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Solar Panel Cleaning Robot Using Embedded System

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Abstract: Solar photovoltaic (PV) systems are an important source of renewable energy, but dust, dirt and environmental particles accumulate on the panel surface and reduce the useful solar radiation reaching the cells. Regular cleaning is therefore an important maintenance activity. Manual cleaning requires repeated human effort, time and water and can be difficult or unsafe for large or inclined installations. This paper reviews solar-panel cleaning robot technologies and presents the design of a project-scale embedded cleaning robot.

Existing approaches including brush-based cleaning, water-assisted cleaning, suction mechanisms, self-propelled robots, Arduino-based systems, ultrasonic sensing and computer vision are reviewed. Based on the reviewed literature and the project hardware configuration, the proposed robot uses Arduino Uno, L298N motor-driver circuitry, 12 V geared DC motors, a 775 DC motor with a nylon brush, a water pump, a lithium-ion battery with 3S,3P BMS, a DC-DC step-down converter and HC-05 Bluetooth communication. The paper covers the problem statement, objectives, literature review, proposed architecture, hardware and software configuration, methodology, implementation, evaluation, limitations and future scope. Numerical performance values are not claimed where experimental measurements are unavailable.

Index Terms: Solar panel, photovoltaic, cleaning robot, embedded system, Arduino Uno, L298N, DC motor, water pump, brush mechanism, Bluetooth.

I. INTRODUCTION

Solar energy is an important renewable energy source for electricity generation. The output of a photovoltaic module depends on the solar radiation received by its active surface. Dust, dirt and environmental particles accumulate over time and reduce the effective incident radiation.

Maintaining a clean surface is therefore an important part of PV operation and maintenance.

Manual cleaning is practical for a small number of modules, but repeated cleaning becomes labour-intensive when installations are large, rooftop-mounted or inclined. Accessibility, worker safety, cleaning time and water consumption are important practical concerns. A cleaning robot can reduce repeated manual intervention by combining a mobile platform with a brush, water delivery system or other cleaning method.

The project presentation specifies Arduino Uno as the central controller, 12 V geared motors and rubber wheels for movement, a 775 DC motor and nylon brush for cleaning, a water pump for wet cleaning, a lithium-ion battery pack with 3S,3P BMS, a DC-DC step-down module, an MPPT charge controller and HC-05 Bluetooth communication.

II. PROBLEM STATEMENT

Dust and environmental particles accumulate on solar panels over time, reducing their efficiency and power output. Manual cleaning requires significant human effort, time and water resources. Cleaning large-scale solar installations manually is difficult, unsafe and increases maintenance costs. Therefore, an automated solar-panel cleaning robot is required to maintain panel cleanliness and support improved energy generation.

III. OBJECTIVES

- 1) To design and develop an automated robot for cleaning solar panels.
- 2) To improve the efficiency and power output of solar panels by maintaining a clean surface.
- 3) To reduce manual labour, maintenance time and operational cost in solar-panel cleaning.
- 4) To design a cost-effective automated system for regular cleaning and maintenance of solar panels.

IV. LITERATURE REVIEW

A. Suction-Based Cleaning Robot

Wang et al. investigated the reliability of a suction-based photovoltaic panel cleaning robot. The work focuses on maintaining reliable contact between the robot and PV surface, which is important for inclined operation. Suction mechanisms, however, require careful surface-contact and reliability design. [1]

B. Modular Brush and Water Cleaning

Chailoet et al. proposed a modular robot for different solar-panel lengths using support and drive mechanisms, water jets and nylon brushes. The approach combines mechanical brushing with water-assisted cleaning and adapts to different panel dimensions. [2]

C. Solar Powered PV Panel Cleaning Robot

Kumar et al. presented a solar-powered PV panel cleaning robot. The study demonstrates robotic automation for PV maintenance and reduction of manual cleaning effort, while navigation and autonomous sensing remain areas for improvement. [3]

D. Arduino-Based Automatic Cleaning

Habib et al. reported an automatic solar-panel cleaning system based on Arduino for dust removal. The work demonstrates a low-cost microcontroller approach; additional sensors can improve edge detection, obstacle detection and autonomy. [4]

E. Self-Propelled PV Cleaning Robot

Rohini and Sharma investigated the mechanism design and kinematic characteristics of a self-propelled photovoltaic cleaning robot. The work highlights mobility and kinematic behaviour, requiring a balance of traction, stability, weight and cleaning coverage. [5]

F. Cylindrical Brush and Liquid Spraying

Phan Doan Phi Tien et al. presented a cleaning robot using a cylindrical brush and liquid spraying with Raspberry Pi vision, ESP32/STM32 control and ultrasonic edge detection. The study integrates cleaning, sensing and intelligent control and reported improved measured PV output after cleaning. [6]

G. Microcontroller-Based Automatic Cleaning

Ayman Hani Marhoon et al. reported a microcontroller-based automatic solar-panel cleaning system, supporting the feasibility of embedded automation and future integration of sensing and monitoring. [7]

V. COMPARATIVE ANALYSIS

Table I summarizes representative studies according to year, cleaning method, control/mobility approach, major contribution and limitation.

Table I. Comparative analysis of representative pv cleaning robot studies

Ref.	Year	Cleaning	Control/Mobility	Contribution	Limitation
[1]	2018	Suction	Suction robot	Reliability study	Contact complexity
[2]	2019	Water + brush	Modular robot	Adaptable length	Mechanical complexity
[3]	2020	Mechanical	Solar-powered robot	Less manual effort	Limited sensing
[4]	2021	Dust removal	Arduino	Low-cost control	Needs sensing
[5]	2023	Mechanical	Self-propelled	Mobility study	Traction/stability
[6]	2024	Brush + liquid	Vision/ultrasonic	Advanced automation	Higher complexity
[7]	2024	Automatic	Microcontroller	Embedded automation	Needs more sensing

The literature shows a progression from simple mechanical and microcontroller-based systems toward more autonomous sensor-assisted systems. Basic embedded architectures are easier to implement, whereas vision and multi-sensor systems provide greater autonomy at higher hardware and software complexity.

VI. RESEARCH GAP

Existing research demonstrates multiple approaches to automated PV cleaning, but there is a practical gap between simple low-cost cleaners and highly autonomous robots using cameras, multiple controllers and several sensors. A student prototype requires a balance between cleaning effectiveness, cost, power consumption, mechanical stability and implementation complexity.

The proposed project addresses this gap by concentrating on the essential functions of mobility and cleaning using readily available embedded hardware. The basic system does not claim complete autonomous navigation; future versions can add edge sensors, obstacle detection, dirt detection, battery monitoring and IoT communication.

VII. PROPOSED SYSTEM ARCHITECTURE

The proposed Solar Panel Cleaning Robot consists of control, movement, cleaning, power-management and wireless-communication subsystems. Arduino Uno is the central controller. L298N motor-driver circuitry interfaces the controller with the geared DC motors. A 775 motor drives the nylon brush and the water pump supports wet cleaning. The lithium-ion battery and BMS provide and protect the power source, while the DC-DC converter provides regulated voltage. HC-05 provides wireless communication between a mobile device and Arduino.

The functional sequence is: Power supply → Arduino Uno → motor driver → wheel motors for movement; Arduino Uno → brush motor and water pump for cleaning; and Arduino Uno ↔ HC-05 for wireless control. An MPPT charge controller is used in the project charging subsystem to regulate solar charging.

VIII. HARDWARE CONFIGURATION

TABLE II. HARDWARE CONFIGURATION

Component	Specification	Function
Arduino Uno	ATmega328P, 5 V, 16 MHz	Central controller.
L298N Motor Driver	5–35 V motor supply, dual H-bridge	Motor direction and PWM control.
12 V Geared Motors	12 V geared DC motors	Four-wheel movement and traction.
Lithium-Ion Battery	3S3P; about 11.1 V nominal	Primary DC power source.
3S3P BMS	3-series battery management	Protection and balancing.
775 DC Motor	12 V-class brushed motor	Drives cleaning brush.
Nylon Smooth Brush	Soft nylon bristles	Removes dust/dirt.
Water Pump	Low-voltage pump in project	Assists wet cleaning.
HC-05	Bluetooth 2.0 SPP	Wireless control.
DC-DC Step-Down	12 V to about 5 V	Regulated low-voltage supply.
MPPT Charge Controller	Maximum Power Point Tracking	Solar battery charging regulation.
Solar Panel	10 W, 12 V-class	Solar charging source.
Push Button / Toggle	Mechanical switches	Start/stop and master power control.

IX. SOFTWARE CONFIGURATION

Arduino IDE is used to write, compile, debug and upload the embedded C/C++ program to Arduino Uno. The program handles Bluetooth commands and controls the drive motors, cleaning brush and water pump. The project presentation identifies Arduino IDE as the software environment for motor control, brush operation, pump control and Bluetooth-based operation.

The control program can be organized into initialization, command reception, movement control, cleaning control and stop/safety functions. Each actuator can be tested individually before integrated operation.

X. METHODOLOGY

- 1) Study PV soiling and existing automatic cleaning technologies.
- 2) Define the robot frame, wheel arrangement, brush mounting and pump location.
- 3) Develop the power subsystem using solar panel, MPPT controller, battery, BMS and DC-DC converter.
- 4) Interface Arduino Uno with L298N and geared motors for movement.
- 5) Mount and control the 775 motor and nylon brush for dust removal.
- 6) Interface the water pump for optional wet cleaning.
- 7) Integrate HC-05 Bluetooth communication.
- 8) Develop and upload the Arduino program using Arduino IDE.
- 9) Test movement, brush, pump and integrated cleaning functions.
- 10) Measure panel voltage and current before and after cleaning under comparable conditions for quantitative evaluation.

XI. IMPLEMENTATION

The implementation begins with the mechanical chassis, four geared motors, rubber wheels, brush assembly and pump. Arduino Uno is connected to the L298N motor-driver stage for movement. The 775 motor is mounted so that the nylon brush contacts the panel surface without excessive pressure. The battery, BMS, converter and charging components are mounted with suitable separation from the wet-cleaning path. During operation, HC-05 receives commands from a mobile device and transfers them to Arduino through serial communication. The controller decodes the command and activates the corresponding motor-driver outputs. The brush can operate during movement, and the pump can be activated when wet cleaning is selected.

XII. PERFORMANCE EVALUATION

The prototype can be evaluated through forward, reverse, left-turn and right-turn tests; brush ON/OFF tests; pump operation tests; and combined cleaning tests. These tests verify the individual subsystems before complete integration. The project material also identifies controlled power testing for evaluating the effect of cleaning on PV output. For quantitative PV evaluation, voltage and current should be measured before and after cleaning under comparable irradiance and temperature conditions. Electrical power is $P = V \times I$. Percentage change in power is $((P_{\text{after}} - P_{\text{before}}) / P_{\text{before}}) \times 100$. Since experimental numerical results for the current prototype are not supplied in the project sources, this paper does not claim a specific percentage improvement.

XIII. ADVANTAGES

- 1) Reduces repeated manual cleaning effort.
- 2) Supports regular PV maintenance.
- 3) Combines mechanical brushing with optional wet cleaning.
- 4) Uses a comparatively simple Arduino-based embedded architecture.
- 5) Provides wireless prototype control through Bluetooth.
- 6) Can be extended with sensors, autonomous navigation and IoT monitoring.

XIV. LIMITATIONS

- 1) Basic operation depends on user control and is not fully autonomous.
- 2) Stable traction is required on inclined panel surfaces.
- 3) Water consumption must be controlled.
- 4) L298N has practical current and voltage-drop limitations.
- 5) Edge and obstacle detection are not included in the basic architecture.
- 6) Battery operating time depends on motor, brush and pump loads.
- 7) Electrical isolation is important when water is used.

XV. FUTURE SCOPE

Future development can include ultrasonic or infrared edge detection, obstacle sensors, dirt detection, automatic path planning and autonomous cleaning schedules. Battery voltage/current monitoring and water-level sensing can improve supervision. IoT connectivity can provide remote status monitoring. The mechanical structure can also be optimized for lower weight, improved traction and adjustable brush pressure.

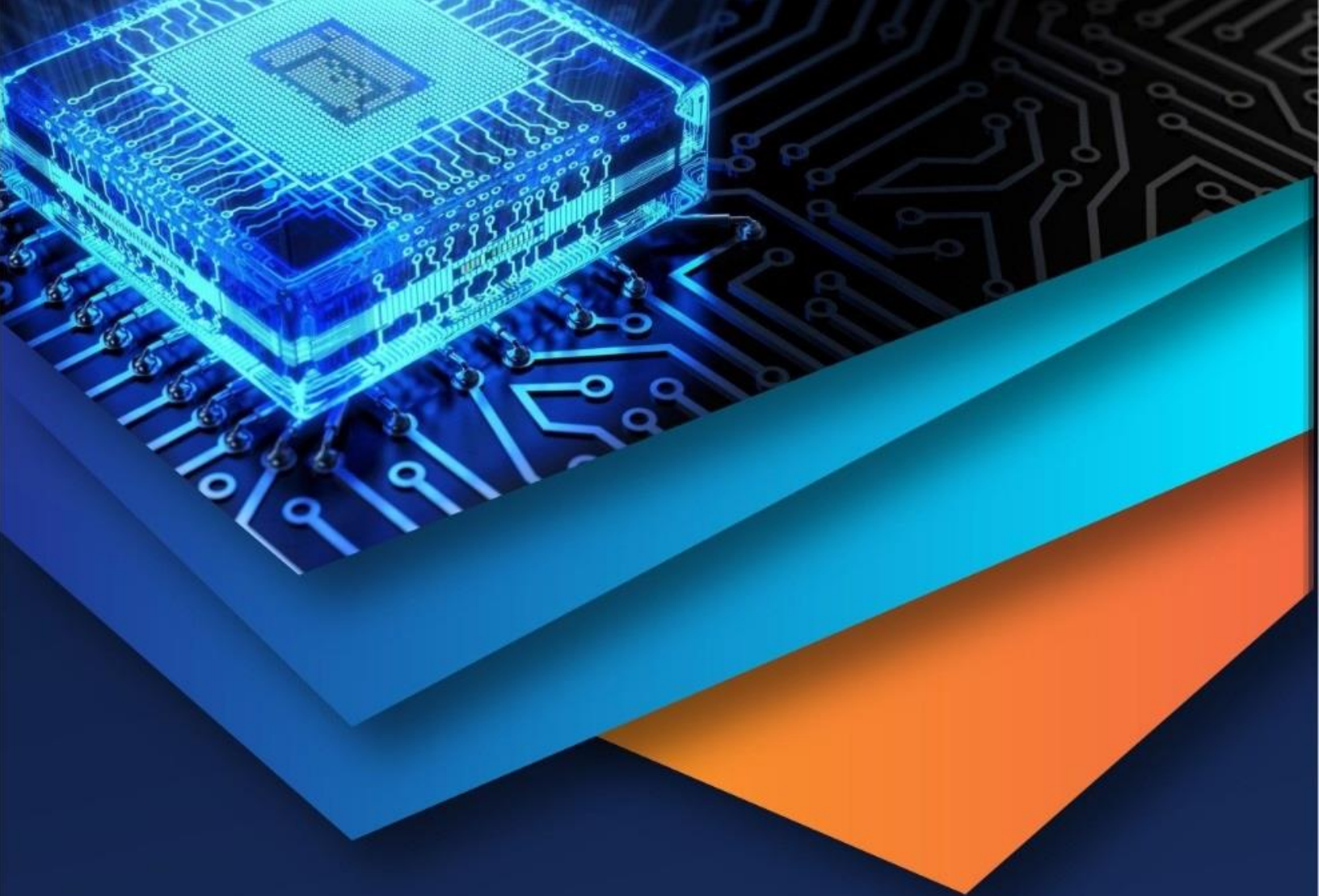
XVI. CONCLUSION

This paper reviewed representative solar-panel cleaning technologies and presented a project-oriented embedded cleaning robot. Existing research includes suction mechanisms, modular brush-and-water systems, solar-powered robots, Arduino-based cleaners, self-propelled mechanisms and advanced robots using vision and ultrasonic sensing.

The proposed project adopts the essential functions in a compact architecture using Arduino Uno, L298N motor-driver circuitry, 12 V geared motors, a 775 motor with a nylon brush, a water pump, a lithium-ion battery with BMS, a DC-DC converter and Bluetooth communication. The design provides a suitable academic prototype for demonstrating embedded control and robotic cleaning. Future work can add autonomous sensing, navigation, monitoring and IoT capabilities.

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