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WasteXpert: An Intelligent Autonomous Waste Detection and Segregation Robot Using Deep Learning and Embedded Systems

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Abstract

Waste management and segregation have become a critical issue in the contemporary urban setting, which requires smart and automatic methods. The paper introduces an autonomous waste detection and segregation system, WasteXpert, built on a Raspberry Pi that leverages computer vision and sensor-based classification algorithms. The proposed system utilizes a four-wheel robotic platform with a mechanism for collecting and moving waste, which is a robotic arm. At the same time, a USB camera is used with the YOLOv8 model to detect and track garbage in the scene in real time. When the waste object is detected, the robot drives towards it, picks it up, and places it using a servo-motorized gripper and a DC motor-controlled lifting system. Waste classification is performed using a hybrid sensing method: a metal detector for metallic waste and a conductivity-based copper plate sensor for wet waste. Waste material that fails to meet either of the two conditions is classified as dry waste. It can be controlled in manual mode and automated mode, with manual mode supported through the Android application and autonomous mode enabled for self-driving, object recognition, and decision-making. The use of artificial intelligence combined with embedded system technology will result in a cost-efficient, adaptable, and scalable method for managing municipal solid waste. Experimental findings demonstrate that this technology is effective for both detection and separation regardless of changing environmental conditions. As such, this proposal presents a good option for developing smart waste management solution which leads to cleaner, more sustainable cities.

Keywords: Smart waste management, autonomous robot, waste segregation, computer vision, YOLOv8, Raspberry Pi, embedded systems, metal detection, moisture detection

INTRODUCTION

As cities become more populous and consumers become more diverse in how they choose to consume products, waste generated worldwide has risen dramatically. This phenomenon poses a major challenge for managing waste through traditional means, which typically rely on manual collection and sorting. Unfortunately, these practices are often inefficient, time-consuming, and pose health risks to workers who collect or sort the goods. For instance, if waste is not properly segregated into separate streams for wet, dry, and recyclable items before collection, it is more likely to be landfilled rather than recycled. In addition to increasing pressure to improve how we manage the growing volume of urban waste, there is a pressing need for smart, automated, scalable solutions to manage it more effectively, safely, and sustainably. To address these challenges, new strategies for

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managing urban waste have emerged in recent years, including robotics, embedded systems, and artificial intelligence (AI). By using smaller, lower-power platforms such as the Raspberry Pi, it is possible to develop small, low-power intelligent systems that can process information instantaneously. Finally, deep learning-based computer vision systems (e.g., YOLOv8) have proven efficient and effective for real-time object detection, which can aid in identifying urban waste in constantly changing environments. Combining sensor-based techniques (metal detection and moisture sensing) with the technologies described above enables the creation of systems that accurately and consistently classify invisible waste, thereby improving classification/segregation through hybrid solutions.

Robotics provides a physical interface with the surrounding environment by enabling autonomous movement and the collection and sorting of items. The use of mobile robotic platforms will enable the pick-and-place of items with little or no human input by using actuators, motor drivers, and robotic arms. Furthermore, the ability to use intuitive user interfaces such as mobile apps or Android-based applications to control and operate these robotic devices will enhance their flexibility and usability. To create effective, efficient, and sustainable smart waste management systems that operate within a smart city environment, computer vision, sensors, and robotics will be developed.

MOTIVATION

The study was undertaken because of the rise in waste management problems associated with the world's rapid urbanization, which lead to environmental pollution and health problems caused by poor waste segregation and manual waste treatment systems. The waste management system is currently not productive. It requires a lot of workforce to operate because there is little "real time" intelligence on how to categorize or group waste properly. There is a higher demand for sustainable solutions that come from creating smart cities; therefore, there will also be a higher demand for automated systems which improve on productivity and which lower the amount of workforce needed to operate these systems. This study will explore the combination of artificial intelligence, robotics, and sensors to create a system that is effective, economical, and intelligent for waste management, automatically identifying and sorting waste as it is generated.

OBJECTIVE

- Develop a smart, autonomous waste-identifying and segregating system that leverages embedded systems and AI (Artificial Intelligence).
- Use deep learning/object detection/vision (YOLOv8) to create a system that will accurately identify waste by detecting it in real-time using computer vision.
- Create a robotic platform (that can navigate autonomously, detect objects autonomously and pick up/move waste autonomously) using a robotic arm mechanism.
- Classify waste into Three categories - metal, wet and dry - using a combined method (hybrid) that uses both sensor-based detection and vision-based detection.
- Integrate both metal and moisture detection to increase the accuracy and reliability of classifying waste as either metal, wet, or dry.;
- Provide the user with two modes; manual and automatic so the control of the system comes from either mode using an Android-based interface.;
- Build the system to be low-cost, scalable, energy-efficient, and suitable for use in smart city waste management systems.; (Sustainable - Ability of system to be sustainable).;
- Minimize public involvement when dealing with hazardous waste and increase the overall efficiency, safety and sustainability of all waste management processes.
- To design a low-cost, scalable, and energy-efficient system suitable for smart city waste management applications.
- To reduce human intervention in hazardous waste handling and improve overall efficiency, safety, and sustainability of waste management processes.

SCOPE

The intended scope of the research will involve the design and development of a smart autonomous waste management system that incorporates an embedded system, computer vision, and sensor-based

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classification methods. The system is dedicated to detecting, collecting, and sorting waste into metal, wet, and dry types in real time using a set of deep learning models (YOLOv8) and combined sensing systems. It has discussed the application of a mobile robotic platform with a robotic arm for picking and placing items, and a Raspberry Pi for processing and control. The system has both manual and automatic functions that enable it to be operated by the user via an Android-based application and to operate in fully autonomous mode. It goes on to develop a low-cost, scalable, and energy-efficient solution for use in smart city settings. Also, the system can be used in controlled and semi-structured settings, and future improvements may include advanced navigation, IoT-based monitoring, and mass implementation.

LITERATURE REVIEW

Monishan et al. [1] discuss implementing an IoT-based solution to optimize waste collection and disposal, thereby reducing costs through efficient routing. They were designed using bins placed at households, automated mobile waste collectors, and a routing algorithm to determine the shortest route to collect waste around the collection points. A synthetic test-bed validation was done experimentally. In this case, it was observed that the routing provided enhanced organization and greater distance covered during collection in simulated settings. One of the gaps identified in the advertised work is that it is not known whether the methodology has been tested in actual urban environments and compared to the extant routing algorithms.

Idwan et al. [2] proposed an IoT-based waste management system to enhance the scheduling and routing of waste collection vehicles within a metropolitan area. The study implemented a two-phase metaheuristic approach that utilized a Genetic Algorithm (GA) to reduce collection distance and the number of trucks. The research consisted of two studies: one applied IoT principles to the experimental design, while the other used traditional research methods. Both studies also collected original geographic data by conducting the studies in Islamabad, Pakistan. The new geographic data used as part of the studies' experimental settings showed that the IoT design produced a statistically significant reduction in overall distance traveled and overall travel time compared with the traditional experimental design and previous research using traditional methods. Yet, continuingly, there is still an absence of research findings available in the literature related to how IoT technologies can extend the studies, which tested optimized multi-vehicle systems and optimized multi-objective systems, to include large sets of original geographic data.

Ahmad et al. [3] propose a recommendation-based optimization system to minimize the distance traveled by collection routes, the associated fuel costs, and the amount of collected waste. The authors formulated the problem as a mixed-integer linear program to optimize the waste collection system, subject to constraints. They modeled the system using Particle Swarm Optimization (PSO), the Genetic Algorithm (GA), and the Bat Algorithm.

Hannan et al. [4] suggest a routing optimization model, which utilizes real-time data of bin status to enhance the efficiency of waste collection and minimize emissions. Even though the suggested system involved both fixed and variable routing models, the modeling methodology was tested in a hypothetical situation with one depot, two vehicles, and 20 randomly located bins on an Euclidean plane. The results demonstrated the ability of the optimized routing models to reduce waste-collection costs significantly and to provide an effective schedule. However, the primary research gap remains the lack of a small-scale, synthetically generated environment and of real-world validation of the routing models in the context of complex logistics networks for waste management systems.

Nidhya et al. [5] conducted research on a novel routing strategy of smart waste management systems with emphasis on Quality of Service (QoS). Their research implemented an Enhanced Route Selection (ERS) algorithm to reduce data communication delay, while enabling routing from bins to dump yards. The researchers tested performance using an NS-3 simulator. The researchers found that ERS routing

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could reduce latency and provide enhanced throughput compared to traditional routing algorithms. However, there is a research gap in the implementation and testing of communication efficiency in a real-world research design that accounts for variable network loads.

Nowakowski et al. [6] proposed a metaheuristic model for vehicle routing of e-waste. The researchers defined their model within the context of a Vehicle Routing Problem (VRP). This study used a Harmony Search algorithm to develop a solution method for identifying optimal waste-collection routes within the available time period. The authors assessed performance on randomly generated problem instances that reflect real-world conditions.

Wu et al. [7] developed a hybrid optimization model for wet waste collection and transport as a constrained capacitated VRP with carbon emissions and credible cost levels. The authors use a combination of PSO and simulated annealing to minimize total operational costs. The authors also tested the heuristics on ten benchmark datasets and achieved superior performance across many scenarios. The research gap remains the lack of real-time validation of routing in dynamic situations and the merging of IoT sensor data to establish adaptive routes.

Abdullah et al. [8] introduce a mixed GA-Dijkstra metaheuristic to optimize routing in wireless sensor networks and ad hoc networks for IoT-enabled waste management. The approach successfully identified effective and alternative communication paths, while also minimizing distance and communication/data costs. Experiments with simulation using various network configurations revealed better path delays and greater failure resistance. The only weakness of the research is that the physical system implementation was not provided, which prevented testing the network's resilience to urban signal interference and hardware limitations.

Lu et al. [9] introduce an ICT-based novel waste collection system that uses a hybrid bi-objective metaheuristic based on OEGA, mixing a Whale Optimization Algorithm and Genetic Algorithm for balancing total cost and workload across multiple disposal centers. The proposed method was tested using real data from the Pudong community in Shanghai, and the resulting multi-objective compound demonstrated better multi-objective optimization performance than NSGA-II and MOEA/D. However, there was no real-life case to substantiate the findings of this study. This demonstrates a gap in future research examining the operational feasibility and maintenance costs of the proposed waste collection system models.

Kshirsagar et al. [10] present a real-time shortest path routing algorithm for waste collection, which draws on the input from Internet of Things (IoT) sensors that exist in the field environment. Generally, the routing model was coupled with fill-level data and inter-bin distance, along with performance measures such as packet size and end-to-end delay. The simulations showed that the algorithm generated a superior overall revenue for waste collection efforts. Nevertheless, there is a research gap: no field experiments and dynamic performance testing with load variation.

According to Ali and coworkers in 2011, they developed a data-driven optimization model using machine learning regression to optimize economic and environmental aspects of a given situation jointly. They employed three regression algorithms: linear regression, multilayer perceptron, and sequential minimal optimization (SMO). These models were created using synthetic data generated within a defined area of Malaysia and were used to validate three different regression models. The multilayer perceptron produced an impressive correlation coefficient of 0.7169 confirming it was the best predictive model overall. The primary shortcoming of the study was that none of the models have been generalized or validated for predicting actual operational outcomes; they are limited to synthetic datasets.

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Akbarpour et al. [12] introduce a hybrid metaheuristic framework that incorporates Geographic Information Systems (GIS), Simulated Annealing (SA), and Particle Swarm Optimization (PSO) algorithms to minimize transportation costs and maximize recycling revenue in a waste management system. Using 10 industrial case studies, the researchers found that the hybrid GA-PSO yielded the most cost-effective routes. The sensitivity analysis further supported the robustness of the parameters. However, the authors' approach was implemented only in a controlled environment, and its performance and scalability were not fully evaluated in a live waste management system.

Bin et al. [13] describe a variation of the Ant Colony Optimization (ACO) algorithm with non-dominated sorting to solve a split-delivery Vehicle routing problem (VRP) for scheduling waste collection. Modeling included cleaning across multiple services at the same location, and the case study was in Tianjin Wudadao, China, with 32 waste collection points and 4 disposal stations. While variations of ACO reduced vehicle use and total costs relative to traditional ACO, a real-world case study supports further research on waste-collection algorithms, and some improvements are needed to enhance algorithm performance under uncertain rates of waste generation.

Manoharam et al. [14] developed an optimization method for waste collection routes through the Tabu Search and Dijkstra algorithms on the ArcMap/ESRI platform. Although validated, the GIS model applied only to 24 companies in an industrial park in Malaysia and reduced operational costs and transportation distances. However, the study does not compare alternative metaheuristics, indicating a need to improve benchmarking for route optimization.

Mekamcha et al. [15] also developed a hybrid Tabu Search and Simulated Annealing algorithm for optimizing waste collection routes in the City of Tlemcen, Algeria. A real dataset was used to analyze 21 circuits. The Simulated Annealing method produced lower total distances than the Tabu Search method. Still, the lack of implementation and validation in real-life municipal operations leaves a gap in a valid assessment of practicality.

Despite the substantial literature on smart waste management, most current systems are primarily oriented toward optimizing waste collection, routing, and IoT-based monitoring. Genetic Algorithms, Particle Swarm Optimization, and Ant Colony Optimization are examples of metaheuristic techniques used in many studies to enhance collection efficiency. Nevertheless, such strategies primarily operate at the system or network level and fail to achieve real-time waste monitoring or on-site separation. Additionally, some IoT-based solutions rely on sensor data to monitor bin conditions but do not provide intelligent means for autonomous recognition and classification of waste materials. Conversely, machine learning-based vision methods can only be used to classify without incorporating physical collection and segregation robots. Moreover, the majority of the current literature is based on simulated or small-scale settings, with limited real-world implementation and scalability testing.

The other major weakness is the lack of an integrated system with computer vision, sensor fusion, and robotics. Not many studies use deep learning models such as YOLO for real-time detection, and even fewer have integrated them with embedded systems and actuator-based segregation systems.

Hence, the lack of research on developing an entirely autonomous, real-time waste detection and separation system that integrates deep learning-based object localization (YOLOv8), sensor-based classification, and robotic automation is evident. The suggested WasteXpert system fills this gap by offering a cost-effective, scalable, and intelligent system that can operate in real-world settings with minimal human intervention.

METHODOLOGY

This paragraph presents an approach to designing and building a functional prototype of a WasteXpert System that uses a smart, autonomous robot for real-time identification and separation of waste.

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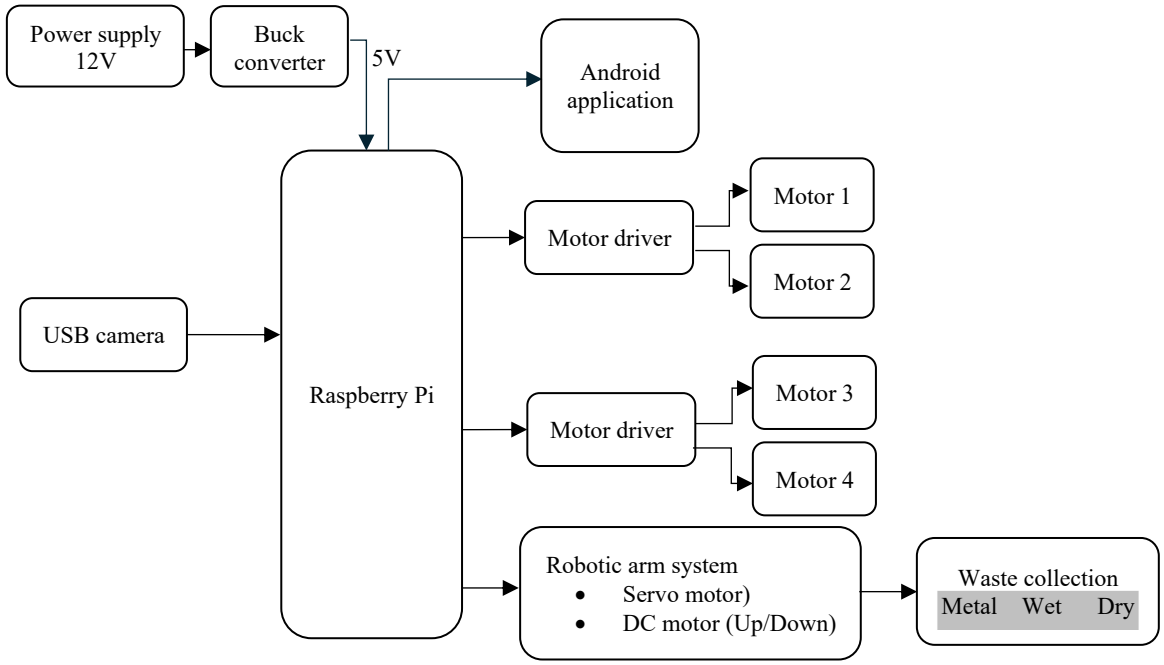


Figure 1. System block diagram of proposed system.

WasteXpert System is an integrated system that combines waste management with embedded computers (a Raspberry Pi) & computerized visioning using YOLOv8 to create an effective means of sorting waste. There are numerous processes involved in completing a workflow for the WasteXpert System (Figure 1), including taking pictures of waste, identifying it, deciding what to do with it, navigating to a designated area, manipulating a robotic arm, and sorting waste using multiple sensors.

Power Management and System Initialization

A 12V power source will be used to operate low-voltage devices via a buck converter that converts it into a stable 5V power source. This means that the Raspberry Pi, sensors, motor drivers, and communication modules can now work together properly without compromising performance or safety when powered by a regulated power source. The hardware interfaces (USB cameras, GPIO pins, motor drivers, and wireless communication devices) will all be configured during system calibration so that their coordinated reading, processing, and rendering can occur seamlessly and efficiently.

Image Acquisition and Waste Detection

The system uses a USB camera to provide real-time visual images of the area. The YOLOv8 model runs on a Raspberry Pi to process the images. The algorithm is an object detector that detects garbage and generates bounding boxes around it. It also provides the spatial positions of the sensed objects relative to the robot. It is enabled by a real-time detection system, which enables the system to accurately identify and monitor waste materials in dynamic environments, where autonomous navigation is based.

Dataset and Model Training Details

The WasteXpert system uses the publicly available dataset of Recyclable and Household Waste Classification on Kaggle, which comprises approximately 15,000 images of 30 types of waste, including plastic, paper, metal, glass, and organic waste. The data are real-world and clean images, making the model more generalizable. It was further split into training (70%), validation (20%), and test (10%) sets.

Pictures were used to label objects with tools such as LabelImg/Roboflow, and to convert them to YOLO format. Training the YOLOv8 model with transfer learning using existing COCO weights on a GPU, along with data augmentation techniques such as rotation, flipping, and brightness adjustment,

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was used to enhance robustness. The most significant parameters were 50 100 epochs, 16 32 batch size, and Adam optimizer with the learning rate of 0.001. The model was then trained and run on a Raspberry Pi to identify waste in real time with high accuracy in various settings.

Decision-Making and Control Logic

The Raspberry Pi is the decision-making node and receives inputs from the vision system and the user interface. Depending on these inputs, the system decides whether to work in manual or automatic mode. The robot is in automatic mode and constantly searching for waste. As soon as the waste is identified, the robot calculates the direction of movement and begins moving in that direction. If there is no waste, the robot moves forward and scans again. In manual mode, the user can operate the robot via an Android application that allows them to move the robot in a direction and operate the arm. This is a dual-mode operation that is both flexible and reliable across various operating conditions.

Locomotion and Navigation

The robot is based on a four-wheel drive (4WD) locomotion system, which operates using DC motors. Motor drivers handle control of these motors, which receive control signals from the Raspberry Pi. The motor drivers control the speed and direction of every motor, which gives the chance to move forward, backward, left, and right. A differential drive system enables the robot to travel accurately towards a detected waste source. As such, it represents a form of mobility that can successfully enable waste collection in real-world situations, thanks to its stability and good maneuverability across various terrain types.

Robotic Arm Operation

The implementation of an arm will allow a robotic device to collect the target waste once it reaches a predetermined location. The arm will use a servo motor to control the actuator that grabs the waste, and a DC motor to control the actuator that moves the robotic system up and down. The combination of both actuators will enable the system to both pick up and place the target waste properly. The system will allow for the safe containment and elevation of the waste after human interaction.

Waste Classification Mechanism

A combined classification process using both sensor-detectable methods and visual classification via YOLOv8 will improve accuracy and reliability. Metallic waste will be detected using an electromagnetic metal detector. Electrical conductivity detection with a moisture conductivity sensor (a copper plate) can identify wet and/or organic waste types. These types of sensors can greatly increase the speed and accuracy of pre-classifying the locations where visual cues may not be available. In addition, the system uses YOLOv8-based waste sorting, where the received image of the collected object is processed to be classified into specific categories, such as plastic, paper, glass, and organic waste. This enables fine-grained object-level classification, followed by physical segregation. The YOLOv8 can run in real time on the Raspberry Pi, producing class labels that can be used to control the segregation process. The sensor fusion approach is utilized to integrate sensor and YOLOv8 model results. For example, when YOLOv8 identifies a plastic object and a moisture sensor records high conductivity, the system will reclassify the object as wet waste. According to this joint decision, the waste is directed to the correct bin with the robot's servo-controlled mechanism. This will guarantee correct, real-time, and smart waste sorting, while also providing room to expand the system to other waste types in subsequent applications.

Waste Segregation Output

As a result of the classification of waste collected by the system, it is sorted into three categories – metal, wet, and dry - which ensures that the waste is sorted correctly. Automated systems have reduced the time and effort required to sort waste, reduced the risk of incorrect handling, and therefore supported the development of a more environmentally sustainable world.

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Communication and User Interface

We are offering users a user interface (UI) via an Android application that enables them to interact with and control the robot. The user can manually control their robotic unit or switch to one of the many available modes. Moreover, users can receive notifications and check the robot's status from anywhere using cloud-based services such as Telegram. The connectivity provided by this method enables the system to be applied in a "smart" environment where remote management/monitoring and control capabilities are paramount.

This methodology has three primary components: establishing a system/control structure and managing power (first); obtaining images in real time (second); and garbage identification using YOLOv8 (third). Upon determining the detection results, the robot navigates toward the target location, using a motor-driven locomotion system. After that, the robotic arm retrieves the garbage, which is then classified using sensor-based techniques. The classification process for waste involves sorting it into specific categories and following the appropriate disposal practices. An efficiently coordinated effort among all operational components of this process allows for effective, independent, and intelligent waste management solutions.

EVALUATION AND RESULTS

To evaluate the WasteXpert System's performance in terms of waste detection accuracy, navigation, and classification, a series of real-time experiments was conducted in semi-structured environments. An example of the WasteXpert Robot is illustrated in Figure 2.

Figure 2 illustrates the physical prototype of the Waste Xpert robot. The object detection module (using YOLOv8) achieved high-quality results in detecting waste objects under different conditions. The model could identify plastic bottles, paper, and metals, common waste materials, with high accuracy (Figure 3). Under good lighting conditions, the average detection rate was over 90 percent during testing.

Table 1 provides the performance analysis of the robotic arm, which demonstrates its effectiveness in working with various waste items in the conditions of real time operating conditions.

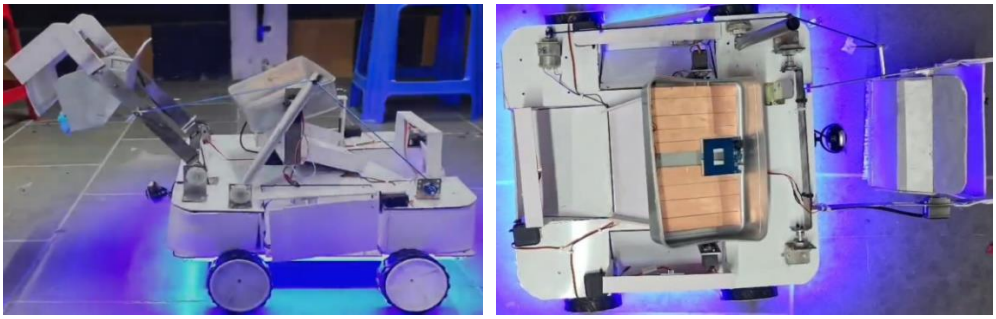


Figure 2. Waste Xpert robot model.

Table 1. Robotic arm and collection efficiency performance,

Parameter	Observation / Result
Gripper Type	Servo Motor-Based Gripper
Arm Movement	DC Motor (Up/Down)
Average Pick Success Rate	85% – 90%
Handling of Regular Objects	High Efficiency
Handling of Irregular Objects	Moderate Efficiency
Response Time per Pick	~2–4 seconds
Failure Cases	Small size, improper alignment
System Stability	Stable under continuous use

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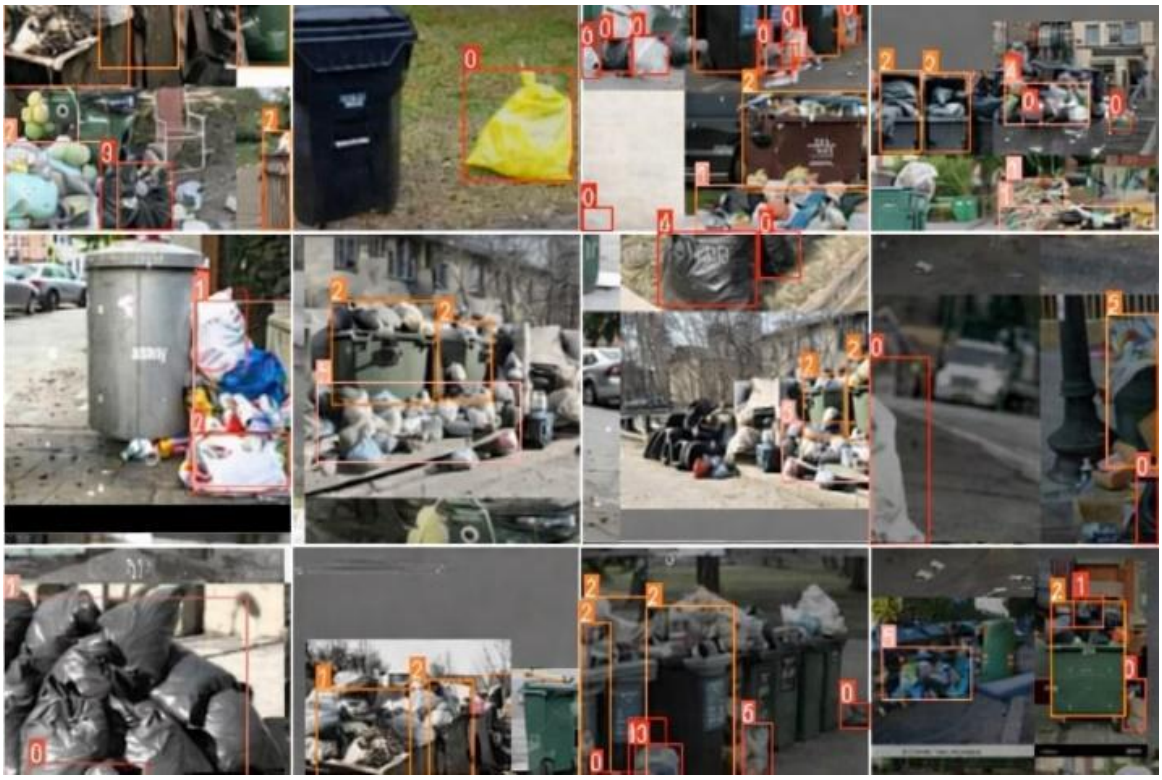


Figure 3. Validation results of waste detection using YOLOv8 Model

Table 2. Manual versus automatic mode comparison.

Parameter	Manual mode	Automatic mode
Control Type	User-Controlled (Android App)	Fully Autonomous
Response Time	Very Fast	Fast (Processing Dependent)
Accuracy	High (Human Precision)	Moderate to High
Human Intervention	Required	Not Required
Navigation Efficiency	Depends on User Skill	Consistent
Adaptability	High	Moderate
Use Case	Testing / Complex Scenarios	Continuous Operation
System Dependency	User Input	AI + Sensors

Table 2 compares the performance between manual and automatic modes and shows the trade-offs between control precision and autonomous efficiency.

Compared to traditional waste management methods, the proposed system offers significantly greater safety, accuracy, and automation. The combination of artificial intelligence (AI) detection and sensor-based classification provides a highly efficient means for real-time segregation of waste materials by type. By requiring less human intervention, reducing human exposure to hazardous waste, and enhancing overall system efficiency, the proposed system will significantly improve the current waste management process. Additionally, since the proposed solution requires relatively inexpensive components, it can be deployed in a smart-city environment at an acceptable cost. The trials' findings show that the WasteXpert system has achieved its goal of providing an autonomous means to detect, collect, and separate waste materials. Although some areas of the currently installed unit need improvement, it demonstrates great potential for future usefulness and further development.

The WasteXpert system evaluation in real-life settings comprised both laboratory-controlled and open-campus-based tests. Semi-structured tests were used to evaluate recognition, accuracy, navigation,

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and refuse collection (plastic, paper, metal) under different lighting conditions (i.e., daytime vs. nighttime and/or cloudy skies). WasteXpert achieved >90% accuracy in detecting objects under the most desirable environmental conditions and demonstrated significant reliability in moving items; however, some operations were affected by poor lighting and/or small/odd-shaped refuse.

WasteXpert and its cloud software work together as a system. Their modular design allows the WasteXpert platform to adapt to future developments in sensor technologies, advanced robotic mechanisms, and improved navigation techniques. Low-cost parts from Raspberry Pi, combined with their modularity, create an economical solution for deploying a city-wide system. Multi-robot systems can also operate together in the urban environment. Using IoT platforms and cloud-based monitoring enables the WasteXpert platform to access real-time information about waste management processes, allowing it to run remotely. As a result of the aforementioned characteristics, WasteXpert is an excellent mobile, adaptable option for various types of waste management across municipalities.

WasteXpert will primarily operate from a rechargeable 12-volt battery, which will be stepped down to 5 volts using a buck converter for the Raspberry Pi, sensors, and control units. High-powered components (e.g., DC motors driving the robotic arm) can be powered directly from the 12-volt power supply, operating more efficiently than when driven through the Raspberry Pi's cycle. The Raspberry Pi will consume around 5-7 watts during operation (live), and motors and actuators will use 10-15 watts during operation, including when they are lifting and placing items. In sleep mode, the sensors will consume less than 1 watt of power. The entire power consumed by the system during operation is roughly 1500 watts, which includes power to the motors and actuators, enabling efficient operation of the total system. The battery should allow the WasteXpert to operate for about 1.5-2.5 hours, which limits the WasteXpert to short-duration missions autonomously. Future opportunities to increase energy efficiency include adding solar power and advanced energy management features.

WasteXpert's system has provided accurate results for many years; however, many barriers exist to the operation of the WasteXpert system due to limitations of detection capabilities, due to the environment, such as very low light levels or background clutter, which may negatively impact YOLOv8, and cause items that are too small or not 100% visible to be missed. In addition, specific scenarios can affect the sensor-based approach's ability to accurately classify items within these categories, such as slightly wet paper that may be misclassified due to a resistance differential, and thin metal objects that a metal detector may not detect. Finally, the classification system currently contains only three categories (metal, wet, and dry) and lacks sufficient complexity to capture the variety of sorting scenarios.

In addition, the robotic arm demonstrated characteristics of having a mechanical limitation (specifically with respect to object shape/size - e.g., a small/emaciated) when performing pick-and-place functions; therefore, it could be considered a cause of a certain identity, just as an example. It should also be noted that a robotic system can suffer from decreased efficiency when navigating in a dynamically changing environment (e.g., one having many obstacles) and is unable to implement sophisticated obstacle avoidance and/or path planning algorithms as are commonly employed in most modern-day autonomous vehicle technologies (e.g., laser rangefinder, GPS, etc.). Consequently, these limitations demonstrate a need for operational enhancements that include training datasets for all possible operating conditions, advancing multi-classification systems, optimizing sensor calibration, and introducing intelligent pathfinding to robotic systems. Addressing these issues will go a long way toward increasing the strength, accuracy, and overall usability of automated systems.

FUTURE SCOPE

The WasteXpert system will improve waste identification and sorting; offer future testing and development opportunities; and improve upon its current algorithm of machine learning as it learns from a larger and more diverse sample of training data (e.g., there will be better identification of different types of waste under different lighting conditions and in different locations). Improved

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navigation methods (including obstacle detection and avoidance algorithms and path-planning) should enhance WasteXpert's autonomous mobility, enabling it to navigate changing manufacturing environments more quickly. By adding depth perception (e.g., LIDAR capabilities), the WasteXpert will more accurately identify waste and other objects, facilitating waste identification during robotic transport. The Internet of Things (IoT) technology, when integrated with the WasteXpert framework, will enable real-time monitoring, data analysis, and Cloud-based remote control of the WasteXpert system. The design of energy-efficient solutions (e.g., solar) has the potential to improve sustainability and operational efficiencies through the WasteXpert system, as well as to identify recyclable vs. non-recyclable waste using advanced machine learning. Enhancements to robotic arm capabilities (e.g., increasing the number of operating degrees of freedom) will provide greater flexibility in handling and easier use. Collectively, these developments will facilitate the development of completely autonomous, scalable, and intelligent waste management solutions that can be deployed in real-world settings.

CONCLUSION

WasteXpert is a new waste detection and separation system that combines an embedded computer, sensor-based classification, and computer vision. It consists of a Raspberry Pi with the YOLOv8 model, which is capable of real-time waste detection. It is operated by a four-wheel-drive robot with a robotic arm performing pick-and-place operations. The WasteXpert system has proven to be an effective demonstration of the integration of AI and robotics for smart waste management. The hybrid metal/moisture classification system is more accurate for classifying waste as metal/moist or dry. The experimental results indicate that WasteXpert provides real-time, trustworthy detection, efficient navigation, and efficient waste disposal. The system has been designed to be very flexible and user-friendly, with both manual and automatic modes accessible via an Android interface. The recycling system has been implemented at low costs due to the use of low-cost hardware, which makes WasteXpert economically viable and applicable in smart city environments. Overall, WasteXpert can help mitigate many of the issues commonly encountered in traditional waste management by reducing human interaction, increasing safety, and improving system efficiency.

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