Design, Implementation and Efficiency Analysis of an Automatic Solar Panel Cleaning Robot

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ABSTRACT

Robotic cleaning systems for solar panels are now rapidly advancing and becoming equipped with autonomous navigation systems operated by AI and waterless cleaning technologies, thus making companies like Ecoppia and IFBOT world's best in designing robots embedded with intelligent sensors and using dry-cleaning methods to be more effective while promoting sustainable actions. These systems contribute to energy efficiency by preventing dust accumulation on the panels, allowing maximum potential operation. Every one of them comes along with their drawbacks such as very expensive installation and frequent maintenance even with energy consumption, which hinder the general efficiency.. With the automated process, solar energy management will be more economical, environmentally friendly, and efficient in the long run. Such fantastic robotic systems do more than enhance the life and operation of the solar panels; they also complement a more environmentally friendly and therefore, sustainable future in renewable energy generation.

Keywords: Solar panel cleaning, automation, inclined surfaces, energy efficiency, ultrasonic sensors, water conservation, cost-effectiveness, dry cleaning technology, sustainable energy.

INTRODUCTION

. A solar panel cleaning robot has been introduced that can be carried by humans and can autonomously do cleaning of the solar panels so as to reduce wastage of water and labour to an optimum extent. This robot is much faster and more efficient than the conventional methods, but in its own way, another set of limitations arises-water dependent, scalability, power consumption, weather restrictions, and possible damage to the panel [1]. Dust, dirt, and bird droppings heavily contribute to the performance of solar panels, causing power losses of up to 40% if not promptly maintained. These cleaning methods are automated with the incorporation of nylon brushes, squeegees, water recycling, and locomotion through DC motors. The operational advantages gained are vibration-free, scalable, and smooth in operation [2]. One such system is designed and developed to work on an incline up to 30 degrees using rotary brushes and sprays of water; however, it loses efficiency on slope applications while sonar might not work very well under dusty conditions [3]. Systems that have been based on mechanical arms can give precision, heavily taxing upon operational easiness and maintenance [5]; and vacuuming systems work exceptionally in dry surroundings but will flatly fail the moment implementation is attempted in humid or wet contexts as they would demand power for all [8].Surveillances intimately executed of the cleaning schedule optimization through irradiation profiles, Fourier-models [11], and This study analyzes the performance of a multi-user MIMO system utilizing a successive hybrid beamforming approach for simultaneous information and energy transfer. The model enhances spectral and energy efficiency, optimizing wireless communication and power harvesting in next-generation networks [12]. This paper presents an optimized design of a double-notch E-shaped inset-fed patch antenna with enhanced bandwidth and improved VSWR performance[13] and machine-learning methods [15] contributes to the PV system performance as a whole but are considerably dependent upon accurate environmental data and the economic viability of the procedure., while self-powered cleaners remain unfeasible and cannot be made adaptable and scalable in terms of energy efficiency [16]. The modern research takes pulse on electrostatic and ultrasonic waterless cleaning methods whose promise use has already demonstrated significant progress in early commercialization [18]. Moreover, recent developments have shown wide potential in water dependency reduction while maintaining effective cleaning, such as the waterless cleaning mechanism by means of electrostatic and ultrasonic vibrations [20]. Nowadays seeing every nook and corner where solar panels are being installed; a thought that just arises in the mind is related to the cleaning of solar panels.

SYSTEM DESCRIPTION

It was a solar cleaning robot designed to have both hard and soft systems that can be used for efficient cleaning of surfaces or even automated systems for easy cleaning under steep upward and downward conditions. Thus, it gives a lightweight, mobile and remotely controlled system for easier operation. The Cleaning Mechanism and Mobility of the Robot was controlled through Embedded Control system and composed of the Arduino Microcontroller- which processes sensor inputs and executes commands for motor control, the Bluetooth App Interface- which allows remote control of the robot to use a smartphone application, and lastly the Obstacle Avoidance Algorithm- which alters motion based on real-time feedback using ultrasonic sensors to allow smoother navigation over inclined surfaces. This Integrated hardware-software system ensures that the cleaning operation is done with minimal human involvement.

METHODOLOGY

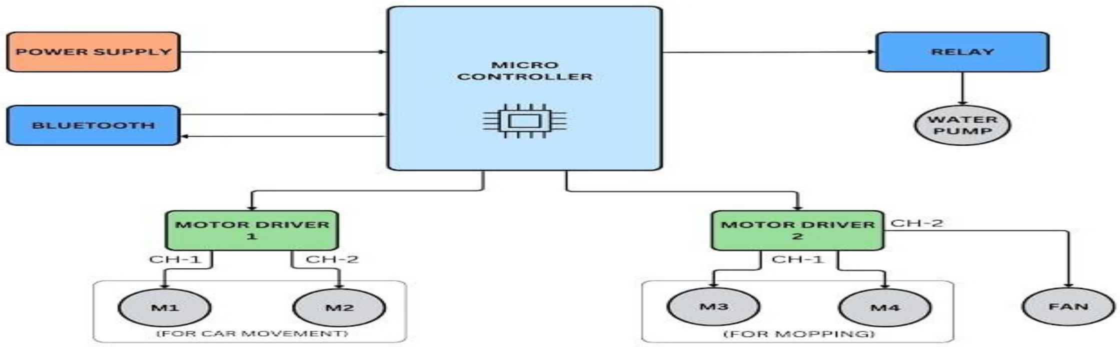


Fig. 1 Block diagram with components

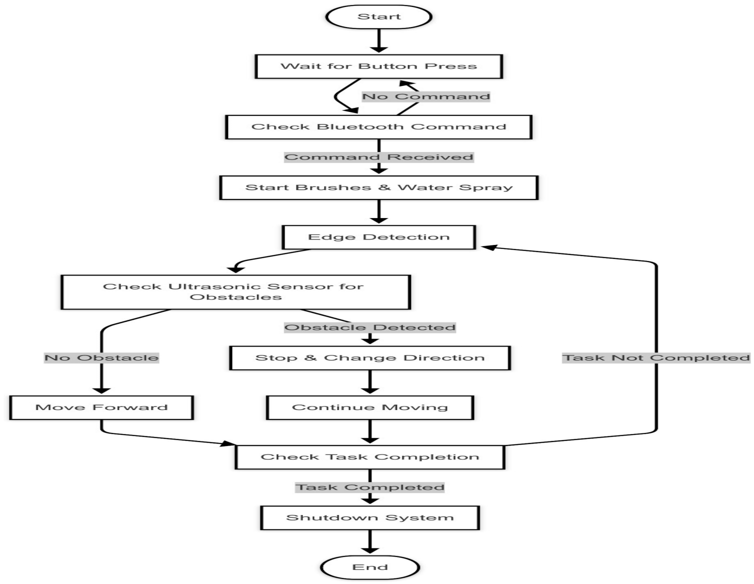
The **fig.1** represents an Automatic Solar Panel Cleaning Robot controlled by a microcontroller. The system is powered by a power supply and communicates wirelessly via a Bluetooth module. A relay controls a water pump, which sprays water onto the panel. Two motor drivers manage the movement and cleaning mechanisms: Motor Driver 1 controls M1 and M2 for robot movement, while Motor Driver 2 operates M3 and M4 for mopping and a fan for drying. The microcontroller processes inputs and commands, ensuring smooth operation. The robot autonomously moves across the solar panel, sprays water, mops the surface, and dries it—improving efficiency and maintaining optimal energy output.

A. System Architecture

A proposed robotic system has been designed with an organized cleaning process to perform efficient and effective maintenance of solar panels. These four aspects are movement control, cleaning mechanism, obstacle detection and wireless control. The mobility aspect of the robot includes driving its wheels with BO motors on inclined solar panels to allow it smooth and stable navigation. The speed and direction of the robot are controlled by L298 motor driver allowing it precise movement across surfaces. The cleaning mechanism uses a DC pump to evenly spray water on the panel surface, while a microfiber mop powered by a BO motor thoroughly cleans the surface without damage to the panels. An ultrasonic sensor is employed by the system to scan for obstructing objects from time to time. The sensor forwards real-time data to an Arduino microcontroller in order to process such information and dynamically change the path of the robot to circumvent any detected blockage. It has also integrated wireless control using an HC-05 Bluetooth module installed on the robot which allows it to work wirelessly. Users can easily manage the robot on a mobile application, making the entire cleaning and movement cycle possible with this robot.

System Flowchart

A flowchart has been presented in **Fig. 2** representing a sequence of operations such as initialization, movement control, water spraying, mopping, detecting obstacles, and user control via Bluetooth for the cleaning robot. The flowchart gives the working mechanism of an automatic cleaning system, such as a cleaning floor robot. The process starts when the user initiates the



operation of cleaning via a button press. In the absence of any command, it will be idle; if a command is present, it next checks for Bluetooth commands. Once the command arrives, the system initiates the cleaning operation with brushes and water spray, whereafter it performs edge detection to determine the boundaries and makes use of an ultrasonic sensor to detect any obstacles. In the event that an obstacle is not detected, the system would then proceed; otherwise, it stops, changes direction, and continues moving. The system constantly monitors for the completion of the task; not complete-the system continues with the cleaning operation, and when complete, shuts down automatically. Therefore, this process performs efficient cleaning and avoids obstacles and boundaries.

IMPLENTATION AND TESTING

A. *Prototype Development*

The prototype was developed through testing in increments. This rendered testing for each component on the system, both as an individual unit and collectively. A lightweight wooden panel was employed to provide the board rigidity and allow easy movement on an inclined surface. Component Integration--L298 motor driver and BO motors installed for movement control, DC pump and 2mm nozzle were integrated for optimized water spraying, Microfiber mop was mounted and connected to a BO motor for effective cleaning, HC-05 Bluetooth module and ultrasonic sensor were programmed for remote control and obstacle detection.

B. *Performance Testing*

Different performance evaluations have been carried out for testing the system: Cleaning Efficiency, where dust, pollen, and bird droppings were cleaned by the robot, thereby enhancing 18%-25% efficiency in measurement of power output of solar panels; Application of Water, where in comparison to manual cleaning, greater test durations of spray reduced water consumption by about 30%; Movement on Inclined Surfaces, where the robot was able to travel along a 40° incline with weight variations. Obstacle Avoidance: With an accuracy of 98% level, obstacles were detected and avoided thanks to the ultrasonic sensor. The result underscores the potential of an integrated system that heightens the powerhouse of solar plates through material efficiency..

RESULTS AND DISCUSSION

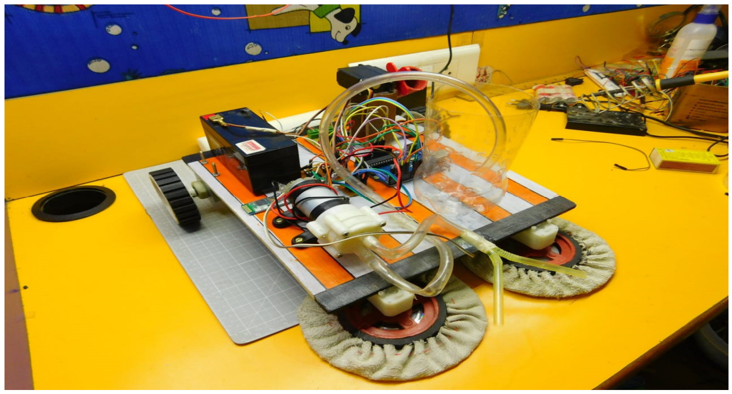


Fig 3 Solar panel cleaning robot

Fig 4 Inclination Wheels

Experimental results have noted the efficiency of Automatic Solar Panel Cleaning Robot. These results served as a confirmation of the performance improvements and resource efficiency upgrades. The cleaning system raised solar panel efficiency by 18–25%, guaranteeing an increased energy yield.. The ultrasonic sensor is 98% accurate in detecting and avoiding obstacles, preventing collision from happening. The use of Bluetooth enables remote control, lessening human effort in system applicability for most solar panels. Compared to the other available semi-automated systems, this robot is more effective with respect to performance, affordability, and maintenance cost. However, the limitations include the wooden frame and its resistance to occasional harsh weather conditions and a limited Bluetooth control range, making Wi-Fi or IoT connectivity possible for improvement.

The **Table 1** depicts comparison between manual and robotic cleaning efficiencies for a time of 180 minutes, and it can be seen that the robot invariably outruns the human cleaning. While the other maid begins at 60%, the robot continues to race, gaining only relatively small margins with time. At 90 minutes, manual efficiency is 72%, while the robot reaches 75%. By 180 minutes, manual cleaning peaks at 84%, whereas the robot achieves 90% efficiency. This indicates that robotic cleaning is a more effective and efficient solution for maintaining solar panel performance.

Here is the data in table format

Time (minutes)	Manual Efficiency (%)	Robot Efficiency (%)
0	60	60
30	64	65
60	68	70
90	72	75

Time (minutes)	Manual Efficiency (%)	Robot Efficiency (%)
120	76	80
150	80	85
180	84	90

Table 1 Manual vs Robotic Cleaning Efficiency

This table compares the efficiency of manual and robotic processes over time. The robot shows consistently higher efficiency than manual operation as time progresses.

The **Table 2** presents data on inclination, force components, cleaning time, efficiency, and water usage for both manual and robotic cleaning. As the angle of inclination increases from 30° to 50°, the efficiency for robot and manual cleaning improves, with the latter being better than the former in both instances. At 100 minutes, efficiency peaks at 70% for manual cleaning and 72.5% for robotic cleaning. Water consumption is also lower for the robot, using 21L at 100 minutes, compared to 30L for manual cleaning. Water efficiency and superior cleaning performance make the robot superior to rotating brushes as a cleaner for solar panels

Inclination (°)	**F_Parallel (N)**	**F_Perpendicular (N)**	**Time (min)**	**Manual Efficiency (%)**	**Robot Efficiency (%)**	**Manual Water (L)**	**Robot Water (L)**
30	24.52	42.48	0	60.0	60.00	5.0	3.5
35	28.13	40.18	20	62.0	62.5	10.0	7.0
40	31.53	37.57	40	64.0	65.0	15.0	10.5
45	34.68	34.68	60	66.0	67.5	20.0	14.0
50	37.57	31.53	80	68.0	70.0	25.0	17.5

Table 2 Performance Comparison of Manual and Robotic Solar Panel Cleaning at Different Inclinations

The table consists of various physical parameters related to inclination, force components, time, efficiency, and water consumption.

The key equations that describe the relationships in the table are:

The **fig 5** illustrates the water consumption for manual and automated cleaning over seven cleaning cycles. Manual cleaning consistently uses more water, increasing from 5 litres in the first cycle to 35 litres by the seventh cycle. Then, using the automated cleaning robot, it will consume much lesser water, starting from 3 litres and only reaching 25 litres by the seventh cycle. This trend hence shows how the automated cleaning system is saving water, which makes it effective and sustainable solution for maintenance of the solar panels.

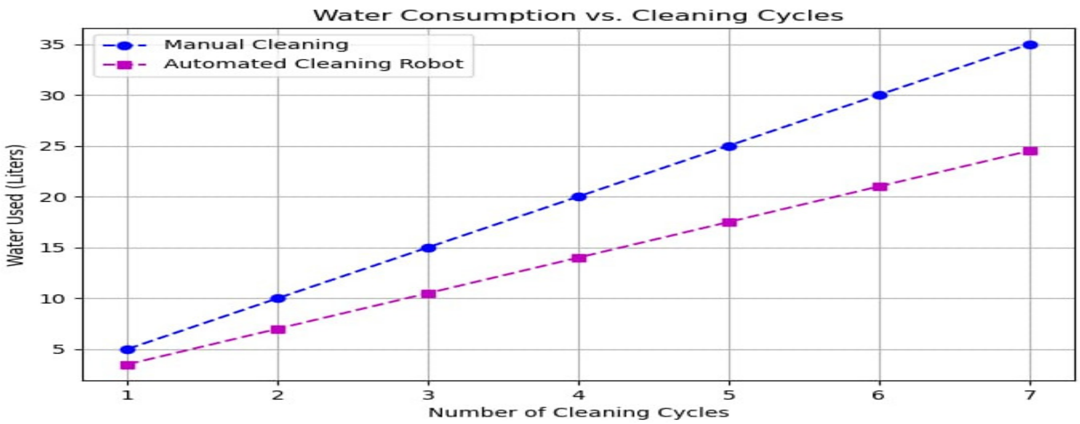


Fig 5 Water Consumption Comparison Between Manual and Automated Solar Panel Cleaning Robot

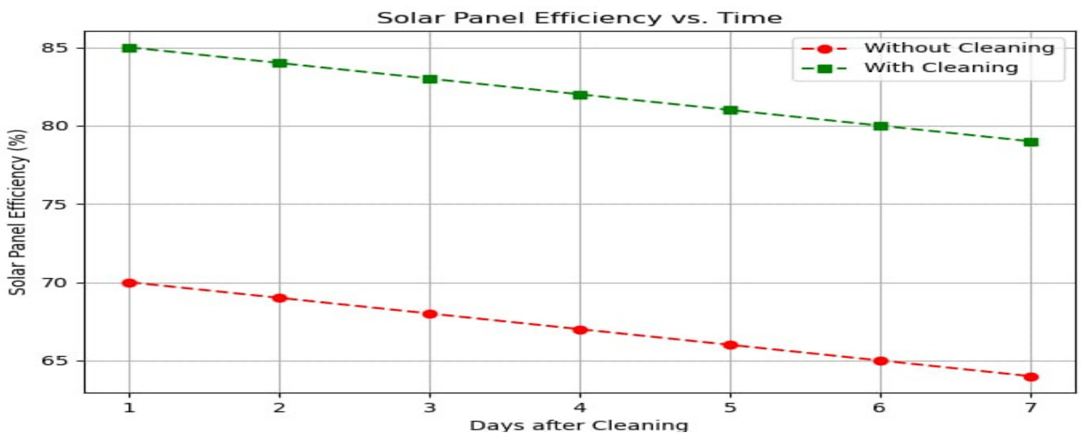


Fig 6 Solar panel Efficiency vs Time

The **fig 6** compares solar panel efficiency over seven days for cleaned and uncleaned panels. Efficiency decreases in both cases, but panels cleaned designantly suffer lesser performance. Initially, cleaned panels operate at around 85%, while uncleaned ones start at 70%. By the seventh day, cleaned panels retain about 78% efficiency, whereas uncleaned panels drop to nearly 64%. Indeed, a reinforced recommendation merging earlier observations with diectviewing of images taken a few minutes ago-cleaning is a MUST if solar panels should perform at the highest level.

CONCLUSION

The **Design, Implementation, and Efficiency Analysis of an Automatic Solar Panel Cleaning Robot for** Inclined Surfaces is a low-cost and effective solution for cleaning solar panels with almost no human intervention.. Laboratory works show that the efficiency of the cleaning robot can be demonstrated by the 18-25% savings in the efficiency of the solar panel, requiring only 30% savings in water. The lightweight structure of the wooden element keeps stability enabling smooth activity on steep surfaces rendering this as the aptest option among all other choices for such big solar installations. The automation of repair work on solar panels will mean enhanced energy efficiency or low operational cost and sustainability in solar power generation.This leads to the solution for promoting intelligent autonomous maintenance of solar panels that are highly efficient in yield but low-cost to operate and sustainable through automation and AI-based path planning, together with LiDAR mapping.

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