

IoT-Driven Smart Waste Management with Integrated Security for Urban Environments-(BinBot)

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Abstract. The rapid growth of the urban population has been challenging, as the waste generated is not efficiently managed. The inefficient methods are not able to coordinate between community needs and the management processes. This failure of management leads to overflowing bins, unpleasant odors and an unhygienic environment, which spreads many diseases, making human beings feel unsafe and uncomfortable in their own surroundings. The role is not only of management, but the first step is to be taken by the people, using bins properly and not throwing the waste on roads or in water bodies. This paper focuses on waste management once waste is thrown into the bins properly. BinBot an IOT-based waste management system designed to assist municipal department and support smart city operations by monitoring bins and taking real-time actions once the bins get full. In this project, sensors microcontrollers and cloud technology are integrated to provide real-time monitoring, data collection and real time alerts along with the location of bin reducing time wastage and ensuring efficient and hygienic waste management.

Keywords: IOT, ESP8266 ,Alerts, Dashboard, Security.

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1 Introduction

With cities becoming more crowded every day, the amount of waste generated increases, making it difficult for municipalities to manage it properly. According to the United Nations, over 68% of the world's population will live in urban areas by 2050, leading to a sharp increase in daily waste generation and collection demands [1]. Traditional waste collection methods rely on manual checking and fixed schedules, which leads to overflowing bins, wasted fuel, longer collection routes and more pollution[2]. These problems not only increase cost of municipalities but also create environmental and health risks[3]. To address this, many cities are now using smart technologies which use Internet of Things(IOT), cloud integration and real-time monitoring so that waste management becomes easy and efficient making surroundings safe and hygienic for communities [4]. One of the useful applications of IOT in smart cities is smart waste management, which includes sensors and microcontrollers for real-time monitoring and sending the data to a dashboard for visualization, helping the collection team to empty bin when needed [5]. This reduces unnecessary travel, reduces costs and helps protect the environment [6]. Studies show that combining IoT with cloud and GIS tools can improve waste collection efficiency by more than 30% [7].

This paper presents BinBot, which is a simple and cost-effective IoT-based system designed to monitor waste levels in real time. It uses sensors (ultrasonic and infrared) and an ESP8266 microcontroller to measure how full a bin is and send the data to a cloud server using Wi-Fi. A ThingsBoard dashboard shows the bin's location, status, and fill percentage. When a bin gets full, the system uses Twilio's API to send an SMS alert with the location link to the waste collection staff. Data is kept secure using TLS/HTTPS encryption, AES-protected messages, and HMAC authentication.

Unlike other smart waste systems that have complex hardware setups and require special software[8], BinBot is cost-effective, easy to operate and scalable for future upgrades. Small towns and developing regions can use it without difficulty, and later it can be upgraded with things like route optimization, ML-based predictions, and connections to municipal fleet systems [9].

The key contributions of this work are therefold:

- The design and implementation of a real-time IoT-based bin monitoring system using ESP8266 with ultrasonic and infrared sensors.
- The development of a lightweight and interactive web interface for real-time visualization and alerts, and the integration of cloud services and mapping tools for efficient routing and scalable deployment.

- Removal of hardcoded secrets like Wi-Fi credentials, Twilio credentials and ThingsBoard token to ensure that our device will be safe from unauthorized access.
- Use of AES so that our data is encrypted and the confidentiality of data is protected. e.g by encrypting the trash level and lid status ,only the server with key can decrypt.

2 Related Work

The rapid adoption of the Internet of Things (IoT) has inspired numerous smart waste management solutions aimed at reducing operational costs and environmental impact. Early approaches focused primarily on real-time bin monitoring using ultrasonic sensors and microcontrollers to measure fill levels and transmit data to cloud platforms. For instance, Magdum *et al.* [10] developed an ultrasonic-sensor-based system with ESP8266 and GSM connectivity for automated alert generation when bins approach capacity. Shinde *et al.* [11] designed a system which can differentiate between wet and dry waste combining ultrasonic and moisture sensors with Firebase Cloud Messaging to provide instant notifications. Das and Mondal [12] extended these concepts by keeping environmental parameters (temperature, humidity, and harmful gases) into consideration along with fill-level detection. Their system targets hygiene-related risks, especially in densely populated areas.

Table 1. Comparative analysis of Existing Smart Waste Management System.

Reference	Sensors / Hardware	Controller / Connectivity	Key Features	Optimization	Limitations
Magdum <i>et al.</i> [10]	Ultrasonic sensor	ESP8266 + GSM	Automated alerts when bins are full	None	No map location, relies on GSM, no dashboard pilot -scale.
Shinde <i>et al.</i> [11]	Ultrasonic + moisture sensors	Cloud via Firebase Cloud Messaging	Differentiates wet and dry waste; instant notifications	None	No precise location; dashboard works within a limit. Fun; Wi-Fi dependent.
Das and Mondal [12]	Ultrasonic + temp, humidity, gas sensors	Wi-Fi	Environmental monitoring+ fill-level detection	None	Requires stable Wi-Fi, no location link; mostly sensor-focused.
Morais <i>et al.</i> [13]	Fill-level sensors	Cloud	Real-time fill-level monitoring; dynamic scheduling	Data-driven route optimization	Assumes perfect sensor data, and need a lot of computation power.
CVRP (Genetic Algorithm / PSO) [14,15]	Fill-level data	Cloud Server /	Route optimization; minimizes distance, cost, pollution.	GA, PSO	Computationally intensive; becomes hard to run in real time.
BIN-CT Project [18]	Fill-level sensors	Cloud / ML model	Predictive fill-level; triggers collection	Machine-learning prediction	Mostly pilot-scale; not low-cost focused
Van Velzen <i>et al.</i> [19]	Fill-level sensors	Cloud / ML model	Bins are grouped based on urgency.	Prize-collecting vehicle routing	Pilot-scale; limited large-scale deployment
Rahman <i>et al.</i> [20]	Time-of-Flight (ToF) sensor	ESP32-S3	Higher accuracy bin monitoring	None	New sensor tech; pilot-scale
Alam <i>et al.</i> [21]	Conventional sensors	Cloud	Predictive bin placement & collection forecasting	Fuzzy logic + machine learning	Pilot-scale; AI integration is quite complex
BinBot (Proposed)	Infrared, Ultrasonic sensors	Cloud / ThingsBoard + ESP8266	Security (Hashing), AES, Real-Time Location	Real-time alerts with bin location and reduced travel cost	None

To enhance the efficiency of waste management, researchers have worked on improving route selection and dynamic scheduling. Morais *et al.* [13] suggested a data based system that uses real-time fill-level data to generate smarter collection plans. Other studies use genetic algorithms and particle swarm optimization (PSO) to solve the capacitated vehicle-routing problem (CVRP), reducing travel distance, costs, and pollution [14], [15]. Real examples from Brazil and Europe show that these smart routing methods can reduce daily mileage and working hours by more than 20% compared with static routing [16]. But the problem is that many of these algorithms assume that sensor data is always perfect, and they need a lot of computing power. This makes it difficult to use them in real-time across an entire city [17].

A new trend in smart waste management is to combine both, the bin monitoring and route planning into one platform. For example the BIN-CT project [18] integrates machine-learning models to predict bin fill levels and trigger collection only when necessary, reducing unnecessary visits while preventing overflow. Van Velzen *et al.* [19] developed a routing model that groups bins based on

how urgent they are and then plans routes accordingly. Their approach even showed that the number of collection vehicles needed can be reduced by up to 40%. But even with these improvements, most of these systems are still used only in small pilot projects, and very few offer a complete solution that is both low-cost and easy to scale with cloud support and optimized routing. Researchers are trying to integrate sensors and AI to make waste monitoring smarter. Rahman et al. [20] used a time-of-flight (ToF) sensor with an ESP32-S3. Alam et al. [21] focuses on predictive analytics by applying machine-learning algorithms to check and predict fill-level in urban environments.

In summary, many studies have worked on IOT for monitoring waste bins and selecting routes. But there are still some limitations ,like the system hardware complexity, difficulty scaling the system in entire city and limited predictive analysis. The proposed Smart Bin system addresses these gaps by combining affordable ESP8266 hardware, Wi-Fi communication, and real-time web visualization with dashboard that displays bin status, fill level, and precise location .Alerts are sent via Twilio SMS, including clickable map links for direct navigation to full bins. To ensure data integrity and system security, the system uses TLS/HTTPS, AES encryption, and HMAC authentication. Since the design is modular, it allows researchers for future upgrade, like integrating with AI for waste segregation, making BinBot a practical, secure, and scalable solution for managing waste in cities.

3 Methodology

The proposed IOT based smart waste bin (BinBot) is designed in a modular way so that it can provide reliable sensing, real-time communication, secure cloud-based data handling, and intelligent decision support. The design is structured into five interrelated layers:

- Sensing : Sensors like Ultrasonic and infrared sensors are used to capture fill-level data and the ESP8266 microcontroller processes it locally.
- Communication: Transmits data to the ThingsBoard cloud via Wi-Fi and triggers Twilio SMS alerts with precise bin locations.
- Cloud Backend: Data is stored, organized, and managed, enabling secure real-time monitoring and future integration with route optimization.
- Security Measures: Use of technologies like Hashing and AES encryption to ensure that data remains same , private and tamper free.
- Application and Decision Support: A responsive web dashboard provides bin status, fill level, and location information for efficient navigation.

Overall, this layered setup makes the system scalable, reliable, and easy to upgrade. Each layer can be implemented and tested separately to check its performance and accuracy.

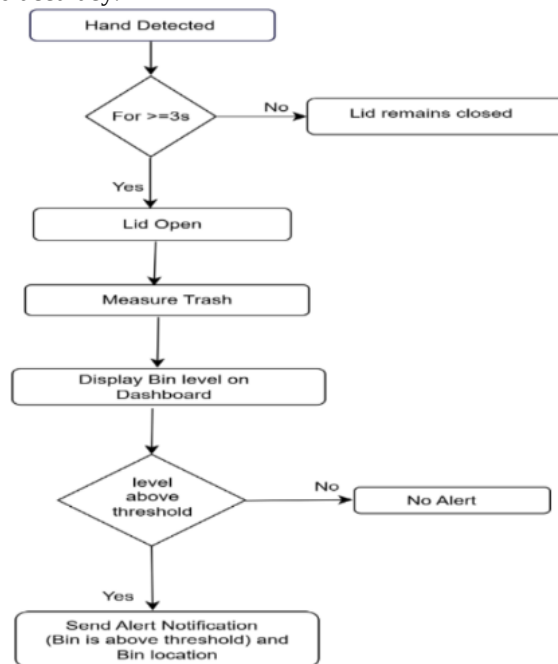


Fig. 1. Flowchart of BinBot.

System Overview

The Smart waste Bin works as an IoT-based waste monitoring system where every bin works separately and act like a small sensing unit. Each bin contains sensors and communication modules, that keep checking bin level and send notification to the dashboard. When the waste reaches a particular threshold an alert is generated to notify operators. This helps in planning better collection routes for the bins and ensuring that the system can be deployed in smart cities and resource constrained urban environments.

Hardware Design and Assembly

The smart bin is designed around an ESP8266 microcontroller that works with an IR sensor for hand detection so that lid gets open. An ultrasonic distance sensor to measure how much waste has been collected inside the bin. The ultrasonic sensor is fixed on the inner side of the lid and points downward to calculate the distance from the sensor to the top of the waste. Using this distance and the known height of the bin, the system computes the fill percentage. The ESP8266 then sends this data to the ThingsBoard platform over Wi-Fi, where it can be monitored on a real-time dashboard. When the bin becomes nearly full, or if the fill level crosses a set threshold, the system also uses the Twilio API to send an SMS alert to the concerned operator. This ensures that the bin is emptied on time and prevents overflow. A rechargeable Li-ion battery supplies power, supported by a small solar panel and charge controller for outdoor installations. This setup keeps the system operate continuously while minimizing the need for maintenance.

Firmware Development

The ESP8266 firmware is developed using Arduino IDE that uses C/C++ programming. The firmware performs four essential tasks: data acquisition, threshold evaluation, network communication and security.

- Data Acquisition: IR sensor detects hand presence and sends this data to ESP8266 for lid opening, and reads the ultrasonic sensor to measure the waste level in the bin.
- Threshold Evaluation: The calculated fill percentage is then checked against the threshold set e.g., 70% for warning. If the threshold exceeds the given limit, a warning signal is triggered otherwise, the system monitors the parameters in its normal mode.
- Network Communication: The ESP8266 collects all the sensor readings like the bin ID, fill %, IR status and bundles it in JSON file and then sends this data to the ThingsBoard platform via Wi-Fi. But if the system crosses the limit, SMS is sent via Twilio API along with the Bin Location to operators.
- Security measures : The data is kept secure using AES encryption and made tamper free during transmission using HMAC.

Cloud Backend

The cloud part of the system uses ThingsBoard, which is an open-source IoT platform. It stores sensor readings including ultrasonic distance and IR status along with metadata such as bin ID and more. The ESP8266 sends this data to ThingsBoard via Wi-Fi using MQTT or HTTP, wrapped in sending JSON packets. ThingsBoard has a rule engine that continuously monitors incoming data for threshold violations. When a bin exceeds a predefined fill level (e.g., 70% warning), the system generates alerts, which are displayed on the web dashboard and sent via the Twilio API as SMS notifications to operators. Overall this setup makes realtime monitoring easy and take immediate action once alert received.

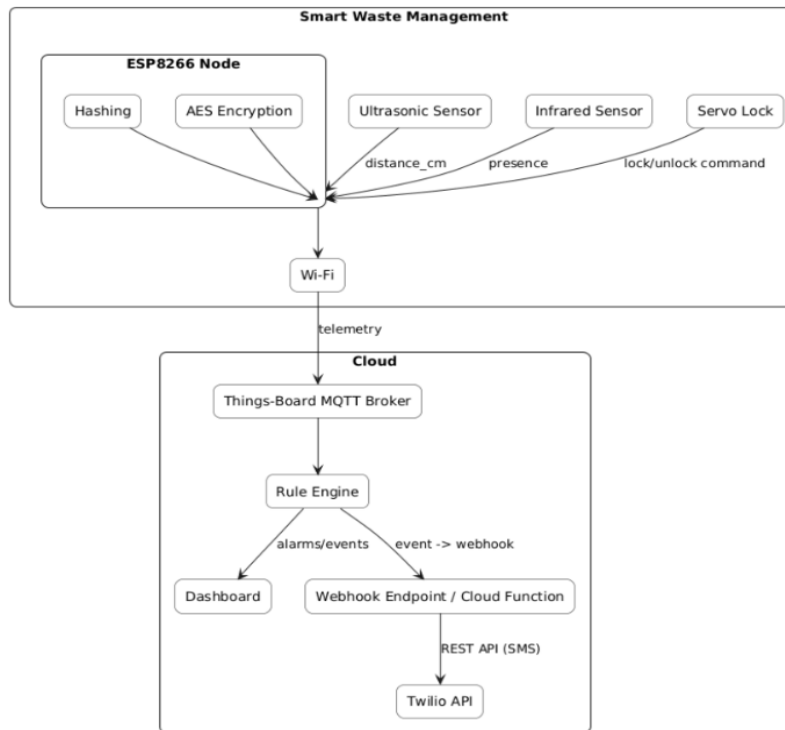


Fig. 2. BinBot Architecture

Web Application and Visualization

The data from the bins like the lid opening, bin level, and the notifications sent once the bin crosses threshold, all is visible on dashboard. It provides a real-time, interactive interface for monitoring bins across locations. Also an SMS is sent along with the location URL to the operator via Twilio API, allowing operators to quickly identify and locate the bin that requires attention. The dashboard updates automatically, so the latest status is always visible without refreshing the page.

Routing and Decision Support

In current systems, when the bin gets full no alert or notification is sent to the department which leads to overflowing and the workers visit after a fixed schedule which makes the system inefficient. But the proposed system sends alert and also location URL along with bin Id to the worker when the bin gets full which makes the work easy and efficient. The workers have to just click on the link and follow the directions on the map. This approach is very simple and is designed to support future enhancements such as automated route optimization. This would make the system more efficient and reduces travel distance improving operational efficiency.

Testing and Evaluation

To test the system, a pilot deployment of 10 bins is planned in different environment conditions. During testing the bins are filled step by step to check how accurately the sensors are measuring the fill levels and also check how often the data packets are delivered successfully. We will also check how many units of power are consumed, check for false alerts. We will use statistical checks, like t-paired or Wilcoxon test to see whether the improvements observed are real.

Scaling and Maintenance

The system is easily scalable for large smart cities. Adding bins with their particular IDs and their respective location like we

have implemented for single bin . The work we have to do will be adding the widgets in dashboard with their IDs and add location in code. No change in the hardware architecture is required. Also with the quick alerts it becomes easy to focus on bins which need attention, and the firmware updates on the ESP8266 is the can be done remotely making the whole system easy to maintain and scalable.

4 Results

At first, the BinBot was implemented using the BLYNK IOT dashboard with lid opening and bin level status but it is beginner friendly and has message limits we switched to Thingsboard which is a professional edition and has additional features. Twilio is used to send SMS notifications and share the bin's location in real time, helping operators to monitor bins and reach the bin location for which a notification was received.

BinBot using BLYNK IOT

While using BLYNK dashboard, the system was implemented using two ultrasonic sensors , one for opening the lid after 3s the hand is detected. The lid gets closed after 7s automatically .The other ultrasonic sensor is used to check bin level present inside the bin. The system monitors the bin level and sends alert when the bin goes above threshold with bin level and an SMS with bin location.

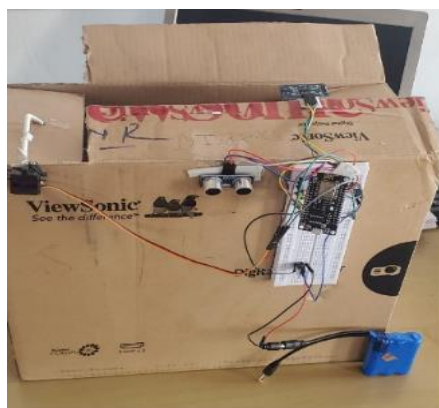


Fig. 3. Hardware implementation of Binbot using BLYNK



Fig. 4. BLYNK dashboard displaying lid opening, bin level status

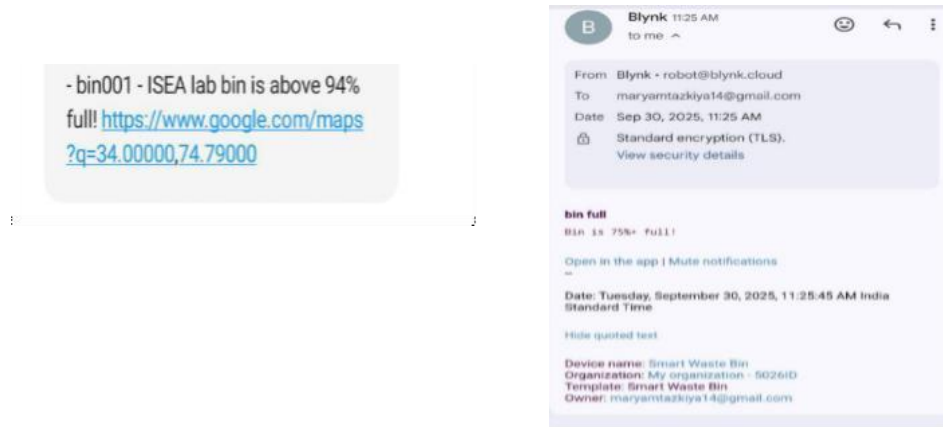


Fig. 5. Alerts generated through SMS and Email

BinBot using ThingsBoard

To overcome the limitations in BLYNK we switched to ThingsBoard which provides a more scalable and robust platform. We replaced ultrasonic sensor with IR for hand detection. It also supports Twilio integration for SMS alerts and real time monitoring.

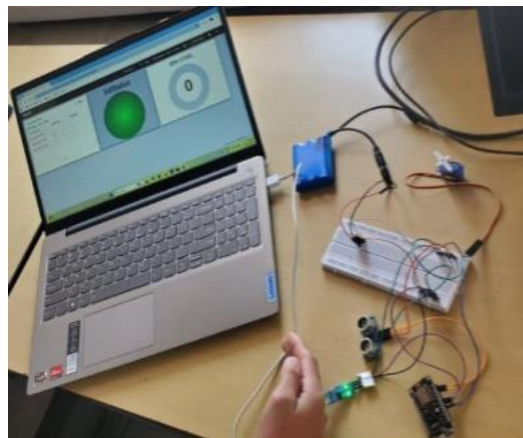


Fig. 6. Hardware implementation of Binbot using Things Board

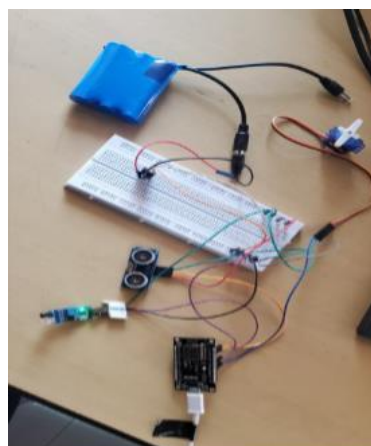


Fig. 7. Hand detection using IR



Fig. 8. Dashboard displaying bin level and lid closed status



Fig. 9. SMS alert with Bin location

5 Conclusion

With growth in urban populations need for smart waste management is necessary. The proposed solution “IoT-Driven Smart Waste Management with Integrated Security for Urban Environments-(BinBot)” is a low cost, real time monitoring system which enhances the efficiency of waste collection. And helps in maintaining hygiene .The system is implemented using ESP8266 microcontroller along with sensors to monitor bin fill levels.The data is sent to dashboard via Wi-Fi and when the bin crosses threshold it sends an alert using Twilio SMS along with bin location allowing operators to easily identify and service the full bins. System has a modular design which supports easy scalability, allowing additional bins to be integrated without significant changes to the system . Future plans include city-wide deployment, predicting fill levels, and cost benefits moving closer to cleaner, safer, and smarter cities.

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