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Design and Development of Automated Smart Waste Bin for Smart City Development in Nigeria

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ABSTRACT
Improper solid waste management is a growing concern in many urban areas, leading to environmental pollution, health hazards, and unsightly living conditions. Manual solid waste collection methods have proven to be inefficient and require a significant amount of human labour. In addition, traditional refuse bins are often overloaded, causing litter to spill onto streets, sidewalks, and other public areas. Thus, there is a need for an efficient and automated waste management system that can reduce the labour and time required for waste collection, improve public health and hygiene, and minimize environmental pollution. Guided by the Design Science Research Methodology, this study explores the design and development of a prototype automated smart refuse bin that utilises a microcontroller equipped with multi-directional proximity detection, bin level detection, temperature and humidity detection, fire detection, automatic lid open/close, bin status display screen, buzzer for alerting disposers, GPS location detection, and SMS notification module for sending alerts to the relevant waste collection agents. Experimental findings highlight the robustness and feasibility of the proposed method, demonstrating its potential as a practical solution for efficient automated waste management and, more importantly, fostering smart city development.

General Terms
Embedded systems, IoT, Smart city, Sustainable development.

Keywords
Waste containers, Waste disposal, Waste management.

1. INTRODUCTION
Waste materials are discarded items or objects that are no longer needed or used by humans. Solid waste can be classified into various types: green waste, recyclable waste, industrial waste, hospital waste, electronic waste, commercial waste, and organic waste [1]. If solid waste is not properly disposed, they are capable of posing a significant problem for public health and the environment.

Waste management is a major challenge faced by various societies worldwide. Previous studies have highlighted the issues associated with the collection, storage, transportation, and final disposal of refuse in Nigeria [2]. The traditional methods of waste disposal, such as: open dumping, open air burning, and burying have proven to be ineffective and hazardous.

In many urban areas in Nigeria, waste management currently entails periodic refuse collection from designated refuse dump sites. Where waste bins are provided, many people are reluctant to touch the lids of the waste bins when emptying their refuse for fear of contacting infections or contagious diseases. Even when the waste bin is left ajar, they are often left unattended for several days by waste collection agents. As a result, it is not uncommon to find the vicinity of the waste collection site littered with refuse that emits a sickening pungent smell capable of facilitating the spread of diseases [3]. The recent spread of Cholera in many urban areas in Nigeria was attributed to improper waste management and sanitary conditions [4].

The rapid population growth in many urban areas in Nigeria has made waste management even more challenging. In densely populated areas (Wimpey, Choba, Rumuola, Rumuodara, Waterlines, Rupokwu and Ozuoba) in Port Harcourt city, which is in Rivers State, Nigeria, Elechi et al. [5] observed, using Matlab/Simulink simulation, that waste bins got filled up to 100% on the fifth day. Thus, by the time waste collection agents come for their weekly exercise, the waste bins are over filled and waste litters the entire vicinity.

In a survey carried out in three LGAs (Asaba, Warri and Ughelli) in Delta State, Nigeria with a study population of 675,149, Obru-Egboro and Eze [6] examined the existing operational management techniques of solid waste. Using purposive sampling technique and applying the Slovin's sample size determinant formula, a sample size of 400 respondents received structured survey questionnaires. Using percentages, tables and pie charts to analyze the data, it was observed that some households consist of up to 6-8 persons (33%), thereby putting pressure on services such as solid waste management.

The empirical study by Obru-Egboro and Eze [6] also observed that in Kano (Northern Nigeria), 79.25% of the respondents dispose waste in unauthorized dumpsites and 68% complained of poor waste collection by the agencies. There is therefore a need for improved seamless waste management processes using modern day information and communication technology (ICT).

If modern day ICT technology and artificial intelligence is applied in waste logistics, Fang et al. [7] estimates that it can significantly reduce transportation distance by up to 36.8%, cost savings by up to 13.35%, and time savings by up to 28.22%. Embedded system quickly comes to mind in designing hardware driven systems. An embedded system is a computer hardware system that includes embedded software [8]. It is designed with a specific purpose in mind and can be based on microcontrollers or microprocessors. It can function as a standalone unit or be part of a larger system.

At a smaller scale, embedded systems can be used to create a Home Automation System to enable users to remotely monitor/control various home sub-systems, such as: lighting, temperature, surveillance, intrusion (motion), access control, fire detection, and electrical appliances [9], [10]. At a larger scale, embedded systems can be integrated across a geographical area to establish a Smart City initiative. At a global scale, embedded systems can communicate with other physical and virtual things, across distances, as part of a global network, called the Internet of Things (IoT).

In a bid to further improve upon their sustainable development practices, several countries have invested significantly in establishing Smart Cities, but waste management remains a significant challenge. The principal objective of a Smart City is to integrate and manage a city's resources (such as: transportation, healthcare, commerce, education, utilities, law enforcement), as well as the city's various e-government information systems. The ultimate aim of a Smart City is to improve the quality of life of citizens and the efficiency of the city's services and processes, ensuring that citizens' day to day needs are met and that the citizens are empowered to affect the city's functioning.

For Nigeria to join the league of countries with Smart Cities, there is a need to deploy automated smart waste management technology. The use of modern technologies in waste management has the potential to reduce the overall environmental impact [11]. Through the use of an embedded system, a smart waste bin can be designed for a more efficient and automated waste monitoring, disposal, recycling, and general waste management.

2. LITERATURE REVIEW

The use of smart waste bins in an interconnected Smart City network can optimize waste collection efficiency by prioritizing bins in need of urgent attention. This will ensure that waste containers are not prematurely emptied, reducing unnecessary waste disposal trips. Moreover, the system will enable city authorities to gain real-time insights into waste level trends, fostering data-driven and proactive waste management strategies for a cleaner, more sustainable urban environment.

A Smart City architecture typically comprises of four essential components: signal sensing and processing layer, network layer, intelligent user application layer, and IoT web application layer [12]. To help in route planning whenever waste collection agents go around with the waste collection trucks, Ishola et al. [13] developed an Android smartphone-based system that utilizes Google Map to display the geo-location of waste bins. However, the system does not have any intelligence built into it to alert waste collection agents of waste bins in need of urgent attention.

Utilizing an Arduino board fitted with ATmega328 microcontroller, proximity sensors, gas sensors, and temperature sensors in the signal sensing and processing layer, together with a Wi-Fi/GSM transceiver which served as the network layer for Internet access, Adeyemo et al. [14] developed a smart waste bin system that made use of a non-browser client application equipped with statistical feature extraction method and pattern classifiers to function as an intelligent user application layer. The IoT web application layer was realised using ThingSpeak, an online web application for IoT based projects. Two GP2Y0A02YK0F proximity sensors with a functional range of up to 150cm were used for bin fill level detection. The waste bin was calibrated into five different levels: level 1, level 2, level 3, level 4 and level 5 representing empty, quarter-full, half-full, three-quarter-full and full statuses respectively. Two MQ 135 gas sensors were used to measure the gaseous emission from the decomposing refuse. Gaseous emissions that can be measured include benzene, methane (CH_4), hexane, and carbon monoxide (CO). Two LM35 temperature sensors were used to measure the temperature of the refuse. The temperature sensors were calibrated directly in Celsius with linear +10 mV/°C scale factor and rated for full −55°C to 150°C. Sensors were duplicated to incorporate redundancy in the circuitry, eliminate data sparsity and provide holistic coverage. However, this system lacks sensors for proximity detection of disposers as they approach the waste bin; and also lacks a servo motor for automatic lid open/close.

For improved solid waste collection, Elechi et al. [3] developed a smart waste bin using PIC18F4620 as the microcontroller integrated with a proximity sensor for detection of disposers, ultrasonic sensors for fill level detection, a smart switching board for automatic lid open/close, a GSM module for sending messages to the waste collection agents whenever the waste bin needs urgent attention, and a 900MHz transmitter for providing route-map. If a disposer approaches a waste bin that is filled up, a message is displayed on a Liquid Crystal Display (LCD) directing the disposer user to nearest waste bin yet to be filled up. However, this system did not have provision for temperature detection, foul smell detection, or smoke detection to cater for other emergency scenarios.

In a follow up study, Elechi et al. [5] incorporated HC-SRO4 ultrasonic sensor to detect a disposer approaching from up to 30cm away, which triggers a servo motor to automatically open the lid and keeps the lid open until the disposer has retreated beyond the functional range of 30cm. The system was also equipped with another HC-SRO4 ultrasonic sensor to measure the waste level, which triggers a message through a GSM module to the relevant waste collection agencies when the waste bin is full. However, this system did not take into consideration other emergency scenarios that could warrant the attention of the waste collection team, such as: foul odour detection, smoke detection, fire detection, and temperature detection.

A similar approach was adopted in the smart waste bin system developed by Abdullahi et al. [15]. It made use of Arduino Uno microcontroller integrated with one HC-SR04 ultrasonic sensor for fill level detection, another HC-SR04 ultrasonic sensors for proximity detection, LED indicator, servo motor for automatic lid open/close, and a SIM800L module for sending messages to waste collection agents. The system was designed to only open the lid if the waste level is not full. However, the system lacks consideration for temperature detection, smoke detection, and fire detection.

After examining several proposed smart waste bin systems, the following limitations were identified: many of the systems did not attempt to detect smoke, fire, or temperature changes which could be an indication of a likely hazard requiring urgent attention by the waste collection agents; many of the systems did not incorporate proximity detection of users; and more importantly, many of the systems did not feature automatic lid open/close which is the likely cause of disposers opting to drop waste around the vicinity rather than touching the lid for fear of contacting infections or contagious diseases neither were there able to send evacuation messages to authorities. Where some of these are present, they are in isolation instead of incorporating all these features in a single system.

This study seeks to address these limitations by providing a more efficient waste management system through the development of a more robust automated smart waste bin. The objectives are as follows:

1) Conduct requirements analysis for an automated smart refuse bin using related literature;

2) Design an optimized automated smart refuse bin using Unified Modelling Language;

3) Develop a prototype automated smart refuse bin using sensors and actuators integrated on ESP32-S3 development board; and

4) Conduct extensive usability and performance tests of the automated smart waste bin and compare with existing systems.

By so doing, this study will contribute to promoting public health and cutting down operational inefficiencies. Most importantly, the proposed system is designed to readily integrate with other city services and e-government information systems to enable Nigeria join the league of countries that deploy Smart City initiatives to further their sustainable development goals.

3. METHODOLOGY

3.1 Research Design

This study is guided by Design Science Research methodology, which is appropriate for studies that seek to create and evaluate an artefact intended to solve a problem in the society [16].

3.2 System Design

The selection of a sensor is based on its performance and specific physical transduction capability. An ultrasonic sensor estimates distance regardless of the colour and illumination of an obstruction. Ultrasonic sensors are primarily used for distance detection. Ultrasonic sensors offer a range of detecting angles to prevent the sensor beam from missing any object. JSN-SR04T (waterproof) ultrasonic sensor were used for multi-directional proximity detection of users while HC-SR04f ultrasonic sensor was used for bin fill level detection. DHT11 was utilized to measure both temperature and humidity in the surrounding environment. A flame sensor module was incorporated for fire detection to ensure system safety.

The ultrasonic sensor has two mesh holes, one to emit sound and the other to capture sound. The advantage of ultrasonic sensing is its ability to discern fine details regardless of the media, except for vacuum, as ultrasound can pass through solids, liquids, and gases. The distance between the smart waste bin and an incoming person is calculated using this formula:.

$$D=\frac{T\times S}{2} \tag{1}$$

where D is distance; T is time it takes for the pulse from sensor to travel from the smart waste bin to an approaching next object; and S is the speed of sound in air.

Effective communication is a crucial aspect of any smart sensing system. For this smart waste bin, NEO-7M Global GPS module was used for location detection. This was complemented with SIM800 GSM module for sending alerts to the relevant waste collection agents.

A 1.3" OLED screen was used as the display component to alert disposers about the bin status. This was complemented with a buzzer for emitting audible alerts whenever smoke or fire is detected by the flame sensor. Whenever the proximity sensor detects the presence of a disposer and the bin fill level is not full, the HM-MS10 (25kg) high-torque servo motor is activated for automatic lid open/close. To ensure round the clock operation, the smart waste bin is powered with a 12V/20A Lithium-ion battery pack, connected to a 100W/18V solar panel for uninterrupted power supply.

The servo motor is an actuator that is commonly used in robotics and automation systems. It is a closed-loop control system that includes a motor, a position feedback sensor (usually a potentiometer), and a controller. The motor rotates the output shaft to a desired position, and the feedback sensor detects the actual position of the shaft. Servo motors are known for their high precision, accuracy, and speed control. This server motor automatically opens/closes the bin lid whenever a disposer enters/exits its signal coverage range.

The OLED is an electronic display device that changes its optical properties by applying a varying electric voltage to a layer of liquid crystal. This is used to display the various outputs by the smart waste bin.

The buzzer transforms audio patterns into sound signals for the purpose of audio signaling. It is used in the smart waste bin to emit audible alarm or warning.

All these components are interconnected with connecting wires. The wires are an essential component of the circuit. They are used to connect different components of a circuit to a power source and/or microcontroller. They come in different gauges, which determine the amount of current that they can carry. Connecting wires are often colour-coded to indicate their function or polarity, which makes it easier to connect them correctly in a circuit.

The activity diagram is one of the diagrams of Unified Modelling Language which describes the dynamic aspects of the system. It is essentially an advanced version of flow charts and model the flow of operations from one activity to another. Figure 1 is the activity diagram of the system showing: lid opening/closing.

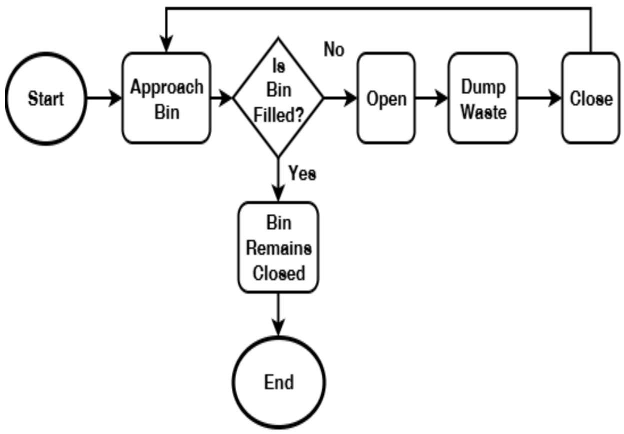

Figure 1: Activity diagram for opening and closing of lid

A sequence diagram describes how objects or group of objects interact within a system. Interacting objects can, for example be classes, program components or the real-world instances. Sequence diagram is an “interaction diagram” that models a single scenario executing in a system. Figure 2 shows the sequence diagram for fire and above threshold temperature detection.

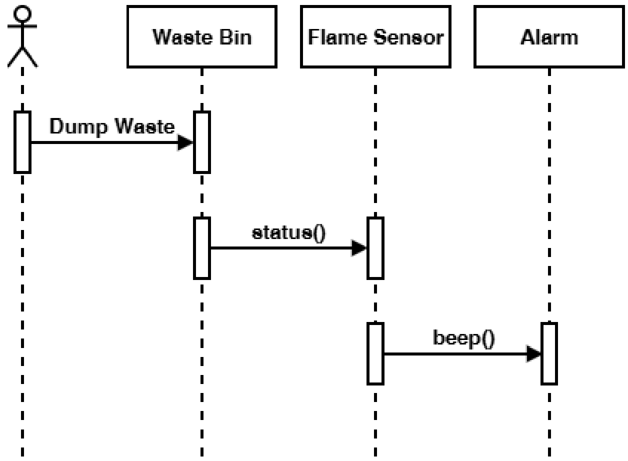

Figure 2: Sequence diagram for fire and above threshold temperature

The algorithm of the smart waste system goes thus:

1: Initialize sensors

2: Initialize servo motor (lid)

3: Initialize buzzer/notification system

4: Initialize microcontroller, dependent hardware and software modules

5: Loop indefinitely:

a: Read ultrasonic sensor distance

b: If distance is less than threshold distance

{

i. Read bin status sensor

ii. If status is greater than threshold

{

Display "Bin is full" message on LCD

Send notification to waste management system via SMS

Wait for bin to be emptied

}

iii. Else:

iv. Read flame sensor

v. If flame sensor state is greater than threshold:

beep alarm

vi. Read temperature and humidity sensor

vii. If temperature & humidity state is greater than threshold:

beep alarm

}

c: Else:

d: Activate servo motor to open waste bin lid

e: Wait for user to deposit waste

f: Close waste bin lid

6: End loop

3.3 Prototype Design

Figure 3 shows the wiring diagram of the smart waste bin. Figure 4 shows the assembly of the Power Supply Unit (PSU), Microcontroller Unit (MCU) and sensors.

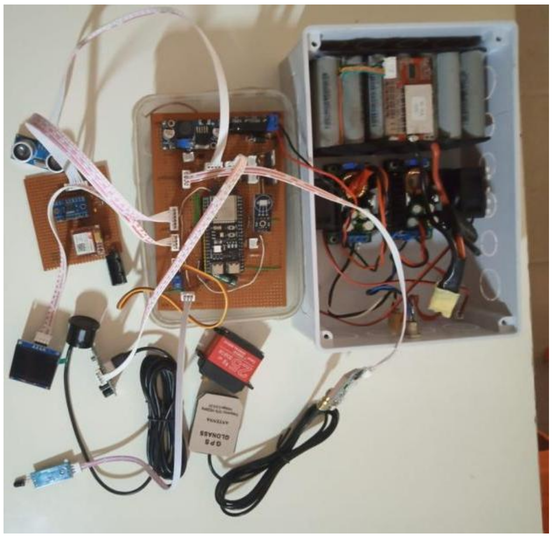

Figure 4: Assembly of the PSU, MCU and sensors

3.4 Prototype Testing

To measure success and performance, the prototype was setup and tested in a laboratory environment. Diverse case scenarios were simulated to test the response of each of the sensors as well as the overall operation of the smart waste bin.

4. RESULTS AND DISCUSSION

4.1 Results

The results presented below show how the developed prototype attempts to meet the stated goals of the study: alerting the user, providing the geographic position of the bin, and making relevant system information available through a local network.

Figure 5 shows the completed prototype smart waste bin in action with the PSU, MCU, sensors and actuators mounted onto a 60-litre plastic lift-up waste bin

The device is powered by ESP32-S3 development board, which is the MCU responsible for controlling the various sensors and components.

As a disposer approaches the waste bin, the proximity sensor detects the presence of the disposer and opens the lid automatically (if the bin is not full). This feature enhances convenience and ensures proper waste disposal, eliminating the need for direct contact with the waste bin.

The smart waste bin is equipped with a flame sensor module capable of detecting ultraviolet (UV) rays emitted at the source of ignition, as well as specific infrared (IR) radiation patterns emitted by hot gases. If the flame sensor module changes status to TRUE, the buzzer is activated to alert on the potential of a fire outbreak and an SMS is sent to the user. Another sensor added to enhance safe operation is one capable of measuring both temperature and humidity. If the measurements obtained exceed the set threshold, the buzzer is also activated so as to give warning to approaching disposers.

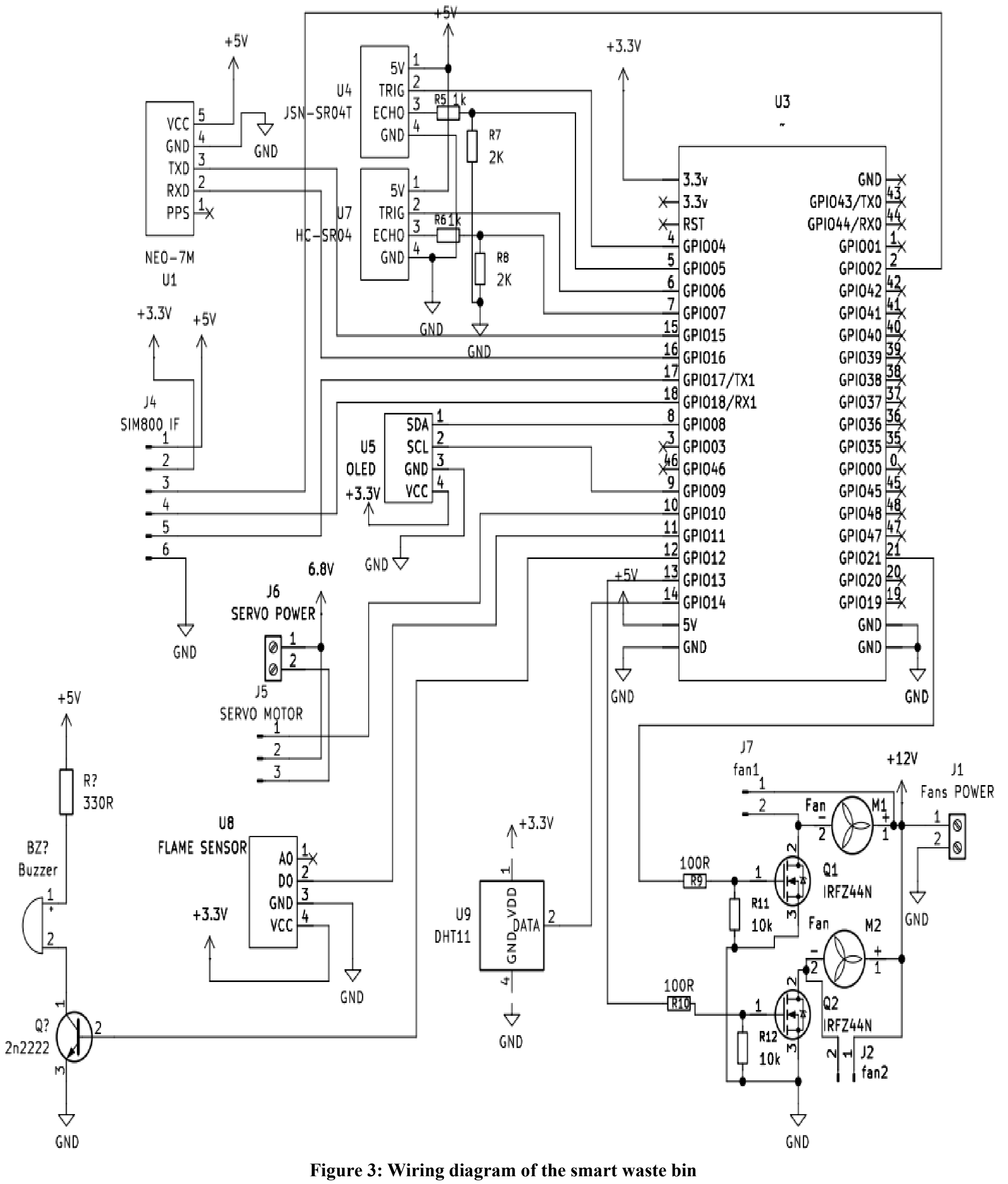

Figure 3: Wiring diagram of the smart waste bin

The OLED display on the smart waste bin shows the current waste level, indicating when the bin is full, see Figure 6. This feature is aimed at providing real-time information to disposers and any waste collection agent that is on site so as to guide proper use and timely waste collection.

The smart waste bin is equipped a GPS module for location tracking and to prevent theft and ensure that the locations of the smart waste bin is easily located for disposal of the waste when situations arise. Lastly, a GSM module is incorporated to send SMS notifications to any specified data repository for record keeping, as well as to the to the waste management team for timely response.

Figure 5: Prototype smart waste bin in action

Figure 6: Bin status showing on the OLED display

4.2 Discussion

This work proposes a model and developed a prototype to illustrate a smart waste bin capable of monitoring fill levels and sending timely notifications to waste collection agents. When adopted, this system will:

1) Provide readings that can be used to determine waste collection frequency.

2) Enable real-time operational waste management monitoring for communities and regions.

3) Facilitate prompt response to potential environmental hazards and emergency situations.

Table 1. Report from the SMS module

Event	Detected?	SMS Generated?	Response Time
Bin Full	Yes	Yes	Actual
Fire	No	No	Actual
Location	5.0389ºN,7.9042ºE		

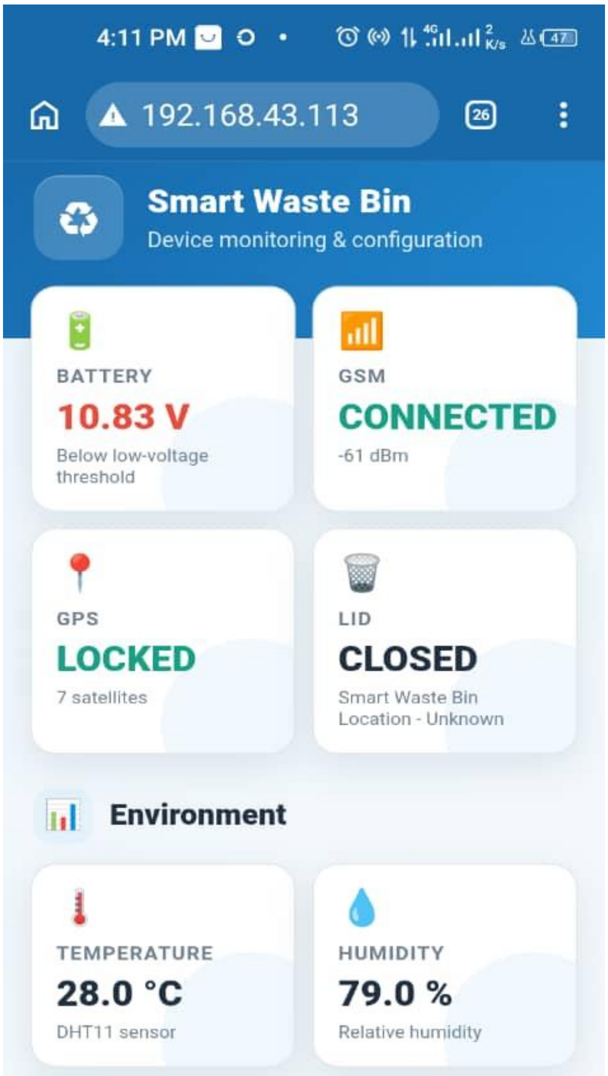

Figure 7: Smart waste bin status at a location

The results obtained demonstrate that the system has extended the traditional and existing functionalities of other smart waste bn systems by incorporating sensing, communication, GPS and network-based monitoring capabilities. Rather than serving merely as a waste container, the developed system can monitor conditions within the waste bin and communicate useful information for necessary human intervention.

Table 1 is a typical report from the system SMS module indicating various conditions, as well as the GPS location of the waste bin as at the time of testing.

The waste level monitoring function helps to keep both users and waste collection agents notified on the waste bin fill level status. Fire detection ensures that an automated warning is sent when a fire is detected. SMS communication is particularly useful and can significantly improve the timely response of waste collection agents by providing real-time updates without the need for a physical inspection.

The GPS further improves the value of the system because messages can be mapped to the physical location of the waste bin. This becomes very useful in a smart city scenarios where multiple bins are deployed across different places. The local Wi-Fi server allows users within the configured network to view the current state of the system on a smartphone interface (see Figures 7 - 9).

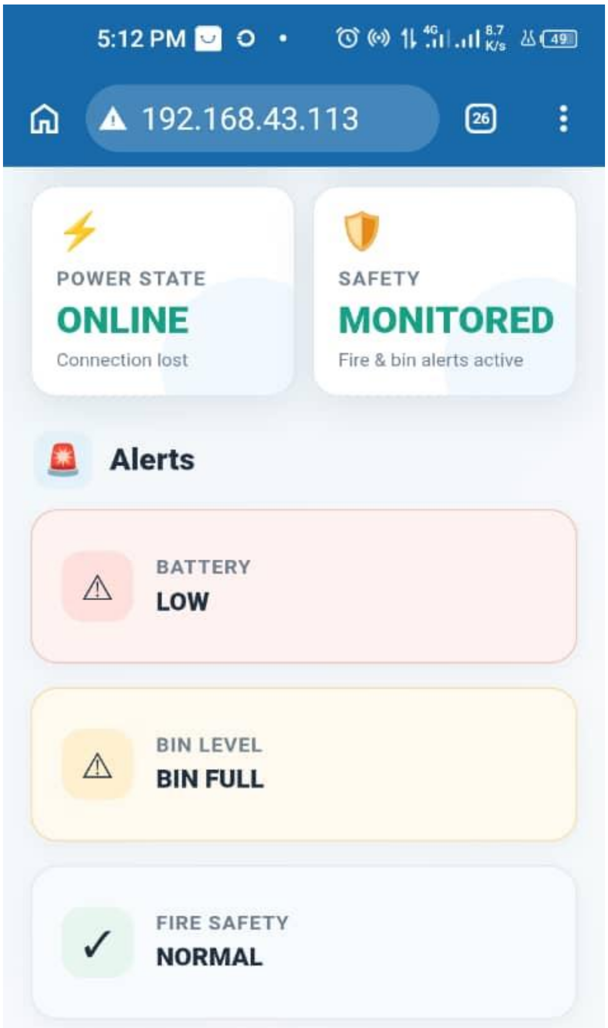

Figure 8: Smart waste bin status of Alerts

The system is fitted with a battery module and is charged though an attached solar system to ensure continuous uninterrupted operation.

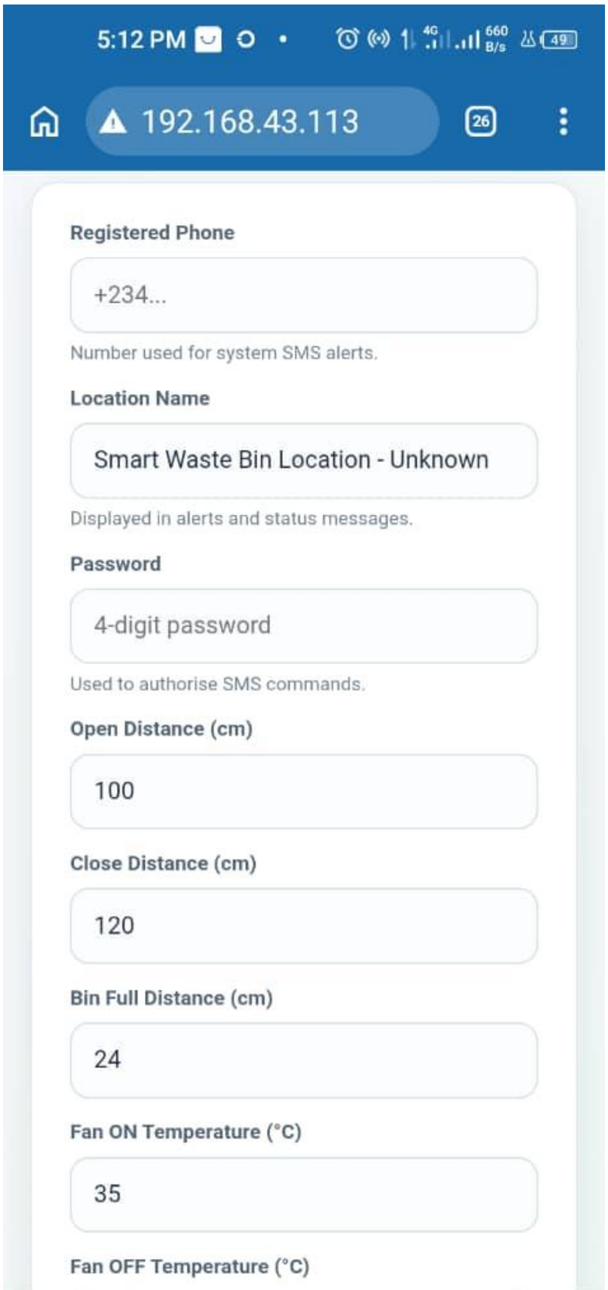

Figure 9: Smart waste bin Device Configuration

5. CONCLUSION

Waste management is a major challenge faced by various societies worldwide. Where waste bins are provided, many people are reluctant to touch the lids of the waste bins when emptying their refuse for fear of contacting infections or contagious diseases. Even when the waste bin is left ajar, they are often left unattended for several days by waste collection agents.

The system developed in this study was able to detect fill level of the bin, the location of the bin and whether fire occurred within the system or not. Tests conducted on this smart waste bin system confirm that it can encourage disposers to properly deposit their refuse inside the bin, as well as ensure that the relevant waste management team receive real-time alerts thereby enhancing their response time and improving the overall efficiency of the waste management process. The proposed model would contribute toward significantly reducing waste monitoring and collection trips, which will invariably translate to cost savings and time savings.

There is a need to consider this model of a smart waste bin system since it is capable of integrating with other Smart City initiatives, as well as contributing towards the sustainable development practices of communities and regions. In future, an IoT web application layer can be developed for ease of bin status monitoring by the waste management team. This will require setting up a database alongside the requisite coding logic to power the web/mobile app. With a database in place, robust descriptive analytical tools can be applied on the raw data in the central repository to ensure that information is presented in a manner that is more comprehensible and actionable by the waste management team.

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