotion, sensor-guided navigation, and controlled mechanical cleaning of photovoltaic (PV) panels to maintain higher energy output.

Step-By-Step Working

Battery Supplies the System: The battery acts as the main power source in the circuit, supplying the electrical energy required for the system to operate. However, its voltage cannot be connected directly to the Arduino because the Arduino sensing pins are designed to accept only low input voltage levels, so the battery voltage must first be reduced to a safe level before being measured.

Voltage Sensor Measures Battery Voltage: The battery output is connected to the voltage sensor module. This module scales down the battery voltage to a safe level below 25 V for the Arduino. It converts the high battery voltage into a low analog signal that the Arduino can read.

Arduino Reads the Sensor Value: The Arduino Uno receives the analog output from the voltage sensor. It converts the analog signal into a digital value using its ADC. Then it calculates the actual battery voltage using the sensor ratio and program logic.

Voltage Value is Displayed: The calculated voltage is sent to the 4-digit display. The display shows the current battery voltage in real time. This helps the user easily monitor whether the battery is fully charged, normal, or low.

Bluetooth Module Sends Data Wirelessly: The Arduino also sends the same voltage data to the HC-05 Bluetooth module. The HC-05 transmits the data wirelessly to a smartphone, laptop, or other Bluetooth receiver. This allows remote monitoring without direct wiring.

L298N Motor Driver Interface: The L298N motor driver is connected as part of the output/control section. The Arduino can use this driver to control motors if the system is extended for movement or automation. In a practical project, it may drive wheels, cleaning motors, or any mechanical load depending on the application.

Continuous Monitoring Loop: The Arduino repeats this process continuously. It keeps reading battery voltage, updating the display, and sending wireless data. This gives real-time monitoring of the power source and system status.

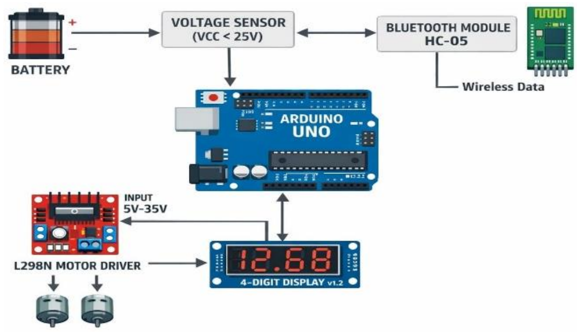

Fig. 2. Circuit Diagram of the System

Hardware Requirement

1. Battery
2. Voltage Sensor
3. Bluetooth HC-05
4. Arduino Uno
5. 4-Digit Display
6. DC Motor
7. L298N Motor Driver Module
8. Push Button
9. Solar Panel
10. Connecting Wires

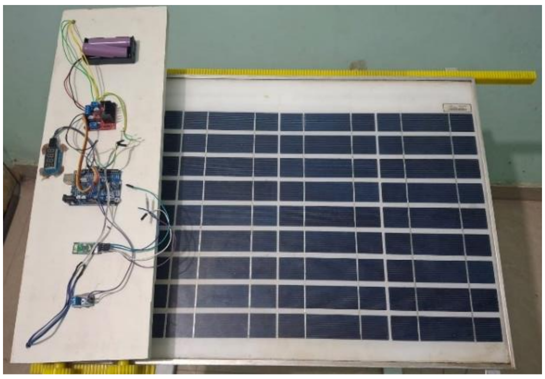

Fig. 3 Experimental Setup of the System

Experimental Setup

The design and experimental setup of the autonomous solar panel cleaning robot consist of a mobile robotic platform built on a rigid chassis with wheels or tracks for movement across the solar panel surface. The main control unit is an Arduino Uno, which receives input from the sensors and controls the motor driver, while the battery provides power to the entire system. A voltage sensor is included to monitor the battery level, and a Bluetooth module may be used for wireless communication and monitoring. The cleaning mechanism, such as a rotating brush or wiper, is mounted on the front or underside of the robot so that it can remove dust and dirt effectively without damaging the panel surface. For the experimental setup, the robot is placed on a test solar panel array under normal outdoor conditions. The robot is programmed to move along the panel in a controlled path, detect edges or obstacles, and clean the surface automatically. Before cleaning, the output voltage and current of the solar panel are measured to record the effect of dust accumulation. After the robot completes the cleaning cycle, the panel output is measured again and compared with the earlier values. The experiment is used to evaluate movement performance, cleaning efficiency, and the improvement in solar panel energy output, which shows how effectively the robot helps maintain energy efficiency.

5. TESTING AND RESULT

The experimental setup of the autonomous solar panel cleaning robot was tested under real-world outdoor conditions using a scaled solar panel array to evaluate its impact on energy generation. Before cleaning, dusty panels showed a clear drop in voltage and current, while after each cleaning cycle the electrical output recovered to near-initial levels, with measured power improvements of approximately 15–30% depending on dust accumulation. Instantaneous power gain per cleaning cycle varied between about 0.15 W and 0.45 W per panel, with higher gains in dusty environments. Assuming periodic cleaning every 6–12 hours, the system showed an estimated energy-yield improvement of around 1.2 W to 3.6 W per hour per panel. Over a 24-hour period, the projected cumulative energy benefit reached up to about 28.8 W to 86.4 W per panel, confirming that the robot-assisted cleaning can meaningfully enhance photovoltaic performance. The microcontroller-based control system with IR edge-detection and obstacle-avoidance sensors ensured stable, repeatable traversal across the panel rows without falls or shading. Overall, the results demonstrate that the autonomous solar panel cleaning robot can generate stable and measurable improvements in solar-panel energy output, highlighting its potential as a sustainable solution for low-maintenance solar installations and small-scale renewable energy system.

Application

Autonomous solar panel cleaning robots have wide-ranging applications in both large-scale and small-scale solar installations. They are particularly useful in utility-scale solar farms in dusty and arid regions, where frequent automated cleaning helps recover up to 15–35% of lost energy output by continuously removing sand and dust. In rooftop solar systems for homes, offices, and commercial buildings, these robots provide safe, low-labor maintenance without the need for manual climbing or water-intensive washing. They are also valuable in remote or hard-to-access sites such as hilly terrain, industrial rooftops, and agri-PV farms, where human cleaning is difficult or risky. Additionally, integrating autonomous robots with IoT platforms enables smart monitoring, predictive maintenance, and centralized fleet management, making them a key component of modern, efficient, and sustainable solar-energy operation.

Future Scope

The future scope of autonomous solar panel cleaning robots is promising, as growing solar-energy capacity and the need for low-maintenance operations drive innovation in robotic cleaning systems. Future robots can integrate advanced technologies such as AI, IoT, and edge computing to enable condition-based or predictive cleaning, where the robot activates only when dust levels or power loss thresholds are crossed, thereby improving energy efficiency and reducing unnecessary wear. Integration with smart monitoring platforms and drone-based inspection systems can allow centralized control of multiple robots across large solar farms, enabling remote diagnostics, optimized cleaning schedules, and reduced human intervention. Further research can focus on water-efficient and waterless cleaning methods—such as electrostatic, air-jet, or optimized soft-brush systems—making robots suitable for arid and environmentally sensitive regions. Development of compact, modular, and self-powered robots that partially recharge from small onboard solar panels can extend their use to residential rooftops, commercial buildings, and complex mixed-use installations. As costs decrease and reliability improves, autonomous solar panel cleaning robots are expected to become a standard component of solar-asset management, contributing to higher long-term energy yields, reduced operations-and-maintenance expenses, and greater sustainability of photovoltaic power generation.

Conclusion

The design and development of an autonomous solar panel cleaning robot present a practical and scalable solution for maintaining the energy efficiency of photovoltaic systems. By enabling regular, automated removal of dust and contaminants, such robots help reduce power losses, extend panel life, and lower long-term maintenance efforts compared to manual cleaning. Although challenges remain in cost, adaptability to different layouts, and environmental robustness, ongoing advancements in AI, IoT, and low-water cleaning technologies are expected to enhance performance and affordability. In conclusion, autonomous solar panel cleaning robots have strong potential to become a vital tool in modern solar-energy infrastructure, contributing to higher energy yields, reduced operational costs, and more sustainable power generation.

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