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Robotic Arm based Solar Panel Cleaning

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ABSTRACT: One of the most important technologies for capturing solar energy is solar panels, which provide an environmentally responsible and sustainable way to fulfil the world's expanding energy needs. When dust is accumulated over the solar panel energy production and operation efficiency reduces. Traditional manual cleaning methods are inefficient and powerful and are not suitable for large scale solar power generation. This paper presents the technology for cleaning of solar cell panel system, which integrates predictions based on deep levels of dust and hybrid robot cleaning mechanisms. The system uses the modules of the Convolutional Neural Networks (CNN) to detect and classify the dust level in real time. Based on the expected gravity of the dust, the robot hand controlled by Arduino provides optimal performance by starting dry (cleaning) or wet (water) purification process. IoT modules provide remote monitoring and data registration. The proposed design is inexpensive and expandable and is especially effective for large scale solar farms. Experimental results show the increase in energy efficiency after cleaning and the significant decrease in human intervention for cleaning.

KEYWORDS: Solar panel, dust prediction, CNN, robotic cleaning, Arduino, IoT, hybrid mechanism, energy efficiency, automation.

I. INTRODUCTION

As demand for clean and stable energy increases, solar energy has found a solid position in today's energy environment. However, one problem often overlooked is how much dust can reduce the effects of the solar battery. Even in medium environments, dust accumulation can lead to a noticeable power loss, and the effect is much greater under extreme conditions. Traditional cleaning methods, such as manual cleaning or six panel downs, can be suitable for a small roof environment. However, in the case of co-solar farms or floating solar panels distributed on the reservoir, it takes a lot of time, expensive and sometimes dangerous. To solve this problem, we have developed a system that automatically performs cleaning. The camera is used to check the panel surface in real time. Trained Convolutional Neural Network (CNN) classifies dust levels. Based on this, the robot hand decides how to perform the cleaning operation using the brush and water. All the sensor information is passed through the Arduino microcontroller and control is done through the IoT platform, so that the conditions can be easily checked or the system can be operated remotely.

II. LITERATURE SURVEY

The increasing deployment of solar photovoltaic (PV) systems has brought with it a critical challenge—dust accumulation, which significantly reduces panel efficiency. To address this, researchers have turned to artificial intelligence and robotics for innovative solutions.

Alatwi et al. [1] explored an AI-driven approach for identifying dust on solar panels. In their study, they evaluated twenty pre-trained deep learning models to determine which best classified solar panel images as clean or dusty. Among the models tested, DenseNet169 combined with a linear Support Vector Machine (SVM) achieved the highest accuracy, reaching 86.79%. Their work demonstrates the viability of using low cost computer vision models for realtime dust detection, which could lead to more efficient solar panel maintenance and improved power generation.

Building upon similar objectives, Onim et al. [2] developed SolNet, a specialized convolutional neural network designed to detect dust on PV panels. SolNet performed with high accuracy in identifying dust-covered panels, offering a foundation for fully automated cleaning systems. Their research supports the integration of AI into solar maintenance workflows, ultimately enhancing the performance of PV systems by responding proactively to dust accumulation.

On the robotics front, Aravind et al. [3] introduced an autonomous vacuum based robotic cleaner designed specifically for solar panels. The robot employs a dual mode cleaning mechanism and is capable of navigating inclined and slippery surfaces. It even features an automated docking and recharging station, allowing for uninterrupted operation with minimal human supervision. This robotic solution is especially promising for large solar farms where manual cleaning is impractical and costly.

In terms of safety and structural reliability, Phan et al. [4] conducted an in-depth analysis of how robotic cleaning impacts the physical integrity of solar panels. Using simulation software like ANSYS, they examined the stress and deformation induced by robotic systems during cleaning operations. Their findings led to the design of a damper system that minimizes mechanical strain, ensuring that regular robotic cleaning does not compromise the longterm durability of PV installations.

Paladugu and Prasad [5] developed a simple, lowcost robot called Project V Star for cleaning solar panels. It is designed to move autonomously using a basic control system, brushes and motors to keep panels clean and efficient. Murshiduzzaman et al. [6] took a broader look, comparing different robotic designs for solar panel cleaning. They examined how various structures like wheeled or railmounted robots perform in different environments. Their study highlights the importance of smart, adaptable cleaning systems, especially in dusty areas and pushes for better design to make these robots even more effective.

III. METHODOLOGY

The proposed autonomous cleaning system for solar panels combines computer vision, machine learning, robotics and IoT technology. This process begins by using a robot hand with a camera next to the panel and the photos of the solar panels are taken in real time under various light and environmental conditions. This image is analyzed using Densenet169 adult neural network, which accurately detects and classifies the dust level of the panel [10], [12]. It is classified as clean, slightly dusty or dusty.

The classification results are sent to the microcontroller based on Arduino and the necessary cleaning work is determined. If the panel is clean, it will not take action. In the case of soft mud, dry cleaning with a brush are performed, and heavy dust is detected a controlled water spray with a wet cleaning process is performed [7], [8], [13]. The robot system is designed for soft movements through the panel, including the slope, using a combination of servo and DC gear motors [14]. Cleaning paths are optimized to minimize energy and water consumption.

The Wi-Fi ESP8266 module connects the system to an IoT platform such as Thingspeak or Blynk to ensure real time monitoring of dust level and cleaning history to the user [16]. The architecture of the system can also reduce the remote execution and manual override. In addition, the cloud connection opens the way of future prediction analysis that can determine graphs based on energy and environmental data models [11] and [16]. In general, this system emphasizes the minimum intervention of human, intellectual automation and efficient use of resources, which is a practical and expandable solution for servicing solar panels, especially in large or remote installation.

BLOCK DIAGRAM:

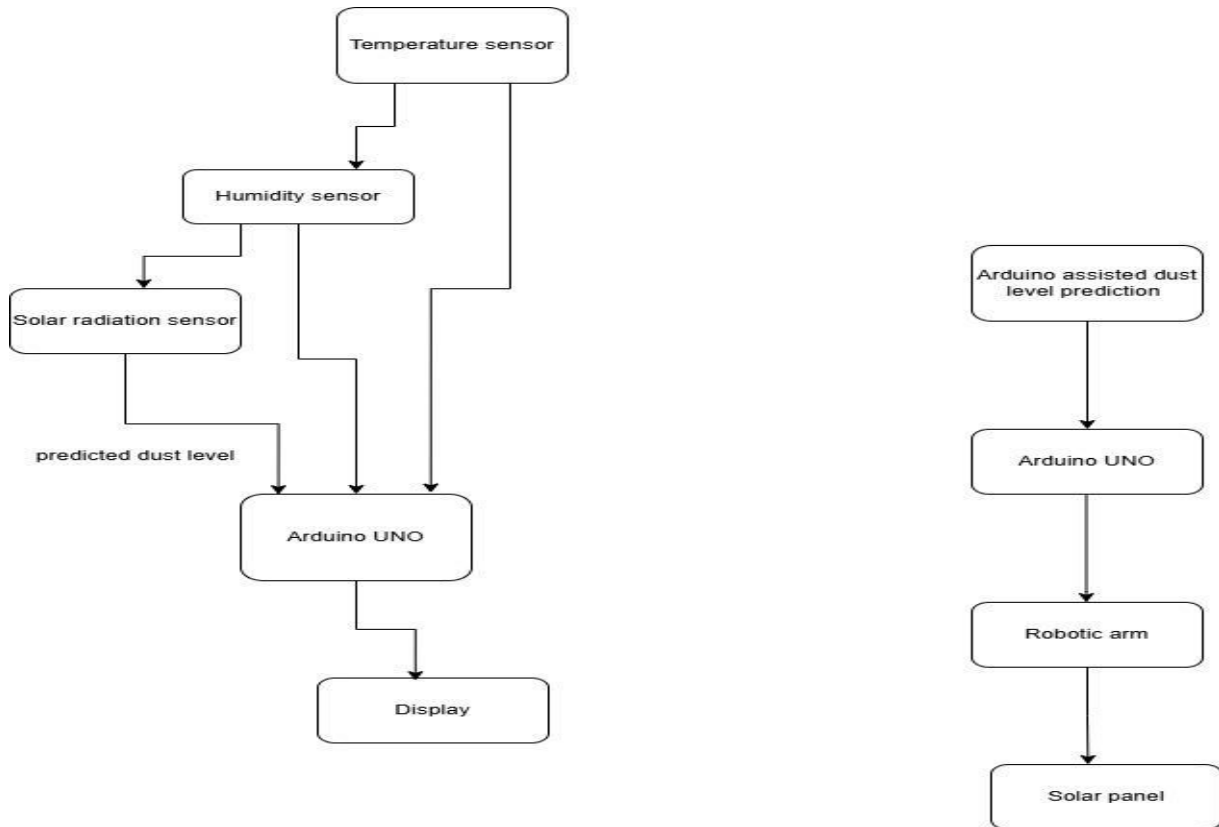


Fig. 1. Block diagram of the proposed method

Fig. 1. shows the block diagram of the proposed method. Temperature sensor and Humidity sensor are used in this proposed work for monitoring the environmental conditions [9], [15]. An Arduino UNO receives real-time data from temperature, humidity, and solar radiation sensors and uses it to forecast the amount of dust. This information is used for monitoring purposes. A robotic arm is controlled by another Arduino to clean the solar panel based on the anticipated level of dust. By automating cleaning according to environmental conditions, this system helps maintain solar panel efficiency.

FLOW CHART:

The flowchart shown in fig. 2 explains an AI-powered system designed to automate solar panel cleaning. It starts by gathering data from sensors that monitor temperature, humidity, sun radiation, and the soiling index. The amount of dust that has accumulated on the panels is then predicted using a hybrid AI model that combines LSTM and KNN algorithms. If the dust level rises above a pre-set threshold, the system starts a hybrid cleaning procedure. If not, it simply stops the process, saving energy and avoiding unnecessary cleaning.

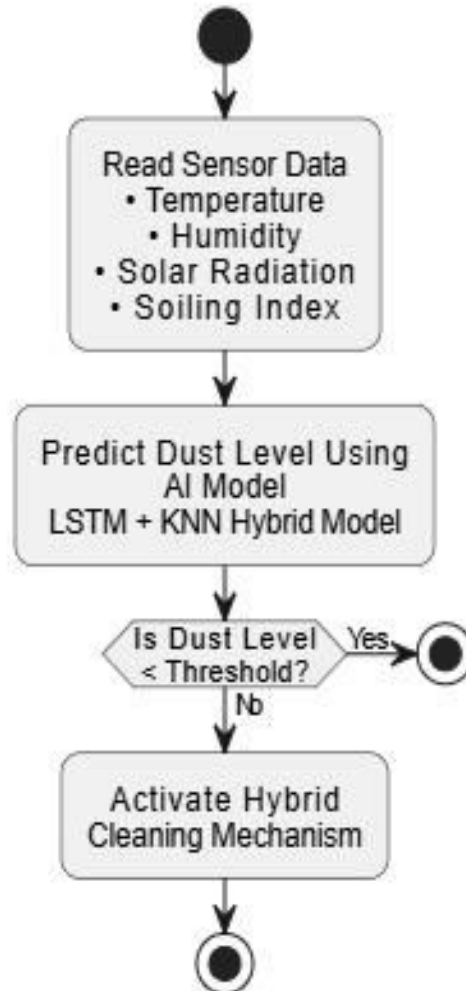


Fig. 2. Flow chart for the proposed method

IV. DATASET AND MODEL TRAINING

The proposed system considers the data set which is 2000 labelled images of solar panels categorized into three classes—clean, mildly dusty, and heavily dusty. The images are collected under various lighting and environmental conditions to augment the model adaptability and accuracy [12], [17]. Data augmentation techniques like flipping of images horizontally and vertically, changing in their brightness, rotating and cropping are performed for exposure of the training data to more variations to improve the model's performance.

DenseNet169 was trained using pre-trained images from the ImageNet dataset and resized to 224 by 224 pixel dimensions fed into the model. The training was done using the Adam optimizer with a batch size of 32 for 25 epochs and a learning rate of 0.0001. The model gave the best performance of 98% training accuracy and 96% validation accuracy. This demonstrated that it could generalize well for unseen data. LIME and Grad-CAM explainability tools are being used to make a model's predictions easier to understand and more transparent. Such methods will highlight the parts of images that will be responsible for the decisions made by the model, thereby ensuring that the predictions are sound and justifiable.

V. IMPLEMENTATION AND RESULT

The hardware components used are Arduino UNO, ESP8266 Wi-Fi module, Motor driver (L298N), DC gear motors and servos, Water pump, Camera module (Raspberry Pi or USB webcam). The software used are Python (TensorFlow/Keras) for AI model, Arduino IDE for robotic control and Blynk/ThingSpeak for IoT UI.

PERFORMANCE SUMMARY:

Metric	Value
CNN Dust Accuracy	96% (DenseNet169)
Voltage Gain Post-Cleaning	20–30% increase
Water Usage Reduction	40% (via smart control)
IoT Latency	< 2 seconds

The table shows the field testing of the proposed system. This table clearly indicate consistent system performance and significant improvement in energy output after timely cleaning.



Fig. 3. Solar panel cleaning system

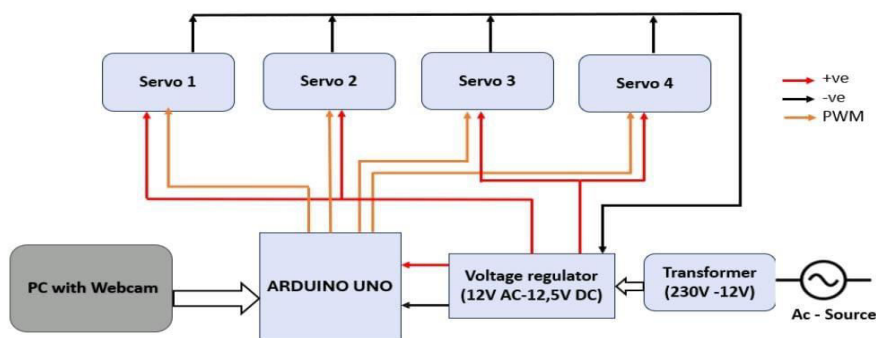


Fig. 4 Arduino Uno setup for controlling a robotic arm

Fig. 3 shows the representation of the solar panel with dust and the sensor available in the proposed system detects dust. The robotic arm starts cleaning process. The schematic diagram shown in fig.4 demonstrates a Arduino Uno setup for controlling a robotic arm. The Arduino receives signals from a webcam-equipped computer that records live video and instructs the four servo motors on how to move. A transformer and voltage regulator are used to transform a standard AC source into a safe voltage that powers the entire system. This is a neat and useful method for ensuring that the robotic arm reacts fluidly to what the camera sees.

VI. CONCLUSION AND FUTURE WORKS

In this article, we have integrated smart dust detection, robot cleaning and IoT connections to present a new AI based system for maintenance of solar panels. The hybrid cleaning system provides an effective, subconscious, and automated method for maintaining clean and energy saving solar panels. The future enhancements can be Solar-powered robotic mobility, Autonomous scheduling via predictive analytics, Integration with mobile apps and cloud services, Scalable deployment for solar farms.

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