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Design and Parametric Optimization of a Solar Panel Cleaning Robot Using Simulink and Regression Techniques

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Abstract: *The performance degradation of solar panels due to dust accumulation necessitates frequent maintenance to ensure optimal energy output. This research presents the design and parametric optimization of a solar panel cleaning robot using experimental data modelled through Simulink and multiple linear regression techniques. Experimental variables such as brush speed, cleaning velocity, and cleaning time were studied for their impact on dust removal efficiency and battery usage. Regression models were developed to predict battery consumption and cleaning efficiency based on these input parameters. Simulink simulations were used to visualize system dynamics and validate the regression outputs. The regression model for battery usage revealed a positive correlation with cleaning velocity and time, while efficiency was inversely related to all three parameters. Simulink block models confirmed the accuracy of these relationships, enabling precise tuning of cleaning operations. Results demonstrated that moderate brush speeds and optimized cleaning velocities yield high efficiency while minimizing energy consumption, thereby ensuring sustainable operation. This dual approach offers a scalable and cost-effective method for improving the functionality and energy performance of solar panel cleaning systems.*

Keywords: Solar Panel Cleaning Robot, Parametric Optimization, Simulink, Regression Techniques, Dust Accumulation, Cleaning Efficiency, Battery Usage, Cleaning Velocity

I. INTRODUCTION

Dust and debris accumulation on photovoltaic (PV) modules significantly reduce their efficiency, particularly in arid and polluted regions where manual cleaning is laborious and water-based methods are unsustainable. To address these challenges, this study investigates a data-driven approach to optimizing a solar panel cleaning robot. The robot is designed with a motor-driven roller brush and chain-based movement system, powered by a 12V battery rechargeable via solar energy. Rather than relying solely on empirical testing, this research integrates Simulink modelling and regression analysis to fine-tune operational parameters. Three independent variables—brush speed (RPM), cleaning velocity (cm/s), and cleaning time (sec)—were varied experimentally. Their influence on two critical outputs—battery usage (Wh) and dust rem oval efficiency (%)—was then modelled using regression equations. This approach provides a foundation for real-time optimization and adaptive control of solar maintenance systems, enhancing their sustainability and autonomy

Figure 1. Automated Solar Panel Cleaning Mechanism Using Rotary Brush System

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II. LITERATURE REVIEW

Magar, S., Phadtare, S., Sayyad, S., Javir, G., Sawant, Y. H., & Deshpande, G. G. (2023). [2] "Design and Development of Solar Panel Cleaning Robot. International Advanced Research Journal in Science, Engineering and Technology":-This study addresses the issue of efficiency loss in solar panels due to dust accumulation by developing an automated cleaning robot. The system incorporates ESP32-CAM and L293D modules to control the robot's movement and cleaning functions across panel surfaces. Designed for autonomous operation, it minimizes manual intervention and water use while improving solar panel efficiency by up to 10%. The system was validated through simulations and practical implementation, confirming its viability for enhancing photovoltaic performance and durability in dusty environments.

Najmi, N. & Rachid, A. A. (2023). "A Review on Solar Panel Cleaning Systems and Techniques. Energies" [6] This review comprehensively examines the impact of dust, environmental conditions, and other soiling agents on solar panel performance. The authors evaluate a range of cleaning technologies including manual methods, automated systems, electrodynamic screens, drone-assisted cleaning, and self-cleaning robotic solutions. Through cost–benefit analysis using Multi-Criteria Decision Analysis (MCDA), the study identifies optimal cleaning methods tailored to environmental and operational contexts. The review underscores the critical importance of panel maintenance in sustaining energy yield, with some methods showing efficiency gains up to 27%.

Siddiqui, M. H., Shinde, S., Malokar, S., Nair, S., Siddiqui, H., Wandhe, K., & Khandelwal, K. K. (2022) [5] "Design and Optimization Technique for Best Suited Solar Panel Cleaning System. International Journal for Research in Applied Science & Engineering Technology (IJRASET)": -This study proposes an automated cleaning system for photovoltaic panels to reduce efficiency losses caused by dust accumulation. The system features a rolling brush mechanism controlled via Arduino and DC gear motors, operating autonomously along a central spline. It achieves enhanced cleaning efficiency, remote control capability, and cost-effectiveness, demonstrating a potential output gain of 5–30%. The research concludes that such automation minimizes manual labor and optimizes performance for large-scale solar installations.

Muhammed, S., Laheb, T., Ma'ad, H., &Maaroof, O. W. (2023).[4] "UTU Compact Solar Panel Cleaning Robot. International Journal of Advanced Natural Sciences and Engineering Research": -This study presents the design and development of "UTU," a compact, IoT-enabled solar panel cleaning robot aimed at enhancing PV performance in dusty environments like Iraq. Equipped with dual roller brushes, IR and IMU sensors, and mobile app control, the robot ensures thorough cleaning while maintaining safety and autonomy. It operates using a bubble-band inspired navigation algorithm and features onboard water and dirt-handling systems. The research highlights UTU's effectiveness in increasing power output, minimizing human risk, and offering a scalable solution for small to medium solar installations.

Patil, S. A., Patil, A. R., Chougule, V. N., &Sanamdikar, S. T. (2023). [3] "Design and Analysis of Automated Solar Panel Cleaning System. Current World Environment": -This study introduces an automated solar panel cleaning mechanism aimed at reducing energy losses from dust accumulation. Using a microfiber cloth-based dry-cleaning system and optional water spray for stubborn stains, the design prioritizes sustainability, especially for arid climates. The robot uses IR sensors and Arduino-based control to operate autonomously across commercial solar arrays. Simulations and prototype testing demonstrated improved energy output and reduced maintenance costs. The system's modularity, scalability, and sensor integration position it as a viable, cost-effective alternative to manual or water-intensive cleaning methods.

Eltayeb, W., Yedukondalu, G., & Srinath, A. (2020). [11] "Design and Development of a Cleaning Robot for Solar Panels with Sun Tracking. Journal of Green Engineering": - This study presents a dual-functional robotic system integrating solar panel cleaning with a sun-tracking mechanism. The robot uses a rotary brush and optional water spray to remove dust, enhancing photovoltaic efficiency. The sun tracker, controlled by LDR sensors and an Arduino-based system, adjusts panel orientation for optimal solar capture. The system was validated through hardware implementation and MATLAB/Simulink simulations, showing a panel efficiency increase up to 90%. Lightweight materials and cost-effective components make it suitable for large-scale solar farms.

Li, Zhiyuan & Wang, Kewen & Liu, Yanhong. (2021). [1] "Optimization of PSVR Parameters of Condenser Based on MATLAB/Simulink Simulation. E3S Web of Conferences": –The study explores the optimization of Power System Voltage Regulator (PSVR) parameters to enhance the dynamic voltage control of synchronous condensers. A dynamic model is developed using MATLAB/Simulink to simulate and analyse the phase-frequency characteristics of the condenser. The authors introduce a novel phase shift index to guide lead/lag time constant adjustments and employ eigenvalue root locus methods to fine-tune gain coefficients. Results from single- and three-machine simulations validate that optimized PSVR parameters significantly reduce voltage oscillations and improve system stability.

III. THEORETICAL BACKGROUND

A. Regression Analysis

Regression analysis is a robust and widely applied statistical technique used to model and analyse the relationships between a dependent (response) variable and one or more independent (predictor) variables. In engineering and system optimization contexts, it serves as a powerful tool for predicting output behaviours based on a set of measurable input conditions. The objective is to identify a mathematical relationship that can best approximate the observed data and forecast future outcomes under similar conditions.

The general multiple linear regression model is expressed as:

$$Y=\beta0+\beta1X1+\beta2X2+\ldots+\beta nXn+\epsilon$$

where:

Y is the dependent variable (e.g., battery usage or cleaning efficiency),

X1, X2…, Xn are the independent variables (e.g., brush speed, cleaning time, velocity),

β0 is the intercept,

β1,…, βn are regression coefficients representing the effect of each predictor,

ϵ is the error term.

In this project, regression modelling was used to analyse empirical data gathered from testing various configurations of the solar panel cleaning robot. The primary goal was to develop two regression equations: one for predicting battery usage and another for estimating dust removal efficiency. These models were created by fitting the experimental data using the least squares method in MATLAB. The derived coefficients offer insight into how each parameter contributes to the system's performance, thereby enabling data-driven optimization.

This method not only minimizes experimental overhead but also provides a quantitative basis for selecting operational settings that maximize cleaning efficiency while minimizing power consumption—a critical trade-off in sustainable design.

B. Simulink Modelling in MATLAB

Simulink, a companion software to MATLAB developed by MathWorks, is a dynamic simulation environment designed for modelling and analysing multi-domain systems. Unlike conventional coding platforms, Simulink utilizes a graphical block

diagram interface, allowing users to construct system models intuitively without writing extensive code. This feature is particularly useful for simulating complex mechanical and electrical systems such as solar panel cleaning robots.

In the context of this study, Simulink was used to build a visual model of the robot's cleaning mechanism, integrating the regression equations as embedded mathematical functions. This allowed for real-time simulations to observe how variations in input parameters—like brush speed (RPM), cleaning velocity (cm/s), and time (s)—affect system outputs such as battery consumption and cleaning efficiency.

The Simulink model provided immediate feedback through live plotting and scope blocks, enabling rapid validation of regression predictions against simulated system responses. Additionally, parameter tuning was facilitated through simulation loops, making it possible to experiment with different operational settings without requiring physical testing.

The combination of Simulink and regression modelling in MATLAB bridges the gap between theoretical analysis and practical implementation. Simulink's real-time simulation capabilities allow engineers to visualize the cause-and-effect

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relationship between design parameters and system performance, while regression analysis offers a mathematical foundation for optimization.

This dual approach enhances the system's overall design by reducing dependency on physical trials, improving accuracy in prediction, and accelerating the prototyping phase. It also opens avenues for future integration of adaptive control strategies and machine learning models, which can further improve the autonomy and efficiency of solar panel cleaning systems.

IV. RESULTS AND DISCUSSION

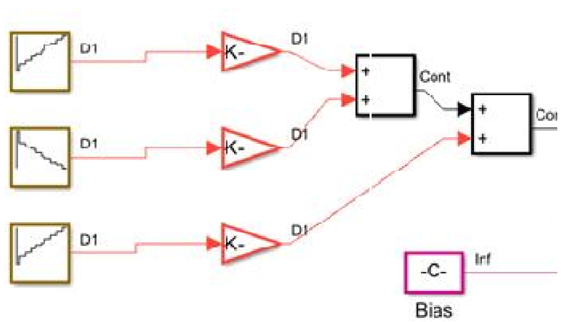

Table 1 Experimental Results of Cleaning parameters

Brush Speed (RPM)	Cleaning Time (sec)	Cleaning Velocity (cm/s)	Dust Removal Efficiency (%)	Battery Usage (Wh)
30	90	1	89	10
35	80	1.2	87	11
38	78	1.3	85	11.2
40	75	1.4	84	11.5
42	72	1.5	82	12
45	70	1.6	80	12.5
48	68	1.7	78	13
50	65	1.8	76	13.5
52	63	1.9	75	14
55	60	2	73	14.5

Regression Equations

1) Battery usage

$y1 = 1.4455 + (-0.0041 * x1) + (0.0349 * x2) + (5.5415 * x3)$

2) Cleaning efficiency

$y1 = 145.3091 + (-0.3786 * x1) + (-0.3189 * x2) + (-16.1987 * x3)$

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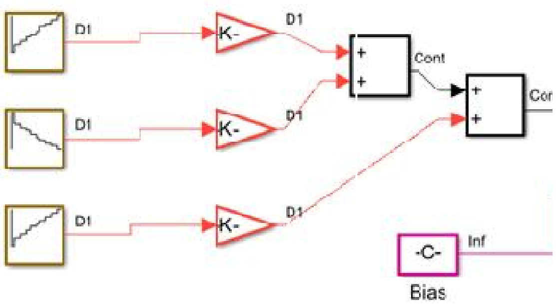

Figure 2 Simulink model for Battery usage

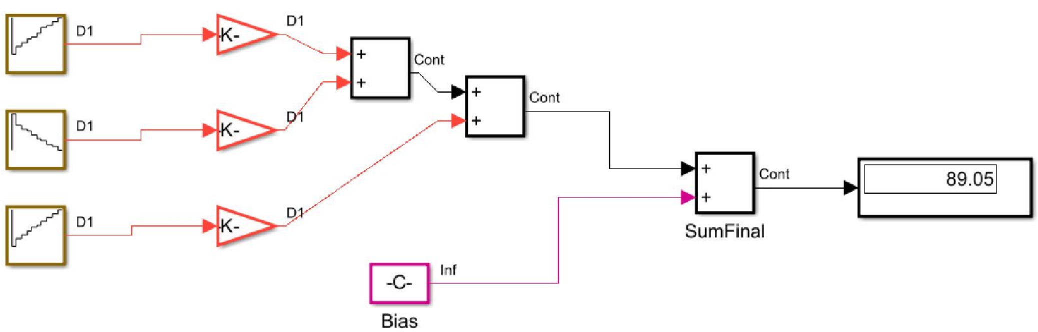

Figure 3 Simulink model for Efficiency

The performance analysis of the solar panel cleaning robot was carried out using a combination of experimental data and regression modelling. Key operational parameters—brush speed (RPM), cleaning time (seconds), and cleaning velocity (cm/s)—were systematically varied to observe their impact on two crucial outputs: battery usage and dust removal efficiency. The data demonstrated clear trends across a range of values: brush speed from 30 to 55 RPM, cleaning time from 70 to 90 seconds, and velocity from 1.0 to 2.0 cm/s.

The regression equation for battery usage was modelled as:

$$\text{Battery Usage (Wh)}=1.4455-0.0041x1+0.0349x2+5.5415x3$$

This equation reveals that cleaning velocity (x_2) and cleaning time (x_3) are the dominant contributors to increased power consumption, while brush speed (x_1) has a slight mitigating effect. As cleaning velocity and time increase, the robot requires more power to maintain motion and brush engagement, leading to higher energy draw. For instance, at maximum values (2.0 cm/s velocity and 90 seconds duration), battery consumption peaked at 14.5 Wh, whereas at lower inputs, consumption stayed near 10 Wh.

For dust removal efficiency, the regression equation was:

$$\text{Efficiency (\%)} =145.3091-0.3786x1-0.3189x2-16.1987x3$$

This model indicates that all three parameters negatively impact cleaning efficiency as they increase. Notably, cleaning time exhibits the steepest negative gradient, implying that prolonged operation beyond optimal timing results in reduced effectiveness—likely due to over-brushing or diminishing returns from repeated passes. The highest efficiency (89%) was achieved at a brush speed of 30 RPM, velocity of 1.0 cm/s, and time of 90 seconds. However, this also coincided with the highest energy usage, indicating a trade-off.

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To visualize and validate these outcomes, Simulink models were constructed. For each regression model, subsystem blocks were created representing the regression functions, allowing real-time input manipulation and dynamic output monitoring. These models confirmed that operating the system around 35–38 RPM brush speed, 1.3–1.4 cm/s velocity, and 78–80 seconds time yields a balanced trade-off: maintaining good efficiency (~85%) while reducing power consumption (near 11.2 Wh). This balance is ideal for energy-constrained and sustainability-focused deployments.

Overall, the integrated use of empirical data, regression modelling, and Simulink simulations enabled precise tuning of operational parameters. The results validate the potential for further integrating sensor feedback and automation to achieve smart, adaptive cleaning behaviours.

V. Conclusion

This study successfully demonstrates how regression modelling and Simulink simulations can be applied to optimize the operational parameters of a solar panel cleaning robot. The experimental analysis and regression-based modeling of the solar panel cleaning robot revealed critical insights into the interplay between brush speed, cleaning velocity, and cleaning time on system efficiency and energy consumption. Regression equations accurately predicted that battery usage increases with greater cleaning velocity and time, while cleaning efficiency declines as any of these parameters increase. Simulink simulations, developed to mirror the regression outputs, validated these trends and enabled dynamic testing of operational scenarios. The optimal performance trade-off was achieved at brush speeds of 35–38 RPM, cleaning velocities of 1.3–1.4 cm/s, and durations of 78–80 seconds. At these values, the robot maintained high cleaning efficiency (~85%) while limiting battery usage to around 11.2 Wh, demonstrating a practical balance between energy sustainability and operational effectiveness. These results confirm that using regression modeling in conjunction with Simulink offers a reliable, data-driven approach for tuning robotic systems. This methodology provides a foundation for future enhancements such as autonomous parameter adjustment, smart control integration, and real-time sensor feedback to further improve solar panel maintenance technologies.

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