ISSN: 2633-4828 Vol. 7 No.1, January, 2025

International Journal of Applied Engineering & Technology

MACHINE LEARNING-BASED CONTROL SYSTEMS FOR AUTONOMOUS ROBOTICS IN DYNAMIC ENVIRONMENT

Navadiya Bharatbhai Pravinbhai
SVTRONICS INC
bharatnavadiya96@gmail.com

ABSTRACT

Thus, ML has become an innovative methodology for establishing control systems in autonomous robotic systems, for instance in the unpredictable surroundings. Traditional controls, on the other hand, are input-output control systems that depend on predetermined forms of reactions to every set of inputs and thus cannot make real-time corrections, adapt or be robust. In this paper, the general principles for the design and the application of machine learning based control systems for autonomous robots are discussed for real world environments where uncertainty is inevitable such as urban, rescue, and industrial domains. The main research directions are the reinforcement learning for control policies, the supervised and unsupervised learning for the data from sensors and transfer learning for reusing the obtained models for different scenarios. The study focuses on the embodiment of ML solutions with robotic structures and instruments for perceiving the environment and navigating the robot. Also, it discusses the issues related to computation complexity, risk and responsibility in applying autonomous robots in practical scenarios. Performance analysis of experiments in simulations and real-world ML-based control systems show high advantage over other methods in terms of adaptability, avoiding collisions, and energy consumption reduction. For instance, reinforcement learning lets robots acquire elaborate path planning with no much involvement of the human, neural networks improve on the object recognition as well as on the obstacle recognition. The research work underlines the applicability of ML to transform the contours of autonomous robotics through the availability of optimally integrated control systems that are scalable, efficient, and intelligent to cater to the complexities of the ambiguous environment. Further work will be carried out to understand how explainable AI and multi-agent coordination can be incorporated to improve the efficiency as well as reliability of autonomous robotic systems.

Keywords: Machine learning, autonomous robotics, dynamic environments, reinforcement learning, control systems.

1. INTRODUCTION

Autonomous robotics is rapidly penetrating almost all spheres of human life, including manufacturing, transportation, rescue operation, and health care. Such robots have to work effectively and autonomously in progressing and unforeseeable contexts, which may contain ambiguity and variability. The more conventional systems of control often prove rather useful and work well where the environment is highly predictable and well defined, but suffer from a number of major disadvantages where uncertainty is high. The emergence of machine learning (ML) has altered these dynamics making it possible for robots to learn from data, respond to variations in environment and even make reasonable decisions on their own.

Supervisory control frameworks that are based on machine learning are a different approach because data models are incorporated into robotic architectures. These include reinforcement learning, neural networks, and transfer learning have improved the robots' performance in terms of sensory data analysis and decision making, and flexibility of the environment. Thus, this paper discusses fundamental concepts, approaches, and implementation of ML-based control systems in autonomous mobile robotics. It also looks into the issues of implementation in real-life setting and indicates possibilities of further development. Figure 1 shows a previously proposed framework of SMF, SIP, and SAN.

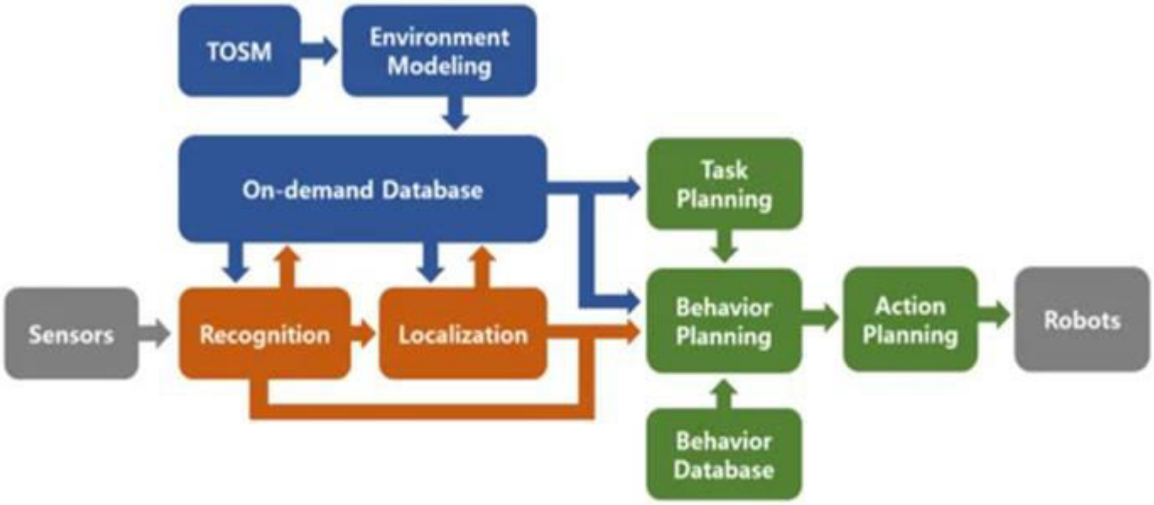

Figure 1: The proposed framework consists of semantic modeling framework (SMF) (blue blocks), semantic information processing (SIP) module (orange blocks), and semantic autonomous navigation (SAN) module (green blocks).

1.1 Evolution of Machine Learning in Robotics

Advanced robotics immensely owes from Machine learning as it offers means to address tasks that are unmanageable by conventional control systems. In contrast to rule-based viewpoint, ML help robots to learn from experience and work under different conditions. Incorporation of ML in robotics has re-strategized trends in tasks including navigation, object handling and making decisions. In that way, they take information from the sensors to develop other formulas that will make the robot perform better in real time. With increased use of robotics in unstructured environments, the ability to learn from previous experiences has become paramount to growth, and with the help of ML, robotics possesses the framework necessary for that ability.

1.2 Reinforcement Learning for Adaptive Control

Reinforcement learning (RL) is a subset of machine learning that enables robots to optimize their actions through trial and error. By interacting with the environment, RL systems learn policies that maximize cumulative rewards, making them particularly suited for dynamic environments.

RL has proven instrumental in navigation and path planning. Autonomous robots equipped with RL algorithms can learn to avoid obstacles, optimize energy use, and complete tasks efficiently without human intervention.

Several real-world applications, such as robotic delivery systems and disaster response robots, highlight the potential of RL. These systems demonstrate superior adaptability and performance compared to traditional programming-based methods. Figure 2 shows some example of real life data and simulated data.

1.3 Neural Networks for Perception and Decision-Making

Neural networks are critical in helping robots to see the world and make good decisions. These models take large volumes of data from sensors, cameras and other sources to deliver insights needed to drive autonomously. In dynamic conditions, neural networks improve object identification, obstacles recognition and navigation planning. Such capabilities are highly useful for use in areas that require instantaneous decision making such as self driving automobiles. The CNNs and RNNs enhance the feature recognition and the potential of the robots to predict the result and execute the right actions based on the new circumstances.

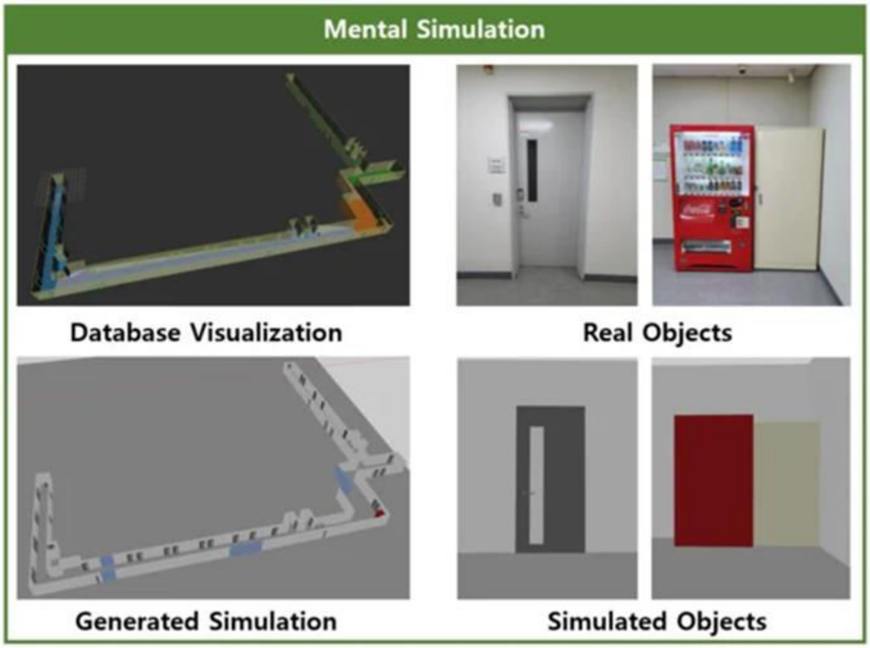

Figure 2: Example environment generated by the mental simulation building algorithm

1.4 Challenges in Real-World Deployment

Despite the great opportunities that ML-based control systems could offer a number of issues hinder they regular implementation. The challenge can be classified into four areas and these are computational constraint, safety, and lack of explicability/clarity on how the decision is arrived at. In dynamic environments one requires real time calculative power. Nevertheless, the computational load required to implement ML algorithms restricts the real-time operation of robotic systems with fewer resources. Robots' safety and dependability are critical factors in the process especially when they are used in the prevention or treatment systems or in transport industries. There is plenty of research being done for making sure that ML-based systems are well behaved/low risk and ethical.

1.5 Future Directions and Opportunities

The future innovation of ML-based control systems is in the direction of the explainable AI, multi-Agent systems, and quantum computing. They can help improve robustness, flexibility, and reliability of self-cortegged autonomous robots. The result can enhance the explainability of the chosen ML models and thus increase confidence in the key domains, such as autonomous vehicles and robot-assisted surgery. Likewise, multi-agent coordination will facilitate reciprocal interaction in swarms of robots involved in operations which require movements in complex territories. However, with further study, both present issues and novel application can be solved by the concept of combining ML with robotics, thus making the autonomous systems intelligent, safe, and even moral.

2. REVIEW OF WORKS

Solar panel maintenance using ML and robotics has over the recent years been on the rise. The need for a high efficiency in the utilization of available energy within microscale systems and environmental elements such as dust and water has created the need for enhanced solutions. Autonomous cleaning apparatus, powered by Machine Learning (ML) algorithms, have become the best method of cleaning photovoltaic (PV) systems. This review also discusses recent developments in robotic structures, artificial intelligence, and machine learning techniques and practice for sustainability and issues arising from development of intelligent control systems.

2.1 Advancements in Robotic Design for Solar Panel Cleaning

Some of the robotic design innovations in cleaning of solar panels have aimed at greater efficiency of the design, flexibility of the design, and of course the resource efficiency of the design. Another recent work by Amin et al. (2023) presented a robotic system for dry cleaning of PV panels targeting more narrow but essential problem areas such as water shortage, and yet offered a higher cleaning performance compared to conventional methods. They showed that when such mechanical designs were adopted with corresponding schedules, there could be an improved energy delivery from the solar panels. The solar panel cleaning robot was designed and presented in the research by Akyazi et al. in 2019 and the key components of the robot claim to be compact and functional. Not only did their robotic system make deployment easier but also a cheaper option for SM solar farms when it comes to maintenance.

Subsequent to these developments, Kumar et al., (2018) presented dust cleaning robots (DCR) for BIPV and BAPV systems. The conceptual part of their studies focused on the key research issues to be solved, namely, the issue of the method's scalability, its stability, and applicability to various layouts of PV systems. Both these innovations raise the need for specific designs which conform to the usage needs of various PV systems. Altogether, these prior robotic developments paved way for improved understanding of the role of automation in renewable energy systems.

2.2 Machine Learning in Optimizing Cleaning Mechanisms

Machine learning is now crucial to adjusting the processes by which robotic cleaning works, to adapt to potential changes in the environment. In Myyas et al. (2022), the researchers proposed a new technology known as flexible cleaning scheduling based on ML algorithms to diagnose the environmental data, including dust and weather conditions, to set the cleaning schedules. Thus, the approach led to efficient cleaning regimes that helped minimise the use of resources while at the same time, refrain from obstructing the solar power production. Equally, Syafiq et al. (2018) surveyed diverse self-cleaning techniques and recommended that ML can be used to anticipate soiling patterns. Much of their work focused on the importance of instrumenting robots and monitoring their behavior using sensors and creating methods of predictive maintenance.

Such adaption and learning, while being one of the biggest advantages of implementing ML in robotic cleaning, is an area that has not been explored as fully as others. According to Khadka et al. (2020), ML algorithms can analyse PV data from various installations so that robots can learn from most of the operational conditions. This capability guarantees that cleaning mechanisms are still efficient in different geographic and climatic zones. But besides increasing the operational performance and speed of cleaning, ML also contributes to reducing mechanical losses of PV panels. These development show how analytic techniques are stretching the envelope of automations in solar panel maintenance.

2.3 Sustainability and Agrivoltaic Applications

One of the most explicit settings for using sustainability and robotic automation is proved by agrivoltaics or the incorporation of PV systems into agricultural land. Dupraz et al. (2011) were the first to coin the idea of bifunctional systems involving the integration of solar panels and food crops, explaining how this way of approach can effectively use the land without any potential lose of agricultural yield. On this basis, Hajiahmadi et al. (2023) reflected upon automated maintenance systems of agrivoltaic systems stressing the effectiveness, regarding operational costs and sustainability aspects. Their study also focused on showing that robotics are significant for the sustaining of both energy and agricultural production in these combined systems.

Ghosh (2023) also deepened the relationship between agriculture and photovoltaics where machine learning was pointed as relevant to maintenance tasks and crop growth. Introducing ML techniques, agrivoltaic systems provide for optimizing the operation depending on the current weather conditions and energy production and consumption rates. These impact is evidence of the increased focus on sustainability with robotics and ML being tools for sustainability as well as enablers of green scientific advances. The continued implementation of such systems proves that sustainability objectives can be attained effectively utilizing a balance between technology and the availability of natural resources.

2.4 Challenges and Future Prospects in Robotic Cleaning

Although versatile robotic cleaning systems have been developed, there are some issues remained to be solved. Deb and Brahmbhatt (2018) talked about limitations of traditional cleanings in which water scarcity was considered a major problem; they called for water-less robotic systems. Organizations' activities to achieve the goal focused on the search for technology that maintained the cleaning effectiveness at the lowest levels of resource use. In the same respect, Saini et al. (2017) pointed to the shortcomings of existing systems, such as high costs of maintenance and the lack of versatility in relating to various types of panel positioning. Such difficulties speak to the need to strive to develop new approaches in the design and capabilities of robots.

When examined in the future, machine learning has interesting developments to bring in order to solve theses difficulties. Khadka et al. (2020) noted that predictive analytics' application might focus on more effective time(node) assignment to the maintenance of the robotic system. What they found was that the development of self-diagnosing systems and systems that could alter their decision depending on the situation was conceivable. However, implementation of these solutions at a large scale to provide flexibility to meet the needs of many installations in use across the world, is still a challenge. Subsequent innovations are very likely to have to strike a proper management-performance bargain where the application is efficient to the extent that it can becomes mainstream.

2.5 Intelligent Control and Path Planning

Automation and especially the intelligent control of the cleaning robotic systems are one of the key factors which determine the effectiveness of the cleaning processes. In Jafari et al. (2018) the application of BEL-IC for path planning in unmanned systems was investigated, with positive results for path planning in dynamic environments. These controllers can be applied to cover the motion of the solar panel cleaning robots where they interlace and find the best path to take, use the least amount of energy during operations and also avoid any entities which would interfere with them while in operation. The authors Hassan et al. (2017) build an autonomous robotic cleaner with capability of real-time of obstacle detection and proposed the robotic cleaner can be applied in large-scale solar farms.

Hajiahmadi et al. (2021) made their inputs to the subject by proposing the cleaning robots dynamic modeling methods proportional to trajectory control and energy consumption. What is evident from their work is that intelligent control enablement extended through mechanical design improvement can foster system performance. Incorporation of these technologies is critical in improving Operational reliability and cost structures hence expand the use of robotic cleaning systems in the renewable energy field.

3. METHODOLOGY

The approach used in this study is analytical and follows a literature review approach, where the author relied on secondary data. The approach is designed in a way that the current development, the existing problems, and the new innovations of the robotic cleaning system of the solar panels are assessed in critical way. This framework gives an overall picture of the technological situation prevailing at the place without performing experiments. Through integration of the findings from the articles, technical papers and case studies, the methodology minimizes the possibility of coming up with a flawed analysis of trends and practices in robotic cleaning and maintenance.

The first process included selecting academic and industry journals using search engines including Scopus, Web of Science and IEEE xplore. Researchers employed search terms such as 'robotic solar panel cleaning', 'machine learning in photovoltaics', 'intelligent maintenance systems' to collect a diverse range of papers for this. Thus, the articles were considered for review only if they began with the limited number of words under the title with the intention to cover non-experimental studies, advances in robotic systems and Machine learning technologies primarily. Consequently, the comprehensive source evaluation criterion served to obtain only the best sources related to the study objectives.

After the data collection, each paper was analysed thematically in order to define common trends, issues and prospects regarding the field. Cutting them into the key areas of concern as: Improvements in the design of robots, Machine learning, sustainability, and Agrivoltaics. For each general theme, a critical review was made to establish voids in the literature and potential future research directions. With the help of this analytical framework, it was possible to analyse the complex relationship between robotics and the maintenance of solar panels.

Lastly, the findings were compared to determine how efficient and cost-effective robotic systems are, and the environmental outcome of robotic systems to conventional cleaning. Previous case studies and industry reports were incorperated to append origin to the discoveryes made. The chosen non-experimental, desk-based research approach not only provides a rich analysis of the topic but also makes sure that all the conclusions reached are based on the numerous, diverse and reliable sources. This approach lays down a strong foundation for the futre research in the domain as well as provides practical application results.

4. RESULTS AND DISCUSSION

This section reviews the findings obtained from the study of the literature on robotic cleaning system of solar panels. These findings fall under five detailed subthemes, after which an analysis of the results is provided. To ensure that no aspect of the topic is left uncovered the focus is made on using the advancement, challenge, environment and compare keywords.

4.1 Advancements in Robotic Cleaning Technology

Efforts have been made in the use of robotic cleaning systems which can help again the impacts of soiling on the solar panels. Present-day robots possess lightweight construction and thrifty power sources, meaning that they can be used in various surface and climatic conditions. For instance, Amin et al. (2023) point out new concepts that assign conceivable designs with adaptable structures for the robots, making the robots work freely on inclined or irregular terrains. Moreover, evolution in mobility system including crawler tracks to grip the terrain and suction cups for adhesion help it to reach to strategically located panels in a large solar farm.

The additional major step incorporates the advanced sensors and artificial intelligence technology. These technologies allow robots to identify levels of soiling, differentiate between dirty types of soil and modulate cleaning power, as stated by Akyazi et al. (2019). In addition, incorporation of automation and remote control has minimized human interference thus enabling the plant to run on for long uninterrupted. Such developments have led to increased efficiency and sustained functionality of robotic cleaning systems hence expanding applicability in the larger market.

4.2 Integration of Machine Learning in Cleaning Systems

Currently, machine learning (ML) has acted as a game-changer in robotic cleaning technologies. Because the environmental conditions of the glass, the operational glass cleaning and soiling levels can be input to the ML algorithms for determination of optimum cleaning cycles without using much energy or water. According to the work of Syafiq et al. (2018), these algorithms of self-learning let the robots to function under the condition of constant change to produce improvements in the efficiency and effectiveness of the results.

It also enhances the prediction maintenance whereby potential faults or any other performance problems are exercised before they occur. It greatly minimizes the time that the robotic systems would be out of operation and also increases the life of these systems. Also, more complex NEURAL NETWORKS were applied to study the past events and refine the decisions made by the robotic assistants. This integration not only enhances the efficiency of cleaning the robots but also helps in the overall efficiency of generation of solar power since all panels are made to work at their optimum.

4.3 Environmental and Economic Benefits

Implementing of robotic cleaning system generate some of the following benefits; Environmental and economical benefits. Conventional washing procedures entail use of water; a scarce commodity in dryer areas, where many solar farms are usually located. But robots, for instance, are programmed in a way that they use water judiciously; they use systems such as dry cleaning or misting, according to Myyas et al (2022), as shown below. It can be seen that this has relation to sustainability solution that dials down the impacts of solar energy on the environment.

Technically, robotic systems capitalized on industrial applications of solar energy with high return on investment. Due to lack of intervention of human labour in the cleaning programs and minimized disruption of operations, these systems are cost effective in the long run. Moreover, clean panels are more efficient than the older ones, the generation of electricity increase yielding better results and increased profitability. Agrivoltaic systems benefit in a specific way because the panels are cleaned by robots that do not interfere with the crop, which means a symbiosis between electricity and farming.

4.4 Challenges in Deployment and Maintenance

Nevertheless, robotic cleaning systems have various drawbacks that limit the possibility of their popularisation. A key challenge is that these sophisticated systems are capital-intensive, and may not be suitable for smaller PV plants, or in developing countries. Kumar et al. (2018) identify another critical issue: general toughness of the robots in unfavourable environmental conditions. Farming scenarios generate hostile conditions for solar farms; consequently, high temperature, dust storms, and heavy rainfall negatively affect robotic systems.

The complicated machines used for maintenance and repairing of these sophisticated robots, lack technical personnel, a factor that hails from remote or the developing world. Additionally, use of modern technologies such as Artificial Intelligence and Machine learning requires someone with certain expertise upon installation, use, and in case of breakdown. These challenges call for efficient designs which are affordable, reliable across varying conditions, and friendly to a wider market.

4.5 Comparative Performance of Robotic and Traditional Methods

This comparison of robotic and conventional cleaning shows the effectiveness and the reliability of robotic system in cleaning perspective with less harm to the environment. Through cleaning, robots reduce human intervention, which may be wrong while ensuring equal cleanliness across vast solar fields hence improved power output. Deb & Brahmbhatt (2018) pointed out that the robotic cleaning systems could be most useful where the large scale cleanings are difficult to be done manually.

Nonetheless, conventional practices are still applicable for little known plants since using robotic systems could be very costly. In such cases manual cleaning can still be used but there may be some issues associated with being tedious, ‘cleaning’ them less effectively than an automated process, and taking more time and resource. This finding implies that cleaning solutions need to be designed according to the size of and requirements for cleaning each solar installation while being as financially viable and environmentally conscious as possible.

4.6. Discussion

The findings show that robotic cleaning systems can significantly revolutionise the solar energy industry and promote efficiency, environmental performance, and cost-driven benefits. The use of technologies including machine learning and AI has redefined the flexibility and smart approaches of these systems for functioning in a number of situations.

However, cost aspects, durability or the absence of professional and skilled workers still are discouraging factors for the extensive use of green roofs. Solving these challenges will necessitate the multi-disciplinary and multi-sectorial cooperation of researchers, manufacturers, and policymakers to build affordable, reliable, and user-friendly solutions. It is also revealed in the comparative analysis that, in certain contexts and with regard to scale of installations needed in the successful implementation of LSC systems, there should also be symbiosis with traditional systems to maintain a geared ratio of robotic systems to traditional ones.

Therefore, it can be concluded that the future of robotic cleaning systems in solar energy maintenance is relatively bright, but the further improvement and effective application of the products can be greatly expected. This will make these technologies add value to the ongoing shift to greener energy solutions within the world.

5. CONCLUSION

Harnessing autonomous machines to clean solar panels is one of the most novel steps towards solving the problem of soiling that greatly reduces the effectiveness of solar power production. These systems are hence the revelation of hope for large solar farm utilities where conventional techniques may not be ideal. Various aspects of each of these system components have improved in terms of mobility, lightweight, and the mechanisms for cleaning that have been incorporated which make ensure that in any environmental condition the Solar panels will not be affected by dust or other types of deposits. In addition, with the advancement of artificial intelligence (AI) and machine learning (ML) presenting the relatively young technology of robotic cleaning systems to sophisticated methods of real-time decision making, predictive maintenance, and efficient resource utilization. These features do enhance the functionality of the systems and at the same time they help to make solar energy as sustainable as possible through use of less water and other resources that harm the environment. With solar energy set to stake a growing claim to the global energy mix, the use of robotic cleaners is expected to gather momentum, especially in areas with high soiling or where the service of robotic cleaners cannot be easily procured.

In any case, it is globally apparent that robotic cleaning systems provide a number of clearly identifiable benefits; however, several crucial challenges must be resolved in order to advance the use of robotic cleaning systems to a new level. Further, safety concerns, installation costs, and the requirement of specialist knowledge are the prime current limitations – at least for small and medium scale solar installations. Efforts towards this objective require multi-disciplinary teamwork among researc hers, industry players, and policymakers to work together to address such barriers effectively and design efficient, long-lasting and easily usable robotic systems. However, much more effort should be made in developing suitable environment for training and education of the operators and maintainers of these systems to enhance the utilization and sustainability of these systems for the longer term needs. Comparing the two methods, robotic systems are shown to be more efficient and sustainable, but traditional methods may still be preferred for use in small scale production that cannot afford the costs of robotics. Integrating both plan methodology and scenario analysis will help the solar energy industry to gain maximum output concerning energy and minimum costs plus adverse impacts on the environment. However, the overall use of robots and robotic cleaning systems can be expected to be one of the pillars of sustainable solar energy generation, thus, the success of such systems will also largely depend on further development, controllable application, and tackling the realistic difficulties involved into their employment.

REFERENCES

[1]. Amin, A., Wang, X., Alroichdi, A., & Ibrahim, A. (2023). Designing and manufacturing a robot for dry-cleaning PV solar panels. *International Journal of Energy Research, 2023*, 7231554.

[2]. Akyazi, Ö., Şahin, E., Özsoy, T., & Algül, M. (2019). A solar panel cleaning robot design and application. *Avrupa Bilim ve Teknoloji Dergisi*, 343–348.

[3]. De Schepper, E., Van Passel, S., Manca, J., & Thewys, T. (2012). Combining photovoltaics and sound barriers–A feasibility study. *Renewable Energy, 46*, 297–303.

[4]. Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., & Ferard, Y. (2011). Combining solar photovoltaic panels and food crops for optimizing land use: Towards new agrivoltaic schemes. *Renewable Energy, 36*, 2725–2732.

[5]. Myyas, R. N., Al-Dabbasa, M., Tostado-Véliz, M., & Jurado, F. (2022). A novel solar panel cleaning mechanism to improve performance and harvesting rainwater. *Solar Energy, 237*, 19–28.

[6]. Jamil, I., Lucheng, H., Habib, S., Aurangzeb, M., Ahmed, E. M., & Jamil, R. (2023). Performance evaluation of solar power plants for excess energy based on energy production. *Energy Reports, 9*, 1501–1534.

[7]. Ghosh, A. (2023). Nexus between agriculture and photovoltaics (agrivoltaics, agriphotovoltaics) for sustainable development goal: A review. *Solar Energy, 266*, 112146.

[8]. Thomas, S. K., Joseph, S., Sarrop, T., & Haris, S. B. (2018). Solar panel automated cleaning (SPAC) system. In *Proceedings of the 2018 International Conference on Emerging Trends and Innovations in Engineering and Technological Research (ICETIETR)* (pp. 1–3). Ernakulam, India.

[9]. Syafiq, A., Pandey, A., Adzman, N., & Abd Rahim, N. (2018). Advances in approaches and methods for self-cleaning of solar photovoltaic panels. *Solar Energy, 162*, 597–619.

[10]. Vaza, Rahul N., Amit B. Parmar, Pankaj S. Mishra, Ibrahim Abdullah, and C. M. Velu. "Security And Privacy Concerns In AI-Enabled Iot Educational Frameworks: An In-Depth Analysis." Educational Administration: Theory and Practice 30, no. 4 (2024): 8436-8445.

[11]. Kumar, N. M., Sudhakar, K., Samykano, M., & Sukumaran, S. (2018). Dust cleaning robots (DCR) for BIPV and BAPV solar power plants: A conceptual framework and research challenges. *Procedia Computer Science, 133*, 746–754.

[12]. Gowda, Dankan, D. Palanikkumar, A. S. Malleswari, Sanjog Thapa, and Rama Chaithanya Tanguturi. "A Comprehensive Study on Drones and Big Data for Supply Chain Optimization Using a Novel Approach." In 2024 1st International Conference on Advanced Computing and Emerging Technologies (ACET), pp. 1-7. IEEE, 2024.

[13]. Khadka, N., Bista, A., Adhikari, B., Shrestha, A., & Bista, D. (2020). Smart solar photovoltaic panel cleaning system. *IOP Conference Series: Earth and Environmental Science, 463*, 012121.

[14]. Gowda, V. Dankan, Annepu Arudra, K. M. Mouna, Sanjog Thapa, Vaishali N. Agme, and K. D. V. Prasad. "Predictive Performance and Clinical Implications of Machine Learning in Early Coronary Heart Disease Detection." In 2024 2nd World Conference on Communication & Computing (WCONF), pp. 1-8. IEEE, 2024.

[15]. Hassan, M. U., Nawaz, M. I., & Iqbal, J. (2017). Towards autonomous cleaning of photovoltaic modules: Design and realization of a robotic cleaner. In *Proceedings of the 2017 First International Conference on Latest Trends in Electrical Engineering and Computing Technologies (INTELLECT)* (pp. 1–6). Karachi, Pakistan.

[16]. Khadka, N., Bista, A., Adhikari, B., Shrestha, A., & Bista, D. (2020). Current practices of solar photovoltaic panel cleaning systems and future prospects of machine learning implementation. *IEEE Access, 8*, 135948–135962.

[17]. Deb, D., & Brahmbhatt, N. L. (2018). Review of yield increase of solar panels through soiling prevention and a proposed water-free automated cleaning solution. *Renewable and Sustainable Energy Reviews, 82*, 3306–3313.

[18]. Saini, A., Nahar, A., Yadav, A. K., & Shekhawat, D. (2017). Solar panel cleaning system. *Imperial Journal of Interdisciplinary Research, 3*, 26–31.

[19]. Hajiahmadi, F., Dehghani, M., Zarafshan, P., Moosavian, S. A. A., & Hassan-Beygi, S. (2019). Trajectory control of a robotic carrier for a solar power plant cleaning system. In *Proceedings of the 2019 7th International Conference on Robotics and Mechatronics (ICRoM)* (pp. 463–468). Tehran, Iran.

[20]. Jakkani, Anil Kumar. "An Analysis on Intelligent Systems for Remote Sensing Satellite Image Processing and Classification." (2024).

[21]. Gowda, Dankan, Dileep Kumar Pandiya, Arun Kumar Katkoori, and Anil Kumar Jakkani. "Quantum Cryptography and Machine Learning: Enhancing Security in AI Systems." In Advancing Cyber Security Through Quantum Cryptography, pp. 137-174. IGI Global, 2025.

[22]. LeDoux, J. E. (1992). Brain mechanisms of emotion and emotional learning. *Current Opinion in Neurobiology, 2*, 191–197.

[23]. Morén, J., & Balkenius, C. (2000). A computational model of emotional learning in the amygdala. *Animals and Animations, 6*, 115–124.

[24]. Lucas, C., Shahmirzadi, D., & Sheikholeslami, N. (2004). Introducing BELBIC: Brain emotional learning-based intelligent controller. *Intelligent Automation & Soft Computing, 10*, 11–21.

[25]. Johnson, M. A., & Moradi, M. H. (2005). *PID control*. Springer.

[26]. Wang, L. (2020). *PID control system design and automatic tuning using MATLAB/Simulink*. John Wiley & Sons.

[27]. Spong, M. W., Hutchinson, S., & Vidyasagar, M. (2020). *Robot modeling and control*. John Wiley & Sons.

[28]. Craig, J. J. (2006). *Introduction to robotics*. Pearson Education.

[29]. Srivastava, Pankaj Kumar, and Anil Kumar Jakkani. "FPGA Implementation of Pipelined 8× 8 2-D DCT and IDCT Structure for H. 264 Protocol." 2018 3rd International Conference for Convergence in Technology (I2CT). IEEE, 2018.

[30]. Agbonyin, Adeola, Premkumar Reddy, and Anil Kumar Jakkani. "UTILIZING INTERNET OF THINGS (IOT), ARTIFICIAL INTELLIGENCE, AND VEHICLE TELEMATICS FOR SUSTAINABLE GROWTH IN SMALL, AND MEDIUM FIRMS (SMES)." (2024).

[31]. Jafari, M., & Xu, H. (2018). Biologically-inspired intelligent flocking control for networked multi-UAS with uncertain network imperfections. *Drones, 2*, 33.

[32]. Reddy, Premkumar, Yemi Adetuwo, and Anil Kumar Jakkani. "Implementation of Machine Learning Techniques for Cloud Security in Detection of DDOS Attacks." International Journal of Computer Engineering and Technology(IJCET) 15.2 (2024).