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AI, Robotics, and the Future of Waste Management: A Systematic Review of Advanced Collection and Sorting Systems

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Abstract

The rapid growth of cities and rise in population have made waste management a major concern that calls for innovative and efficient solutions. Conventional waste collecting techniques are dangerous, time-consuming, and frequently ineffective. The development of automated waste management systems powered by cutting-edge technology like robotics, deep learning, artificial intelligence (AI), and the Internet of Things (IoT) is examined in this study. Vision-based systems, convolutional neural networks (CNN) for garbage identification, IoT enabled smart bins, and solar-powered autonomous cars are just a few of the methods that are examined in a thorough literature analysis. The report emphasizes how well these technologies work to improve waste collection precision, cut down on human labor, and lessen pollution in the environment. However, limitations are noted, including restricted object differentiation, complex navigation, and scalability limitations. The study makes recommendations for future research topics, such as increasing energy economy, refining navigation algorithms, and increasing object identification accuracy. It is not only possible but also crucial to incorporate cutting-edge technologies into waste management systems in order to create cleaner and more intelligent urban settings.

Keywords: Waste management, collection and sorting of waste, artificial intelligence, robotics, robot navigation, IoT in waste collection

INTRODUCTION

Waste management plays a significant role in today's society, and the need to support autonomous equipment is growing exponentially, owing to population growth and modern living. Sorting waste into different categories is an essential step in the process, and the health and safety risks of waste collectors are another significant issue that can be avoided. Municipality bodies collect waste from homes and offices separately and send it for processing and disposal. Because waste management is one of the main issues facing modern society, automated machines are now needed for this job [1]. The goal of "Swacch Bharat Abhiyan," which calls for a clean India, has not yet been achieved. One of the main issues we deal with is land contamination, particularly in cities, shopping centers, airports, and train stations [2]. Cleaning and garbage collection by hand is a challenging, monotonous, and repetitive process; however, autonomous robots may be a good fit for this particular application. Although autonomous floor-cleaning, aquatic-cleaning, wall-cleaning, and garbage-collecting robots have been developed for years, it is still

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difficult to find a self-driven cleaning robot that can work on grass because it lacks garbage identification features [3]. Various projects have been carried out to overcome this problem using unique ideas, such as Wi-Fi-controlled garbage collector robotic vehicles [4], solar-based robots [5], smart bin systems, waste-sorting robots, sensor-based waste monitoring, and chemical analysis of waste using artificial intelligence (AI).

LITERATURE SURVEY

J. Dani Reagan Vivek et al. proposed removing floating debris from bodies of water, including lakes, ponds, and rivers, using a remotely controlled aqua garbage-collecting robot. Garbage was collected by a conveyor belt mechanism and placed in a container. The system was remotely monitored. While the ESP32 CAM module streams live video for remote control, the robot has an ultrasonic sensor to identify floating garbage. Both manual and autonomous modes are available for operation, enabling people to step as required. By automating waste collection, lowering human labor, and decreasing water pollution, this robot improves efficiency compared to earlier methods. The study suggests further improvements for complete autonomy, Wi-Fi dependency, and capacity constraints while highlighting its potential to preserve aquatic life and improve water quality [6].

Jinqiang Bai et al. stated a deep learning-based autonomous garbage-picking robot that can function in grassy areas such as parks and school grounds. With an accuracy of up to 95%, the robot detects and recognizes garbage using a convolutional neural network (CNN). In addition, it uses a ground-segmentation technique to avoid obstacles and to navigate. The robot picks up bulkier waste objects, including paper, plastic bottles, and cans, using a robotic manipulator rather than a vacuum or a brush. GPS and ultrasonic sensors improved the navigation system, enabling the robot to move effectively and steer clear of obstructions. After testing two operational modes—random navigation and path-planned cleaning— path planning was found to be more effective. According to experimental data, robots may effectively reduce human labor in outdoor rubbish collection and may find practical use in keeping public areas clean but lack fine object differentiation and quick cleaning processes [3].

Aditya P.P. Prasety et al. stated the designed and deployed GACOBOT, a self-sufficient garbage collection robot for the distribution of dry waste. It incorporates mobile robotic systems, ultrasonic sensors, and robotic manipulators to efficiently identify, collect, and transport garbage. With a manipulator arm for collecting trash and placing it in a container, the robot moves on a four-wheeled platform that resembles a car. Three ultrasonic sensors were positioned at different angles (45°, 90°, and 135°) to enhance the detection of obstructions and trash. Navigation and pattern recognition in the environment were accomplished using the Fuzzy Kohonen Network (FKN) algorithm. Through several revisions, experimental experiments showed that GACOBOT could successfully gather various types of dry waste, such as plastic bottle tops and egg waste. The study emphasizes how robot-assisted trash management might lack complex obstacle avoidance and a large coverage area but also lessen human labor while enhancing environmental cleanliness [7].

Kavya C. et al. presented a garbage-collecting robot using IoT, an autonomous robotic system that combines IoT technologies to enhance waste collection and management. This method attempts to solve the expanding issue of dispersed and disorganized waste, particularly in cities. To effectively locate and gather trash, the robot used wireless connectivity, RFID technology, and an Arduino Uno. DC motors, robotic arms, and ultrasonic sensors were used to travel and collect rubbish. The Internet of Things (IoT) capability makes it possible to remotely manage robots through a web interface and monitor garbage levels in bins in real-time. The suggested method is affordable, scalable, and flexible enough to work in a variety of settings, even dangerous ones, where it is risky for humans to intervene. According to one study, smart waste management technologies have the ability to improve city cleanliness and lower the risks involved with manual rubbish collection [8].

Bhavita Bhoir et al. introduced a modular garbage collector robot, a robotic device controlled by Wi-Fi, which is intended to increase waste collection efficiency while lowering the need for human intervention in the processing of hazardous materials. The robot has a flap-based collection mechanism that collects waste and sweeps it into a connected bin, four motor-driven wheels for movement, and a Raspberry Pi camera for real-time garbage identification. The system was operated remotely through a user-friendly smartphone application that was created with the MIT App Inventor and linked to a Firebase Realtime Database. Cost-effectiveness, modularity, and adaptability are given top priority in the design, enabling robots to be utilized in a variety of settings, including public spaces, schools, hospitals, and beaches. The IoT-enabled remote operation of the robot makes it a viable solution for contemporary trash management, and it has successfully proven its capacity to gather various forms of dry garbage [4].

N. Varuneshreddy et al. explained a garbage collection robot that uses solar power and wireless connectivity to clean beaches. Built on caterpillar wheels, the robot runs sustainably on a 12V 30Ah battery that is attached to a 40 W solar panel. A Visual Basic 2005 application running on Windows XP was used for remote control. User commands are sent to a PIC18F4550 microcontroller via Bluetooth. The robot also has an IP camera that can pan and tilt, sending live footage to the operator over an ad-hoc network. The robot can pick up huge trash items up to 12.5 × 49 cm, such as plastic and glass bottles, and travel over sand at an average speed of 0.5 meters per second. Its efficiency in collecting rubbish has been proven in tests at Bangsan Beach, Thailand; however, enhancements are required for full automation and longer-range control. This study emphasizes how robot-assisted beach cleanup can help save marine life and reduce plastic pollution [9].

Shreya Gupta et al. examined several automated trash management options created in earlier studies. It draws attention to the shortcomings of conventional infrared sensors, which have trouble identifying tiny waste elements, and recommends the use of vision-based systems to improve accuracy. CNNs are used in trash detection, and their review highlights how they outperform traditional techniques in terms of classification accuracy. Additionally, it makes reference to robotic garbage collection manipulator systems, highlighting the necessity of RGB-D cameras for depth measurement to precisely localize objects. Additionally, it highlights how the IoT and Robot Operating Systems (ROS) integrate sensors and controllers to provide real-time garbage-bin status monitoring. To improve automated garbage segregation and collection efficiency, this study expands on these experiments by integrating robotic manipulators, CNN-based object detection, and IoT [10].

Bingbing Fang et al. discussed the expanding use of AI in recycling, tracking, sorting, and waste collection. High operating costs, ineffective logistics, and environmental issues are some of the difficulties faced by traditional garbage management systems. Numerous studies have demonstrated the effectiveness of AI-based garbage identification and classification with accuracy rates ranging from 72.8% to 99.95% when using machine learning and deep learning models. Numerous studies have been conducted on smart garbage bins with sensor-based monitoring, which improves the effectiveness of waste collection and lowers overflow. Robots that sort waste using deep learning and computer vision have successfully separated recyclables from non-recyclables. Predictive models powered by AI improve the forecasting of waste generation, thereby improving resource management. AI-driven logistics also saves money and time by reducing transit distances by up to 36.8%. Additionally, AI optimizes waste pyrolysis and recycling efficiency and aids in carbon emission analysis and waste-to-energy conversion. The literature addresses issues such as data availability and cost, while highlighting AI's revolutionary potential in creating intelligent, sustainable waste management solutions [11].

Haruna Abdu et al. provided a thorough examination of deep learning applications for waste classification and detection. It discusses different models for object identification and image classification, emphasizing how CNNs, YOLO, Faster R-CNN, and SSD may automate waste management. In addition, the study gathered more than 20 benchmark datasets that were utilized to train waste recognition deep learning models. This review highlights several significant obstacles, such as limited data, changes in lighting, occlusions, and problems with object localization. It also provides a roadmap for future advancements in AI-driven trash management solutions by summarizing previous studies on satellite imaging, remote sensing, smart bins, and IoT-based garbage management systems [12].

Komal Tumsare et al. explored the development of several automated waste collection solutions. It discusses current garbage-collecting robots and points out their drawbacks, such as physical labor, inefficiency, and lack of automation. Robotic arms, vacuum-based collecting systems, and intelligent sensors for waste identification have been introduced in previous research. Ruide et al. created vision-based automated waste collection prototypes, whereas John et al. conducted research on mechanically operated garbage collection trucks. Other studies, including those by Apoorva et al., have focused on garbage collection robots that are Arduino-based and made for particular types of terrain, such as parks and walkways. Samrudhi et al. suggested a Raspberry Pi-based vision system that uses vacuum and computer vision technology to identify and gather waste. By combining solar energy, autonomous navigation, and sensor fusion, this study expands these findings to improve the effectiveness, sustainability, and affordability of industrial waste management [5].

Bhagyashree P Hegde et al. explained several automated waste collection and sorting methods that make use of deep learning and image recognition. Robotic waste collection has been studied using a variety of techniques, including autonomous robots with sensors and artificial intelligence algorithms, as well as mobile rubbish collectors that use visual recognition. Samruddhi et al. created vision-based mobile waste collectors, whereas Apoorva et al. conducted studies that introduced path-following garbage collector robots. Singh et al. also integrated deep learning (TensorFlow) with IoT for smart garbage management, demonstrating how AI and real-time data processing can be combined for effective waste collection. While Zhuang Kang et al. presented automatic waste classification models utilizing deep learning, Yang and Li suggested neural network based garbage categorization systems. By combining robotic automation and CNN-based image processing for improved garbage collection and segregation, this study expands on previous research and provides a clever and effective method of contemporary waste management [13].

Shravani Konga et al. investigated several automated trash management options utilizing AI-driven robots, deep learning, and the IoT. It discusses a variety of waste segregation methods that help sort materials according to density, size, and conductivity, including turbostratic separation, hydrocyclone sorting, disc screening, and eddy-current-based separation. Conventional approaches, such as vision-based methods like X-ray sorting and feature matching, have also been studied, but their applicability is restricted. This study emphasizes the benefits of CNNs and deep neural networks (DNNs) for waste classification, highlighting how well-trained these models are on huge datasets and how accurate and efficient they are. The report also examines the current developments in IoT-enabled smart waste management systems, where AI-powered garbage identification systems, automated sorting robots, and sensor-based solutions increase collection efficiency and lower pollution levels. Additionally, the integration of MobileNet, Mask R-CNN, and transfer learning in garbage categorization shows gains in real-time waste monitoring and recognition accuracy [14].

Vikas Kumar Tiwari et al. examined how trash management might benefit from developments in robotics, image processing, and the IoT. It examines inexpensive object sorting robotic arms that use Raspberry Pi and Arduino, highlighting their affordability, while pointing out that their precision is limited by lighting. Research on robotic arms controlled by Arduino demonstrates its high precision, but limited load capacity. Although there are difficulties in places with inadequate markings, vision-based lane-recognition techniques have been explored for navigation. Robotic arms with IoT integration show promise for automation; however, they require a constant power source. Deep learning research on intelligent garbage classification (ResNet50) demonstrated 98.67% accuracy, demonstrating its effectiveness while being constrained by large initial costs and dataset dependencies. By combining robotic arms, autonomous navigation, and real-time image processing, this study expands these findings with the goal of improving waste collection automation, sustainability, and efficiency [15].

Sanjay B. et al. investigated different methods for robotics and image-processing-based automated waste collection and segregation. Semi-autonomous garbage-collecting robots that are controlled by Bluetooth and Arduino, which utilize a robotic arm to gather trash and place it in a bin, are part of the current study. In another study, proximity sensors and computer vision were combined to lower processing costs and electricity by only turning on a camera when an object was identified. To identify and separate waste according to its size and material type, several researchers have concentrated on mechanical garbage collection systems that use robotic arms and sensors. Additionally, the distinction between biodegradable and non-biodegradable trash was made using AI-based classification methods. By combining image recognition, GPS tracking, real-time waste monitoring, and Raspberry Pi-based automation, the proposed system expands upon existing research and provides a more effective and scalable approach to urban waste management [16].

CONCLUSION

Urbanization and population growth have made garbage management more difficult, calling for creative and effective solutions. Conventional waste collection techniques are often ineffective, labor-intensive, and hazardous to human health. An encouraging substitute is the development of autonomous robotic systems driven by AI, IoT, and deep learning technology. To improve waste collection and management, a literature study identified a number of strategies, such as robotic manipulators, IoT-enabled smart bins, deep learning-based garbage detection, and solar-powered autonomous vehicles.

Despite notable advancements, problems such as restricted object differentiation, intricate navigation, and scalability limitations still exist. To make these systems completely autonomous and dependable, future research should concentrate on improving object identification accuracy, creating more effective navigation algorithms, and optimizing energy consumption. Automated waste management systems can significantly reduce human intervention, reduce environmental pollution, and promote sustainable urban living by addressing these issues. Thus, it is not only possible but also necessary to include cutting-edge technologies in waste management procedures to create cleaner and smarter cities.

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