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Research Article

Enhancing Solar Energy Harvest: The Development of a Microcontroller-Based, Remote-Controlled Cleaning System for Photovoltaic Panels

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ABSTRACT

Dust and surface debris reduce the amount of solar radiation reaching photovoltaic (PV) cells and create a recurring maintenance problem, particularly where manual cleaning is difficult or unsafe. This study developed a remote-controlled Photovoltaic Module Cleaning (PVMC) prototype that integrates mechanical cleaning, sensor monitoring, and web-based control. The prototype uses an aluminum frame and rails, 3D-printed brackets, two DC motors, a brush, a squeegee, water nozzles, a reservoir and pump, a Raspberry Pi 3 Model B+, an Arduino Uno R3, an ultrasonic water-level sensor, and a camera. Through a locally hosted web interface, the operator can view the reported water level, access the camera feed, and initiate the cleaning cycle. Prototype evaluation focused on functional operation and visual comparison of panel surfaces before and after cleaning under dusty and muddy conditions. The recorded images show visible removal of surface contaminants after the cleaning cycle. Operational observations also indicated more consistent cleaning on damp surfaces and during repeated runs. The available trial records, however, do not include calibrated measurements of PV voltage, current, power recovery, cleaning time per unit area, water consumption, or battery energy use. The study therefore demonstrates the feasibility and operation of the integrated cleaning prototype but does not quantify the resulting increase in energy yield. Future testing should combine the cleaning procedure with electrical and resource-use measurements to establish cleaning efficiency and net operating benefit.

Keywords: *Automated Solar Panel Maintenance, Photovoltaic Module Cleaning (PVMC), Photovoltaic Soiling, Remote-Controlled Cleaning, Web-Based Monitoring*

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Introduction

Photovoltaic (PV) systems are widely used to convert solar radiation into electrical energy, but their field performance depends on how much sunlight reaches the cell surface. Dust, grit, mud, and other deposits can block part of the incident radiation and reduce the useful output of a PV module. The effects of dirt accumulation and related environmental conditions on PV performance have been documented in experimental and review studies (Mekhilef et al., 2012; Hussain et al., 2017; Sulaiman et al., 2014).

Soiling is a practical maintenance concern because PV modules are exposed continuously to outdoor conditions. The degree of loss varies with the type and amount of deposited material, weather, and site conditions. Regular cleaning can restore the exposed surface, but manual cleaning requires labor, repeated site access, and direct contact with the installation. These limitations become more important when panels are mounted in locations that are difficult to reach or when several modules must be maintained on a routine basis.

Automated and semi-automated cleaning systems have therefore been explored using brushes, water jets, mobile mechanisms, and embedded controllers. Previous work has demonstrated Raspberry Pi-, Arduino-, robotic-, and Internet-of-Things-based approaches to PV cleaning (Andres et al., 2022; Habib et al., 2021; Khadka et al., 2020; Ramapraba et al., 2021). Reviews of PV cleaning technologies likewise emphasize the need to balance cleaning effectiveness, mechanical simplicity, water use, cost, and adaptability to different installations (Patil et al., 2017; Farrokhi

Derakhshandeh et al., 2021; Olorunfemi et al., 2022).

The present project addresses this maintenance problem through a compact cleaning prototype that can be operated remotely. Its controller architecture combines a Raspberry Pi 3 Model B+ and an Arduino Uno R3 with DC motors, motor drivers, a relay-controlled water pump, an ultrasonic water-level sensor, and a camera. A brush, squeegee, and water nozzles are mounted on a lightweight aluminum assembly that travels along rails positioned over the PV panel.

The study had three objectives: (1) to design and construct a portable PV module cleaning mechanism; (2) to develop a web-based interface for remote activation, water-level monitoring, and camera viewing; and (3) to evaluate the prototype through functional operation and visual inspection of the panel surface before and after cleaning. The study focuses on prototype feasibility and cleaning operation. It does not claim a quantified improvement in PV energy yield because calibrated pre-cleaning and post-cleaning electrical measurements were not included in the available trial data.

Methods

Conceptual Framework

Figure 1 presents the study's input-process-output framework. The input side consists of the Wi-Fi connection, web interface, water-level information, and camera preview used by the operator. These inputs support remote access to the cleaning system and provide basic operating information before and during a cleaning cycle.

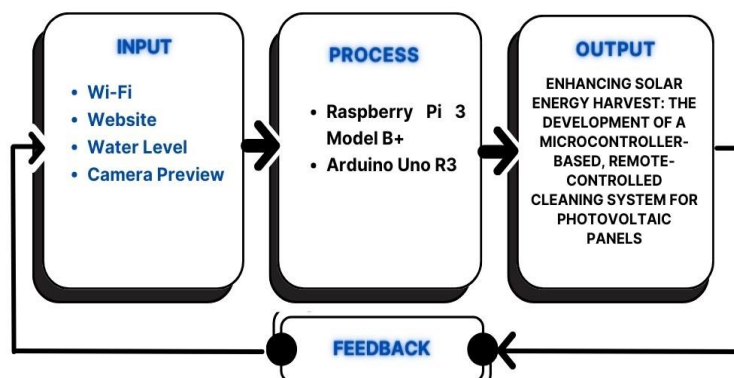


Figure 1. Conceptual Framework

The process is carried out through the Raspberry Pi 3 Model B+ and Arduino Uno R3. The Raspberry Pi handles the web interface and higher-level communication, while the Arduino executes direct control commands for the motors and related hardware. The intended output is a clean PV surface that can receive solar radiation with less obstruction from visible dust or mud. Feedback is provided through the camera view and water-level display, allowing the operator to decide whether another cleaning pass or an operating adjustment is needed.

Conceptual Design

Figure 2 shows the overall arrangement of the PVMC prototype. The operator connects to the system through Wi-Fi and a web interface. The power section consists of a solar charge controller and a 12 V battery, while the control section includes the Raspberry Pi 3 Model B+, Arduino Uno R3, relay, BTS7960 motor driver, Raspberry Pi camera, and ultrasonic sensor.

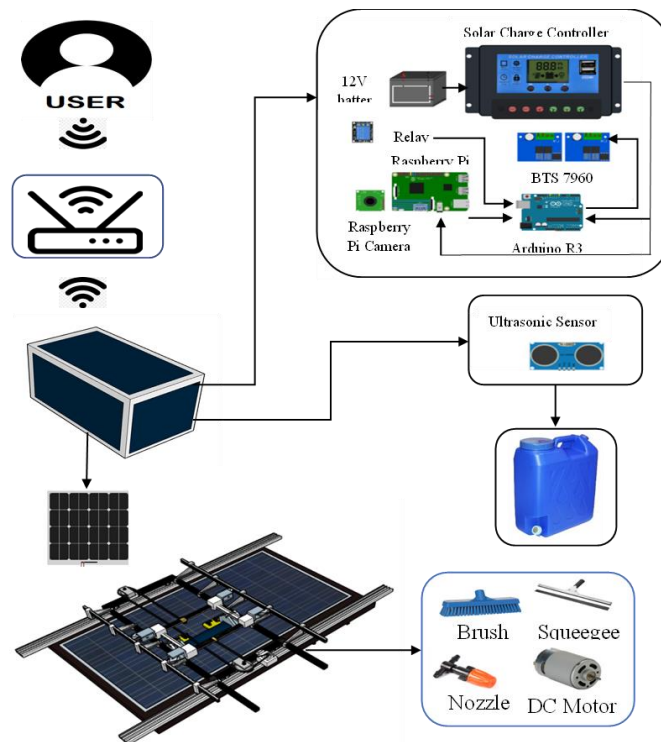


Figure 2. Conceptual Design

The cleaning assembly combines two DC motors with a brush, squeegee, and water nozzle. The motors provide the movement required to carry the cleaning assembly across the panel through the aluminum rail system. The water pump supplies the nozzles during wet cleaning, while the brush loosens deposited material and the squeegee removes remaining water and debris.

The camera provides the operator with a live view of the panel, and the ultrasonic sensor reports the water level in the reservoir. These functions are used for remote observation rather than autonomous visual decision-making. The design keeps the operator in the

control loop: the user views the available information and initiates the cleaning cycle through the interface.

System Block Diagram

Figure 3 summarizes the flow of commands and data among the system components. A mobile device accesses the web server hosted through the Raspberry Pi 3 Model B+. The Raspberry Pi receives the camera feed and water-level data and communicates control instructions to the Arduino Uno R3.

The Arduino interfaces with the BTS7960 motor driver to operate the two 775 DC motors. A relay module switches the water pump

during the cleaning cycle. This division separates the web-based monitoring and command functions from the direct motor and actuator

control required by the mechanical cleaning assembly.

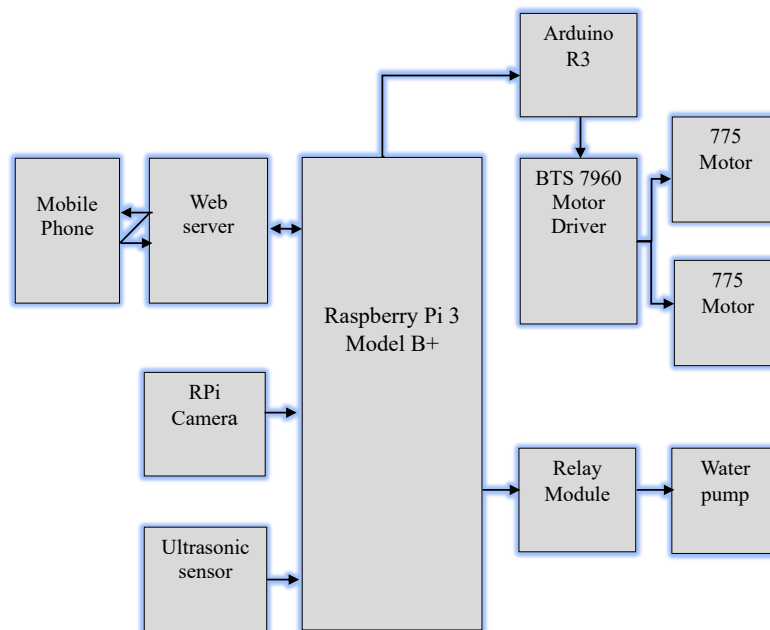


Figure 3. System Block Diagram

Wiring Diagram

Figure 4 documents the electrical connections used in the prototype. The solar charge controller regulates charging of the 12 V battery, which supplies the control and actuation components. The Raspberry Pi 3 Model B+ is connected to the camera and ultrasonic sensor, while the Arduino Uno R3 interfaces with the motor drivers that operate the 775 DC motors.

The relay module provides switching for the water pump. Together, these connections allow the web-based controller to receive monitoring information and send cleaning commands to the mechanical subsystem. The diagram is presented as the implemented wiring reference for the prototype rather than as evidence of electrical performance or energy efficiency.

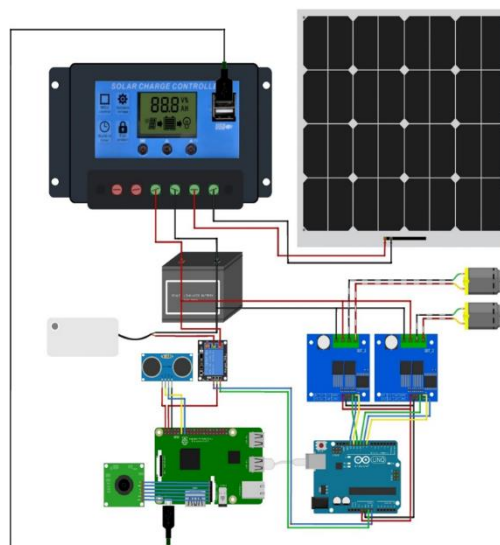


Figure 4. Wiring Diagram of the System

Process Flow Chart

The operating sequence is shown in Figure 5. After the system starts, the controller initializes its functions and connects to the Wi-Fi network. The interface then displays the reservoir water level so that the operator can check the available water before starting the cleaning cycle.

Once the operator initiates cleaning, the system runs the cleaning mechanism while the camera feed can be displayed for remote observation. At the end of the programmed sequence, the cycle terminates and the system is available for another command. The flowchart uses the water-level display as an information step; it does not document an automatic low-water lockout.

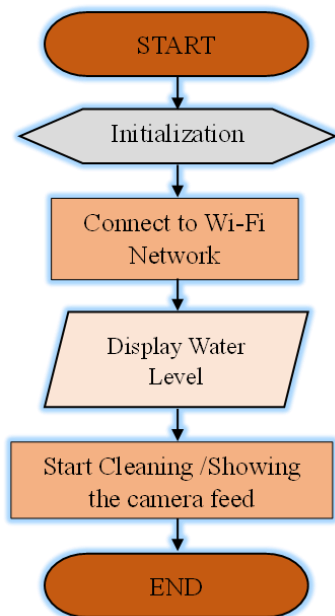


Figure 5. Process Flow Chart

Program Flow Chart

Figure 6 presents the software logic used to connect the web interface with the cleaning hardware. After initialization, the user accesses the website. If the camera is enabled, a frame is sent to the website for viewing. The program then waits for the user to press the start-cleaning command.

When the command is received, the controller sends the required GCODE instructions to the Arduino, which executes the hardware sequence. The program checks whether the

cleaning path has been completed; if not, the sequence continues until completion. This logic confirms that the prototype is remote-controlled and operator-initiated rather than fully autonomous.

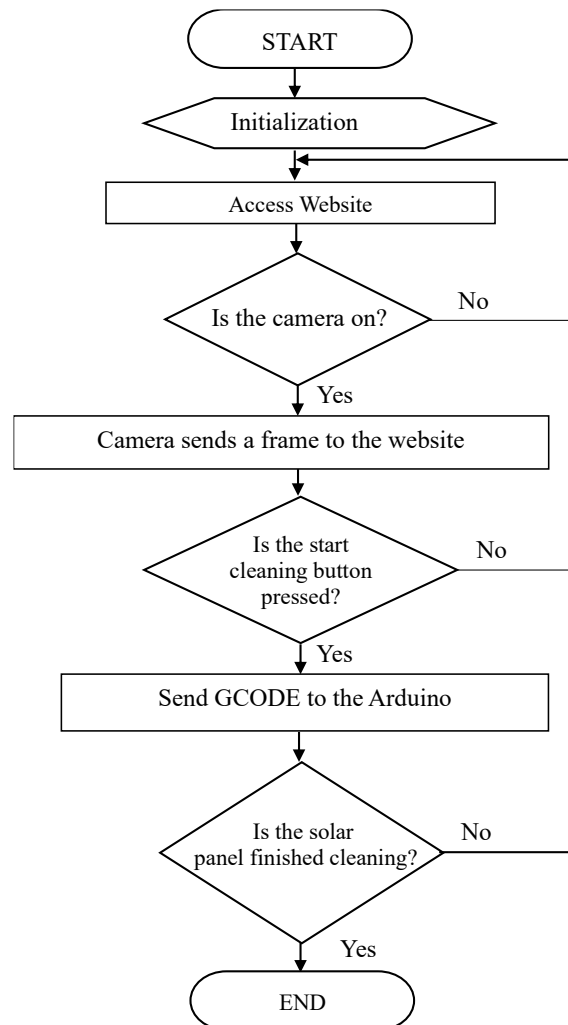


Figure 6. Program Flow Chart

Prototype Evaluation

Prototype evaluation focused on whether the system could execute the intended cleaning sequence and whether visible contaminants were removed from the PV surface. Camera images were recorded before and after cleaning for dusty and muddy surface conditions. The researchers also noted differences in operation between dry and damp surfaces and across repeated runs. No calibrated pre-cleaning and post-cleaning measurements of PV voltage, current, power output, cleaning time per square meter, water use, or battery energy

consumption are available in the study record; therefore, these quantities are not estimated or inferred in the present paper.

Result and Discussion

Prototype Design and Operation

Figure 7 shows the completed PVMC mechanical arrangement. The prototype uses an aluminum frame and rail system to support a movable cleaning assembly over the PV panel. Timing belts and two 775 DC motors provide the motion needed to move the assembly across the panel surface.

The cleaning head combines a brush, squeegee, and water nozzle. During a wet-cleaning pass, water is applied ahead of the mechanical

wiping elements; the brush loosens visible deposits and the squeegee removes residual water and dislodged material. The arrangement allows the cleaning elements to move over the panel while the main support structure remains fixed to the rail system.

The design also incorporates 3D-printed brackets for mounting selected components and panel rollers to support movement over the cleaning path. The Raspberry Pi camera is positioned to provide a remote view of the panel and the cleaning activity. These features demonstrate the integration of the mechanical, electrical, and monitoring subsystems in a single prototype.

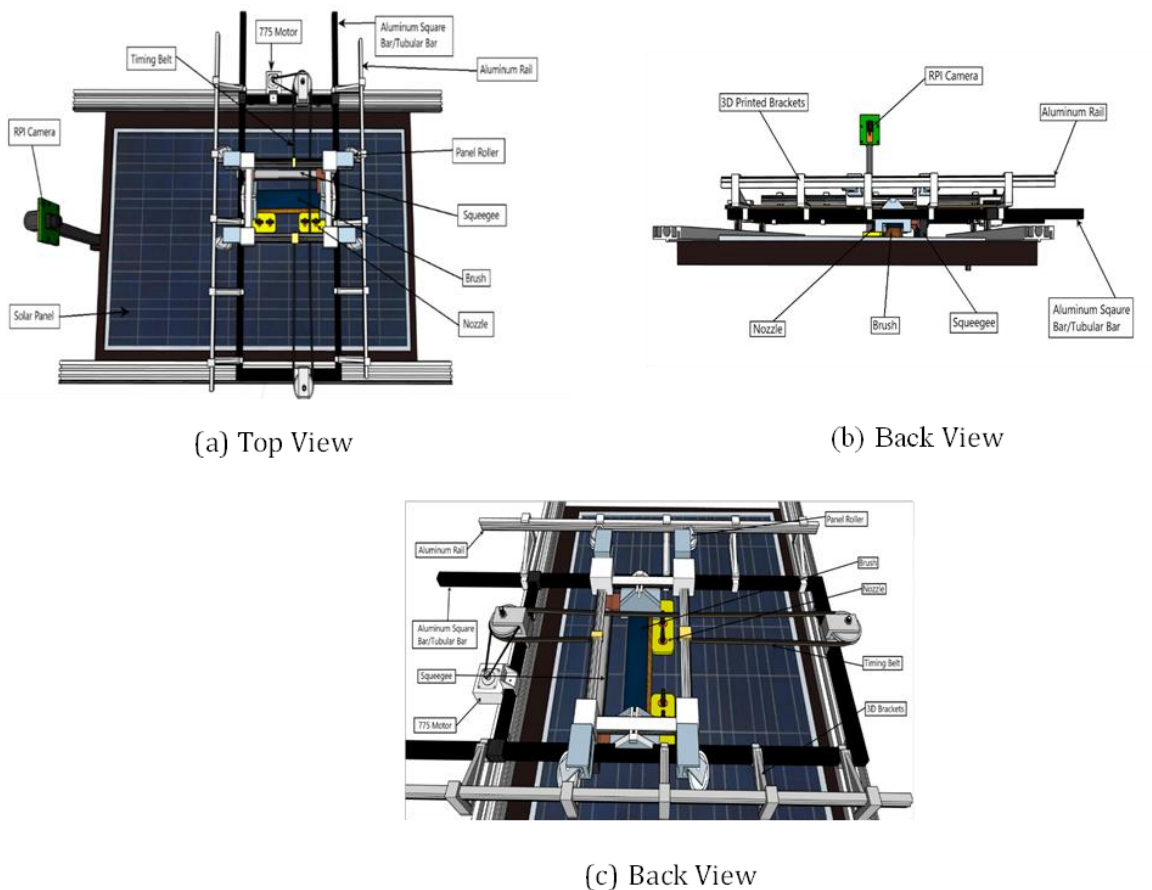


Figure 7. System Design

The prototype should be interpreted as a functional engineering build rather than a final commercial design. The present study verifies that the components can be integrated and operated as intended, but it does not report

durability testing, long-term outdoor exposure, standardized cleaning-force measurements, or comparative testing against other cleaning methods.

Specifications

Table 1 summarizes the physical specifications reported for the prototype. The aluminum rail is 130 cm long, and the main aluminum tubular frame measures 132.5 cm by 41.5 cm. The brush measures 34.5 cm by 6.5 cm, while the squeegee is 14 inches wide. The assembled PVMC unit has an approximate mass of 1.5 kg.

The panel rollers measure 5.2 cm by 1.8 cm by 4.5 cm (length by width by height), and the nozzle provides approximately 40 cm of droplet coverage. These dimensions describe the tested prototype and establish the scale of the cleaning mechanism used in the reported trials.

Table 1. Component Specifications for the Automated Solar Panel Cleaning System

Item	Specification
Aluminum rail	130 cm
Aluminum tubular	132.5 cm x 41.5 cm
Brush	34.5 cm x 6.5 cm
Squeegee	14 inches
PVMC Weight	Approximately 1.5 kilograms
Panel roller dimension	5.2 cm x 1.8 cm x 4.5 cm (Length x Width x Height)
Nozzle	Loose, 40 cm droplet coverage

Cleaning Performance and Evaluation Limits

Figure 8 presents before-and-after camera images for two surface conditions used during prototype evaluation. The first pair documents a visibly dusty panel, and the second pair documents a panel with muddy surface contamination. In both cases, the post-cleaning images show a visibly clearer panel surface after operation of the PVMC system.

For the dusty condition, the cleaning pass removed much of the visible material that had covered the panel surface. For the muddy condition, the combination of water and mechanical wiping also reduced the visible residue. These observations support the basic functional claim that the prototype can remove surface contamination under the demonstrated test conditions.

The images provide qualitative evidence only. They were used to document visible changes in surface condition and were not processed through a calibrated image-analysis method. Accordingly, the study does not assign a numerical cleaning-efficiency percentage from Figure 8.

Operational observations indicated that the cleaning mechanism performed more

consistently when the panel surface was damp than when it was dry. Repeated operation also produced more consistent movement and cleaning behavior. These observations are reported as prototype behavior and should not be interpreted as evidence of machine learning or adaptive control because no learning algorithm was implemented or evaluated in the study.

The principal limitation of the present performance evaluation is the absence of electrical and resource-use measurements. The available records do not provide pre-cleaning and post-cleaning PV voltage, current, or power; battery energy draw; water consumption; or cleaning duration normalized by panel area. As a result, the study cannot calculate percentage power recovery, net energy benefit, water efficiency, or cleaning throughput.

A stronger validation protocol should measure PV electrical output under comparable irradiance and temperature before and after cleaning, record the energy consumed by the motors and pump, measure water use, and time each cleaning cycle. Reporting these values across repeated trials would allow the visual results shown here to be linked to quantitative cleaning and energy-performance metrics.

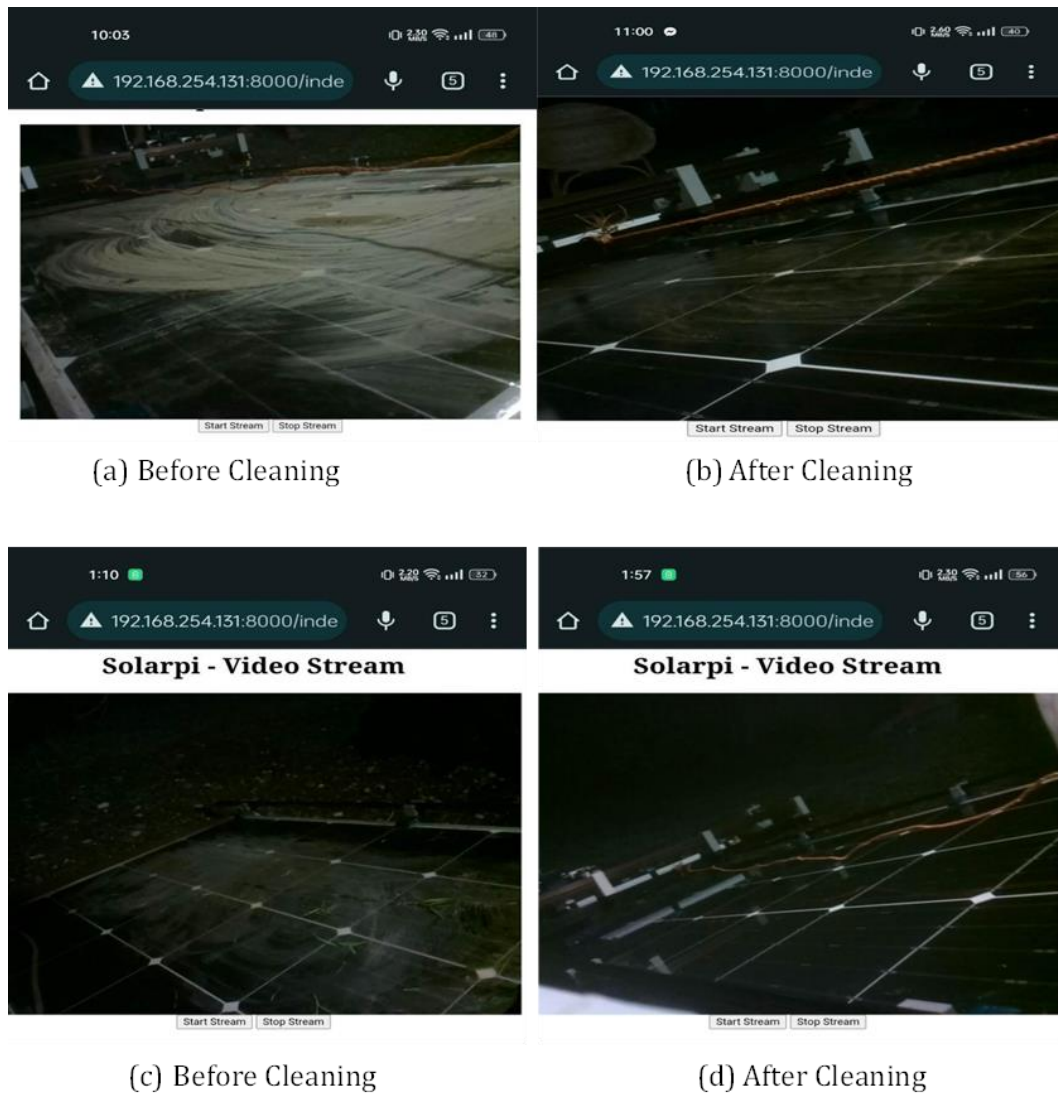


Figure 8. Cleaning performance before and after cleaning: (a-b) dusty condition; (c-d) muddy condition

Web-Based Interface for Remote Operation

Figure 9 shows the web interface developed for remote operation of the PVMC system. The page is accessed through the Raspberry Pi's network address and provides the functions needed for the reported prototype: water-level display, a start-cleaning command, and access to the camera view.

The interface was implemented using HTML, CSS, and JavaScript for the front end, with Python used in the Raspberry Pi software environment. Arduino IDE programming was used for the motor- and relay-control functions. This arrangement links the browser-based controls to the physical cleaning hardware.

The interface keeps the operator directly involved in the cleaning process. The camera allows visual inspection of the panel, the water-level reading provides reservoir information, and the start command initiates the programmed cleaning sequence. Remote access therefore reduces the need to stand beside the panel during operation while preserving operator oversight.

The implemented interface demonstrates successful integration of monitoring and control in the prototype. The present study, however, evaluates functionality rather than network performance; connection range, latency, cybersecurity, multi-user access, and operation outside the local Raspberry Pi network were not quantified.

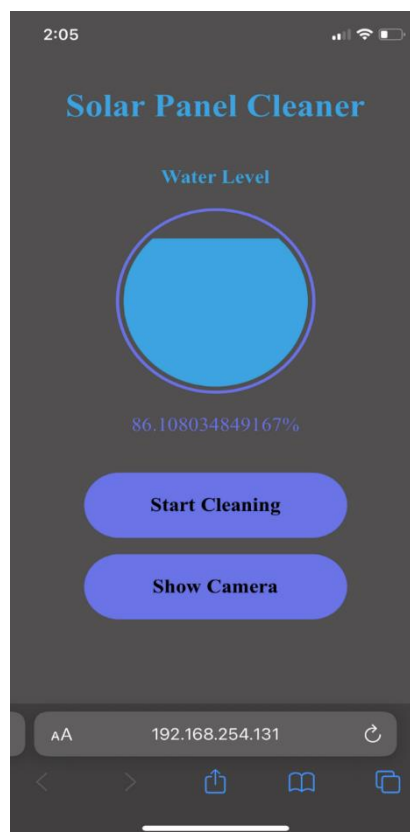


Figure 9. Photovoltaic Module Cleaning (PVMC) Remote-Control Web Interface

Conclusion

The study developed a lightweight, remote-controlled Photovoltaic Module Cleaning (PVMC) prototype that combines an aluminum rail-and-frame structure, 3D-printed mounting components, two DC motors, a brush, squeegee, water nozzles, reservoir and pump, camera monitoring, water-level sensing, and web-based control. The Raspberry Pi 3 Model B+ and Arduino Uno R3 coordinate the monitoring, communication, and hardware-control functions required to execute the cleaning sequence.

Functional trials and before-and-after images show that the prototype can remove visible dust and muddy deposits under the demonstrated test conditions. The system was observed to operate more consistently on damp surfaces and during repeated runs. These findings support the feasibility of the prototype as a remotely operated cleaning device. They do not establish adaptive learning, autonomous decision-making, or a quantified increase in PV energy yield.

The main limitation is the absence of calibrated performance measurements linking cleaning to electrical output and resource consumption. Future evaluation should record PV voltage, current, and power before and after cleaning under comparable environmental conditions; cleaning duration per unit area; water consumption; and battery or system energy use. Repeated trials using these measures would allow the prototype's cleaning efficiency, energy benefit, and operating cost to be assessed quantitatively.

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