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(Research Article)

Design and Implementation of IoT-Based Optimized Waste and Energy Management System for Maiduguri as a Strategy towards Smart City

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Abstract

Rapid urbanization in developing regions has intensely exacerbated infrastructure stress, particularly concerning waste management and energy distribution in cities characterized by infrastructural fragility. This study addresses these critical urban challenges by presenting an innovative IoT-enabled framework for smart waste management and energy optimization, using Maiduguri, the capital of Borno State, Nigeria, as a representative case study. The developed system integrates low-cost, accessible hardware: an Arduino Uno microcontroller, dual ultrasonic sensors, an MG996 servo motor for automated operation and a SIM900 GSM/GPRS module for wide-area network connectivity, all powered by a stabilized buck converter. The smart bin prototype offers real-time fill-level monitoring and contactless operation. Data on fill status and time stamps are transmitted via GPRS at 60-second intervals to the remote ThingSpeak cloud platform, transforming raw sensor readings into actionable time-series data. The system's critical alerting mechanism is triggered when the bin reaches a capacity threshold of 90%, dispatching immediate SMS notifications to municipal authorities for prompt collection scheduling. Experimental validation demonstrates that the implementation significantly reduces the need for manual inspection, optimizes route planning through data-driven insights, and contributes to enhanced energy efficiency by minimizing collection vehicle mileage. These findings affirm the viability and effectiveness of deploying scalable, cost-sensitive IoT solutions as a foundational strategy for achieving sustainable urban management goals in emerging smart cities.

Keywords: IOT; Smart Cities; Waste Management; Energy Optimization; Arduino; SIM900 GSM Module; Ultrasonic Sensors; Data-Driven Systems; ThingSpeak; GPRS

1. Introduction

The trajectory of urbanization across Nigeria has placed immense pressure on municipal services, notably in waste and energy management. Maiduguri, currently experiencing an estimated population growth rate of 3% annually, epitomizes the strain placed on outdated and undersized urban infrastructure. Traditional, scheduled-based waste collection systems are grossly inefficient, failing to keep pace with dynamic waste generation patterns. This leads to overflow, environmental blight, and significant public health risks, contradicting the principles of sustainable urban development [7], [9]. Simultaneously, the energy sector is hampered by infrastructural deficits, inconsistent supply and reactive management practices that prevent optimization of resource use.

1.1. Related Problems

Nigeria's estimated annual generation of over 32 million tons of municipal solid waste (MSW) highlights a significant resource management crisis. With only 20 to 30% of this volume officially collected and treated, open dumping remains a dominant practice in cities like Maiduguri, resulting in blocked drainage channels, widespread environmental

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pollution and the proliferation of vector-borne diseases. Furthermore, the decomposition of uncollected waste releases greenhouse gases, including methane and carbon dioxide, ammonia and hydrogen sulfide, accelerating climate change and contributing to local air quality degradation, directly impacting public health (WHO estimates 3 million annual deaths globally related to COPD). The current energy infrastructure crisis, characterized by inadequate metering and lack of real-time monitoring, mirrors this inefficiency, leading to increased reliance on high-emission diesel generators and hindering progress toward SDG 7 (Affordable and Clean Energy) [15]. The underlying issue is the reliance on a fragmented, non-data-driven management approach.

1.2. IoT as a Transformative Solution

Recent advancements in the Internet of Things (IoT) offer a paradigm shift from reactive to proactive urban management. IoT platforms enable the deployment of interconnected devices (sensors, microcontrollers and communication modules) to gather real-time data, allowing for automated decision-making and infrastructure optimization [1], [13]. Specifically in waste management, smart bins equipped with ultrasonic sensors provide critical fill-level data. This data, when analyzed centrally, allows for dynamic route optimization, reducing operational costs (fuel, labor), minimizing carbon emissions from collection vehicles and enhancing the aesthetic and hygienic quality of the urban environment [6], [8]. This research focuses on harnessing these low-cost IoT technologies to develop a practical, scalable solution for the specific urban context of Maiduguri.

2. Literature Review

2.1. IoT Applications in Smart Waste Management

The integration of IoT into waste management provides foundational tools for smart cities. Al Mamun et al. [1] quantified the cost savings achieved through dynamic route planning enabled by sensor data. Wijaya et al. [2] and Sharma et al. [3] explored multi-sensor approaches, integrating both weight and volume monitoring to enhance data accuracy, while Nagham et al. [4] focused on providing immediate status updates using Wi-Fi communication protocols. Folinate et al. [5] further investigated mesh networking topologies as an energy-efficient alternative for localized bin communication.

2.2. IoT-Based Route Optimization and Data-Driven Logistics

The critical outcome of smart waste monitoring is the optimization of logistics. Chaudhari and Bhole [6] detailed an integrated platform that translated bin fill data into actionable route sequences, minimizing travel distance. Gupta and Kumar [7] proposed a centralized architecture utilizing an IoT edge node to synchronize communication between smart bins and collection vehicles. Reddy et al. [8] highlighted the convergence of environmental monitoring (humidity and gas sensors) with route optimization, illustrating the multi-faceted benefits of comprehensive sensor data in urban logistics.

2.3. Low-Cost IoT Solutions in Emerging Cities

The economic constraints of developing nations necessitate a focus on low-cost, replicable IoT frameworks. Abubakar and Bala [9] specifically addressed the challenge of affordability in the African context. Abdallah et al. [10] provided a practical case study from Accra, Ghana, demonstrating tangible results (33% food waste reduction) using a hybrid mesh/SMS-based alerting system. More recent works, such as Rahman et al. [11] and John et al. [12], introduced automated lids and waste categorization systems, although scalability and reliability in harsh, limited infrastructure environments remain subjects of ongoing research.

2.4. IoT Communication Protocols for Smart Waste Systems

The choice of communication protocol is vital for system reliability and energy efficiency. Koohang et al. [13] and Alex et al. [14] underscored the need for integrated sensor-connectivity-power management solutions in smart bins. While advanced technologies like LPWAN, LoRaWAN, and NB-IoT [15], [16] are standard in developed smart cities, the reliance on readily available GSM/GPRS technology remains a practical, cost-effective necessity for widespread deployment in Nigerian urban centers, as discussed by Tahir et al. [17].

3. Methodology

The implementation involved a robust design approach focused on maximizing system stability and minimizing operational cost, divided into five key stages.

3.1. Hardware Architecture and Component Selection

The system's efficiency is rooted in its choice of proven, reliable hardware components, as summarized in Table I.

Table 1 Key Hardware Components and Functionality

Component	Function	Justification
Arduino Uno	Microcontroller, Control Logic	Low cost, high reliability
Ultrasonic Sensors (2)	Proximity Detection (External) and Fill Level Measurement (Internal)	Non-contact sensing, low cost, sufficient accuracy.
Servo Motor (MG996)	Automated Lid Control	High torque ensures reliable opening/closing.
GSM/GPRS	Data Transmission (GPRS) and SMS Alerting	Wide-area network coverage, cost-effective communication for developing regions.
Buck Converter (XL6009)	Power Stabilization (output)	Mitigates voltage transients, crucial for GSM/Servo stability

The XL6009 buck converter is mandatory for regulating the input power supply, efficiently stepping it down and stabilizing it to provide the consistent voltage required for the Arduino, sensors, GSM module and servo motor. This component is essential to mitigate voltage fluctuations which commonly cause the power-intensive GSM module and servo to reset, thus ensuring continuity of operation [14].

3.2. Embedded Software Development and Logic

The embedded code, written in Arduino C/C++, implements specific operational logic:

- Contactless Operation: The external sensor triggers the lid opening when an object is detected within 20 cm of the bin opening. The servo rotates to the open angle, waits for 5 seconds for waste disposal and then returns to the closed angle.
- Fill-Level Calculation: The internal sensor measures distance to the waste surface. Given the bin height H, and the measured distance d, the fill percentage F is calculated as: $F = (1 - d/H) * 100\%$
- Intelligent Alerting Mechanism: The critical fill threshold is set at 90% of capacity. A robust anti-spam mechanism is implemented using a Boolean state flag (SMS Sent). The SMS is sent only once upon crossing the 90% threshold. The flag is automatically reset only when the bin's capacity drops below 60%, which signifies successful emptying of the bin and re-enables the alert mechanism for the next fill cycle. Furthermore, the fill level data is sent to the cloud platform via GPRS HTTP requests at a consistent interval of 60,000 milliseconds (1 minute).

3.3. Cloud Platform Implementation and Data Flow

The system employs a client-serverless architecture using the ThingSpeak IoT Cloud Platform for data aggregation and storage.

Data Transmission Protocol: The Arduino initiates a GPRS connection using the SIM900 and sends HTTP GET requests every 60 seconds to the dedicated Thing Speak API endpoint.

ThingSpeak Role: ThingSpeak receives the fill level data as a time-series dataset. It acts as the central data repository, providing the necessary APIs (read keys) for the external web dashboard to retrieve the information for visualization.

3.3.1. Dashboard and User Interface

The web-based dashboard serves as the central management interface, built using standard web technologies (HTML, CSS and JavaScript) and utilizing the Chart.js library for graphic representation. Data is queried in real-time from the ThingSpeak Read API. Key features include:

- Visualizing a live gauge or bar graph displaying the current fill percentage, coupled with a status traffic light system (Green, Red/Blinking).
- Historical Analysis in an interactive line chart displaying the fill level over the past 24-72 hours.

3.3.2. System Integration and Operational Flow

The system integration is structured into two parallel, synchronized loops: the physical automation loop and the data communication loop. This parallel structure ensures redundancy. Figure 1 provides a detailed visualization of the system's operational sequence.

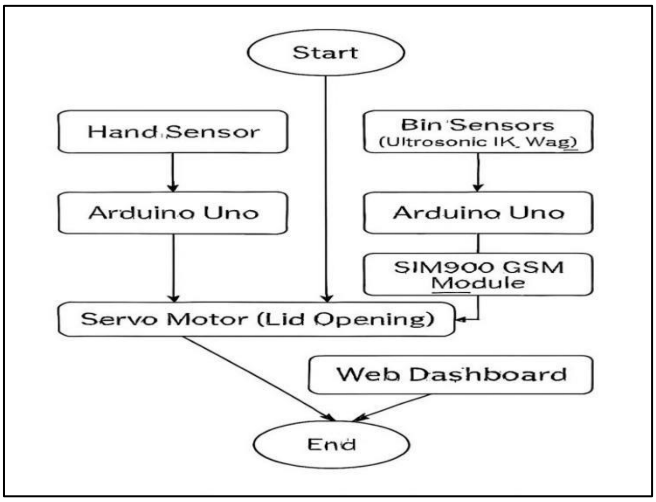

Figure 1 System Integration Flowchart

4. Results And Discussion

The implemented prototype underwent rigorous testing to validate its performance parameters against the design specifications and operational objectives.

4.1. System Testing and Operation

The integration testing confirmed the robust operational performance of the automated system:

- Contactless Activation Reliability: The system consistently achieved hands-free operation. The 20 cm proximity detection range was found to be optimal. The lid delay provided sufficient user time before secure closing.
- Accuracy of Fill Level: The internal ultrasonic sensor provided fill-level measurements accurate within a margin of relative to the bin height. The calculated percentage fill successfully translated the raw distance data into actionable capacity metrics, demonstrating the reliability required for effective route planning [8].

4.2. Hardware Stability and Power Management

The MG996 servo motor maintained its torque and precision throughout extended testing cycles. The stability provided by the buck converter was a critical success factor by eliminating the voltage transients, it ensured the system's resilience against power instability, a common challenge in developing regions.

SMS and Thing Speak Communication Reliability

- The communication subsystem demonstrated high reliability:

- Alert Responsiveness: The SMS alerting system, triggered instantly upon crossing the 90% threshold, ensured immediate notification to waste management personnel, facilitating rapid intervention.
- Anti-Spam Effectiveness: The state-based logic requiring the fill level to drop below 60% before the alert flag is reset successfully eliminated the issue of message spamming.

Data Integrity: Data transmission to the ThingSpeak cloud platform occurred consistently every 60 seconds via GPRS. Analysis of the Thing Speak channel logs showed near 100% data packet reception rates.

As shown in Figure 2, the final integrated prototype encapsulates all functional components the Arduino, sensors, servo and GSM module into a single, deployable unit, ready for field testing.

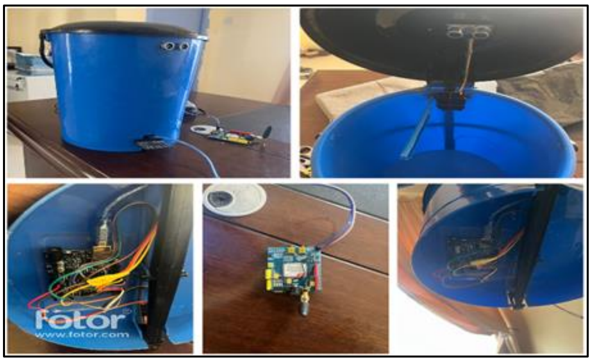

Figure 2 Smart Waste Bin Prototype

4.3. Dashboard Visualization and Management Utility

The dashboard provided immediate and substantial managerial utility. The ability to visualize the current fill status and historical trends from the ThingSpeak API allowed managers to move away from rigid routes to dynamic route planning. This data driven approach allows for the prioritization of bins nearing the 90% threshold, leading to optimal vehicle dispatch and significant reduction in wasted trips and fuel consumption, thereby directly contributing to SDG 12 (Responsible Consumption and Production).

4.4. System Performance Summary

The overall system performance met the design objectives by the hands-free operation minimized physical contact, the fill-level detection was accurate within a margin of and the ThingSpeak integration proved reliable for data logging. Limitations identified include the system's dependence on adequate GSM network coverage for GPRS and SMS functionalities, and the necessity of stable regulated power, which was successfully resolved by the buck converter.

5. Conclusion

This research successfully developed and validated a robust, low-cost IoT-enabled smart waste management system designed specifically to enhance operational efficiency and sustainability in constrained urban environments like Maiduguri. The system's architecture, leveraging the Arduino Uno and ThingSpeak cloud platform, provides automated contactless disposal, accurate fill-level monitoring with a 90% threshold, and reliable, time-stamped data transmission every 60 seconds. This transition from static scheduling to proactive, data-informed logistics minimizes operational costs and addresses urgent public health concerns related to overflowing waste.

Future work will focus on integrating advanced environmental monitoring (e.g., MQ-4 methane sensors) into the prototype to capture real-time gas emissions. Furthermore, the collected time series data in the ThingSpeak platform will serve as the input for developing and testing sophisticated route optimization algorithms, such as those based on genetic algorithms or machine learning, to further enhance the efficiency of collection vehicle dispatch and solidify Maiduguri's transition towards a truly smart city framework.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

Statement of ethical approval

No human participants or animals were involved. The study followed institutional safety protocols.

Data and Code Availability

Data and code will be available upon reasonable request through ayshabirma13@hotmail.com.

Author Contributions (Credit)

Author A conceptualized the study and designed the overall architecture of the IoT-based optimized waste and energy management system. Author B developed and implemented the hardware and software components, including sensor integration, data acquisition and IoT communication modules. Author C performed data pre-processing, feature engineering, optimization modeling and system simulations for waste collection and energy management. Author D conducted performance evaluation, comparative analysis with conventional systems, results interpretation and manuscript preparation. All authors reviewed the manuscript, provided critical revisions and approved the final version.

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