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Solar Photovoltaic Panel Cleaning Robots: A Survey of Technologies and a Microcontroller-Based Automatic Operation Approach

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Abstract: *Solar power is growing fast. In 2025, the world added about 511 GW of new solar capacity, which is almost three-quarters of all new renewable power. Solar panels are used on rooftops, in shops, offices and factories, and in large solar farms. Dust on a panel blocks sunlight and reduces the electricity it makes. Cleaning by hand takes a lot of work, costs money and is risky at heights, so automatic cleaning is needed. This paper reviews solar panel cleaning robots according to the controller they use. Arduino Uno robots have shown cleaning without water, using a fan and a wiper, and washing on a fixed schedule. These robots increased the panel's power output. ESP32 robots added dust sensors, started cleaning automatically and sent data to the internet. Raspberry Pi robots used cameras to find dust and to choose which part of the panel to spray. But these robots use small 8-bit controllers, fixed schedules or tracks fitted on the panel frame. Some also need Wi-Fi, cameras and complex software. This paper proposes an STM32-based cleaning robot in which one microcontroller with timer and PWM (a way to control motor speed) support runs the drive motors, a water pump with a fine spray and a soft cleaning roller. Edge-detection sensors find the edge of the panel, so the robot can move without a fixed track. It does not need a camera. The goal is steady, on-time control with simpler hardware and software than the ESP32 and Raspberry Pi robots. The paper also gives the future scope.*

Keywords: solar photovoltaic panel, PV cleaning, cleaning robot, microcontroller, edge detection, embedded systems

I. INTRODUCTION

Solar photovoltaic (PV) power is now one of the main sources of new electricity. The world added about 511 GW of solar capacity in 2025, and total installed solar capacity reached about 2.4 TW [1]. Asia alone has more than doubled its solar capacity since 2022 [1]. A growing share of these panels is mounted on rooftops and on open land, where they are exposed to dust, sand and bird droppings, and where they are not easy to reach.

Dirt on a panel acts like a thin screen on the glass. It cuts the light reaching the cells, so the same panel delivers less power. Cleaning by hand is slow, needs workers and water, and is unsafe on sloping roofs and at height. Rubbing hard can also scratch the glass. Automatic cleaning is therefore an important part of keeping a PV plant productive.

Many automatic cleaners have been built, and they can be grouped by the controller they use. Arduino Uno systems include a waterless cleaner that uses an air blower and a wiper and reported efficiencies of 87–96% for different sands [2], and an automatic washer after which the efficiency of the panel system rose to 12.11% [3]. A wiper-and-sprinkler prototype raised the clean area of a panel from 1% to 97.9% in a test with incense ash [4]. ESP32 systems added dust sensors, started cleaning automatically and reported to cloud platforms [5], [6]. Raspberry Pi systems used camera

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images to choose the area to spray [7], and a Raspberry Pi camera model detected dust with 94.53% accuracy on a glass test surface [8]. Other designs used a PLC [9] or other microcontrollers [10], [11].

These studies show that automatic cleaning works, but they also show a gap. The Arduino Uno is an 8-bit controller, and several designs clean on a fixed schedule or run on a track fixed to the panel frame [3], [4]. The ESP32 and Raspberry Pi systems gain sensing and remote monitoring, but they depend on Wi-Fi, cameras and more complex software. A robot that moves freely on the panel, finds the panel edge by itself and coordinates its motors, pump and cleaning roller with fixed, predictable timing, without cameras or an internet link, is not covered by the systems reviewed here.

Objectives of this paper.

To address this gap, this paper has the following objectives:

1) To review automatic PV cleaning robots by controller type (Arduino, ESP32 and Raspberry Pi) and to state what each type achieved and where it falls short.

2) To propose a microcontroller-based cleaning robot in which one microcontroller with timer and PWM (a method to set motor speed) support runs the drive motors, a fine-spray water pump and a soft cleaning roller.

3) To use edge-detection sensors so that the robot can move over the panel without a fixed track.

4) To keep the design simple by leaving out cameras, artificial intelligence and internet connectivity.

5) To test a prototype and measure the gain in panel power after cleaning, the time of one cleaning run, the water used and the accuracy of edge detection.

II. SUBSYSTEMS OF A PV CLEANING ROBOT

A. Mechanical Structure

The frame carries the electronics, motors, sensors and cleaning unit. It must be strong yet light, and it must spread the robot's weight so that too much pressure is not put on the PV panel.

B. Movement Mechanism

The movement mechanism lets the robot travel across the panel. Reported systems use wheels, tracks, rollers or a mix of these. The choice depends on panel tilt, surface condition, robot weight and the grip required.

C. Cleaning Mechanism

The cleaning mechanism does the actual cleaning and may be a rotating brush, a roller, a wiper or a water-assisted arrangement. Water spray loosens surface dust, while a soft roller or wiper removes it.

D. Sensors

Sensors tell the controller about the robot's position or the panel edge. Simple designs can use basic proximity sensors to find the edge, whereas advanced systems may add cameras, distance sensors and encoders.

E. Control Unit

The microcontroller is the central unit. It reads sensor signals and drives the motors, pump and cleaning mechanism. The controller options are compared in Section IV.

F. Motor Driver and Power Supply

A motor driver supplies the current needed by the DC geared motors and lets the controller set their direction. A rechargeable battery powers the controller, sensors, motors and pump, and suitable voltage regulation is needed for reliable operation.

III. REVIEW OF EXISTING WORK

Table 1 summarises representative studies. Arduino-based prototypes are the most common among the reviewed works [2], [3], [12]; a PLC-based approach has been reported for robust automatic operation [9]; and a microcontroller-controlled three-speed machine has also been described [10]. Other studies address a dry-cleaning robot [13], a robot for the residential sector [14], and general automatic cleaning system design [11], [15].

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A. Arduino-Based Systems

Habib et al. [2] built a waterless cleaner on an Arduino Uno that combines an exhaust-fan air blower with a DC-motor-driven wiper and reported efficiencies of 87–96% for different types of sand. Not using water is useful in dry areas. Intamas and Boonraksa [3] tested an Arduino-controlled automatic washer on an 80 W monocrystalline panel, compared washing every hour with washing every three months, and reported that the efficiency of the panel system rose to 12.11%. Prastomo et al. [4] designed a prototype that uses the panel frame as a track and compared a wiper with a sprinkler, a wiper alone, a sprinkler alone and running water. In their test with incense ash, the wiper-and-sprinkler combination raised the clean area from 1% to 97.9% and the panel power from 5.3 W to 11.2 W.

B. ESP32-Based Systems

Salman et al. [5] built a portable dry-cleaning robot in which an ESP32 manages the cleaning, monitors PV power, battery charge, time and weather, and reports to the ThingSpeak cloud platform. They showed that periodic cleaning improves performance. Rafie [6] used an ESP32 with a dust sensor, two DC motors, a water pump and an L298N driver, so that cleaning starts automatically when dust passes a set level, and reported a clear improvement in voltage output.

C. Raspberry Pi-Based Systems

Uçkan and Oğuzay [7] divide a camera image of the panel into four areas. When an area is covered with dust or snow, a servo motor turns the sprinkler aimed at that area and it sprays water. Elkhoundafi et al. [8] used a Raspberry Pi camera to detect dust and reported a classification accuracy of 94.53% on a 200 × 200 mm glass surface that imitated a panel.

Taken together, these works show that automatic cleaning restores panel output and that a wiper or brush used with water spray cleans better than either alone. The limits that motivate this work are also visible: 8-bit controllers, motion guided by a fixed track or a timed schedule, and a single cleaning method per prototype in the Arduino-based work, and added Wi-Fi, dust sensors, cameras and software in the ESP32- and Raspberry Pi-based work.

Table 1: Summary of Reviewed Cleaning Systems

Ref.	Year	Platform	Cleaning approach
[2]	2021	Arduino Uno	Waterless dust removal
[3]	2022	Arduino	Automatic cleaner prototype
[5]	2021	ESP32	Dry-cleaning robot, cloud
[6]	N/S	ESP32	Dust-triggered pump and motors
[7]	2025	Raspberry Pi	Camera-selected sprinklers
[8]	2025	Raspberry Pi	AI dust detection
[9]	2021	PLC	Automatic cleaning
[12]	2024	Arduino Uno	Automatic cleaning prototype

IV. CONTROLLER PLATFORMS FOR CLEANING ROBOTS

Arduino Uno, ESP32 and Raspberry Pi are common choices for robot control. Table 2 compares them. A Raspberry Pi runs a full operating system and suits vision tasks, and the ESP32 adds wireless connectivity; both are more than a robot needs if it uses only simple edge sensing and timed control of motors and a pump. A microcontroller with hardware timers, PWM outputs and several serial interfaces, and with low power use, suits deterministic control of motors and a pump.

Table 2: Comparison of Controller Platforms

Feature	Arduino Uno	ESP32	Raspberry Pi 4
Processor	8-bit AVR, 16 MHz	32-bit dual-core, 240 MHz	64-bit quad-core, 1.5 GHz
Memory	2 KB SRAM	520 KB SRAM	1–8 GB RAM

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Real-time control	Good	Good (FreeRTOS)	Limited (Linux)
Power use	Low (about 0.2 W)	Moderate (more with Wi-Fi)	High (3–7 W)
Peripherals	1 UART, 1 SPI, 1 I2C	3 UART, SPI, I2C	UART, SPI, I2C
PWM	6 channels	16 channels	4 hardware
ADC	6 ch, 10-bit	12-bit	None
Wireless	No	Wi-Fi, Bluetooth	Wi-Fi, Bluetooth
Programming	Arduino IDE	Arduino IDE / ESP-IDF	Python / C++

V. PROPOSED MICROCONTROLLER-BASED CLEANING ROBOT

A. System Architecture

Figure 1 shows the general architecture of the proposed robot. It has four parts: sensing, control, actuation and power. Edge-detection sensors, one on the left and one on the right of the robot, tell the microcontroller when the robot reaches the edge of the panel. The microcontroller reads these signals continuously and decides how the robot moves. Through a motor driver it controls the direction and speed of the drive motors with PWM signals. It also switches the water pump, which sprays water through a fine nozzle, and the motor that turns the soft cleaning roller, each through its own control stage. A rechargeable battery supplies the system through power regulation. The robot has no camera, no AI and no wireless link, so all decisions are made by the microcontroller alone.

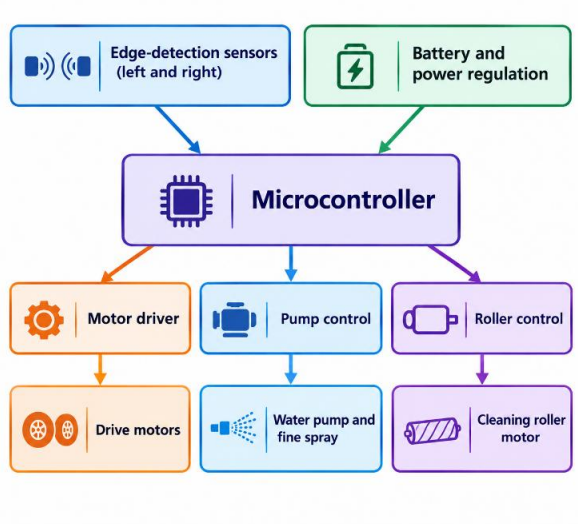


Figure 1: General block diagram of the proposed microcontroller-based cleaning robot.

B. Major Components and Differences from Prior Work

Table 3 lists the major components. For each one it shows what the reviewed work used and the approach proposed here. In the reviewed abstracts we did not find a single microcontroller that runs motors, pump and roller together without Wi-Fi or a camera, panel-edge detection that lets the robot move freely, or a moving robot that combines a fine water spray with a soft roller.

Table 3: Major Components: Reviewed Work and Proposed Approach

Component	Reviewed work	Proposed approach
Controller	Arduino Uno, Arduino; ESP32; Raspberry Pi	One microcontroller with timers and PWM; no operating system, Wi-Fi or camera
Sensors	Dust sensor, camera, panel frame as track	Edge-detection sensors on the left and right

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Movement	Track on the panel frame	Driven wheels, free movement on the panel, turning by driving one side
Cleaning	Blower and wiper, wiper and sprinkler, sprinklers, dry cleaning	Fine water spray with a soft cleaning roller
Water use	Pump, pressurised sprinklers	Spray only while cleaning; water per unit area to be measured
Power	Self-powered, portable	Rechargeable battery; solar charging as future work
Communication	Wi-Fi and cloud	Standalone

C. Cleaning Method

Cleaning combines two operations. A small pump supplies water through a fine spray nozzle to loosen dust before mechanical cleaning, and the fine spray spreads water over the cleaning area instead of applying a large quantity at once. A soft rotating roller then removes the loosened dust; a soft surface lowers the chance of scratching compared with a hard cleaning element. The method is meant for loose dust and light-to-moderate dirt. Strongly stuck stains may need other methods. Water use, roller speed and cleaning effectiveness must be found by experiment during prototype testing.

D. Advantages and Applications

The design reduces manual effort, keeps the mechanical structure simple with a two-motor drive, uses a gentle cleaning surface, and needs only a single embedded controller. It is suited to rooftop, residential, commercial and small-to-medium industrial installations, and to places where regular manual cleaning is inconvenient.

E. Difference from Earlier Work

Robotic PV cleaning is already well studied, so the idea itself is not claimed as new. The proposed design differs in four ways. First, one microcontroller with hardware timers and PWM coordinates sensing, both drive motors, the pump and the roller, whereas Arduino Uno-based systems [2] use an 8-bit controller, and ESP32 and Raspberry Pi systems add Wi-Fi or cameras. Second, a fine water spray with a soft roller combines wetting and gentle wiping, whereas the waterless blower-and-wiper design [2] removes dust without water and so avoids water use. Third, edge detection lets the robot move over the panel without a frame-mounted track [4]. Fourth, it avoids cameras, artificial intelligence and internet connectivity, which keeps the hardware and software simple.

These are differences in design. Whether they give better cleaning or lower power use than the reviewed systems has to be shown by prototype tests.

VI. FUTURE SCOPE

Future versions of the solar panel cleaning robot can include:

- Improved edge detection
- Obstacle detection
- Wheel encoders
- Camera-based contamination detection
- AI-based cleaning decisions
- Improved path planning
- Remote monitoring
- Optimized water dispensing
- Improved traction and stability
- Battery-status monitoring
- Solar-assisted charging

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- Integration with PV plant monitoring systems

Future research can also investigate intelligent robotic systems capable of determining when cleaning is required and selecting an optimized cleaning path.

VII. CONCLUSION

Solar panel cleaning robot technology is an important application of robotics, embedded systems and renewable-energy maintenance. Such systems can reduce manual effort by automatically moving across photovoltaic panels and performing cleaning operations.

The review shows that successful solar panel cleaning robot systems require proper integration of mechanical movement, cleaning mechanisms, sensors, boundary detection, control systems, power management and stability.

The proposed project focuses on a practical automatic robot based on the STM32F103C8T6, two IR sensors, two DC geared motors, a fine water spray and a soft rotating microfiber roller.

Consequently, the STM32F103C8T6 microcontroller provides a cost-effective and high-performance processing solution for real-time control in this application

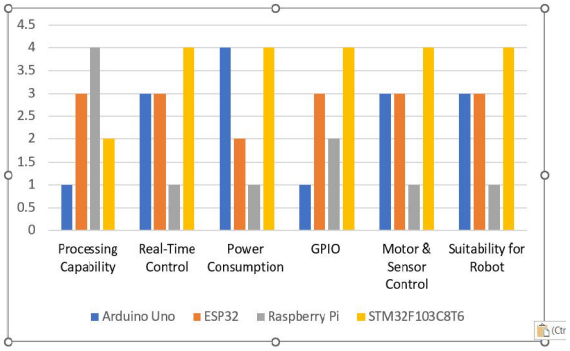


Figure 2: Comparative evaluation of reviewed microcontroller platforms for the proposed solar panel cleaning robot

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