SmartBin: An IoT-Enabled Object-Oriented Waste Management System for Real-Time Monitoring and Pickup Scheduling

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***Abstract*—This project research paper proposes an improved design and conceptual implementation of SmartBin, an IoT enabled waste management system. The system is developed with Object-Oriented Programming principles and is developed using the first four steps of the waterfall design method. The proposed system attempts to improve efficiency, scalability, and cost-efficiency, while also ensuring that the inefficiencies of traditional waste collection processes are being addressed. The proposed system also attempts to improve the current prototypes of SmartBin with the introduction of real-time bin fulness monitoring and intelligent pickup scheduling with optimized route planning. To this purpose, the system utilizes ultrasonic sensors and microcontrollers to collect bin status data and uploads the collected information into the IoT cloud database where it can be accessed. The system comprises of key entities such as sensors, SmartBins, and a comprehensive IoT system, enabling completion of the priorities and providing a modular and scalable architecture. The system anticipates results of improved responsiveness and efficiency regarding waste pickups, which would greatly enhance urban waste management systems.**

Keywords—Sensors, IoT (Internet of Things), SmartBins, Database, Waste management system.

I. INTRODUCTION

A.Background

With the development of cities around the world, urbanization and modernization, the trend of concentrating people in cities is getting stronger. The amount of garbage produced by city residents' daily lives is increasing dramatically, municipal governments are increasingly at a loss when it comes to handling waste in cities. The old method of picking up garbage - it's not dead yet - does not provide for dynamic planning, problems such as leaving full garbage cans uncleaned arise; which means unnecessary fuel and time consumption.

B.Motivation

To solve these problems, this paper puts forward the idea of introducing Internet of Things technology into urban construction. Based on the integration of sensing network and cloud computing, an intelligent data-driven waste sorting system -- SmartBin is developed for real-time monitoring and dynamic dispatching with flexible deployment.

C.Main Contribution:

Faced with this situation, this paper designs an Internet of Things based city waste disposal system called SmartBin. This application adopts object-oriented designing methods to enhance the independence and flexibility of function units in the program. Through using ultrasonic sensors that are placed in smart trash cans, it can capture the real-time level of garbage from each trash can, upload the captured data to the cloud platform, and calculate the best garbage collection route through algorithm calculation in real time.

II. RELATED WORK

In previous studies, such as the research by Pardini K et al. (2019)[1], comprehensive arguments have been presented regarding the surge in global urban waste caused by urbanization and IoT-based urban waste management solutions. These studies thoroughly examined their feasibility, advantages, and limitations.

Building upon this foundation, researchers like Bano A et al. (2020) [2]explored various IoT-enabled waste management approaches. For instance, Bano A et al. (2020) designed a smart trash bin system incorporating fuzzy logic decision-making and the 3R (Reduce, Reuse, Recycle) principles. This mechanism achieved real-time response to bin overflow and effectively reduced empty-load rates of collection vehicles, though it still faced challenges in route optimization and collection efficiency. Other attempts included RFID-based waste tracking systems, but their failure to integrate real-time data with cloud analytics resulted in suboptimal efficiency.

Furthermore, a study which analyzes 173 primary studies to examine smart waste management (SWM) systems, covering sensor applications, stakeholder roles, data flows, and research gaps, with implementation recommendations for city- and SGB-level solutions (Sosunova and J. Porras, 2022)[3].

Compared to previous solutions, SmartBin adopts object-oriented principles to encapsulate system components and behaviours, establishing a lightweight yet highly scalable waste management framework. What distinguishes SmartBin is its enhanced modularity and reusability, enabling deeper integration with municipal infrastructure and improved operational convenience. This foundation positions SmartBin as a practical solution for cities seeking scalable waste management systems that balance adaptability with urban service requirements.

In 2020, a research paper published in the International Journal of Engineering Research and Technology (IJERT) proposed a variation of the smart bin system containing components that differ from the original such as shredders, weight sensors, and load sensors. Their system focuses on low cost, functionality, and a simple module. This proposed system utilizes ultrasonic sensors, GSM models, and microcontrollers (Arduino boards). They utilized a web-based interface to allow the users to access the data from the ultrasonic sensor GSM module and the central monitoring unit. They used Arduino boards to make the system low-cost but functional and implementable (T. Kadus, et al, 2020)[4].

III. PROBLEM STATEMENT

Static waste collection schedules fail to consider bin usage trends and unexpected changes, either causing large pileups of waste or underutilizing collection efforts. This would lead to environmental problems, public health risks and increased waste collection system costs.

IV. SYSTEM REQUIREMENTS AND DESIGN GOALS

SmartBin has been designed by taking into consideration not only functional but also non-functional requirements to fulfill the complex requirement of urban waste management i.e. practical, scalable and resourceful.

A. Functional Requirements

Each unit comes with an ultrasonic sensor that constantly monitors the fill level. Data acquired from the ultrasonic sensor will be sent to the cloud processing center using the communication interface on board. With each SmartBin's location and fill level information, the SmartBins automatically plan their routes to reduce cost and time while increasing efficiency.

City staff or users can simply use a Web browser to interact with our system and check the status of each bin or set new collection orders. Every piece of data from each device will be stored in the same central cloud database for quick device switching and keeping track of history data.

B. Non-Functional Requirements

SmartBin uses a modular structure, so every sub-system can be deployed, updated and serviced separately from others without any disturbances. Therefore, it is easy to modify SmartBin based on different requirements. In terms of sensor nodes, we specially designed them such that they could consume almost no power in daily applications. Thus, the life span would be much longer when there were more deployments.

With regards to various usage environments, SmartBin was designed to scale up easily. Additional sensor nodes/modules could be added as needed. Since sensors must work under harsh conditions when deployed outdoors, some error-proofing has been programmed into SmartBin so that the system can still run smoothly even if all networks experience failures temporarily or there are problems with the whole system's sensors and some strange things happen.

In addition, since SmartBins will probably be used in many places in cities, for example at bus stops or train stations, we need to make sure that there won't be too many dust and trash. Otherwise, it might block the way and become inconvenient for people. We did take dust proofing into consideration when designing SmartBins. Therefore, we chose materials that do not attract too much dust. However, regarding trash, we did not consider that part. If you really want us to add it, we could.

C.Overall Design Goal

In summary, SmartBin aims to be a lightweight easy-to-adopt and reliable smart waste management platform. Hence, while designing the system, we would like to separate different modules following object-oriented programming such that the system is flexible for future upgrades while being simple, very dependable and without sacrificing efficiency by implementing codes repetitively. Objects' easy reusability in the future is also maintained.

V. SYSTEM ARCHITECTURE

SmartBin adopts the general layered architecture model used by most IoT systems. Its constituent parts, namely hardware sensing, cloud processing, user interaction, and data transfer, are broken down into interacting layers of functionality rather than a single entity.

The entire software stack can be viewed as consisting of four layers: the sensing layer, the communications layer, the cloud platform layer, and the management layer. Because of this design, it is easier to add more functionalities while keeping each layer cohesive.

A.Sensing Layer:Each SmartBin includes an ultrasonic fill-level detection sensor. Data samples are taken periodically using low-power ESP32 microcontrollers, which communicate with their counterparts in upper layers by sending out bin statuses.

Communication Layer:The communication protocol implemented over the wireless link should support reliable message transmission at minimum latency. We chose MQTT (Message Queuing Telemetry Transport), a lightweight messaging transport application protocol commonly used for building Internet of Things applications that deliver fast messages without filling up the narrow available bandwidth (Wi-Fi/LoRa).

Cloud platform layer:After receiving it, the data is preprocessed and then input to the route optimization algorithm that generates real-time waste collection routes based on the latest bin data dynamically.

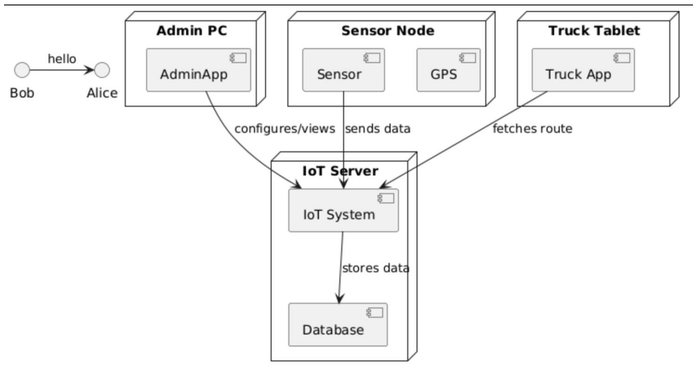
Management Layer:The web-based control panel used by the municipal operator to check the status of the bins, browse real-time route plans, and obtain anomaly alerts in order to schedule and maintain efficiently.

A.Advantages of Layered Design

Flexibility & Maintenance: Decoupling modules ensures that failures in one module do not affect the entire system.

Scalability: Modules can be added or removed as needed to suit different city environments or deployment scales.

Feather's future extension: Separation of collecting and processing allows for the future integration of big data or machine learning.



deployment diagram

B.Object-Oriented Design Approach

SmartBin's software uses the object-oriented designing technology. According to the encapsulation, inheriting and modular design ideas, the whole software system is easy to be extended; it can be reused easily and modified conveniently. Each function module was abstracted as a class with its particular attributes and methods' interfaces. Therefore, the whole structure is clear and flexible.

C.Core Class Definitions

Bin Class: Describes each physical trash bin (ID, location, current status), and whether it needs to be serviced and real-time status update methods.

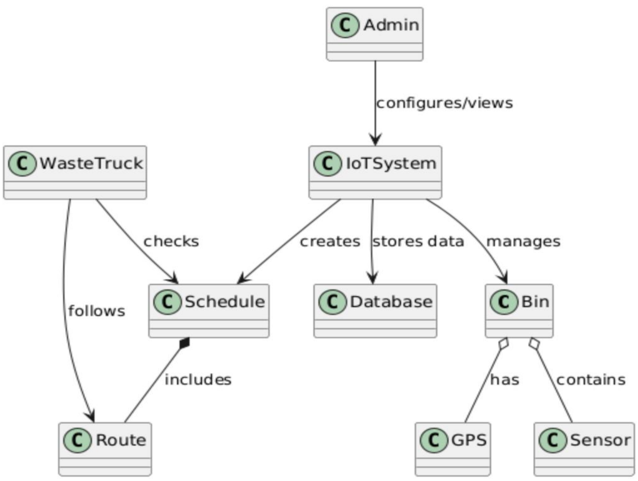
Sensor Class: Handles data collection, transmission, and anomaly detection from sensor hardware.

RoutePlanner Class: Receives the status data of all bins and generates optimized collection routes using shortest-path algorithms.

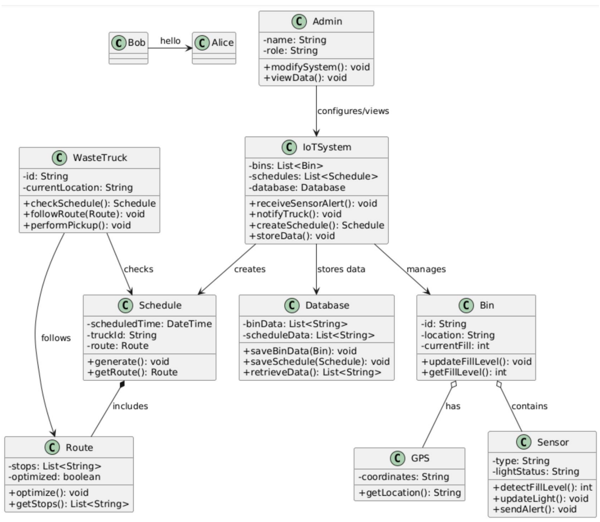
DatabaseHandler Class: Manages read/write interactions with the cloud database, including data synchronization, caching, and exception handling.

Specific emphasis is placed on SmartBin's software architecture to decrease dependencies and clearly distinguish class responsibilities to achieve low coupling and high independence between functions.

Design can also inherit subclasses from bin and sensor classes based on different device types or deployment needs. This object-oriented design will be very convenient for upgrading and replacing hardware in the future, which greatly simplifies the upgrade process.

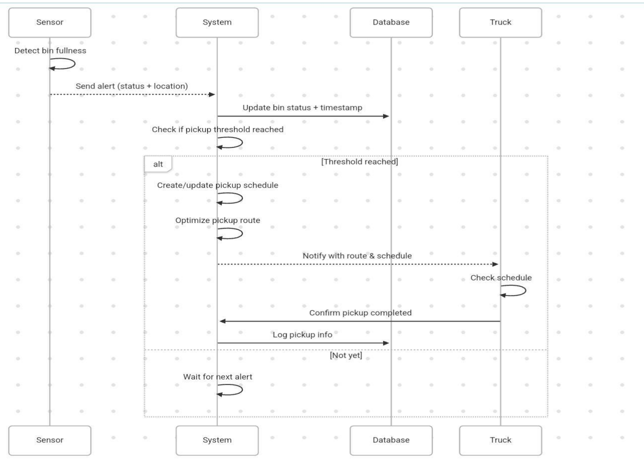


class diagram analysis level

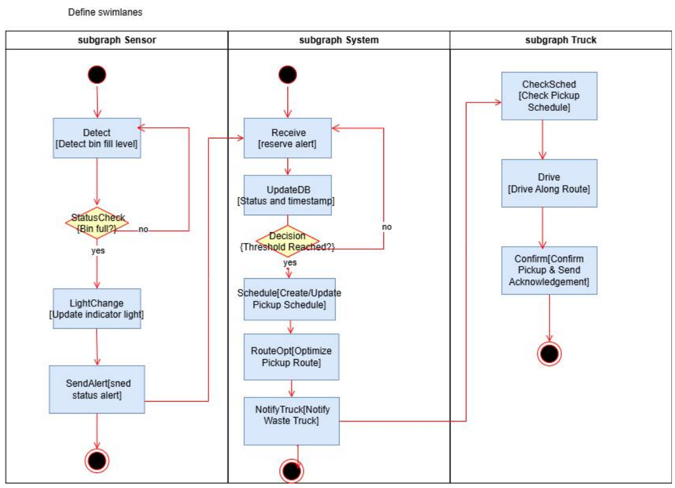


class diagram design level

Sequence_diagram: The sequence diagram describes the interaction among the sensor, system, database, and collection truck in the smart waste management process. The sensor detects the fill level of the bin and sends an alert containing the status and location to the system. The system updates the bin status and timestamp in the database, then checks whether the pickup threshold has been reached. If the threshold is met, the system creates or updates the pickup schedule, optimizes the collection route, and notifies the truck with the assigned route and schedule. The truck reviews the schedule, performs the pickup, and confirms completion back to the system. The system then logs the pickup information in the database. If the threshold is not reached, the system waits for the next alert to repeat the evaluation process.



Activity_diagram



Sequence diagram

The activity diagram illustrates the operational flow of the smart waste management system, which consists of three main components: sensors, the backend system, and collection trucks. Sensors continuously monitor the fill level of trash bins, change indicator lights based on status, and send alerts when bins reach overflow conditions. Upon receiving alerts, the backend system updates the database, evaluates whether the pickup threshold has been met, and, if so, generates optimized collection routes and notifies trucks. The trucks then execute the pickup tasks, confirm completion, and send receipts back to the system, which updates its records accordingly. This cycle repeats, ensuring efficient and timely waste collection.

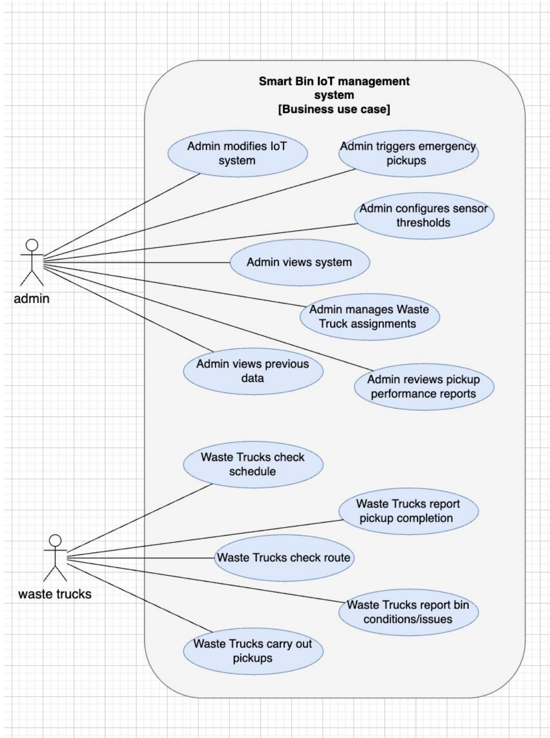
D.Business Use-case

Use-case diagrams not only help in visualizing the functional requirements and the actors, but also the relationships and the interactions between them. The use-case diagrams provide insight into how the System can be used in real situations, providing an insight into the system's behaviors and boundaries.

The business use-case diagram captures high-level goals from the perspective of municipal stakeholders and service operations.

The business use cases in sentence form are provided below for an easier understanding:

- Admin can modify the IoT system
- Admins can view the system
- Admins can view previous data
- Admin configures sensor thresholds
- Admin manages Waste Truck assignments
- Admin reviews pickup performance reports
- Admin triggers emergency pickups
- Waste Trucks check schedule
- Waste Trucks check the route
- Waste Trucks carry out pickups.
- Waste Trucks report pickup completion
- Waste trucks report bin conditions/issues



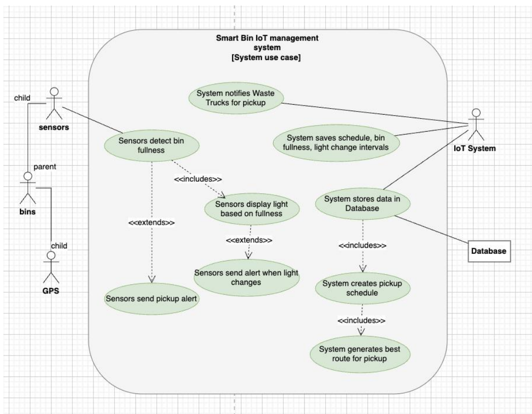
Business Use-case Diagram

E.System use case

The System use case diagram details specific system interactions, such as data collection, bin status updates, and route generation.

The system use-cases in sentence form:

- Sensors detect the bin fullness
- Sensors display light corresponding to bin fulness
- Sensors send alert to system when the light changes
- Sensors send an alert to the main system notifying of a pickup
- Bins contain sensors {Association} (internal)
- Bins contain GPS {Association} (internal)
- The system notifies Waste Trucks for pickup
- System generates best route for pickup
- System creates schedule
- IoT system stores data in the Database

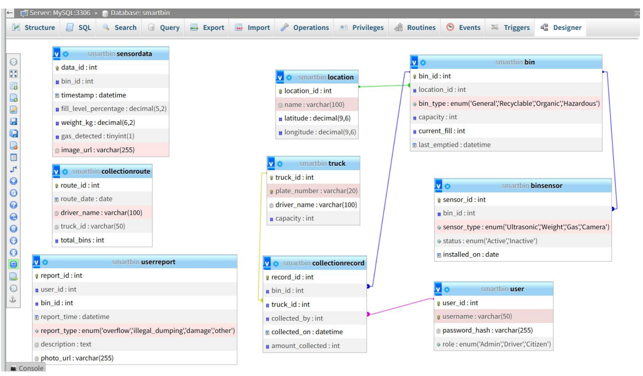


System use-case Diagram

VI. Database Design

The SmartBin system employs a relational MySQL database to ensure structured, consistent, and scalable data management. The core tables include Locations, which store GPS coordinates and area names; Bins, which record each smart bin's type, capacity, and its associated location through foreign key references; SensorData, which logs timestamped fill levels, gas detection, and temperature readings from each bin; CollectionRoutes, which map out optimized waste collection paths; RouteBins, a linking table to assign multiple bins to specific routes; and AdminUsers, which handle authentication and authorization of system operators. Data is primarily written into the database via RESTful APIs: smart bins automatically push sensor readings to the SensorData table, while city administrators interact through web or mobile dashboards to create new bins, define routes, and manage users. Queries are designed to efficiently retrieve bins nearing full capacity, generate real-time optimized routes by joining Bins and Routes tables, and track historical waste patterns through SensorData logs. Foreign key constraints enforce referential integrity between tables, while the InnoDB engine supports ACID compliance, ensuring reliable transactions across the system. This robust design positions SmartBin for seamless scaling in larger smart city deployments, while maintaining accurate and timely waste management records.

Table	Action	Rows	Type	Collation	Size
bin	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	32.0 KiB
binsensor	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	32.0 KiB
collectionrecord	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	64.0 KiB
collectionroute	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	1.0 KiB
location	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	16.0 KiB
route	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	48.0 KiB
routebin	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	48.0 KiB
sensordata	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	1.0 KiB
truck	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	32.0 KiB
user	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	32.0 KiB
userreport	Browse Structure Search Insert Empty Drop	0	InnoDB	utf8mb4_0900_ai_ci	1.0 KiB



Database

VII. Hardware and Software Implementation

The SmartBin system is built using simple hardware and easy-to-manage software. For hardware, each smart bin uses sensors like ultrasonic sensors (to check how full the bin is) and gas sensors (to detect bad smells or dangerous gases). These sensors are connected to a small computer called a microcontroller (such as the ESP32), which can send the data wirelessly using Wi-Fi. A battery powers the system, and for outdoor bins, solar panels can be added to keep the battery charged.

On the software side, the sensor data is sent to an online server through APIs (a way for devices to talk to servers). The server stores all the data in a MySQL database, which keeps track of bins, locations, sensor readings, routes, and admin users. City workers and admins can log in to a simple web dashboard to see which bins are full, plan the best routes to collect the trash, and manage the system. The dashboard is made using web technologies like HTML, CSS, and JavaScript, and works on both computers and mobile phones.

This setup makes it easy to monitor waste collection and helps cities keep the streets cleaner with less effort.

VIII. Challenges and Limitations

In the duration of developing the design of the proposed SmartBin with Integrated IoT system, the authors considered some problems that may occur when the system is implemented in practice. The first of which is the sensor and bin readings.

To prevent the issue of wrong or inconsistent data, the sensors and bins all have to be of the same shapes and makes. Signal averaging and filtering techniques will also need to be uniquely modified for each situation in the firmware to improve the confidence level of the data.

The second problem that may occur is the problem of data loss because of unstable network connections. In real world situations, networks are not always constant, they are prone to instability and slow data flow. In the event that the devices lose their network connectivity, the data collected while not connected to the network may not be stored properly and may result in data gaps. To prevent this from happening, it is necessary that the microcontroller have measures in place to temporarily store the data.

Furthermore, to ensure that modularity of the system is maintained while integrating real time communication between sensors, databases, and visualisation tools (website) requires detailed planning of system architecture. Through our proposed steps, utilising Object Oriented Design principles in the planning of the system will greatly help with the process of creating the real world system, despite still having complex cross component relationships and issues.

These challenges not only prove that designing a system with flexibility, scalability, and Object Oriented design principles is important for a modern system that can fulfil the requirements that a modern optimised urban waste collection system needs.

IX. CONCLUSION

This paper presents the design and implementation plans for SmartBin, a smart waste management system enabled with an IoT system and designed using Object Oriented designing principles. The proposed system addresses common inadequacies and limitations of traditional waste collection systems and build on prior research on similar topics. By enabling real time monitoring of the status of bin fulness, optimised scheduling of waste collection timings, and integrated database management using a modular structured software and hardware architecture.

The proposed system is possible to achieve high cohesion and a low coupling rate using encapsulation and reusable class features, allowing it to have high scalability and easy maintenance of the system. Its lightweight and modular design allows for quick and easy implementation in real world urban environments. It is cost effective and is well suited for environments with limited resources with a demand for an optimised, scalable, and effective urban waste collection system.

Overall, the proposed SmartBin system offers a practical, extensive framework for creating a new and optimised system for waste collection without ineffective utilisation of resources. Representing a step forward in optimising urban environments with new smart city technologies.

X. FUTURE WORK

The current SmartBin system has established a robust framework for efficient waste management, but further research and development can significantly expand its functionality and societal impact. Below are key areas for future exploration:

A. Machine Learning for Predictive Waste Management

Presently, SmartBin operates reactively, triggering collections only when bins reach capacity. Future iterations should integrate machine learning models trained on historical waste generation patterns—such as increased volumes during weekends, public events, or holidays—to forecast fill levels proactively. This predictive capability would allow dynamic scheduling of waste collection, reducing unnecessary truck dispatches, cutting operational costs, and lowering carbon emissions.

B. Advanced Sensor Integration

While ultrasonic sensors provide a cost-efficient method for measuring fill levels, their accuracy diminishes with lightweight or irregularly shaped waste. Future enhancements should incorporate:

Weight sensors to differentiate between low-density materials (e.g., plastic) and dense waste (e.g., food scraps).

Gas sensors to detect hazardous substances (e.g., battery leakage) or early-stage organic decomposition.

Camera-based recognition to flag misclassified waste (e.g., non-recyclables in recycling bins), improving sorting compliance.

C. Real-Time Route Optimization

Current route planning relies primarily on bin status and distance. Future upgrades should integrate live traffic data (via APIs like Google Maps) to dynamically adjust routes, avoiding congestion. Additional considerations should include:

Fuel efficiency optimization based on truck load.

Weather adaptability (e.g., rerouting during heavy rain or snow).

Priority zones (e.g., tourist areas requiring frequent cleanups).

D. Citizen Engagement via Mobile Applications

Public participation remains an underutilized yet critical aspect of waste management. A dedicated mobile app could:

Display real-time bin capacity to guide users to available bins.

Enable reporting of illegal dumping through geotagged photos.

Offer incentives (e.g., discounts, municipal rewards) to encourage proper recycling.

E. Toward Smarter, More Sustainable Cities

By implementing these advancements, SmartBin can evolve from a standalone waste management tool into a cornerstone of smart urban infrastructure. Combining predictive analytics, enhanced sensing, adaptive logistics, and public engagement will position SmartBin as a key enabler of sustainable, citizen-focused cities.

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