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Solar Panel Cleaning Bot

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***Abstract*— In recent times as the implantation and use of Solar technology has increased it also has brought some challenges like dust, moisture and environmental debris have a significant impact on solar panel efficiency, lowering energy output. Thus, the idea to design and development of solar panel maintenance bot able to clean and cover the panel surface is explored in this study as a solution to this problem. A microcontroller is used to control and interact with different sensors such as motion sensor, dust sensor, moisture sensor and light dependent resistor supporting in automate cleaning activities. Through ultrasonic edge detection the cleaning unit's motorized dust roller mechanism runs across the solar panel on its own. The system can be accessed through remote control or manual override. This integrated system delivers a safe and inexpensive way to preserve solar panel efficiency particularly for situations where it is exposed to great amount of dust or rain.**

***Keywords*— solar energy, photovoltaic efficiency, panel cleaning robot, automation, node mcu, environmental sensors, solar technology, rain detection, smart solar maintenance.**

I. INTRODUCTION

Owing to the absence of pollution and its large and inexhaustible supply, solar energy is seen as a promising renewable energy source. The rise in global energy consumption and the need to lower greenhouse gas emissions has created demand for photovoltaic (PV) technology in today's energy systems. The decreasing average cost of PV modules and their ability to scale up have facilitated the installation of PV technology on residential rooftops, industrial sites and commercial buildings. However, solar panels will have reductions in efficiency over time due to dust, bird droppings, moisture and atmospheric pollutants experienced from prolonged exposure to environmental conditions. In response to these challenges, this research presents a semi-autonomous Solar Panel Cleaning and Covering Bot which can intelligently perform cleaning. This solution addresses notable gaps in existing research by integrating both major functions into a single compact and modular unit.
Moreover, the use of cheap materials (like PVC for the chassis and ultrasonic sensors for edge detection) promotes mechanical safety and flexibility, suitable for a variety of panel configurations and mounting angles. This is an all-in-one system that will work in both urban rooftops and rural off-grid installations. Future improvements could include self-charging utilizing solar panels on the bot itself, GPS positioning and weather API integrations to offer increased autonomy. Overall, this project is a scalable and innovative approach to extend the lifespan of PV systems to enhance cost effectiveness and energy output tied to sustainability efforts globally.

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II. LITERATURE REVIEW

A significant amount of research has sought strategies to boost the performance of solar panels and enhance automated sustainment systems. In particular, Gupta and Sandhu [1] demonstrated that Particle Swarm Optimization (PSO) algorithms outperformed traditional Maximum Power Point Tracking (MPPT) algorithms under partially shaded conditions, demonstrating the promising of intelligent algorithms for enhancement of energy consumption. Mohana Sundaram et al. [2] proposed a self-cleaning photovoltaic panel to help efficiencies and minimize manual tasks through the use of microcontrollers and object-recognition algorithms. Manju et al. [3] proposed an Arduino based rolling-brush cleaning mechanism capable of recovering nearly fifty percent of output loss from the accumulation of dust; however, their work lacked full autonomy and needed modifications to implement sticky dust removal.

Bhandari et al. [4] developed a semi-automated cleaning system, which led to an improvement in panel performance of seven percent while remaining cost-effective. Najmi and Rachid [5] conducted an extensive review study of manual and automated cleaning approaches (including robotic systems, drones, and electrostatic cleaning screens) while delineating clean between cost, environmental impact, and efficiencies. The authors provided further reasoning that while several techniques have been developed to combat performance loss due to dust coverage (upwards of forty percent), adjusting reliance on intelligent control, automation and dual-function methodology merits more exploratory thought, as it is an evolution.

Recent publications have highlighted AI-enabled scheduling and data-driven maintenance. For instance, Oluwamuyiwa et al. [6] and Navle et al. [7] examined smart solutions that utilize programmable logic controllers (PLCs) with IoT integration for monitoring and cleaning the panels in relation to dust. Alghamdi et al. [8] and Gheitasi et al. [9] proposed designs for portable, automated systems to clean extensive photovoltaic systems, whereas Jawale et al. [10] designed surface-sensing bots that clean panels in a more effective and creative way. Chakraborty et al. [11] developed a cleaning robot with wireless communication to allow users to manage the cleaning robot remotely, enhancing access and control. Similarly, Rajgure and Shahakar [12] proposed a cheaper machine design through (a) engineering towards simplicity, while reliability was also highlighted as an important feature.

In addition, Sandey et al. [13] and Ghate et al. [14] examined robot mobility through new mechanical developments surrounding flexibility to traverse the panels more efficiently. Kulkarni et al. [15] employed semi-automated methods with IoT to increase robot responsiveness and minimize dust detection and modified a cleaning robot. Jaradat et al. [16] proposed a fully portable robot cleanings system prototype to facilitate field cleaning of PV installations. Last, Deshmukh et al. [17] added to the advancement with "CLEAROSO", a design for a solar-panel cleaning robot that utilizes modular construction and adaptable sensors. Sairaj and Reddy [18] examined robotic cleaning in a more automated perspective, applying control algorithms to enhance cleaning precision and clean reliability.

Collectively, these studies indicate an impressive advancement in robotic solutions for solar PV maintenance and also signal a persistent gap in research system. It is this gap that the present study is motivated to address.

III. METHODOLOGY

A. Bot Architecture

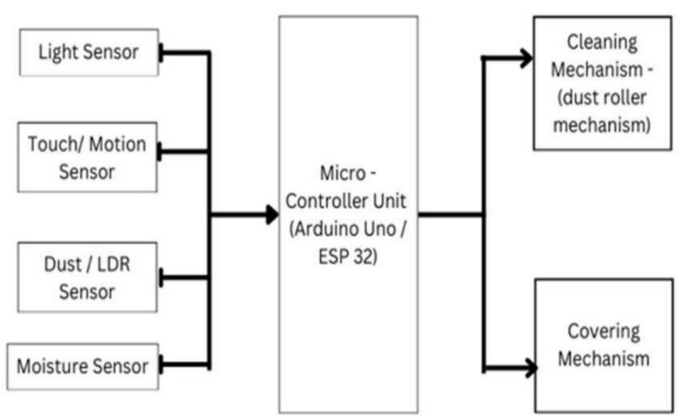


Fig.1. Circuit Design of System

The design as show in Fig. [1] below aims to reduce the performance decline in solar panels as a result of various environmental conditions like dust accumulation, moisture retention and adverse weather. The system is based on a Node MCU / ESP8266 microcontroller, which is the central unit of process and communication and will receive inputs from several environmental sensors (dust, moisture, LDR, ultrasonic distance sensors). Each of these sensors contributes to environmental sensing which allows the system to assess current conditions and make automated or physical movements.

The cleaning mechanism shown in Fig. [2] features a rotating brush that is driven by a motor, mounted horizontally to traverse the surface of the solar panel for cleaning dust and debris. This brush assembly is located on a small chassis made from lightweight PVC material for corrosion resistance and stability. Ultrasonic sensors are positioned along both sides of the bot, allowing it to continuously assess proximity to panel edges, preventing the device from slipping off the end of the device edges. The brush motors are concurrently activated through the motor drive circuit in situations where either dust accumulation exceeds defined parameters or in situations where sunlight exceeds defined parameters for acceptable conditions.

B. System Working

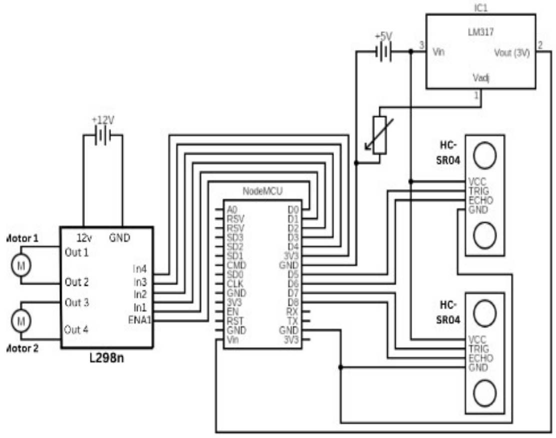


Fig.2. Block Diagram of Cleaning System

The ESP8266 Node MCU is the core processing unit with built-in Wi-Fi and it is responsible for processing the sensor data and driving the motors for the cleaning operation. The DC Motors will drive the rotating brush to remove any dust and debris to allow for maximum solar absorption. The Servo Motor will actuate the foldable cover to deploy when there is rain or inclement weather, controlled by the Node MCU. Ultrasonic Sensors will detect the edges of the solar array to halt motor operation and prevent tipping, while the Light Dependent Resistor (LDR) monitors for sunlight intensity that would indicate he solar panels needed to be cleaned due to a decrease in amount of light produced because of shade or dust accumulation.

The bot employs a cleaning mechanism that consists of a rotating brush system driven by a DC gear motor to clear dust, debris and light moisture from the solar panel's surface. The rotating brush is placed horizontally across the frame of the bot and extends the full width of the solar panel ensuring that the entire surface of the panel is covered in one pass while cleaning. The brush is linked to a 12V DC motor powered by a motor driver module (L298N) that connects to the Node-MCU microcontroller.

The automated cleaning is operated by predefined sensor thresholds that enables an accurate response to environmental conditions. The dust sensor initiates a cleaning cycle whenever the dust exceeds the preset level, provided that no moisture is detected on the panel surface. Moisture readings around 30%-40% stops the cleaning to prevent damage to the bot during rainfall. The LDR ensures that cleaning is restricted to daylight when light surpasses the required 12,000–15,000 lux range. Ultrasonic sensors continuously monitor the distance to the panel edges and trigger a stop or reverse action when the bot approaches 4-5 cm of a boundary, preventing accidental falls.

C. Power Consumption & Provision

To evaluate the energy requirements of the Solar Panel Cleaning Bot, each active component in the system was analysed for its voltage, current, and estimated power draw under typical operating conditions. Table 1 summarizes the power requirements of all components. The DC motors usually have the highest power consumption while the microcontroller and sensing modules in comparison have low consumption but remain active during complete operation, contributing to the total energy demand of each cleaning cycle. During each cleaning cycle, the system consumes energy from all components for approximately three minutes of operation. Based on measured power levels, the estimated total energy required for a single cleaning cycle around 0.27 W

TABLE I. POWER REQUIREMENTS OF COMPONENTS

Component	Voltage(V)	Avg-Current(A)	Power(W)
NodeMCU	5	0.08	0.40
DC Motor	12	0.35	2.10
Motor Driver	12	0.02	0.05
Ultrasonic Sensor	5	0.015	0.15
Dust Sensor	5	0.02	0.10
Moisture Sensor	5	0.035	0.175
LDR	5	0.005	0.025
Total Peak Power	~5.3		

IV. RESULTS AND DISCUSSION

In order to evaluate autonomous responsiveness, cleaning efficacy and electrical output improvement, the prototype solar panel cleaning and covering system was tested in a variety of operating and environmental conditions. Different operating modes, dust accumulation conditions and lighting levels were used to test the bot. The controlled test conditions taken into consideration during the experiments are compiled in Table 2.

When the dust concentration surpassed the predetermined threshold during autonomous operation, the system reliably started cleaning cycles. By successfully limiting device operation to daylight hours, the Light Dependent Resistor (LDR) module helped cut down on wasteful energy use. Throughout, the dust sensor operated steadily, allowing the cleaning sequence to be started on time. Throughout every trial, precise and quick decision-making was guaranteed by the Node-MCU microcontroller's integration of sensor logic.

TABLE II. TEST CONDITIONS FOR SOLAR PANEL CLEANING BOT

Sunlight Int.	Dust	Mode	Panel
5,000–10,000	Low	Automatic	20° tilt
20,000–40,000	Medium	Automatic	20° tilt
50,000–70,000	High	Automatic	20° tilt
50,000–70,000	High	Manual	20° tilt
5,000–10,000	Low	Automatic	20° tilt

TABLE III. ELECTRICAL OUTPUT BETWEEN DUSTY AND CLEAN PANEL

Time	Dusty	Clean	Diff	Change
06:00	~0.008	~0.008	0.000	0%
07:00	~0.012	~0.015	+0.003	+25.0%
08:00	~0.017	~0.023	+0.006	+35.3%
09:00	~0.020	~0.030	+0.010	+50.0%
10:00	~0.035	~0.040	+0.005	+14.3%
11:00	~0.050	~0.060	+0.010	+20.0%
11:30	~0.070	~0.070	0.000	0%
12:00	~0.085	~0.112	+0.027	+31.8%
12:30	~0.100	~0.120	+0.020	+20.0%
13:00	~0.090	~0.100	+0.010	+11.1%
13:30	~0.112	~0.130	+0.018	+16.1%
14:00	~0.100	~0.120	+0.020	+20.0%
15:00	~0.100	~0.125	+0.020	+25.0%
16:00	~0.050	~0.070	+0.020	+40.0%
16:30	~0.060	~0.070	+0.010	+16.7%
17:00	~0.012	~0.015	+0.003	+25.0%
18:00	~0.005	~0.008	+0.003	+60.0%

Table 3 displays the current output produced throughout the day by the dusty and clean panels. With the exception of 06:00 and 11:30, when both panels showed equal output, the clean panel continuously generated more current during all significant solar hours. The graphical trend Fig. [3] showed the bell-shaped curve predicted by irradiance, with midday performance at its peak.

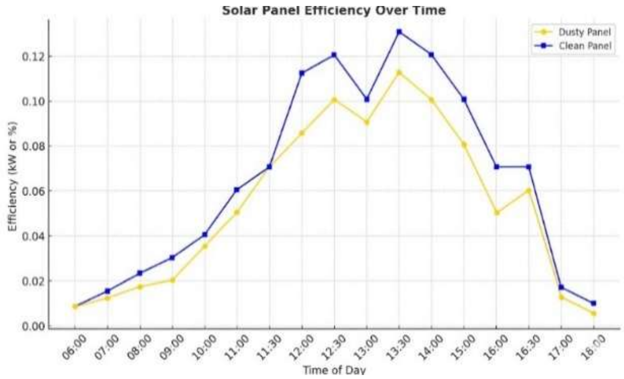
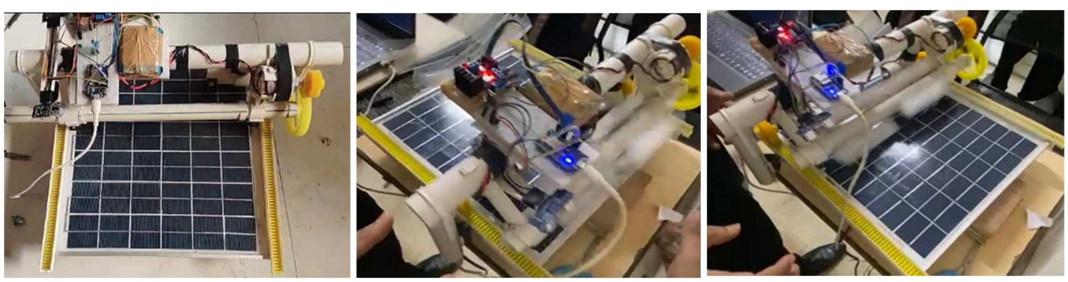


Fig. 3. Graphical representation of time v/s dust collection

Throughout the day, the clean panel continuously produced more current. At 13:30, the dusty panel only reached 0.112 A, while the maximum observed current was roughly 0.130 A. This corresponds to a 16.1% increase in peak efficiency. Due mainly to the lower baseline output at lower irradiance levels, the clean panel outperformed the dusty panel by 60% at 18:00, exhibiting the largest relative gain. According to the data, dust accumulation has a major effect on photovoltaic output, especially between 12:00 and 15:00 when irradiance is high. The significance of routine or automated cleaning was confirmed by the clean panel's performance advantage, which ranged from 20% to 32% during these hours.



(a) At Idle (b) Cleaning Process (c) Cleaning Completed (Idle again)

Fig. 4. Final Prototype of Proposed Cleaning Bot

The working model in Fig[4] shows how the Solar Panel Cleaning Bot's operational behaviour was verified through physical trials in addition to quantitative measurements. While the sensors assess environmental factors like dust concentration, sunlight intensity, and surface moisture, the bot stays motionless on the surface of the solar panel in its initial state. The system enters the cleaning phase when the dust threshold is surpassed, turning on the dual-motor rotating brush mechanism and moving laterally across the panel. The ultrasonic sensors ensure controlled motion without crossing panel boundaries by continuously monitoring edge proximity. The bot automatically stops moving and turns off the brush motors after finishing a sweep, going back to an idle state.

The bot showed great promise for field deployment by finishing entire cleaning cycles in a matter of minutes. Moisture sensing functionality was confirmed for future integration, even though the rain-covering function was not included in the Phase I implementation. Real-time control and decision-making were made possible by the Node-MCU microcontroller's effective integration of dust, LDR and ultrasonic sensors. The system demonstrated the resilience of the sensor logic by reacting instantly to changes in the surrounding environment. The Blynk platform's IoT connectivity allowed for remote monitoring and control, proving that a scalable cloud-enabled solar installation maintenance system is feasible.

V. Conclusion

This work presents the design, implementation and evaluation of a semi-autonomous solar panel cleaning robot as shown in Fig[4] to improve photovoltaic efficiency and reduce the need for manual maintenance. On a lightweight PVC chassis, the prototype incorporates a dual-motor spinning brush assembly, an LDR-based daylight activation module and a Node-MCU microcontroller with ultrasonic edge-detection sensors. According to experimental results, the system can effectively clean, detect environmental conditions and support both manual and autonomous operation through an Internet of Things interface. The shown performance confirms that automated cleaning is a feasible addition to utility-scale and rooftop solar systems.

Several improvements and features for future have been identified, including the fact that the current implementation only focuses on cleaning. These include enhanced sensor-fusion techniques to improve environmental perception, expanded IoT-based diagnostics for predictive maintenance, on-board solar charging for energy autonomy and the realisation of a weather-resistant protective covering mechanism. Furthermore, better mechanical structure, coordinated sensor control and future- ready hardware can be implemented to scale the system for large solar farms. The prototype and its results offer a technical base for upcoming efforts to standardise and improve with it being looking to develop automated solar maintenance systems.

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