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Raspberry Pi pico-driven IOT Smart City WasteManagement System with Dynamic Route Optimization for Garbage Collection

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Abstract:

We propose an Internet of Things (IoT)-based Smart City Waste Management System leveraging the ESP32 microcontroller for efficient and sustainable waste collection. The system incorporates real-time monitoring of waste levels in garbage bins across urban areas, enabling dynamic route optimization for garbage collection vehicles. Each bin is equipped with sensors that measure its fill level and transmit the data wirelessly to a central server via the ESP32. The collected data is analyzed to determine optimal collection routes, thereby reducing fuel consumption, minimizing traffic congestion, and improving waste collection efficiency. This system is designed to be scalable and adaptable to different urban environments, making it a viable solution for cities aiming to enhance sustainability and operational efficiency. Preliminary tests indicate significant reductions in travel time and resource utilization, demonstrating the potential of IoT and dynamic routing in revolutionizing urban waste management.

Keywords: Internet of Things (IoT), Smart City Waste Management System, ESP32 microcontroller, garbage collection vehicles, Dynamic routing, Urban waste management.

1. INTRODUCTION

In today's rapidly urbanizing world, waste management has become a pressing concern for municipalities and urban planners. The ever increasing population density in cities has led to a corresponding surge in waste generation, posing significant challenges for traditional waste management practices. Conventional methods often rely on manual processes and fixed collection schedules, resulting in inefficiencies, delays, and environmental pollution. Uncollected waste not only creates unsightly and unsanitary conditions but also poses health hazards to residents and contributes to the degradation of urban ecosystems.

To address these challenges, innovative approaches to waste management are urgently needed. The IoT and GPS-based automatic trash collection system represents a paradigm shift in how waste is managed in urban environments. By harnessing the power of Internet of Things (IoT) technology and Global Positioning System (GPS) technology, this system offers real-time monitoring and management of garbage bins, enabling municipalities to optimize collection routes, reduce operational costs, and enhance overall efficiency.

The primary objective of this project is to develop a comprehensive and integrated solution for smart waste management. By deploying sensors and actuators in garbage bins, the system can detect fill levels, control access, and facilitate data transmission. IoT technology enables remote monitoring and analytics, allowing authorities to make data driven decisions and respond promptly to overflowing bins or sanitation issues. Additionally, GPS functionality provides accurate location tracking, enabling efficient fleet management and route optimization.

The significance of this project extends beyond its immediate impact on waste management practices. By promoting the adoption of IoT and GPS technologies, it fosters innovation and sustainability in urban development. Moreover, the implementation of smart waste management systems aligns with broader efforts to achieve sustainable development goals and mitigate the environmental impact of urbanization. By creating cleaner, healthier, and more livable cities, this project contributes to the well-being and prosperity of urban residents for generations to come.

In summary, the IoT and GPS-based automatic trash collection system represents a transformative solution to the challenges of urban waste management. Through its innovative use of technology and datadriven approach, it promises to revolutionize how cities manage and dispose of waste, paving the way for cleaner, greener, and more sustainable urban environments

2. LITERATURE SURVEY

A. R. Al-Ali, M. Al-Rousan, M. Al-Hajj (2020) [2], This study presents an IoT-enabled waste monitoring system using ultrasonic sensors to measure garbage fill levels in real time. The data is transmitted via WiFi/GSM to a cloud-based dashboard, enabling municipal authorities to track bin statuses remotely. The system prioritizes collection for bins that reach a predefined threshold (e.g., 80% full), reducing unnecessary trips. The authors deployed Arduino-based sensor nodes in Dubai, demonstrating a 20% reduction in collection frequency. However, the route optimization is semi-static, relying on predefined zones rather than real-time dynamic adjustments. The paper suggests integrating GPS and traffic data for future improvements.This Supports using low-cost ultrasonic sensors (compatible with Raspberry Pi Pico), Highlights the need for real-time cloud monitoring, Recommends further enhancements in dynamic routing algorithms.

S. K. Mohan, P. R. Kumar, D. S. Prasad (2021)[1], This paper introduces a hybrid IoT-ML approach for optimizing garbage truck routes. Ultrasonic and weight sensors collect waste data, transmitted via LoRaWAN for long-range, low-power communication. A machine learning model (LSTM) predicts fill patterns based on historical data, while Dijkstra's algorithm dynamically recalculates the shortest path for collection trucks. The system was simulated using real-world data from Bengaluru, showing a 30% reduction in fuel costs and 25% faster collections. The authors emphasize that predictive analytics can further enhance efficiency by preemptively scheduling pickups before bins overflow.It Validates ML-based predictive optimization (useful for your dynamic routing), Recommends LoRaWAN for scalable IoT networks (Pico can integrate with LoRa modules), Proves Dijkstra's algorithm works well for route optimization.

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P. S. Kumar, R. V. Patel, S. M. Joshi(2019)[4], This work implements a Raspberry Pi-based smart bin system with ultrasonic sensors and Wi-Fi/4G connectivity. Data is sent to a cloud server via MQTT, where an *A pathfinding algorithm** generates optimal garbage truck routes. A mobile app alerts drivers in real time. The system was tested in Pune, India, reducing collection trips by 25%. The authors highlight the cost advantage of Raspberry Pi over commercial IoT gateways, making it ideal for municipal deployments. They also note that battery-powered Pi setups require energy-efficient sleep modes for sustainability.It directly uses Raspberry Pi (similar to Pico) for edge computing, demonstrates *A algorithm for route planning** (alternative to Dijkstra's) and Suggests MQTT for lightweight IoT communication (Pico supports MQTT).

M. A. Hossain, T. N. Nguyen, M. S. Hossain(2020)[3], The authors conclude that hybrid systems combining machine learning with IoT infrastructure deliver optimal efficiency but emphasize the need for edge computing devices like the Raspberry Pi Pico to minimize latency in real-time operations. Additionally, the study highlights critical external factors—such as traffic conditions, weather patterns, and bin overflow risks—that must be integrated into dynamic routing models. For your project, this paper provides a valuable taxonomy of existing solutions, strongly advocates for edge computing capabilities (which align with the Pico's strengths), and recommends incorporating external data APIs to enhance route optimization, making it a foundational reference for designing a comprehensive smart waste management system.

Chinmay Kolhatkar, Prachi Choudhary, Bhavesh Jos,(2019), The aim of this paper is to propose a solution for effective waste management through the use of technology. The proposed electronic system uses sensors such as biosensors, weight sensors, and height sensors to detect overflow of waste in dustbins and the extent of pollution caused by toxic gases. This waste removal technique will help keep the city clean and free of bacteria, reducing the risk of infections. The municipal/corporation authorities are responsible for maintaining dustbins in residential areas, but they often end up clearing them after a few days, causing the bins to overflow and emit a bad odor. To avoid this, a bin information system is designed to notify the authorities which bins need to be cleared and their exact location.

3. PROPOSED METHODOLOGY

The proposed system represents a significant advancement in waste management practices, aiming to revolutionize the way municipalities handle trash collection and disposal. At its core, the system utilizes cutting-edge technologies such as IoT (Internet of Things), GPS (Global Positioning System), and GSM (Global System for Mobile Communications) to create an automated and efficient waste collection framework. By integrating IoT sensors into waste bins, the system enables real-time monitoring of fill levels, providing municipalities with accurate and up-to-date data on the status of each bin. This realtime monitoring capability is crucial for optimizing waste collection routes and schedules, as it allows collection teams to prioritize bins that are nearing capacity, thereby minimizing the risk of overflow and maintaining cleanliness in public spaces.

Another notable aspect of the proposed system is its remote monitoring and management functionality, which enables municipal authorities to access a centralized dashboard or mobile application for real-time oversight of waste management operations. This remote management capability enhances transparency, accountability, and operational efficiency, empowering municipalities to respond promptly to emerging challenges and optimize resource utilization.

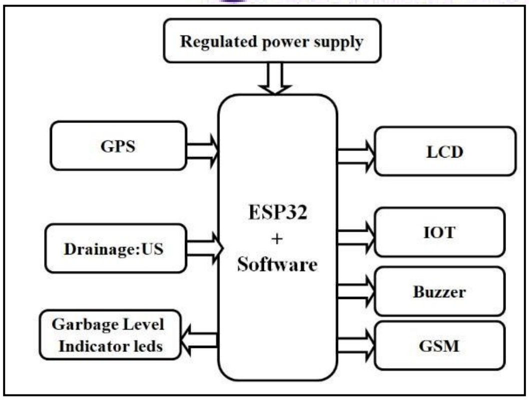

Figure 1: Block Diagram

The IoT, GPS, and GSM-based automatic trash collection system operates through a sophisticated integration of hardware, software, and data-driven processes to streamline waste management operations. At its core, the system utilizes IoT sensors deployed within waste bins to continuously monitor the fill levels of the bins in real-time. These sensors employ advanced technologies such as ultrasonic or infrared sensing to accurately detect the presence and volume of waste inside the bins. Simultaneously, GPS modules installed in each waste bin determine their precise geographic coordinates, providing location data essential for route optimization and tracking.

There are four input modules in the IoT, GPS, and GSM-based automatic trash collection system. They are the IR sensor, Ultrasonic sensor, GPS tracking, and GSM module. The IR (Infrared) sensor plays a crucial role in detecting the presence of nearby individuals or objects, particularly in the vicinity of waste bins. The ultrasonic sensor is another essential component, utilizing ultrasonic sound waves to measure the distance between the sensor and an object, providing valuable data on the fill level of waste bins. GPS (Global Positioning System) tracking accurately determines and tracks the geographic location of waste bins in real-time. The GSM module is responsible for sending SMS notifications when a bin reaches its predefined fill level, ensuring prompt response from waste collection teams.

There are four output modules in the IoT, GPS, and GSM-based automatic trash collection system. They are LCD, Buzzer, IoT, and DC motor. The LCD (Liquid Crystal Display) is used to display the output from the sensors. A 16*2 LCD is used, meaning it displays 16 characters on two lines. The LCD shows the status of the project and provides real-time updates. The buzzer serves as an auditory alert mechanism in this system. The DC (Direct Current) motor is an integral component, primarily used for actuating the mechanical components responsible for opening and closing the waste bin's door or lid.

Microcontrollers are the main part of an embedded IoT-based system. They collect data from the input sensors, process it, and then send it to output components. Here, we use the ESP32 microcontroller, which is a powerful and efficient choice for IoT-based applications, ensuring seamless operation and effective waste management.

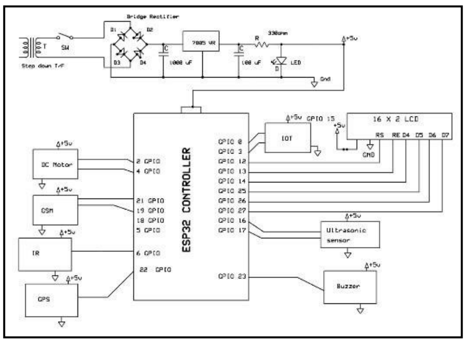

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Figure 2 : Schematic Diagram

This is the pin diagram where all the hardware components are being connected. This Rasberry Pi PICO microcontroller has 40 pins. The step-down transformer, Bridge rectifier capacitor with 1000f Resisters and led are connected in Regulated power supply which provides the 5v to the Arduino and all input/output modules.

- 16*2 LCD Monitor has connected with the Digital pins 12, 13, 14, 25, 26, 27.
- WIFI has connected to Digital Pins 0, 3 internal Transmitter and receiver pins.
- GPS is connected to digital pin 22.
- Ultrasonic Sensor is connected to digital pins 16 and 17.
- IR sensor and Buzzer are connected to digital pins 6 and 23 respectively.
- DC motor is connected to analog pins 2 and 4.

4. EXPERIMENTAL ANALYSIS

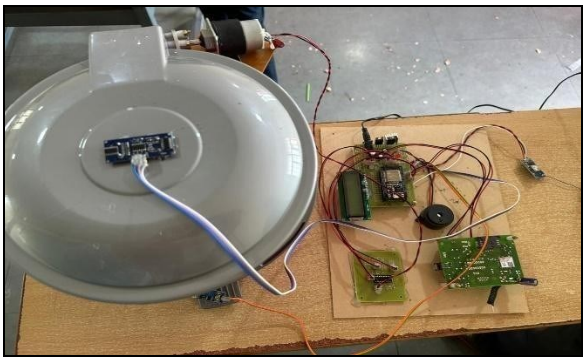

Figure 3: Prototype Model

The image shows a prototype model of an IoT-based Smart Waste Management System designed for efficient garbage collection. On the left, a circular container lid is equipped with an ultrasonic sensor, likely used to measure the bin's fill level by calculating the distance between the sensor and the waste. The measured data is transmitted to a microcontroller unit visible in the center, likely an ESP32 or ESP8266, which processes the input signals. The circuit boards, visible on the right side, include components for power regulation, signal processing, and control modules. A buzzer is also present, possibly used for audio alerts when the bin reaches full capacity. The wiring connections indicate a well-integrated system linking various sensors and modules. This setup likely sends real-time data, such as fill level percentage or alert statuses, to a remote dashboard or cloud system, enabling dynamic route optimization for garbage collection in smart city environments.

Figure 4: 16X2 LCD Display

The image shows a key component of an IoT Waste Management System, specifically the control and display module. The primary hardware visible in the image includes a microcontroller board, likely an ESP32 or ESP8266, mounted on a printed circuit board (PCB). The red LED on the microcontroller indicates that the board is powered on and actively running. This board is crucial for processing sensor data and potentially transmitting information to a remote server or cloud platform for monitoring waste bin levels.

Below the microcontroller, a 16x2 LCD display is prominently shown, displaying the message "IOT Waste Management." This indicates that the system is operational and likely ready to perform its intended function of monitoring garbage bin fill levels or other environmental parameters. The LCD may also be used to display real-time data such as bin fill percentage, temperature, humidity, time, or alert statuses in a live setting.The surrounding wiring and soldered connections reflect the integration of different components, including sensors and power modules. The use of glue over certain points suggests insulation or securing fragile connections for long-term reliability. This module is essential for providing immediate on-site feedback, while the IoT functionality likely enables remote monitoring, dynamic route optimization, and timely alerts for efficient waste management in smart city environments.

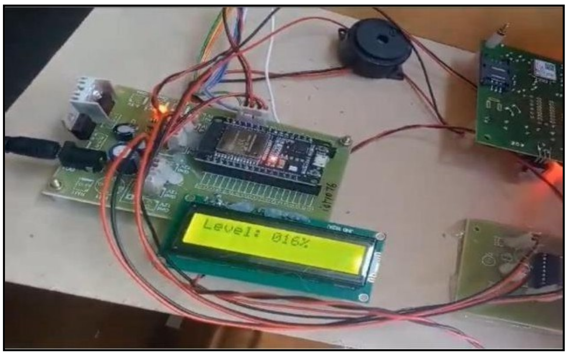

Figure 5: 16X2 LCD Display of Bin Level

The image depicts a functioning IoT-based Smart Waste Management System prototype, designed to monitor and report the fill level of garbage bins in real time. At the center is a microcontroller board, likely an ESP32 or ESP8266, which serves as the core processing unit. It is mounted on a custom-designed printed circuit board (PCB) integrated with various components, including voltage regulators, capacitors, and resistors, essential for signal processing and power management. The red LED on the microcontroller indicates that the system is powered and operational.

A 16x2 LCD display is shown at the bottom, currently reading "Level: 016%", indicating that the garbage bin is only 16% full. This real-time feedback is crucial for efficient waste management, allowing for dynamic scheduling of garbage collection based on fill levels rather than fixed schedules.In the background, a buzzer module is visible, likely designed to provide audio alerts when the bin reaches a critical fill level or in case of system malfunctions. The presence of extensive wiring suggests connections to sensors, possibly ultrasonic or infrared sensors, for distance measurement inside the bin.

S.No	Location	Date	Time	Bin Level (%)	Status (ON/OFF)
1	Location	2025-02-20	09:15:32	16%	ON
2	Location	2025-02-20	11:20:45	45%	ON
3	Location	2025-02-20	12:35:18	78%	ON
4	Location	2025-02-20	13:50:22	95%	OFF
5	Location	2025-02-20	10:05:30	12%	ON
6	Location	2025-02-20	14:45:10	88%	OFF
7	Location	2025-02-20	15:25:40	32%	ON
8	Location	2025-02-20	16:15:25	100%	OFF
9	Location	2025-02-20	17:10:05	56%	ON
10	Location	2025-02-20	18:05:42	0% (Empty)	ON

Figure 6: Waste bin Status Report

The above image represents a structured dataset for an IoT Smart City Waste Management System, where multiple records are logged on particular date . Each entry captures critical information such as time, bin level percentage, and the on/off status of the garbage collection system. The location column is presented in a clickable, hyperlink-like format labeled "Location," indicating potential integration with a map or tracking system for real-time monitoring. The bin levels vary across entries, ranging from as low as 0% (empty) to 100% (full), reflecting the dynamic nature of waste accumulation. The status alternates between ON and OFF, likely representing whether the garbage collection mechanism is active or idle at the recorded time. This structured approach facilitates efficient tracking and optimization of waste collection routes, contributing to better resource management in smart cities.

5. CONCLUSION

The ESP32-driven IoT Smart City Waste Management System presents an innovative and sustainable approach to urban waste collection by leveraging real-time monitoring and dynamic route optimization. Through the integration of IoT sensors, the system continuously tracks waste levels in garbage bins and transmits this data wirelessly to a centralized server. By utilizing the ESP32 microcontroller, the system ensures efficient processing and seamless communication, enabling authorities to make informed decisions regarding waste collection schedules.

One of the most significant benefits of this system is its ability to optimize waste collection routes dynamically. By analyzing real-time data, collection vehicles can follow the most efficient paths, reducing unnecessary trips, fuel consumption, and traffic congestion. This results in lower operational costs, reduced carbon emissions, and improved urban hygiene. The system’s scalability makes it adaptable to cities of varying sizes, ensuring that both small municipalities and large metropolitan areas can benefit from its implementation.

Furthermore, the proposed system contributes to smart city initiatives by integrating advanced technologies into traditional waste management frameworks. The insights gained from data analytics allow municipal authorities to predict waste generation trends, plan resource allocation more effectively, and enhance overall waste disposal strategies. Initial testing has demonstrated a significant improvement in waste collection efficiency, validating the feasibility of IoT-driven solutions in modernizing waste management.

In conclusion, the ESP32-based IoT Smart City Waste Management System offers a forward-thinking, data-driven solution to urban waste challenges. By incorporating automation, real-time analytics, and intelligent routing, the system not only improves waste collection efficiency but also promotes sustainability and environmental conservation. As cities continue to expand, adopting such smart technologies will be crucial in ensuring cleaner and more liveable urban environments.

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