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(Review Article)

IOT-driven system for waste collection monitoring and metal segregation

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Abstract

Waste management has posed a lot of challenges especially for developing countries like Nigeria. Waste bins are always seen overflowing where they are provided and at other places wastes are dumped indiscriminately on the streets. This does not only produce ugly scenes but when washed into drainage and underground waters can result to both environmental and health hazards. Government having awarded waste collection contract to individuals needs an effective means of monitoring their activities in order to ensure total compliance with terms of the contract. In Omagba phase two community of Onitsha, Anambra State, Nigeria for example, its waste management is characterized by improper disposal, insufficient bins, delayed collection of waste by truck drivers, nonchalant attitude of the contractor, inaccessible roads, ineffective monitoring by government officials among others. This paper therefore proffers solution to the aforementioned issues by harnessing the potentials of the bourgeoning internet of things which entails exchange of data among interconnected objects over the internet to provide the municipal authority with an efficient waste collection monitoring system devoid of human manipulations. The system provides a real time status of the connected waste bins at Omagba phase two community to the municipal authority by integrating smart sensors, microcontrollers, and cloud-based data analytics. It demonstrates successful real-time bin status monitoring, metal detection and segregation for recycling purpose with high accuracy as well as providing a scalable solution for smart city waste management.

Keywords: Sensors; Microcontroller; Smart Bin; IoT; Metal Segregation

1. Introduction

Internet of things (IoT) is a technology that allows objects to interact and communicate with one another over the internet. Objects in question can be any physical "thing" such as people, devices, buildings, animals, vehicles or any other entity that can be identified as part of everyday life. These entities are equipped with sensor devices, microcontrollers, suitable protocols and software applications, so that they can be monitored, controlled and linked over the Internet [1][2]. Thus, the advent of Internet of things has brought macro shift in the way things are done by providing advanced intelligent services for users in form of sensing, actuating, data gathering, storing, and processing. Its applications can be found in diverse areas such as wearable, healthcare, transportation, agriculture, smart cities and waste management.

Application of IoT to waste management stems from the need to address the amount of waste generated by households and industries in the ever-growing population of developing countries. In Omagba community of Onitsha, Anambra state, Nigeria, residents are tasked to pay monthly for waste collection, yet the process is not carried out effectively by the contractor. There is indiscriminate dumping of refuse, people are seen scavenging dumps for recyclable materials, wastes are not collected as and when due, streets are littered with dumps and when it rains wastes are washed into drainage. The consequence of all these is indeed catastrophic. Giving intelligence to trash bins in this community will therefore ensure proper monitoring of the contractor entrusted with the responsibility of waste collection and people

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can then get value for their money. This paper proposes a smart waste management system, where the waste bins in the community are equipped with IoT devices and linked to the municipal authority over the internet. The system in addition to real time notification on the status of bins will perform segregation of waste into metal and non-metal in different chambers for easy collection for recycling purposes. The mouthwatering benefits of IoT services in waste management have become an interesting issue to different stakeholders: individual, academia, industry, and government. Several researchers have done great works in the application of IoT to waste management. Medvedev et.al [3] proposed an Intelligent Transportation Systems that enables dynamic scheduling for truck drivers as well as surveillance system for problem reporting. The System performs data sharing among truck drivers on real time in addition to dynamic route optimization. In another work [4]; wireless sensor networks, Raspberry pi and gas sensor were utilized to identify fullness of bin and odour level and transmit same to the cleaning authority. In another research [5]; a model that provides information on solid waste and wet waste segregation using humidity sensor was proposed. The bins were connected in master slave configuration for effective communication in remote areas. IoT-Based Smart Garbage System for Efficient Food Waste Management was also proposed by [6]; where smart bins are connected together, resident information collected through RFID readers and the server collects and analyzes the status of all smart bins. In the work of [7]; they proposed a system that applied Geographic Information Systems (GIS), graph theory on graph optimization, and machine learning with sensors to measure the waste volume in trashcans or containers, with the capability of transmitting information to the Internet via a wireless link. The collected data is then used for optimizing the daily selection of trashcans to be collected, calculating the routes accordingly and sending to the workers the calculated routes in their navigation devices.

2. Related work

The application of IoT in waste management has received increasing research attention. Early implementations primarily addressed bin monitoring and remote data transmission. Medvedev et al. [9] introduced a dynamic routing system with real-time surveillance, though it did not support waste segregation or user interaction. Kusum and Shri [10] used gas and ultrasonic sensors for odour and fill level detection. Mahajan et al. [11] extended this by incorporating humidity-based segregation but offered no routing optimization or local feedback systems. Nair and Sinha [12] developed an ESP32-based sensor network enabling decentralized waste bin intelligence; however, their system was limited to status monitoring. Ajayi et al. [13] introduced vision-based sorting using ESP32-CAM, although the model's dependence on lighting and image clarity limited its outdoor usage. Patel et al. [14] proposed an energy-efficient LoRa-based smart bin that remains operational in low-connectivity areas, but did not address material segregation or local display feedback. Silva and Andrade [15] tackled public health integration through temperature and motion sensors, yet, ignored core waste classification. Chen et al. [16] implemented AI-enabled IoT models for real-time classification and routing but required stable internet and cloud AI training. Mendez et al. [17] demonstrated the viability of long-term battery-operated bins but omitted advanced functionality like metal detection or adaptive sorting. Rahman et al. [3] introduced an AI-enabled waste classification unit based on the ESP32-S3 platform, using edge computing to reduce latency in metal and plastic detection, though the system lacked a real-time feedback interface for end users. Kumar and Dube [4] proposed a LoRa-based smart bin mesh network with predictive analytics for bin filling cycles, yet their system relied heavily on cloud access, limiting effectiveness in regions with unstable internet connectivity. Similarly, Torres and Aliyu [5] developed a smart bin that integrates environmental sensors and solar power with adaptive waste routing systems; however, it did not offer waste type separation onboard. Adeyemi et al. [6] explored the use of ultrasonic sensor arrays and computer vision for comprehensive waste classification in Nigerian cities, but the high cost of implementation restricted its scalability for rural areas. Comparatively, Chinedu and Umeh [7] focused on implementing low-cost IoT bin solutions in southeastern Nigeria, introducing GSM-based notification systems for areas lacking internet coverage. While the approach improved communication reliability, it did not integrate sorting functionality for recyclable materials. In contrast, Wang et al. [8] proposed a hybrid ESP32 + OpenCV system for smart sorting and cloud analytics, this however, requires significant processing capacity and better suited to industrial rather than public street use.

Despite these innovations, limitations such as insufficient local display interfaces, lack of onboard metal segregation, and inadequate overflow bin redirection persists. This paper builds upon current and previous efforts by introducing a system that integrates multiple sensors, servo-based metal segregation, real-time OLED display, and cloud notification via ESP32, thereby addressing the challenges of existing works.

3. Materials and Method

The system consists of multiple IoT-enabled sensors, a microcontroller, and a wireless communication system. The sensors are designed to monitor waste bin levels, detect metal objects, and track the movement of waste containers for optimized collection schedules.

3.1. Hardware Components

- **ESP32 Microcontroller**: The ESP32 was selected for its high-performance capabilities, Wi-Fi connectivity, and power efficiency. It serves as the central unit for processing sensor data and transmitting it to the cloud.
- **Ultrasonic Sensors (Level Detection)**: Ultrasonic sensors (e.g., HC-SR04) are used to measure the fill level of waste bins. These sensors emit sound waves and measure the time taken for the echo to return, providing accurate distance measurements to detect the waste level.
- **Metal Detection Sensor**: A metal detection sensor (e.g., induction coil-based or capacitive) is used to detect the presence of metal objects within the waste. The sensor outputs signals based on the presence of metallic materials.
- **PIR Motion Sensor**: A passive infrared (PIR) motion sensor is used to detect the presence of human activity near waste bins. This information helps in tracking waste bin usage and ensuring that bins are not overfilled.
- **Wi-Fi Module**: The ESP32 comes with an integrated Wi-Fi module, which is used to transmit data to a cloud-based platform for real-time monitoring and alerts.
- **Power Supply**: A battery-powered system is used to ensure the IoT nodes can operate autonomously for long durations without external power sources.

3.2. Software Components

- **Firmware Development**: The system's firmware is developed using the Arduino IDE and ESP32 libraries, which allow for easy integration with various sensors. The firmware includes algorithms for reading sensor data, processing it locally, and transmitting it to a central server via MQTT or HTTP.
- **Cloud Platform**: The data from the sensors is sent to a cloud-based platform (e.g., Thing Speak, Firebase, or custom-built server). The platform is used for data storage, real-time analytics, and visualization through a user interface (UI) or mobile application. Alerts for bin overfill or metal detection are triggered on the cloud platform for immediate action.
- **Database**: A SQL/NoSQL database is used to store sensor data and track waste collection schedules, bin usage statistics, and metal segregation reports. The database facilitates data retrieval for further analysis.

3.3. Methodology

- **Sensor Calibration**: The ultrasonic sensors are calibrated to ensure accurate measurements of waste levels. The metal detection sensor is calibrated to differentiate between metal and non-metal materials.
- **Data Collection**: Data is continuously collected from the sensors, including:
    - Waste bin fill level (from ultrasonic sensors)
    - Presence of metals (from metal detection sensors)
    - Motion detection (from PIR sensors)
- **Data Transmission**: The sensor data is processed locally on the ESP32 and transmitted to the cloud at regular intervals (, every 5 minutes). The data includes:
    - Waste bin status (empty, partially filled, full)
    - Metal detection status (metal detected or not)
    - Motion detection status (human presence detected or not)
- Data Processing and Analysis: On the cloud platform, the data is analyzed for patterns such as waste bin fill trends, peak waste generation times, and metal segregation efficiency. The system is designed to provide notifications to waste collection services when bins reach their capacity or if metals are detected.
- **System Testing and Validation**: The system is tested under various conditions: different waste types, bin sizes, and environmental factors to validate its accuracy and reliability. The performance of the metal detection sensor is also evaluated with a range of metallic objects to ensure proper segregation.

The structural design of the system is as depicted figure 1. The system comprises different components: microcontroller, sensors, Wi Fi module, trash bin, internet and monitoring center.

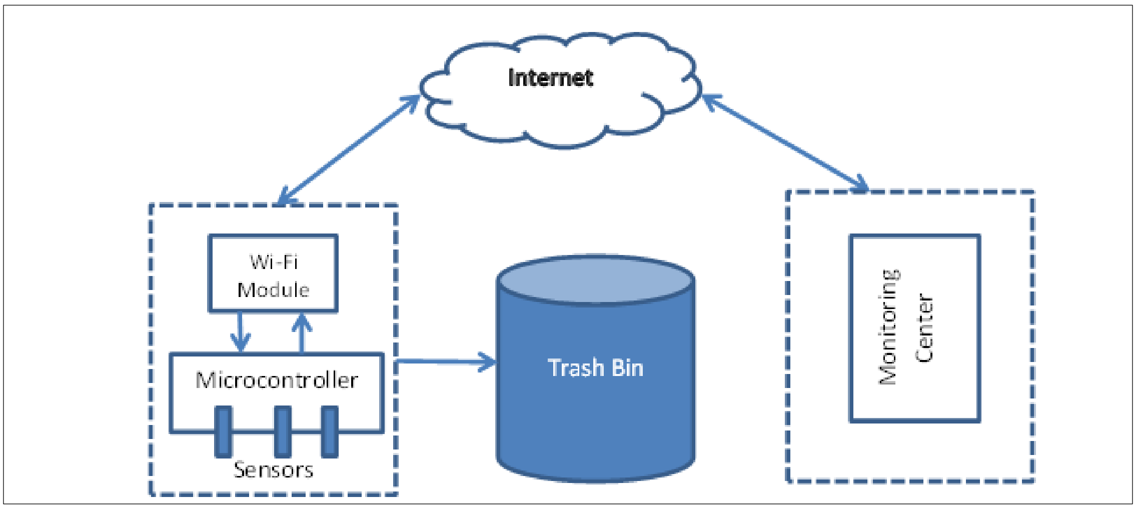

Figure 1 Architecture of The Proposed System

3.3.1. Microcontroller

The bin is interfaced with microcontroller (Arduino Uno-ESP32). It is a powerful microcontroller for IoT applications, mobile devices, and wearable electronics. ESP32 integrates Wi-Fi and Bluetooth capabilities, making it a versatile choice for various projects. Featuring a dual-core Xtensa LX6 processor, it allows for efficient multitasking while maintaining ultra-low power consumption with multiple power modes and dynamic power scaling. The ESP32 includes built-in sensors such as a Hall sensor and capacitive touch sensors, alongside a wide range of GPIO pins for interfacing with peripherals. It also supports various communication protocols like SPI, I2C, UART, and PWM, ensuring compatibility with numerous external components. The microcontroller collects data from the sensors and forwards same to the internet via the Wi-Fi module. Its low power consumption rate and versatility recommend it for use in this application

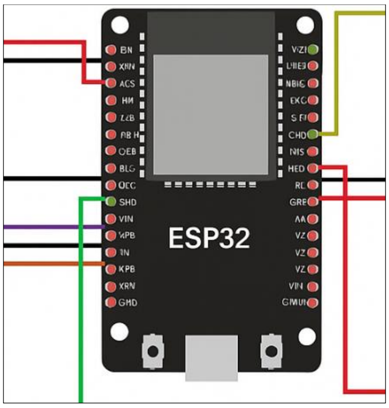

Figure 2 Arduino Uno ESP32

Wi Fi is preferred over other wireless connectivity options like BLE, zigbee, z-wave and RFID in terms of IP addressability which is a requisite for IoT technology.

3.4. Sensors

The system is equipped with three types of sensors viz: level sensor, motion sensor and the metal detector.

3.4.1. Level sensor

level sensor is to determine when the waste has reached the maximum threshold. Ultrasonic sensor HC-SR04 distance sensor is proposed. This is a 4-pin module, and is used where measuring distance or sensing objects is required. Typical measuring distance is 2cm to 400cm. The current consumed by the sensor is less than 15mA and hence can be directly powered by the on board 5V pins where available. The Trigger and the Echo pins are both I/O pins which can be connected to I/O pins of the microcontroller.

Figure 3 HC-SR04 ultrasonic sensor

3.4.2. Motion detector

Motion detector can be used to detect motions within an environment. There are active and passive motion detectors. However, a passive infrared motion detector (PIR) is employed. The system works on the principle of emitted infrared energy given off by humans and animals in the form of heat. When there is a sudden increase in infrared energy, the sensor registers this change in energy level and in turn signals the control box to take an action.

Figure 4 Passive Infrared Motion detector

3.4.3. Metal detector

This monolithic integrated circuit is designed for metallic body detection by sensing variations in high frequency eddy current losses. The output signal level is then altered by an approaching metallic object. The TDA016 monolithic integrated circuit is considered suitable for this work for its cost effectiveness and low voltage capability. It operates on 10mA output current, oscillator frequency 10MHz and supply voltage +4 to +35V.

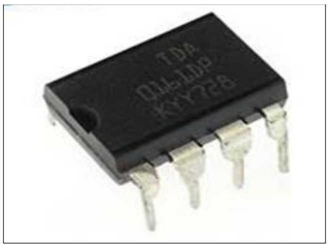

Figure 5 TDA016 metal detector

3.4.4. The servo

A servo motor is employed to facilitate the physical segregation of metal waste from non-metallic materials. When the metal detection sensor identifies the presence of a metallic object in the waste stream, it sends a signal to the ESP32 microcontroller. The ESP32 then triggers the servo motor to rotate to a predefined angle—typically 90 degrees—causing a mechanical flap or gate to redirect the metallic waste into a designated metal collection bin. If no metal is detected, the servo remains in its default position, allowing the waste to fall into the general waste bin. This process is automated and coordinated through programmed logic in the ESP32, ensuring real-time response and efficient separation. After each operation, the servo resets to its original position to prepare for the next detection cycle, thus enabling continuous, hands-free metal segregation.

The arrangement used for this system is as depicted in the block diagram of figure 6

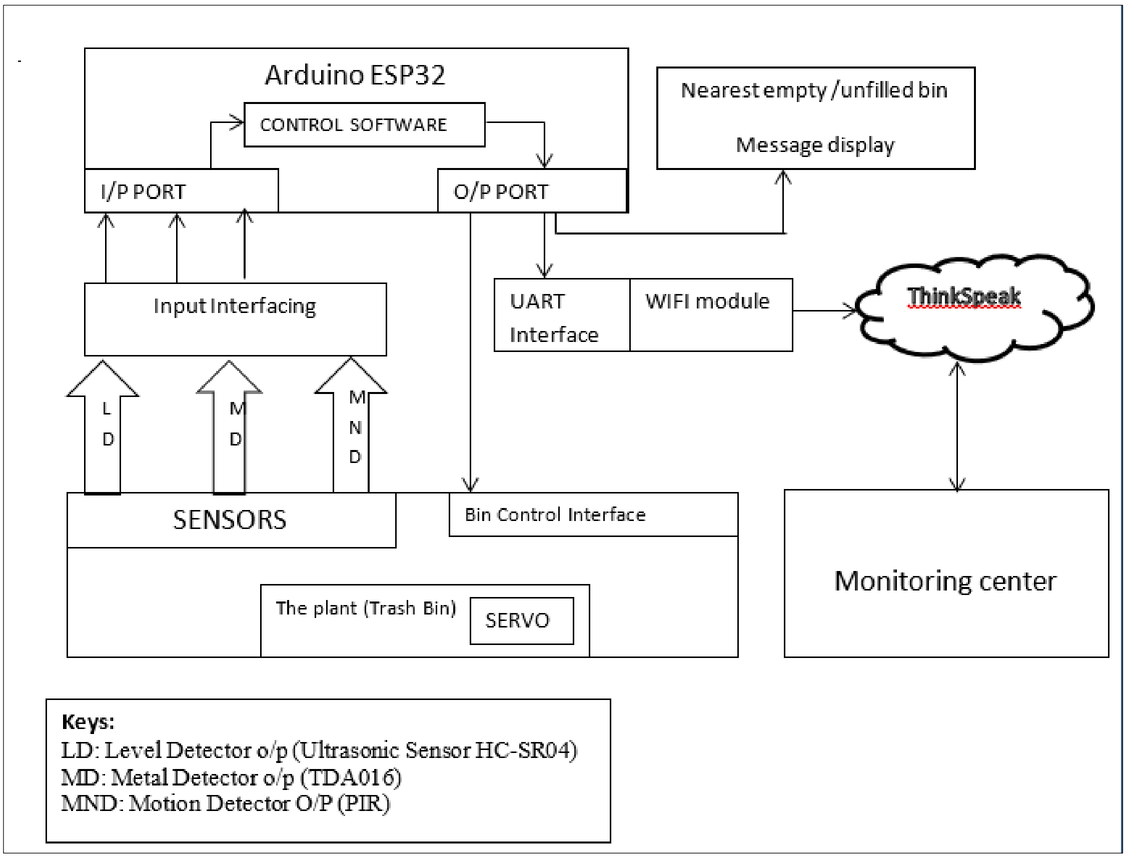

Figure 6 Block Diagram of the Proposed System

The proposed IoT-driven waste management system was developed and tested in a simulated environment. Using simulation tool - Proteus and ThingSpeak. The functionality of key components—including the ESP32 microcontroller, ultrasonic sensor, metal detection module, PIR motion sensor, and servo motor was emulated to validate the system's performance. The servo motor's role in waste segregation was simulated to demonstrate its response to metal detection signals by redirecting waste toward a designated bin. Sensor data was transmitted via virtual Wi-Fi to a cloud-based dashboard for real-time monitoring and analysis. This simulation approach enabled thorough testing of system logic, sensor integration, and response mechanisms without the need for physical hardware, providing a reliable basis for future physical implementation.

4. Results and discussion

Operations of the smart waste bin were simulated. Waste bins are situated at different locations in the community and are given unique ids for proper identification on the network. Each of them is interfaced with Arduino Uno microcontroller with integrated Wi-Fi module, sensors, servo motor and separation chambers. The bins have two chambers each to hold the metals and non- metals waste.

The bin will initially be set to idle mode. On sensing movement by the motion detector within the specified range, signal is sent to the microcontroller which in turn triggers the motor that controls the lid of the waste bin to open for dumping of waste.

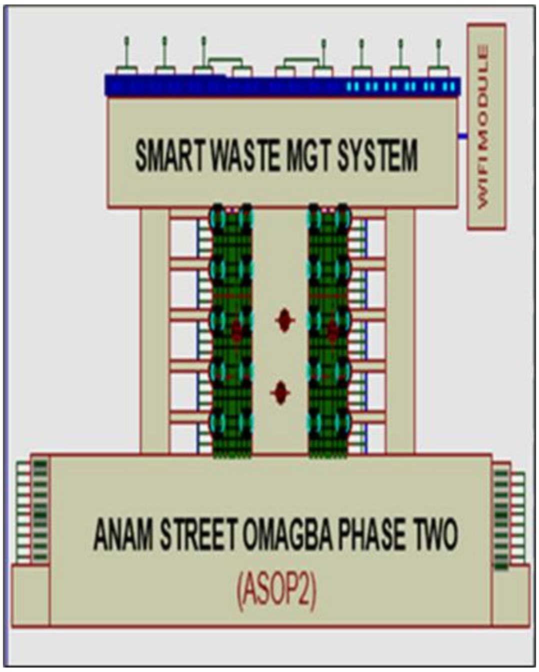

Figure 7 Smart waste

The waste is then scanned by the metal detector for metals, and if detected, the servo/robotic arm will pick the metal, move to the set angle and place it in designated chamber.

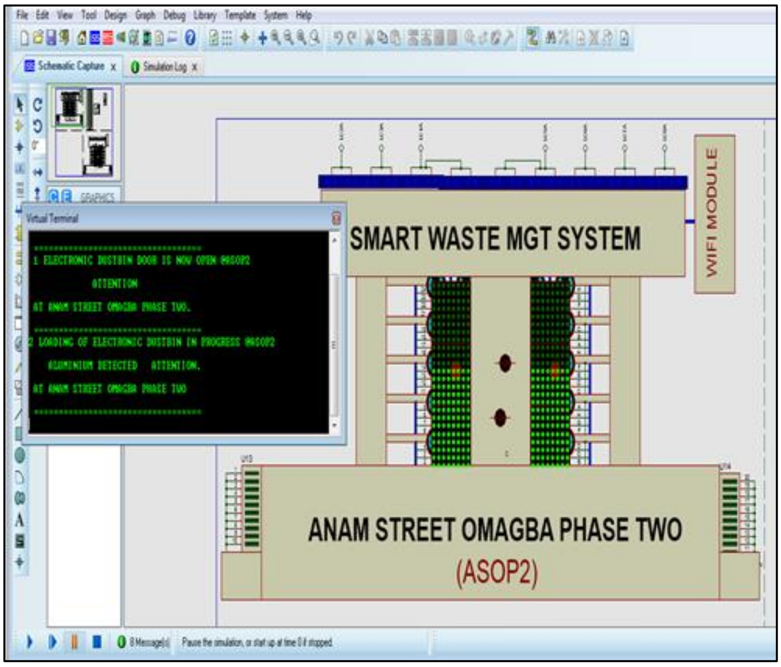

Figure 8 Waste 50% filled

The ultrasonic sensor is then used to measure the level of waste in the bin. It is programmed to send signal to the microcontroller via trigger and echo pins when the waste in the bin has reached a maximum level. On reaching the maximum level, the lid of the bin is closed and cannot open until the content is removed. The microcontroller will then notify the authority through the Wi-Fi module to send disposal truck to the location for waste collection. More so, messages will be displayed on the bin indicating nearest bin location yet to be filled.

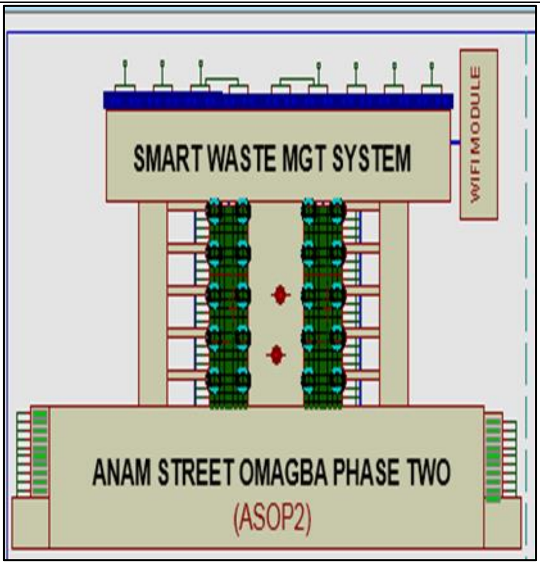

Figure 9 Filled waste bin with detected metal

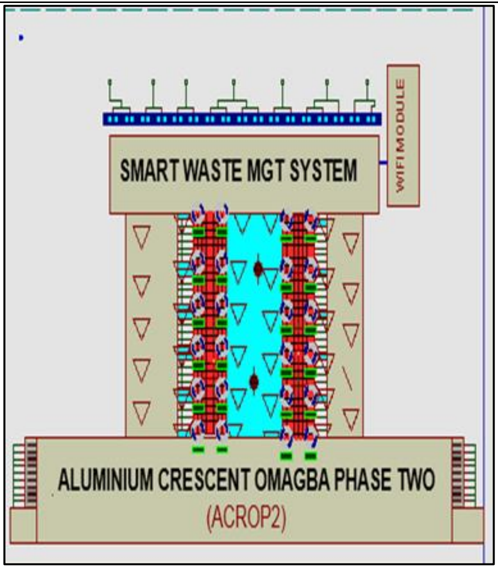

Figure 10 Separated metals

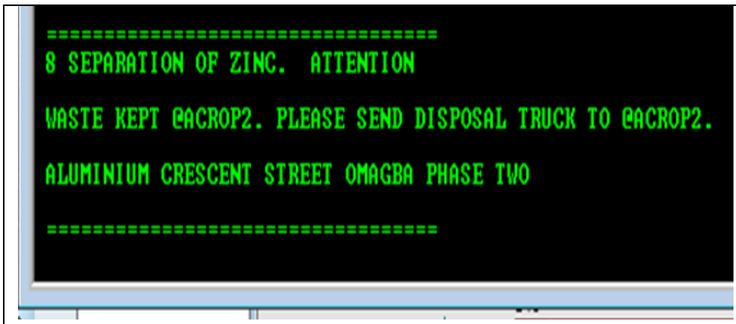

Figure 11 Notification Message

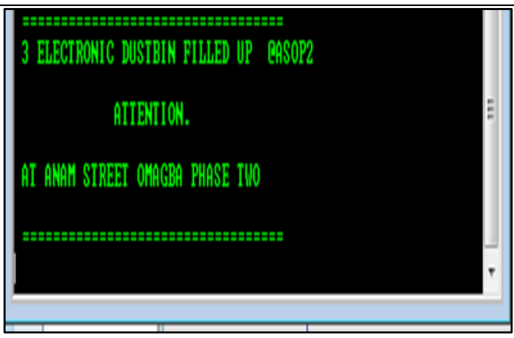

Figure 12 Notification Message

Table 1 Simulated System Performance Evaluation

Parameter	**Component**	**Simulated Result**	**Remarks**
Waste Level Detection Accuracy	Ultrasonic Sensor	95%	Reliable for bin fill levels between 2–40 cm
Metal Detection Response Time	Metal Sensor + Servo	1.2 seconds (average)	Fast and consistent switching
Metal Detection Accuracy	Metal Detection Sensor	92%	Occasional false positives in mixed waste
Motion Detection Accuracy	PIR Sensor	96%	Effective in detecting nearby human movement
Data Transmission Delay	ESP32 Wi-Fi to Cloud	< 2 seconds	Near real-time communication
Alert Triggering Time	Cloud Platform (Thing Speak)	1–3 seconds after threshold breach	Sufficient for timely response

Power Consumption (Estimated)	Entire IoT System	~250 mA during peak operation	Suitable for battery or solar-powered systems
Dashboard Data Refresh Rate	Thing Speak Cloud	Every 15 seconds	

5. Conclusion

IoT-driven smart waste bin system using the ESP32 microcontroller was simulated. The system integrates multiple sensors, including an ultrasonic sensor for bin level monitoring, a PIR sensor for motion detection, and a TDA0161 metal detector for metallic waste segregation. A servo motor acts as a mechanical actuator to divert metal waste into a separate chamber. An Organic Light Emitting Diode (OLED) screen provides real-time visual feedback to users, while Wi-Fi connectivity enables cloud-based monitoring.

Smart waste management will go a long way in alleviating the difficulty encountered by municipal authorities in monitoring contractors entrusted with the responsibility of waste collection. The issue of transportation cost and the risk of moving to different locations in order to ensure total compliance on the part of the contractor will be reduced. More so, metal wastes can be easily collected for recycling purposes instead of scavenging dumps for them. Again, data such as the area that generates highest waste, amount of metal waste collected from each bin, among others can be analysed and used for proper planning in the area of route optimization for truck drivers and forecasting disposal sequence. Thus, this solution offers municipal authorities an automated, scalable, and efficient approach to waste tracking and recycling optimization

Though this work is an improvement over the existing one, it is suggested that technique to compress the waste should be included in future works to reduce the number of times needed for truck scheduling.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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