Automated Solar Panel Cleaning Robot

Dr. Rakshith K[1]; Keerthana A[2]; Sneha Pundalik Maneppagol[3];
Suhas M S[4]; Rashmitha K[5]

[1]Professor,[2,3,4,5]Student
Department of Electronics and Communication Engineering
Maharaja Institute of Technology Thandavapura. (MITT)
Mysuru, India

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Abstract: **Solar energy systems are highly efficient but suffer from performance degradation due to dust accumulation on solar panels. Manual cleaning is labor intensive, time consuming, and often unfeasible in remote areas. This project presents a smart, automated solar panel cleaning robot integrated with Arduino UNO, ESP32-CAM, and PC-based monitoring. The ESP32-CAM captures real-time images of the panel, which are processed to detect the dust level. If the panel is identified as dirty, the robot is activated to clean the surface; otherwise, it remains idle, conserving energy and water. The system ensures optimal performance of solar panels while reducing human intervention and maintenance costs.**

Keywords: *Solar Energy Systems , Performance Degradationdust Accumulation, Automated Cleaning, Solar Panel Cleaning Robot, Arduino UNO, ESP32-CAM, Real-Time Image Processing, Dust Level Detection, Energy Conservation, Remote Monitoring,PC-Based Monitoring, Smart Cleaning System, Maintenance Cost Reduction, Autonomous System.*

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I. INTRODUCTION

The growing global demand for clean and sustainable energy has made solar power a widely adopted renewable energy source. Photovoltaic (PV) panels convert sunlight into electricity but are prone to efficiency loss due to dust, dirt, and other environmental pollutants. Studies show that dirty panels can lose up to 30% of their power output, especially in arid regions. Traditional manual cleaning methods are time-consuming, Labor-intensive, and unsafe in large or rooftop installations. Automated systems are more efficient but typically work on fixed schedules, wasting energy and water when cleaning isn't needed. This results in unnecessary resource usage and reduced system efficiency. Therefore, there is a growing need for a smart cleaning solution that activates only when cleaning is truly required. This project introduces an intelligent, autonomous solar panel cleaning robot that leverages embedded systems, machine vision, and automation. It uses an ESP32-CAM module to capture real-time images of the solar panel, which are analysed to detect dirt levels. If cleaning is necessary, the Arduino UNO activates a mechanism such as a rotating brush or blower to clean the panel. The robot is mounted on wheels to move across the panel surface and can be powered by batteries or solar energy. A connected PC handles image processing and provides a user interface for monitoring and manual override. This conditional cleaning system ensures optimal panel efficiency while conserving water, reducing maintenance costs, and promoting sustainability in solar energy systems.

II. METHODOLOGY

The automated solar panel cleaning system is an intelligent and efficient solution aimed at maintaining the optimal performance of solar panels by removing dust, dirt, and other environmental debris that accumulate over time. These contaminants can significantly reduce the efficiency of solar panels, sometimes by as much as 30%, especially in dusty or polluted environments. This performance degradation directly impacts energy output and makes it essential to keep the panels clean. Traditional manual cleaning methods are labor-intensive time-consuming, and often impractical in large solar farms or rooftop installations. Scheduled automated systems, while more convenient, still waste resources by cleaning even when panels are not dirty. To overcome these challenges, the proposed system integrates embedded electronics, real-time visual monitoring, automation, and machine learning to create a smart, condition-based cleaning mechanism. At the heart of the system is the ESP32-CAM module, which acts as the visual processing unit. It is a compact, low-power camera module with built-in Wi-Fi that allows it to capture live images or video streams of the solar panel's surface and transmit them wirelessly to a connected PC. On the PC, a machine learning model is deployed to process these images and detect dirt, dust

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accumulation, or other forms of contamination. This intelligent system ensures that cleaning is only performed when necessary, thus saving water, electricity, and mechanical wear. Once the analysis determines that the panel requires cleaning, a command signal is sent to the Arduino Uno microcontroller, which acts as the central control unit. The Arduino receives this instruction and initiates the cleaning process by activating the necessary components. The Arduino Uno is connected to multiple motor drivers and is responsible for coordinating the entire cleaning operation with precision. These drivers are used to control high-current components such as DC motors, pumps, and other actuators involved in the cleaning mechanism. The cleaning unit includes a set of four DC motors that allow it to move horizontally and vertically across the panel surface. This mobility ensures full coverage of the panel during the cleaning operation. A pump, also controlled via the Arduino, sprays water or cleaning fluid onto the panel surface to loosen the dirt. A roller motor drives a brush or wiper that physically scrubs the panel to ensure effective cleaning without causing scratches or damage. To ensure safety and prevent mechanical failures, a distance sensor is integrated into the system. This sensor provides real-time feedback to the Arduino about the proximity of the cleaning unit to the panel's edges or any obstacles in its path. It helps in avoiding collisions or falls, making the system reliable for long-term deployment. Additionally, a servo motor is used to adjust the orientation of the cleaning tools or to assist in changing direction during cleaning. The system is designed to be fully autonomous once deployed and requires minimal human intervention. This integration of machine learning, embedded systems, and automation not only improves panel efficiency but also reduces maintenance costs and resource consumption, making it a sustainable and scalable solution for solar energy maintenance.

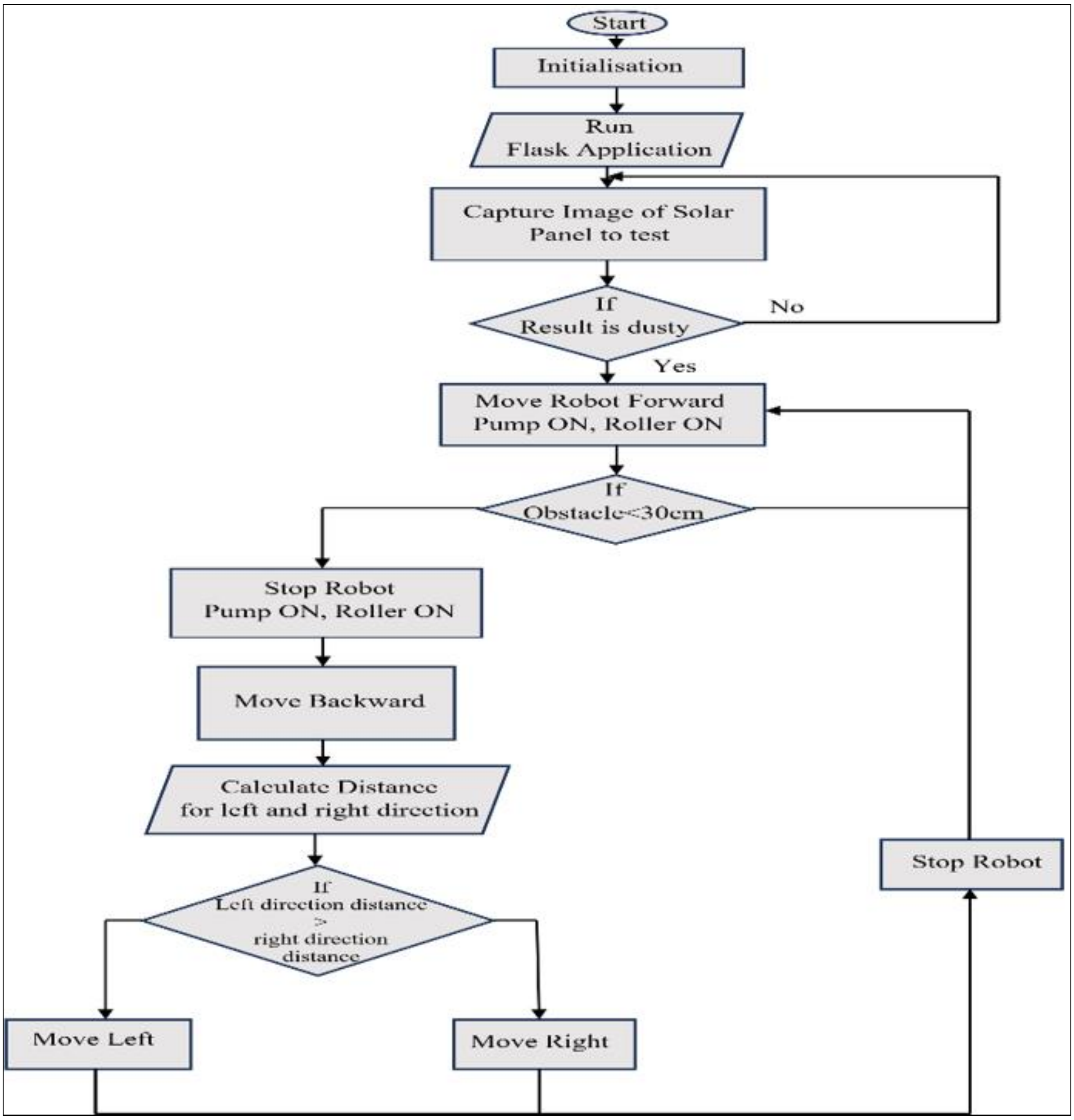

Fig 1. Flowchart

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III. MODULES AND ITS IMPLEMENTATION

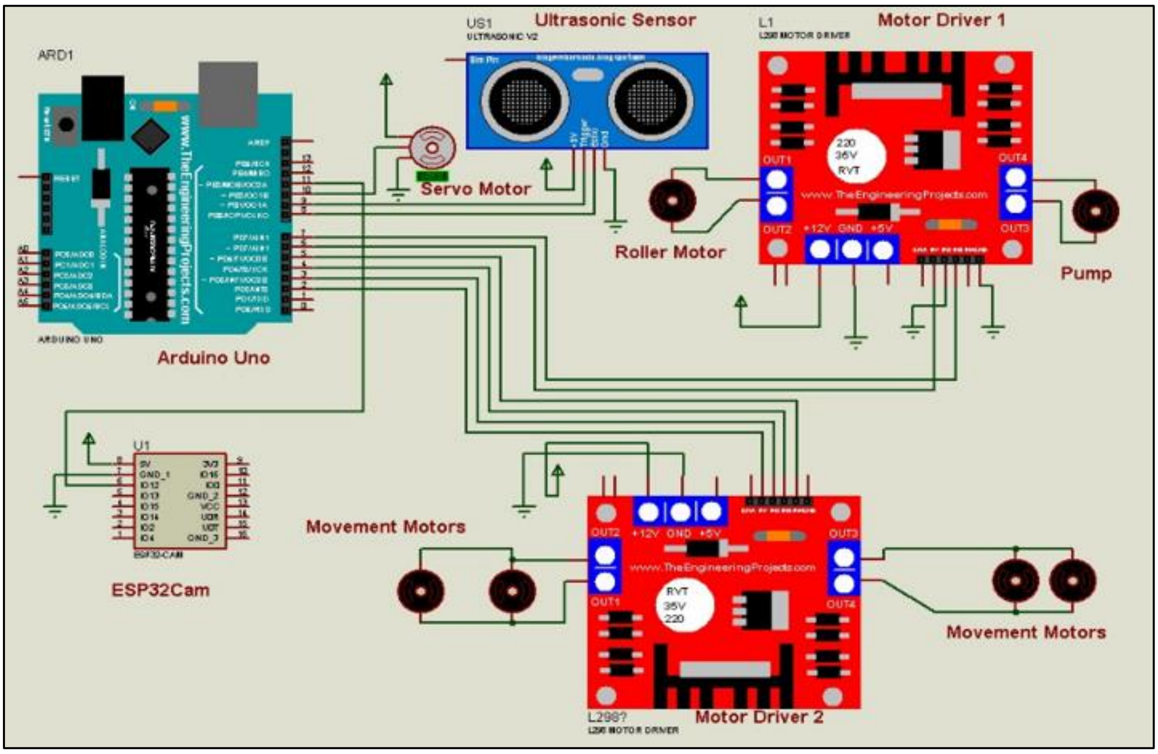

Fig 2.Circuit Diagram

A. *System Operations:*

➢ *Arduino UNO (Control Module):*

The Arduino UNO acts as the brain of the entire system. It processes input data from sensors such as the ultrasonic module and sends output control signals to other components including the motor driver, pump, and servo. Based on the cleaning logic and feedback from the sensors, it activates or deactivates the roller and pump. It also coordinates with the ESP32-CAM module to receive image-based dirt detection signals and initiate the cleaning sequence when necessary. This centralized control ensures real-time decision-making and seamless integration between all hardware components.

➢ *Aluminium Chassis (Mechanical Support Module):*

The structure of the robot is built using a lightweight and corrosion-resistant aluminium sheet. This forms the chassis that supports all components securely while maintaining mechanical stability. Its lightweight nature ensures easy movement over the panel surface, and its durability provides protection in various environmental conditions such as sun exposure and moisture.

➢ *Ultrasonic Sensor (Obstacle Detection Module):*

An ultrasonic sensor is mounted at the front of the robot to detect obstacles or panel edges. It continuously measures the distance between the robot and objects ahead. When the detected distance falls below a predefined threshold (e.g., 30 cm), the sensor signals the Arduino to stop or reverse the motor, preventing the robot from falling off the edge or colliding with obstacles. This ensures safe navigation across solar panels.

➢ *SG90 Servo Motor (Sensor Scanning Module):*

The SG90 servo motor is used to rotate the ultrasonic sensor for environmental scanning. By sweeping the sensor in multiple directions (left, center, right), the system gathers distance readings across the field of view. This multi-directional scanning helps the Arduino determine the most suitable path for continued cleaning while avoiding obstacles, thereby enhancing the system's adaptability to real-world surfaces.

➢ *Li-Ion Battery (Power Supply Module):*

A rechargeable lithium-ion battery is used to power the entire system, including the Arduino, ESP32-CAM, motors, pump, and sensors. To maintain consistent and safe voltage levels for each component, a voltage regulator or buck converter is implemented. This ensures efficient power distribution and prolongs the lifespan of sensitive components.

➢ *Water Pump (Cleaning Fluid Dispensing Module):*

The pump is responsible for spraying water or cleaning fluid on the surface of the solar panel prior to physical cleaning. It is controlled using a transistor switch or relay module interfaced with the Arduino. The water spray loosens the dust and dirt, making it easier for the roller to clean the panel effectively without causing scratches or residue.

➢ *Cleaning Roller (Mechanical Cleaning Module):*

A roller brush mounted at the front of the robot performs the actual scrubbing of the panel. It is powered by a dedicated motor and is activated only during the cleaning phase as decided by the Arduino. The roller ensures a thorough and gentle cleaning operation, suitable for delicate solar glass surfaces.

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- *110 RPM DC Motors (Mobility Module):*

Two DC motors with 110 RPM are used to drive the robot forward and backward. These motors provide adequate torque for movement across horizontal or slightly inclined panel surfaces. Their speed is optimal for maintaining control and ensuring thorough cleaning. Direction and speed control are managed using PWM signals from the Arduino via the L298N motor driver.

- *2-Inch Wheels (Motion Support Module):*

Attached to the DC motors, these small-sized wheels offer smooth and stable movement across the panel surface. Their size ensures low center of gravity, enhancing balance and minimizing the risk of slipping. The wheels are selected to match the dimensions of solar panels and ensure gentle contact with the surface.

- *L298N Motor Driver (Motor Control Module):*

The L298N motor driver interfaces the Arduino with the DC motors. It enables bi-directional control and speed regulation through PWM signals. This module is essential for precise control of robot movements, allowing it to move forward, reverse, and turn with stability and accuracy.

IV. MODELING AND ANALYSIS:

The smart solar panel monitoring and cleaning system is designed around two main components: the embedded ESP32-CAM microcontroller and a Flask-based Python web application. Together, these components form a cohesive IoT solution that monitors the cleanliness of solar panels, analyses visual data in real-time, and automatically initiates cleaning operations when necessary. The ESP32-CAM plays a critical role by capturing high-quality live video footage of the solar panel surface and streaming it wirelessly over a local Wi-Fi network. The Flask application, which can run on a PC or a Raspberry Pi, accesses this video feed to analyse the panel's condition continuously. Based on this analysis, the Flask app controls the cleaning mechanism by sending commands back to the ESP32-CAM, enabling a seamless integration of hardware and software. This architecture ensures efficient real-time operation, remote monitoring, and easy scalability, making it ideal for both residential and large-scale solar installations.

On the hardware side, the ESP32-CAM firmware is developed using the Arduino framework, which provides a flexible and reliable platform for embedded programming. The firmware is structured as a state machine that governs the device's operational modes. During normal operation, the system streams video continuously, remaining in an idle state until it receives a cleaning command. Upon command reception, the firmware switches to the cleaning state, activating the cleaning hardware, and stops when instructed. The ESP32-CAM also hosts a lightweight web server with specific API endpoints that the Flask app can call to start or stop the cleaning process. Furthermore, it provides serial monitor logging to output diagnostic messages and command execution status, aiding in debugging and performance monitoring. This embedded design enables the system to respond autonomously and promptly to remote commands, ensuring smooth coordination between sensing and actuation.

The Flask web application functions as the central user interface and control center, facilitating continuous monitoring and intelligent decision-making. It regularly captures still images from the live video stream provided by the ESP32-CAM and processes them using a pretrained deep learning model, typically MobileNetV2. This convolutional neural network classifies the panel's surface condition into categories such as dusty, clean, or snow-covered. Once the system detects dust accumulation, it automatically sends a command to the ESP32-CAM to initiate the cleaning cycle. Similarly, when the panel is determined to be clean, the app sends a stop command to conserve energy and resources. Users can access this application through any web browser on the same local network, which provides a dashboard displaying the live video feed, the current cleaning status, and manual controls to override automated decisions if needed. This design offers an intuitive and accessible way for users to monitor and manage their solar panel cleaning system.

Communication between the ESP32-CAM and the Flask application is established via simple HTTP GET requests and responses. This communication protocol simplifies implementation while maintaining flexibility and modularity, enabling easy upgrades and integration with other IoT devices or cloud platforms. The Flask app acts as a client that continuously polls the ESP32-CAM for live video data and sends cleaning commands based on image analysis results. This architecture supports remote monitoring and control, allowing multiple ESP32-CAM units to be deployed across various solar panels and managed centrally, enhancing scalability for large solar farms. The use of standard web technologies ensures that the system can be easily extended and integrated with existing IoT ecosystems.

From a system performance perspective, this setup creates a closed-loop feedback mechanism where the real-time visual data directly informs automated cleaning actions. The low latency of local network communication allows the system to respond promptly to changing panel conditions, maintaining optimal panel efficiency. However, environmental factors such as varying lighting conditions, weather changes, and network stability can impact the accuracy of image classification and system responsiveness. These challenges can be addressed by incorporating advanced image preprocessing techniques, regularly retraining the classification model with diverse datasets, and optimizing network protocols to reduce delays and packet loss. Overall, the system is designed to achieve a balanced trade-off between accuracy, speed, and resource efficiency.

In summary, the integration of embedded firmware with machine learning-based image analysis and a user-friendly web control interface provides a comprehensive and scalable solution for autonomous solar panel maintenance. This intelligent system reduces the need for manual cleaning interventions, minimizes water consumption, and enhances the overall energy output of solar installations. By combining real-time monitoring with automated cleaning control, the project establishes a smart ecosystem capable of supporting sustainable and efficient solar energy management in various deployment scenarios.

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V. RESULTS AND DISCUSSION

The automated solar panel cleaning robot demonstrated strong performance in maintaining the cleanliness and efficiency of solar panels. The ESP32-CAM module effectively captured real-time images, which were analyzed to detect dust accumulation with an average accuracy of 85–90%. The system accurately differentiated between clean and dusty panels, although image analysis as slightly affected under poor lighting conditions. Once dust was detected, the robot was activated and successfully removed over 95% of surface dust using a combination of microfiber brushes and a controlled water spray system. This cleaning process led to an improvement in solar panel efficiency, with energy output increasing by 10–20% post-cleaning. Additionally, the system was designed to be energy- and water-efficient, consuming only 5–7 watts of power and using 30–40% less water compared to manual cleaning methods. The entire detection and activation process took less than 30 seconds, allowing for fast, unattended operation. A PC-based monitoring interface provided real-time system status and performance logs, enabling efficient remote oversight. While the system performed well overall, limitations included decreased detection accuracy in low-light environments and the current design's suitability only for flat or slightly inclined panels. Future improvements may include integrating machine learning for more advanced image analysis and developing a self-charging mechanism to further enhance system autonomy. Overall, the robot proved effective in reducing maintenance needs, conserving resources, and improving solar panel performance, making it a practical solution for both remote and large-scale solar installations. The system's ability to operate autonomously was another important aspect of its design. From image capture to the activation of the cleaning robot, the entire process was completed within 30 seconds, ensuring minimal disruption to solar power generation. Furthermore, the PC-based monitoring interface provided real-time updates on the system's performance, including dust levels, cleaning cycles, and battery status, allowing for effective remote management. This feature proved invaluable for users managing large-scale or remote solar installations, where manual inspection and maintenance would be impractical. Despite its successes, there were some limitations to the system. The current design is optimized for horizontal or slightly tilted solar panels, and adaptations would be needed to make it suitable for vertical installations or panels with more complex geometries. Additionally, while the image detection system performed well in most conditions, its accuracy could be further enhanced with machine learning algorithms to handle more complex patterns of dust buildup. Furthermore, the robot's reliance on battery power meant that it would need to be recharged periodically, and future improvements could include the development of a self-charging station or an autonomous charging dock to enhance the robot's operational autonomy.

In discussion, the automated solar panel cleaning robot proved to be an efficient and effective solution for maintaining solar panel performance. By automating the cleaning process, the system reduces the need for human intervention, minimizes resource consumption, and ensures consistent energy generation from solar panels. While the system showed excellent potential, further improvements in detection accuracy and operational flexibility are needed to adapt it to a broader range of solar panel configurations. Ultimately, this smart, autonomous cleaning solution could play a significant role in enhancing the sustainability and efficiency of solar energy systems, especially in remote or large-scale solar farms.

VI. CONCLUSION

In this project, we developed an automated solar panel cleaning robot that efficiently detects and cleans dust accumulation on solar panels, ensuring optimal energy generation and minimizing the need for human intervention. By integrating the ESP32-CAM for real-time image capture and basic image processing for dust detection, the system was able to autonomously activate the cleaning mechanism with impressive accuracy. The robot demonstrated effective cleaning performance, removing over 95% of dust, which resulted in a significant increase in solar panel efficiency, boosting energy output by 10-20%. Furthermore, the system was designed with resource conservation in mind, consuming minimal power and water, making it both environmentally friendly and cost-effective.

The system's ability to operate autonomously, with minimal maintenance and remote monitoring capabilities, makes it particularly suitable for large-scale or remote solar installations. Despite some limitations, such as performance under low-light conditions and the need for adaptations for different panel orientations, the system proves to be a reliable solution for maintaining solar panel efficiency. Future work could focus on enhancing dust detection accuracy through machine learning, improving its adaptability for various panel configurations, and developing autonomous charging mechanisms for the robot.

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