

Design & Implementation of Smart Waste Collection System with Optimized Route Planning

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Abstract— With the growth of the global population, the challenge of waste management has become more complex. Effective waste management is no longer just a necessity but a critical concern for public health, urban sanitation, and ecological sustainability. Identifying the filled public waste bins in cities and collecting them effectively is one of the essential initial tasks of waste management, to address it more effectively and cost-efficiently the "Smart waste collection system with optimized route planning" is designed. The prototype system utilizes microcontrollers, a Photo-Voltaic power supply unit, ultrasonic sensors, and a wireless module to detect and communicate bin status in a multi-hop wireless network cluster. Each bin is equipped with an Ultrasonic sensor to measure the garbage level and the data is transmitted through neighboring bins to a central control unit using the ISM-based wireless communication multi-hop network, enabling remote monitoring. When bins are detected as filled, their locations are processed to determine the shortest and most efficient route for the collection of garbage using the Google Maps Directions API. The system was tested successfully using a prototype with three waste bins equipped with sensing units, and setting the location on the maps through a cloud-based web visualization built using basic HTML, Python, and Javascript, the system performed accurate fill-level detection and real-time route planning for garbage collection. This solution offers a cost-effective and scalable approach to smart urban waste management by reducing manual monitoring and optimizing collection routes with traffic awareness.

Keywords – *Waste Collection, Optimized Route Planning, ISM, Multi-hop communication, Arduino Uno*

I. INTRODUCTION

In recent years, the rapid growth of urban populations has created significant challenges in waste management, particularly in effectively collecting garbage from public bins. Conventional waste collection systems typically operate on pre-established routes and timetables, causing trash trucks to make unnecessary trips to empty public bins and delaying the collection of full bins due to inefficient collection routes. Also, this method of waste collection fails to escape from the city traffic resulting in unwanted delays. This lack of efficiency, not only increases operational expense but also has environmental and sanitary risks.

Considering the complex and larger road traffic conditions identifying the best waste collection route is extremely useful, as stepwise identification of filled bin locations needs to be addressed and an optimal real-time path through the busy road traffic must be identified with the shortest route, that can remove the unwanted time delays of waste collection for the trash trucks.

Through the review of recent work, it was noted that several smart solutions for waste collection were addressed as follows, each with varying effectiveness and cost. S. Rathi et al. developed a system using stereoscopic cameras and Raspberry Pi with OpenCV for estimating bin levels, which uses image processing for garbage identification [1]. Similarly, G. Prajakta et al. combined camera and load cell data for monitoring fill levels and sending alerts via email [2]. Yan Li et al. created a sensor-heavy real-time monitoring system that relies on GSM and RF modules, which require a network service provider for communication [3]. A similar system to Yan Li 's, developed by S. S. Chaudhari et al., introduced a cloud-based IoT system for real-time monitoring [4]. Jose M. Gutierrez et al. also used IoT, GIS, and graph theory to dynamically optimize trash collection [5], while H. N. Saha et al. proposed a compact smart bin for household purposes with cloud connectivity [6]. K. Nirdel et al. used sonar and weight sensors for status updates via LCD and web, with a wireless module [7]. M. S. Chaudhari et al. developed a smart bin system designed for smart cities using cloud-based IoT sensors and actuators. Collectively, these systems reveal significant use of smart technology to resolve certain parts of waste collection. Most systems use costly parts that come with maintenance requirements, both for the system itself and for the communication network and are unable to address efficient route planning for waste collection.

To handle these waste collection problems a better communication network should be established, without any unwanted costs involved with GSM or for internet payments. One of the simplest and most cost-effective ways of communication is using radio frequency bands. For the purpose use of specific frequency ranges that are reserved for Industrial, Scientific, and Medical (ISM) applications

channels can be utilized for cost-free communication without restrictions. For the bin level detection, a basic Microcontroller unit (MCU) unit mounted with an ultrasonic sensor can be used.

II. DESIGN METHODOLOGY

The proposed system is designed in phases. Each phase is divided in such a way that the development process achieves optimal time usage during the development of the system. No iterative approach was involved, so it removes the excessive time requirement and helps speed up the process. The initial phase started with problem identification, where the initial problem was identified and its impact along with the benefits of an ideal solution were analyzed to tune the throughput of the system to make it an ideal solution.

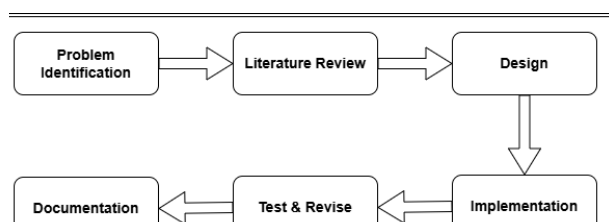


Figure 30: Design Methodology

Design methodology in Figure 1 shows the development stages of this product, initiating with the problem identification phase during which both the scope of the challenge and its real-world practicality were evaluated. During the second phase, literature solutions were analyzed to identify current flaws in them and develop an optimal solution. The designing phase begins with the primary high-level architecture of the system, which is extended into the circuit, network, software, and physical design. Then, the novel concept was developed during the implementation phase based on the outlay of each sketched design. Once the design was complete, the prototype was tested in units and as an integrated whole system, with revisions applied to the design for its betterment. Finally, the research project was concluded with the final documentation of all identified results, performance, and rate of success against the preset evaluation criteria set during the problem identification phase.

III. DESIGN

The design of the system consists of a base station and the bin nodes which are interconnected through an RF network cluster. Each bin node is fixed to a public garbage bin which measures the bin fill level using an HC-SR04 Ultrasonic sensor unit connected to an Arduino Uno microcontroller board with ATmega328p main microcontroller unit. For the RF network, NRF24L01+PA+LNA transceiver with Rubber Ducky antenna module is used to utilize the 2.4GHz ISM band to send and receive data. The setup enables bins to talk through one another in a multi-hop network, where each bin

can transmit its fill level to the central control unit through the network cluster. An optimized waste collection route is identified based on the filled bins, eliminating the need for wasteful inefficient routes, reducing time, and increasing efficiency using the Google Maps Directions API.

The individual units are powered by a simple Photo-Voltaic panel-based rechargeable battery setup which was designed separately. The use of simple and practically usable components focuses on a cost-effective, scalable, and energy-efficiency solution. With this system waste collection in a very densely populated area like a city with many public waste bins and even rural areas can be made more efficient.

A. Base Station Design

The base station is the primary computing unit which displays the bin fill status of each bin and the optimal path to collect the garbage from the filled bins. During the prototype design, a Windows-based PC is used as the base

node which connects to the RF module via an Arduino Uno. Using a Python program, the serial port data is captured and sent to the web application to update the bin data logs into a Google sheet. The application integrated the Google Maps Directions API, which provided real-time and accurate routing based Dijkstra algorithm, A* algorithm, Contraction Hierarchies, Real-time traffic, Machine Learning, and User feedback-based efficient path routing on actual road conditions, including one-way streets, traffic congestion, and road closure. Finally, the optimum route is displayed web-based application for the filled bins's waste collection for the trash trucks using Google Maps.

B. Bin Node Design

Each smart bin is equipped with a main MCU unit, ultrasonic sensing unit, RF communication module, and a PhotoVoltaic power supply unit.

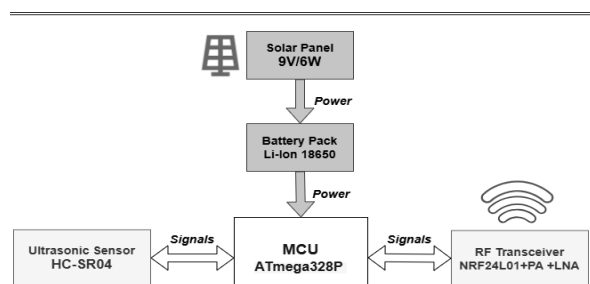


Figure 2: High-level Architecture – Bin Node

The high-level architecture of the bin nodes in Figure 2 represents how each module is interconnected in a bin node. The primary system is powered with a battery pack automatically charged by solar energy. The MCU receives the bin level from the ultrasonic sensor and initiates the transmission of data through the SPI interface in between the RF module to send the data to the base station through

the intermediate bin nodes. Then the data is transmitted via serial communication to a base station.

C. Network Design

The Multi-hop network cluster is designed using the NRF24L01+PA+LNA, RF modules. A single module can communicate up to 1100 m, since it uses a cluster to communicate the maximum distance between bin nodes must be less than 1100m, but the system can transmit data through other nodes which increases the data transmission distance of the overall system.

As shown in Figure 3, the bin nodes are connected to a maximum of 5 other bin nodes in the network, up to 5 levels. Theoretically, it can accommodate up to 3125 bin nodes (5^5). Since the transmission of data is done through the 2.4GHz ISM band there is no legal restriction for the system for transmission of data through the RF network.

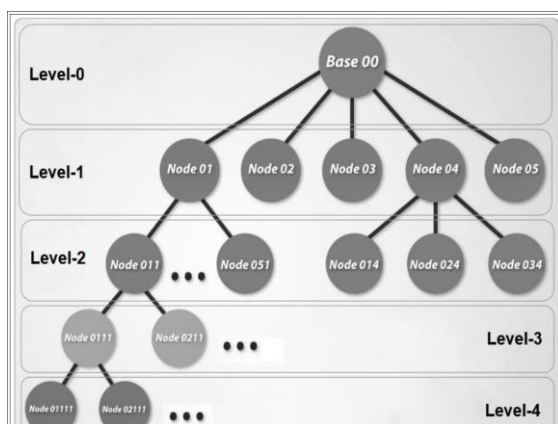


Figure 3: Network Design – NRF24L01+PA+LNA Modules

IV. RESULTS

The system is tested with three basic physical bin nodes and six predefined bin nodes in the web application. When the bin levels are sent through the RF network it logs the date to the Google sheet.

Timestamp	Control Center	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9
2025-05-17 14:39:08	Filled	Empty	Empty	Empty	Filled	Empty	Filled	Empty	Filled	Empty

Figure 4: Bin Status - Google Sheet

Bin node status in Figure 4 shows the data from the network updated into the Google sheet. Then the system can be prompt by using the web application to identify an optimal path for the waste collection for the trash trucks.

The system considers only the filled bin locations and then the route will be generated using Google Maps Directions API, which uses sophisticated routing algorithms with real-time traffic awareness.

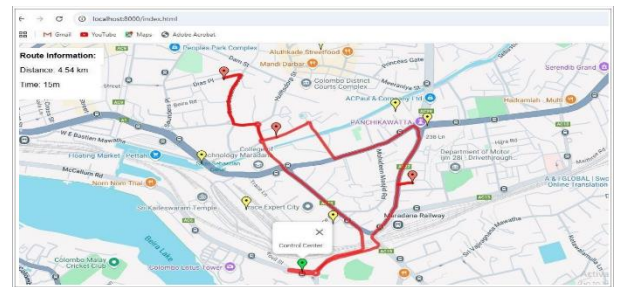


Figure 5: Final Route – Google Map

As shown in Figure 5 the test result gets generated from the system for the waste collection routes considering the real-time data. During the test, it was identified that communication through the RF network nodes is ideal to place in a line of site to each neighboring bin node for better communication. Also, during the startup of the nodes, it is better to initiate the communication of the nodes, in an environment free of 2.4 GHz interferences like Wi-Fi networks for faster connectivity establishment.

V. CONCLUSION

This work presents a prototype smart waste management system capable of monitoring bin fill levels, transmitting data via RF modules, and generating optimized routes mapping Ultrasonic sensors ensured fill level detection of the bins, while the web interface provided clear visualization of bin status and paths using the Google Maps. The main functions of the system were validated in a controlled environment.

To upgrade the system into a more robust solution the MCU unit can be upgraded into an industrial-grade counterpart. Also, bin node-to-node distance can be increased by upgrading it to a long-range RF transceiver in the ISM band (ex: LoRa-WAN network).

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