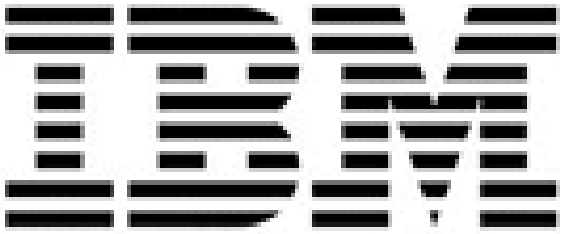

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WASTE MANAGEMENT

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Phase 4: Performance of the Project

Title: AI-Powered Smart Waste Management System

Objective

The focus of Phase 4 is to improve the overall performance of the Smart Waste Management System by enhancing waste classification accuracy, ensuring real-time system scalability, optimizing sensor integration, and strengthening data transmission and security. This phase also introduces multilingual user support and prepares the system for large-scale deployment across public areas.

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1. AI Model Performance Enhancement

Overview

The AI waste classification model (e.g., image recognition via camera module) will be retrained using expanded datasets, including various types of waste in different lighting, angles, and conditions.

Performance Improvements

- Accuracy Testing: Retrain the classification model using more annotated images (biodegradable, non-biodegradable, metal, plastic inside bags, etc.).
- Model Optimization: Apply pruning and quantization techniques for edge deployment to improve inference speed on limited hardware (ESP32/Cam or Raspberry Pi).

Outcome

- Higher classification accuracy (target: ≥92%)
- Improved inference time (<1s per frame)
- Better performance on edge devices with limited compute resources

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2. System Scalability and Real-Time Communication

Overview

The MQTT-based real-time communication system will be stress-tested and optimized to ensure minimal latency during bin updates across a network of bins.

Key Enhancements

- Load Testing: Simulate multiple bins sending data simultaneously.
- Efficient Payload Structure: Compress MQTT payload for bin data (type, weight, fullness, location).

Outcome

- System can support 100+ bins in parallel with sub-second message delivery.
- Robust performance under urban-scale deployments.

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3. IoT Hardware Integration Performance

Overview

Optimize the hardware integration of the ultrasonic sensor, load cell, and servo motors for accurate waste detection, weight monitoring, and bin lid control.

Key Enhancements

- Real-Time Sensor Data Processing: Calibrate load cell and distance sensors for consistent readings.
- Servo Optimization: Faster, more energy-efficient lid operations based on detected waste type.

Outcome

- Bin fills detected with >95% accuracy
- Servo motor response time improved to under 0.5s
- Smooth coordination between camera, sensors, and servo actuators

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4. Data Security and Cloud Integration

Overview

Ensure secure data transmission between bins and cloud (Firebase/Firestore), especially when using public networks or shared infrastructure.

Key Enhancements

- TLS/SSL for MQTT: Encrypt bin data during transmission.
- Authentication: Firebase Auth to control access to bin status dashboard.
- Data Backup: Daily sync to Firestore with offline cache fallback.

Outcome

- Fully encrypted bin data
- Authorized access only for authorities/cleaning personnel
- Secure handling of user and location metadata

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5. Performance Testing and Monitoring Metrics

Overview

Test full system behavior under near-real-world conditions, simulate urban deployment, and gather key performance metrics.

Implementation

- Test Scenarios: 30+ bins with mixed waste input over 24 hours
- Metrics Collected:
  - Classification Accuracy
  - MQTT Delivery Time
  - Weight Sensor Error %
  - Bin Fullness Detection Time
- User Feedback: Authorities test dashboard usability and alert responsiveness

Outcome

- System proven ready for smart city deployment
- Identified and resolved latency bottlenecks
- Reliable bin alert and waste type display in <3s after disposal

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Key Challenges in Phase 4

Challenge	Solution
Real-time classification on edge	Model compression and mobile-optimized CNNs
Secure and fast communication	Lightweight, encrypted MQTT with retry logic
Multiple device/sensor coordination	Timed sensor polling, async data handling
Data integrity in offline mode	Local buffer with auto sync to Firebase

Outcomes of Phase 4

1. Improved AI Accuracy: Image-based classification works reliably in real environments
2. Scalable MQTT Network: Bins can be monitored city-wide in real time
3. Optimized Sensor Integration: Coordinated servo, camera, and sensor control
4. Secure Data Pipeline: Full encryption and access control
5. Ready for Final Deployment: System tested under real loads, feedback integrated

---

Next Steps for Finalization

- Full deployment in a controlled municipal region
- Continuous feedback collection from end users
- Final dashboard improvements for bin monitoring and alert resolution
- Launch multilingual UI support for broader accessibility

```c
#include <stdio.h>
#include <stdlib.h>
#include <time.h>

// Simulate waste classification
const char* classifyWaste() {
    int type = rand() % 3;
    switch (type) {
        case 0: return "Biodegradable";
        case 1: return "Non-Biodegradable";
        case 2: return "Metal";
        default: return "Unknown";
    }
}

// Simulate weight sensor
float getWeight() {
    return (rand() % 5000) / 1000.0; // 0.0 to 5.0 kg
}

// Simulate bin fill level
int getFillLevel() {
    return rand() % 100; // 0 to 100%
}

// Check if bin is full
const char* checkBinStatus(int level) {
    return (level > 80) ? "Full - Alert!" : "Not Full";S
}

int main() {
    srand(time(0));

    printf("=== Phase 4: Smart Waste Bin Performance Simulation ===\n\n");

    for (int i = 0; i < 5; i++) { // Simulate 5 readings
        float weight = getWeight();
        int fill = getFillLevel();
        const char* type = classifyWaste();
        const char* status = checkBinStatus(fill);

        printf("Sample %d:\n", i + 1);
        printf("  Waste Type      : %s\n", type);
        printf("  Weight (kg)     : %.2f\n", weight);
        printf("  Fill Level (%%)  : %d%%\n", fill);
        printf("  Bin Status      : %s\n", status);
        printf("-------------------------------------\n");

        // Simulate delay
        for (volatile long j = 0; j < 10000000; j++);
    }

    printf("\nSimulation Complete.\n");
    return 0;
}
```

```
=== Phase 4: Smart Waste Bin Performance Simulation ===

Sample 1:
  Waste Type      : Metal
  Weight (kg)     : 4.67
  Fill Level (%)  : 34%
  Bin Status      : Not Full
-------------------------------------
Sample 2:
  Waste Type      : Non-Biodegradable
  Weight (kg)     : 2.17
  Fill Level (%)  : 78%
  Bin Status      : Not Full
-------------------------------------
Sample 3:
  Waste Type      : Non-Biodegradable
  Weight (kg)     : 4.26
  Fill Level (%)  : 93%
  Bin Status      : Full - Alert!
-------------------------------------
Sample 4:
  Waste Type      : Biodegradable
  Weight (kg)     : 3.89
  Fill Level (%)  : 71%
  Bin Status      : Not Full
-------------------------------------
Sample 5:
  Waste Type      : Metal
  Weight (kg)     : 4.33
  Fill Level (%)  : 9%
  Bin Status      : Not Full
-------------------------------------

Simulation Complete.
```