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AI-Powered Solar Panel Cleaning Scheduler: Detecting Efficiency Drop, Dust Levels, And Automating Scheduling

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Abstract:
Dust and pollutants settling on solar panels have a dramatic effect of reducing the energy conversion efficiency of solar panels and hence result in a de-performance and increased maintenance. The paper will introduce an AI-based solar panel cleaning scheduler that identifies the presence of dust and performance decline on the panel and performs autonomous cleaning scheduling. The proposed system combines the solar and mobile powered rover stationed on an ultrasonic sensor, motor driver, DC motor as well as real-time clock (RTC) in order to have intelligent monitoring and time-controllable operation. The panel surface is traversed by the rover using an automated cleaning mechanism in which the rover is driven by a motor in order to clean itself whenever a pre-established decrease in efficiency or increase in dust level has been detected. Based on the trends in the intensity of sunshine, dust density, and power output, the AI module, which is educated on real-time efficiency and environmental data, predicts the best cleaning time. A small controller is powered by a 10 V solar battery and manages sensor values, the rover and cleaning controls and coordinates the movement of the rover and sensor-reads, as well as broadcasting the obtained readings to the display and related management systems. Experimental confirmation proves that the proposed design will be efficient in keeping the panel functioning and reduced cleaning cycles will be minimized making the design efficient in yielding energy and using less water and workforce. This paper showcases the opportunities of using AI in conjunction with IoT sensing and robotic automation in order to create self-scheduling, intelligent solar maintenance systems.

Keywords: Artificial Intelligence, Solar Panel Cleaning, Efficiency Prediction, Dust Detection, IoT, Rover System.

INTRODUCTION

World recognition of the need to use sustainable and clean energy has enhanced the rapid application of solar photovoltaic (PV) systems in residential, industrial and utility industries and application. The long-term performance of PV installations, however, is deteriorated severely by the soiling which is a phenomenon due to deposition of the dust and pollutants and bird droppings on the face of solar modules. It has been found that the soiling may lead to losses of power between 5 and more than 30 percent based on the local climatic conditions and frequency of maintenance [1]. The old school forms of maintenance like periodic (or manual) cleaning are ineffective, as they either consume resources or they cannot react quickly to actual degradation of performance in real-time [2]. In order to break these inefficiencies, researchers have progressively embraced the use of Artificial Intelligence (AI) and Internet of Things (IoT) to allow predictive and adaptive cleaning to PV systems [3], [4]. Parameters that AI algorithms use in calculating efficiency losses and determining the optimal cleaning period are irradiance, temperature, voltage, humidity, and dust density. In combination with IoT sensors, the following systems are always able to retrieve real-time data, so this data enables an automated decision-making process without human intervention [2], [8]. In addition to increasing the yield of energy, such integration reduces water, labour and energy expenditure, which are incurred in the process of cleaning periodically by man [1], [5]. The predictive maintenance structure has also been made even stronger with the latest developments in machine learning (ML) and computer vision. Convolutional Neural Networks (CNNs) and Reinforcement Learning (RL) architectures are effective deep learning architectures employed to detect dirt presence, identify intensity of the soiling spot, and optimize the cleaning process using dynamically controlled deep networks [3], [5]. The AI-based approaches are better than the conventional cleaning solutions because they are more accurate and efficient in cleaning and produce a more reliable and sustainable PV system [9]. On the same note, camera-fitted smart sensors on robotic cleaning mechanisms are now in a position to undergo autonomous cleaning round trips that can be triggered by data [5], [10]. Simultaneously, with these developments, Digital Twin (DT) and AIoT (Artificial Intelligence of Things) technologies have been noted to be a prospective solution to virtual modelling and predictive optimization of solar assets. A Digital Twin combines the data of IoT sensors and creates an imaginary environment that enables operators to simulate the soil effects, approximate energy loss, and organize maintenance schedules [6]. Additionally, the optimization methods like linear programming have also been incorporated in order to determine the most economical frequency of cleaning by balancing the trade-off between the cleaning and recovery of energy [7]. Although much has changed, there are still a number of research gaps. Most of the existing models continue to be based on threshold-based activation or localized datasets and this constrain their ability to adapt to varied environmental conditions [8]. Moreover, to create large solar farms, edge-enabled AI systems with the ability to process data of multiple sensors in a real-time manner are needed [3], [10]. The emphasis of future work is on creating self-learning AI processes to adapt dynamically to changes in climatic conditions and dust particle composition and site-specific conditions. The interplay of AI, IoT, and robotic automation, therefore, is the future of attaining smart, sustainable, and cost-effective maintenance of the solar panels.

LITERATURE REVIEW

One of the most significant achievements of recent years in the field of monitoring and maintenance of photovoltaic (PV) systems is the use of Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), and robots. Several papers of 2020-2025 have examined predictive cleaning, efficiency optimization, and intelligent scheduling system of solar panels. This part is a summary of major contributions made in ten exemplary works among this new research. Dhimish and Al-Habaibeh [1] presented an algorithm based on machine learning to predict predictive maintenance in an installation of PV panels. In their model, they were based on the environmental and weather conditions including irradiance and temperature data to forecast the soiling rates and suggest cleaning time. Experimental verification expressed that annual increment of energy yield was about 5.2 percent, and as a result, it was acceptable that substituting fixed-interval cleaning with information-driven scheduling is advantageous. The need of the localized soiling sensor and models that would manage the micro-climatic variations was identified in the study, though. Kale et al. [2] designed an IoT-based system of automation that used motorized wipers, light sensors and a microcontroller to control cleaning in real-time. Remote monitoring and mobile alerts helped the system to maintain a consistent cleaning of the surface and power enhancement. Despite its effectiveness, it was based on the idea of threshold activation, as opposed to the actual predictive algorithm, which encouraged the use of AI in the future to develop intelligent scheduling. An AI-based robot vacuum with Deep Learning and reinforcement learning (RL) was presented by A. R. L. R. A. M. H. F. N. A. H. with a preprint [3]. The CNN-LSTM-based vision model identified the dirty parts on the surface with the help of aerial and ground photos, whereas RL was trained to plan the cleaning process in the most resource-efficient way possible. The cleaning efficiency (91.3) and the savings in energy and water (34.9 -) of the system were achieved. Some recommendations were made on the edge-computing performance to improve in the future to enable large-scale deployment. Al-Humaira et al. [4] used ensemble ML models, such as stacking and boosting, to estimate predictive cleaning schedule with the help of historical performance data. They also were much more accurate than the single algorithms, which proved the importance of the data augmentation approach in maintenance prediction. They observed that the ability to add to robustness would be through the introduction of particle composition and diversity of dust size. Patidar et al. [5] built a computer-vision-based floor cleaner with the help of CNN (VGG-16) to detect dust and bird droppings. The robot was dynamically chosen to choose between dry cleaning and wet cleaning depending on the type of contamination, and more power was provided to the robot after cleaning. The authors recommended their design to multi-robot coordination of large solar farms. Ossa et al. [6] examined a Digital Twin (DT) architecture that combined AI and IoT data to PV performance Modelling. A virtual model of physical panels, such as that offered by the DT, could predict the maintenance needs and optimize the energy consumption of construction. The study revealed the scope of DTs in predicting soiling and logistics of clean up though the scope was extended to smart-city uses. Al-Dmour et al. [7] suggested the optimization model based on linear programming, according to which the most cost-effective cleaning intervals were determined based on the environmental (wind, humidity) and cost factors (water, labour). The model found ideal timing in terms of maximizing net energy gain but in comparison to AI-based soiling prediction, they failed to be as adaptable, and their recommendation that should be added in future developments. The article by Jumaa et al. [8] elaborately came up with a low-cost IoT cleaning mechanism through the use of LDR and INA219 sensors that identified a lower light intensity and voltage due to dust. A pump was used to lavish the panes at the thresholds. Although the design was cost-effective and convenient, the authors admitted that threshold-based logic may be substituted by ML prediction to enhance its efficiency. Alnami et al. [9] worked on the problem of machine-learning-based soiling classification with Support Vector Machines (SVM) and Logistic Regression models trained on sensor and weather-station data, embedded into the machine. Their system had more than 92% classification accuracy and more or less 30% reduction of unnecessary cleanings. They suggested that this work be extended to a time-serial prediction of the soiling accumulation to predict when cleaning is required. Lastly, Al-Shehri et al. [10] published hybrid cleaning robotic system enhanced with real-time efficiency monitoring. The experimental findings have shown that, following every cycle of cleaning, the power output for improvement is 10-30% which confirms the influence of automated intervention. They advised having the efficiency-monitoring unit attached to an AI scheduler, which will fully automate it. Altogether, all these papers demonstrate that the solar panel maintenance practice is changing due to AI-augmented predictive maintenance and IoT-based sensing. The initial literature focused on activated by a frequency signal or threshold [2], [8], whereas the latest literature manages the deep-learning-based approach, digital twin, and optimization model to adjust to real-time adaptability [3], [4], [6], [7]. However, there are still major obstacles, including incorporation of heterogeneous sensor data, generalization in terms of climatic regions, as well as, energy-efficient calculation as an edge device [1], [9], [10]. Future attempts should therefore aim at self-education, scalable and resource conscious systems that could autonomously take care of PV cleaning to promote greater sustainability and endurance at a cause reasonable expense.

PROPOSED METHODOLOGY

The proposed AI-based solar panel clean schedule will be an intelligent system that is used to monitor and predict the cleaning of photovoltaic (PV) panels, with intelligent management of the cleaning process to maintain maximum efficiency with a minimum of human intervention. The system architecture is designed to have five main modules including sensing unit, control and processing unit, mobility system, power management unit, and AI-based decision module. All the modules work in concert to recap dust buildup, determine the loss of efficiency and carry out the cleaning procedure automatically, depending on real-time information analysis.

A. Sensing Unit

The sensing subsystem constantly records the environmental and performance parameters which determine the solar panel output. The ultrasonic sensor is used to measure the level of dust deposition by measuring the intensity of the reflected signal at the panel surface. The fluctuations in the returning signal are used to approximate the degree of soiling. At the same time, voltage and current sensors are used to determine the electrical performance of the panel to compute the instantaneous efficiency. Data that are gathered is communicated to the controller to be processed and made decisions.

B. Control and Processing Unit

The microcontroller is in the centre of the system, which processes sensor information and implements the cleaning program. The controller is joined to DC motors used to move the cleaning rover through a motor driver. The controller has an algorithm of comparing real-time efficiency data and dust levels to intended thresholds. A Real-Time Clock (RTC) integrated component makes sure that time tracking is performed correctly during the maintenance operations schedule and events recording. This facilitates short term implementation as well as long term tracking.

C. Rover Mobility System

The cleaning agent which is the rover mechanism. It travels independently across the surface of the solar panels with DC motors being powered by Pulse Width Modulation (PWM) signals to provide a high level of accuracy and smooth movement. The rover has a mechanical cleaning brush or air-blowing arm that code sly cleans the dust and debris stuck on the surface of the rover. The ultrasonic sensor has also been used as an obstacle-avoidance device with the purpose of making sure the rover does not run into something which would damage the panel surface.

D. Power Management Unit

The power subsystem will be powered by a 10 V solar battery that will be charged right through PV array. The design ensures that the cleaning system is self-sustainable and energy-saving even in off-grid or remote installations. The power regulation circuit provides constant voltage levels to other modules as well as focuses at conserving energy in case of the system being in the standby or low-activity state.

E. AI-Based Decision Module

The smartness of the system suggested is in the model of Artificial Intelligence (AI), which promises to predict the best times to clean the house based on the correlation between the environmental condition and system performance. Supervised machine learning methods are used in the model of regression analysis or a small-scale neural network using datasets consisting of irradiance, temperature, dust density, and of power output. When the forecasted efficiency drop in the future surpasses a predetermined limit, the AI agent automatically sets up a cleaning task. It reduces cleaning cycles which are not required and conserves energy and water thus being an adaptive strategy.

F. System Communication and Data Logging

The operational parameters such as efficiency records, cleaning schedules and performance history are stored locally through the RTC module and either sent remotely to an IoT platform in the cloud to be monitored and analysed. The connectivity can be used to perform long-term performance monitoring, predictive maintenance, and optimization of operating solar panels, which depends on the data.

PROPOSED WORK:

The proposed project is aimed at creating a smart, independent system, which will monitor and clean the solar panels automatically according to the efficiency analysis in real-time and the environmental factor. The system incorporates several modules such as sensing, control, mobility, and power management that operate as a single module on the basis of an AI-oriented decision-making system. A ultrasonic sensor constantly monitors the dust on the surface of the solar panel, voltage and current sensors monitor the performance degradation. These inputs are processed by a microcontroller that sends feedback to the motor driver to operate the cleaning mechanism mounted on the rover that is driven on DC motors. The Real-Time Clock (RTC) module that is built-in logs cleaning cycles and coordinates it with time. The set up uses a 10 V solar battery to provide power to the whole system and therefore the system does not need external sources of power. An artificial intelligence system estimates the efficiency decrease based on data of past cycles and environmental patterns and cleans only when it is needed. This flexible system makes the process more efficient in energy production, causes less maintenance, saves both water and electricity, and leads to more sustainable use of this robotic system.

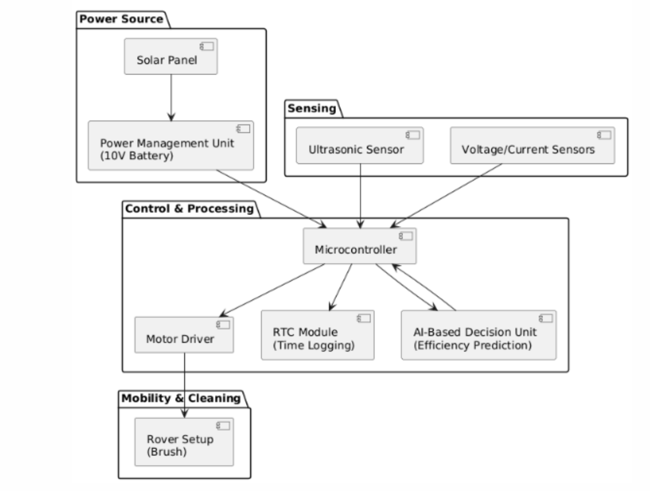

Fig. 1. Work Flow of proposed system

DATA AND PREPROSSING:

Data Description:

The data needed in this work is received via the suggested AI-supported solar panel cleaning planning device, with the help of real-time measurements of sensors. The information indicates the functioning condition and output features of photovoltaic (PV) panel system. Data samples are buffered at constant time intervals and time-stamped with a Real Time Clock (RTC) module in order to log the data accurately. The data of every dataset record is completed with the following parameters: inputs of the ultrasonic sensor which show dust concentration, panel voltage, panel current, computed power output, estimated efficiency, ambient temperature, solar irradiance (when present), cleaning status, and the date and time. The dataset comprises of the readings taken in normal conditions of dusty panels, partially soiled, and heavily soiled panels in order to simulate the real-life operating conditions.

Data Collection Process:

The microcontroller keeps on receiving the information in the sensing unit. The electrical output of the PV panel is measured using voltage sensors, current sensors and ultrasonic sensor measures surface dust deposition by de-resonating reflected signals. The instantaneous power output is determined with regard to the values of voltage and current obtained. Data that is being collected remain locally and can be sent to the external storage or cloud-computer-based platform to be analysed and monitored on a long-term basis.

Data Preprocessing:

Raw sensor presentation can have noise, irregularity, and lose of values owing to environmental changes and sensor constraints. Thus, the dataset is pre-processed prior to making decisions based on the dataset. To remove noise, first, an abnormal sensor readings removal and averaging to smoothen the data is done. Second, values (via lack of sensors or communication) are eliminated expectedly by substituting with the last validity of the readings, or by eliminating records. To make the parameters numerical, all of them are placed on a shared scale. It eliminates the tendency of any individual feature, e.g. voltage or current, to overtake the decision process of the system. Solar panel performance is then determined based on the electrical parameters measured and against the output of the panel based on rating to determine performance degradation due to accretion of dust.

Data Labelling and Segmentation:
According to the efficiency loss and level of dust, every piece of information is assigned to Cleaning required or No Cleaning Required. These tags assist the system to understand the circumstances that lead to the need to clean. The final processed data is further split into training and testing data to test the performance of the cleaning scheduler in various environmental and operating conditions.

Prepared Dataset for System Operation:
Following pre-processing, the dataset is organized, predictable, and viable towards predicting the best cleaning schedules. The resulting processed data allows identifying efficiency loss with proper accuracy, unnecessary cleaning procedures, and efficient use of the energy within the systems aimed at solar panel maintenance.

Hardware setup

- Solar panel
- DC Motor
- Rover Setup
- Ultrasonic Sensor
- Real-Time Clock (RTC) Module
- Motor Driver
- NODE MCU

Software setup

- Arduino IDE
- Embedded C

NODEMCU

The NODEMCU is a compact, low-cost microcontroller based on the ESP8266 Wi-Fi module, serving as the central processing unit for the AI-powered solar panel cleaning scheduler. It collects real-time data from ultrasonic sensors, voltage, and current sensors, processes this information using the AI decision algorithm, and sends control signals to the motor driver to operate the DC motors of the rover. Its built-in Wi-Fi allows for remote monitoring and data logging, while PWM outputs enable precise control of motor speed and direction. The NODEMCU also interfaces with auxiliary components such as the Real-Time Clock (RTC) module to maintain accurate cleaning schedules. Its combination of processing capability, connectivity, low power consumption, and ease of programming makes it ideal for autonomous, intelligent, and IoT-enabled solar panel maintenance systems.

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ULTRASONIC SENSOR

The ultrasonic sensor measures the distance between the rover and the solar panel surface to detect the accumulation of dust or debris. By sending and receiving high-frequency sound waves, the sensor calculates the surface distance, providing real-time data to the microcontroller. This data is used by the AI-based decision module to assess cleaning needs and ensure obstacle avoidance, thereby preventing collisions or damage to both the rover and the panels during autonomous operation.

Motor Driver

The motor driver module acts as an interface between the NODEMCU microcontroller and the DC motors of the rover. It receives low-power control signals from the microcontroller and amplifies them to provide sufficient current and voltage for smooth and precise motor operation. The motor driver ensures coordinated movement of the rover across the solar panel surface while preventing overloads or damage to the motors. By enabling forward, reverse, and speed control through PWM signals, the motor driver plays a critical role in the autonomous navigation and operation of the cleaning mechanism.

10V Solar Battery

Stores energy from the solar panel and supplies regulated power to the microcontroller, motor driver, sensors, and rover motors.

Solor panel

Connected to the microcontroller, it measures the dust accumulation by detecting the distance from the panel surface. It also functions in obstacle detection, sending real-time signals to the controller to prevent collisions.

Real-Time Clock (RTC) Module

The Real-Time Clock (RTC) module provides accurate timekeeping for the entire system, enabling scheduled cleaning operations and precise logging of all maintenance activities. It interfaces with the NODEMCU microcontroller to record timestamps for each cleaning cycle, sensor readings, and operational events. By maintaining consistent timing even during power fluctuations or temporary outages, the RTC ensures that cleaning schedules are reliably followed, supporting the adaptive AI-based maintenance strategy of the solar panel cleaning system.

DC MOTORS

DC motors provide the locomotion required for the rover to traverse the solar panel array. Controlled via the motor driver module, the motors allow precise speed and directional control, ensuring that the cleaning brushes or air jets effectively remove dust without damaging the panel surface.

Their robust construction and compatibility with PWM signals make them suitable for sustained operation in outdoor environments, supporting the autonomous cleaning cycles dictated by the AI scheduler.

Embedded C Programming

Embedded C is a specialized extension of the C programming language designed specifically for programming microcontrollers and other embedded systems. Unlike standard C, Embedded C provides features for directly interacting with hardware, such as addressing specific memory locations, performing fixed-point arithmetic, and handling input/output hardware directly. Embedded systems themselves are dedicated devices created to perform specific tasks, comprising both hardware and integrated software (firmware). Embedded C is widely used to program microprocessors and microcontrollers efficiently, requiring fewer system resources compared to lower-level languages like assembly.

The language also includes unique data types and keywords tailored for hardware interaction. For instance, SBIT and SFR are used to access special function registers in memory. Embedded C facilitates direct communication with sensors, actuators, and other I/O devices, making it ideal for real-time control applications. Programs written in Embedded C can be compiled using various compilers such as Keil, SPJ Compiler, and Embedded GNU C Compiler. Embedded systems can range from simple devices to complex machinery, and Embedded C is employed in everyday electronics such as air conditioners, printers, and mobile phones.

Arduino's programming concept

Arduino is a user-friendly platform designed for creating interactive physical computing projects. Built around a microcontroller, Arduino provides a direct interface with the physical world, allowing devices to sense inputs from switches, sensors, or other components and control outputs such as motors, lights, or displays. Its integrated development environment (IDE) simplifies programming and uploading code to the board.Arduino boards can operate independently or communicate with computer software for more advanced applications. They are available as pre-assembled or DIY kits, and the open-source design allows anyone to download and modify the hardware and software. The Arduino programming language is derived from Wiring and inspired by the Processing multimedia framework, enabling intuitive coding for interactive objects and physical computing devices. This combination of simplicity, flexibility, and accessibility makes Arduino widely used in robotics, automation, and IoT projects.

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RESULTS AND ANALYSIS

The effectiveness of the proposed system of cleaning solar panels was checked by testing them in different dust and body conditions. The system was constantly checking the dust levels and electrical parameters like voltage, current and power output and cleaning was only done when the efficiency was reduced to a given limit. The findings indicated that panel efficiency decreased slowly as dust was deposited and could be regained by cleaning guiding the power production to nearly normal levels. The proposed system prevented needless cleaning and minimized on maintenance work as compared to the conventional method of cleaning that followed a fixed schedule. It also decreased cleaning frequency according to the real dust conditions and so efficiency loss was not severe during the high damp hours. This system used less energy than the one that was used after cleaning and hence it is self-sustaining. All in all, all the findings prove the enhanced efficiency, the increased energy usage, and the stable automated functioning.

Comparison tables:

TABLE 1: SOLAR PANEL PERFORMANCE BEFORE AND AFTER CLEANING

Condition	Voltage (V)	Current (A)	Power Output (W)	Efficiency (%)
Clean Panel	18.6	3.2	59.52	100
Moderately Dusty	16.9	2.8	47.32	79.5
Heavily Dusty	15.2	2.4	36.48	61.3
After Cleaning	18.4	3.1	57.04	95.8

Observation:
The table shows a clear reduction in voltage, current, and power output as dust accumulation increases. After cleaning, the panel performance is restored close to its original condition.

TABLE 2: CLEANING FREQUENCY ANALYSIS OVER 30 DAYS

Method	Number of Cleanings
Fixed Interval Method	12
Proposed System	06

Observation:
The suggested system also minimized the cleaning processes by an estimated 50 percent showing improvement in utilization of resources.

CONCLUSION:

The suggested photovoltaic system cleaner with a solar panel cleaner is an effective system towards ensuring that the performance of photovoltaic systems is maintained via automated monitoring and cleaning. When fitted with sensors, microcontroller, and a mobile cleaning mechanism, the system can identify the presence of dust and diminishing efficiency, and it can clean up only when it is necessary. Its utilization of a solar-powered battery assists in the active and energy-efficient functioning, even in the far-off areas. A Real-Time Clock is used to schedule it correctly and it can be optionally monitored remotely to track how it performs over time. The outcome means enhanced power production, less manual interaction and less effort in maintenance. In general, the system represents a feasible and scalable approach to enhance the solar panel efficiency and allow sustainable energy production.

FUTURE SCOPE:

The performance of the proposed solar panel cleaning system can be enhanced further by including more environmental sensors like wind speed, humidity and rainfall sensor to improve the performance of the dust detectors. It is also possible to expand the system to handle larger solar farms by using a centralized system with several cleaning rovers. Cleaning prediction can be done by using advanced techniques of data analysis to take into account long-term performance data. It can be integrated with weather forecasting systems and allow avoiding unnecessary cleaning when it rains. Furthermore, mechanisms of lightweight and waterless cleaning may be used to minimise the use of energy and other resources. This will improve system reliability, scalability, and applicability in large scale solar energy institutions.

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