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Design and Implementation of an IoT-Enhanced Smart Dustbin for Waste Management

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ABSTRACT

The growing challenge of waste management calls for innovative solutions to enhance efficiency and sustainability. This paper presents the design and implementation of an IoT-enabled smart dustbin aimed at improving waste disposal processes. The system integrates ultrasonic sensors for waste level detection, an ESP32 microcontroller for data processing, and a servo motor for automated lid operation. Real-time monitoring is achieved through the Blynk app, which alerts authorities when the bin reaches a predefined capacity. Field tests demonstrated high accuracy in waste level detection and reliable notification delivery. The proposed system enhances waste management efficiency, prevents overflow, and promotes environmental hygiene, offering a scalable solution for smart cities.

INTRODUCTION

Effective waste management is a critical issue in developing countries, including Nigeria, where improper disposal of solid waste leads to severe environmental and health hazards. Inadequate waste collection planning and funding have resulted in widespread pollution, water contamination, urban drainage blockages, and air pollution from uncontrolled burning. These conditions contribute to the spread of vector-borne diseases such as malaria and cholera, exacerbating public health risks (Amrutha *et al.,* 2017). Traditional waste collection methods, which rely on manual monitoring and periodic collection, are inefficient, often resulting in overflowing bins and unsanitary conditions (Gupta *et al*. 2021). The lack of an optimized waste tracking system further compounds these challenges, leading to resource mismanagement and environmental degradation (Jardosh *et al.,* 2020). To address these inefficiencies, the integration of smart technologies such as the Internet of Things (IoT) has been proposed as a transformative approach to waste management. IoT facilitates real-time monitoring, automation, and data-driven decision-making, enhancing the efficiency of waste collection systems (Pandey *et al.,* 2020). By leveraging IoT, interconnected sensors and microcontrollers can continuously monitor waste levels, optimize collection schedules, and transmit real-time data to waste management authorities (Kansara *et al.,* 2019). Singh and Tiwari (2021) describe IoT as a network of embedded devices and sensors that collect, process, and communicate data seamlessly, enabling automation and remote monitoring in various applications, including waste management.

The IoT-based smart dustbin aims to address key challenges in waste management by ensuring real-time tracking, reducing operational inefficiencies, and promoting sustainable waste disposal practices. The research highlights the potential of smart waste management solutions in urban and rural settings, offering a scalable and cost-effective approach to improving sanitation and environmental sustainability.

LITERATURE REVIEW

The integration of the Internet of Things (IoT) in waste management has been extensively studied, with various designs and implementations aimed at improving efficiency, sustainability, and real-time monitoring. Several researchers have proposed and developed innovative smart dustbin systems to enhance waste collection and disposal mechanisms. Nursakinah (2024) designed a prototype for an automatic waste disposer integrated with IoT technology. The system utilizes an Arduino, an HC-SR04 sensor, and an Infrared Line Tracking sensor for input processing, while ESP8266 enables remote monitoring via a smartphone or laptop. The infrared Line tracking sensor has a limitation of being easily affected by obstacles. Similarly, (Sadana *et al.,* 2024) proposed a Smart Garbage System incorporating waste segregation, a hybrid energy storage system powered by batteries and solar panels, and real-time notifications to authorities when bins reach full capacity. This system ensures timely waste disposal, improving urban cleanliness, but it cannot monitor the status of the waste bin; the notification is only when the bin is full.

Park *et al (*2023) focused on designing and implementing a smart dustbin system using IoT for efficient waste management. Their study highlights the integration of sensors, communication networks, and cloud platforms to optimize waste collection routes and promote sustainability. Likewise, Haque *et al*. (2023) introduced a dual-compartment smart dustbin for office spaces, incorporating ultrasonic and load sensors, servo motors for automated lid operation, and Arduino Uno for data processing. It was concluded that smart hands-free waste bins significantly enhance waste management, though further research is needed for wider accessibility.

Singh *et al*. (2022) developed an IoT-enabled smart dustbin for smart cities, integrating sensors, communication networks, and cloud computing for real-time waste monitoring. The study emphasized the role of such systems in optimizing collection routes and promoting sustainability. Gupta *et al.* (2021) also explored the development of an IoT-based smart dustbin, discussing the integration of sensors, microcontrollers, and wireless communication to enhance waste collection efficiency. Zhang *et al.* (2020) presented a smart waste management system based on IoT, incorporating sensors and data analytics for real-time monitoring. Their study demonstrated the advantages of IoT-based solutions in reducing environmental impact. Similarly, Williams *et al.* (2020) implemented an Arduino-based smart dustbin system, highlighting its benefits in optimizing waste collection and improving overall management practices in smart cities. The notification usually experiences a delay and therefore affects the reliability of the system.

This work presents the design and implementation of an IoT-based smart dustbin system to optimize waste collection processes. The proposed system integrates ultrasonic sensors, an ESP32 microcontroller, and GSM technology to provide real-time updates on waste levels and notify waste management authorities when a bin reaches capacity, utilizing an App. Additionally, an automatic lid mechanism, controlled via proximity sensors, facilitates hygienic waste disposal. The system's performance is evaluated through field tests to assess its efficiency, reliability, and impact on optimizing waste collection logistics

MATERIALS AND METHODOLOGY

Materials

This design was achieved in two parts – the software and the hardware aspects. The hardware part involves the interconnection of components, starting from the servo motor, ultrasonic sensor, down to the microcontroller and Blynk app. The second aspect involves the software programming of the ESP-32 through carefully generated instructions using the C++ language.

Methods

The design of the smart dustbin involves integrating sensors to detect the level of waste, microcontrollers for data processing, and actuators to automate lid movements. Wi-Fi as connectivity means allows for real-time monitoring and alerts.

Operational Units

The block diagram of the proposed system and connection is shown in Figure 1. The processed result from the microcontroller, ultrasonic sensor and Blynk App and LCD screen serves as a status display screen.

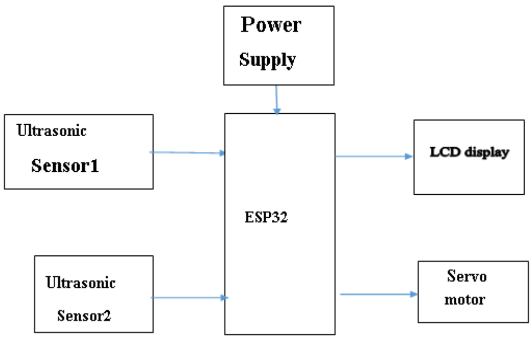

Figure 1: Block Diagram of the Proposed Smart Dustbin

The block diagram consists of a power supply to provide energy to the entire system, two ultrasonic sensors, where sensor 1 detects the distance of an object (e.g., a user's hand) and sensor 2 detects the level of waste in the bin. An ESP32 microcontroller serves as a processor, which processes data obtained from the sensors and also controls the servo motor to open or close the dustbin lid based on the input. Additionally, an LCD provides real-time status information, such as "Open" or "Closed," enhancing user interaction and functionality.

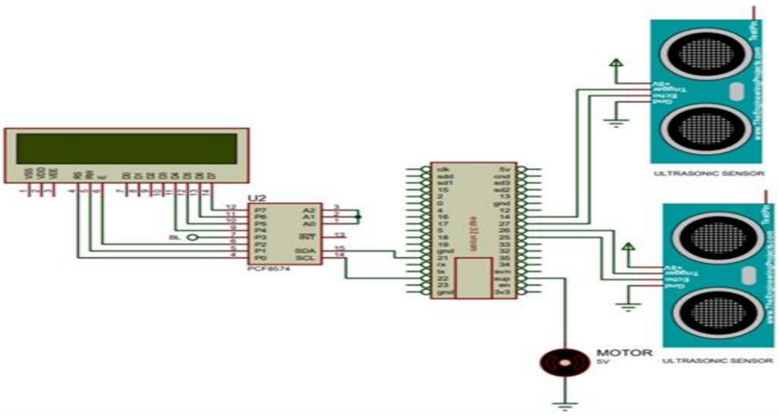

Figure 2: Circuit Diagram of the Smart Waste Bin

System Circuit Implementation

Circuit implementation in electronic designs involves the practical arrangement of electronic components on a circuit board to achieve a desired function. This step translates theoretical designs into functional hardware, enabling devices to perform tasks like signal processing, power management, or data communication. The system circuit diagram shows how various components like the ultrasonic sensor, servo motor, LCD's and ESP-32 microcontroller are interconnected.

Hardware Construction

The IoT Smart Dustbin hardware setup requires several components, including the ESP32 board, two ultrasonic sensors (HC-SR04), an I2C adaptor (PCF8574), a 16x2 LCD, a servo motor, a breadboard, jumper wires, and a 5V, 2A power supply. The ESP32 board was connected to the power supply, with the VCC linked to 5V and GND to GND. The GPIO18 was connected to I2C SCL on the I2C adaptor and GPIO19 was connected to I2C SDA. For the Ultrasonic sensor, the 1's TRIG pin was connected to ESP32's GPIO23, while its ECHO pin was connected to GPIO22. Ultrasonic sensor 2's TRIG pin was connected to GPIO21, and its ECHO pin to GPIO20, while the servo motor's SIG pin was connected to ESP32's GPIO15. For the display, the I2C adaptor was connected to the 16x2 LCD. The SCL was linked to SCL on the LCD, SDA to SDA, VCC to 5V, and GND to GND. The RS was connected to the I2C adaptor's P0, EN to P1, D4 to P2, D5 to P3, D6 to P4, and D7 to P5. Connecting the ultrasonic sensors to the power supply, the VCC was linked to 5V and GND to GND, while the servo motor was connected to the power supply with VCC linked to 5V and GND to GND.

Figure 3: Picture showing placement and connection of the system hardware

Programming of the System and Blynk App Configuration

The software requirements for this project include the Arduino Integrated Development Environment (IDE). The Arduino IDE is a cross-platform application used for writing and uploading programs to Arduino-compatible boards. It supports C and C++ with special rules for code structuring. The IDE employs the AVRDUDE program to convert the executable code into a text file encoded in hexadecimal, which is then loaded onto the Arduino board by a loader program in the board's firmware. After writing the code, it should be verified for compatibility with the target board before uploading. The Blynk app was downloaded from the Google Play Store and was installed on the smartphone. The new project was created on the Blynk App, the ESP32 was selected as the hardware, and the Wi-Fi settings were configured. The network was authenticated and widgets were added to monitor and control the smart dustbin. Using the Blynk's API keys, the ESP32 was connected to the Blynk server.

Working Principles Flow Chart

The system operational flow chart is presented in Figure 3.4, showing stepwise system operation. The operation of a smart dustbin system begins with the ultrasonic sensor, which constantly monitors the waste level inside the bin. When the sensor detects that the waste has reached a certain threshold, it sends a signal to the Atmega328p microcontroller, which serves as the brain of the system. The microcontroller processes the data and activates the servo motor, which opens the lid of the bin for waste disposal. Simultaneously, the LCD provides real-time information about the bin's status, such as whether it is full or empty. If the bin reaches its maximum capacity, the microcontroller sends a signal through the Blynk app on the smartphone, notifying the user that the bin needs to be emptied.

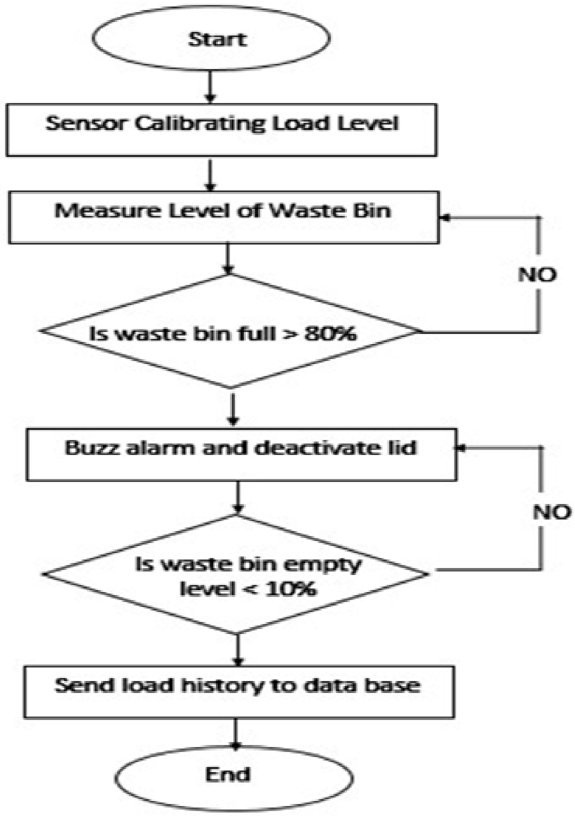

Figure 4: Flowchart Diagram of the Proposed Smart Dustbin

RESULTS AND DISCUSSION

Sensitivity of Ultrasonic Sensor Results

This test was conducted to measure the level of sensitivity of the sensor in detecting objects. The maximum distance the system can measure is 10 Inches. The operation was carried out by comparing the measured value by the system to a ruler; hence, the percentage error was determined, where the average percentage error was calculated to be 0.3, as shown in Table 1.

Table 1: Ultrasonic Sensitivity Test

S/N	Ultrasonic sensor HCyep-SR04 Measurement (Inch)	Ruler Measurement (Inch)	Percentage error (%)
1.	9.98	10	0.2
2.	7.98	8	0.3
3.	6	6	0
4.	3.97	4	0.8
5.	2	2	0
		Average	0.3

Operational Procedure Results

The operational procedure is a dynamic test conducted on the smart dustbin to check the operation of the ultrasonic sensors indicated as Sonic 1 and Sonic 2 in Table 2.

Table 2: Mode of Operation of the Smart Dustbin

Sensor	Condition	Action (Result)
Sonic 1	Distance ≤ 2 inches	Bin lid opens
	Distance > 2 inches	Bin lid remains closed
	Bin level ≥ 80% and Distance ≤ 2 inches	Bin lid remains closed and buzzer alarm ON
	Bin level > 80% and Blynk button pressed	Bin lid open
Sonic 2	Bin level > 80%	Notification sent and alarm active
	Bin level < 80%	No alarm and no notification

Initialization Testing Result

Figure 5 shows the testing result for the initialization process of the smart dustbin. Upon switching ON the system, the LCD displayed "IOT SMART DUSTBIN", which is an indication that the system is in the booting stage and becoming responsive

Figure 5: Initializing Stage Booting of the smart dustbin

Opening and Closing Testing

Figures 6 and 7 show the opening and closing of the smart dustbin by using a hand to block the ultrasonic sensor responsible for object detection. Upon detecting an object within the stipulated range, the microcontroller signals the servo motor to perform the opening operation, hence the LCD's "OPEN". The dustbin remained closed when there was no object detected within the range, hence the LCD displayed "CLOSED"

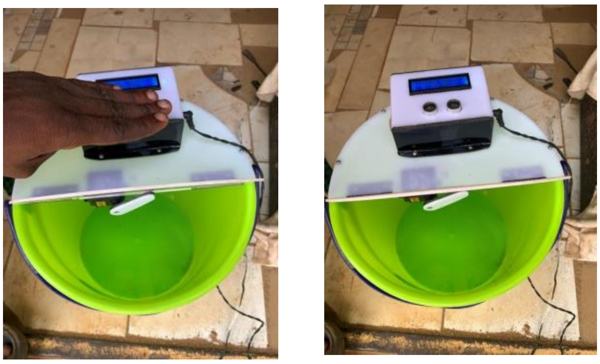

Figure 6: The opening of the smart dust bin for testing.

Figure 7: The closing of the system

Dustbin Status result on BlinkApp

Figure 8 displays the smart dustbin real state and the corresponding status on the BlynkApp as the BlynkApp was connected to the dustbin using Wifi module. The level of dirt is measured in percentage, ranging from 0 – 100%. When the dustbin was empty, the LCD read 0% and showed closed with the corresponding BlynkApp indicating empty. When the dustbin was 67% full, the LCD displayed the same 67% and showed closed, the same information was indicated on the corresponding App.CLOSED" and the Blynk App bar remain at 0% while at 100% full, the LCD displayed status "BIN FULL" and the Blynk App. Sows full bar meaning that the bin is full and the a need for disposal.

Figures 9 and 10 show the output of the smart dustbin regarding notification of the end user. When the dustbin is full, meaning that the level of dirt in the bin is > 80%, as shown in Figure 8. When the bin is seen to be 100% displayed by the LCD, a notification message will be sent to the user via email with text displaying "ATTENTION!!! DUSTBIN FULL," and the same will be displayed in the Blynk app as shown in Figure 10.

Figure 8: The Status of the Bin on the Blynk App

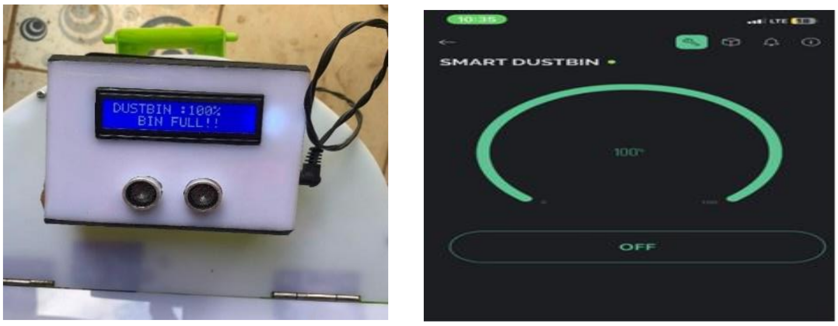

Figure 9: The Dustbin Status at 100% Full

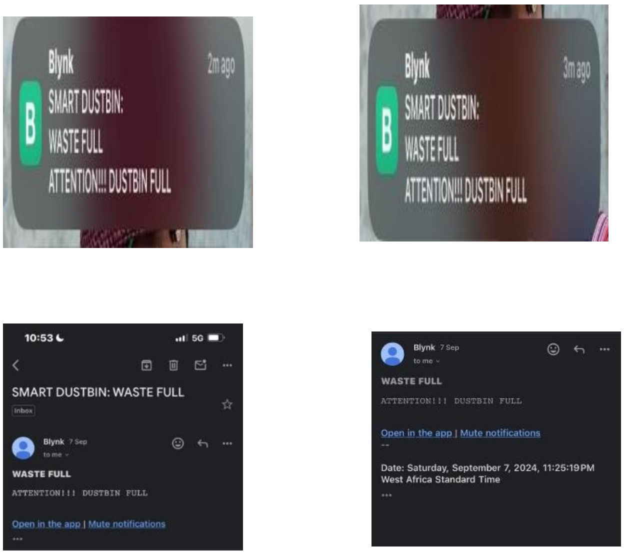

Figure 10: The Notification in the Blynk App/Email

The feature of the obtained result is shown in Table 3. The table compares the work with a conventional waste bin and the results make it more effective for smart city technology

Table 3: Comparing Smart Waste Bin with the Conventional Waste Bin

Feature	IoT-Enhanced Smart Dustbin	Conventional Waste Bin
Response Time	Real-time notification when full	Manual checking required
Manual Effort	Minimal (automated lid and alerts)	High (manual opening and monitoring)
Accuracy	High (ultrasonic sensors detect waste level)	Low (visual inspection)
Hygiene	Improved (touchless operation)	Poor (manual handling)
Waste Collection Efficiency	Optimized (real-time updates enable timely disposal)	Inefficient (fixed schedules may lead to overflow)

CONCLUSION

The smart dustbin prototype system was designed and implemented, with dynamic and static tests conducted on the system, showing that each unit circuit was well connected. The design was successfully tested, enabling the lid to open automatically when an object approaches within 2 inches. Height detection tests showed a 0.3% error, demonstrating sensor accuracy in measuring waste levels. The smart dustbin software effectively sends full-bin notifications to a phone via the Blynk App.

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