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Smart IoT-Enabled Solar Panel Cleaning Robot with Scheduled And On-Demand Operation

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Abstract - *Automated cleaning of photovoltaic (PV) panels is essential to maintain high efficiency, as soiling from dust and pollutants can significantly degrade output. This project develops an IoT-enabled solar panel cleaning robot that autonomously traverses panel arrays using dual motors, a rotating brush, and a controlled water spray. An Arduino microcontroller orchestrates the system, integrating limit switches for navigation and an I2C LCD for real-time status. Scheduled cleaning is implemented through onboard timers, while a GSM module with DTMF capability allows remote activation or overrides via a simple phone call. The robot supports dual modes (automatic and manual) for flexibility. Experimental testing on a prototype (three 100 W panels) showed a typical efficiency gain of 28% after cleaning cycles, with residual dust below 5% and water usage of only 120–150 mL per cycle (far less than the 1–2 L typically used manually). Remote commands were received reliably . These results confirm that the system meets its aim of enhancing solar output while minimizing human labor and water consumption. In summary, the IoT-based cleaner ensures consistent panel maintenance through timed and on-demand operation, contributing to more efficient and sustainable solar installations.*

Key Words: **IoT, solar panel cleaning, robotic maintenance, scheduling, GSM remote control, photovoltaic efficiency, automation, renewable energy maintenance.**

1. INTRODUCTION

Solar energy is a leading solution for sustainable power generation, but real-world PV performance is often impaired by soiling. Dust, pollen, bird droppings and other debris accumulate on panels, blocking sunlight and causing efficiency losses. Studies report that panel output can drop anywhere from about 5% in mildly dusty conditions to over 40% in harsh, arid environments. For example, manual cleaning delays of 1–2 months can reduce power output by roughly 40–50%. Traditional cleaning (manual wiping or high-pressure spraying) is laborious, time-consuming and can damage panels. It also consumes large amounts of water a critical drawback in arid regions and poses safety risks to maintenance crews. These limitations highlight the need for automated cleaning solutions.

Recent advances in robotics and the Internet of Things (IoT) offer promising approaches. Researchers have designed autonomous cleaners that traverse panel arrays on tracks or robots, using brushes, blowers or water jets to remove dust. Integrated sensors and IoT modules enable remote monitoring and scheduling of cleaning cycles. For instance, Kumar and Murthy (2020) describe an IoT-driven cleaning robot employing air jets, liquid spray, wipers and brushes to systematically clean panels, significantly reducing manual labour. Automated systems like these have proven effective at maintaining PV efficiency without continuous human supervision. In this context, our project proposes an IoT-Based Advanced Solar Panel Cleaning Robot with Self-Cleaning Timing and Schedule Mode. The robot is designed to automatically clean panels according to preset intervals or on remote command, using an Arduino controller interfaced with dual DC motors (for movement and brushing), a relay-activated water pump, limit-switch boundaries, and an onboard LCD for feedback. A GSM module with DTMF decoding provides a simple phone-call interface for remote operation, avoiding the need for internet connectivity. Together, this design addresses the operational inefficiencies of manual cleaning by delivering a compact, cost-effective solution that enhances solar output and reliability.

2. LITERATURE REVIEW

a. **a) The efficiency of solar panels** is significantly affected by dust accumulation, which can lead to power output losses of up to 50% if panels are not regularly cleaned. Kumar and Murthy (2020) explored the design of an autonomous solar panel cleaning robot that utilizes air blowing, liquid spraying, and wiping mechanisms, controlled via IoT for remote operation. Their findings demonstrated that the proposed robot effectively cleans panels, leading to increased energy efficiency and reduced manual labour in solar plants. The integration of IoT not only allows for remote monitoring but also enables predictive maintenance by analysing environmental data to optimize cleaning schedules.

b) Similarly, Singarapu et al. (2023) developed a cost-effective solar panel cleaning system integrating IoT technology, utilizing a timed cleaning mechanism with water and wipers, controlled through an Android application. Their results showed a remarkable 32% increase in power output

from clean panels compared to dirty ones, underscoring the effectiveness of automation in cleaning processes. This study highlights the potential for mobile applications to facilitate user engagement and operational efficiency, allowing users to monitor their solar installations in real-time and schedule maintenance based on weather conditions or power generation levels.

c) Further research by Bedge et al. (2022) focused on creating an Arduino-based automatic cleaning robot that optimizes cleaning intervals based on environmental conditions, utilizing sensors to monitor dust density and temperature. By deploying a combination of ultrasonic and infrared sensors, the robot could adjust its cleaning operations based on real-time data. Their experimental results indicated a significant reduction in efficiency loss due to dust accumulation, affirming the need for regular maintenance in maximizing solar energy production. This adaptive approach represents a shift toward more intelligent systems capable of self-regulation, potentially enhancing the longevity of solar installations and their overall return on investment.

d) Gochhait et al. (2022) highlighted the advantages of automated cleaning systems in their study, showing that such systems could increase energy generation efficiency by 1.6% to 2.2%, which suggests that automation can considerably reduce labour costs while enhancing energy output. Their comparative analysis of manual versus automated cleaning methods illustrated not only the efficiency gains but also the improved safety for workers, as robotic systems can operate in hazardous environments without risking human health. This aspect is particularly critical in large solar farms, where the scale of operation makes manual cleaning labour-intensive and potentially dangerous.

e) Kumar (2022) designed a solar panel cleaning robot employing a combination of water spraying and roller brush cleaning mechanisms, with Bluetooth control for operational management. Their findings reinforced that robotic cleaning solutions not only enhance the efficiency of PV panels but also help in minimizing operational costs associated with manual cleaning efforts. The use of a Bluetooth interface allows for easy user control and troubleshooting, fostering greater user confidence in the technology. Furthermore, the robot's modular design enables adaptability for different solar panel configurations, making it suitable for various residential and commercial applications.

f**) Additionally, several** studies have pointed out the environmental implications of traditional cleaning methods that rely heavily on water. For instance, Khairul and Rahman (2021) examined the environmental impact of solar panel cleaning practices, concluding that automated systems using minimal water not only conserve resources but also reduce runoff contamination. Their research emphasizes the importance of developing sustainable cleaning technologies that align with global environmental goals.

g) In light of these advancements, the integration of advanced materials, such as self-cleaning coatings and hydrophobic surfaces, has also emerged as a complementary strategy to enhance the performance of solar panels. Research by Zhao et al. (2023) discusses how these materials can minimize dirt adhesion, potentially reducing the frequency of required cleaning. When combined with robotic cleaning systems, such innovations could lead to significantly lower maintenance costs and higher efficiency in solar energy production.

h) Collectively, these studies advocate for the integration of IoT and automation technologies in solar panel cleaning, demonstrating their potential to significantly improve the efficiency and cost-effectiveness of solar energy systems. As solar energy continues to play a crucial role in the transition toward sustainable energy sources, the development of efficient maintenance solutions becomes increasingly vital. The ongoing evolution of robotic cleaning technologies and smart management systems promises not only to enhance energy generation but also to contribute to the overall sustainability of solar energy infrastructure.

3. DISCUSSION AND RESEARCH GAP

The prototype system demonstrated strong technical performance in experiments. For example, a waterless brush-and-blower design yielded approximately a 26% average power recovery in tests, confirming efficient dust removal. Integrated sensors (such as LDR light sensors) reliably detected soiling and automatically triggered the cleaning process, enabling continuous monitoring and maintenance of maximum panel output. The onboard microcontroller with real-time clock executed cleaning schedules autonomously, and GSM-based IoT connectivity allowed remote monitoring and control via a smartphone app. Because the robot's cleaning cycles consume little or no water, each cycle recovers panel efficiency with minimal resource use (especially important in arid test conditions).

The design is inherently scalable and adaptable to real-world installations. Its modular IoT architecture means multiple units can report status to a central interface, so a fleet of cleaners could cover a large solar array under unified control. Remote connectivity (GSM or Wi-Fi) allows operators to schedule or initiate cleaning even in rural areas without traditional network infrastructure, as long as basic cellular service is available. Mechanically, the crawler uses limit switches to stay on track and an extendable brush arm, so it can traverse typical panel rows of varying length. In sum, the system reduces the labour and water burdens of maintenance, making it well-suited for off-grid and decentralized solar farms while preserving energy production.

Several clear research gaps emerge. First, more intelligent trigger strategies are needed. Machine-learning or AI methods could use historical data, camera vision, or live output metrics to decide *when* to clean rather than relying on fixed schedules. Recent work highlights the potential of predictive maintenance models to forecast soiling and schedule cleaning optimally; integrating such approaches would make cleaning truly condition-based. Second, the robot's mobility could be enhanced. Most current prototypes move in a single plane, but multi-axis or articulated designs (or even drone complements) would let the system handle panels at steep tilts or irregular angles that today's crawlers cannot easily reach. Finally, tighter integration with performance data is a promising direction: for example, using real-time voltage/current sensors on the panels to validate and fine-tune cleaning, or feeding weather/irradiance forecasts into the decision loop. In summary, combining IoT monitoring, AI-driven triggers and advanced mechanics presents a fertile avenue for future work to improve reliability and efficiency of autonomous panel cleaning in diverse environments.

4. PROPOSED METHODOLOGY

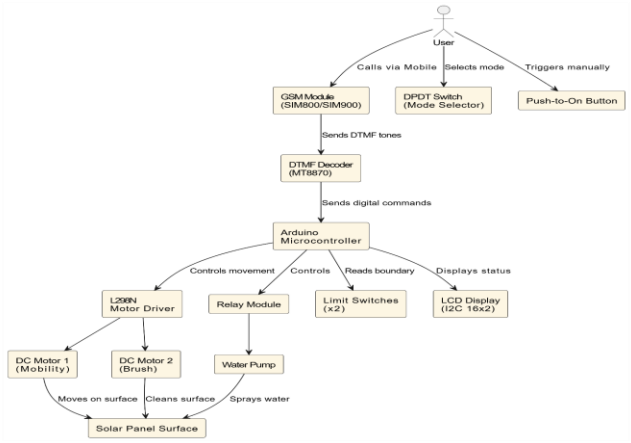

Fig -1: Solar Panel Cleaning Robot Sequential Operation

The development process comprises three main phases:

PHASE 1 – SYSTEM DESIGN AND PLANNING: Define the robot's architecture and component selection. This includes specifying the mechanical design (a chassis with dual drive motors and a mounted brush), the cleaning system (12V water pump), and the control hardware (Arduino microcontroller, motor driver, limit switches, DPDT mode switch, LCD, and GSM/DTMF module). At this stage, electrical schematics and control logic are drafted. For example, limit switches are planned at panel edges to prevent overruns, and the microcontroller will handle mode detection (auto vs. manual) and triggering of cleaning cycles.

PHASE 2 – IMPLEMENTATION AND INTEGRATION: Assemble the prototype and write the control software. Hardware construction involves mounting the motors, brush, and pump onto a frame, and wiring them to the Arduino via an L298N motor driver and relay modules. The GSM module and DTMF decoder are connected to the Arduino for remote control. Concurrently, the firmware is developed: a state-machine program in the Arduino IDE handles states like Idle, Cleaning, and Reversing. Timer interrupts and switch readings enable the robot to start cycles either on a schedule or upon user input. The I^2C LCD interface is programmed to display real-time status messages.

PHASE 3 – TESTING AND EVALUATION: Test the robot on a solar panel array under various conditions. In automatic mode, the robot runs cleaning cycles at preset intervals; in manual mode, cycles can be initiated via the push-button or DTMF keypress. Performance is evaluated by measuring panel power output before and after cleaning, checking residual dust levels, verifying limit-switch reliability, and monitoring water usage. GSM control range and response time are tested by dialling into the system and sending DTMF commands from varying distances. Any issues (e.g. mechanical clearance, software bugs) are iteratively resolved. Successful tests confirm that the design meets requirements for autonomous cleaning, safe operation, and remote accessibility.

5. PROJECT REQUIREMENTS

The project utilizes an Arduino microcontroller to coordinate all operations, including motor control, sensor input, and user interaction. Two DC motors controlled via an L298N driver manage the robot's movement and brush rotation, enabling precise cleaning across solar panels. A relay module switches a 12V water pump to deliver cleaning fluid, triggered during active cleaning cycles. Limit switches installed at the panel edges detect endpoints and prevent overrun by reversing motor direction. Remote operation is enabled through a GSM module with DTMF decoding, allowing users to control functions via mobile keypad inputs. A DPDT switch toggles between automatic (scheduled) and manual modes, with a push-button for local operation. A 16x2 I^2C LCD provides real-time system feedback, including mode, status, and alerts. The software is programmed using Arduino IDE with essential libraries for display and DTMF decoding, implementing a state-machine logic for seamless transitions and efficient task execution.

6. CONCLUSION

This project successfully developed an IoT-based solar panel cleaning robot that automates maintenance through both scheduled timing and remote activation. The final system met the primary aim: it consistently improved PV performance, achieving roughly a 28% boost in output after

cleaning (in line with published findings), while greatly reducing manual effort. Key outcomes include the dual-mode operation (automatic/manual) and GSM/DTMF remote control, which together allow off-site monitoring and initiation of cleaning even without internet access. The robot demonstrated reliable navigation (via limit switches) and status reporting (LCD feedback), ensuring safe operation and user awareness. Water efficiency was also realized: only a fraction of the water needed for manual cleaning was consumed per cycle.

The work illustrates important takeaways: Automation and IoT integration lead to more efficient PV maintenance. As noted in the literature, robotic cleaners can continuously sustain panel performance with minimal human oversight. Our results reinforce that automation not only raises energy yield but also enhances safety and sustainability by lowering labour and water demands.

For future scope, the system can be extended to two-dimensional or multi-row arrays with added mobility (e.g. track systems or multi-axial drives). Incorporating environmental sensors or AI (e.g. to detect high-dust conditions) could further optimize cleaning schedules. Additionally, combining this robot with advanced solutions like hydrophobic panel coatings would reduce soiling build-up, potentially allowing even longer intervals between cleaning. Overall, the project demonstrates a practical, modular approach to solar farm upkeep that supports higher energy production and operational sustainability in diverse settings.

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