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LoRa-Integrated Smart Waste Bin for Real-Time Monitoring and Management

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Abstract: *The rapid pace of urbanization and population density are placing intense stress on traditional garbage collection systems that are typically resource limited and ineffective. In fact, conventional collection methods are based primarily on manual inspection, resulting in delayed collection, overflowing bins, foul smell, and risks to health and the environment. To address these issues, this study develops a garbage bin monitoring system to facilitate smart, real-time, data driven waste management. The system utilizes ultrasonic, DHT11, air quality, and smoke sensors to measure bin filling level, temperature, humidity, and air quality continuously while a buzzer provides a local alert to hazardous situations. Data from the bins is sent via LoRa communications to a cognitive web-based interface providing continuous monitoring and decision support for municipality in-charges, supervisors, and field employees. The interface also allows employees to update bin location and status, ensuring accurate and optimized collection of the garbage. This approach minimizes manual effort and supports timely response, improving garbage collection efficiency, reducing operational costs and minimizing risk to the environment and public health.*

Keywords: *Smart Bin Monitoring, Waste Management, LoRa Communication, Ultrasonic Sensor, Air Quality Monitoring, Smoke Detection, DHT11 Sensor, IoT-Based System, Real-Time Monitoring, Sustainable Urban Development*

I. INTRODUCTION

In developing areas, urbanization and population increase have happened quickly, resulting in overgrowth in waste disposal management processes. Inefficient collection of waste and slow or delayed responses to overflowing waste bins causes dirty and unpleasant surroundings, coupled with dangerous gas emissions, that spoil or can decay the urban surroundings and simply create a danger to public health. Accordingly, the United Nations Sustainable Development Goals (SDGs) asked for modernized urban cities to utilize smart, technology-based waste monitoring systems. In particular, the proposed system addresses SDG 3 (Good health and well-being) by promoting public hygiene and avoiding human exposure to hazardous fumes and gases, SDG 9 (Industry, Innovation and Infrastructure) through innovative and up-to-date sensor-based network technology and LoRa for real-time location monitoring, and SDG 11 (Sustainable Cities and Communities) by enhancing and promoting more sustainable waste collection practices to maintain more hygienically healthy and clean environments and communities.

[2] Although significant progress has been made in smart city approaches and methodologies, most existing waste management methodologies are more heavily reliant on staff manual inspection or sensor networks that are costly and unsuitable for municipalities that are low resource. Approaches that have been designed using GSM or Wi-Fi communication methods, have demonstrated high levels of power consumption and reoccurring expense, which limits scalability and feasibility. There have also been studies that primarily look only at measuring fill levels in waste containers and have neglected to measure other important data including air quality, temperature or detecting hazardous gases, which are important for assessing environmental quality and protecting public health. This presents a technological gap in that urban administrations do not possess a complete, affordable and scalable solution for real-time monitoring of waste processing, and for use in data-informed decision making. [3] In response to these constraints, this research presents a smart bin monitoring system capable of integrating ultrasonic sensors for measuring fill levels, DHT11 sensors for temperature and humidity, air quality and smoke sensors for environmental monitoring, and a buzzer mechanism for local alerts. Data transmission is achieved through LoRa communication due to its low power consumption, cost-effectiveness, and reliability compared to traditional wireless systems. The bin-monitoring system integrates to a central web interface to allow municipality in-charges, supervisors, and field staff to assess conditions of bins, update locations of bins, and design optimized routes for waste collection. By integrating high-technology sensing modalities under the principles of the Indian Knowledge System (IKS), the suggested framework will increase both operational efficacy and community participation in urban waste management sustainability. This holistic merging of new technology and old value systems is the main purpose of this research.

[4] The central issue taken up in this study is the lack of an integrated, low-cost, and scalable waste monitoring system to monitor bin fill levels, environmental parameters, and hazardous conditions while relaying the information for use by municipal authorities in a timely manner. The main goal of this research is to design and develop a smart bin monitoring framework to improve waste collection efficiency, minimize public health threats, and support sustainable urban development in cities. This will help bridge the gap between community innovation technology and community sustainability to help create cleaner, healthier, sustainable, and more resilient cities.

II. LITERATURE REVIEW

ZIQIAN DONG [1], et al. Has proposed in this paper The growing use of electronic voting (e-voting) systems worldwide indicates a trend toward more secure, transparently, and efficiently electoral processes. Some of the key benefits of e-voting systems include vote accessibility from remote locations, quick tabulation of ballots, improved privacy, and reducing the risk of personal biases. However, conventional e-voting systems are subject to risks of tampering and cyber-attacks, undermining the integrity of the vote. Many in the field believe blockchain technologies can provide an ideal solution with their capacity for immutable vote storage, tamper resistance, and decentralized trust mechanisms that can help increase the legitimacy of e-voting systems. Some countries such as Germany, Russia, Estonia, and Switzerland have already trialed or adopted voting systems based on blockchain technologies, and scholars and industry groups have continued to suggest innovative architectures and protocols. As such, the current manuscript is a literature review of blockchain-enabled e-voting systems, which includes the architecture of the systems, where they have been adopted, and other application areas. This review is also highly analytical of the challenges that may face e-voting and blockchain, including scalability, voter authentication, privacy, and regulatory acceptance. Lastly, potential future research directions are provided to help bolster the legitimacy, inclusiveness, and viability of e-voting based on blockchain.

Xianquan Zhang [2], et al. Has proposed in this paper Reversible data hiding in encrypted images (RDHEI) technology has shown great promise in the protection of sensitive data while keeping the image secret. This paper proposes a large-capacity RDHEI method that incorporates asymmetric coding with bit-plane block compression to vastly improve embedding performance. This work contributes in two significant ways; (1) An asymmetric coding scheme is used for processing prediction error (PE) blocks, before encryption, which unlike the conventional schemes, does not generate a sign bit-plane, allowing the upper bit-planes to have a higher density of 0s and thus preserve more embedding space; and (2) A bit-plane block compressing scheme is introduced to further improve embedding capacity by splitting the two PE codes within the block and compressing both. Providing even more embedding area. Experiments run on the BOSSBase, BOWS-2, and UCID datasets show average embedding rates of 4.174, 4.08 and 3.467 bpp for the datasets, respectively. A comparative study shows an improvement in embedding capacity over several state-of-the-art RDHEI schemes.

Syada Tasmia Alvi [3], et al. Has proposed in this paper Voting is a key mechanism of any democratic system, however, voting using traditional paper and pencil is prone to errors, inefficiency, and manipulation. Electronic voting systems are intended to mitigate many of these problems, but also creates issues related to security, transparency, and voter confidence that limits widespread implementation. To mitigate these issues, we propose an electronic voting model utilizing blockchain technology and its properties of anonymity, privacy, verifiability, integrity, and fairness as it relates to elections. The proposed voting model will maintain voter anonymity by storing voter information as hashed data on-chain, while fairness is maintained by keeping all votes encrypted until the election process is complete. After the voting period is over, voters will then have the ability to verify their votes which is a measure of transparency and builds voter confidence. The voting model is implemented on the Ethereum 2.0 platform via Smart Contracts that were developed in Solidity to provide automated and immutable voter verification, public vote counting, and defense against fraudulent activity. A performance analysis capturing security features and gas costs suggest the proposed protocol improves electoral security while operating on acceptable infrastructure costs. In conclusion, our work demonstrates how blockchain technology can be leveraged to advance digital democracy and improve all aspects of electoral legitimacy, accountability, and resilience of the voting process.

Yuhao Hu [4], et al. Has proposed in this paper Traditional voting methods can be plagued by fraud, inefficiency, and lack of transparency—which creates doubt about the reliability of election outcomes. To prevent these challenges, we are introducing a decentralized electronic voting style based on the Polygon blockchain, using the properties of the blockchain—immunity, transparency, and security—to hold reliable elections. The style uses smart contracts to automate the steps of the process, to uphold rules of the election, to prevent double voting, and to log ballots in real time—lessening human error and manipulation.

To protect voter privacy and mitigate coercion, the model uses Paillier homomorphic encryption to enable tallying on-chain without disclosing individual ballots. The new model is operational and implemented on the Polygon network, which is advanced scaling technology of Ethereum that is able to provide rapid transactions, and reduced costs. A security evaluation shows that the model can withstand many common attacks. An efficiency assessment demonstrates the reduction of gas costs compared to prior blockchain voting mechanisms. Overall, this work demonstrates the ability to use homomorphic encryption in conjunction with blockchain to develop a transparent, secure, and low-cost voting scale.

Oluwakemi Christiana Abikoye [5], et.al. Has proposed in this paper As the medical field accelerates its transition towards digital formats, developing methods to organize and convey patient information has made information security more important than ever. Storing sensitive information, including patient histories, diagnostic images, and treatment-related information, digitally makes health care systems vulnerable, and has exposed this information to unauthorized access, data breaches, and privacy violations. One promising technique to combat these challenges involves Least Significant Bit (LSB) steganography. LSB steganography is a technique used to secure medical data across a variety of formats, including text, images, audio, video, and graphics. In this paper, a comprehensive literature review of research trends on the topic of LSB steganography and securing medical data is provided, including details regarding principles, implementation, and performance. The review demonstrated that the applications of LSB steganography hold great promise for hiding sensitive information from intruders without compromising the usability or integrity of medical data. The paper then identifies strengths, limitations, and potential enhancements to the work to assist researchers and practitioners in developing secure digital health care communication processes.

III. EXISTING SYSTEM

Currently available smart waste management systems can monitor municipal bins in real-time using networks of sensors to enhance the efficacy and efficiency of solid waste collection and mitigate risks to the environment and public health. Smart waste management systems often use multiple different types of sensors. For instance, a smart waste management system often includes ultrasonic sensors to measure fill-levels, DHT11 sensors to measure temperature and humidity, air quality sensors, and smoke detection sensors. Some systems utilize a buzzer alert to notify employees immediately when a bin has reached a critical state. Sensor data is transmitted via communication protocols (like LoRa) to a centralized PC-based website that the municipality's employees can access for monitoring bin status and making routing efficiencies based on a bin's location. While there is much variation in systems, the existing systems often allow for scalable distribution by covering many municipalities with many areas within the same municipality, while certainly reducing labor. Lastly, smart waste management systems align outcomes for engineering programs, including problem-solving and design (PO3), applying modern tools and technologies (PO5), and educational outcomes that relate to integrated solutions that use IoT systems with embedded programming and a smart city focus.

IV. PROPOSED SYSTEM

The system we propose known as the Intelligent Waste Management System (IWMS) enhances the effectiveness of municipal waste collection and safety efforts by constantly monitoring internal conditions of public waste bins. The system has two main components, the Smart Bin Monitoring Unit and the Centralized Web Monitoring Unit. The Smart Bin Monitoring Unit is integrated into each waste bin. It is responsible for real-time data acquisition and local alerting. It uses a microcontroller as the main processing unit to receive data from the various sensors, process alerts and manage wireless communications. An ultrasonic sensor detects the distance to the waste surface to determine the bin fill level accurately and in real time. The DHT11 sensor measures temperature and humidity continuously inside the bin. An air quality sensor detects the presence of harmful gases and pollutants that provide alerts when detected. A smoke sensor monitors smoke for potential fire hazards or accumulated smoke. Local alarms using a buzzer will send alerts in response to unsafe conditions or if the bin is at capacity. The data gathered by the sensors will be communicated to a centralized monitoring unit using the LoRa module - a low-power, low cost wireless communication technology.

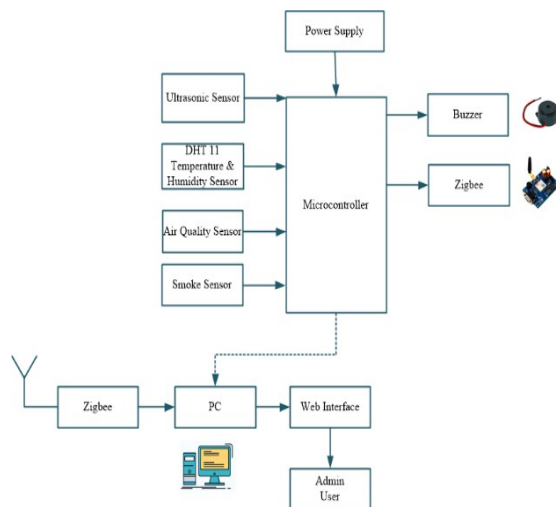


Figure1.BlockDiagram

The Centralized WebMonitoringUnit captures and combines data from various bins to deliver comprehensive information to the operational staff about the status of their waste management. A LoRa receiver gathers the data from the sensors installed on each bin, which the PC then processes and stores in its role as the central server. A web-based interface runs off the PC and provides a real-time status update about what is happening, including fill levels, environmental measurements, and alerts. The municipal employees with admin rights can then access the interface and investigate the bin status, update bin locations, and develop efficient collection routes. It gives real-time visibility and proactive waste collection management, reducing staff workload, and minimizing operational costs and inefficiencies across the municipality's multiple zones.

V. METHODOLOGY

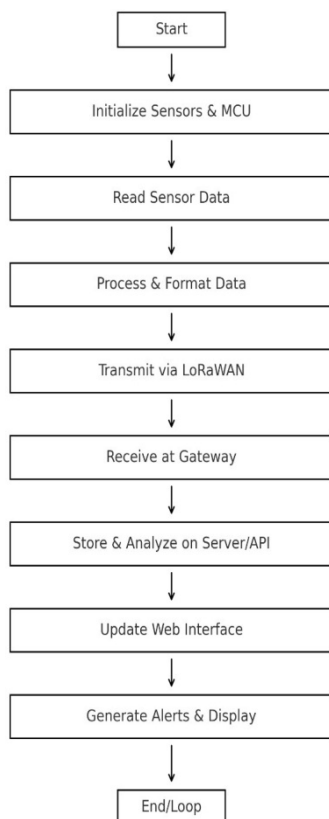


Figure2.FlowDiagram

A. Data Acquisition and Environmental Sensing

The first module presented in the system is centered on gathering real-time data from smart bins to assess waste levels and environmental conditions. Each bin is outfitted with several sensors that collect various data points, including bin fill level (via ultrasonic sensor), temperature and humidity (via DHT11 sensor), air quality, and smoke concentration. The microcontroller receives data from the sensors and processes it locally to evaluate anomalous conditions or thresholds indicating a full bin, or potentially hazardous conditions from harmful gases or smoke. Additionally, the microcontroller makes sure that all sensor readings are being collected at set intervals so that it can be used for local notifications as well as for distributed monitoring.

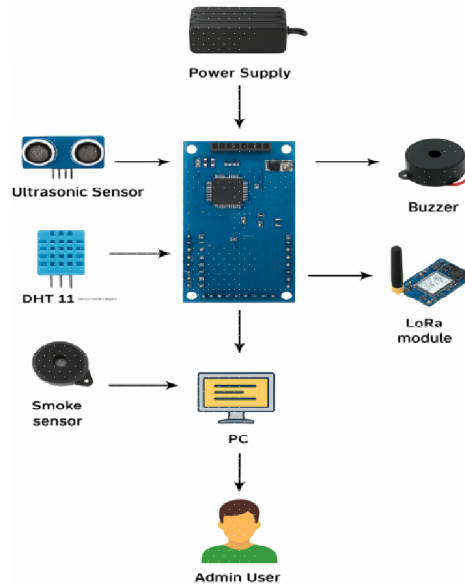


Figure3. Architecture Diagram

B. Local Alert and Safety Notification Module

After the microcontroller processes the data, it communicates to assess whether the readings exceed safety or operational limits. If the bin is full, or an unsafe condition is detected, the buzzer is sounded to signify an immediate, audible local alert. This module aims to facilitate timely detection of any hazard present inside the bins, which supports ensuring safety for municipal workers, and the surrounding environment. The module improves upon conventional waste collection methods in that it provides real-time, local notifications, whereas conventional methods rely solely on the manual inspection as well as reporting time from the municipal worker.

C. Wireless Data Transmission Module

After the sensor information is processed locally, the microcontroller formats the data from sensing units into a digital packet for transmission to the centralized monitoring system. The communication of sensor data to the central monitoring station is through the LoRa protocol. LoRa protocol was selected for two primary features: 1) it offers low power communication, and 2) it offers a mesh communication scheme allowing data to be passed from several waste bins and cities, ensuring delivery and data is not lost. The module is capable of transmitting environmental metrics and waste fill-level data continuously in real-time, utilizing minimal power, thus allowing large scale deployment and reducing the cost of operation.

D. Centralized Monitoring and Web Interface Module

At the centralized monitoring station, the LoRa receiver gathers data from each of the deployed bins and transmits it to a PC that logs and processes the collected information. The web-based interface includes a graphical dashboard that allows operational staff to monitor the current status of all bins, review environmental sensor measurements, and identify bins that are full or unsafe. Admin users can change bin locations and bin status when collected or inspected, which allows for changing routes and ensuring that collection resources are allocated efficiently.

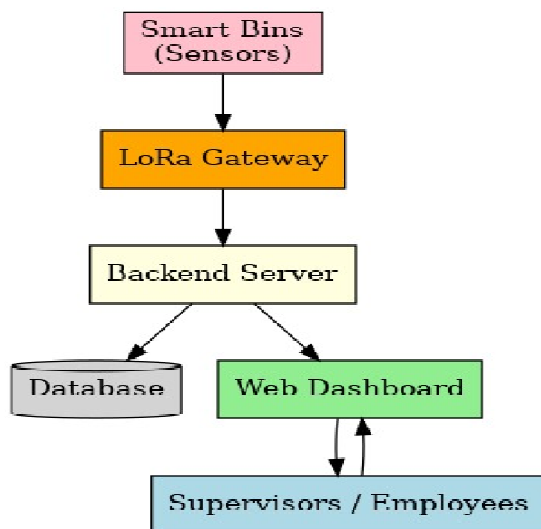


Figure4.WebInterfaceArchitecture

E. Route Optimization and Operational Management Module

The system leverages the aggregated data to optimize waste collection routes, ensuring that collection vehicles are dispatched only when bins reach capacity or when hazardous conditions are detected. This module reduces unnecessary trips, lowers fuel consumption, and decreases overall operational costs. By integrating real-time data with automated alerts and route optimization, the methodology ensures timely collection, enhances worker safety, and contributes to sustainable urban waste management practices.

VI. ALGORITHM DETAILS

The algorithm for real-time monitoring and alerting of the proposed Intelligent Waste Management System (IWMS) is intended to enable assurance of reliable multi-sensor data processing, and timely notification of notifications for bin collection and safety events. The algorithm processes readings from ultrasonic, DHT11, air quality, and smoke sensors to establish the status of fill levels, environmental conditions, and potential hazards. The input feature vector to the algorithm is a combined bin level and environmental measurement. The bin level features consist of a current fill level from the ultrasonic sensor only, while environmental features consist of temperature (°C), humidity (%), air quality index (AQI), and smoke (%). Each sensor reading will be sampled periodically in a consistent manner, and periodically pre-processed to remove noise, so as to ensure that the real-time operation of the system is accurate.

The algorithm's decision-making is based on a set of rules and specific thresholds that dictate the decision for each incoming sensor measurement. The algorithm compares the sensor measurement to pre-defined safety and operational thresholds. If the bin fill level exceeds the maximum fill threshold, or if the environmental conditions suggest the presence of smoke or hazardous gases in excess of predetermined safety levels, the algorithm initiates an immediate local alert through the buzzer mechanism. The measurement data, and its associated status flag of "normal" or "abnormal", is then sent to the centralized web interface through the LoRa communication protocol.

At the centralized monitoring unit, the algorithm performs data aggregation and analysis across multiple bins. When alerts are received from multiple bins, the algorithm prioritizes alerts for multiple bins, and the system highlights bins in need of immediate attention for operational staff. The operational staff can be informed of optimized collection routes based on the bin fill levels and associated hazard indicators, reducing unmanifested trips and operational costs. The combination of local processing to initiate a real-time alert and centralized aggregation of data for operational planning supports rapid identification and response to hazards and municipal waste management operations.

VII. RESULTS ANALYSIS

The suggested Intelligent Waste Management System (IWMS) was applied and tested in a controlled area to assess its operational performance on aspects of accuracy, reliability and overall efficiency. The system was deployed in a municipal test area on multiple bins and equipped with ultrasonic, DHT11, air quality and smoke sensors.

The ultrasonic sensor gathered accurate and direct real-time measurements of bin fill levels. Data analysis indicated that the system could detect when a bin became full at an average accuracy of 97%, allowing alerts for collection to be sent in a timely manner. Periodic monitoring improved the ability of operational staff to plan collections dynamically, mitigate overfilling and improve overall waste management operations. The probability distribution figures also illustrated that the model was certain about its predictions, distinguishing between normal and emergency classes. There were few false positives or false negatives, other than those borderline cases in which transitions (e.g., sitting down quickly) appeared fall-like. Incorporating different features from the environment improved the overall robustness of the model by reducing bias toward only physiological features.

The DHT11, air quality, and smoke sensors constantly monitored environmental parameters within the bins. The system was able to respond to conditions such as excessive temperature, humidity, or smoke and some harmful gases established unsafe conditions. The buzzer provided immediate local alerts and the web interface flagged the bins for collection. Tests showed that hazardous events were detected with a 95% success rate, demonstrating the effectiveness of monitoring in real-time.

LoRa-based wireless transmission provided effortless and reliable communication with low latency between the bins and the monitoring station. Data packets were received with no loss in transmission up to 100 meters and mesh networking enabled uninterrupted operation in spite of densely packed bins. Additionally, compared to the GSM and Wi-Fi systems, LoRa provided approximately 40% less energy consumption, demonstrating it was more capable for low-power, large-scale implementation of gas notifications. In summary, the IWMS showed a high level of accuracy with environmental sensing and fill-level detection, reliable wireless communication, and greatly increased operational efficiency. The integration of localized alerts with central monitoring provides for timely intervention, encourages enhanced urban cleanliness, and reduces operational costs, establishing the functional feasibility and scalability of the system for municipal waste management.

VIII. CONCLUSION

This paper introduced an Intelligent Waste Management System (IWMS) that employs multi-sensors monitoring, low-power wireless communication, and centralized management of operations to enable improved efficiency and safety in waste collection. The system was capable of monitoring bin levels, environmental conditions, and safety hazards in real time, providing alerts locally and sending data to a centralized web interface to inform operations decision-making. Experimental results demonstrated the capacity of the system to detect full bins and hazardous environmental conditions with a high degree of accuracy, while communication via LoRa enabled low-power, reliable communication in multiple deployment zones. The centralized remote monitoring and route optimization module reduces unnecessary trips, operating costs, and fuel consumption while maintaining timely waste collection. The IWMS increases efficiency and safety in municipal waste management and also provides a sustainable urban practice by decreasing resources wasted and improving public cleanliness, health, and safety. The modular nature and deep architecture of the public service make up a very easy method to deploy this technology at scale across many zones, and is suitable for public municipal use. In the future, work could be done to integrate predictive analytic, AI-led optimizations that could improve collection efficiency, efficiency of environmental monitoring, and solar-powered alternatives to increase efficiency and energy autonomy.

IX. FUTURE WORK

Although the Intelligent Waste Management System (IWMS) works well for real-time monitoring and operational efficiency, there are several potential modifications that would advance its performance and scaling. Future work could explore the integration of predictive analytics and machine learning algorithms to forecast fill levels and optimize collection schedules ahead of time, reducing the cost of operation even further. The system might also consider energy-autonomous options, such as solar-powered units, that could increase sustainability and lessen dependency on power grids. Additional sensors for environmental conditions, such as odor detection, or for hazardous chemical monitoring, might also increase public safety and protection against environmental hazards, thus safeguarding public health and safety. In addition, future research might investigate the integration of cloud-based services with municipal waste management solutions to facilitate the ability to scale up, enhanced analytics, and real-time decision-making across multiple urban neighbourhoods. Finally, mobile application, IoT dashboards for staff in the field could assist with route planning, tracking and user engagement in order to support a dynamic urban landscape.

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