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ENHANCING SOLAR PANEL EFFICIENCY AND SUSTAINABILITY THROUGH AUTONOMOUS CLEANING

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Abstract– Solar energy is one of the most promising renewable energy sources, yet the efficiency of solar panels can decline by up to 30% due to dust and debris accumulation. Conventional cleaning practices, such as manual wiping or water-based methods, are often labor-intensive, water-dependent, and unsuitable for large-scale installations. To overcome these limitations, this study proposes an autonomous robotic cleaning system that operates without human intervention. The system combines a sensor-based efficiency monitoring unit, a brush and water-spray mechanism, and a programmed movement algorithm to ensure effective cleaning. It is further equipped with intelligent navigation to prevent falls from panel edges and wireless communication for real-time voltage tracking. Experimental validation shows notable improvements in power output, reduced maintenance effort, and enhanced operational reliability. The findings highlight the potential of autonomous cleaning technology as a sustainable solution for long-term solar panel performance and efficiency.

Keywords: Solar energy, Autonomous cleaning, Dust removal, Efficiency enhancement, Intelligent navigation, Automated maintenance.

1. INTRODUCTION

The global energy demand is steadily increasing, necessitating a shift towards sustainable and renewable energy sources. Among these, solar energy has gained significant traction due to its abundance, reliability, and minimal environmental footprint. However, maintaining the efficiency of solar panels is a critical challenge, as dust accumulation, bird droppings, and environmental pollutants can drastically reduce energy output. Studies indicate that uncleaned solar panels can suffer from efficiency losses ranging from 7% to 30%, depending on geographic and climatic conditions.

Traditional cleaning methods, such as manual washing and automated water-based cleaning, pose several limitations, including high labour costs, water wastage, and frequent maintenance requirements. In regions with water scarcity, such as deserts and arid zones, water-based cleaning is not a viable option. These challenges necessitate the development of autonomous cleaning systems that use less water and a brush system to effectively maintain solar panel efficiency without human intervention.

To address this issue, we have developed a solar panel cleaning robot mounted on a mobile car platform that enhances accessibility and adaptability for different solar installations. Unlike stationary cleaning solutions, our robotic system can navigate across small-scale solar installations such as homes, schools, colleges, and small ground areas to provide systematic and efficient cleaning. The system is designed to autonomously spray water and wipe the panels using controlled pressure mechanisms, ensuring minimal water usage while maintaining optimal cleaning efficiency.

This paper explores the design and implementation of an autonomous robotic solar panel cleaning system that ensures maximum energy yield through efficient, sustainable, and cost-effective cleaning techniques. The system incorporates intelligent sensors for surface mapping, adaptive cleaning mechanisms, and real-time performance monitoring. Our study evaluates the performance of the proposed robotic cleaning system compared to conventional methods, highlighting improvements in energy efficiency, operational feasibility, and economic viability. Through this research, we aim to contribute to the advancement of smart solar panel maintenance technologies, promoting widespread adoption and sustainability in the renewable energy sector.

2. MECHANISM AND FUNCTIONALITY OF THE CLEANING ROBOT

The autonomous solar panel cleaning robot operates using a combination of sensor-based decision-making and mechanical cleaning mechanisms. The working of the system is divided into two main parts:

2.1 Sensor System (Voltage Drop Detection & Navigation)

The system continuously monitors the efficiency of the solar panel using a voltage sensor. If a drop in output voltage is detected due to dust accumulation, a signal is sent to initiate the cleaning process.

An Arduino Nano is used to measure the voltage drop and transmit the data wirelessly using an HC-12 RF module to an Arduino Uno, which acts as the main controller.

For obstacle detection and edge avoidance, the robot is equipped with two IR sensors (for detecting the panel’s edges) and two ultrasonic sensors (for detecting obstacles in front and behind).

Based on the sensor readings, the Arduino Uno determines the movement path and prevents the robot from falling off the panel.

2.2 Car System (Mobility & Cleaning Mechanism)

The robot moves on four wheels, with two wheels grouped in pairs connected by belts to ensure friction and prevent slipping on the panel

The movement is controlled using an L298D motor driver shield, which drives the motors in different directions based on the programmed movement logic.

The cleaning system consists of a brush system and a water spray mechanism, which activate once the robot starts moving. The brush remove dust, while minimal water is sprayed for effective cleaning.

The robot follows a predefined cleaning pattern, ensuring full coverage of the panel and avoiding redundant movements.

The system stops cleaning only after reaching the final designated point, ensuring a systematic and complete cleaning cycle.

2.3 Functionality

The solar panel cleaning robot is designed to autonomously navigate and clean rectangular solar panels using a systematic zig-zag movement. Its functionality is divided into key phases:

2.3.1 Measurement Phase

The robot first moves along the panel's length while cleaning, then turns and moves along the width to measure dimensions.

It calculates the number of full-width cleaning sections (M) and any remaining partial width (Q).

2.3.2 Cleaning Phase

The robot moves along the panel's length until its front sensor detects no surface.

It then turns 90° and moves sideways by one full car width (X) before continuing.

This process repeats M times to ensure complete coverage.

If $Q > 0$, the robot shifts sideways by Q and cleans the final strip.

2.3.3 Edge Detection & Turning

IR and ultrasonic sensors detect panel edges and determine turning directions.

The robot alternates turning directions at each end to maintain an efficient zig-zag cleaning path.

2.3.4 Stopping Condition

The robot counts corners using edge sensors and stops only at the third corner, ensuring the full panel is cleaned.

2.3.5 Returning to Start Position

If the number of cleaning sections (M) is even, the robot naturally ends at the starting position.

If M is odd, it moves back along the length to return to its starting position with the same orientation.

3. HARDWARE COMPONENTS USED

The system consists of various electronic and mechanical components that enable efficient operation. The key components used in the project are:

3.1 Microcontrollers & Communication

Arduino Uno–Main controller for processing sensor data and controlling motors.

Arduino Nano–Used for voltage sensing and wireless communication.

HC-12 RF Module – Facilitates long-range wireless data transmission between Arduinos.

3.2 Sensors & Navigation

Voltage Sensor – Detects efficiency reduction due to dust accumulation.

Ultrasonic Sensors (x3) – Detect panel edges to prevent falling.

3.3 Motor & Movement System

L298D Motor Driver Shield – Controls the movement of motors.

DC Motors (x4) – Drive the wheels for robot movement.

Belt System – Provides stability and prevents slipping on the panel.

3.4 Cleaning Mechanism

Brush System – Rotates to remove dust from the panel.

Water Spray System – Sprays minimal water for effective cleaning.

Servo Motor – Controls the movement of the cleaning mechanism.

3.5 Power System

12V, 2A Power Supply – Provides power to the robot's motors and sensors.

4. ADVANCEMENTS IN SOLAR PANEL CLEANING: A LITERATURE REVIEW

4.1 Impact of Dirt on Solar Panel Efficiency

Efficiency Loss: Studies show that dust, bird droppings, and environmental debris can reduce solar panel efficiency by 15-25% over time if not cleaned.
Source: A study in Renewable Energy Journal highlights that uncleaned solar panels can lose up to 25% efficiency within 6 months in dusty environments.
Geographical Impact: In arid regions (e.g., India, Middle East), solar panel efficiency decreases faster due to high dust accumulation.
Fact: Research by Solar Energy Journal indicates that panels in arid regions lose efficiency at 0.4-0.5% per day.
Voltage Fluctuations: As dirt accumulates, the voltage output of the panel decreases, indicating a direct correlation between cleanliness and power generation.
Fact: Research from IEEE Transactions on Energy Conversion suggests that voltage drops by 5-10% within 4 weeks of exposure to dust.

4.2 Efficiency Monitoring & Smart Activation

Traditional cleaning methods operate on fixed schedules, leading to unnecessary cleaning cycles.
Research from IEEE Transactions on Energy Conversion highlights that voltage output decreases by 5-10% within four weeks of dust accumulation.
Our project uses a voltage sensor to monitor panel efficiency in real time, ensuring cleaning is activated only when necessary, optimizing energy use.

4.3 Minimizing Water Usage

Studies show that manual cleaning consumes 3-5 Liters per panel, while automated systems still use 1-2 Liters per panel.
Our project reduces water consumption by implementing a fine misting system, ensuring up to 90% water savings, making it ideal for water-scarce regions.

4.4 Advanced Mobility & Complete Coverage

Existing robotic cleaners often struggle with panel edges and require external guidance systems for full coverage.
Our project follows an optimized movement pattern using sensor-based navigation, ensuring complete cleaning coverage without external intervention.
IR and ultrasonic sensors enable precise turning logic, allowing the robot to navigate panels without slipping or stopping prematurely.

4.5 Wireless Data Transmission & Remote Monitoring

IoT-enabled solar maintenance systems reduce operational costs by 15-20%, as per research from Springer Link.
Our project integrates an HC-12 RF module to transmit real-time efficiency data, allowing remote monitoring and reducing manual intervention.

4.6 Economic & Environmental Impact

Studies show that automated cleaning reduces maintenance costs by 20-30% over five years.
By combining intelligent activation, minimal water usage, and autonomous operation, our project provides a cost-effective and sustainable cleaning solution.
This approach aligns with global efforts to maximize solar energy efficiency while reducing environmental impact.

6. POTENTIAL

Cleaning solar panels involves removing accumulated debris from their surface, including dust, bird droppings, and ash from wildfires. When collected particles operate as an obstruction between the solar panels and sunlight, this technique is carried out to restore the power conversion capabilities of the panels. As a result of their effectiveness in increasing power output and recovering module efficiency, other ways are also utilized in the process for a variety of applications.
As per Zion Market Research, the global Solar Panel Cleaning market is estimated to grow annually at a CAGR of around 5.5% over the forecast period (2023-2030).
In terms of revenue, the global Solar Panel Cleaning market size was valued at around USD 1200 million in 2022 and is projected to reach USD 1800 million, by 2030.
The growing installation of solar panel modules is expected to propel the solar panel cleaning market growth over the forecast period.
Based on the technology, the wet cleaning segment is expected to capture the largest market share over the forecast period.

The growing product launches offer a lucrative opportunity for solar panel cleaning market growth during the forecast period. For instance, in May 2022, a clean-tech company called Skilancer Solar introduced a waterless automated robot for cleaning small-scale solar power plants that are installed on residential rooftops. This breakthrough will enhance their current product line, which already includes a waterless robot with AI that can clean massive industrial solar arrays. Skilancer intends to go after the home market with the new robot. An efficient cleaning method is essential not only to save water but also to encourage the use of alternative energy since there has been a rise in water shortage challenges on a worldwide scale.

CONCLUSION

The Solar Panel Cleaning RC Car presents an innovative, autonomous, and cost-effective solution for maintaining the efficiency of solar power systems. By integrating real-time voltage monitoring, automated cleaning mechanisms, and remote-controlled mobility, this system ensures that dust accumulation does not compromise the power output of solar panels.

Unlike conventional solar panel cleaning systems that operate at fixed time intervals, our robot stands out by working on a real-time voltage monitoring mechanism. This ensures that cleaning is performed only when necessary, making the process more efficient and reducing unnecessary wear and tear. The combination of precise water spraying, controlled wiping pressure, and minimal water usage makes this approach highly sustainable, addressing the common challenge of water wastage in solar panel maintenance.

Additionally, the remote operation enhances its applicability in large-scale solar farms and rooftop installations where manual cleaning is difficult. The system's efficiency is further reinforced by its low-power design, ensuring reliable operation while minimizing energy consumption.

With further enhancements such as improved navigation, better water distribution, and more efficient cleaning mechanisms, this RC-based cleaning system can revolutionize the way solar panels are maintained, ensuring maximum energy efficiency, reduced maintenance costs, and long-term sustainability in renewable energy production.

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