ISSN 1840-4855
e-ISSN 2233-0046

Original scientific article
http://dx.doi.org/10.70102/afts.2025.1732.132

INTELLIGENT ROBOTIC SYSTEM FOR EFFICIENT SOLAR PANEL MONITORING

E. Veera Boopathy[1*], S. Samraj[2], S. Vishnushree[3], L. Vigneash[4], I. Sheik Arafat[5], L.S. Karthick[6]

[1]Department of ECE, Karpagam Institute of Technology, Coimbatore, India.*
e-mail: boopathy.veera@gmail.com, orcid: https://orcid.org/0000-0001-8413-840X
[2]Department of ECE, Arjun College of Technology, Coimbatore, India.
e-mail: ssamraj@actechnology.in, orcid: https://orcid.org/0009-0003-6160-4465
[3]Department of ECE, Akshaya College of Engineering and Technology, Coimbatore, India.
e-mail: sindhuvishnu3095@gmail.com, orcid: https://orcid.org/0009-0006-4946-5281
[4]Department of ECE, Arjun College of Technology, Coimbatore, India.
e-mail: lvigneash2504@gmail.com, orcid: https://orcid.org/0000-0002-5764-8620
[5]Department of ECE, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India. e-mail: drsheikarafati@veltech.edu.in,
orcid: https://orcid.org/0000-0002-5145-9386
[6]Department of ECE, Rathinam Technical Campus, Coimbatore, India.
e-mail: karthickls8888@gmail.com, orcid: https://orcid.org/0009-0006-6780-2843

Received: January 08, 2025; Revised: February 20, 2025; Accepted: March 03, 2025; Published: March 28, 2025

SUMMARY

In this paper, we will introduce a new concept of improving the efficiency of solar panels and the ease of their maintenance by applying relevant robotics and a mobile application concept. This component relies on various sensors, such as rain sensors, dust sensors, and real time clocks (RTCs), to enhance thorough cleaning and maintenance. The robotics system operated through the application, and the data provided by these sensors independently identified and characterized environmental conditions that impact the solar panels. The smartphone application acts as a user control where one can view the status of the solar panels in real-time. Moreover, it offers functionalities that permit the analysis of data on the current produced by the solar panels and also inform the user when the panels are obscured by dust or mist. Using the features of the RTC, the system can effectively automate the scheduling of routine maintenance activities, which helps to achieve maximum efficiency and long-lasting effectiveness of the solar panels. In sum, this proposed integrated approach allows total control of solar panel systems and enhances energy yield through proper internal and external conditions, reduced maintenance, and reduced costs.

Key words: *solar panels, robotics, ai, sensors, mobile applications.*

INTRODUCTION

Solar energy is one of the significant actors in the transformation to a green source. While searching for renewable energy sources to reduce the usage of fossil fuels and mitigate the effects of climate change, solar energy becomes one promising way out. Solar power generation through photovoltaic (PV) panels has become common in homes and organizations since they convert sunlight into power. It becomes important to answer how these installations should be managed effectively to ensure their sustainability. Challenges relating to dust accumulation, shading, and imperfections remain significant barriers to realizing the system's full potential. With an ever-increasing number of solar panel systems installed, the performance and durability of PV systems as part of a real-world system have become major concerns [1]. However, potential issues with this technology include the formation of a layer of dust on the surface of solar panels changes in environmental conditions [2], which leads to the need to carry out maintenance and cleaning practices.

Traditionally, solar panel maintenance has required a lot of labor and time, with much focus being on physical checks and the use of tools. Still, with the improvement of robotics and AI, there is a greater likelihood of revolutionizing how solar panel maintenance is conducted [48]. Integrating AI with robotics offers a chance to amplify the efficiency, accuracy, and reliability of maintenance work, along with the level of human implication [4].

In response to these challenges, this project proposes an innovative solution that integrates robotics and a mobile application to enhance the efficiency and maintenance of solar panels [3].

In light of these problems, this project seeks to devise a solution that employs robotics mobile application to increase the effectiveness and proper care for solar panels. This system should employ all the modern technologies and enhanced sensing mechanisms to avoid soil accumulation, a reduction in energy generation, and time wastage through the cleaning process. It also involves the use of, among others, rain sensors, dust sensors, and Real-Time Clocks (RTCs) for the monitoring of the environment and panel in real-time. Such sensors offer information that is collected and put through an easy-to-use smartphone application enable users to track the efficiency of their solar panels and when they should call for servicing [49].

Moreover, the mobile application to control the robotics system is flexible and capable of monitoring and beginning an automatic process to notice and perform more efficient cleaning operations [8]. What makes this project relevant is that it tapped into robotics and mobile technology to deliver an all-encompassing solution for solar panel systems, thus ensuring cost-effective and sustainable energy generation with limited intervention from humans. In the following sections, we will describe the details of the mathematical model of the proposed system, illustrate its possible applications, and discuss possible practical benefits within the context of renewable energy [12].

EXISTING SYSTEM

This paper aims to examine the intersection of AI and robotics with the maintenance of solar panels. In the current research setting, we'll further consider how robotics are used to perform inspection and cleaning tasks, with the additional integration of artificially intelligent methodologies for enhancing robotic capabilities. According to the concepts of bibliographic analysis of scholarly publications, industry reports, and case studies, we aim to comprehend the state of the art in the field, identify the most significant challenges, and define possible directions of development in this rapidly evolving area [6].

Integrating AI with robotic technology provides several benefits concerning the maintenance of these structures. The skills include enabling robots to move in complex environments without assistance, perceiving and identifying imperfections, and updating cleaning patterns [7]. Further, digital twins, through AI-combined maintenance models, can predict and prevent any issues that may arise, which will reduce downtime and maximize energy production [50].

Yet, despite the enticing potential of AI-powered robotics, technical, regulatory, and ethical factors attention [9]. Issues like durability in outdoor conditions, adaptability to extensive installations, and compliance with safety protocols necessitate meticulous consideration [10]. Moreover, inquiries into data privacy, security, and the societal implications of automation merit thorough examination [11].

The amount of sunlight that hits the panel surface determines how much electricity it can create. The solar energy panels are placed outside to optimize their exposure to solar radiation [15]. The accumulation of dirt on the top layer of energy cells over the open air lowers the amount of successful sunshine that strikes cells [51]. Likewise, ice, salt buildup, and waste from birds can block sunlight from reaching cells [13]. Solar panel cleaning technologies are utilized to address such problems. A detailed discussion of the many kinds of cleansing technologies that are employed to maintain solar panels [14]. Automated robotic cleaners are one of the most modern innovations for maintaining solar cells. Robotic devices that operate cell glide across their exterior, utilizing gentle bristles to prevent damaging the cells' exterior [52]. The front part is moved sideways by powered rollers. Generally, belt-based mechanisms control lateral movement. An assessment of several photovoltaic maintenance initiatives and systems was conducted [16]. Researchers examined the operation of washing frames and UAV robots. The drone hovers dangerously adjacent to the top layer of the cell, using pressurized air and a gentle brush contact to clean the cell [17]. Adopting this kind of automation has the primary benefit of having a small portion of the device in close touch with the surface, which lowers the likelihood that the surface will sustain considerable pain [18].

The Ecopia photovoltaic maintenance machine cleans its array using a marginally distinct method [19]. A directing fence is fastened above the photovoltaic cells. The lateral orientation of the ranting structure allows it to pass across the entire array's exterior. The robotic arm operates across a ranting structure [53]. The Ecopia photovoltaic cell cleansing system sweeps the photovoltaic array's exterior using bristles attached to it. The device features a built-in battery that receives power from an internal array. The battery backup capability enables the device to perform nighttime cleaning. Moreover, web-services may be used to manage equipment [21].

Washpanel photovoltaic cleaning method: cleanse photovoltaic cells with an inclined bristle [22]. This scrub doesn't come off the cells. Whenever the framework's component shifts, water drips onto each cell and bristles against the cell to remove dirt buildup. The Ecopia and Nomad systems are almost identical. The bristles that rotate across the exterior of cells vary mostly from one another. Within the Ecopia framework, little motors with bristles travel around the structure. The maintenance machine is moved by several shafts and machines. The nomad mechanism [23] has fewer machines than the Ecopia mechanism. Its pair of motors move the bristle in a straight direction. Generally, the framework over cells is where the bristle rollers are placed. The bristle rotates in a clockwise direction about its center as the setup travels laterally. The bristle clears any dust from the cell surface. The intelligent, completely autonomous unit may be wirelessly operated and set up to follow different maintenance regimens.

A different sort of automated photovoltaic cell maintenance framework equipment [24]. The maintenance arm scrubs the bristles over the cells. DC machines operating at twelve volts for rotating the driving systems. The device may wipe surface areas in a symmetrical pattern with high capability [25].

Sunflower Solar Panel Cleaning Robot is a pioneering solution for autonomously cleaning solar panels using brushes and water [26]. This innovative system integrates sensors to detect dust accumulation and environmental conditions, allowing for timely cleaning operations [5]. Controlled via a mobile application, the Sunflower offers real-time monitoring and scheduling of cleaning tasks, while machine learning algorithms optimize cleaning patterns and efficiency [27]. Similarly, the Solar Panel Maintenance System with IoT Integration employs IoT sensors to measure the intensity and duration of sun radiation, panel temperature, humidity levels, and dust on panels [28]. The obtained data is transferred to the central control system without cables, the smartphone application allows the users to monitor the status in real-time and get notified of the maintenance required. This system entails capabilities for setting up cleaning processes dependent on sensors and climate parameters for tendencies in home and industrial sections to enhance electricity output while reducing use periods [29].

A new exciting business venture was launched to present the Solar Panel Cleaning Drone, a convenient and quick method of cleaning the panels. With cleaning attachments, the drones are operated with a mobile application where users choose the zones that need to be cleaned and see how the process is proceeding [30]. A fine video image and subsequent picture analysis allow for identifying the solar panel dust buildup; GPS and navigation aid placement accuracy in proximity to solar arrays. This solution is mostly suitable for large-scale solar farms and nearly inaccessible installations since it cuts maintenance expenditures and raises energy production [31].

Recent surveys have been rapidly evolving over the past few years because of enhancements in aspects like sensors, computers, and algorithms that support the concept of machine learning. Such advancements have enabled the timely development of flexible robotic systems capable of performing complex operations in different environments. The maintenance of solar panels denotes a chance to address timeless challenges and disparities associated with conventional manual practices [32].

Solar panel maintenance through robotic means is categorized in various ways, legged robotic systems, wheeled ones that can work fountains and circles, and flyers such as drones. These robots are fitted with sensors, cameras, and actuators that enable them to move around, detect anomalies, and perform maintenance tasks as and when required [33]. Thus, using robotics can reduce potentially fatal accident risks and improve reliability in difficult or hazardous conditions for workers and activities in general [20].

However, the realistic flexibility of robotics towards the practicality of solar panel maintenance comes to fruition when integrated with artificial intelligence. The application of intelligent technologies such as computer vision, machine learning, and path planning enables robots to learn from their surroundings and past experiences and make decisions in real time [34]. For example, computer vision algorithms can analyze images captured by cameras installed on the robotic scrubbers to identify defects such as cracks, heat checking, or dirt deposits, algorithms can predict the optimal sweeping patterns depending on the environment and prior information [35].

The AI based robotics allows us to create systems ready to learn and adapt to new conditions, improve productivity, and minimize stops. These AI-integrated robotic systems offer the prospects of improving the state of practice of solar panel maintenance to efficiency, reliability, and economic feasibility [36]. Moreover, data analytics viewpoint, one can obtain valuable information about the condition and functioning of solar setups.

However, robotics in such a field as solar panel cleaning brings about certain complicating factors and considerations. Many technical challenges, such as the ability to withstand outdoor conditions, energy efficiency, and the involved algorithmic nature, are bound to ensure that the functional capability of AI-powered robotics is feasible [37]. Moreover, the characteristics of the regulation safety and ethics play crucial roles in determining the possibilities for applying and using these systems in rather practical fields [38].

DESIGN CHALLENGES OF THE PROPOSED SYSTEM

Adaptability to Various Panel Types

There are similarities and differences in the surface properties of technologies such as monocrystalline, polycrystalline, and thin-film. Hence, flexibility in compatibility with types of solar panels is important. Therefore, there is a need for the creation of a cleaning robot with procedural flexibility.

Environmental Conditions

Environmental conditions such as high and low temperatures, wind, and humidity issues can be encountered for cleaning robots. Since these robots have to work in various conditions, they must have robustness and durability.

Efficiency and Effectiveness

Cleaning services concern efficiency and effectiveness, greatly impacts sustainability because water and energy utilized for cleaning are conserved. The cleaning algorithms and mechanisms to clean the surface of the panel and eliminate contaminants without damaging the panel is still a challenge.

Safety

The safety of solar panel structure must be protected from any damages. This entails probable risks, including collisions with obstacles, electrical dangers, or contact with chemicals, using secure safety measures and procedures.

Autonomy and Navigation

Design of complex navigation and avoidance system for the robot that would allow the robot to navigate complex environments all by itself and efficiently clean large fields of solar panels brings technological challenge.

Maintenance and Reliability

This means that maintaining the cleaning robot throughout its lifetime requires the use of preventive maintenance techniques predicting probable faults that may occur in the near future.

Regulatory Compliance

It remains challenging to ensure compliance with safety regulations and industry standards for how these cleaning robots should be designed and operated for electrical safety, environmental impacts, and the safety of human workers. One more important point is compliance with the current legislation and the satisfactory functioning of the robot.

Remote Operations and Connectivity

One disadvantage is the prospect of providing reliable connections and some form of remote operational capability within distant or difficult-to-access environments. This entails reliable communication interfaces, protection mechanisms against cyber assaults, and backup measures remote oversight and management of infrastructure.

Cost-effectiveness

The dilemma lies in achieving the optimum balance of the initial outlay costs against the long-term benefits and effectiveness of the efforts to be made. These include concerns such as delivering cost-effective solutions, optimizing production processes, and extending the service life of cleaning robots.

Public Acceptance and Perception

Dealing with uncertainty and the lack of perceived trustworthiness is the key to making cleaning robots popular across the country. To this end, there is a need to dispel misinformation, promote awareness, and make people aware of probabilities and opportunities. This is essential when it comes to gaining support from others engaging in the project.

Scaling Operations

Increasing cleaning activities to capture a growing solar market poses challenges because of this effort. The above issues imply that cleaning robots on a large scale requires close coordination and leadership, special planning and infrastructure in a facility must be established.

DESIGN METHODOLOGY FOR THE PROPOSED SYSTEM

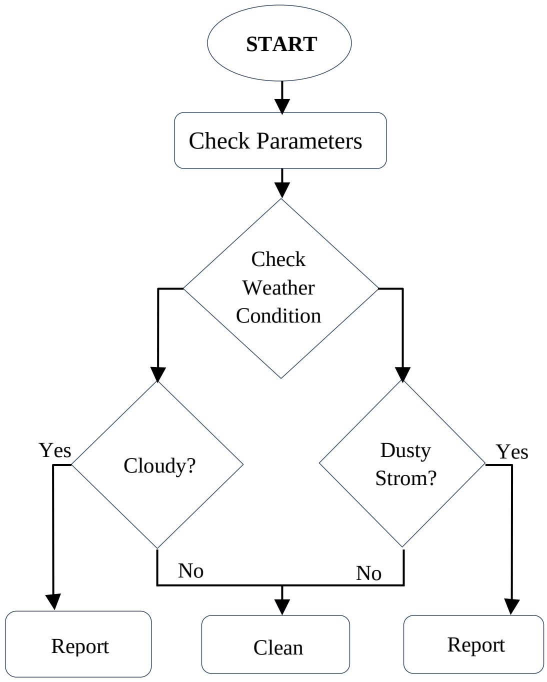

Figure 1. The Cleaning System Algorithm Diagram

The proposed system is segmented into multiple stages and phases. The primary goal is to develop a self-cleaning smart solar panel that operates autonomously and remotely.

Initially, we conducted primary research to ascertain the project's technical feasibility. Subsequently, we explored various sensors, controllers, and motors. Then, we categorized the project based on its functionalities. Notably, the project comprises two main subsystems.

By extracting wattage data from the charge controller to the Raspberry Pi, we will develop a Python code to identify dirt on the panel based on three variables: the determined efficient wattage, time, and weather conditions, as illustrated in the algorithm diagram in Figure 1.

The proposed system represents a pioneering approach to revolutionizing solar panel maintenance, blending cutting-edge robotics and advanced sensor technologies with the convenience of mobile application control, as shown in Figure 2.

Figure 2. Proposed System Setup

The basic structure includes diverse sensors such as rain sensors that detect precipitation and stop the cleaning process and dust sensors to measure the levels of dust introduced into the environment. It also uses a real-time clock to schedule the cleaning operations. These sensors help ensure speed maintenance so that environmental impacts degrade the performance of these photovoltaic panels. At the core of the system lies the application-friendly interface, which empowers users with unique possibilities to monitor and regulate the performance of solar panels for maintenance tasks. These sensors assist in preventive maintenance, thereby eliminating the impact of these factors on the efficiency of the solar panels.

At the core of the system is the sleek mobile application user interface, the operators to have enhanced control and monitoring of their solar panel maintenance activities. Users start cleaning cycles without any complications, modify settings depending on the necessities or climate, and obtain notifications concerning the panels' functioning maintenance.

Besides easing maintenance, such integration is also effective in enabling users to make the right decision after analyzing comprehensive data. Additionally, data analyze brings the possibility of improving the efficiency of the panel.

Again, using historical data and performance history, the users would be able to adjust the cleaning schedule, optimize energy generation, and prolong the lifespan of solar panels. This kind of approach not only improves the overall functionality and reduce cost, but also leads to important savings in the long term and hence builds a healthier energy system.

In conclusion, the proposed system is more effective than the current approach to solar panel maintenance that integrates computer science elements such as hardware, machine learning algorithms, and user-friendly interfaces.

IMPLEMENTATION AND WORKING

Hardware Setup

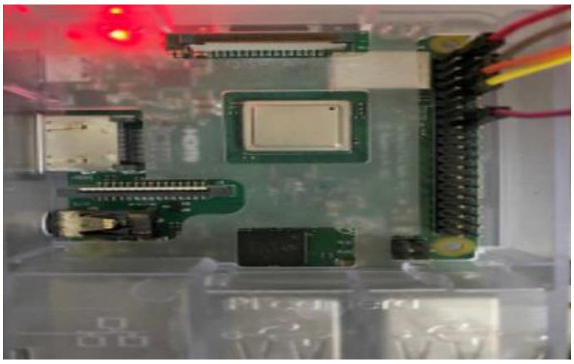

Figure 3. Internal Connection of Raspberry Pi

Assemble the robotic platform with cleaning accessories such as brushes and sprayers. Install the rain sensor and dust sensor on the robotic system. Solder the RTC module to the microcontroller unit. Ensure all the power subsystems are properly supplied with power through batteries or solar panels.

Sensor Calibration

Program the rain sensor to differentiate between clean and dirty rain so that cleaning activities can be initiated. Tune dust sensor accurately to detect the dust buildup on the solar panels.

Microcontroller Programming

Create firmware for the microcontroller unit, which will be used to control the robotic movements following the data received from the sensors. Capture algorithms for analyzing data from the sensors, for using the RTC to set maintenance tasks, and for controlling the cleaning mechanisms as depicted in Figure 3.

Ensure the Raspberry Pi is properly connected to a power source. Because solar panels onboard may draw the power from a solar battery, a solar battery charging unit, or a combination of the solar panel's charge controllers. Wired sensors on the Raspberry Pi capture aspects related to solar panel system performance. This could include sensors for measuring the intensity of solar radiation, the temperature of the battery, or the currents generated by the battery. Make sure the Raspberry Pi is connected to the same network that your laptop or computer is on, either by Ethernet to send data over the network and receive commands.

Software Configuration

Begin by installing the essential software on the Raspberry Pi operating system. This may involve any of the popular operating systems, such as Raspbian or a custom OS designed for Internet of Things projects. The Python programming language is widely used on Raspberry Pi, since it is relatively easy and suitable for different environments. Implement a web server or dashboard using the Raspberry Pi on a UI that will help data gathered from the sensors.

Launch Smartphone Interfaces

Design and deploy a simple application interface for easy control of the robotic system and data feeds. Use tools like remote access and control, data acquisition, scheduling, alarms, and historical reviews.

Backend Server Setup

This implies establishing a backend server that will serve as a repository for the data analytical platform. Enforce interface between the mobile application and the server side.

Integration and Testing

Implement the integration of the hardware parts, the microcontroller, and the communication modules. Perform a check of system functionality in the existing environment, checking the sensitivity of sensors, correcting the movement of robots, and integrating with the mobile application.

Deployment

Mount the robotic system atop the solar panels. Set up the mobile application. Verify proper connectivity and communication within different elements of a network.

Operation

It runs independently, and the rain sensor is used to identify the occurrence of rain and adjust the cleaning schedules. The dust sensor in its operation keeps measuring the dust accumulation on the solar panels. To increase the efficiency of the DC motor, the dust sensor always checks for dust accumulation on the solar panels. The RTC should also plan habitually repetitive activities, including cleaning sessions, for such timing periods. Owners and other users can monitor the robot and alter its operations from a distance using the mobile application, select cleaning cycles, or change the already-set ones if necessary. For instance, the efficient performance of solar panels can be observed in real-time through a mobile application of the system, which generates notifications about dust or mist coverage of the panels.

Monitoring and Maintenance

It is also necessary to monitor the system frequently else the status of the sensors may produce faulty data. Perform routine maintenance on the robotic components and sensors so that they will continue functioning properly. Conduct statistical studies of past cleaning events to design efficient and effective cleaning schedules.

RESULTS AND DISCUSSION

Figure 4. Fitting the Solar panel on Board

Figure 5. Final Implementation of the Proposed System

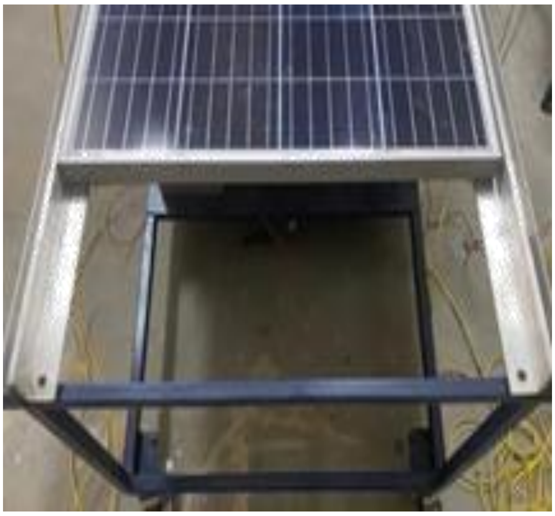

Figure 6. Adjusted Frame

Figure 7. Motor Steel Track

The boards optimize the function of solar panels where cleaning and maintenance chores are autonomously performed with the benefits of reduced cost and longer panel durability. Constant tracking of dust and weather parameters provides information about timely cleaning or corrections, allowing for efficiency in energy generation and minimal emissions.

Remote control and real-time data monitoring features make this a unique and valuable addition providing improved user experience and satisfaction of mobile applications. Additionally, alerts and notifications promptly inform users of any issues requiring attention. The system's robustness and reliability are demonstrated through rigorous testing and integration, with potential for future enhancements such as AI algorithms for predictive maintenance and integration with smart home systems as shown in Figure 4 and 5. As seen in Figure 6 and 7, a metallic apparel rail has been fitted for smooth movement. Scalability is facilitated by the modular design, allowing for integration with larger panel arrays and diverse environments. Continuous data analysis enables optimization of cleaning schedules and maintenance strategies, ensuring the system remains at the forefront of renewable energy technology.

FUTURE DIRECTIONS

Advanced AI and Machine Learning

Integrating cutting-edge AI and machine learning methodologies empowers the robot to assimilate and refine its cleaning approaches in response to real-time feedback and environmental factors [39]. This encompasses refining cleaning schedules, forecasting panel deterioration, and detecting irregularities.

Robot Swarms and Collaboration

Applying swarm robotics strategies to deploy many cleaning robots that cooperate and coordinate their work for enhanced cleaning of vast solar panels. This strategy increases scalability and fault tolerance. Since the second tier may be spread across different geographic regions, this strategy helps to increase scalability [40].

Solar-Powered Robots

Desiring cleaning robots charged by solar can enhance sustainability because it eliminates the need to rely on other forms of power [41]. This means they have to design energy-saving parts and integrate solar cells utilizing technology.

Nanotechnology and Self-Cleaning Surfaces

To identify how nanotechnology is used to develop self-cleaning coatings for solar panels, reducing the need for external cleaning. This might include the use of hydrophobic or anti-adhesive coatings to avoid the formation of dust or debris on its surface [42].

Internet of Things (IoT) Integration

As an example, the use of IoT sensors for the connectivity of cleaning robots and distant monitoring and control for supervisory management, as well as for collecting data to be used for predictive maintenance on equipment and boosting the performance of these robots [43], Real-time monitoring continuously improves the chances of noticing gaps for improving of the reliability of the system.

Ecosystem Integration

The integration of cleaning robots into already present solar panel management and monitoring systems to create one united system for both solar power generation and cleaning [44]. That would mean being compatible with SCADA systems or energy management platforms, as well as predictive analytics tools, if present.

Artificial Intelligence and Predictive Analytics

AI can be further improve historical data, weather forecasting, and real-time feed to calculate the probable need for cleaning and schedule the cleaning activities and workers more efficiently. It can also be used to predict problems before the productivity of services provided is compromised.

Modular and Interchangeable Components

Crafting cleaning robots equipped with modular and replaceable elements facilitates straightforward maintenance, repair, and enhancements. This boosts scalability, and adaptability against future advancements.

Environmental Sensing and Feedback

Incorporating environmental sensors and feedback systems into cleaning robots enables the continuous monitoring of air quality, dust concentration, and meteorological conditions in real time. This information can be utilized to devise effective cleaning strategies and aid in environmental monitoring initiatives [45].

Collaborative Robotics

Investigating collaborative robotics methodologies wherein cleaning robots cooperate with human operators or other robotic systems to improve efficiency and safety [46]. Collaborative robots can harness human expertise for intricate tasks while automating repetitive or perilous activities.

Energy Harvesting and Storage

Deploying energy harvesting mechanisms like capturing kinetic energy and regenerative braking to augment the robot's power reservoir. Utilizing energy-efficient components and sophisticated energy storage systems can prolong operational independence and diminish dependency on external power outlets [47]. Certain solar power facilities harness surplus electricity produced during sunny intervals to warm fluid, subsequently storing it for future utilization in generating steam for turbine propulsion.

Circular Economy Principles

Embracing circular economy concepts involves creating cleaning robots using recyclable materials, reducing waste production, and embracing eco-friendly manufacturing techniques. Incorporating end-of-life strategies like reuse, refurbishment, and recycling into the design process is essential.

CONCLUSION

The implemented solar panel cleaning and maintenance system, powered by robotics and controlled via a mobile application, presents a comprehensive solution for optimizing solar panel performance. By automating cleaning tasks, the system enhances efficiency, reduces costs, and extends the lifespan of solar panels. Real-time monitoring and remote-control capabilities provided by the mobile application offer users comfort and tranquillity. The proposed framework's robustness, reliability, and scalability ensure its suitability for various applications and environments. With ongoing advancements and refinements, including AI algorithms and continuous data analysis, the system remains poised to drive further innovation in renewable energy technologies, contributing to a more sustainable future. The fusion of AI with robotics presents significant potential for advancing solar panel maintenance. AI methods like computer vision, machine learning, and path planning algorithms, robotic systems can function independently, adjust to changing environmental factors, and enhance maintenance operations with accuracy and effectiveness. Nonetheless, effectively tackling technical, regulatory, and ethical hurdles will be paramount in fully unlocking the benefits of AI-driven robotics for solar panel upkeep.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Mana AA, Allouhi A, Hamrani A, Rahman S, el Jamaoui I, Jayachandran K. Sustainable AI-Based Production Agriculture: Exploring AI Applications and Implications in Agricultural Practices. Smart Agricultural Technology. 2024 Feb 17:100416. https://doi.org/10.1016/j.atech.2024.100416

[2] Nallakaruppan MK, Shankar N, Bhuvanagiri PB, Padmanaban S, Khan SB. Advancing solar energy integration: Unveiling XAI insights for enhanced power system management and sustainable future. Ain Shams Engineering Journal. 2024 Jun 1;15(6):102740. https://doi.org/10.1016/j.asej.2024.102740

[3] Lee H, Enriquez JL, Lee G. Robotics 4.0: Challenges and Opportunities in the 4th Industrial Revolution. Journal of Internet Services and Information Security (JISIS). 2022;12(4):39-55. https://doi.org/10.58346/JISIS.2022.I4.003

[4] Heo M, Yang J, Kim B, Lee C, Park H, Kim SK, Lee J, Son S, Cheon J, Choi J, Seung W. Self-powered electrodynamic dust removal for sustainable solar panels using triboelectric nanogenerators. Nano Energy. 2024 Mar 1;121:109257. https://doi.org/10.1016/j.nanoen.2024.109257

[5] Lee JH, Teraoka F. Guest editorial: Advances in wireless mobile and sensor technologies. Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications. 2010 Sep;1(2-3):1-2.

[6] Ekinci F, Yavuzdeğer A, Nazlıgül H, Esenboğa B, Mert BD, Demirdelen T. Experimental investigation on solar PV panel dust cleaning with solution method. Solar Energy. 2022 May 1;237:1-0. https://doi.org/10.1016/j.solener.2022.03.066

[7] Tang W, Yang Q, Dai Z, Yan W. Module defect detection and diagnosis for intelligent maintenance of solar photovoltaic plants: Techniques, systems and perspectives. Energy. 2024 Apr 16:131222. https://doi.org/10.1016/j.energy.2024.131222

[8] Karimov N, Kalandarova M, Makhkamova N, Asrorova Z, Saydamatov F, Ablyakimova R, Karshiboeva M, Odilov B. Impact of Mobile Applications on Tourism Development in Uzbekistan. Indian J Inf Sources Serv. 2024;14(4):175–81. https://doi.org/10.51983/ijiss-2024.14.4.27

[9] Pawlak-Jakubowska A. Retractable roof module with photovoltaic panel as small solar power plant. Energy and Buildings. 2023 Jun 1;288:112994. https://doi.org/10.1016/j.enbuild.2023.112994

[10] Pathak SP, Patil S, Patel S. Solar panel hotspot localization and fault classification using deep learning approach. Procedia Computer Science. 2022 Jan 1;204:698-705. https://doi.org/10.1016/j.procs.2022.08.084

[11] Bawankar N, Kriti A, Chouhan SS, Chaudhari S. IoT-Enabled Water Monitoring in Smart Cities With Retrofit and Solar-Based Energy Harvesting. IEEE Access. 2024 Apr 23. https://doi.org/10.1109/ACCESS.2024.3392852

[12] Ivan S, Sabahudin H, Jovana J. Environmental, Social and Other Non-profit Impacts of Mountain Streams Usage as Renewable Energy Resources. Archives for Technical Sciences/Arhiv za Tehnicke Nauke. 2023 Jul 1(29). https://doi.org/10.59456/afts.2023.1529.057S

[13] Mohandes M, Schulze F, Rehman S, Suliman W. Cleaning photovoltaic solar panels by drone aerodynamic. In2021 4th International Symposium on Advanced Electrical and Communication Technologies (ISAECT) 2021 Dec 6 (pp. 1-5). IEEE. https://doi.org/10.1109/ISAECT53699.2021.9668543

[14] Ledmaoui Y, El Maghraoui A, El Aroussi M, Saadane R, Chebak A, Chehri A. Forecasting solar energy production: A comparative study of machine learning algorithms. Energy Reports. 2023 Nov 1;10:1004-12. https://doi.org/10.1016/j.egyr.2023.07.042

[15] Kadhim MJ, Alradha RM, Jawad HK, Al-Dabbagh B, Al-Khafaji Z. Investigating the Effect of the Yellow Chlorophyll on the Characteristics of Liquid Polyethylene Glycol for Liquid Electrolyte Solar Cells. Natural and Engineering Sciences. 2024 Sep 1;9(2):244-56. https://doi.org/10.28978/nesciences.1479785

[16] Al-Amri F, Saeed F, Mujeebu MA. Novel dual-function racking structure for passive cooling of solar PV panels–thermal performance analysis. Renewable Energy. 2022 Oct 1;198:100-13. https://doi.org/10.1016/j.renene.2022.08.047

[17] Gupta M, Dubey AK, Kumar V, Mehta DS. Experimental study of combined transparent solar panel and large Fresnel lens concentrator based hybrid PV/thermal sunlight harvesting system. Energy for Sustainable Development. 2021 Aug 1;63:33-40. https://doi.org/10.1016/j.esd.2021.05.008

[18] Lee S, An KE, Jeon BD, Cho KY, Lee SJ, Seo D. Detecting faulty solar panels based on thermal image processing. In2018 IEEE International Conference on Consumer Electronics (ICCE) 2018 Jan 12 (pp. 1-2). IEEE. https://doi.org/10.1109/ICCE.2018.8326228

[19] Olorunfemi BO, Nwulu NI, Ogbolumani OA. Solar panel surface dirt detection and removal based on arduino color recognition. MethodsX. 2023 Jan 1;10:101967. https://doi.org/10.1016/j.mex.2022.101967

[20] Zhang X, Rodriguez S. Advanced Optimization Techniques for Vehicle Dynamics in Robotics. Association Journal of Interdisciplinary Technics in Engineering Mechanics. 2023 Oct 9;1(1):1-3.

[21] Jaiganesh K, Reddy KB, Shobhitha BK, Goud BD. Enhancing the efficiency of rooftop solar photovoltaic panel with simple cleaning mechanism. Materials Today: Proceedings. 2022 Jan 1;51:411-5. https://doi.org/10.1016/j.matpr.2021.05.565

[22] Almadhoun AS, Jaafar H. Enhanced solar systems efficiency and reduce energy waste by using IoT devices. Materials Today: Proceedings. 2023 Jun 21. https://doi.org/10.1016/j.matpr.2023.03.264

[23] Shao Y, Zhang C, Xing L, Sun H, Zhao Q, Zhang L. A new dust detection method for photovoltaic panel surface based on Pytorch and its economic benefit analysis. Energy and AI. 2024 May 1;16:100349. https://doi.org/10.1016/j.egyai.2024.100349

[24] Bendale H, Aswar H, Bamb H, Desai P, Aher CN. Deep Learning for Solar Panel Maintenance: Detecting Faults and Improving Performance. In2023 14th International Conference on Computing Communication and Networking Technologies (ICCCNT) 2023 Jul 6 (pp. 1-5). IEEE. https://doi.org/10.1109/ICCCNT56998.2023.10307465

[25] Malik H, Alsabban M, Qaisar SM. Arduino based automatic solar panel dust disposition estimation and cloud based reporting. Procedia Computer Science. 2021 Jan 1;194:102-13. https://doi.org/10.1016/j.procs.2021.10.063

[26] Jothikrishna K, Rithika SM, Swetha SV, Kavitha K. Solar Power Remote Monitoring And Controlling Using IoT. In2023 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA) 2023 Jun 16 (pp. 1-5). IEEE. https://doi.org/10.1109/ICAECA56562.2023.10200775

[27] Boriratrit S, Fuangfoo P, Srithapon C, Chatthaworn R. Adaptive meta-learning extreme learning machine with golden eagle optimization and logistic map for forecasting the incomplete data of solar irradiance. Energy and AI. 2023 Jul 1;13:100243. https://doi.org/10.1016/j.egyai.2023.100243

[28] Yang H, Wang H. Numerical simulation of the dust particles deposition on solar photovoltaic panels and its effect on power generation efficiency. Renewable Energy. 2022 Dec 1;201:1111-26. https://doi.org/10.1016/j.renene.2022.11.043

[29] Patil PA, Bagi JS, Wagh MM. A review on cleaning mechanism of solar photovoltaic panel. In2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS) 2017 Aug 1 (pp. 250-256). IEEE. https://doi.org/10.1109/ICECDS.2017.8389895

[30] Wan L, Zhao L, Xu W, Guo F, Jiang X. Dust deposition on the photovoltaic panel: A comprehensive survey on mechanisms, effects, mathematical modeling, cleaning methods, and monitoring systems. Solar Energy. 2024 Jan 15;268:112300. https://doi.org/10.1016/j.solener.2023.112300

[31] Milidonis K, Eliades A, Grigoriev V, Blanco MJ. Unmanned Aerial Vehicles (UAVs) in the planning, operation and maintenance of concentrating solar thermal systems: A review. Solar Energy. 2023 Apr 1;254:182-94. https://doi.org/10.1016/j.solener.2023.03.005

[32] Pal U, Chandra S. ANN based performance forecasting for dusty solar panel. Materials Today: Proceedings. 2024 Jan 1;100:147-51. https://doi.org/10.1016/j.matpr.2023.05.558

[33] Priyadharshini N, Kumar SH, Gomathy S, Krithik S, Elakiya V, Shubhashree S. A Review on Solar Panel Monitoring and Enhancing the Performance by Temperature and Dust Maintenance. 2021 Innovations in Power and Advanced Computing Technologies (i-PACT). 2021 Nov 27:1-6. https://doi.org/10.1109/i-PACT52855.2021.9696805

[34] Sayyah A, Horenstein MN, Mazumder MK. Energy yield loss caused by dust deposition on photovoltaic panels. Solar Energy. 2014 Sep 1;107:576-604. https://doi.org/10.1016/j.solener.2014.05.030

[35] Jamal J, Mansur I, Rasid A, Mulyadi M, Marwan MD, Marwan M. Evaluating the shading effect of photovoltaic panels to optimize the performance ratio of a solar power system. Results in Engineering. 2024 Mar 1;21:101878. https://doi.org/10.1016/j.rineng.2024.101878

[36] Alam MN, Aziz S, Karim R, Chowdhury SA. Impact of solar PV panel cleaning frequency on the performance of a rooftop solar PV plant. In2021 6th International Conference on Development in Renewable Energy Technology (ICDRET) 2021 Dec 28 (pp. 1-4). IEEE. https://doi.org/10.1109/ICDRET54330.2021.9752681

[37] Syafiq A, Pandey AK, Adzman NN, Abd Rahim N. Advances in approaches and methods for self-cleaning of solar photovoltaic panels. Solar Energy. 2018 Mar 1;162:597-619. https://doi.org/10.1016/j.solener.2017.12.023

[38] Boopathy EV, Akalaya C, Sathish S, Magesh M, Santhosh D. A Novel Portable Smart Prayer Assistant Using RFID. International Journal of Pharmaceutical Research (09752366). 2020 Jan 1;12(1). https://doi.org/10.31838/ijpr/2020.12.01.189

[39] Parappully ND, Joseph S, Rajeswari PS, Sabu PI, Madhanmohan VP. IoT Based Solar Performance Monitoring System. In2023 9th International Conference on Smart Computing and Communications (ICSCC) 2023 Aug 17 (pp. 627-631). IEEE. https://doi.org/10.1109/ICSCC59169.2023.10334989

[40] Deb D, Brahmbhatt NL. Review of yield increase of solar panels through soiling prevention, and a proposed water-free automated cleaning solution. Renewable and Sustainable Energy Reviews. 2018 Feb 1;82:3306-13. https://doi.org/10.1016/j.rser.2017.10.014

[41] Abdallah FS, Abdullah MN, Musirin I, Elshamy AM. Intelligent solar panel monitoring system and shading detection using artificial neural networks. Energy Reports. 2023 Oct 1;9:324-34. https://doi.org/10.1016/j.egyr.2023.05.163

[42] Boopathy EV, Sathya S, Vennila R, Subhasree P, Swathi S. High Efficient IoT based modern soil composition identifier for smart yield farming. InJournal of Physics: Conference Series 2019 Nov 1 (Vol. 1362, No. 1, p. 012005). IOP Publishing. https://doi.org/ 10.1088/1742-6596/1362/1/012005

[43] Myyas RE, Al-Dabbasa M, Tostado-Véliz M, Jurado F. A novel solar panel cleaning mechanism to improve performance and harvesting rainwater. Solar Energy. 2022 May 1;237:19-28. https://doi.org/10.1016/j.solener.2022.03.068

[44] Alagumeenaakshi M, Umamaheswari S, Mevis AA, Seetha S, Hema G. Monitoring and controlling of solar photovoltaic cells using LoRa technology. In2021 International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA) 2021 Oct 8 (pp. 1-6). IEEE. https://doi.org/10.1109/ICAECA52838.2021.9675732

[45] Gupta V, Sharma M, Pachauri RK, Babu KD. Comprehensive review on effect of dust on solar photovoltaic system and mitigation techniques. Solar Energy. 2019 Oct 1;191:596-622. https://doi.org/10.1016/j.solener.2019.08.079

[46] Sinvula R, Abo-Al-Ez KM, Kahn MT. Maintenance and Disposal of the solar panels. In2021 International Conference on Electrical, Computer and Energy Technologies (ICECET) 2021 Dec 9 (pp. 1-6). IEEE. https://doi.org/10.1109/ICECET52533.2021.9698627

[47] Zele S, Joshi A, Gogate N, Marathe D, Shitole A. Experimental investigation on utilization of crushed solar panel waste as sand replacement in concrete. Solar Energy. 2024 Feb 1;269:112338. https://doi.org/10.1016/j.solener.2024.112338

[48] Wu Z, Chen Z, Wang C, Zhou M, Wang J, Chen L. Unlocking the potential of rooftop solar panels: An incentive rate structure design. Energy Policy. 2024 Jul 1;190:114159. https://doi.org/10.1016/j.enpol.2024.114159

[49] Piotrowski LJ, Farret FA. Feasibility of solar tracking and fixed topologies considering the estimated degradation and performance of photovoltaic panels. Solar Energy Materials and Solar Cells. 2022 Aug 15;244:111834. https://doi.org/10.1016/j.solmat.2022.111834

[50] Aboagye B, Gyamfi S, Ofosu EA, Djordjevic S. Investigation into the impacts of design, installation, operation and maintenance issues on performance and degradation of installed solar photovoltaic (PV) systems. Energy for Sustainable Development. 2022 Feb 1;66:165-76. https://doi.org/10.1016/j.esd.2021.12.003

[51] Hegde V. Data acquisition systems for monitoring real time parameters of rooftop solar panels. In2022 IEEE 2nd Mysore Sub Section International Conference (MysuruCon) 2022 Oct 16 (pp. 1-5). IEEE. https://doi.org/10.1109/MysuruCon55714.2022.9972631

[52] Gochhait S, Asodiya R, Hasarmani T, Patin V, Maslova O. Application of IoT: a study on automated solar panel cleaning system. In2022 4th International conference on electrical, control and instrumentation engineering (ICECIE) 2022 Nov 26 (pp. 1-4). IEEE. https://doi.org/10.1109/ICECIE55199.2022.10000375

[53] Mane KC, Pawar DA, Kalhapure SM, Aher SG, Thokal PV, Pardeshi DB. Automatic Cleaning and Maintenance of Solar Panel and Efficiency Monitoring. In2023 2nd International Conference on Edge Computing and Applications (ICECAA) 2023 Jul 19 (pp. 1582-1586). IEEE. https://doi.org/10.1109/ICECAA58104.2023.1021223