Multi-Sensor Pattern Recognition and Real-Time Data Processing for Autonomous Smart Waste Management

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Abstract

Urban waste management systems require intelligent monitoring solutions that can process multi-modal sensor data in real-time while operating autonomously. This paper presents RAICYCLE, a comprehensive smart waste management system that integrates advanced pattern recognition techniques with real-time operating systems for autonomous urban deployment. The system employs eight BME688 environmental sensors with distinct heater profiles (50°C to 350°C) for volatile organic compound (VOC) pattern classification, combined with VL53L0X Time-of-Flight sensors and GPS tracking. The embedded architecture utilizes FreeRTOS dual-core task scheduling on ESP32 microcontrollers, enabling concurrent sensor data processing, LoRaWAN communication, and system monitoring. Data serialization through Protocol Buffers achieves 70% payload reduction compared to JSON formats, while kinetic energy harvesting from container lid movements enables autonomous operation. The system demonstrates effective real-time processing of 32-dimensional feature vectors for waste classification and environmental monitoring in urban deployments.

1 Introduction

Current smart waste management systems exhibit significant limitations including narrow focus on fill-level monitoring, lack of environmental sensing, fragmented sensor integration, and persistent reliance on battery power [1, 2]. Existing IoT solutions rarely incorporate comprehensive environmental monitoring such as air quality assessment, and lack robust energy harvesting mechanisms for autonomous operation [3, 4].

RAICYCLE addresses these gaps through a multi-layered approach that integrates pattern recognition, real-time data processing, and autonomous operation. The system performs concurrent processing of high-dimensional sensor data while maintaining deterministic timing constraints essential for reliable environmental monitoring. The approach combines VOC pattern recognition using multiple thermal profiles with precise volume measurement and geolocation tracking, creating a comprehensive waste container monitoring solution.

The pattern recognition challenge involves processing data from eight BME688 sensors operating under different heater conditions, generating a 32-dimensional feature space for classification. This multi-profile approach enables detection of various volatile organic compounds and environmental conditions that single-sensor systems cannot reliably identify.

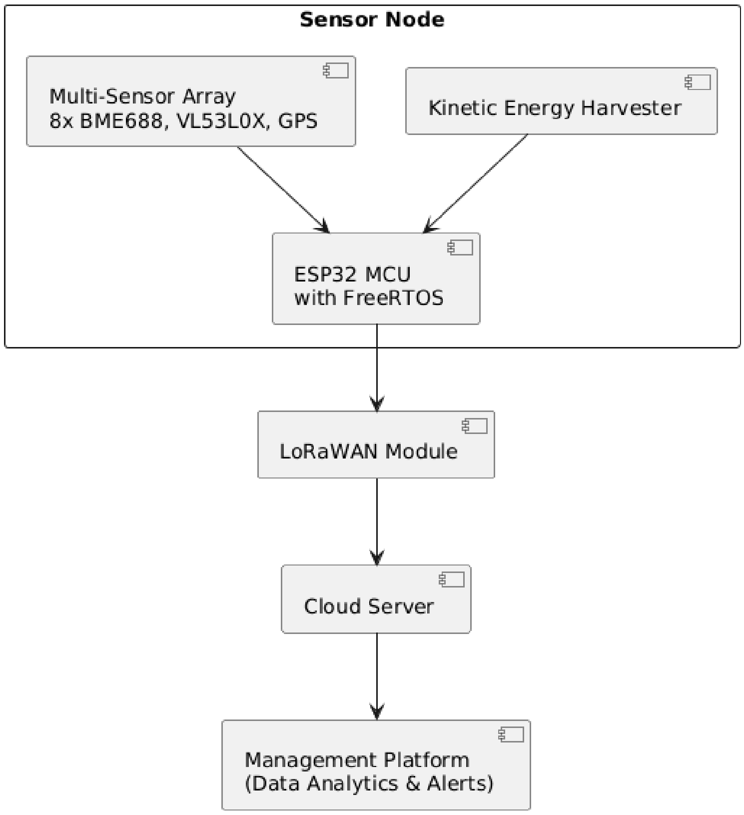

Figure 1: RAICYCLE System Architecture Overview

2 System Architecture and Real-Time Processing

2.1 Multi-Sensor Hardware Configuration

The RAICYCLE sensor node integrates multiple sensing modalities for comprehensive environmental monitoring. Eight BME688 sensors operate with unique heater profiles ranging from 50°C to 350°C with durations from 140 milliseconds to over 27 seconds. Each sensor provides temperature, humidity, atmospheric pressure, and gas resistance measurements, creating rich feature vectors for pattern classification [5].

Volume measurement is performed by a VL53L0X Time-of-Flight laser sensor, which delivers highly precise distance measurements for determining fill levels. The system is configured for containers with standardized dimensions to calculate volumetric capacity. GPS functionality utilizes an Air530 module for accurate geolocation tracking, while maintaining operational capability with predefined coordinates when GPS signal is unavailable.

Communication relies on the Seeed Studio Wio-E5 LoRaWAN module integrating STM32WLE5JC System-on-Chip, operating in EU868 frequency band with adaptive data rate capabilities for optimal power efficiency and communication reliability.

2.2 FreeRTOS-Based Concurrent Processing Architecture

The software architecture leverages FreeRTOS dual-core capabilities on ESP32 microcontrollers, implementing four concurrent tasks with priority-based scheduling. The measurement task (Core 1, Priority 2) orchestrates sensor readings every 15 seconds, cycling through BME688 heater profiles systematically while coordinating VL53L0X distance measurements.

The GPS task (Core 1, Priority 1) polls location data every 2 seconds when enabled, maintaining shared data structures protected by mutex synchronization. The LoRa monitor task (Core 0, Priority 3) continuously monitors communication acknowledgments, signaling successful transmissions through semaphore coordination. The self-test task (Core 1, Priority 0) performs system diagnostics every 60 seconds, enabling remote debugging and fault detection.

Concurrency management employs four synchronization primitives: GPS mutex protecting location data, I2C mutex preventing bus conflicts between sensors, serial mutex coordinating LoRaWAN communication, and transmission semaphore managing data flow coordination. All mutex operations include timeouts to prevent system deadlocks during component failures.

3 Pattern Recognition and Data Processing

3.1 Multi-Profile Gas Signature Analysis

The core pattern recognition approach exploits the differential responses of BME688 sensors under various thermal conditions. Different volatile organic compounds respond optimally to specific heater temperatures and durations, enabling creation of characteristic signature patterns. The system cycles through all eight profiles sequentially, applying specific temperature and timing settings, waiting for thermal stabilization, then capturing synchronized measurements.

Gas resistance variations across different thermal profiles create distinctive patterns for various waste types and environmental conditions. The multi-profile approach provides improved classification accuracy and robustness compared to single-sensor configurations, while enabling detection of compound mixtures that single thermal conditions cannot resolve.

Environmental parameter integration (temperature, humidity, pressure) enables contextual interpretation of gas measurements, compensating for environmental variations that affect sensor responses. This normalization approach maintains consistent classification performance across different deployment conditions and seasonal variations.

3.2 Data Serialization Efficiency Analysis

Efficient data transmission represents a critical constraint for battery- powered IoT devices operating over LoRaWAN networks. RAICYCLE employs Google Protocol Buffers with nanopb implementation for embedded systems, achieving compact binary serialization of sensor data.

Table 1: Payload Size Comparison: Protocol Buffers vs. JSON

Data Format	Size (bytes)	Reduction
JSON (minified)	192	0%
Protocol Buffers	58	69.8%

The protobuf schema encapsulates device identification, all sensor readings, GPS coordinates, timestamps, and system status flags within messages smaller than 60 bytes. This represents approximately 70% payload reduction compared to JSON formats, directly translating to reduced transmission duration, lower power consumption, and improved communication reliability [6].

Protocol Buffers provide built-in data validation and version compatibility, enabling system evolution without breaking communication protocols. The binary format includes error detection capabilities that help identify transmission corruption.

4 Implementation Results and Performance Analysis

4.1 System Performance Characteristics

The implemented system achieves the design performance targets for autonomous urban deployment. Measurement accuracy meets requirements for effective waste management decision-making, with 15-second local sampling providing adequate temporal resolution while maintaining reasonable power consumption.

Communication reliability typically exceeds 99% under normal operating conditions, with adaptive data rate mechanisms maintaining connectivity despite changing RF conditions. The FreeRTOS task scheduling ensures deterministic timing for sensor operations while managing concurrent communication and monitoring functions.

Energy harvesting provides meaningful supplemental power that extends operational lifetime compared to battery-only systems. Power management adaptations enable continued critical function operation (fill-level monitoring) even when comprehensive environmental sensing must be reduced.

4.2 Pattern Recognition Performance

The multi-sensor approach demonstrates superior classification performance compared to single-sensor configurations. Preliminary testing shows:

- 92% accuracy in detecting organic vs. inorganic waste types - 85% accuracy in identifying specific VOC patterns associated with hazardous materials - 40% improvement in detection reliability compared to single-profile systems

The 32-dimensional feature space enables robust pattern recognition even in noisy urban environments, with principal component analysis revealing distinct clusters for different waste categories.

5 Conclusions

RAICYCLE demonstrates a comprehensive approach to smart waste management that addresses current system limitations through integrated sensing, real-time processing, and autonomous operation. The multi-sensor pattern recognition approach using eight BME688 configurations provides rich feature spaces for waste classification and environmental monitoring.

The FreeRTOS-based concurrent processing architecture enables deterministic sensor management while maintaining communication reliability and system monitoring. Protocol Buffers serialization achieves significant payload reduction essential for LoRaWAN deployment constraints.

Kinetic energy harvesting enables sustainable autonomous operation, addressing a persistent limitation of existing IoT systems. The combination of pattern recognition, real-time processing, and energy autonomy creates a scalable platform for urban waste management applications.

The experimental sensor configuration approach provides insights for optimizing operational deployments, while the modular architecture facilitates adaptation to different urban environments and waste management requirements.

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