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Solar Panel Cleaning Robot Embedded with Camera Sensor

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***Abstract* — The increasing adoption of solar energy systems has created a growing need for efficient and regular maintenance, particularly cleaning. One of the primary challenges affecting solar panel efficiency is the accumulation of dust, dirt, and environmental particles, which can cause a drop in performance of up to 50% within a few weeks. To address this issue, we have designed and built a semi- automated solar panel cleaning robot that provides both mechanical cleaning and basic panel health monitoring. The robot uses a rotating roller brush and a water spray nozzle to clean panel surfaces efficiently. It is manually controlled through the Blynk IoT application via a Wi-Fi-enabled ESP32 module. A Raspberry Pi and Pi Camera module are also included to capture real-time images and perform simple diagnostics like crack detection. This dual-purpose robot provides an affordable, scalable, and effective maintenance solution for small- and medium-scale solar installations.**

I. INTRODUCTION

Solar energy has become a prominent renewable resource, widely used in residential, commercial, and industrial sectors. However, maintaining the efficiency of solar panels over time remains a challenge due to environmental factors such as dust, dirt, bird droppings, and pollution. These contaminants can block sunlight from reaching the photovoltaic cells, drastically reducing the output of a solar panel system. According to studies, energy production can fall by up to 50% if panels are not cleaned regularly.

Manual cleaning techniques are still the most common, but they are time-consuming, costly, and often impractical for large-scale or rooftop systems. Additionally, improper cleaning materials can damage the glass surface of panels, reducing their lifespan.
To overcome these limitations, we developed a manually controlled cleaning robot that simplifies and speeds up the cleaning process. This robot not only handles the physical cleaning through a motorized brush and water spray system but also monitors the panel's condition using an onboard camera module. This combined functionality reduces labor dependency and helps in maintaining consistent energy output.

Fig 1 Before and After Cleaning

II. SYSTEM ARCHITECTURE AND DESIGN

The overall architecture of the solar panel cleaning robot consists of four key layers that work in coordination to perform cleaning and monitoring tasks efficiently:

1. Power Management Layer: The robot's components operate on different voltages. A 12V supply is used to power high-current components such as the L298 motor driver, relay circuit, and the brush motor. A regulator board converts this to 5V for low-power modules like the ESP32 and Raspberry Pi.

2. Control and Communication Layer: This layer is built around the ESP32 NodeMCU, which receives commands wirelessly from the Blynk app. The microcontroller handles real-time control by communicating with the L298 motor driver and relay circuit. This allows users to manage the robot's movement and cleaning functions remotely using a smartphone.

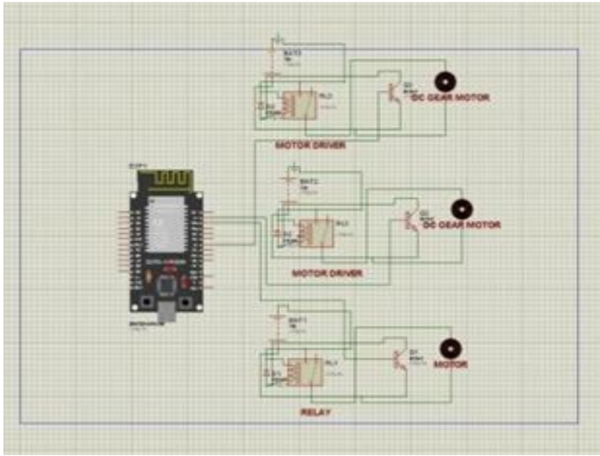

Fig 2 ESP32 Circuit Diagram

3. Actuation and Cleaning Layer: The robot's movement relies on four DC motors connected to rubber-tracked wheels, enabling smooth traversal over glass surfaces. The roller brush, powered by a 200 RPM Johanson motor, is positioned at the front. A spray nozzle is mounted near the brush and is supplied water externally via a polyurethane (PU) tube and union tee connector, which softens dirt for more effective brushing.

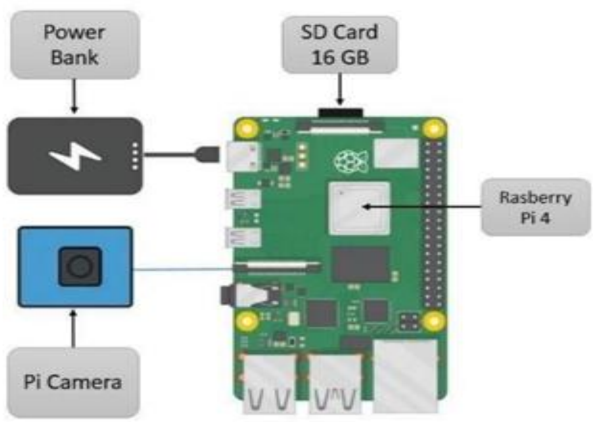

Fig 3 Image Processing

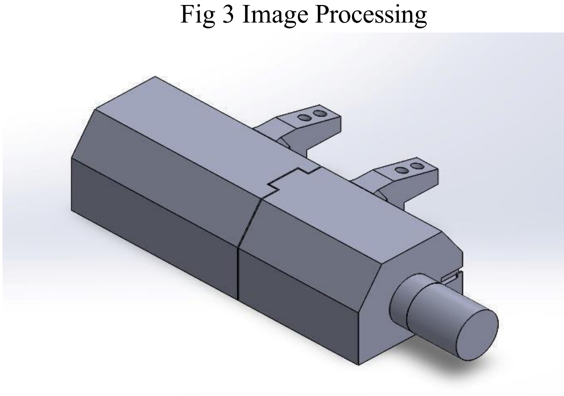

Fig 4 Roller Brush 3D Model

4. Monitoring and Feedback Layer: A Raspberry Pi 4 with a Pi Camera module captures images of the solar panel before or after cleaning. These images are analyzed to detect cracks, dust build-up, or panel discoloration. Once analysis is complete, a health report is generated and emailed to the user automatically.
   3D Printing: Custom-designed 3D-printed enclosures were used to house the Pi Camera, Raspberry Pi, brush cover, and nozzle support. This ensures secure mounting, protection from dust and water, and easy maintenance.

III. METHODOLOGY

The methodology followed in the project was divided into the following stages, ensuring organized progress from concept to deployment:

1. Design and Fabrication

The robot's chassis was designed for optimal stability and surface coverage. Materials were chosen for their weight and durability to avoid damaging fragile solar panels. Key components such as mounts and enclosures were designed using CAD software and fabricated using 3D printing.

2. Cleaning System Integration

The roller brush and water spray system were installed in a manner that ensured synchronized operation. The brush is driven by a 200 RPM DC motor, while the water nozzle is connected to an external pump via flexible polyurethane tubing and a union tee. The nozzle is positioned to direct water just ahead of the brush path for maximum effectiveness.

3. Control and Connectivity Setup

The ESP32 was programmed using Arduino IDE to interface with the Blynk platform. Virtual controls were created within the app, including directional buttons and brush toggles. The L298N driver was wired to the ESP32 to relay movement commands to the motors.

4. Camera and Monitoring System

A Python script was developed on the Raspberry Pi to capture images and process them for panel condition analysis. The Pi Camera captures snapshots at predefined intervals or on user command, which are then analyzed for visible defects or dirt patches. A report is generated and automatically emailed using an SMTP-based script.

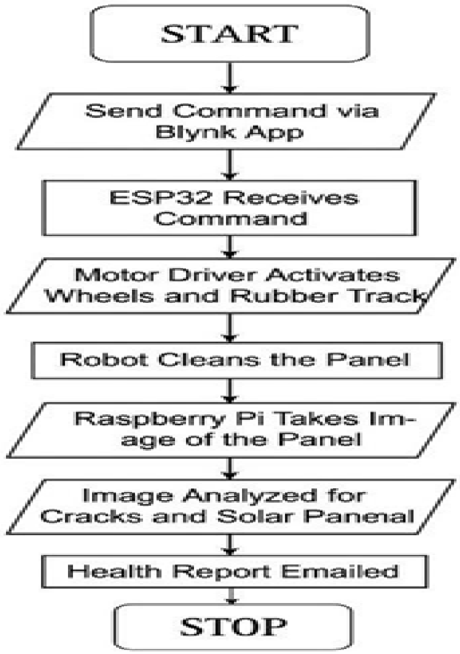

Fig 5 Flow Diagram

5. Power Supply Management

A shared power supply was implemented using a 12V DC source regulated to 5V where necessary. The system was tested to ensure consistent voltage distribution and protection for sensitive electronics. A relay system was incorporated to allow safe toggling of high-current components.

6. Testing and Performance Analysis

Multiple field tests were conducted to evaluate robot performance on real solar panels. Movement speed, brush torque, cleaning effectiveness, image clarity, and Wi-Fi command response were measured. Data was also collected on processing delays, and plotted in time vs delay graphs for visual performance analysis.

Fig 6 Robot Image

EQUATION

Power Usage Design Calculation:

To estimate the total power consumption of the solar panel cleaning robot, the system is divided into three major subsystems:

Drive system (P_drive): for the movement of the robot via 4 DC gear motors

Cleaning system (P_brush): for operating the roller brush motor

Control and Monitoring (P_control): for Raspberry Pi, ESP32, Pi Camera, and relay circuits

The total power requirement of the robot is given by the equation:

$P_{total} = P_{drive} + P_{brush} + P_{control}$ Calculated Values (Based on Provided Data): $P_{drive} = (12V \times 0.3A \times 4 \text{ motors}) / 0.8 \approx 18\text{ W}$ $P_{brush} = (12V \times 7.5A) / 0.75 \approx 120\text{ W}$

$P_{control} = (5V \times 2.5A) + (5V \times 0.25A) + (5V \times 0.5A) = 16.25\text{ W}$Total Power Consumption:

$P_{total} = 18W + 120W + 16.25W = 154.25\text{ W}$

Energy per Cleaning Cycle (1 minute): $E_{cycle} = P_{total} \times (1 / 60 \text{ hour}) = 2.57\text{Wh}$

The robot consumes approximately 154.25 watts during operation and uses about 2.57 watt-hours of energy per 1-minute cleaning cycle. This calculation helps in estimating the required battery capacity and can guide future improvements in energy efficiency.

IV. CONCLUSION

This project presents a practical and effective solution to the persistent challenge of maintaining solar panel efficiency in dusty and exposed environments. By bringing together mechanical cleaning and basic image-based monitoring, the robot fulfills two major maintenance needs—physical surface cleaning and visual health diagnostics. The cleaning mechanism, which includes a rotating roller brush and a front-mounted water spray nozzle, efficiently removes accumulated dirt and debris, helping to restore the solar panel's performance.

The use of the Blynk IoT platform enables wireless control, allowing users to operate the robot from a distance through a smartphone interface. This makes it particularly useful for rooftop installations where manual access is limited. Meanwhile, the Raspberry Pi and Pi Camera module provide image-based inspection capabilities, allowing users to monitor panel condition and receive automated health reports via email. This adds a smart layer of preventive maintenance.

Real-world testing has shown that the robot performs reliably across its intended functions—movement, cleaning, image capture, and remote control. Its modular, lightweight design and 3D-printed parts make it easy to adapt, maintain, and scale for different panel setups. Overall, the project demonstrates how combining affordable electronics, basic automation, and smart monitoring can lead to an accessible and impactful solution for improving solar energy reliability.

V. FUTURE SCOPE

While the current prototype successfully meets its core objectives of cleaning and basic monitoring, there are several promising opportunities to improve and expand the system's capabilities. These enhancements would not only increase efficiency but also enable the robot to function more autonomously and in larger-scale solar installations.

Integration of Autonomous Navigation: Adding sensors for edge detection, obstacle avoidance, or even GPS-based path planning could allow the robot to navigate solar panel arrays automatically without user input. This would reduce manual control and make the system more efficient for larger solar fields.

Solar-Powered Operation: Incorporating a compact solar charging unit onboard the robot would enhance its energy efficiency and make it more self- sustaining, especially in remote or off-grid locations where charging access is limited.

AI-Based Crack Detection: Upgrading the image processing module with machine learning or artificial intelligence could improve the accuracy of fault detection. It could also classify different types of damage, such as hairline cracks or discoloration, and alert the user accordingly.

Cloud Integration and Data Logging: By connecting the robot to a cloud platform, cleaning logs, panel health data, and image archives could be stored and accessed over time. This would provide users with long-term insights and help in predictive maintenance.

Multi-Panel Cleaning System: A scalable design could be developed where multiple cleaning units work together or one robot can clean several panels sequentially using path optimization algorithms. This would be ideal for commercial or industrial-scale solar farms.

Voice or Gesture-Based Control: For improved user interaction, the system could be made compatible with voice assistants or gesture control technologies, making it even more accessible for non-technical users.

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