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Smart Street Level Autonomous Dustbin for Door-to-Door Waste Collection

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Abstract: The rapid expansion of urban populations has increased pressure on conventional waste-collection practices, which largely depend on manual operations and lack real-time monitoring capabilities. To address these limitations, this paper presents the Smart Street-Level Autonomous Dustbin (SSAD), a mobile robotic system designed for door-to-door waste collection and on-device segregation. The SSAD integrates an Internet of Things (IoT) framework with embedded sensing modules, GPS-assisted navigation, and lightweight machine-learning-based waste classification. Ultrasonic and infrared sensors support obstacle detection and bin identification, while a convolutional neural network deployed on an onboard processor categorizes waste into biodegradable and non-biodegradable types. The system transmits operational data—including bin status, location, and segregation logs—to a cloud-based dashboard for real-time monitoring. Experimental evaluation demonstrates an average classification accuracy of 85–90% and a 25% improvement in route efficiency compared to manual collection. The proposed system illustrates the potential of autonomous mobile platforms for enhancing waste-management efficiency and enabling scalable smart-city solutions.
Keywords: IoT, Smart Waste Management, Autonomous Dustbin, Machine Learning, High Performance Computing.

I. INTODUCTION

The increasing adoption of Smart City initiatives has highlighted the need for more efficient, data-driven waste-management solutions capable of addressing the growing strain on municipal infrastructures. Conventional waste-collection systems largely depend on static bins and manual pickup processes, which often result in delayed collection, inefficient routing, and limited visibility into system status. Moreover, the absence of source-level waste segregation reduces the effectiveness of recycling programs and contributes to higher operational costs for urban administrations.

Recent developments in the Internet of Things (IoT), embedded systems, autonomous navigation, and lightweight machine-learning models offer opportunities to modernize waste-collection mechanisms. However, most existing approaches provide only partial improvements—such as fill-level monitoring or route optimization—and still rely heavily on human intervention.

To address these limitations, this work introduces the Smart Street-Level Autonomous Dustbin (SSAD), a mobile robotic platform designed to perform door-to-door waste collection, real-time waste segregation, and cloud-based status reporting. SSAD integrates a combination of sensors, embedded computing units, and wireless communication modules to enable autonomous navigation through residential environments. An onboard machine-learning model classifies collected waste into biodegradable and non-biodegradable categories, eliminating the need for manual sorting at later processing stages.

The primary objectives of the SSAD system are:

1) Enhanced Operational Efficiency**:** Reduce collection time and fuel consumption through optimized autonomous navigation.
2) Real-Time Waste Segregation**:** Perform on-device classification of waste at the point of collection using machine-learning techniques.
3) Reduced Manual Dependency: Minimize human involvement in routine collection tasks, improving worker safety and reducing labour costs.
4) Cloud-Based Monitoring**:** Provide real-time analytics on bin status, location, battery level, and segregation logs through an IoT-enabled dashboard.

By transitioning from static smart bins to a mobile, self-operating robotic collector, SSAD demonstrates a practical pathway for scalable automation in urban waste-management systems.

II. LITERATURE REVIEW

Research on smart waste-management systems has progressed across several technological dimensions, including IoT-based monitoring, route optimization, robotic assistance, and machine-learning-driven waste segregation. The following subsections summarize key contributions and highlight gaps addressed in this work.

A. IoT-Based Waste Monitoring

Early studies in smart waste management focused on integrating sensors such as ultrasonic or infrared modules into fixed waste bins to measure fill levels and transmit updates to a central server. These systems reduced the frequency of manual inspections and provided basic situational awareness. However, collection processes continued to rely on human-operated vehicles, limiting the overall improvement in efficiency. Additionally, most IoT-enabled bins lacked integrated waste segregation mechanisms, thereby offering little enhancement to recycling workflows.

B. Route Optimization Using GPS and GIS

Subsequent research emphasized improving municipal waste-collection routes through the use of Global Positioning System (GPS) and Geographic Information System (GIS) tools. Dynamic route-planning algorithms and real-time mapping helped decrease travel distances and optimized fuel usage for collection vehicles. Despite these advancements, such methods primarily targeted fleet-level optimization and did not address the household-level pickup challenges that contribute to inefficiencies in dense urban areas.

C. Robotic Waste-Collection Platforms

Several researchers have proposed robotic systems to automate aspects of waste transport and material handling. While these prototypes demonstrated potential benefits in controlled or indoor environments, many lacked robust navigation, perception, and mechanical capabilities required for deployment in outdoor residential settings. Challenges such as uneven terrain, unpredictable obstacles, and varying bin placement restricted the practical implementation of these robotic solutions.

D. Machine-Learning-Based Waste Classification

Machine-learning and computer-vision approaches have been widely adopted in industrial waste-processing facilities for automated material sorting. High-performance models are typically deployed on stationary equipment operating under consistent lighting and controlled conditions. Although these techniques achieve strong classification accuracy in industrial contexts, their computational demands and environmental constraints make them unsuitable for lightweight, mobile, door-to-door classification systems.

E. Research Gap and Contribution of SSAD

A review of existing literature indicates several gaps: limited mobility of smart bins, continued reliance on manual waste retrieval, insufficient adaptability to outdoor environments, and the absence of real-time, on-device waste classification. The SSAD system addresses these shortcomings by integrating autonomous navigation, IoT-enabled monitoring, and embedded machine-learning capabilities into a single mobile platform. Unlike conventional smart bins or static classification systems, SSAD offers an end-to-end automated solution tailored for real residential deployment.

III. METHODOLOGY

The SSAD operates as an integrated Cyber-Physical System consisting of sensing hardware, embedded computing modules, cloud communication, and machine-learning components.

A. System Architecture (Rewritten)

The architecture is organised into three functional layers:

1) Perception and Action Layer**:** Incorporates sensors, actuators, and motion-control mechanisms that enable environmental awareness and physical interaction.
2) Embedded Processing and Communication Layer**:** Utilises a microcontroller for low-level control tasks and a Raspberry Pi for ML inference, data handling, and wireless connectivity.
3) Cloud and Application Layer**:** Oversees route optimisation, data analytics, and visualisation through HPC-supported servers and dashboards.

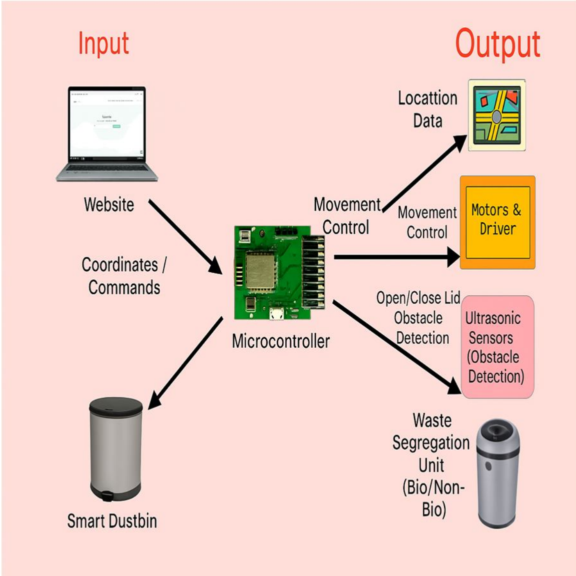


Fig. 1: System Architecture

B. Hardware Implementation (Updated Version)

The hardware configuration of the SSAD integrates multiple sensing, processing, and actuation components to support autonomous operation. The system is powered by two primary computing units: a Raspberry Pi, responsible for executing machine-learning models and handling GPS data, and an Arduino microcontroller, which governs motor functions and sensor inputs.

Motion control is achieved using DC motors driven through an L298N module, while servo motors manage lid movements and internal waste-diversion mechanisms. Environmental perception is supported by a set of sensors, including a GPS module (NEO-6M) for real-time positioning, ultrasonic sensors for detecting obstacles, IR sensors for identifying household bins, and a compact camera for capturing waste images.

Data transmission is facilitated through Wi-Fi, using either an ESP8266 module or the Raspberry Pi's onboard interface, allowing the system to communicate with cloud platforms such as Firebase or ThingSpeak. A rechargeable lithium-ion battery pack powers the full setup, ensuring sufficient operating time for routine household-level waste-collection tasks.

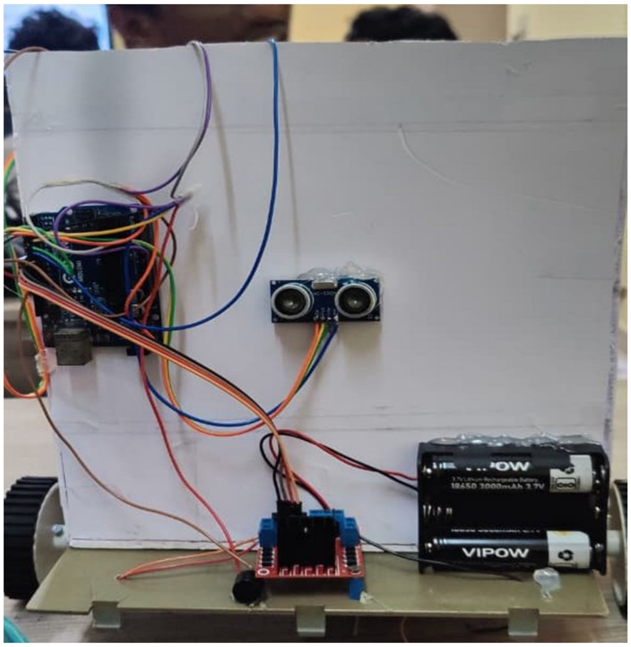
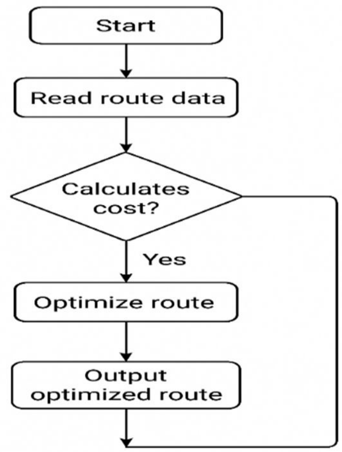


Fig. 2: Hardware Implementation

C. Autonomous Navigation and Communication (Rewritten)

Navigation proceeds through several coordinated stages. First, the system loads predefined GPS waypoints corresponding to individual households. A central server uses a TSP-inspired optimisation algorithm to compute the most efficient route. During movement, real-time GPS feedback assists the robot in following the planned path, supported by PID-based motor control. Ultrasonic sensors continuously check for obstacles and trigger avoidance behaviour when required. IR sensors detect household bins, prompting the system to initiate the waste-collection sequence automatically.



(Fig. 3: Route Optimization Flow)

D. ML-Based Waste Segregation (Rewritten)

A compact CNN model is deployed on the Raspberry Pi to classify captured waste images into biodegradable or non-biodegradable categories. The model is trained on a curated dataset containing representative samples of both classes. Based on the predicted class, servo-controlled mechanisms route the waste to the corresponding compartment. Classification outcomes and confidence levels are simultaneously uploaded to the cloud.

IV. RESULTS AND DISCUSSION

A. Waste Segregation Accuracy

Testing on 200 mixed waste samples achieved an 85% accuracy rate. Most errors were due to poor lighting or unclear visuals, which can be improved using better image preprocessing or additional sensors.

B. Route Efficiency

Using an optimized route reduced travel distance by about 25% compared to manual paths, showing a clear improvement in speed and fuel savings.

C. IoT Dashboard and Cost Analysis

The Wi-Fi module achieved a 98% data transmission success rate, providing reliable real-time updates on:

1) Bin status
2) Battery level
3) Location
4) Segregation logs

While initial setup costs are higher than standard bins, savings from reduced labor, fuel efficiency, and better recyclables lead to a quick return on investment (3–5 years).

V. CONCLUSION AND FUTURE WORK

The Smart Street-Level Autonomous Dustbin demonstrates that waste collection can be significantly enhanced through a combination of IoT technologies, autonomous navigation, and lightweight machine-learning-based segregation. The system reduces dependency on manual labour, increases operational efficiency, and provides continuous cloud-based monitoring.

Future improvements include integrating solar charging, adopting reinforcement learning for adaptive navigation, scaling deployment to larger municipal networks, and extending ML capabilities to identify more diverse waste categories. The SSAD framework offers a solid foundation for developing cleaner and more sustainable smart-city waste-management solutions.

Future work will focus on:

1) Solar Integration: Adding solar panels for self-charging.
2) AI Navigation: Implementing reinforcement learning for adaptive route planning.
3) Scalability: Managing large city-wide deployments using HPC-powered cloud systems.
4) Advanced Segregation: Expanding ML capabilities to detect more waste types like e-waste or plastics.

The SSAD concept represents a significant move toward a cleaner, smarter, and more sustainable urban future.

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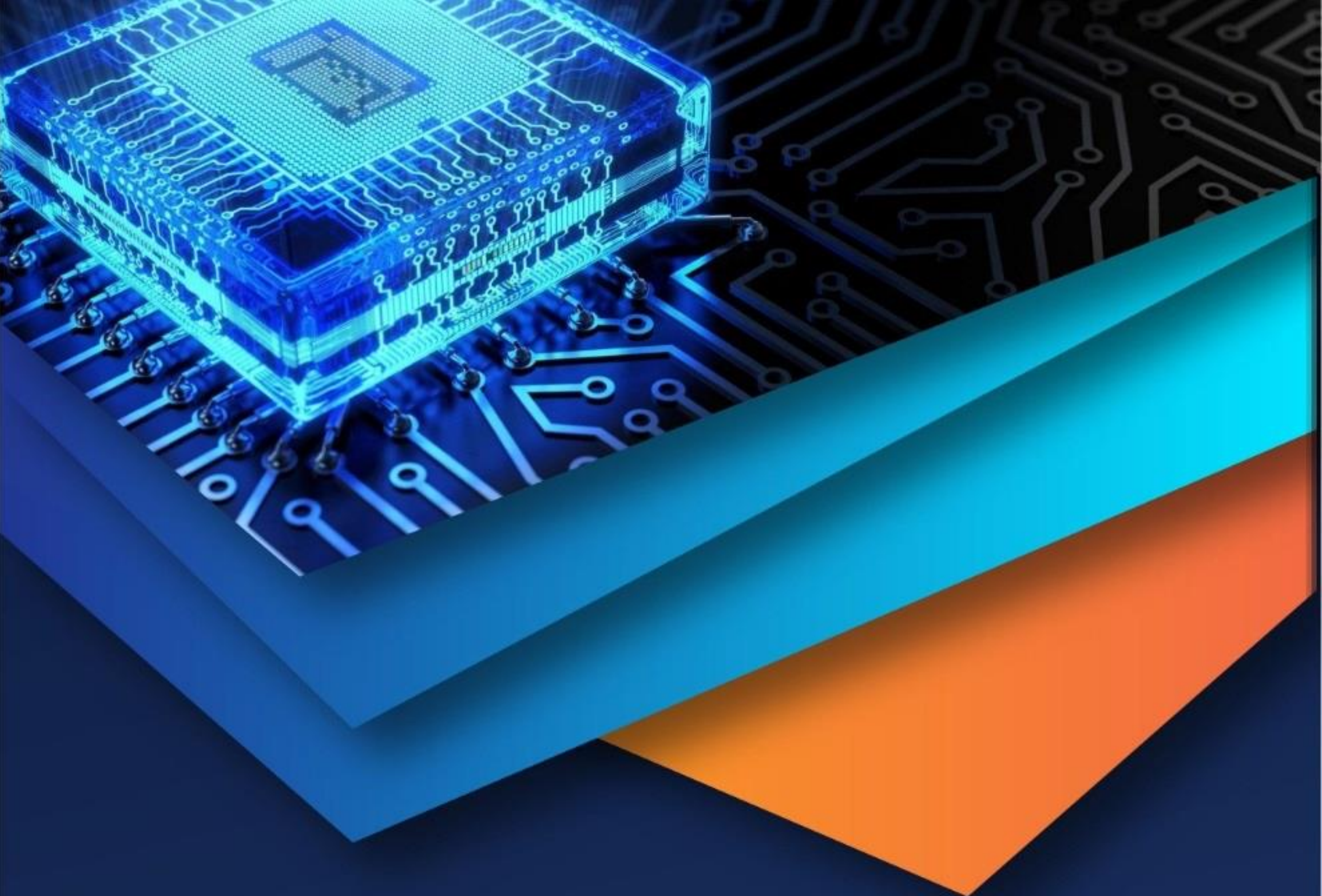

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