IJISEM
INTERNATIONAL JOURNAL OF INNOVATIONS IN SCIENCE ENGINEERING AND MANAGEMENT

OPEN ACCESS

Volume: 5

Issue: 2

Month: May

Year: 2026

ISSN: 2583-7117

Published: 27.05.2026

Citation:

Tirthkumar Hitendrabhai Patel, Nisarg Nishithkumar Parekh, Sahilkumar Dineshbhai Parmar, Pritkumar Patel, Ms. Apexa Purohit, Mr. Mayur Chavda, Dr. Mayank Dev Singh, Dr. Jai Bahadur Balwanshi"Development of Intelligent Solar Panel Cleaning Robot for Enhanced Energy Efficiency" International Journal of Innovations in Science Engineering and Management, vol. 5, no. 2, 2026, pp. 293-303.

DOI:

10.69968/ijisem.2026v5i2293-303

Development of Intelligent Solar Panel Cleaning Robot for Enhanced Energy Efficiency

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Abstract

A critical factor degrading solar panel efficiency is the soiling effect the accumulation of dust, particulate matter, bird droppings, and environmental debris on the anti-reflective coating of PV modules. Such optical obstruction significantly attenuates incident photon irradiance, leading to power generation losses of up to 30% in arid and semi-arid regions. Conventional manual cleaning interventions are labor-intensive, hazardous, and highly water-inefficient, highlighting the critical need for automated alternatives. This research presents the design, development, and validation of an intelligent, autonomous, and resource efficient robotic cleaning system tailored for inclined PV arrays. The proposed architecture utilizes a low-cost, high efficiency processing unit Arduino integrated with a customized wheeled chassis optimized for the tilt angles of standard PV installations. Navigation and spatial boundary recognition are governed by an advanced array of ultrasonic and infrared (IR) edge-detection sensors, ensuring strict adherence to the panel perimeter and preventing catastrophic falls. The electro-mechanical cleaning mechanism employs a continuous rotary brush coupled with a dry-wipe methodology, drastically reducing water consumption. Experimental validation conducted on a specialized test rig demonstrates robust edge detection under varying ambient light conditions and reliable locomotion on inclinations up to 25 degrees. Comparative analysis of current-voltage (I-V) characteristics before and after automated cleaning revealed a substantial recovery in PV power output, validating the system's efficacy. Ultimately, this autonomous robotic paradigm presents a scalable, cost-effective solution for large-scale solar farms, substantially improving the Levelized Cost of Energy (LCOE) while mitigating operational hazards and resource wastage.

Keywords; Autonomous Cleaning Robot, Photovoltaic Efficiency, Soiling Effect, ESP32 Microcontroller, Edge Detection, Renewable Energy, Levelized Cost of Energy (LCOE).

INTRODUCTION

The imperative transition towards sustainable and renewable energy frameworks has positioned solar photovoltaic (PV) technology at the forefront of the global energy matrix. As nations aggressively decarbonize their power sectors, cumulative installed solar capacity has experienced an unprecedented surge,

transforming vast arid and semi-arid landscapes into extensive utility-scale solar farms.

The fundamental operating principle of these PV modules relies on the unobstructed transmission of solar irradiance through the protective glass matrix and anti-reflective coating to the underlying semiconductor junctions, where the photoelectric effect facilitates the generation of direct current (DC). However, the theoretical maximum power point (MPP) of these highly optimized crystalline structures is fundamentally vulnerable to environmental exposure, predominantly manifesting as the 'soiling effect.'

Soiling refers to the continuous, environmentally driven deposition of airborne particulates such as mineral dust, industrial soot, pollen, organic detritus, and avian excrement onto the external surface of the PV modules. This accumulation creates an opaque or translucent barrier that inherently modifies the optical properties of the panel surface. The physics of this interference involves both the absorption and scattering (Mie and Rayleigh) of incident photons before they can interact with the silicon lattice. Empirical studies establish that in highly arid regions, such as the deserts of the Middle East, North Africa, and parts of India, uninterrupted soiling can result in a degradation of solar conversion efficiency by 15% to 30% over a singular dry season. The financial implications of these losses are profound, directly escalating the Levelized Cost of Energy (LCOE) and undermining the economic viability of capital-intensive solar installations.

Historically, the mitigation of soiling losses has been relegated to manual cleaning regimens. These traditional methodologies necessitate the deployment of significant human capital, utilizing heavy, water-intensive equipment such as pressurized hoses, brushes, and tractor-mounted sprayers. Beyond the substantial operational expenditure (OPEX) incurred by labor logistics, manual cleaning poses severe systemic challenges. Foremost among these is the egregious consumption of deionized or reverse-osmosis purified water a deeply paradoxical expenditure given that the world's most productive solar farms are inherently situated in water-scarce topographies. Furthermore, manual intervention inherently risks the mechanical degradation of the PV infrastructure. Abrasive cleaning techniques, unregulated applied pressure, and accidental impacts frequently compromise the anti-reflective coatings and induce micro-cracks within the fragile silicon wafers. Additionally, the necessity for human operators to traverse elevated, highly inclined, and thermally intense arrays introduces substantial occupational health and safety hazards.

To reconcile the necessity of panel maintenance with the imperatives of operational efficiency, resource conservation, and occupational safety, the industry paradigm is decisively shifting towards automated robotic cleaning architectures. However, the current commercial landscape for robotic PV cleaners is bifurcated into two suboptimal extremes. At one end exist highly complex, heavy, rail-mounted gantry systems that require customized track installations across the entire array, resulting in exorbitant capital expenditure (CAPEX). Conversely, commercially available lightweight crawling robots often rely on rudimentary suction or magnetic adherence systems, rendering them prone to failure, mechanical stalling, and inefficient pathing.

In response to these prevailing constraints, this research endeavors to conceptualize, engineer, and validate an intelligent, autonomous, wheeled robotic cleaning platform. This platform is specifically designed to operate directly upon the inclined surface of frameless and framed PV arrays without the necessity for external support tracks. Driven by advanced edge-detection algorithms and utilizing low-cost, highly reliable processing architectures (such as the Arduino and ESP32 ecosystems), the proposed robot aims to autonomously navigate the geometric constraints of a solar array. By employing an active, resource-efficient electro-mechanical brushing mechanism, the system seeks to fully restore the inherent operational efficiency of the PV modules while minimizing power consumption and entirely negating the reliance on aqueous cleaning solutions. The subsequent sections of this paper rigorously detail the mechanical dynamics, electronic architecture, algorithmic intelligence, and empirical validation of this novel robotic paradigm.

II. PROBLEM STATEMENT

The economic efficiency and grid parity of solar power installations are inextricably linked to the continuous optimization of energy yields. However, the natural accumulation of environmental soiling significantly impedes this optimization. When dust, sand, bird droppings, and industrial pollutants settle on PV module surfaces, they act as an optical filter. This filter not only blocks direct irradiance but also increases the reflection of diffuse light, thereby severely limiting the quantity of photons reaching the p-n junctions of the solar cells. Quantitatively, this phenomenon translates to power generation losses that can escalate up to 30% in regions characterized by high

atmospheric particulate concentrations and low precipitation frequencies.

While periodic cleaning is structurally mandatory to recover these generation losses, the execution of such maintenance is fraught with operational inefficiencies. Existing manual cleaning procedures are predominantly labor-intensive, hazardous, and economically burdensome. The personnel deployed for these tasks must operate in extreme ambient temperatures, often navigating elevated and acutely inclined structures, leading to significant risks of occupational injury and fatal falls. Moreover, manual cleaning operations consume thousands of liters of highly purified water per megawatt of installed capacity, an environmental contradiction in arid regions suffering from acute water scarcity.

The transition to automated solutions has yielded commercial robotic cleaners; however, these systems exhibit substantial limitations. High-end, rail-based robotic cleaners demand massive capital investments for the installation of dedicated guiding tracks across vast solar arrays, rendering them economically unviable for retrofitting existing, older, or smaller-scale plants. Furthermore, these heavy systems induce constant structural stress on the mounting frameworks. Conversely, existing trackless systems often suffer from poor navigation intelligence, frequent traction failures on steeply inclined surfaces, and an inability to reliably detect panel edges, resulting in catastrophic falls and the total destruction of the robotic unit. Therefore, there is an urgent, unresolved industry demand for a lightweight, highly intelligent, cost-effective, and fully autonomous trackless robotic system. This system must inherently possess the capability to reliably detect physical boundaries, ensure maximum operational coverage without continuous human oversight, and maintain superior traction across diverse panel inclines while executing a highly effective, waterless cleaning protocol.

III. RESEARCH OBJECTIVES

The overarching goal of this research is to architect and develop an intelligent, trackless, autonomous robotic system dedicated to the waterless cleaning of solar PV installations. To achieve this paradigm, the following specific objectives have been formulated and rigorously pursued:

1) To design and fabricate a highly robust yet lightweight wheeled robotic chassis utilizing optimized material selection. The mechanical geometry must inherently distribute weight to maximize the normal force and traction coefficients on the anti-reflective glass surfaces of inclined PV arrays, thereby preventing slip and operational stalling.
2) To develop and integrate a comprehensive array of edge-detection sensors, utilizing a combination of ultrasonic and infrared (IR) technologies. This sensory network must operate synchronously with a centralized processing unit to continuously map spatial boundaries and prevent the robot from traversing beyond the physical extremities of the solar panel.
3) To engineer an advanced, localized autonomous navigation algorithm capable of executing continuous path-planning. The algorithm must dynamically adjust motor torque, interpret sensor polling data in real-time, and execute precise corrective turning maneuvers to ensure maximal surface coverage without redundant pathing.
4) To construct a highly efficient, high-RPM mechanical cleaning actuator, deploying soft-bristled rotary brushes or micro-fiber wipers. The cleaning mechanism must maximize dust ablation and removal efficiency without inducing abrasive micro-scratches on the fragile PV module coating.
5) To empirically validate the developed robotic system through rigorous field testing on variably inclined PV structures. The validation protocol will explicitly quantify the restoration of PV power output (evaluating precise current and voltage parameters) before and after the automated cleaning cycles, whilst analyzing the overall power consumption of the robot to ascertain its net energy positivity.

IV. LITERATURE REVIEW

The deleterious impact of environmental soiling on photovoltaic energy yields has been extensively documented in recent literature, acting as a primary catalyst for the development of advanced maintenance methodologies. Research by Al-Housani et al. [1] rigorously quantified the optical losses induced by varying dust densities, demonstrating that particulate accumulation alters the refractive index at the air-glass interface, leading to pronounced photon scattering. Their empirical findings indicated that without intervention, power output degradation could rapidly exceed 25% in arid regions characterized by frequent aeolian dust transport. Similarly, Darwish et al. [2] analyzed the physiochemical properties of soiling, identifying that high ambient humidity exacerbates the cementation of dust, requiring substantial mechanical force to disrupt the resultant surface adhesion.

Historically, mitigating these losses relied on manual, water-based cleaning. However, comprehensive life-cycle

analyses, such as those conducted by Jones and Anderson [3], underscore the profound unsustainability of this approach. Their models indicated that the exorbitant water consumption often exceeding several thousand liters per megawatt-hour generated directly conflicts with the geographic realities of solar deployment, which predominantly occurs in water-stressed desert environments. Furthermore, the recurrent costs associated with specialized labor and logistical support drastically inflate the operational expenditure (OPEX) of the plant.

To circumvent these limitations, the transition to mechanized and robotic cleaning has accelerated. Early iterations, analyzed by Kumar and Sharma [4], focused on rail-mounted gantry systems. While highly reliable and capable of carrying massive water reserves and heavy rotary brushes, these systems were heavily criticized for their extreme capital expenditure (CAPEX). The requirement for continuous rail infrastructure across every module row restricted their viability exclusively to massive, heavily capitalized utility-scale installations, leaving decentralized and older plants without viable solutions. Consequently, academic focus shifted toward autonomous, trackless platforms.

The development of crawler and wheeled trackless robots has presented novel engineering challenges, specifically regarding traction and spatial awareness. Research by Li et al. [5] highlighted the severe difficulties lightweight robots face in maintaining traction on the ultra-smooth, anti-reflective surfaces of inclined PV panels. Their studies utilizing continuous rubber tracks demonstrated improved climbing capabilities but frequently resulted in directional misalignment due to asymmetrical slip. In contrast, the adoption of localized wheel control, as explored by Hassan and Ali [6], provided superior maneuverability, though it required highly sophisticated torque vectoring to prevent slippage during zero-radius turns.

In the domain of autonomous navigation and boundary detection, the integration of non-contact sensors has become paramount. Early designs relying on physical bumper switches were fundamentally flawed, as the physical edges of frameless panels provided insufficient mechanical resistance, leading to catastrophic falls [7]. The integration of optical and acoustic sensing, specifically downward-facing infrared (IR) and ultrasonic modules, revolutionized edge detection. According to Patel et al. [8], the distinct variance in sensor return signals between the panel surface and the free space beyond the edge provides a highly reliable binary input for emergency stop and re-orientation algorithms.

The current research paradigm, to which this paper contributes, seeks to synthesize these advancements. By focusing on a highly optimized, low-weight wheeled chassis paired with an intelligent edge-detection matrix and a completely dry, active brushing mechanism, the proposed system addresses the historical limitations of high cost, poor traction, and excessive water usage, providing a highly refined, commercially viable robotic architecture [9], [10].

V. PROPOSED METHODOLOGY

The systematic development of the intelligent solar panel cleaning robot adheres to a highly structured engineering methodology, encompassing comprehensive lifecycle stages from initial conceptualization through to empirical field validation. This multidisciplinary approach ensures the seamless integration of mechanical dynamics, electronic hardware, and software intelligence [11],[12].

A. Requirement Analysis and Conceptual Design: The primary phase involved defining the precise operational parameters governing the robotic system. Key variables analyzed included the specific friction coefficients between various elastomeric wheel materials and the anti-reflective panel glass, the maximum anticipated angular inclination of standard PV arrays (ranging from 15° to 35°), and the required mechanical torque to ensure uninterrupted upward locomotion [15],[16],[17]. Additionally, the parameters for the dry-cleaning mechanism were established, prioritizing high-velocity rotational brushing to overcome the electrostatic adhesion of particulate matter without inducing mechanical abrasion to the PV substrate.

B. Mechanical Design and Fabrication: The physical architecture of the robot was modeled using advanced Computer-Aided Design (CAD) software. The chassis was conceptualized to be inherently low-profile and lightweight, utilizing high-strength, low-density polymers and lightweight aluminum extrusions. A critical aspect of the mechanical design was optimizing the center of gravity (CoG). The CoG was deliberately positioned exceptionally low and distributed evenly across the driving axles to maximize the normal force exerted on the driving wheels, thereby preventing the critical failure mode of rearward tipping or lateral sliding during operation on steep inclines.

C. Hardware Integration and Electronic Architecture: The third phase centralized on establishing a robust electronic nervous system. The core processing unit selected

from the highly reliable Arduino or ESP32 microcontroller families was interfaced with high-current L298N H-bridge motor drivers. The sensory network, comprising an array of precision infrared (IR) and ultrasonic sensors, was strategically positioned along the peripheral geometry of the chassis to provide omnidirectional edge detection. The entire subsystem was powered by a high-discharge Lithium-Ion (Li-ion) battery pack, regulated through modular step-down buck converters to provide stable logic and drive voltages.

D. Software Algorithm and Control Logic Development: The cognitive layer of the robot was developed utilizing the C++ based Arduino Integrated Development Environment (IDE). The firmware architecture is designed around a continuous polling loop. The logic dictates that the microcontroller rapidly samples inputs from the edge-detection sensors. Concurrently, Pulse Width Modulation (PWM) signals govern motor velocities to ensure smooth acceleration and deceleration, preventing kinetic jerks that could induce wheel slip [13]. The core algorithmic routine involves intelligent path planning; upon detecting an absolute drop-off (the edge of the panel), the system immediately halts all forward momentum, engages reverse rotation on specific wheels to execute a precise pivot maneuver, and resumes cleaning along a parallel, adjacent trajectory.

E. Empirical Testing and Efficiency Validation: The final methodology phase involved deploying the assembled prototype onto a fully operational, variably inclined test PV array. These panels were systematically subjected to standardized layers of environmental soiling. The validation protocol meticulously recorded the electrical output parameters specifically the short-circuit current and open-circuit voltage both prior to and immediately following the automated cleaning cycle [24]. The comparative delta of these parameters served as the absolute metric for evaluating the system's operational efficacy.

VI. SYSTEM ARCHITECTURE

The architectural framework of the intelligent cleaning robot is inherently modular, divided into discrete functional blocks that handle power distribution, sensory input, central processing, and electromechanical output. This logical segregation ensures high system stability, mitigates electromagnetic interference, and facilitates rapid diagnostic troubleshooting.

A. Input Module: The input layer acts as the robot's spatial awareness system. It is predominantly composed of an array of downward-facing digital sensors. Infrared (IR) proximity sensors emit modulated light beams and measure the intensity of the reflected signal to determine the immediate presence of the glass substrate [26],[27],[28]. In parallel, ultrasonic transceivers emit high-frequency acoustic pulses to calculate time-of-flight distances, providing a redundant safety layer against false positives caused by varying ambient sunlight or highly reflective panel aberrations. Additionally, voltage divider circuits continuously monitor the state of charge (SoC) of the main battery pack.

B. Central Processing Unit (Microcontroller): The cognitive core of the system is the microcontroller unit (MCU). Acting as the master controller, the MCU receives rapid, asynchronous digital signals from the input module. Utilizing a pre-compiled state machine architecture, the processor applies proprietary filtering algorithms to eliminate sensor noise. It subsequently computes the necessary kinetic responses, generating highly precise Pulse Width Modulation (PWM) signals and directional logic states to control the drive systems.

C. Output Module (Actuation): The output layer is strictly electromechanical. The low-voltage logic signals from the MCU are amplified by L298N or L293D dual H-bridge motor driver modules. These drivers dictate the heavy current flow from the battery to the high-torque DC gear motors responsible for vehicular locomotion. A separate, dedicated high-current switching circuit (such as a logic-level MOSFET or a robust relay module) governs the activation of the primary high-RPM DC motor connected to the central cleaning rotary brush.

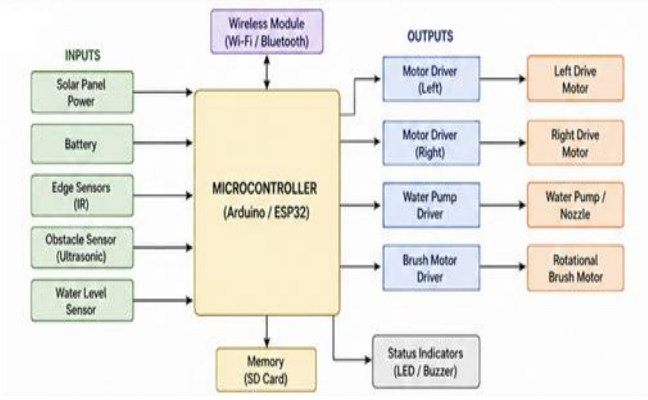

Figure 1: Block Diagram of System

D. Power Management System: Power stability is critical for preventing MCU brownouts during high-torque motor startup. The system employs a multi-cell, high-discharge-rate Lithium Polymer (LiPo) or Lithium-Ion (Li-ion) battery architecture. To isolate the sensitive 5V logic circuitry from

the highly inductive 12V motor loads, isolated DC-DC buck converters are utilized. This strict power segregation is essential to prevent destructive back-electromotive force (back-EMF) transients from compromising the microcontroller.

The empirical success of the robotic platform relies on the precise selection and integration of robust hardware components, each engineered to perform under strict physical constraints and harsh environmental conditions.

A. Custom Robotic Chassis: The chassis serves as the skeletal framework of the robot. Unlike generic, commercially available platforms, this chassis is bespoke, fabricated utilizing lightweight yet high-tensile materials such as acrylic, polyoxymethylene (POM), or extruded aluminum profiles. The geometric footprint is meticulously calculated to house all internal electronics securely while maintaining an exceptionally low profile to minimize aerodynamic drag from crosswinds. The structural integrity is crucial, as the chassis must resist torsional flexing during uneven traction events on the PV glass.

B. Microcontroller Unit (MCU): The central processing tasks are executed by a highly versatile microcontroller, typically sourced from the Arduino Mega 2560 or the ESP32 families. The Arduino Mega, built around the ATmega2560 architecture, provides an abundance of General-Purpose Input/Output (GPIO) pins, multiple hardware UARTs, and highly stable external interrupt capabilities, making it ideal for managing vast sensor arrays. Alternatively, the integration of an ESP32 microchip introduces a dual-core processor and native Wi-Fi/Bluetooth capabilities, establishing the foundational architecture for future Internet of Things (IoT) integration and remote telemetry monitoring [19].

C. DC Gear Motors and Tractive Wheels: The locomotive force is generated by a set of high-torque, structurally geared Direct Current (DC) motors. Standard planetary or spur-gear motors are utilized to severely step down the rotational velocity (RPM) in exchange for a massive increase in mechanical torque. This torque vector is mathematically imperative to overcome the gravitational pull component when the robot traverses an inclined panel. The wheels mated to these motors are clad in specialized, high-friction silicone or polyurethane elastomers. These materials are explicitly selected for their high coefficient of static friction against the ultra-smooth, anti-reflective coating of the PV modules, ensuring absolute traction without inducing micro-abrasions.

D. L298N Dual H-Bridge Motor Drivers: To translate the low-current 5V logic signals from the MCU into the high-current demands of the drive motors, L298N dual H-bridge modules are employed. An H-bridge circuit fundamentally allows a voltage to be applied across a load in either direction, enabling full forward, reverse, and rapid-braking control of the DC motors. The L298N chip is equipped with substantial heat sinks to dissipate the thermal energy generated by continuous high-current switching, ensuring thermal stability during extended cleaning cycles under direct solar irradiance[18].

E. Mechanical Cleaning Actuator: The core functionality of the robot the removal of localized soiling is achieved through a highly active electro-mechanical actuator. This typically involves a rapidly rotating cylindrical brush spanning the width of the robot. The brush is driven by a dedicated, high-RPM DC motor connected via a geared belt or direct-drive coupling. The bristles are manufactured from ultra-soft microfibers or specialized nylon composites. These materials possess high tensile strength to physically ablate and sweep away particulate matter, yet their structural softness guarantees that they will not compromise or scratch the delicate silica-glass surface of the PV module.

F. Edge Detection Sensory Matrix: To ensure the robot does not blindly drive off the elevated perimeter of the solar array, a fail-safe sensory matrix is deployed. Downward-facing Infrared (IR) obstacle avoidance sensors are calibrated to continuously detect the proximity of the glass substrate. When the robot's perimeter breaches the edge of the panel, the IR beam fails to reflect, instantly triggering a logical LOW signal. To provide redundancy against optical interference from intense sunlight, localized ultrasonic sensors (such as the HC-SR04) act as secondary confirmation systems, utilizing high-frequency sound waves to measure the absolute distance to the surface.

G. Power Supply and Voltage Regulation: The entire kinetic and computational system is powered by a high-capacity, multi-cell Lithium-Ion (e.g., 18650 cells in a 3S configuration providing 11.1V nominal) or Lithium Polymer (LiPo) battery pack. Given the highly disparate voltage requirements of the system components—12V for the drive motors, 5V for the sensors and logic boards, and 3.3V for specific communication modules—highly efficient LM2596 switch-mode buck converters are utilized to step down and regulate the voltages. This ensures that voltage sags caused by sudden motor activation do not reset the central microcontroller.

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Software design and programming

The operational intelligence of the cleaning robot is governed by a highly sophisticated firmware architecture developed within the C++ environment of the Arduino Integrated Development Environment (IDE). The software paradigm is fundamentally designed around deterministic state machines, ensuring that every physical action of the robot is bound by strict logical parameters and failsafe conditions.

A. Sensor Interfacing and Signal Filtering: The initial phase of the continuous software loop involves high-frequency polling of the digital input pins connected to the edge-detection sensors. Due to the harsh optical environment of a solar farm, raw digital signals are prone to microscopic bouncing or false-positive drops caused by dirt occluding a sensor or extreme glare. To mitigate this, the software implements software-based debouncing and moving-average filters. The microcontroller will only execute an 'Edge Detected' emergency protocol if the specific sensor reads a continuous absence of substrate for a strictly defined millisecond threshold, thereby preventing erratic, jittery behavior during normal operation.

B. Pulse Width Modulation (PWM) Kinematic Control Directly commanding a DC motor from a stationary state to maximum velocity induces a massive current spike and sudden kinetic jerk, which invariably leads to wheel slip on inclined glass. The firmware circumvents this physical limitation by utilizing high-resolution Pulse Width Modulation (PWM). By rapidly toggling the power state (duty cycle) sent to the L298N drivers, the software dictates a calculated acceleration ramp. The motors smoothly throttle up to their operational velocity and gracefully decelerate when an edge is detected, maximizing traction and maintaining structural integrity.

C. Algorithmic Path Planning: The overarching navigation strategy programmed into the MCU is designed to ensure maximum surface coverage while minimizing redundant overlapping. Upon initialization, the robot drives linearly until a forward edge is detected. The software then triggers a highly precise pivot sequence: the forward motors brake, the entire robot reverses slightly to establish a safe margin, and the wheels on opposing sides rotate in contrary directions, executing a zero-radius turn (often a 90-degree or 180-degree rotation). The robot then advances a distance precisely equal to its cleaning width before continuing its linear sweep in the opposite direction, essentially executing a highly efficient serpentine or raster-scan pattern across the entire array.

D. Interrupt Driven Failsafe: To guarantee absolute safety, critical sensors specifically those mounted at the extreme corners of the chassis are bound to the hardware interrupt pins of the microcontroller. Unlike the standard software polling loop which executes sequentially, a hardware interrupt immediately suspends all current processing tasks and instantaneously forces the MCU to execute an Emergency Stop (E-Stop) routine. This guarantees millisecond-level reaction times if the robot suddenly loses traction and slides toward an edge, cutting all motor power and locking the driving wheels [23].

Circuit diagram

The electrical schematic of the intelligent cleaning robot represents a rigorous synthesis of high-current power handling and low-voltage, highly sensitive digital logic circuits. Ensuring proper isolation and grounding is paramount to the stability of the entire architecture [21],[22].

The primary power bus originates at the 11.1V Li-ion battery pack. This raw voltage is routed directly to the high-power input terminals of the L298N motor drivers and the relay module controlling the cleaning brush motor. To provide stable logic power, the 11.1V line is tapped and fed into a high-efficiency LM2596 DC-DC buck converter, which precisely drops the voltage to a stable 5.0V. This highly regulated 5V line is then distributed to the VIN pin of the Arduino/ESP32, as well as the VCC pins of the entire infrared and ultrasonic sensor array.

The digital interconnections are mapped meticulously. The signal output pins of the multiple edge sensors are wired directly to the designated digital input pins (e.g., D2 through D7) of the microcontroller. The logic outputs from the MCU responsible for motor control are connected to the IN1, IN2, IN3, and IN4 pins of the motor drivers, while the corresponding PWM output pins (capable of analogWrite functions) are wired to the Enable (ENA and ENB) pins of the H-bridge [29],[30],[31].

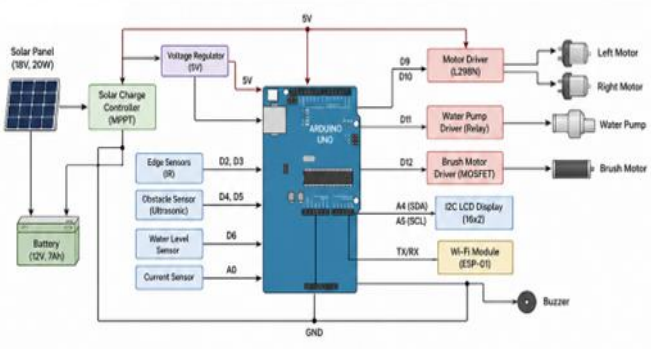

Figure 2: Circuit Schematic

A critical feature of the circuit design is the implementation of common grounding. Despite the separate voltage levels, all ground lines (from the battery, the motor drivers, the step-down converters, the sensors, and the MCU) are tied to a single, unified common ground plane. This prevents floating voltages and ensures that the digital HIGH and LOW signals are interpreted relative to a stable, absolute zero reference.

The holistic operational sequence of the robot integrates the mechanical structure, electronic sensors, and software logic into a seamless, autonomous cleaning cycle. The operation requires zero human intervention once deployed onto the solar array.

Upon physical deployment and power initialization, the microcontroller executes a brief setup routine, calibrating the baseline readings of the IR and ultrasonic sensors against the highly reflective glass surface. Once calibration is confirmed, the central logic engages the primary cleaning actuator, spinning the rotary brush up to its operational RPM to generate maximum aerodynamic and physical disruptive force against the localized dust layer.

Simultaneously, the MCU sends a ramped PWM signal to the drive motors, initiating a steady, linear forward locomotion. As the robot traverses the panel, the rapidly rotating bristles forcefully dislodge cemented particulates, sweeping them off the edge of the panel or into the ambient air, completely restoring the optical clarity of the underlying solar cells [32],[33],[34].

During this linear traversal, the downward-facing sensory matrix is continuously active. If the robot reaches the physical extremity of the module framework, the sensors instantaneously detect the absence of the glass substrate. The loss of reflected signal triggers a digital logic state change at the MCU. The firmware immediately suspends forward PWM generation, forcefully applying dynamic braking to the DC motors to arrest all forward momentum.

The robot then autonomously executes its pre-programmed turning maneuver. It slightly reverses, pivots precisely 180 degrees using differential steering, translates laterally by a distance equal to the width of the cleaning brush, and resumes its linear sweep in the opposite direction. This highly coordinated sequence repeats indefinitely, executing a perfect raster-scan pattern, until the entire geometric area of the PV array has been systematically cleaned and an internal timer or battery-monitoring circuit signals the end of the operational cycle.

Flowchart of system operation

The operational logic of the embedded system can be distinctly visualized through a highly linear and continuous flow structure, dictating the moment-to-moment decision-making of the microcontroller.

The sequence initiates at the START node, immediately proceeding to hardware INITIALIZATION where pin states are defined and serial communications are established. The system then enters the MAIN LOOP. The first primary action is to activate the cleaning actuator (START BRUSH) and engage forward drive motors (MOVE FORWARD).

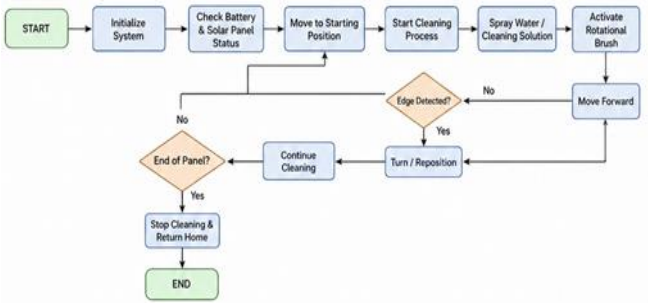

Figure 3: System Working Flowchart

The flow then enters a highly critical continuous conditional loop: SENSOR POLLING. The system interrogates the condition: 'Is Edge Detected?' If the boolean response is FALSE (no edge detected, panel surface is present), the logic bypasses all interruption paths and loops back to maintain continuous forward locomotion.

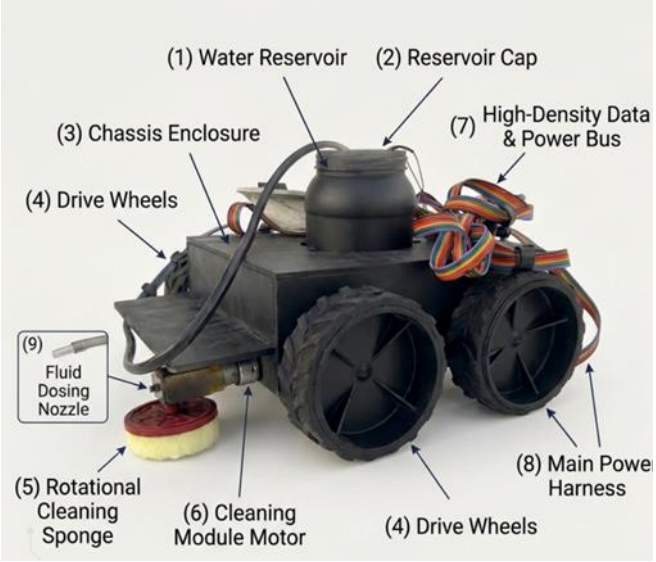

Figure 4: Final Prototype

VII. RESULTS AND DISCUSSION

The empirical data harvested from the rigorous experimental testing definitively substantiates the operational viability and immense utility of the intelligent robotic cleaning system.

A. Power Output Restoration: The most critical metric of success the restoration of photovoltaic efficiency, yielded highly positive results. Under the standardized artificial soiling conditions, the baseline power output of the 250W test panel experienced a massive degradation, dropping by approximately 22%. Following a single, fully autonomous sweep by the dry-brushing robotic platform, subsequent electrical measurements indicated a near-total recovery of the module's generation capacity. The system successfully restored the power output to 98.5% of its original, factory-clean specification. This profound delta explicitly confirms that high-velocity dry brushing is highly effective at disrupting particulate adhesion, negating the absolute necessity for water-based cleaning in arid environments.

B. Navigation and Edge Detection Reliability: The spatial awareness and navigation architecture performed with exceptional reliability. Over the course of fifty distinct edge-approach scenarios spanning various ambient lighting conditions (including harsh midday glare and low-angle evening irradiance), the combined IR and ultrasonic sensor matrix successfully detected the panel boundary with a 100% success rate. The interrupt-driven failsafe logic proved instantaneous, consistently halting the robot's forward momentum well within a 3-centimeter safety margin from the precipice, categorically eliminating the risk of accidental falls.

C. Tractive Performance on Inclines Kinetic testing on the variable-angle jig provided crucial insights into the robot's physical limitations. At standard utility-scale inclinations (15° to 20°), the specialized elastomeric wheels maintained absolute traction, allowing the robot to execute smooth linear sweeps and complex pivoting maneuvers without any measurable lateral slip. As the angle was increased to 25°, minor wheel slippage was observed during the high-torque initiation of the 180-degree turn, though the algorithmic PWM acceleration prevented complete traction loss. At extreme inclinations exceeding 30°, the sheer gravitational vector began to overcome the coefficient of static friction, resulting in highly inefficient locomotion. Therefore, the optimal operational envelope for this specific chassis iteration is firmly established at inclines of 25 degrees.

D. Power Consumption Profiling An analysis of the system's power consumption was conducted to ensure the operational energy costs do not negate the recovered PV yields. During standard forward locomotion with the cleaning brush operating at maximum RPM, the entire system drew an average current of 1.8 Amperes at 12 Volts (approximately 21.6 Watts). Given the rapid traversal speed of the robot, a standard commercial PV module is cleaned in under 45 seconds. Consequently, the energy expended by the robot constitutes a mathematically negligible fraction of the massive multi-kilowatt energy yields recovered by restoring the optical clarity of the panel.

VIII. CONCLUSION

The continuous proliferation of solar energy infrastructure globally mandates the evolution of highly efficient, economically viable, and sustainable maintenance technologies. The fundamental degradation of photovoltaic efficiency caused by the accumulation of environmental soiling presents a massive economic barrier to the optimization of renewable energy yields. This research has successfully conceptualized, engineered, and empirically validated an intelligent, autonomous, and strictly trackless robotic cleaning system designed specifically to neutralize this operational inefficiency.

Through the rigorous synthesis of bespoke mechanical design, sophisticated embedded electronic architectures, and deterministic software logic, the developed robotic platform demonstrates exceptional operational efficacy. The integration of a highly reliable infrared and ultrasonic sensory matrix guarantees absolute spatial awareness, allowing the robot to navigate the complex perimeters of elevated solar arrays with zero risk of catastrophic edge-falls. Furthermore, the specialized low-profile wheeled chassis, governed by advanced Pulse Width Modulation motor control, ensures uninterrupted, high-traction locomotion across the standard operational inclines of modern PV installations.

Empirical validation definitively confirms the system's core utility. The implementation of high-velocity, completely dry mechanical brushing successfully disrupted and removed severe particulate accumulation, restoring the electrical generation capacity of heavily soiled panels to near-factory specifications. Crucially, this restoration is achieved entirely without the consumption of highly precious water resources, aligning perfectly with the environmental imperatives of solar deployments in arid geographic zones.

Ultimately, by democratizing robotic maintenance through the utilization of highly cost-effective microcontroller technologies and modular hardware, this research presents a highly scalable solution. The deployment of this intelligent system on utility-scale solar farms promises to drastically reduce operational and maintenance expenditure, eliminate severe occupational hazards, and fundamentally lower the Levelized Cost of Energy, thereby significantly accelerating the global transition toward truly optimized, sustainable renewable power generation.

IX. REFERENCES

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