IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 11, April 2026
Impact Factor: 8.2

Design and Development of a Solar Panel Cleaning Robot with AI-Based Dust Detection

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Abstract: *This study delineates the design and development of an intelligent autonomous solar panel cleaning robot that incorporates Artificial Intelligence (AI), the Internet of Things (IoT), and embedded systems. Dust buildup can cut the efficiency of solar panels by as much as 40%, so they need to be cleaned often. The proposed system uses an ESP32-CAM module to take pictures in real time and a Tiny ML model trained on Edge Impulse to find dust. An ESP8266 microcontroller starts automated cleaning using a motor-driven mechanism and water pump system based on the results of the classification. The robot moves in a cycle and uses limit switches to control its movement. Also, Firebase makes it possible to connect IoT devices so that they can be monitored and controlled from a distance using a mobile app. The system is a cheap, scalable, and effective way to keep solar panels working well*

Keywords: Solar Panel Cleaning, AI, IoT, ESP8266, ESP32-CAM, Automation, Embedded Systems

1. INTRODUCTION

The growing need for renewable and sustainable energy sources has led to the widespread use of solar photovoltaic (PV) systems in homes, businesses, and factories. Solar energy is thought to be one of the best alternatives to fossil fuels because it is good for the environment and will be available for a long time. The efficiency of solar panels, on the other hand, depends a lot on how clean their surfaces are. Dust, dirt, bird droppings, and other pollutants in the environment can greatly lower the energy conversion efficiency of PV modules. Studies have shown that losses can be as high as 40%, depending on the conditions in the environment [1], [3]. To make sure that solar panels work at their best, they need to be cleaned and maintained on a regular basis. Cleaning methods that involve manual labor and water-based washing are time-consuming, labor-intensive, and often dangerous, especially for large solar farms and rooftop installations. These methods also raise costs and use too much water, which makes them inefficient and not good for the long term [2], [6]. In order to address these problems, researchers have focused on automation and intelligent approaches for solar panel cleaning. With recent innovations in robotics, cleaning robots are being introduced which would help decrease human involvement and increase efficiency in cleaning tasks. It has been observed that using an automated approach is more feasible and reliable than a manual cleaning approach [7], [10]. In addition to this, integrating Artificial Intelligence (AI) and Machine Learning (ML) technologies into such systems has improved their performance in identifying dirt and optimizing the cleaning process [4], [9]. Computer vision has become a very popular technology for detecting dust, owing to its high accuracy in comparison with other conventional methods, such as the use of sensors [5]. The technique makes it possible to analyze the surface condition of the panels and make decisions about cleaning based on the results obtained, thus saving time and resources that would be used for cleaning.

The implementation of the Internet of Things (IoT) technology is another innovation that can enhance the efficiency of the maintenance system for solar panels. IoT technology will enable users to monitor and control the process remotely by using cloud computing technologies. Although there have been some developments in this field, most of the existing systems do not integrate artificial intelligence dust detection, IoT monitoring, and embedded control within one system. These developments indicate the necessity of implementing a smart, economical, and scalable solution that can combine these different techniques to maximize the effectiveness of solar panels and minimize cleaning costs.

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For this reason, this study recommends developing an autonomous solar panel cleaning robot based on artificial intelligence, where an image classifier will be developed using TinyML and an IoT platform will be utilized for monitoring purposes. Furthermore, the proposed system will include an embedded controller for managing cleaning activities and will use the ESP32-CAM module to detect dust accumulation. Cleaning will only be carried out when necessary, and the ESP8266 microcontroller will manage the process.

II. LITERATURE REVIEW

Several researchers have studied the impact of dust on solar panel performance and proposed various cleaning techniques. Traditional cleaning methods are inefficient and labor-intensive, while automated systems often lack intelligent decision-making. Recent works have introduced machine learning, computer vision, and IoT-based monitoring systems; however, most existing solutions focus on individual technologies rather than an integrated approach. A summary of key literature is presented in Table 1.

Table 1: Summary of Existing Literature

Reference	Author(s) & Year	Technology Used	Key Contribution	Limitation
[1]	D. A. Quansah et al., 2023	Review Study	Analysis of dust deposition on PV panels	No practical system
[2]	N. Naimi et al., 2023	Cleaning Techniques	Overview of solar cleaning methods	No automation
[3]	Y. Shen et al., 2024	Performance Analysis	Effect of dust on PV efficiency	No cleaning system
[4]	A. K. Tripathi et al., 2022	Machine Learning	ML-based dust detection	No IoT integration
[5]	I. Abdulhadi, 2024	Computer Vision	Image-based dust detection	No automation
[7]	A. Sayyah et al., 2022	Robotic Cleaning	Automated cleaning systems	Fixed schedule
[8]	A. Mani et al., 2020	IoT Monitoring	Remote monitoring of PV systems	No intelligent cleaning
[9]	M. S. Kabir et al., 2025	AI-based Analysis	AI-based efficiency evaluation	No hardware system
[10]	T. D. Phan et al., 2023	Cleaning Robot	Study of robotic cleaning systems	No AI-based decision

From Table 1, it is observed that most existing works focus on individual technologies such as automation, IoT, or AI. However, the integration of AI-based dust detection, IoT monitoring, and automated cleaning in a single system is limited, which is addressed in the proposed work.

III. METHODOLOGY

The approach adopted by the system will include the combination of AI, IoT, embedded systems, and mechanical automation in order to ensure that cleaning of solar panels is done efficiently and autonomously. This approach will enable the system to identify dust particles by using image recognition technology and trigger its cleaning operation whenever necessary. This process will help in conserving both energy and water consumption. In the proposed system, the use of the ESP32-CAM module will enable real-time image acquisition and dust particle detection based on the AI. The decision-making and control processes will be facilitated by the ESP8266 microcontroller. In addition, the cleaning operation will be accomplished using motorized movements and a water-powered system.

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Block Diagram

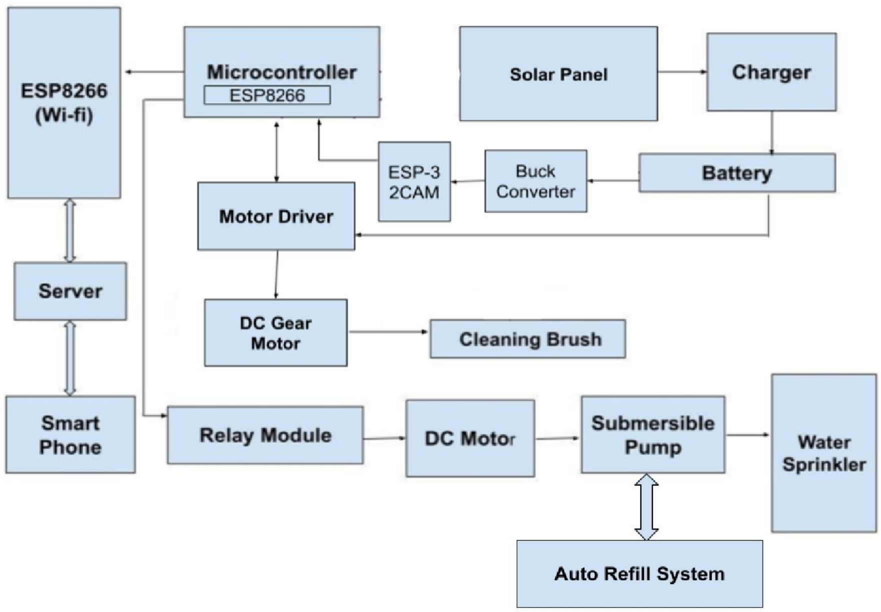

Fig1: Block diagram of an IoT-based automated solar panel cleaning system

The schematic diagram of the proposed system depicts an IoT-based automatic solar panel cleaning robot. The ESP32-CAM module works as a sensing module where real-time images from the solar panel are taken and dust detection is done by AI-based image processing techniques [5]. The result is sent to the microcontroller ESP8266 that works as a control unit where the cleaning decision-making is done [9]. If the decision is positive, then the control unit sends signals to L298N motor driver through which DC motors are operated, and the robot performs movement on the panel [10]. Relay module is responsible for turning on/off the water pump in order to get rid of stubborn dust particles from the panel. Limit switches have been fixed at both the ends of the solar panel in order to perform safe movement of the robot on the panel. The whole process is powered by a solar power source and with battery and voltage regulation. Besides, IoT connectivity helps in monitoring of the whole process via a web-based dashboard on the smartphone.

Circuit Diagram

The circuit diagram for the solar panel cleaning robot provides an idea of how various hardware components are incorporated into the system with respect to ESP8266 NodeMCU as the major control element. The circuit is powered from a battery that can be recharged. This battery delivers regulated power to other modules such as the controller module, motor drivers, relay modules, and sensors. The L298N module interfaces with the ESP8266 to control two DC motors responsible for controlling the movement of the robot along the direction of the solar panels. Input signals from the limit switches are taken in by the controller module in order to detect the end position of the robot.

ESP32-CAM is introduced into the circuit in order to detect the dust on the solar panel using machine learning algorithms and the outputs are taken in by the ESP8266[5]. A relay module is introduced in order to control the operations of a water pump. Voltage regulation module has been provided in the circuit in order to maintain consistent power delivery. In addition to the relay module, a water level sensor has been provided in order to sense the water level. Interconnection between sensing, controller, and actuator systems ensures synchronized operation between sensing, control, and actuation units, enabling efficient and automated solar panel cleaning. The overall system also supports IoT-based monitoring through wireless communication, enhancing usability and performance [8], [9], [10].

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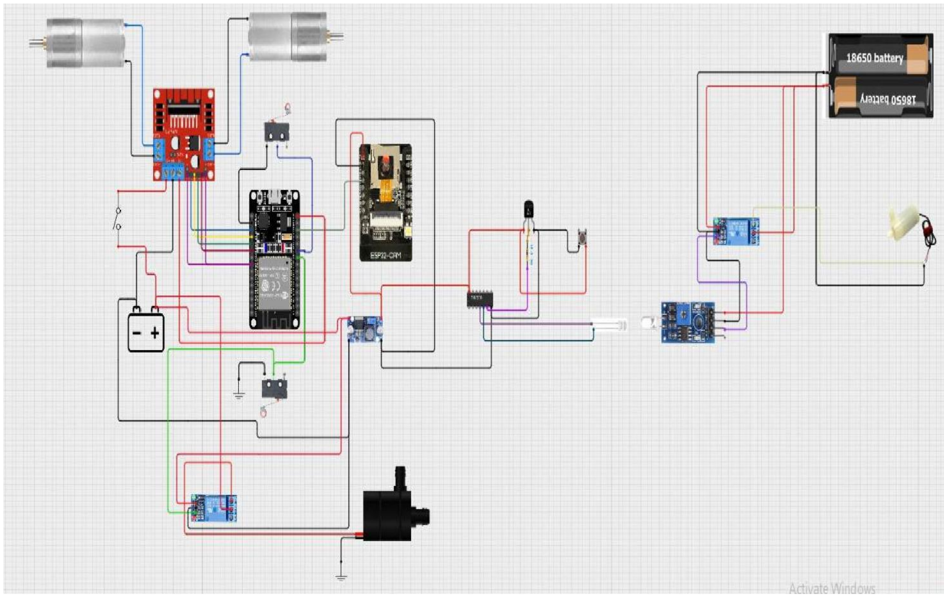

Fig2: Schematic Circuit Diagram

Working Flow chart

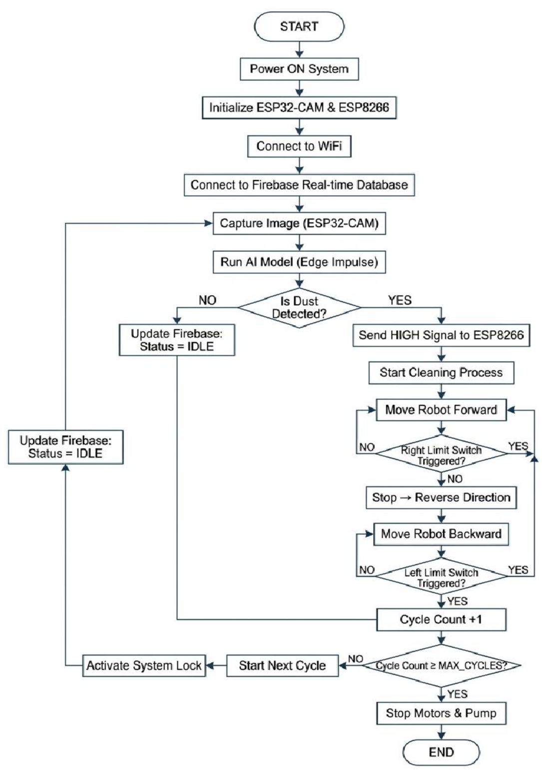

Fig3: flow chart

This system is the use of intelligence and automation technologies to develop an intelligent solar panel dust removal system by use of image processing techniques, IoT, and embedded control mechanisms. This paper presents the system design workflow as discussed below:

1. System Initialization
This process starts with turning ON the system which requires the initialization of both ESP32-CAM and ESP8266 microcontrollers. In this case, ESP32-CAM is used in capturing real-time images and ESP8266 is for handling control processes and communication. This system connects to Wi-Fi and Firebase Realtime Database [8],[9].

2. Image Acquisition and Processing
After initialization, the ESP32-CAM takes the image acquisition role whereby real-time images of solar panel surfaces are captured. These images are analyzed by an embedded AI algorithm developed using the Edge Impulse platform to identify any dust present on the panel [4], [5].

3. Decision for Dust Detection
Depending on the outcome of the analysis, a decision is made regarding whether dust is present or absent;
* If dust is not detected, IDLE status is registered in the Firebase database [9].
* If dust is detected, a HIGH signal is sent to the ESP8266 microcontroller for further processes.

4. Cleaning Process
As soon as the trigger signal arrives, the ESP8266 board initiates the cleaning process by switching on the motor and water pumps. The cleaning robot moves in the forward direction along the surface of the solar panels. Once the right limit switch is activated, the robot halts and changes its direction to backward movement until the left limit switch is activated [10].

5. Cleaning Cycles
Forward and backward movement is referred to as one cleaning cycle. Upon the completion of each cleaning cycle, the number of cycles is counted and increased. In case of the number of cycles being less than the predetermined maximum limit, the process continues. On the other hand, the process terminates once the maximum limit is reached.

6. System Termination
Once the maximum limit of cleaning cycles has been met, the motor and water pump halt their operations. The system locks, disabling any further actions, which reduces unnecessary power consumption [9].

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IV. ANDROID APP INTEGRATION

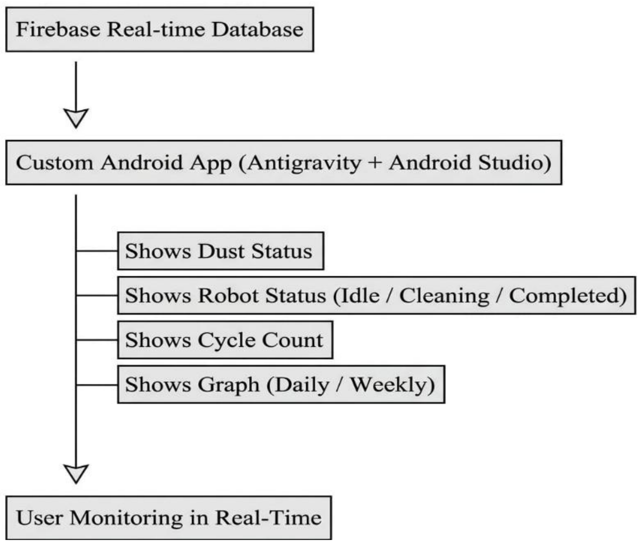

Fig4: IoT-Based Monitoring & Android Application Flow Chart

An IoT-based monitoring system has been implemented in the proposed design that enables the user to visualize the collected data and control the system remotely via the cloud platform and Android application. The ESP8266 microcontroller periodically sends the updated information about the system parameters including dust status, robot status (Idle, Cleaning, and Completed), and cleaning cycles to Firebase Realtime Database that serves as an intermediary between hardware and software components of the system [8].

An Android application has been created using Android Studio and Google Antigravity to receive information stored in the Firebase Database and display it to the user. In addition to presenting real-time information about the status of dust detection, robot operation, and cleaning cycles completed by the system, the app also provides graph analysis by displaying daily and weekly performance reports.

This feature allows not only to improve the efficiency of the system but also enables remote monitoring and controlling it, increasing user-friendliness of the system as well. This IoT-based approach is also useful for data logging and analysis purposes that make the system applicable to both small and large solar plants [8], [9].

V. SYSTEM MANUFACTURING

The manufacture of the proposed solar panel cleaning robot consists of designing and assembling of various mechanical and electrical systems to develop an effective and compact unit. The body or chassis of the unit is designed via computer-aided software (Fusion 360) and developed using 3D printing techniques making them easy-to-produce and cost-effective [10]. A DC geared motor along with wheel units is fitted in the chassis for providing mobility to the robot. A brush cleaning unit along with water pumps is installed to provide efficient cleaning of solar panels. Various electronic components including ESP8266, ESP32-CAM, motor driver, and relay unit are connected together and mounted on the chassis for proper operation. A rechargeable battery voltage regulator provides continuous power.

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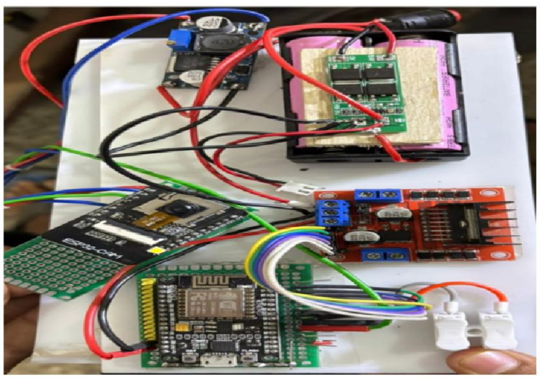
VI. HARDWARE MANUFACTURING



There are various hardware components that need to be considered to make the solar panel cleaning robot work effectively. The ESP8266 Node-MCU microcontroller serves as the core control unit of the device, responsible for controlling the system operations [5]. An ESP32-CAM camera and AI sensor enable the detection of dust on the solar panels for better cleaning results [5]. To move from one point to another, DC geared motors are used; their movement is controlled by an L298N motor driver. Limit switches have been introduced to sense the position of the robot to help with navigation. Also, a relay module controls the water pump for the process of wet cleaning. Lastly, the voltage regulator together with a rechargeable battery supplies power to all components [9], [10].

VII. CONTROL SOFTWARE FOR OPERATION

The control operation for the suggested system has been developed via embedded software designed in the Arduino IDE. This software is aimed at managing all the processes of the system's operation, such as the reaction to the detected dust, managing motor activities, controlling cleaning operations, and performing IoT functionality. The ESP8266 receives the digital signal provided by ESP32-CAM on the basis of artificial intelligence dust detection [5, 9]. As far as the control process is concerned, the software performs the operation of running motors using an L298N driver and moving the robot backward and forward depending on the signal received via limit switches. A cycle count mechanism that determines the maximum amount of cleaning procedures was introduced. Once the necessary cleaning cycles have been completed, the process will be locked to avoid any further movements. Also, the ESP8266 provides IoT functionality in terms of sending various data to the Firebase Realtime Database. Namely, data regarding dust detection status, robot position, and cycle count will be sent to enable monitoring of the cleaning process.

DOI: 10.48175/IJARSCT-33624

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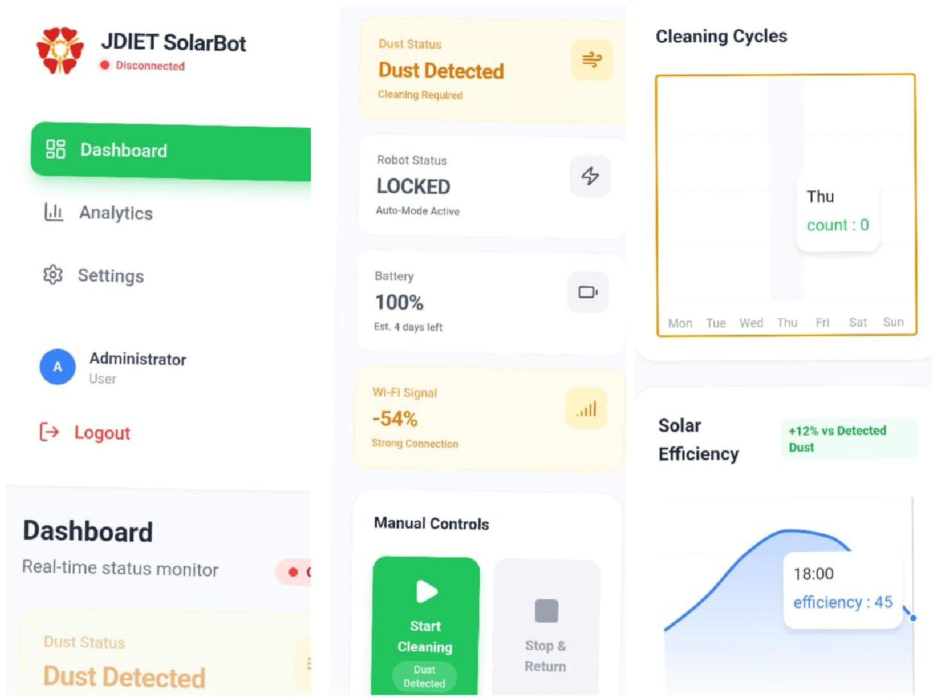
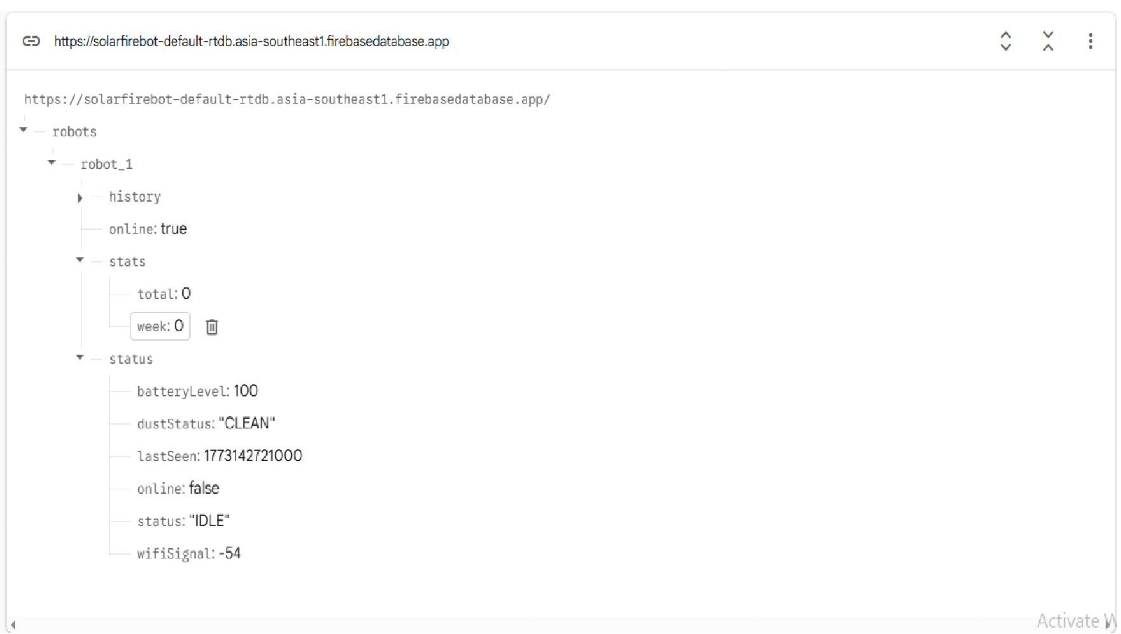


Firebase Real-time Database



VIII. RESULT AND DISCUSSION

The proposed solar panel cleaning robot has been successfully realized and tested in different operating conditions in order to assess its performance. Specifically, the robot showed efficient dust detection based on the machine learning algorithm, which was used for classification of images. Therefore, the robot was capable of distinguishing between clean panels and those covered by dust. As a result, only when necessary would cleaning operations be performed [4], [5]. The robot operated efficiently as far as movement and navigation were concerned. In particular, the use of limit switches provided accurate control of motion in forward and backward directions, thus protecting the robot from mechanical damage and ensuring that the entire surface would be covered. Furthermore, the proposed cycle-based cleaning approach proved effective as far as removal of dust was concerned, and incorporation of the water pump was particularly useful for cleaning persistent dust particles [10]. As for the performance of the system, the use of IoT allowed monitoring and controlling the robot in real time via Firebase platform. Dust status, cleaning status, and number of cleaning cycles were successfully displayed in the mobile application [8], [9]. On the whole, the proposed system provided higher cleaning efficiency, reduced manual effort, and optimized resource utilization. The results confirm that the proposed AI and IoT-based approach provides a reliable and cost-effective solution for maintaining solar panel performance under varying environmental conditions.

a) Global Perspective

Dust build up can hamper solar panel efficiency by about 20-40% in dry and polluted regions. Typical cleaning processes take a long time and are labour-demanding and ineffective for large installations. In addition, existing automated systems work on a set schedule that frequently causes them to clean unnecessarily, wasting water and energy. Created a smart clean system, which is capable of monitoring air quality can go a long way in reducing the number of diseases. This strategy not only increases operational efficiency, but it also uses resources wisely while improving the functioning of solar panels.

b) **System Performance Analysis**

To determine dust detection effectiveness, cleaning efficiency, motion control and reliability, and overall working of the proposed system, experiment has performed under controlled experimental conditions. The classification accuracy of the AI model running on ESP32-CAM proves its worth, with an F1 score of 0.93 for clean panels and 0.95 for dusty panels. The model was able to classify the clean and contaminated panel surfaces with high-reliability although some sensitivity to lighting was noted. The cleaning mechanism proved to be efficient as dust was effectively removed within 2–4 cleaning cycles. The panel surface is cleaned uniformly and without scratches by motor-driven brush with low power consumption. The robot's motion control system was supported by limit switches, which helped to detect the position of the robot properly and move it forward and backward without wobbling or overshooting. With respect to system reliability, the robot automatically performed an emergency stop on their own upon completing the assigned number of cleaning cycles to avoid redundancy in cleaning. The inclusion of a manual reset feature also enhanced safety during operation. The system was also deemed power efficient due to its use of a single motor-driven mechanism and AI-based cleaning that happens only when necessary making it suitable for solar-powered uses. Additionally, we could monitor all live parameters of the system through our Firebase and android app. The application shows important information like dust status, robot working status, count of cycles of the cleaning robot and the performance data that remained stable and continued. The robot was lightweight in nature due to its 3D printing technology, which made its design stable, compact, and easily customizable for various solar panels from a mechanical point of view. The overall performance of the proposed system is summarized in Table 1.

Table 2: Performance Evaluation of Proposed System

Parameter	Observed Value	Remarks
Dust Detection Accuracy	F1 Score: 0.93 (Clean), 0.95 (Dusty)	High accuracy with slight lighting sensitivity
Cleaning Cycles Required	2–4 cycles	Effective dust removal
Cleaning Quality	Uniform & scratch-free	Safe for panel surface
Motion Control	Stable movement	No overshoot or instability

System Reliability	Automatic stop after cycles	Prevents unnecessary cleaning
Power Consumption	Low (single motor)	Energy efficient
Water Usage	Optimized	Cleaning only when required
IoT Monitoring	Real-time via Firebase	Continuous data tracking
Mechanical Design	Lightweight & compact	Easy customization

The above table summarizes the performance of the proposed system, highlighting its efficiency, reliability, and intelligent operation compared to conventional methods

IX. CONCLUSION

In conclusion, this paper illustrates the design and implementation of an automated solar panel cleaning system that uses AI, IoT technology, and embedded systems. It is a system that solves the problem of dirtiness of solar panels, making it less effective at generating power. With ESP32-CAM image sensor for detecting dust and ESP8266 microcontroller for controlling activities, the robot operates intelligently by performing tasks only when necessary [5], [9]. From the analysis, it is evident that the developed robot performs well in terms of dust detection, movement, and cleaning, with a cycle-based approach. Moreover, the incorporation of a water pump improves the effectiveness of cleaning, whereas limit switches offer safety measures for navigating the robot. Further, using IoT-based monitoring, the robot can be monitored in real-time through the Firebase platform [8], [10]. Finally, from the discussion above, it is clear that integrating AI, IoT, and embedded systems into a solar panel cleaning machine makes it reliable, intelligent, and scalable.

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