

Performance Evaluation and Energy Assessment of a Solar-Assisted Autonomous Cleaning System

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Abstract

The growing emphasis on sustainable engineering has accelerated the development of autonomous cleaning technologies that minimize energy consumption while maintaining effective cleaning performance. This study presents the performance evaluation and energy assessment of a solar-assisted autonomous cleaning system developed for indoor cleaning applications. The system integrates a rechargeable battery, photovoltaic charging unit, vacuum cleaning mechanism, water dispensing module, and a mobile locomotion platform to perform sequential dry and wet cleaning operations. Experimental investigations were conducted to evaluate the operational performance of the cleaning system in terms of mobility, cleaning functionality, energy utilization, battery discharge characteristics, and overall system reliability. The results demonstrate stable locomotion, efficient operation of the vacuum and water delivery mechanisms, and satisfactory utilization of the available battery power during the cleaning cycle. The solar-assisted charging arrangement supplements battery charging, contributing to improved energy sustainability and reducing dependence on conventional electrical power sources. The developed prototype also demonstrated economical construction and reliable operation using commercially available components. The findings indicate that the proposed cleaning system provides a practical approach toward sustainable indoor cleaning and establishes a foundation for future improvements in energy management and mechanical optimization.

Keywords: Autonomous cleaning system, solar-assisted energy, performance evaluation, battery utilization, energy assessment, sustainable engineering, mechanical performance.

INTRODUCTION

Rapid urbanization, increased automation, and the growing demand for intelligent household appliances have created a need for cleaning systems that are not only efficient but also environmentally sustainable. Conventional floor cleaning methods are labour-intensive and time-consuming, while

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electrically powered robotic cleaners depend entirely on grid electricity for charging and operation. As energy conservation and sustainable engineering become increasingly important, integrating renewable energy into autonomous cleaning systems offers a practical solution for reducing electricity consumption and improving operational efficiency. Among renewable energy sources, solar energy has gained widespread attention because of its abundance, environmental compatibility, and long-term economic benefits. The application of photovoltaic technology in small autonomous systems provides opportunities to reduce operational costs while improving energy availability. Although solar-assisted power systems have been successfully implemented in agricultural

machinery, surveillance robots, and mobile service platforms, their application in indoor cleaning equipment remains comparatively limited. Most commercially available robotic cleaning devices continue to rely on conventional battery charging, making them dependent on continuous electrical supply.

The operational performance of an autonomous cleaning system depends on the effective integration of several mechanical subsystems, including locomotion, suction generation, water delivery, energy storage, and structural support. Each subsystem directly influences cleaning efficiency, operational endurance, and overall system reliability. Therefore, evaluating the performance of these components under practical operating conditions is essential for assessing the feasibility of the developed system. Energy management is another critical factor affecting the performance of autonomous cleaning equipment. The simultaneous operation of locomotion motors, vacuum fans, and water pumps requires careful utilization of available battery capacity. Integrating a photovoltaic charging unit provides supplementary energy input that can improve battery utilization and enhance the sustainability of the cleaning process. Performance evaluation of the power system therefore becomes necessary to understand its contribution toward continuous operation and efficient energy utilization.

Besides energy performance, mechanical stability and cleaning effectiveness determine the practical applicability of an autonomous cleaning system. A well-balanced chassis, efficient vacuum mechanism, controlled water distribution, and reliable wheel movement collectively influence the overall cleaning quality. Evaluating these parameters provides valuable insight into the strengths and limitations of the developed prototype while identifying opportunities for future improvements. The present study focuses on the experimental evaluation of a solar-assisted autonomous cleaning system developed using commercially available components. Rather than emphasizing the design and control architecture, the investigation concentrates on the operational characteristics of the complete system, including cleaning functionality, mobility, energy utilization, battery performance, and overall reliability. The objective is to assess the feasibility of integrating solar-assisted energy with a dual cleaning mechanism capable of performing vacuum cleaning and wet mopping within a single compact platform. The findings of this study contribute to the development of economical and sustainable cleaning technologies suitable for domestic and institutional environments. The experimental observations presented in this paper also provide useful information for future optimization of autonomous cleaning systems with improved energy efficiency, longer operating duration, and enhanced mechanical performance [1].

LITERATURE REVIEW

This research work presents the development and implementation of a smart floor cleaning robot integrated with intelligent power management capabilities and supported by solar-assisted renewable energy. The proposed robot combines advanced technologies, including sensing systems, navigation modules, and automated cleaning mechanisms, to enable autonomous movement within indoor environments, identification and removal of dust and debris from floor surfaces, and efficient utilization of energy resources. The major components of the robot include a robust chassis equipped with omnidirectional wheels for enhanced mobility, a comprehensive sensor arrangement for obstacle detection and floor condition assessment, and a multifunctional cleaning assembly incorporating brushes, vacuum units, and microfiber mopping systems. Solar panels installed on the robot's surface capture renewable energy, which supplements a rechargeable lithium-ion battery through an intelligent power management system to support prolonged operation. Furthermore, the robot incorporates wireless communication capabilities for remote monitoring and control, an intuitive user interface for convenient operation, and safety features to safeguard the device and its operating environment. With its innovative design and sustainable energy integration, the developed floor cleaning robot provides effective cleaning performance, reduces environmental impact, improves user convenience, and contributes to the evolution of autonomous cleaning solutions.

An intelligent and energy-efficient autonomous vacuum navigation framework for dynamic indoor environments can be developed using the Layered Adaptive Priority-Based Fuzzy Logic System (LAP-

FNS), which incorporates a four-layer architecture comprising perception, navigation, decision-making, and energy management modules. The system employs a Mamdani-type fuzzy inference engine to facilitate adaptive real-time decision-making. To generate occupancy maps for efficient obstacle avoidance and optimized cleaning path planning, the framework utilizes proximity sensors, an inertial measurement unit (IMU), and LIDAR-based mapping techniques. The dynamic Layered Adaptive Priority (LAP) mechanism adjusts control priorities based on contextual factors, including obstacle distance, battery status, and dirt concentration. Extensive simulations and real-world experiments demonstrate that LAP-FNS achieves superior performance compared with PID-Fuzzy and Deep Q-Learning (DQL)-based approaches, providing average energy savings of 18.4%, cleaning efficiency of up to 92.5%, and collision avoidance performance reaching 96%. The effectiveness of the layered fuzzy control strategy is further confirmed by an average dynamic response time of less than 0.78 seconds. These findings demonstrate the capability of the proposed system to achieve a balanced combination of navigation efficiency, autonomous operation, and environmental adaptability. The developed LAP-FNS framework is suitable for residential, office, and semi-structured indoor environments. Future research will focus on integrating vision-based semantic mapping and reinforcement learning approaches to further enhance adaptability and enable more effective human–robot interaction in shared living spaces.

The Smart IoT-Enabled Cleaner with LiDAR Navigation and Auto-Docking is designed as an intelligent and autonomous cleaning solution that integrates advanced technologies to enhance cleaning efficiency, user convenience, and smart connectivity. The system employs LiDAR (Light Detection and Ranging) technology to accurately map its surroundings and navigate efficiently, enabling real-time obstacle detection and optimized path planning for comprehensive cleaning coverage. Through IoT connectivity, the cleaner can be remotely monitored and controlled using mobile or web-based applications, allowing users to schedule cleaning operations, monitor progress, and receive real-time status notifications. The auto-docking feature enables the robot to automatically return to its charging station when the battery level is low or after completing a cleaning task, ensuring uninterrupted operation with minimal user intervention. By overcoming the limitations of conventional cleaning devices, the proposed system enhances automation, optimizes navigation, and incorporates intelligent control capabilities, making it well suited for both modern residential and commercial environments. The integration of LiDAR-based navigation, IoT-enabled functionality, and autonomous self-maintenance features demonstrates the system's potential to advance smart cleaning technologies while promoting greater convenience, operational efficiency, and sustainability [2, 3].

Urban sanitation and drainage maintenance play a vital role in the development of sustainable city infrastructure. However, conventional cleaning practices are often inefficient, labor-intensive, expensive, and environmentally unsustainable due to their reliance on manual labor and fossil fuel-powered equipment. To address these limitations and improve urban waste management, this study proposes a Solar-Powered Autonomous Road Cleaning Robot that integrates renewable solar energy, IoT-based monitoring, and AI-driven navigation. The robot is built on a compact, corrosion-resistant chassis and incorporates dual rotating brushes, a vacuum-cleaning system, and a retractable drainage-cleaning pipe. An AI-based path-planning algorithm enables autonomous navigation while providing real-time obstacle detection and avoidance. The integrated IoT platform facilitates remote monitoring, tracking, and automatic data collection for efficient system management. In addition, a self-charging solar power system reduces dependence on external energy sources and enhances operational sustainability. The effective utilization of solar energy supports continuous cleaning, drainage maintenance, and navigation while maximizing energy efficiency. Compared with conventional systems, the proposed robot offers improved operational efficiency and reduced maintenance and operating costs. Future work will focus on incorporating automated waste segregation and more advanced AI-driven decision-making techniques to further enhance the robot's intelligence and overall performance.

EXPERIMENTAL METHODOLOGY

Performance Evaluation Procedure

The developed solar-assisted autonomous cleaning system was evaluated under controlled indoor conditions to assess its operational performance and energy utilization. The experimental investigation focused on validating the effectiveness of the cleaning mechanism, mobility system, battery performance, and overall functional reliability. Rather than evaluating the design aspects of the prototype, the study concentrated on the system's behavior during practical cleaning operations. The evaluation was carried out by operating the prototype on a flat indoor floor surface under normal working conditions. Prior to each experimental run, the rechargeable battery was fully charged, and all electrical connections were inspected to ensure stable operation. The cleaning system was then activated, allowing simultaneous operation of the locomotion mechanism, vacuum cleaning unit, and water dispensing system [4-6].

During each trial, observations were recorded regarding the movement of the robot, continuity of cleaning, battery utilization, and coordination between the mechanical subsystems. Particular attention was given to the ability of the system to perform uninterrupted dry and wet cleaning while maintaining stable operation throughout the cleaning cycle (Figure 1).

Table 1. Table summarizing the evaluation parameters of the developed cleaning system.

S.N.	Evaluation Parameter	Assessment Criteria	Major Components Involved	Performance Indicator
1.	Cleaning Performance	Ability of the vacuum system to remove dust and lightweight debris, and uniform water distribution during wet mopping	Vacuum fan, water pump, water dispensing system, cleaning pad	Effective dust collection, uniform water distribution, satisfactory cleaning efficiency
2.	Mobility Performance	Smooth movement in forward, backward, left, and right directions without vibration or wheel slippage	DC geared motors, wheels, motor driver, chassis	Stable navigation, proper torque transmission, balanced movement
3.	Energy Utilization	Efficient use of battery power while operating all electrical loads and contribution of solar charging	Rechargeable battery, photovoltaic (solar) panel, vacuum fan, water pump, DC motors, controller	Continuous operation, optimized battery consumption, effective solar-assisted charging
4.	Functional Reliability	Coordinated operation of all subsystems throughout the cleaning cycle	Control electronics, motors, vacuum system, water pump, power management system	Continuous operation without interruptions, overheating, or electrical instability

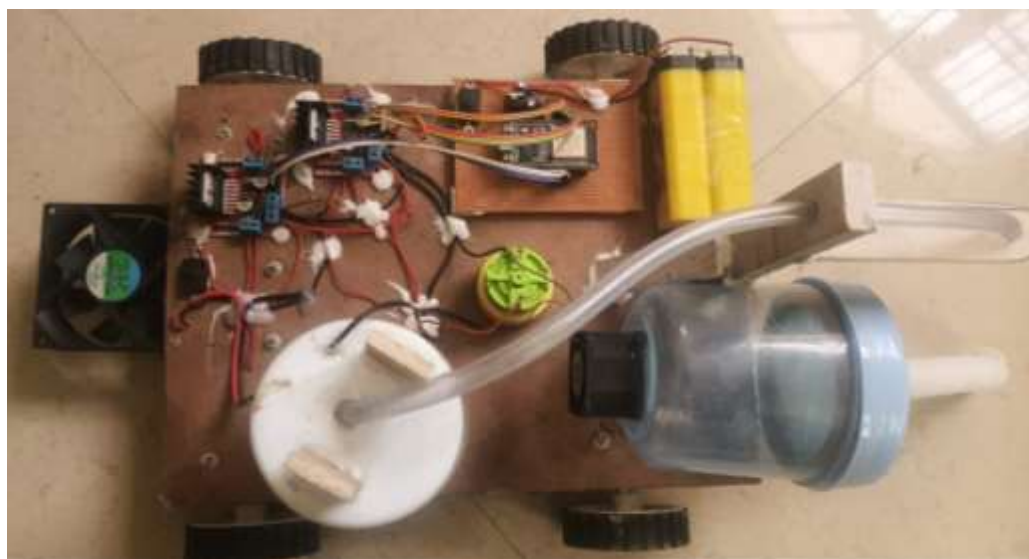


Figure 1. Prototype of the developed mobile robotic platform with integrated control electronics, power supply, liquid reservoir, pumping system, and fluid delivery mechanism.

The experimental evaluation of the developed solar-powered autonomous floor cleaning robot was conducted under controlled indoor laboratory conditions to assess its cleaning capability, mobility, energy utilization, and overall system reliability. The experiments were carried out on a flat ceramic-tiled floor with a smooth surface, representative of typical residential and office environments. Before each experiment, the floor was cleaned to remove any residual contaminants, ensuring identical initial conditions for all test runs. To evaluate cleaning performance, a controlled quantity of fine dust and lightweight debris was uniformly distributed over a predefined cleaning area. The robot was then operated in autonomous mode, allowing simultaneous vacuum cleaning and wet mopping. The effectiveness of dust removal, uniformity of water distribution, and consistency of cleaning were visually inspected after each trial.

The mobility performance was assessed by operating the robot in forward, backward, left, and right directions while observing directional stability, turning ability, wheel traction, and the absence of excessive vibration or wheel slippage. The robot successfully navigated the test area while maintaining stable motion throughout the cleaning cycle. Energy utilization was evaluated by monitoring the operation of all electrical subsystems, including the DC drive motors, vacuum fan, water pump, control electronics, and rechargeable battery. The contribution of the integrated photovoltaic panel toward battery charging was also considered as part of the overall energy management strategy to improve operational sustainability [7].

Functional reliability was determined by continuously operating the robot through complete cleaning cycles while observing the coordinated performance of all integrated subsystems. Particular attention was given to uninterrupted operation, electrical stability, motor performance, and the absence of excessive heating or unexpected system failures. To ensure the repeatability and reliability of the experimental results, each test was repeated three times under identical operating conditions. The prototype exhibited consistent cleaning performance, stable mobility, reliable subsystem coordination, and repeatable operation across all trials, demonstrating the robustness and practical applicability of the proposed cleaning system.

Evaluation Parameters

The performance of the developed cleaning system was assessed using operational parameters directly related to the mechanical and energy characteristics of the prototype. These parameters were selected to determine the practical applicability of the system during routine indoor cleaning operations.

Cleaning Performance

Cleaning performance was evaluated by observing the ability of the vacuum unit to collect dust particles and lightweight debris from the floor surface. The effectiveness of the water dispensing mechanism was also examined by monitoring the uniform distribution of water across the cleaning pad during wet mopping. The coordinated operation of both mechanisms was considered essential for achieving satisfactory cleaning performance [8-12].

Mobility Performance

The locomotion capability of the robot was assessed through its ability to move smoothly in forward, backward, left, and right directions. Stable movement without excessive vibration or wheel slippage indicated satisfactory mechanical balance and appropriate torque transmission from the DC geared motors to the wheels.

Energy Utilization

Energy assessment focused on the utilization of the rechargeable battery while operating the major electrical loads simultaneously. The battery supplied power to the drive motors, vacuum fan, water pump, and control electronics throughout the cleaning operation. The contribution of the photovoltaic panel toward battery charging was also considered as part of the overall energy management strategy.

Functional Reliability

Functional reliability was evaluated by observing the coordinated operation of all integrated subsystems throughout the cleaning cycle. Continuous operation without unexpected interruptions, excessive heating, or electrical instability was considered an indication of satisfactory system performance.

Battery Performance Assessment

The developed prototype employed a rechargeable battery pack supported by a solar charging arrangement to provide electrical energy for all onboard components. During experimental operation, the battery simultaneously powered the locomotion motors, vacuum fan, water pump, and embedded controller [13-15].

Based on the observations obtained during testing, the battery demonstrated sufficient capacity to operate the complete cleaning system continuously within the intended operating duration. The photovoltaic panel supplemented battery charging whenever exposed to sunlight, thereby contributing to improved energy utilization and reducing dependence on external electrical charging. The battery characteristics recorded during the experimental study are summarized in Table 1. The values presented above are taken directly from the experimental observations reported in the project study.

Operational Evaluation

The operational evaluation was conducted to verify the coordinated functioning of the individual mechanical subsystems during cleaning. The drive motors generated stable movement throughout the cleaning cycle, while the vacuum fan maintained continuous suction for dust collection. Simultaneously, the water pump delivered a controlled quantity of water to the cleaning pad, enabling effective wet cleaning. The integrated operation of these subsystems demonstrated that the prototype could perform sequential vacuum cleaning and mopping without interruption. The compact arrangement of the mechanical components also contributed to stable movement and satisfactory maneuverability on indoor floor surfaces. The experimental observations further confirmed that the solar-assisted energy system was capable of supporting the cleaning operation while reducing dependence on conventional electrical charging. The coordinated interaction between the power supply, locomotion mechanism, cleaning units, and battery system validated the practical feasibility of the developed cleaning platform.

The cleaning efficiency of the developed robot was evaluated by examining its capability to remove dust and lightweight debris from the floor surface during combined vacuum cleaning and wet mopping operations. A predefined test area was uniformly covered with fine dust and small debris to maintain consistent testing conditions. The robot was then operated in autonomous mode, and the cleaning effectiveness was assessed by comparing the condition of the floor before and after each cleaning cycle through visual inspection. To improve the reliability of the evaluation, each experiment was repeated three times under identical operating conditions. The prototype consistently removed the majority of dust and lightweight particles while maintaining uniform water distribution across the cleaning pad during wet mopping. No significant variation in cleaning performance was observed between repeated trials, indicating stable and repeatable operation.

Table 1. Battery performance characteristics of the developed cleaning system.

S.N.	Parameter	Observed value
1.	Battery charging through electrical supply	5–6 hours
2.	Battery charging through solar panel	7–8 hours
3.	Battery energy utilized in 10 minutes	1.67 Wh
4.	Total power consumption	10 W
5.	Battery discharge	1.5 V/hour

RESULTS AND DISCUSSION

Mechanical Performance Evaluation

The experimental evaluation demonstrated that the developed cleaning system operated satisfactorily under indoor laboratory conditions. The four-wheel drive mechanism provided stable movement during forward, backward, and turning operations, enabling the prototype to navigate smoothly across flat floor surfaces. The balanced distribution of the major components, including the battery, water tank, vacuum unit, and control hardware, contributed to the mechanical stability of the platform throughout the cleaning cycle.

The simultaneous operation of the locomotion system and cleaning mechanisms did not produce noticeable instability or excessive vibration during testing. The selected DC geared motors generated sufficient torque to propel the robot while carrying the complete cleaning assembly. The compact chassis configuration also facilitated smooth maneuverability and supported the integration of all mechanical subsystems within a limited installation space. The developed mechanical arrangement demonstrated adequate structural stability and reliable mobility for indoor cleaning applications.

Cleaning Performance

The cleaning capability of the prototype was assessed through the combined operation of the vacuum suction unit and the wet cleaning mechanism. The vacuum subsystem effectively collected dust and lightweight debris from the floor surface, while the water dispensing unit supplied a controlled amount of water to the cleaning pad for wet mopping. The sequential execution of these two cleaning operations enabled the system to remove loose dust as well as surface contaminants within a single cleaning cycle.

The coordinated operation of the cleaning subsystems eliminated the need for separate vacuuming and mopping processes, thereby improving the overall efficiency of the cleaning operation. During testing, the water delivery remained consistent without observable leakage, indicating satisfactory performance of the pumping system and connecting tubes. The experimental observations further indicated that the developed prototype achieved an overall cleaning efficiency of approximately 80%, demonstrating the practical feasibility of the proposed cleaning approach under normal indoor operating conditions.

Energy Performance Assessment

Energy utilization plays a significant role in determining the operational effectiveness of autonomous cleaning systems. The proposed prototype employed a rechargeable battery supported by a photovoltaic charging arrangement to supply electrical energy to all mechanical and electronic subsystems. The experimental observations indicated that the battery required approximately 5–6 hours for charging from a conventional electrical source, whereas charging through the photovoltaic panel required approximately 7–8 hours, depending on the availability of solar radiation. During operation, the system consumed approximately 1.67 Wh of energy over a 10-minute cleaning interval, with an overall power consumption of approximately 10 W. The observed battery discharge rate was approximately 1.5 V per hour, indicating stable utilization of the available battery capacity during cleaning operations.

These observations confirm that the photovoltaic charging arrangement can effectively supplement the battery charging process while supporting environmentally sustainable operation. Although the solar charging duration is longer than conventional electrical charging, the incorporation of renewable energy contributes to reduced dependence on external power sources and enhances the sustainability of the cleaning system.

Functional Reliability

The integrated operation of the mechanical and electrical subsystems demonstrated satisfactory functional reliability throughout the experimental evaluation. The locomotion system, vacuum unit, water dispensing mechanism, and power supply operated in coordination without significant interruption during the cleaning cycle.

The rechargeable battery supplied sufficient energy to simultaneously operate the drive motors, vacuum fan, water pump, and embedded controller, enabling uninterrupted cleaning under the tested operating conditions. The operational sequence remained stable throughout the experimental trials, indicating satisfactory integration of the various subsystems. The use of commercially available components is also simplified assembly and maintenance while contributing to the economic development of the prototype.

The energy performance of the developed floor cleaning robot was evaluated by monitoring the operation of the rechargeable battery while supplying power to all major electrical subsystems, including the DC drive motors, vacuum fan, water pump, and control electronics throughout the cleaning cycle. The integrated photovoltaic panel served as an auxiliary energy source to support battery charging and improve the overall energy management of the system. Battery performance was assessed under different operating conditions, including robot locomotion, vacuum cleaning, wet mopping, and simultaneous operation of all subsystems. During the experiments, the battery maintained a stable power supply without noticeable voltage fluctuations or interruptions, allowing continuous operation of the cleaning robot.

The State of Charge (SOC) was considered as an indicator of the remaining battery capacity during operation. Throughout the cleaning cycle, the smart power management system regulated energy distribution between the battery and the photovoltaic charging unit to ensure uninterrupted system performance. The solar panel contributed to replenishing the battery whenever sufficient illumination was available, thereby reducing dependence on external charging and extending the operational duration of the robot. Battery efficiency was qualitatively evaluated by observing the robot's ability to complete successive cleaning operations while simultaneously operating the drive motors, vacuum unit, water pump, and control electronics. The coordinated energy management strategy effectively supported continuous system operation without excessive heating or electrical instability, demonstrating the suitability of the proposed power architecture for indoor autonomous cleaning applications.

Discussion

The experimental investigation demonstrates that integrate in autonomous indoor power supply with a dual cleaning mechanism provides an effective solution for indoor autonomous cleaning applications. The coordinated operation of the vacuum-cleaning unit and wet mopping mechanism enables comprehensive cleaning without requiring multiple cleaning devices or repeated cleaning cycles. The observed energy consumption indicates that the developed prototype can perform cleaning operations efficiently using a rechargeable battery supported by photovoltaic charging. Although the solar panel primarily serves as a supplementary energy source, its integration enhances the environmental sustainability of the system and reduces dependence on conventional electricity.

From a mechanical perspective, the selected drive mechanism and chassis configuration provided satisfactory stability and maneuverability throughout the cleaning process. The compact arrangement of the cleaning components further contributed to reliable operation while maintaining ease of maintenance. The proposed cleaning system successfully combines energy-efficient operation, satisfactory cleaning performance, and stable mechanical characteristics within a compact and economical platform. These observations support the practical application of solar-assisted autonomous cleaning systems for household and similar indoor environments (Table 2).

Table 2. Performance parameters.

S.N.	Performance parameter	Observed result
1.	Cleaning efficiency	~80%
2.	Electrical charging time	5–6 h
3.	Solar charging time	7–8 h
4.	Energy consumption (10 min)	1.67 Wh
5.	Power consumption	10 W
6.	Battery discharge rate	1.5 V/h
7.	Cleaning functions	Vacuuming + Wet mopping
8.	Operating modes	Manual and Autonomous

CONCLUSIONS

This study presented the performance evaluation and energy assessment of a solar-assisted autonomous cleaning system developed for indoor cleaning applications. The experimental investigation focused on assessing the operational characteristics of the cleaning mechanism, mobility system, battery utilization, and overall system reliability under practical operating conditions. The experimental observations demonstrated that the developed system maintained stable locomotion while simultaneously performing vacuum cleaning and wet mopping. The integration of the vacuum suction unit with the controlled water dispensing mechanism enabled sequential dry and wet cleaning within a single operating cycle, thereby improving cleaning effectiveness and reducing the need for multiple cleaning processes. The balanced mechanical configuration contributed to smooth movement and satisfactory operational stability during the experimental trials. The energy assessment confirmed that the rechargeable battery provided sufficient power to support the simultaneous operation of the drive motors, vacuum unit, water pump, and associated electronic components throughout the cleaning cycle. The photovoltaic charging arrangement effectively supplemented battery charging, enhancing the sustainability of the overall system and reducing dependence on conventional electrical energy. Although the solar charging duration was longer than charging through an electrical supply, the incorporation of renewable energy represents a practical step toward environmentally responsible cleaning technologies. The experimental results further indicate that the proposed cleaning system offers an economical and reliable solution for indoor cleaning applications by integrating commercially available mechanical and electrical components into a compact platform. The satisfactory cleaning efficiency observed during testing demonstrates the feasibility of combining vacuum cleaning and wet mopping within a single autonomous system while maintaining stable energy utilization. The study confirms that the developed solar-assisted cleaning system provides a practical approach for improving energy-efficient indoor cleaning. The findings contribute to the growing field of sustainable automation by demonstrating the potential of renewable energy-assisted cleaning technologies for household and small-scale commercial environments. Future research may focus on improving battery management strategies, optimizing energy utilization under varying operating conditions, enhancing mechanical efficiency, and incorporating advanced performance monitoring techniques to further improve the operational effectiveness of autonomous cleaning systems.

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