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Design and Development of a Smart IOT Enabled Garbage Bin Mechanism for Optimized Volume Utilization

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Abstract: - The rapid pace of urbanization and population growth has led to a significant increase in solid waste generation, posing substantial challenges for conventional waste management systems. In response, the Internet of Things (IoT) offers a transformative solution through the development of Smart Garbage Bin (SGB) systems. This study focuses on the design and implementation of an IoT-enabled SGB mechanism aimed at optimizing waste collection and management. The proposed system integrates advanced sensors within garbage bins to enable real-time monitoring and measurement of waste volume. These sensors utilize technologies such as ultrasonic, infrared, and motion detection to accurately assess fill levels. The collected data is then transmitted wirelessly to a centralized cloud platform using communication protocols like LoRaWAN or NB-IoT. Within this cloud-based environment, sophisticated data analytics and machine learning algorithms process the incoming data, enabling optimized decision-making regarding waste collection schedules and routes. By dynamically allocating resources based on real-time fill levels, the system improves collection efficiency while reducing operational costs. Additionally, the SGB system offers environmental benefits, such as reduced carbon emissions through optimized routes, improved urban cleanliness, and enhanced sustainability in waste management practices. The practical implementation of the system in an urban setting demonstrates its effectiveness and feasibility, with evaluations covering aspects such as system reliability, data accuracy, energy efficiency, and user interface design. The results indicate that IoT-enabled SGBs have the potential to revolutionize traditional waste management practices, fostering more efficient, data-driven, and environmentally sustainable approaches. This system could play a pivotal role in advancing smart city initiatives and improving urban living standards through optimized waste management strategies.

Keywords: IoT, Smart garbage bin, waste management, volume utilization, sustainability

1. Introduction

The rapid growth of urbanization and population has led to a dramatic increase in solid waste generation, posing significant challenges to traditional waste management systems. To address these challenges, the Internet of Things (IoT) has emerged as a promising technology, offering innovative solutions to transform waste management practices [1,2]. The development of Smart Garbage Volume Utilization and Management Systems (SGVUMS) presents opportunities for real-time data insights, optimized collection routes, and improved efficiency and sustainability [3,4].

However, there are key research gaps within the field of IoT-based smart waste management that require focused attention. First, existing studies highlight the need for a comprehensive exploration of sensor technologies that can accurately and cost-effectively measure garbage volume [5]. It is crucial to understand the trade-offs between different sensor types, such as ultrasonic, infrared, and weight-based sensors, and to evaluate their performance across various urban environments to ensure long-term reliability and viability [6-8].

Second, the design of data communication infrastructure and the selection of appropriate communication protocols require thorough investigation. The effectiveness and scalability of wireless communication technologies like LoRaWAN or NB-IoT in transmitting real-time garbage volume data from multiple smart bins to a centralized cloud platform must be carefully evaluated and optimized [9-11].

Additionally, while progress has been made in IoT data analytics for waste management, there is a pressing need to develop sophisticated machine learning algorithms that address the specific complexities of waste management processes [12]. Tackling this gap is essential for enabling the dynamic allocation of collection resources based on real-time garbage volume data, traffic conditions, and contextual factors, leading to more cost-effective and efficient waste collection strategies [13].

Lastly, implementing IoT-based smart waste management systems in densely populated urban areas requires a detailed examination of energy consumption and environmental sustainability [14]. It is imperative to conduct a rigorous assessment of energy efficiency, including the power requirements of sensors and communication devices, to ensure that the benefits of waste management optimization do not inadvertently lead to increased carbon emissions or resource depletion [15].

This study aims to address these research gaps by designing, developing, and implementing a comprehensive and scalable IoT-based Smart Garbage Volume Utilization and Management System. By tackling the challenges in sensor technology, data communication, advanced analytics, and energy efficiency, this research seeks to fully leverage the transformative potential of IoT to advance waste management practices towards a more sustainable and environmentally friendly future.

The study of IoT-based waste management systems unveils several significant research gaps that need to be addressed to advance the field. One of the primary challenges is identifying optimal sensor technologies that can accurately and affordably measure garbage volume in diverse urban settings. This is crucial for ensuring that the system functions effectively across different environments and waste types [16]. Additionally, there is a need to develop efficient waste collection routes that leverage real-time volume data along with contextual factors such as traffic patterns and environmental conditions. This can lead to more streamlined and responsive waste collection processes [17]. Furthermore, evaluating the environmental impact and energy efficiency of IoT-based waste management systems is essential for ensuring sustainability, as these systems should contribute positively to reducing carbon footprints and conserving energy. [18] Lastly, there is a pressing need to explore cost-effective IoT waste management solutions that are accessible and practical for resource-constrained areas, where the benefits of such systems could be particularly transformative.

The novelty of this topic lies in its potential to revolutionize traditional waste management practices by integrating cutting-edge IoT technologies with data-driven decision-making. By addressing these research gaps, the field can move toward more intelligent, sustainable, and scalable solutions that not only enhance urban waste management but also contribute to the broader goals of smart city initiatives and environmental stewardship.

2. Methodology

This study focuses on designing and developing a smart trash bin, with an emphasis on detailing the hardware components used and their interconnections. The proposed Smart Garbage Bin (SGB) design is depicted in Figure 1, showcasing its essential components. The system determines the bin's fullness by measuring the distance between the bin's lid and the waste inside using a distance sensor [16]. A predefined threshold distance, based on the bin's dimensions, triggers an alert when the bin is full. Upon detecting that the bin is full, an Arduino-based microcontroller activates a GSM module to send an SMS alert. This alert includes the bin's ID and a notification message, which is sent to predesignated user phone numbers and the municipal corporation office. The location of the bin is pre-registered by a sanitation worker, who uses the SMS alert to identify and locate the full bin based on its ID [2,7]. Once the bin is emptied by the sanitation worker, the system resets to its default mode of operation. An LED indicator continues to blink until the bin is completely emptied. Additionally, a memory card logs all usage data and fullness alerts for later analysis. A motion sensor detects user activity and triggers a prerecorded audio message stored on the memory card, which is played through a speaker to acknowledge and encourage the users of the bin [17]. The methodology for developing the IoT-based smart garbage bin for optimized volume utilization is divided into two key sections, as outlined below:

2.1 Design and development of the smart garbage bin

The system design prioritizes cost-effectiveness and user-friendliness. Figure 1 illustrates the initial design concept of the Smart Garbage Bin (SGB) before metal fabrication [18]. The design consists of several key elements: an Infrared (IR) sensor-activated lid that controls the garbage inlet (Figure 1a) and a controller box mounted on the side of the SGB, which manages communication between the SGB, the municipal corporation office, the waste collection truck, and the users (Figure 1b). The operational behavior of the SGB is regulated by commands sent to the controller through various onboard sensors [3,5,19].

Moreover, the SGB includes an RFID reader mechanism (Figure 1c) that enables rear access for cleaning once an RFID card is detected. The dimensions of the SGB are 5.6 feet in height and 4 feet in width. Figure 1d provides an overview of the internal design and architecture, detailing the specific measurements of the internal bin and the mechanisms that control its operation, including a tray-fitted compartment to hold the bin. This adaptable design can be applied to standard outdoor trash bins.

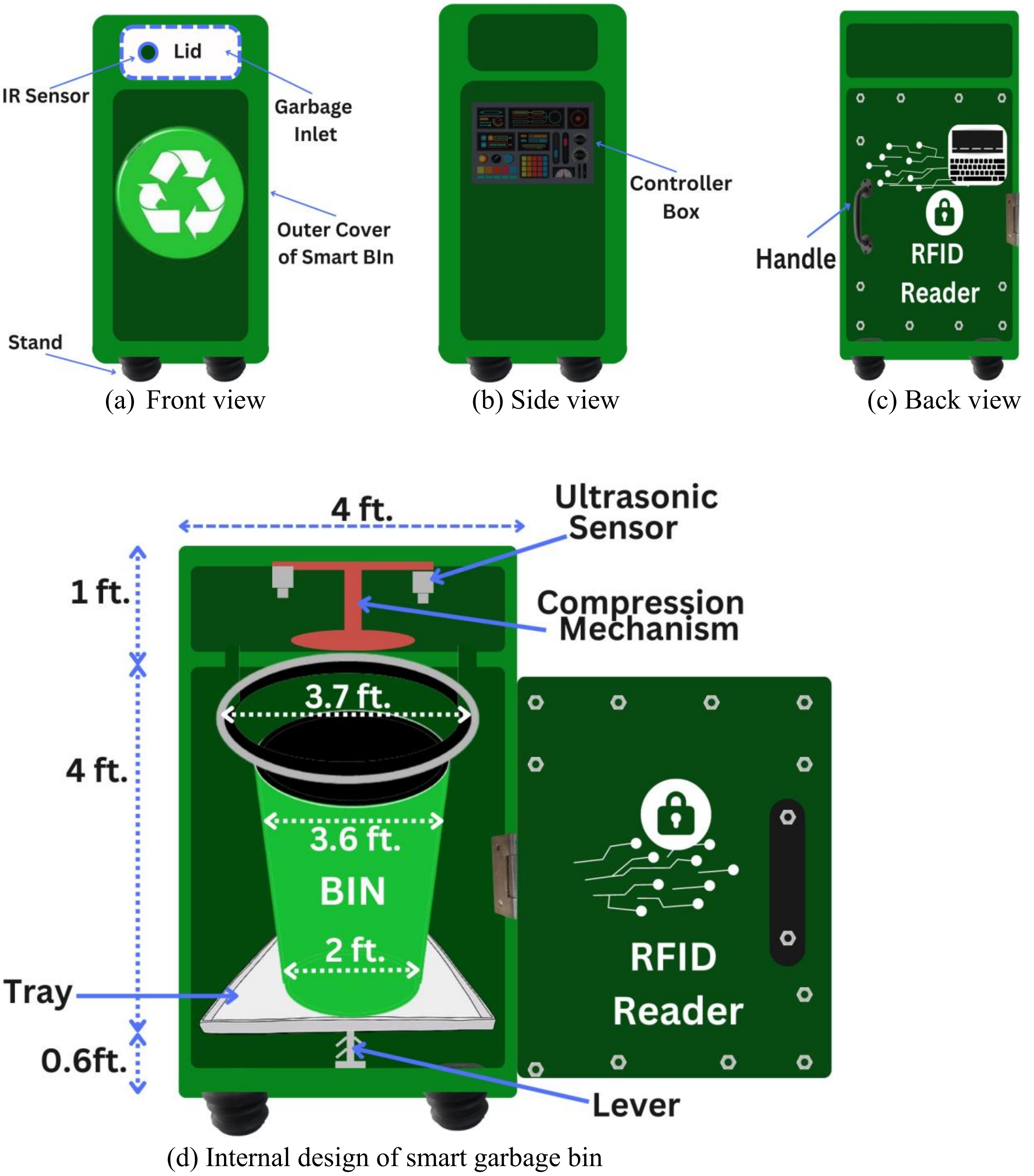

Figure 1: Proposed design of smart garbage bin (a) Front View (b) side view (c) back view (d) internal design

2.2 IOT Implementation and communication for smart garbage bin

Enhancing the decision-making capabilities of the Smart Garbage Bin (SGB) system involves integrating data collected from multiple smart bins with other relevant urban data sources [20]. By analyzing garbage volume in conjunction with various urban parameters, the system can significantly optimize waste collection processes. Figure 2 illustrates the architectural framework of the IoT techniques employed, showcasing the integration of different sensors and communication technologies. Choosing an appropriate wireless communication protocol, such as LoRaWAN or NB-IoT, is crucial for ensuring efficient and reliable real-time data transmission from the smart bins to a centralized cloud platform. The designed communication infrastructure aims to be robust and scalable, capable of handling extensive data flows effectively [2,8, 21]. The proposed IoT-based waste management system architecture, depicted in Figure 2, is divided into four primary modules:

- **Smart Control and Lid Sensing System:** This module comprises various sensors and actuators, including Ultrasonic Sensors, Infrared (IR) Sensors, Servo Motors, and RFID Readers. These components work together to monitor waste levels and control the automatic opening and closing of the bin lid.
- **Transceiver Unit:** Centralized around an Arduino controller, this unit integrates multiple communication interfaces such as GSM, GPS, Wi-Fi, and ThingSpeak. It manages data transmission between the smart bin and external systems, ensuring seamless communication and location tracking.
- **Smart Display Unit:** Featuring LCD screens, databases, and monitoring sections, this module provides real-time visual feedback on the status of the garbage bins, facilitating easy monitoring and management by sanitation workers and municipal authorities.
- **Solar Power Battery Backup System:** Equipped with solar panels and batteries, this unit ensures uninterrupted power supply to the smart bin system, promoting energy efficiency and sustainability.

2.3 System Operation Flow

The operational workflow of the implemented SGB system is outlined in Figure 2. The process proceeds as follows:

*User Detection***:** An IR sensor acts as a motion detector by sensing the presence of a person approaching the garbage bin. Upon detection, it signals the servo motor to automatically open the bin lid, allowing for hands-free and hygienic waste disposal.

*Waste Level Monitoring***:** After waste is deposited, ultrasonic sensors within the Lid Sensing System measure the fill level of the bin by detecting the distance between the lid and the garbage. These measurements help determine whether the bin has reached its predefined capacity threshold.

*Data Transmission***:** When the bin is identified as full, the Arduino controller activates the GSM module to send an alert to the municipal office's server. This alert includes critical information such as the bin's unique ID and its precise location provided by the integrated GPS module.

*Cleaning Confirmation***:** Once a sanitation worker empties the bin, they use an RFID tag to confirm the completion of the task. The RFID reader detects this tag and updates the server accordingly, ensuring accurate and up-to-date maintenance records.

*Status Display and Data Logging***:** The LCD screen on the smart bin displays real-time status updates, indicating current fill levels and maintenance activities. Additionally, all usage data and alerts are logged into a database via the Wi-Fi module and ThingSpeak platform, facilitating detailed analysis and future optimization of waste collection routes and schedules.

*Energy Efficiency***:** The entire system is powered by a solar panel and battery setup, ensuring continuous and eco-friendly operation even in areas without reliable access to conventional power sources.

To further optimize operational costs and efficiency, graph theory-based optimization algorithms are applied to determine optimal bin placement and waste collection routes. This comprehensive approach ensures that waste management processes are not only efficient and responsive but also sustainable and adaptable to various urban environments.

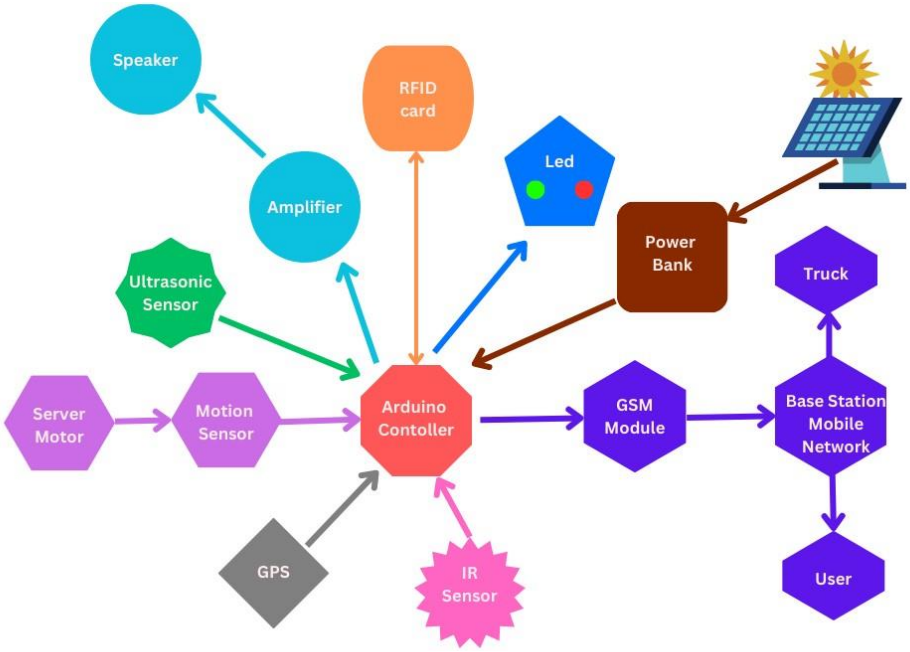

Figure 2: IOT architecture block diagram

3. Result and Discussion

This section delves into the development and implementation of advanced algorithms designed to process real-time garbage volume data and other contextual information. These algorithms are pivotal in dynamically optimizing waste bin volume based on the collected data, ensuring efficient and timely waste management.

.

```
#include<bits/stdc++.h>
using namespace std;
 void dustbin (int percentage, int i,int id)
 {
    id= i+id*123;
  if(percentage>=70)
  {
  cout << "Lever will start working i.e compress." << endl;
  cout << "Now enter new percentage" ;
  int percentage1;
  cin >> percentage1;
  if(percentage1 >percentage)
  { cout << " Invalid"<< endl;
  }
  else if(percentage1>=90 && percentage1<=percentage)
  {
   cout << " Inform to municipal cooperation, truck department, and Users:"<< endl << endl;
   cout << " To Municipal cooperation: This garbage bin id no. " <<  id <<" is filled." << endl;
   cout << " To Trck Department: This garbage bin id no. " <<  id <<" is filled, inform the
   nearest truck driver to collect it." << endl;
  cout << " To User: This garbage bin id no. " <<  id <<" is filled, please use another dustbin
   or wait till it is collected." << endl <<endl ;
    }
  else
  {
```

```
    cout << "All in control" << endl;
   }
   }
  else
  {
  cout << "Nothing to be done." << endl;
  }
  }
 int main(){
       int t;
    cout << "No. of Dustbin " ;
   cin >> t;

   for(int i = 1;i<=t;i++){
    int id;
      cout << "Enter filled percentage in " << i << " ";
 int percentage;
 cin >> percentage;
 dustbin(percentage,i,id);
}
    return 0;
  }
```

The outcomes of this advanced algorithm, which is part of the IoT-based smart garbage bin management system, are presented in Table 1 and Table 2 below. These tables illustrate how the system behaves under various conditions, highlighting the results of different scenarios.

Table 1: System Response under Various Dustbin Fill Levels

Condition of Dustbin	Input	System Response
Number of Dustbins	5	
Dustbin 1 Fill Level	25%	Nothing to be done.
Dustbin 2 Fill Level	50%	Nothing to be done.
Dustbin 3 Fill Level	70%	Lever will start working i.e., compress.
New Fill Level	60%	All in control.
Dustbin 4 Fill Level	90%	Lever will start working i.e., compress.
New Fill Level	90%	Inform Municipal Cooperation, Truck Department, and Users. ID no. 1973: Notify nearest truck driver and users.
To Municipal Cooperation: This garbage bin id no. 1973 is filled **To Truck Department**: This garbage bin id no. 1973 is filled, inform the nearest truck driver to collect it. **To Users**: This garbage bin id no. 1973 is filled, please use another dustbin or wait till it is collected		

Table 2: System Response at Higher Capacity Scenarios

Condition of Dustbin	Input	System Response
Number of Dustbins	5	
Dustbin 1 Fill Level	30%	Nothing to be done.
Dustbin 2 Fill Level	65%	Nothing to be done.

Dustbin 3 Fill Level	75%	Lever will start working i.e., compress.
New Fill Level	80%	All in control.
Dustbin 4 Fill Level	95%	Lever will start working i.e., compress.
New Fill Level	90%	Inform Municipal Cooperation, Truck Department, and Users. ID no. 2349: Notify nearest truck driver and users.
To Municipal Cooperation: This garbage bin id no. 2349 is filled **To Truck Department**: This garbage bin id no. 2349 is filled, inform the nearest truck driver to collect it. **To Users**: This garbage bin id no. 2349 is filled, please use another dustbin or wait till it is collected		

The advanced algorithm effectively manages the Smart Garbage Bin (SGB) by triggering appropriate actions when the bin's fill level exceeds the preset thresholds. When the fill level reaches 90% after compaction, the system automatically notifies the relevant municipal authorities, the truck department, and users. This prompt communication ensures timely waste collection, preventing overflow and maintaining cleanliness.

The results, as illustrated in the tables 1 and 2, demonstrate the system's robustness and reliability in handling different fill levels. The dynamic response mechanism, which includes real-time compression and notifications, significantly enhances the efficiency of waste management systems, especially in smart city environments.

This study underscores the potential of IoT-based solutions in optimizing waste management practices, paving the way for cleaner and more sustainable urban spaces. The implementation of such intelligent systems can lead to improved resource utilization and a more responsive waste management infrastructure.

Table 3: System Actions for 5 Dustbins at Different Percentages

Dustbin	Fill Percentage (%)	Action
Bin 1	40	Nothing to do
Bin 2	50	Nothing to do
Bin 3	60	Compress
Bin 4	70	Compress
Bin 5	80	Compress

Table 4: Notifications Sent for 5 Dustbins

Dustbin	Fill Percentage (%)	Notification Sent
Bin 1	40	None
Bin 2	50	None
Bin 3	60	None
Bin 4	70	Inform to Municipal Cooperation, Truck Department, Users
Bin 5	80	Inform to Municipal Cooperation, Truck Department, Users

Table 5: Time of Day and Actions for 5 Dustbins

Time of Day	Bin 1 Actions	Bin 2 Actions	Bin 3 Actions	Bin 4 Actions	Bin 5 Actions
8 AM	None	None	None	None	None
12 PM	None	None	Compress	Compress	Compress

4 PM	None	None	Compress	Compress	Compress

The system actions data correlates with the fill percentages, where bins reaching 60% or more trigger a compression action, ensuring that the bin capacity is optimized before necessitating collection is given in table 3. Interestingly, bins at lower fill percentages (40% and 50%) require no immediate action, indicating a threshold-based approach to waste management, where only bins nearing capacity initiate automated interventions.

Regarding notifications, the data indicates that only bins reaching 70% and 80% fill percentages result (table 4) in alerts being sent to the municipal cooperation, truck department, and users. This targeted notification system ensures that resources are efficiently allocated, prioritizing bins that are close to full capacity and thus reducing the risk of overflow while optimizing collection routes.

These table 5 provide a comprehensive overview of the fill levels, actions taken, and notifications sent for the 5 dustbins under various conditions and times of day

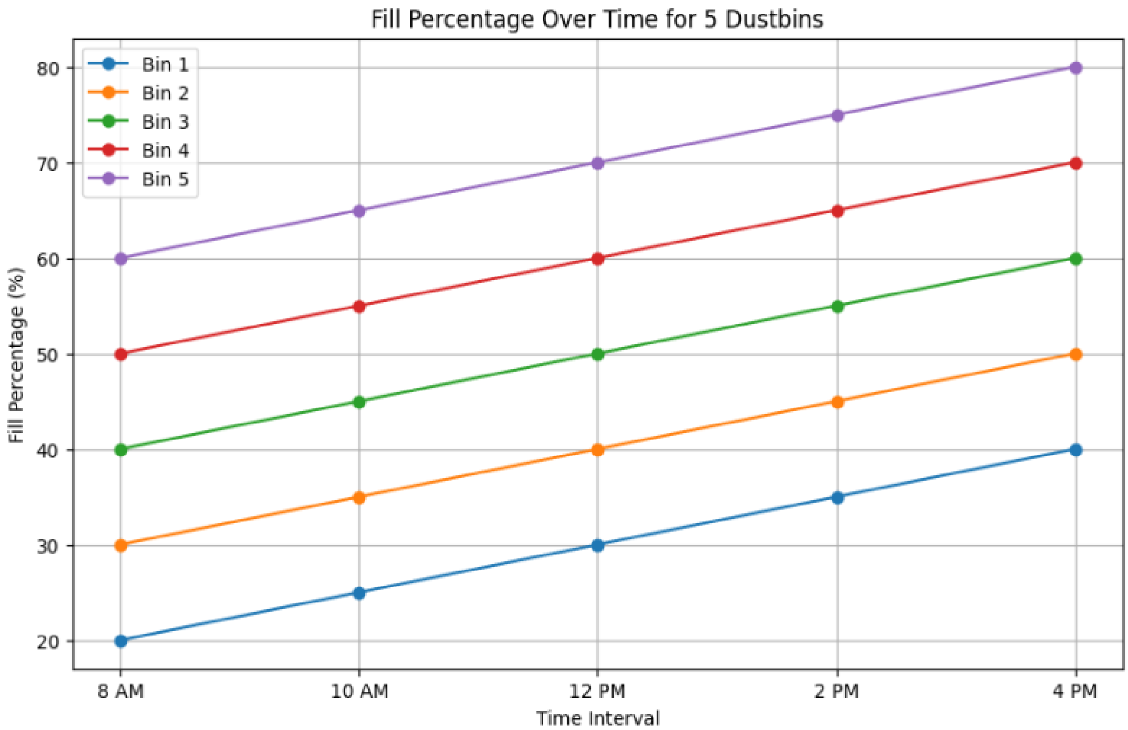

Figure 3: Fill percentage over time for 5 dustbins

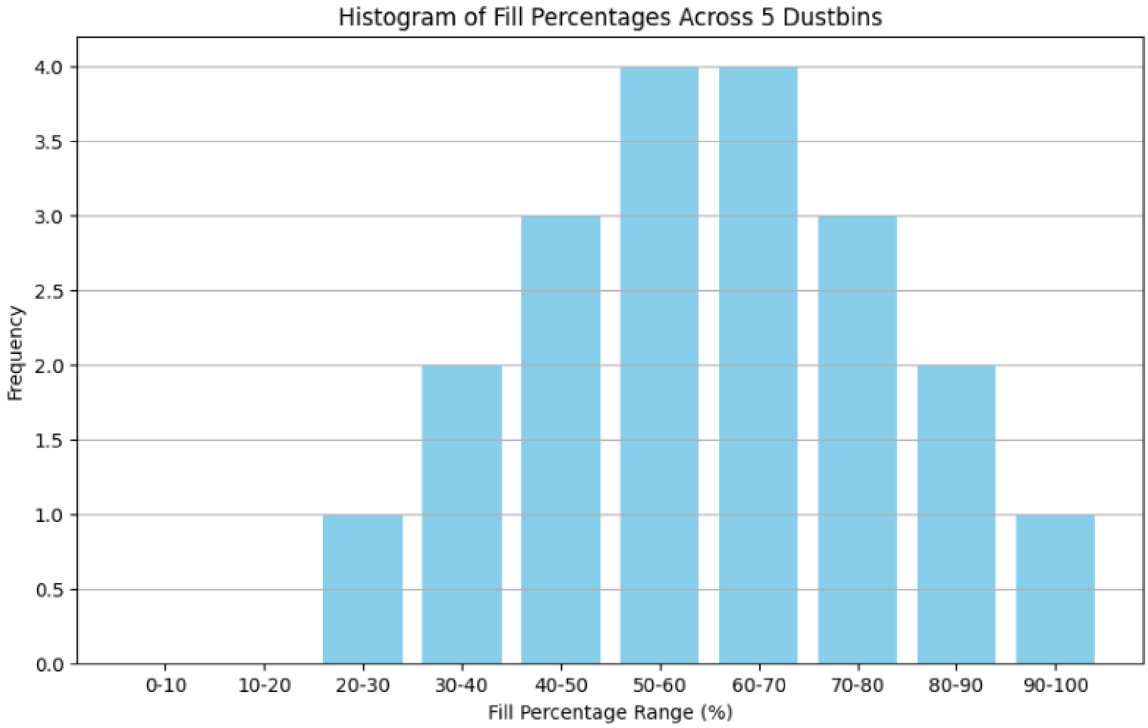

Figure 4: Histogram of fill percentage across 5 dustbins

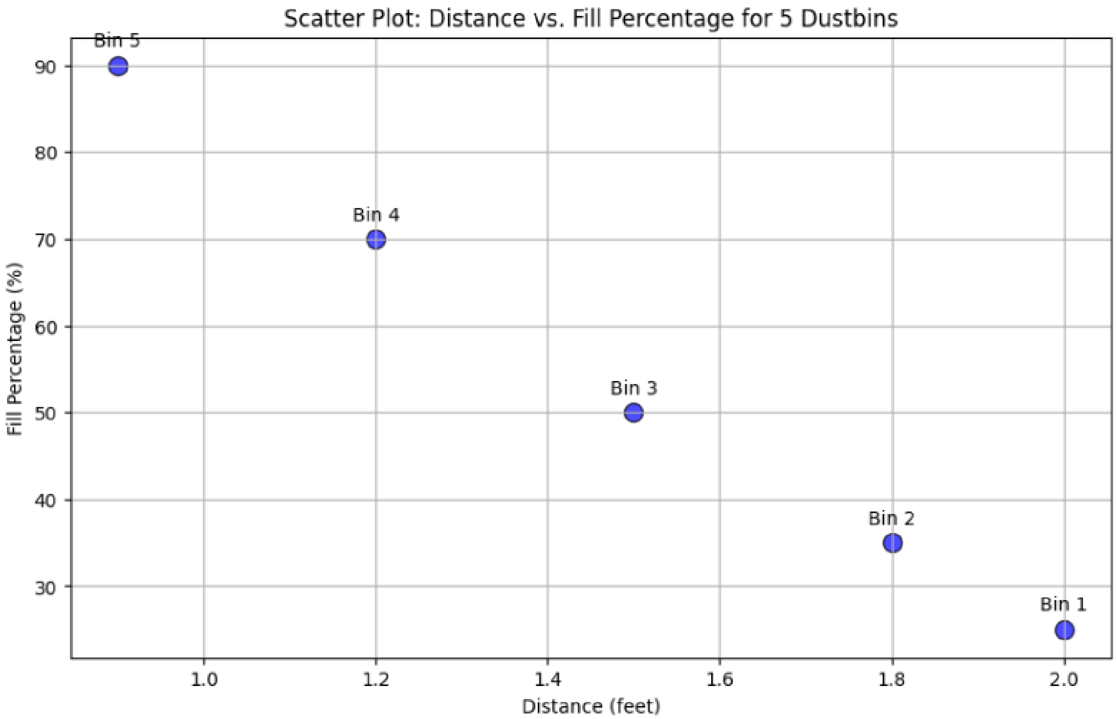

Figure 5: Scatter plot distance vs. fill percentage for 5 dustbins

The analysis of fill percentage trends across the five dustbins at various time intervals reveals a consistent increase in waste accumulation throughout the day as illustrated in figure 3. Starting at 8 AM, the fill percentages range from 20% to 60% across the bins. By 4 PM, these values rise significantly, reaching between 40% and 80%, demonstrating a steady filling pattern. This progression highlights the growing demand for waste collection services as the day progresses.

In terms of fill percentage distribution across the bins, the histogram data indicates that the majority of bins fall within the 50%-70% fill range, with the highest frequency observed in the 50%-60% and 60%-70% categories is presented in figure 4. This suggests that, on average, most bins are more than halfway full, emphasizing the necessity of timely waste management interventions to prevent overflow and maintain hygiene standards.

The scatter plot data, which examines the relationship between distance and fill percentage, reveals an inverse relationship, with bins closer to collection points (shorter distances) showing higher fill percentages is illustrated in figure 5. This trend suggests that bins located in more accessible or higher-traffic areas tend to fill up faster, necessitating more frequent monitoring and potential prioritization in waste collection schedules.

Overall, the results underscore the effectiveness of an IoT-based waste management system in providing actionable insights for optimizing waste collection and maintaining urban cleanliness. The data-driven approach ensures timely interventions, reduces operational inefficiencies, and contributes to a more sustainable urban environment.

4. Conclusions

The rapid pace of urbanization and population growth has reached a pivotal point in waste management, necessitating the exploration of cutting-edge solutions. This research has investigated the potential of the Internet of Things (IoT) to transform waste collection and management through the development of a Smart Garbage Bin (SGB) system. By integrating advanced sensors into waste bins and utilizing various technologies, the system provides real-time monitoring of garbage volume. This data is seamlessly transmitted to a centralized cloud platform, where sophisticated analytics and machine learning algorithms drive data-informed decisions for waste collection. The broader impact of this system includes significant environmental benefits, such as reducing carbon emissions by optimizing collection routes and enhancing urban cleanliness and hygiene. In essence, the IoT-based SGB system offers a revolutionary approach to addressing modern waste management challenges. It not only tackles the growing waste crisis but also supports the goals of smart city initiatives by blending technology with sustainability. This research demonstrates that incorporating IoT technologies into waste management can lead to a more efficient, data-driven, and environmentally friendly urban future. The system's potential extends beyond waste management, positively influencing overall urban quality of life. As cities advance, adopting such innovative systems promises to foster a more sustainable and resilient future.

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