PROJECT REPORT

ON

Smart Waste Bin Network (Virtual IoT Design Challenge)

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Introduction

Rapid urban growth has made efficient solid waste management a critical challenge for city authorities. Conventional waste collection systems rely on fixed schedules and predefined routes, which do not reflect the real-time condition of waste bins. This often results in overflowing bins in busy locations and unnecessary collection of partially filled bins in low-usage areas. Such inefficiencies increase fuel consumption, operational costs, and negatively impact public hygiene.

To address these challenges, this project proposes an **IoT-based Smart Waste Bin Monitoring and Collection Optimization System**. The system focuses on practicality, reliability, and ease of deployment. Instead of fully automating waste collection, it adopts a **human-centered hybrid approach**, where sensor data assists municipal workers in making informed decisions. This design ensures better acceptance, reduced system failures, and scalable deployment in real-world city environments.

1.System Architecture

End-to-End Working of the System

The proposed system follows a **layered IoT architecture** that ensures smooth and reliable data flow from individual waste bins to city authorities. Each layer is designed to handle a specific task, making the overall system efficient, scalable, and easy to manage.

1.1 Sensors and Microcontroller

Ultrasonic Sensor

An ultrasonic sensor is installed on the inner side of the bin lid to measure the distance between the sensor and the waste surface. By comparing this distance with the known depth of the bin, the system accurately calculates the **fill level percentage** of the bin. Since the sensing is non-contact, it remains hygienic and reliable even in harsh environments.

Microcontroller: ESP32 / LoRa Node

The ESP32 acts as the brain of the system. It collects data from the ultrasonic sensor, performs basic filtering to remove noise, calculates the bin’s fill level, and manages wireless communication with the network. Its built-in low-power features make it well suited for battery-powered deployments.

Why Ultrasonic Sensor with ESP32?

This combination is chosen because it is:

- **Cost-effective** and easily available
- **Hygienic**, as ultrasonic sensing does not require physical contact

- **Energy-efficient**, with the ESP32 supporting deep-sleep modes
- **Flexible**, offering multiple communication options for future scalability

1.2 Data Communication Method

For communication between the bins and the central gateway, **LoRaWAN** is used. It is ideal for smart city deployments because it offers:

- **Long-range coverage** (approximately 5–15 km)
- **Very low power consumption**, extending battery life
- **High reliability**, even in dense urban environments

Cloud and Edge Computing Strategy

Edge Level (Bin Side)

At the bin level, raw sensor readings are filtered, and the fill percentage is calculated locally. This reduces unnecessary data transmission and improves response time.

Cloud Level

At the cloud layer, the processed data is stored and analyzed. Rule-based logic is applied to identify bins that need immediate attention. Alerts are generated, and data is prepared for visualization.

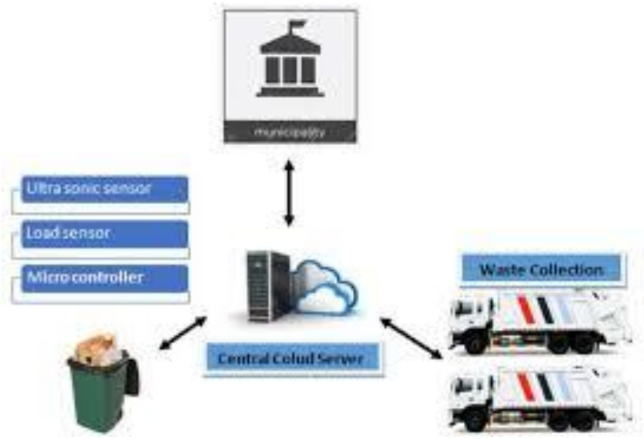
By dividing tasks between the edge and the cloud, the system minimizes bandwidth usage while maintaining fast and reliable decision-making.

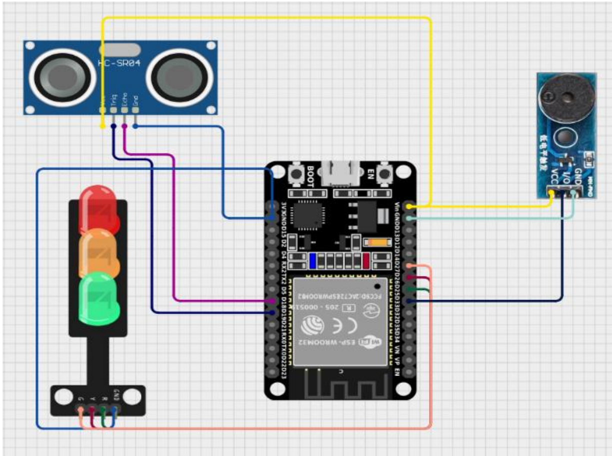
Dashboard and Visualization Concept

A **web-based dashboard** is provided for city authorities to monitor waste levels in real time. The dashboard includes:

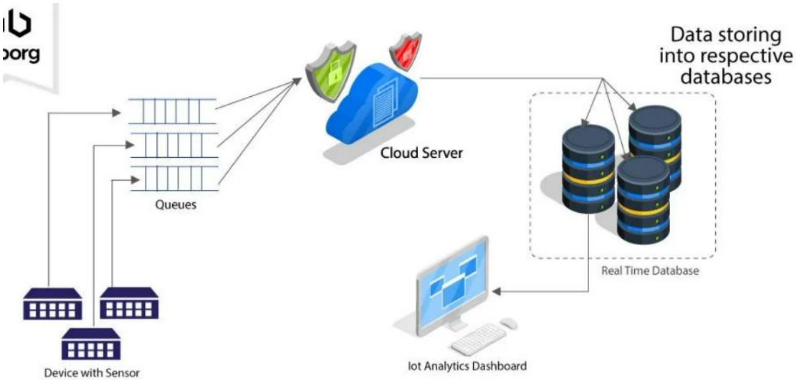
- A **map view** displaying the location of all bins
- **Color-coded bin status** for quick identification:
    - Green: Less than 50% full
    - Yellow: 50% to 80% full
    - Red: More than 80% full

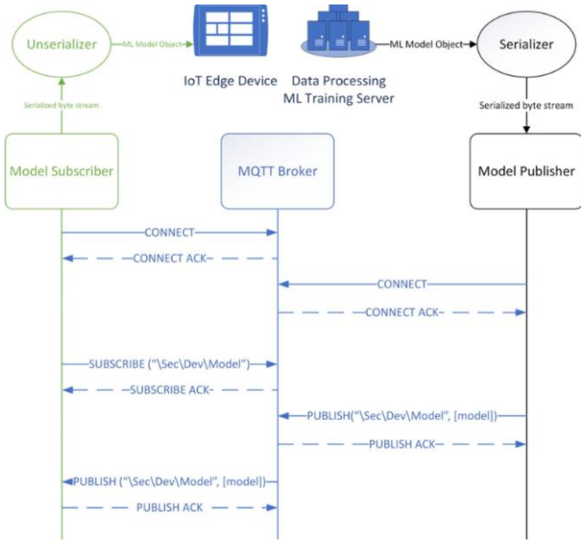
A separate, simplified view is designed for **garbage truck drivers**, showing only high-priority bins that require immediate collection. This helps optimize routes and reduces unnecessary trips.





2. Data Flow Design





2.1 Step-by-Step Data Flow

The data flow in the system follows a simple and efficient sequence to ensure real-time monitoring and quick decision-making.

1. The **ultrasonic sensor** continuously measures the distance between the sensor and the waste surface inside the bin.
2. The **ESP32** processes this data and calculates the bin's fill percentage based on the known bin depth.
3. The calculated data is packaged into a small data packet and transmitted using **LoRaWAN**.
4. The **LoRaWAN gateway** receives the data from multiple bins and forwards it to the cloud server.
5. The **cloud platform** applies predefined rules and logic to analyze the bin status.

6. The **dashboard** is updated in near real time, reflecting the current fill levels of all bins.
7. If the fill level crosses a defined threshold, the system automatically **generates alerts** for timely action.

2.2 Communication Protocols Used

MQTT (Preferred Protocol)

MQTT is used as the primary communication protocol between the gateway and the cloud due to its efficiency and reliability in IoT environments. MQTT is particularly suitable because it is:

- **Lightweight**, requiring very low bandwidth
- Based on a **publish/subscribe model**, which allows scalable and decoupled communication
- Well-suited for **resource-constrained IoT devices**
- Capable of **reliable message delivery**, even in unstable network conditions

3. Route Optimization Strategy

3.1 Decision Logic

The system intelligently decides **when to collect waste and which bins to prioritize** by continuously analyzing the fill level of each bin. This ensures that collection efforts are focused only where they are actually needed, reducing fuel usage, time, and operational costs.

3.2 Rule-Based Logic

A simple and effective rule-based approach is used as the first level of decision-making:

- Bins are scheduled for collection when their **fill level exceeds 80%**
- Bins with a fill level **below 50% are ignored**, as they do not require immediate attention
- Bins that exceed **90% fill level are treated as high priority**, since they are close to overflowing

This logic helps prevent overflow while avoiding unnecessary collection trips.

3.3 Priority Classification

Based on the fill level, each bin is assigned a priority as shown below:

Fill Level	**Priority**
Greater than 90%	High
80% – 90%	Medium

Fill Level	Priority
Below 80%	Low

This classification allows the system to clearly identify which bins need urgent attention and which can be serviced later.

3.4 Algorithmic Approach

Once high- and medium-priority bins are identified, an algorithmic approach is applied to optimize collection routes:

- Nearby bins are **grouped into geographical clusters**
- For each cluster, a **shortest path algorithm** is applied to determine the most efficient route
- The system then assigns the **nearest available garbage truck** to each cluster

By combining priority-based decisions with route optimization algorithms, the system ensures faster collection, lower fuel consumption, and improved overall efficiency.

4. Power Management Plan

Efficient power management is a critical requirement for smart waste bins, as they are often deployed in outdoor locations where frequent battery replacement is impractical and costly. The proposed system is therefore designed to minimize energy consumption while ensuring reliable and timely data reporting.

4.1 Energy Optimization Techniques

To achieve low power consumption, multiple optimization strategies are employed at the hardware and firmware levels:

- **Periodic UltraSonic Sensing**
  The ultrasonic sensor is activated only once every **30 to 60 minutes**, instead of continuous sensing. This interval is sufficient because waste accumulation is generally gradual and does not require continuous monitoring.
- **ESP32 Deep Sleep Mode**
  After completing each sensing and transmission cycle, the ESP32 microcontroller enters **deep sleep mode**, where it consumes only a few microamperes of current. The device wakes up automatically using a timer interrupt for the next measurement cycle.

- **Event-BasedDataTransmission**
  Data is transmitted to the cloud only when:
  - There is a significant change in the fill level (e.g., more than 10%), or
  - The bin crosses a predefined critical threshold (e.g., 80% full).
    This avoids unnecessary transmissions and significantly reduces power consumption.
- **Solar-AssistedBatteryCharging**
  A small solar panel is integrated with the power system to recharge the battery during daylight hours. This approach reduces dependence on manual battery replacement and ensures continuous operation even in long-term deployments.

Expected Battery Life

Configuration	Expected Battery Life
Battery Only	6–9 months
Solar + Battery	1+ year

By combining deep sleep modes, low-frequency sensing, and solar-assisted charging, the system ensures **minimal maintenance requirements** and supports **long-term, unattended deployment** in urban environments.

5. Reliability & Fault Handling

In real-world conditions, waste bins are exposed to dust, moisture, plastic waste, uneven garbage surfaces, and accidental damage. Therefore, reliability and fault tolerance are essential design considerations.

5.1 Handling False Readings

To prevent incorrect decisions caused by faulty sensor readings, the system incorporates multiple validation mechanisms:

- **Multiple Readings and Averaging**
  Instead of relying on a single measurement, the system takes multiple ultrasonic readings and calculates an average value. This reduces the impact of temporary obstructions or reflections.
- **Spike Filtering**
  Sudden changes in measured distance—often caused by plastic sheets or irregular waste surfaces—are ignored if they do not persist across consecutive readings.

- **Time-Based Validation**
  A bin is considered genuinely full only if the high fill level is consistently observed over multiple measurement cycles. This prevents false alerts due to momentary disturbances.

5.2 Redundancy & Calibration

- **Periodic Sensor Calibration**
  Sensors can be recalibrated periodically during maintenance checks to account for drift or environmental effects.

- **Optional Secondary Sensor**
  A **load cell** can be added as a secondary sensor to measure the weight of waste. This redundancy improves accuracy and helps validate ultrasonic readings.

- **Self-Diagnostic Alerts**
  If sensor values remain abnormal for extended periods, the system automatically flags the bin for inspection and sends a diagnostic alert to the maintenance team.

5.3 Failure Handling

- If no data is received from a bin for **24 hours**, the system generates a maintenance alert.
- The failure of a single bin does **not affect the operation of the overall system**.
- Garbage collection can continue normally while the faulty bin is serviced.

This fault-tolerant design ensures that the system **fails gracefully**, rather than disrupting waste collection operations.

6. Scalability & Network Considerations

The proposed system is designed to scale from a small pilot deployment to city-wide installations involving hundreds or thousands of bins.

6.1 Handling 100+ Bins

- **Multiple LoRa Gateways**
  Each LoRa gateway can support hundreds of bins. Additional gateways can be deployed as the system expands.

- **Zone-Wise Bin Grouping**
  Bins are grouped based on geographic zones or municipal wards, allowing efficient management and monitoring.

- **Cloud Auto-Scaling**
  The cloud backend uses scalable infrastructure that automatically adjusts storage and processing capacity as the number of connected bins increases.

6.2 Network Topology

- **Star Topology** is used, where each bin communicates directly with a gateway.

Reasons of Using Star Topology

- Simple and fast deployment
- Easy troubleshooting and maintenance
- Failure of one node does not affect others
- Well-suited for LoRaWAN-based networks

This topology ensures high reliability and supports large-scale deployments without increasing system complexity.

7. Cost & Feasibility Discussion

A major goal of the proposed system is affordability, as large-scale municipal deployment requires cost-effective solutions.

Approximate Cost Per Bin

Component	**Cost (₹)**
ESP32	350
Ultrasonic Sensor	120
Battery & Power System	250
Enclosure	200
Total	**~1000**

This low per-bin cost makes the system financially viable even for medium and large cities.

Trade-Off Analysis

Factor	Low-Cost Choice	High-Accuracy Choice
Sensors	Ultrasonic	Ultrasonic + Load Cell
Network	Wi-Fi	LoRaWAN
Power	Battery	Solar + Battery

The proposed design carefully balances **cost, accuracy, power efficiency, and scalability**, ensuring that the system delivers maximum benefit without excessive expenditure.

Conclusion

The Smart Waste Bin Monitoring and Collection Optimization System presented in this work offers a **practical, reliable, and scalable solution** to modern urban waste management challenges. By combining low-power IoT hardware, long-range communication, rule-based decision logic, and human oversight, the system significantly improves operational efficiency while minimizing complexity.

The human-centered design ensures easy adoption by municipal authorities, reduces fuel consumption, minimizes overflow incidents, and lowers maintenance costs. Furthermore, the modular architecture allows future enhancements such as predictive analytics and advanced optimization algorithms. Overall, this system demonstrates how thoughtful integration of IoT technologies can lead to cleaner, smarter, and more sustainable cities.

GitHub Repositories Link

https://github.com/KalangiMounami/WM---Mounami-Kalangi---Anurag-University