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IOT-INTEGRATED AUTOMATED ROBOT FOR SOLAR PANEL CLEANING

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Abstract
The growing adoption of solar energy as a major contributor to the global energy transition highlights the need to maintain maximum photovoltaic efficiency. One of the primary issues affecting solar panel performance is the buildup of dust, dirt, and environmental pollutants. This study introduces the design, fabrication, and evaluation of an IoT-enabled automated robot developed to mitigate these losses. The system uses four DC geared motors for locomotion, driven by an ESP32 microcontroller connected to the Arduino IoT Cloud for wireless monitoring and control. The robot supports three modes of operation: remote manual control via the internet, a fully autonomous cleaning mode guided by embedded algorithms, and a patrol mode equipped with a water-spray cleaning feature. Experimental evaluation confirms that the robot delivers reliable cleaning performance under diverse surface conditions without causing any physical harm to the solar modules. IoT connectivity further facilitates scheduled or on-demand cleaning, making the system especially suitable for large solar farms and hard-to-reach installations. Overall, the proposed solution reduces labor effort and operational costs while sustaining optimal panel efficiency across residential, commercial, and industrial setups.

1. INTRODUCTION

Solar photovoltaic (PV) systems represent a growing share of global electricity generation capacity. Total installed solar power capacity reached 405 GW by 2018, with 89% installed in the preceding seven years [1]. However, actual energy output frequently falls short of theoretical capacity due to environmental factors that reduce panel efficiency. Among these factors, soiling from dust accumulation presents one of the most persistent operational challenges, particularly in regions with arid climates, high pollution levels, or limited rainfall [2].

The soiling effect on PV panels depends on multiple environmental and design variables including soil composition, panel surface material, tilt angle, atmospheric conditions, and local weather patterns. Accumulated particles such as sand, pollen, bird droppings, and organic matter directly impede solar irradiation reaching photovoltaic cells, thereby reducing power generation capacity. Studies indicate that energy loss due to soiling can reach 25-30% in severe cases, with even modest dust accumulation causing efficiency reductions of 6-8% [3]. Research conducted in Saudi Arabia found that panels left uncleaned for six months experienced power output reductions of up to 50% [4]. Soiling, primarily from dust, is the most significant of these factors (see Figure 1).

Current cleaning methods include manual cleaning with water and brushes, pressurized water jets, and robotic systems. Manual cleaning presents safety concerns for rooftop installations

and requires ongoing labor costs. Water jet systems consume considerable water resources, which proves impractical in water-scarce regions. Existing robotic cleaning solutions are typically designed for large-scale solar farms and remain economically unfeasible for residential or small commercial installations [5].

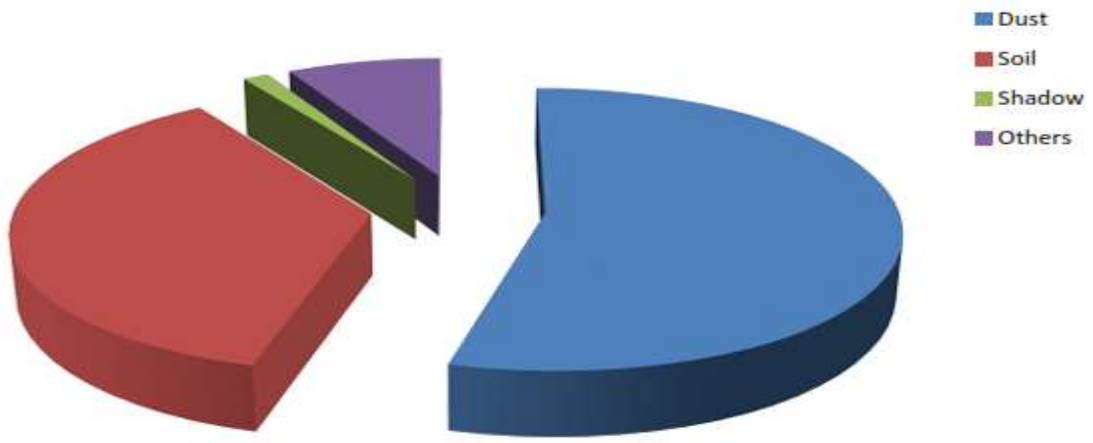


Figure 1: Factors affecting efficiency of solar panel

This research addresses these limitations by developing an automated solar panel cleaning robot that combines mechanical cleaning capability with Internet of Things (IoT) connectivity. The system is designed to operate on standard residential and commercial solar panel installations while providing remote monitoring and control through cloud-based platforms. The robot's modular design allows for cost-effective deployment across different scales of solar installations.

The primary research objectives are: (1) to develop a functional automated cleaning robot capable of maintaining solar panel efficiency through regular removal of surface contaminants, and (2) to reduce manual labor requirements and associated cleaning costs through automated operation and remote system management.

2. Literature Review

2.1 Impact of Soiling on Photovoltaic Performance

Dust accumulation on PV module surfaces reduces incident solar radiation and alters the angular dependence of light transmission. Sayyah et al. [6] investigated energy yield losses caused by dust deposition and found that both physical and chemical properties of deposited particles affect light transmission and reflection characteristics. Their analysis showed that soiling effects vary significantly based on geographical location, with relative humidity, temperature, wind velocity, and frequency of dust episodes all contributing to accumulation rates.

Research by Salameh et al. [7] provided a detailed review of dust accumulation effects across different climate regions. Their findings confirmed that dust deposition significantly affects PV performance, with output power reductions reaching 40% in extreme cases. The study noted that irradiance loss varies throughout the day, exhibiting symmetry around solar noon where losses reach minimum values due to higher incident angles.

Experimental work on different pollutant types demonstrated that specific contaminants produce varying degrees of performance degradation. Testing with red soil, ash, sand, calcium carbonate, and silica showed that both pollutant mass and composition affect voltage and power output. Temperature effects compound these losses, with higher operating temperatures producing greater performance reductions in soiled panels [8].

2.2 Existing Cleaning Methods and Technologies

Current cleaning approaches range from manual methods to automated robotic systems. Manual cleaning with water and detergents remains the most common method but involves

substantial labor costs and safety risks for rooftop installations. Water consumption presents another concern, with typical cleaning operations requiring 200-400 liters per cleaning cycle for residential installations [9].

Automated cleaning systems developed for utility-scale solar farms employ various technologies including water spraying systems, rotating brushes, and air blowing mechanisms. However, these systems are designed for large-scale operations and prove economically impractical for smaller installations. The Gecko solar robot represents one commercial solution that offers improved safety and handling capacity, but its cost structure limits adoption to industrial-scale facilities [10].

Recent research has explored dry cleaning methods using soft brushes and electrostatic forces to remove particles without water consumption. While these approaches show promise for water conservation, effectiveness varies significantly based on particle adhesion strength and environmental humidity levels [11]. The development of cleaning robots for residential and small commercial applications remains an active research area with limited commercially available solutions.

2.3 IoT Integration in Solar System Management

Integration of IoT technologies in solar system monitoring and control has expanded rapidly over the past decade. Cloud-based platforms allow remote monitoring of system performance parameters including voltage, current, power output, and environmental conditions. Studies demonstrate that IoT-enabled systems improve maintenance response times and allow predictive maintenance scheduling based on performance data analysis [12]. Application of similar connectivity to cleaning robots enables automated scheduling, remote operation, and integration with broader energy management systems.

3. Methodology

3.1 System Architecture

The automated solar panel cleaning robot consists of two primary subsystems: a mobile platform for panel-to-panel navigation and a cleaning mechanism for dust removal. The mobile platform uses a carrier frame that travels across the solar panel array, while the cleaning unit moves longitudinally along the panel surface to ensure complete coverage.

The system architecture incorporates the following design principle: the cleaning robot does not make direct contact with the photovoltaic panel surface during movement. Instead, it travels on a dedicated moving frame that functions as a rail system. This approach prevents mechanical stress on the panel surface while maintaining precise cleaning paths. The cleaning brush extends downward from the robot to perform the cleaning operation without transferring the robot's weight to the panel.

3.2 Hardware Components

Table 1 lists the major hardware components used in the robot assembly. Component selection prioritized availability, cost-effectiveness, and compatibility with the ESP32 microcontroller platform.

Table 1: Major hardware components and specifications

Component	Specification
Microcontroller	ESP32 development board with WiFi and Bluetooth
Drive Motors	4x DC geared motors (12V, 200 RPM) for wheel drive
Brush Motor	1x DC geared motor (12V, 100 RPM) for rotating brush
Motor Driver	L298N dual H-bridge motor driver modules
Water System	Mini DC water pump (12V) with 2L water tank
Sensors	Infrared proximity sensors for edge detection

Component	Specification
Power Supply	Lithium-ion battery pack (12V, 5000 mAh)
Cleaning Brush	PVC pipe wrapped with microfiber cloth



Figure 2: Key hardware components: (a) ESP32 microcontroller, (b) DC geared motor, (c) mini water pump, and (d) chassis assembly.

The ESP32 microcontroller serves as the central processing unit, managing motor control, sensor inputs, and wireless communication. Its integrated WiFi capability enables connection to Arduino IoT Cloud for remote monitoring and control. The L298N motor drivers provide bidirectional control for the DC motors with pulse-width modulation (PWM) for speed regulation. Figure 2 illustrates several of the key hardware components listed in the table.

3.3 Mechanical Design

The mechanical structure comprises a chassis frame fabricated from aluminum extrusions, providing structural rigidity while minimizing weight. The moving frame uses aluminum profiles with low-friction linear bearings to ensure smooth motion across the panel array.

The cleaning unit attaches to the moving frame through a sliding mechanism that allows longitudinal travel.

The cleaning brush assembly consists of a PVC pipe core wrapped with microfiber cloth, selected for its balance of cleaning effectiveness and gentle contact with panel surfaces. Two linear actuators support the brush assembly and allow vertical position adjustment. A geared DC motor rotates the brush during cleaning operations.

To address motor speed variation issues common in DC motor systems, cushion brushes are mounted on the robot sides. These components absorb minor collisions with the frame rails and reduce friction during lateral movements. This design feature compensates for speed differences between motors that could cause the robot to deviate from its intended path.

3.4 Control System and Software

The control system software was developed using Arduino IDE and implements three operational modes. In manual mode, users control robot movement and cleaning functions through the Arduino IoT Cloud web interface or mobile application. Autonomous mode follows pre-programmed cleaning patterns that systematically cover the entire panel surface. Patrol mode combines autonomous navigation with periodic water spraying at predetermined intervals.

Motor speed control uses PWM signals with adjustable duty cycles. Initial testing revealed that motor speed variations caused path deviations, requiring individual motor calibration. The final implementation includes motor-specific PWM offsets to achieve synchronized movement.

Infrared sensors positioned at the front and rear of the cleaning unit detect the frame boundaries. When a sensor detects the frame edge, the microcontroller halts forward motion and initiates the return sequence. Aluminum brackets mounted around the sensors provide physical protection during operation, addressing sensor damage observed during initial testing.

3.5 Water Delivery System

The water delivery system incorporates a 2-liter reservoir, mini DC pump, connecting tubing, and an adjustable spray nozzle. The pump draws water from the reservoir and delivers it to the nozzle positioned ahead of the rotating brush. The nozzle can be adjusted to produce either a fine mist or a more direct spray pattern depending on cleaning requirements. This system operates intermittently during autonomous mode to conserve water while ensuring adequate surface wetting for effective dust removal.

4. Results and Discussion

4.1 Prototype Development

The completed prototype successfully demonstrated the design concept of non-contact movement over solar panel surfaces. Figure 3 shows the assembled robot on its moving frame. The frame-based approach effectively eliminated direct loading on the panel surface while maintaining accurate cleaning paths.

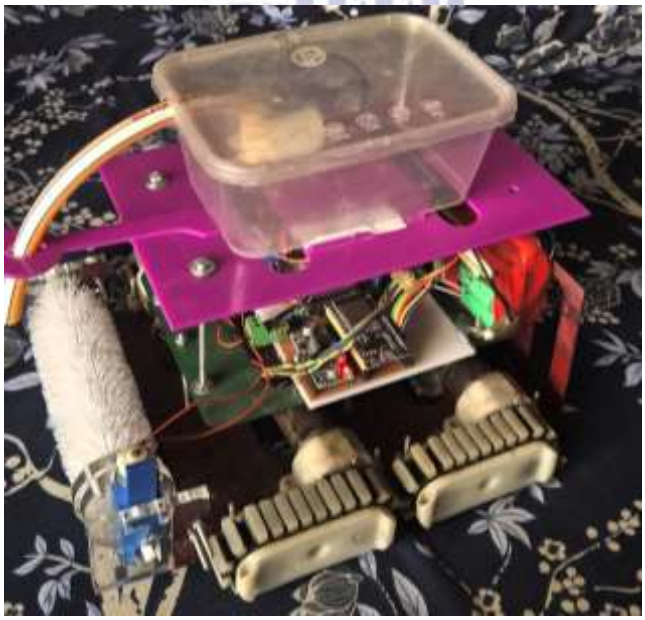


Figure 3: Assembled prototype of the IoT-based solar cleaning robot.

Wire management proved critical during development and testing phases. Removable wire connectors facilitated rapid component testing and replacement. All connections were labeled with identification tags to prevent wiring errors during reassembly. This approach significantly reduced debugging time when troubleshooting control system issues.

4.2 Performance Testing

Functional testing evaluated the robot's cleaning effectiveness, movement precision, and operational reliability. The rotating brush with water spray effectively removed dust accumulation without leaving visible residue or causing surface damage. Multiple cleaning cycles on test panels confirmed consistent performance.

Motor speed synchronization required iterative calibration. Initial tests revealed path deviations of up to 5 cm over a 1-meter travel distance due to motor speed mismatches. Implementation of motor-specific PWM adjustments reduced deviation to less than 1 cm, falling within acceptable tolerance for the cleaning application.

The infrared sensor system successfully detected frame boundaries and triggered appropriate motor responses. However, early testing revealed that sensor collision during rapid stops could cause damage. Addition of protective brackets resolved this issue, with no sensor failures observed during subsequent testing cycles.

4.3 IoT Integration and Remote Control

Arduino IoT Cloud integration provided reliable remote access to robot controls and status monitoring. Connection stability proved adequate for residential WiFi networks, with control latency averaging 200-300 milliseconds. This response time proved acceptable for the application, as cleaning operations do not require real-time control precision.

The web interface allows users to initiate cleaning cycles, monitor battery status, and adjust operational parameters. Scheduled cleaning capability enables automated operation during optimal times, such as early morning before peak solar generation hours. This feature proved particularly valuable for maintaining consistent panel performance without user intervention.

4.4 Power Consumption and Battery Life

Battery consumption measurements indicated that a complete cleaning cycle for a typical 6-panel residential array requires approximately 30-40 minutes of operation, consuming 60-70% of battery capacity. This allows for one complete cleaning cycle per battery charge under normal operating conditions. Future iterations could incorporate solar charging capability to extend operational time between manual recharging.

4.5 Water Consumption Analysis

Water consumption measurements showed that cleaning a 6-panel array requires approximately 1.5 liters of water when using the spray system intermittently. This represents a reduction of more than 90% compared to typical manual cleaning methods that use garden hoses. The adjustable spray pattern allows users to modify water application based on soiling severity and water availability.

5. Conclusion and Future Work

5.1 Conclusion

This research successfully developed and demonstrated an automated solar panel cleaning robot integrating mechanical cleaning mechanisms with IoT-based remote control. The robot effectively removes dust and debris from solar panel surfaces while operating without direct contact on the panels themselves, eliminating mechanical stress concerns. The ESP32 microcontroller platform provides adequate processing capability for motion control, sensor management, and wireless connectivity.

The system's three operational modes provide flexibility for different user requirements and environmental conditions. Manual control allows direct user intervention when needed, while autonomous mode enables scheduled cleaning without user input. The patrol mode with water spraying offers improved cleaning effectiveness for more severe soiling conditions.

Water consumption analysis demonstrates substantial reduction compared to conventional cleaning methods, making the system practical for water-scarce regions. The modular design facilitates maintenance and allows component upgrades as technology advances.

5.2 Future Work

Several enhancements could further improve robot performance and expand its application range:

- Integration of ultrasonic sensors for improved obstacle detection and navigation in complex installation geometries

- Addition of camera modules for visual inspection capability, enabling detection of panel damage or defects during cleaning operations
- Implementation of machine learning algorithms for adaptive cleaning patterns based on soiling levels and weather conditions
- Development of solar-powered battery charging to reduce manual recharging requirements
- Expansion of IoT capabilities to include performance monitoring and predictive maintenance scheduling

These improvements would enhance the robot's autonomy and make it suitable for larger commercial installations and solar farms where human intervention must be minimized.

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