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Solar Power Autonomous Rover for Beach Shore Waste Management

Shyna Nazar[1], Srijith S[2], Muhammad Rafi[3], Rahul R S[4], Harish B[5]

[1]Assistant Professor, Dept. of ECE, Vidya Academy of Science and Technology Technical Campus, Kilimanoor, Kerala, India

[2,3,4,5]Dept. of ECE, Vidya Academy of Science and Technology Technical Campus, Kilimanoor, Kerala, India

Abstract

Beach pollution is an increasing environmental concern caused by the accumulation of plastic, metallic, and biodegradable waste in coastal areas. Manual cleaning methods are often inefficient, labor-intensive, and unsuitable for continuous large-scale operations. To overcome these challenges, autonomous robotic systems powered by renewable energy have gained importance. A solar-powered autonomous rover offers an efficient and sustainable solution for beach waste collection and segregation, reducing human effort and improving environmental cleanliness

I. INTRODUCTION

Beach shore pollution has become a major environmental concern as a result of the rapid accumulation of waste products like plastics, metals, and other non-biodegradable elements. Coastal areas, which are critical for marine ecosystems and human activities, are increasingly being impacted by incorrect waste dumping and inadequate waste management procedures. The presence of such waste not only diminishes the aesthetic value of beaches, but it also poses major risks to marine life, since animals frequently consume or become entangled in debris. Furthermore, waste accumulation along coastlines damages natural habitats and contributes to long-term ecological imbalances.

Traditional beach cleaning methods rely largely on laborious chores, which is time-consuming, labor-intensive, and inefficient in large-scale operations. Workers are needed to manually collect and sort waste, which elevates the risk of health problems from exposure to hazardous materials. In addition, harsh coastal circumstances like high temperatures, humidity, and uneven sandy terrain impede the cleaning procedure. These problems underline the necessity for an automated and efficient solution capable of doing continual cleaning with minimal human interaction.

Limited battery power of sensors is one of the biggest challenge for Wireless Sensor Network (WSNs) designs. Not only is the replacement of batteries cumbersome, but as sensor nodes are usually deployed in large numbers and at remote locations, replacing or recharging them may not be feasible. Hence, energy management techniques are necessary to prolong the durability of the network. Energy efficiency is an important consideration in the design of autonomous systems, especially for outside applications like beach cleaning. Conventional robotic systems frequently rely on battery power, limiting their working time and necessitating frequent recharge. To overcome this limitation, the usage of renewable energy sources such as solar power has been extensively researched. Solar energy offers a sustainable and environmentally beneficial method for powering autonomous devices.

Another significant aspect of waste management is the classification of collected waste into wet, dry, and metallic items. Effective segmentation increases recycling efficiency while decreasing the stress on waste processing systems. However, most existing beach cleaning methods rely solely on waste collection and do not include clever segregation processes. The use of sensors such as proximity sensors, infrared sensors, and moisture sensors allows for the detection and classification of various waste products. By including these sensors into an autonomous system, real-time trash segregation is easily achieved, increasing total waste management efficiency.

The construction of a stable power supply system is critical for ensuring the autonomous rover's continuous operation. A dual power system that prioritizes AC charging while also using solar energy as a backup supply can greatly increase system reliability. The usage of components such as step-down transformers, bridge rectifiers, and Maximum Power Point Tracking (MPPT) controllers results in efficient energy conversion and utilization. Furthermore, battery management systems play an important role in maintaining steady voltage levels and preventing the system from overcharging and power fluctuations.

Microcontrollers, such as the ESP32, offer a robust foundation for integrating control and communication operations in autonomous systems. ESP32-based systems, which include wireless communication, real-time computing, and low power consumption, allow for efficient control of motors, sensors, and actuators. By separating system operations across different controllers, tasks like rover mobility and waste segregation may be managed independently, enhancing overall system performance and reliability. Additionally, battery management systems play a crucial role in maintaining stable voltage levels and protecting the system from overcharging and power fluctuations. Additionally, battery management systems play a crucial role in maintaining stable voltage levels and protecting the system from overcharging and power fluctuations It is more efficient in terms of its work, that's why we proposed this model.

This project proposes the development and deployment of a solar-powered autonomous rover for beachside rubbish control. To promote effective and sustainable operation, the system has a trash collection mechanism using sand filtration, intelligent sensor-based waste segregation, and a dual power supply system. Using a combination of sensors and actuators, the rover can traverse across beach surfaces, gather waste, and sort it into relevant categories. The use of solar energy and efficient power management techniques ensures eco-friendly operation and extended system lifetime.

The suggested system seeks to solve the constraints of current beach cleaning methods by offering an automated, energy-efficient, and dependable solution. The system promotes long-term environmental management by minimizing human effort, enhancing waste segregation, and utilizing renewable energy sources. This project highlights the potential for integrating robotics, renewable energy, and intelligent control systems to solve real-world environmental concerns.

II. LITERATURE REVIEW

A. G. Chandrasekaran et al. (2025)

This author developed an autonomous robotic boat that collects plastic waste and reduces maritime pollution. The system was designed to gather floating waste from bodies of water with automated navigation and waste collection technologies. The authors stressed the need of decreasing marine pollution using intelligent robotic systems. The proposed approach exhibited efficient garbage collection in aquatic environments. However, the technique is limited to water surfaces and does not handle garbage accumulating along coastline or beachfront areas. Furthermore, it does not include effective waste segregation techniques or dual power management systems for continuous operation.

B. F. M. Talaat et al. (2024)

In his study, introduced EcoBot, an autonomous beach-cleaning robot aimed at improving environmental sustainability. The system was designed to automate the process of waste collection on beaches using robotic movement and basic sensing mechanisms. The study highlighted the need for reducing human effort in waste collection and improving efficiency using automation. Although the robot successfully performs cleaning operations, the system lacks advanced waste segregation capabilities and does not differentiate between wet, dry, and metallic waste. Furthermore, energy management strategies are not optimized, which may affect long-term operation.

C. T. Mallikarathne et al. (2023)

The author developed a beach cleaning robot equipped with artificial intelligence and a Node-RED interface for debris sorting and monitoring. The system used AI approaches to recognize various sorts of garbage and offered real-time monitoring capabilities. The proposed method increased the accuracy of trash classification and established a smart monitoring system. However, the system is significantly reliant on computational resources, increasing power consumption. Furthermore, the complexity of AI integration increases the system's cost and makes it unsuitable for large-scale deployment in resource-constrained contexts.

D. A. Malhotra et al. (2023)

Author proposed proposed an optimum solar-powered autonomous cleaning robot. The concept aimed to increase sustainability by powering the robot with renewable energy from solar panels. The study emphasized the need of incorporating energy-efficient power sources into autonomous robots. The use of solar charging increased operational efficiency and decreased reliance on traditional power sources. However, the system is dependent on sunlight availability, making it less reliable in low-light or nighttime circumstances.

E. D. Varghese and A. Mohan (2022)

The author unveiled Binman, an autonomous beach cleaning robot that collects rubbish effectively. The system was designed to automate waste collecting, reducing manual work and increasing cleaning efficiency. In beach settings, the robot displayed good movement and rubbish collection capabilities. However, the system lacks suitable waste segregation systems and makes no distinction between different types of waste materials. Furthermore, power management tactics are not fully optimized, which may impede continued operation.

From the above literature, it is observed that most existing systems focus on autonomous waste collection and basic environmental cleaning. However, limitations such as lack of efficient waste segregation, absence of dual power management systems, and insufficient optimization of energy consumption are still present. Therefore, there is a need for an integrated system that combines intelligent waste segregation, efficient power management, and autonomous operation to improve overall system performance.

III. LIMITATIONS OF EXISTING SYSTEMS

Despite their contributions to automation, present beach cleaning and trash management systems have a number of drawbacks. The autonomous robotic boat proposed by Chandrasekaran et al. (2025) is primarily intended to gather floating garbage from water surfaces. Although it effectively combats marine pollution, the device is limited to aquatic areas and cannot be used on sandy beach terrain. Furthermore, it lacks a waste segregation system, reducing total waste management efficiency.

Talaat et al. introduced the EcoBot technology, which automates rubbish collection on beaches. While the technology lowers manual labor and increases cleaning efficiency, it lacks sophisticated waste segregation capabilities. The lack of classification systems for wet, dry, and metallic trash limits its usefulness in organized waste management. Furthermore, the system lacks an efficient power management approach, which may impact its long-term operational performance.

Mallikarathne et al. (2023) created an AI-based beach cleaning robot with superior garbage identification and real-time monitoring capabilities. Although the use of artificial intelligence enhances classification accuracy, it consumes much more power due to computational complexity. The system has substantial implementation costs, rendering it unsuitable for large-scale deployment in resource-constrained situations.

Malhotra et al. (2023) propose a solar-powered cleaning robot that uses renewable energy to operate sustainably. While the use of solar electricity increases energy efficiency, the system is heavily reliant on sunlight availability. This reliance impairs dependability during low-light or nighttime operation. In addition, the system lacks modern waste sorting mechanisms, restricting its effectiveness.

The Binman robot developed by Varghese and Mohan (2022) focuses on automating waste collection in beach environments. The system demonstrates effective movement and collection capabilities; however, it lacks a proper waste classification mechanism. The absence of intelligent segregation reduces its efficiency in handling different types of waste. Moreover, the system does not implement advanced power optimization techniques, which may limit its operational efficiency.

Overall, it can be observed that most existing systems primarily focus on waste collection and basic automation while lacking integrated features.

IV. EVOLUTION OF THESE TECHNOLOGIES

Beach cleaning and garbage management technologies have evolved dramatically over time, from manual methods to complex autonomous systems. Initially, rubbish collection on beaches was done manually by hand, which was time-consuming, inefficient, and risked health due to exposure to toxic pollutants. These traditional methods lacked effective waste segregation and were not appropriate for large-scale or continuous operations, particularly in harsh coastal locations.

With the evolution of mechanical systems, semi-automated equipment were used to help with beach cleaning. These systems increased waste collection efficiency by eliminating manual work, but they still required human interaction for operation and control. Furthermore, these computers were primarily intended for collection purposes and did not include intelligent capabilities.

The adoption of robotics represented a fundamental leap in waste management technology. Autonomous and semi-autonomous robots were created to navigate beach terrains and gather trash with little human intervention. These systems used simple sensors and microcontrollers to accomplish navigation and obstacle detection. While robotic systems increased efficiency and reduced labor dependency, early designs had limitations in terms of intelligence, power management, and adaptation to changing environmental circumstances.

In recent years, the integration of advanced technologies like as artificial intelligence, the Internet of Things (IoT), and renewable energy systems has increased the possibilities of self-cleaning systems. AI-powered robots offer intelligent trash detection and classification, which improves the accuracy of segregation procedures. IoT integration enables real-time monitoring and control of systems, resulting in improved management and data analytics.

Despite these developments, existing technologies continue to confront issues such as excessive power consumption, system complexity, and a lack of integrated solutions. As a result, modern research focuses on the development of efficient and cost-effective systems that combine autonomous operation, intelligent waste segregation, and optimal power management. The suggested solar-powered autonomous rover further this evolution by combining numerous technologies into a single system with the goal of improving performance, sustainability, and dependability in beachside garbage management.

V. RESEARCH GAP

The review of existing methods and technology demonstrates that great progress has been made in the development of autonomous beach cleaning solutions. However, some key gaps remain unresolved. Most existing systems prioritize garbage collection and basic automation above the incorporation of intelligent waste segregation techniques. The lack of adequate classification systems for various types of garbage, such as wet, dry, and metallic materials, affects waste management efficiency and limits recycling opportunities.

Another important gap exists in the domain of power management. Many contemporary models rely on traditional battery systems or only partially use renewable energy sources, without implementing efficient energy optimization strategies. Systems supplied by solar energy frequently experience reliability concerns due to their reliance on environmental conditions, while others lack a hybrid or dual power supply system to assure ongoing functioning. Furthermore, modern power optimization measures are not fully applied, resulting in higher energy consumption and lower system efficiency.

At the same time, simpler systems lack the intelligence required for efficient operation, indicating a gap between complexity and practicality.

Another significant disadvantage is the absence of a unified framework that integrates autonomous navigation, efficient garbage collection, intelligent segregation, and optimum power management into a single system. Most existing methods address these issues separately rather than as a cohesive system. This fragmentation diminishes the solution's overall effectiveness and reliability.

As a result, a complete and efficient system is required that combines autonomous operation, sensor-based waste segregation, and a dependable dual power management mechanism. The suggested solar-powered autonomous rover seeks to close these gaps by combining intelligent waste classification, sustainable energy use, and efficient system design to increase overall performance in beachside waste management.

VI. FUTURE DIRECTIONS AND OPPORTUNITIES

The evolution of automated beach cleaning devices opens up several potential for future study and development. One of the important future approaches is to use more advanced artificial intelligence and machine learning algorithms to improve waste detection and classification. Deep learning algorithms can improve the system's accuracy in identifying distinct forms of garbage under varying environmental conditions. This innovation has the potential to considerably increase trash segregation efficiency and contribute to more successful recycling procedures.

Another key area of growth is the improvement of power management systems. Future systems can prioritize the installation of more efficient hybrid energy solutions that mix solar power with additional renewable sources like wind or kinetic energy. The integration of advanced battery management systems and energy storage technologies can further improve reliability and ensure uninterrupted operation even under fluctuating environmental conditions. Additionally, optimizing power consumption through adaptive control mechanisms can enhance overall system efficiency.

The introduction of Internet of Things (IoT) technology opens up new options for real-time monitoring and control of autonomous systems. IoT-enabled beach cleaning robots can send operational data to centralized systems, enabling remote monitoring, predictive repair, and effective resource management. This can be especially effective for large-scale deployments to numerous beach sites.

Future developments could also focus on enhancing the rover's mechanical design and movement so that it can handle different terrains better. Advanced navigation systems, GPS integration, and obstacle avoidance algorithms can improve the system's performance in challenging terrain. Furthermore, modular designs can be used to facilitate maintenance and scalability.

VII. CONCLUSION

In this paper, the study describes the design and deployment of a solar-powered autonomous rover for beachside rubbish management. The study focuses on the expanding environmental issues posed by incorrect garbage disposal in coastal areas, as well as the limitations of traditional hand cleaning methods. Existing systems, while capable of automating waste collection in some cases, lack effective waste segregation mechanisms, dependable power management, and integrated system design.

To solve these difficulties, the suggested system combines autonomous navigation, sensor-based waste segregation, and a dual power supply method that includes both solar and conventional charging. The integration of advanced sensors allows for optimal trash sorting, while the utilization of renewable energy provides long-term and environmentally beneficial operation.

Furthermore, the system design prioritizes increasing efficiency, minimizing human effort, and improving overall performance in real-world beach conditions.

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