IoT Smart Waste Bin System with Real-Time Fill-Level Analytics, Toxic Gas Monitoring, and GPS-Based Collection Optimization

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ABSTRACT

Proper waste management is pivotal to environmental sustainability and public well-being, especially in fast-developing cities. This paper introduces the design and implementation of an Automatic Waste Management System through Internet of Things (IoT) technology and Thingsspeak cloud platform to overcome common issues with conventional waste management. Our system incorporates sophisticated sensors for automating the classification of waste into dry and wet forms to ensure effective disposal. Real-time monitoring features send timely alerts when the bins are filled to capacity and sense dangerous gases released during decomposing waste, so immediate action can be taken. It is run by a solar panel, so it encourages green operations. Using a microcontroller (Raspberry Pi Pico W), GPS, and numerous sensors, our solution reduces human interactions, making operations more efficient and cost-effective. Early trials show encouraging performance in waste detection and notification procedures, setting the stage for further development and expanded use in urban waste management.

Keywords

Internet of Things (IoT), Global Positioning System (GPS), Raspberry Pi Pico W, Thingsspeak platform, Sensors.

1. INTRODUCTION

Effective waste management is the most critical thing to achieve while developing smart cities. For urban sanitation, various technologies such as IoT, GPS, blockchain, and machine learning have been integrated into waste management. One system comprises ultrasonic sensors within dustbins to monitor the volume of waste within the dustbins, wireless reporting to optimize collection routes and timings for enhancement [1]. Another system proposes integrating real-time waste collection management and an alert system to notify municipal personnel and residents with minimal human intervention [2].

Alternatively, GPS technology is utilized to track waste bin locations within cities to allow the optimization of collection truck travel and the reduction of fuel consumption [3]. Predictive models based on machine learning are utilized to forecast waste generation patterns to allow cities to optimize collection routes to avoid full bins [4]. Blockchain technology is also integrated within some systems to allow for transparency and accountability in securely recording all on waste collection operations [5].

Other technologies are automated refuse collection trucks, which are controlled by GPS and sensors and thus reduce the need for human drivers [6]. Artificial intelligence-driven autonomous waste collection systems can collect and transport waste independently to collection points [7]. Trash cans also contain environmental sensors that detect air quality and smells to assist in making the city healthier [8]. Solar-powered sensors and smart grids are also employed to make the system greener by lowering the energy usage of the system while enhancing waste monitoring [9].

Mobile apps have been created to allow real-time communication between waste management staff and residents to indicate full bins and optimize waste collection routes [10]. Some systems also apply real-time analysis to maximize dispatching of waste collection trucks, minimizing unnecessary emissions and fuel consumption [11]. Remote monitoring of system performance and more control over operations are also made possible by integrating the systems [12]. Coupling waste management solutions with other smart city technologies enhances data gathering, which translates to more effective utilization of resources [13].

Intelligent bins that are IoT technology-enabled notify the authorities when they are full, enabling timely collection and preventing spillage [14]. GPS communication and navigation technology is employed by some to provide real-time data to the waste management system [15]. Some employ big data analytics to predict waste generation and adjust waste collection schedules accordingly [16]. Blockchain solutions are increasingly being employed since they can enable traceability and security in waste management systems [17].

Several studies have shown that machine learning algorithms can, with great effectiveness, be applied in waste management to enhance waste collection predictive models [18]. Application of green data combined with smart infrastructure makes waste management systems respond more effectively and adjust more efficiently with evolving urban dynamics [19]. Robotic automation development will be most likely to persist, thereby further enhancing waste collection activities and reducing labour while enhancing system efficiency as well [20]. In addition, urban waste management systems are now more commonly incorporating solar-powered technologies to make their environments cleaner without affecting waste collection reliability [21].

Aside from that, better remote monitoring systems enable waste management authorities to perform preventative maintenance, minimizing downtime and enhancing operation efficiency [22]. IoT-solutions are also being implemented into garbage bins to monitor not just the waste, but also environmental aspects like odours and air quality with the aim to promote a cleaner city environment [23]. Frontline research has touched on the interface between intelligent sensors and AI in enabling automatic sorting and automatic classification of wastes, further leading the way to more initiatives towards recycling wastes [24]. Finally, integrating urban waste management and cloud computing enables centralized analysis of data and real-time decision-making, enhancing resource allocation and system performance [25].

In our project, we aim to enhance waste management systems using IoT-based sensor integration with real-time data analysis. With the advancements in GPS and IoT technology, we aim to streamline waste collection routes and scheduling to reduce environmental footprint and maximize operations.

2. METHODOLOGY

The designed smart waste monitoring system adopts a step-by-step approach to facilitate real-time functionality and reliability. The system uses current hardware and software to present real-time data to users and regulators for proper decision-making. From Figure 2, the system includes real-time sensing, data processing, and communication. Fill levels are sensed by ultrasonic sensors, and gas sensors monitor dangerous gases such as methane and CO_2. Raspberry Pi Pico W executes this data, and when the bin is more than 80% full or gas levels are above a set limit, an alarm is raised. Sensor data is sent through MQTT to ThingSpeak and cloud storage. A Python-based dashboard is used to monitor and analyze the system. If a critical state is sensed, a worker is automatically allocated, and an SMS or WhatsApp notification is made. Moreover, a buzzer in the bin is sounded every 5 minutes until the waste is picked up, which helps to ensure quick response.

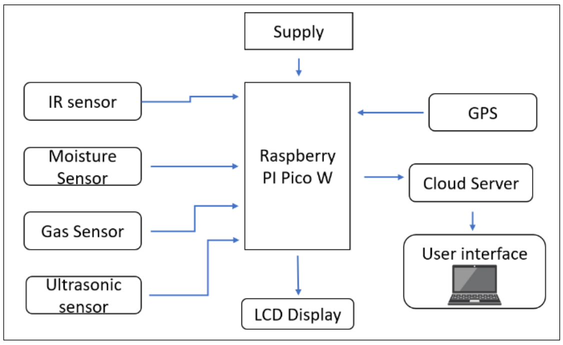

Fig.1: Block diagram of Smart Garbage Container

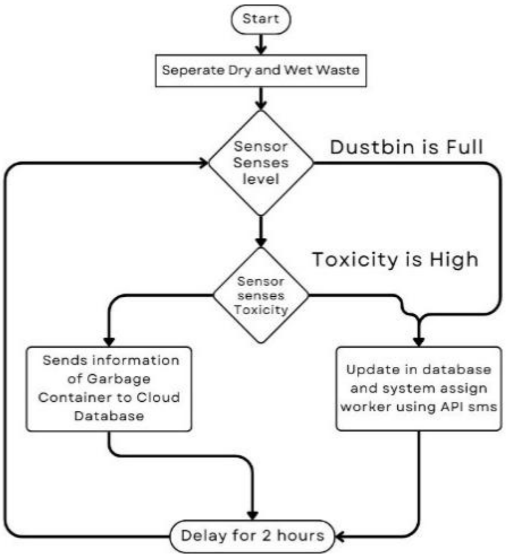

Fig.2: Flow chart of proposed system

The entire system is systematically described in the following subsections.

A. System Controller :

The Raspberry Pi Pico WH is the central processing unit of the system.It has a small form factor, low power usage, and built-in Wi-Fi for wireless connectivity.Its dual-core ARM Cortex-M0+ processor provides robust sensor data management and transmission.These characteristics make it best suited for real-time, IoT-based intelligent waste monitoring solutions.

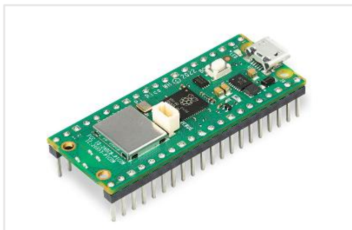

Fig.3: Raspberry Pi Pico WH

Table.1: Specifications of Raspberry Pi Pico WH

Parameter	Specification
Operating Voltage	5v DC
Clock Speed	133 MHz
DC current per I/O pin	20mA at 5v

B. To measure the fill level of the dustbin:

An ultrasonic sensor is used. This sensor calculates the distance between itself and the garbage through the use of sound wave reflection. It uses a transmitter, which sends out high-frequency pulses of sound at regular intervals, and a receiver, which receives the waves after they reflect off the surface of the trash. Because the waste is an impediment, the sensor measures the round-trip time of the sound waves and employs it to calculate the distance. The distance is calculated by the formula:

Distance = (Speed of Sound × Time) / 2

Fig.4: Ultrasonic Sensor HC-SR04

The operating parameters of Ultrasonic sensor are shown in table.2.

Table.2: Specifications of Ultrasonic Sensor

Parameter	Specification
Supply Voltage	5 Volts (DC)
Current Consumption	15 milliamperes
Detection Range	2 cm to 400 cm

C . Gas Sensor for Toxicity Detection:

To detect the presence of toxic gases released from waste bins, the system uses the MQ3 methane gas sensor. This sensor is highly sensitive to methane, which is a typical product of decomposing organic waste like rotten food, animal carcasses, eggshells, and spoiled vegetables. The sensor is important in the detection of high levels of gas that can cause environmental or health hazards. A graphical representation of the MQ3 sensor is shown in Figure 5, and its technical details are given in Table 3.

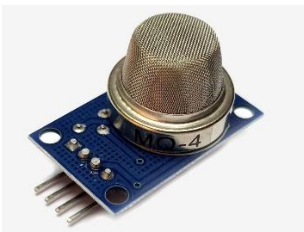

Fig.5: MQ3 Gas sonsor

Table.3: Specifications of MQ3 Gas Sensor

Parameter	Specification
Supply Voltage	5V DC
Heater Voltage Range	4.8V to 5.2 V
Heater Resistance	28 ohm to 40 ohm
Load Resistance	Approx 20 ohm

D. To detect garbage container location:

The system also incorporates a GPS (Global Positioning System) sensor in order to achieve real-time geolocation of all smart dustbins. This enables the tracking of the precise location of trash bins in various regions, which is particularly useful for optimizing routes of waste collection and providing timely service. The GPS module receives signals from satellites at all times to identify its coordinates (latitude and longitude) and sends these along with sensor data to the cloud.

Fig.6: GPS Sensor (For positioning)

The operating parameters of GPS sensor are shown in table.4

Table.4: Specifications of GPS Sensor

Parameter	Specification
Operating Voltage	3.3 v to 5 v dc
Communication Interface	UART (Universal Asynchronous Receiver-Transmitter)
Positioning Accuracy	±2.5 meters
Antenna Type	External Active Antenna (Patch)

E.For Segregating waste:

In this project, the use of the moisture sensor differentiates the wet and dry trash depending on the detection of water content within the garbage bin. The sensor monitors moisture levels when the trash is thrown into the bin. The sensor communicates the information to the Raspberry Pi Pico W for processing, which in turn sends it to the cloud for real-time tracking. Depending on levels of water content, the appropriate measure can be initiated.

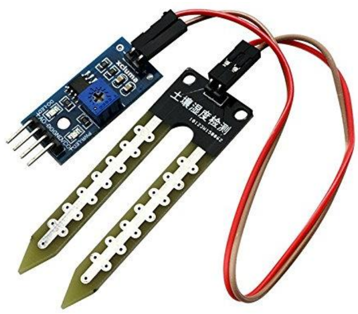

Fig.7: Moisture Sensor

Table.5: Specifications of Moisture sensor

Parameter	Specification
Supply Voltage	3.3V – 5V DC
Output Type	Analog(voltage)/ Digital
Detection Range	0% – 100% Moisture Level
Response Time	< 1Sec

F. To detect waste is dropped:

In this system, an Infrared (IR) sensor is employed to sense when waste falls into the garbage bin. The sensor detects any break in its beam, which means that an object (waste) has moved through.

Fig.8: Infrared sensor

Table.6: Specifications of IR sensor

Parameter	Specification
Operating Range	3.3V – 5V DC
Output Type	Digital (High/Low)
Detection Range	2 cm – 30 cm (adjustable)
Wavelength	~940 nm

G . Software Tools and Platform Integration:

The Raspberry Pi Pico W firmware was coded in Embedded C, selected due to its ability to manage low-level sensor interaction and real-time data processing. For enabling communication between the device and cloud services without hindrance, the MQTT protocol was utilized for lightweight and asynchronous data exchange. Sensor readings are published on ThingSpeak for real-time visualization and saved in Firebase and PostgreSQL databases for future analysis and backup.

Moreover, an executable (.exe) desktop application based on Python was created that served as the master monitoring panel. This software compiles statistics from all intelligent waste bins and has a simplified interface for monitoring in real time. It further supports logging customer complaints, looking up assigned cleaners tasked with dustbin cleaning, and showing a news feed window for sanitation notices and alerts.

3. RESULTS

All the parts such as the Raspberry Pi Pico W, gas and ultrasonic sensors, and the GPS module were correctly soldered and tested. The system is successful in triggering real-time alerts through MQTT when the dustbin is full or if there is high toxic gas level. Sensor information is shown on ThingSpeak for real-time observation and saved in Firebase and PostgreSQL for future reference. Basic simulations were carried out prior to the application of the circuit on hardware. The firmware was coded in Embedded C, whereas the monitoring dashboard was coded in Python and compiled into a.exe application. When the garbage container is 80% full, the system automatically identifies the status using the ultrasonic sensor and sends this information to the cloud database via the MQTT protocol.

Upon discovery of the breach of threshold, the system systematically assigns a worker to duty of cleaning. It sends an automatic SMS notification to the assigned worker through the Twilio API with information on the location, time of assignment, and deadline of completion. Once completed, an acknowledgment message is also sent in response to indicating completion of duty. This automatization increases efficiency through minimization of manual input and ensuring proper timing of waste disposal.

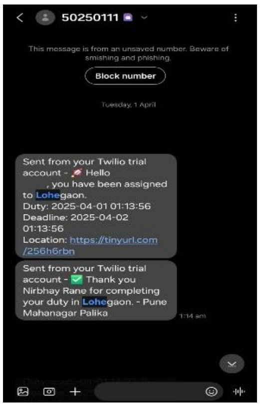

Fig. 9. Message send

A specific webpage is created to capture the complaints regarding overflowing or uncleared trash cans. Users can report the same manually, and the information is captured in a cloud-based database to enable the authorities to act. This guarantees public opinion is taken into account along with automated sensor notifications. The portal can be accessed at: https://waste-management-de5b9.web.app/

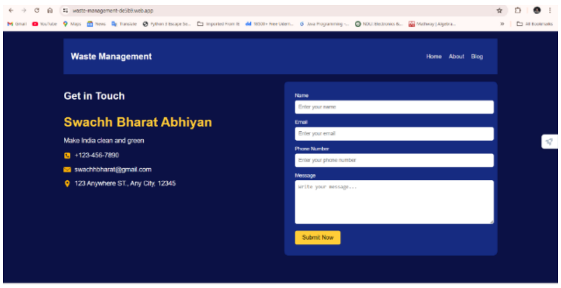

Fig. 10. Complaint Webpage

The homepage of the software, which is Python-based, is a unified monitoring dashboard of the smart waste management system. It has necessary navigation buttons like Status (for real-time monitoring of rubbish containers), Regions (to look at bin positions in the city), Workers (to monitor allocated staff), and Complaints (to look at and respond to user-reported complaints). This allows real-time observation.

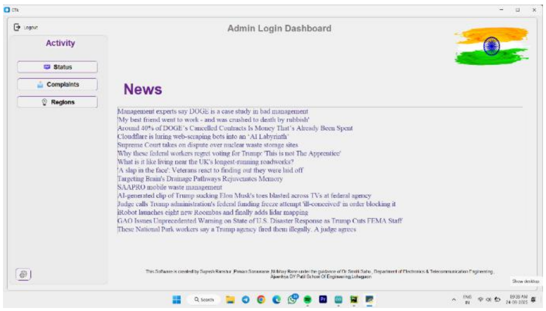

Fig. 11. Admin Login Dashboard

The Monitoring aspect of the application shows current data for each refuse container, including toxicity, percentage wet and dry bin fills, and the condition of assignment to workers. The administrators are enabled to readily know areas that present high-risk problems and instantly make decisions by allocating workers and inspecting locations for containers.

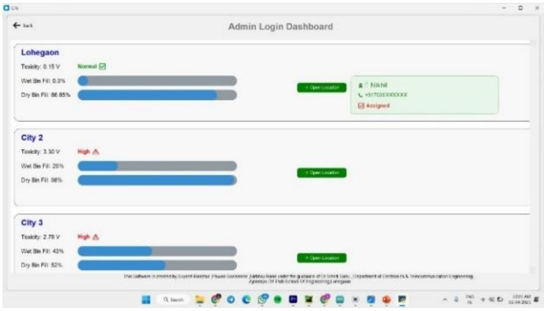

Fig. 12. Monitoring Section

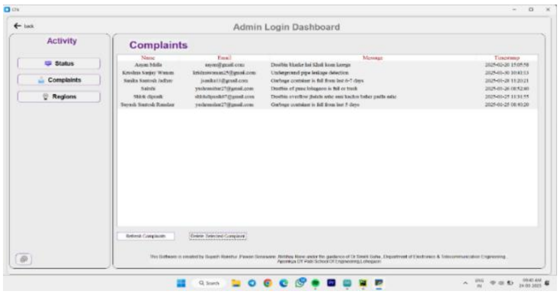

Fig 13. Complaints Dashboard

Fig 14. Smart Dustbin Prototype

This intelligent garbage monitoring system can be implemented in different public places like parks, railway stations, bus stops, and historical sites. As Wi-Fi connectivity becomes more common at public places, future implementations of the system can substitute GSM modules with Wi-Fi-based communication for improved efficiency and cost savings. Even though the existing configuration has been illustrated with one smart bin only, the system is expandable—several bins can be mounted, each having a distinct ID for convenient location tracking and data handling. Alerts about bin status and cleanup shift are automatically directed to the responsible staff in accordance with such distinct IDs, facilitating prompt garbage disposal from anywhere.

4. CONCLUSION

The following study introduces an IoT-enabled real-time waste management and monitoring system for measuring bin levels of waste, detecting danger levels of decompostiton gas, and optimizing GPS localization for effective waste collection. In general, it offers a solution for the government to enable wireless monitoring of individual bins and initiate autonomous labor deployment when bins are 80% full. The mechanism proposed will ensure effective and safe municipal cleanliness and minimize waste spillover emissions. Enhancements in the coming future will include implementing machine learning algorithms to predict waste generation levels, optimizing collection vehicle schedules dynamically using machine learning algorithms and multi-node systems with low-power network backups like LoRa and GSM.

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