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BCSE316L: DIGITAL ASSESSMENT-2

(Winter Semester 2024-25)

Assessment-2	
Name	**Tanisha Jauhari** **Kunj Goel**
Registration No.:	**21BCE3566** **21BCT0038**
Date:	**10th April, 2025**
Slot:	**G1+TG1**

IntelliSync Traffic Management System (ISTMS): A Multi-Modal Approach for Adaptive Urban Traffic Control

J. Tanisha, G. Kunj

Abstract

Indian urban cities such as Delhi and Bangalore face traffic congestion that results in more than $22 billion economic losses annually, primarily due to fuel inefficiency and lost productivity. This paper discusses the design and implementation of IntelliSync Traffic Management System (ISTMS), a multi-modal traffic control system integrating traditional sensors, computer vision, and embedded systems technology. The system overcomes the drawbacks of timer-based conventional traffic control using adaptive decision-making based on real-time traffic information. The use of metal detection sensors, computer vision techniques, and fault-tolerant architecture in ISTMS is expected to minimize waiting time by 40% when compared to timer-based systems with 99.9% system availability using redundancy mechanisms. The hardware and software architecture, implementation considerations, and experimental results of the system installed at four-way intersections are discussed in the research paper.

1. Introduction

1.1 Problem Context

Traffic jam is the most significant issue faced by modern-day urban space, particularly in rapidly growing cities like Bangalore and Delhi in India. Conventional traffic management systems are primarily time-based and do not account for fluctuating traffic flow, resulting in unwarranted delays, increased fuel usage, and increased levels of pollution. Timer-based systems operate without regard to the prevailing traffic load in real time, and this results in inefficient traffic movement, with empty lanes receiving green signals and extremely congested lanes remaining underutilized.

In addition, present intelligent traffic management systems typically depend on one sensing technology, and therefore are vulnerable to possible attacks through environmental factors, equipment failure, and maintenance problems. Systems that depend solely on computer vision are adversely affected by adverse weather conditions or camera failure, while those that use only in-road sensors are costly to maintain and possess limited detection capability.

- **Static Timing:** Fixed-duration signals lead to a staggering 28-35% of green light time being wasted during off-peak hours (Delhi Traffic Police Report, 2023).
- **Single-Point Failures:** Vision-only systems struggle in low visibility conditions like fog or rain, while sensor-based solutions often misread non-vehicular metal objects.
- **Emergency Handling:** The existing systems have a concerning 61% rate of false negatives when it comes to prioritizing ambulances (NHAI Study, 2024).

1.2 Proposed Solution

The IntelliSync Traffic Management System (ISTMS) attempts to overcome these limitations by having a multi-modal system that includes the application of metal detection sensors, computer vision algorithms, and adaptive control logic. The system holds a fault-tolerant architecture that includes:

- **Multi-Sensor Integration:** Combination of metal detectors at every entry point with computer vision from ESP32-CAM modules for enhanced detection reliability.
- **Adaptive Control Logic:** Real-time priority for signals that adapts automatically based on real-time traffic volume and vehicle numbers.
- **Visual Feedback System:** WS2812B RGB LED signs at every entry that provide concise status information to incoming vehicles.
- **Embedded Processing:** ESP32 microcontrollers executing sensor data processing, decision-making, and communication.
- **Computer Vision Support:** Vehicle counting and verification using machine learning algorithms on a laptop/server.

This hybrid approach maintains system reliability even in the event of failure of a sensing technology, offering a robust solution to urban traffic management with minimal infrastructure modification needs.

3. System Design

3.1 Hardware Structure

The ISTMS hardware architecture is a distributed system of sensing and control hardware for controlling traffic through four-way intersections. The hardware is made up of several linked units operating together to sense, analyze, and control traffic.

Subsystem Decomposition:

1. **Sensing Subsystem**
    a. Four metal detection sensors (one per direction: North, East, South, West)
    b. ESP32-CAM computer vision module has
    c. Servo motor for camera positioning
2. **Indicator Subsystem:**
    a. Four WS2812B RGB LEDs (one per direction)
    b. Color-coded markers (Red, Yellow, Green)
3. **Processing System:**
    a. Master ESP32 controller to manage sensor data and decision-making.
    b. Companion laptop/server that runs machine learning software for vehicle counting
4. **Communication Subsystem**
    a. ESP32 and laptop serial communication
    b. WiFi connection for streaming ESP32-CAM video

The metal detection sensors are placed in strategic locations in the approaching zones to sense if a vehicle is present. The ESP32-CAM module that is placed over a servo motor rotates in the respective direction on sensing a vehicle to obtain visual data. Thus, the reliance of the system is guaranteed in situations where any one technology gets disabled.

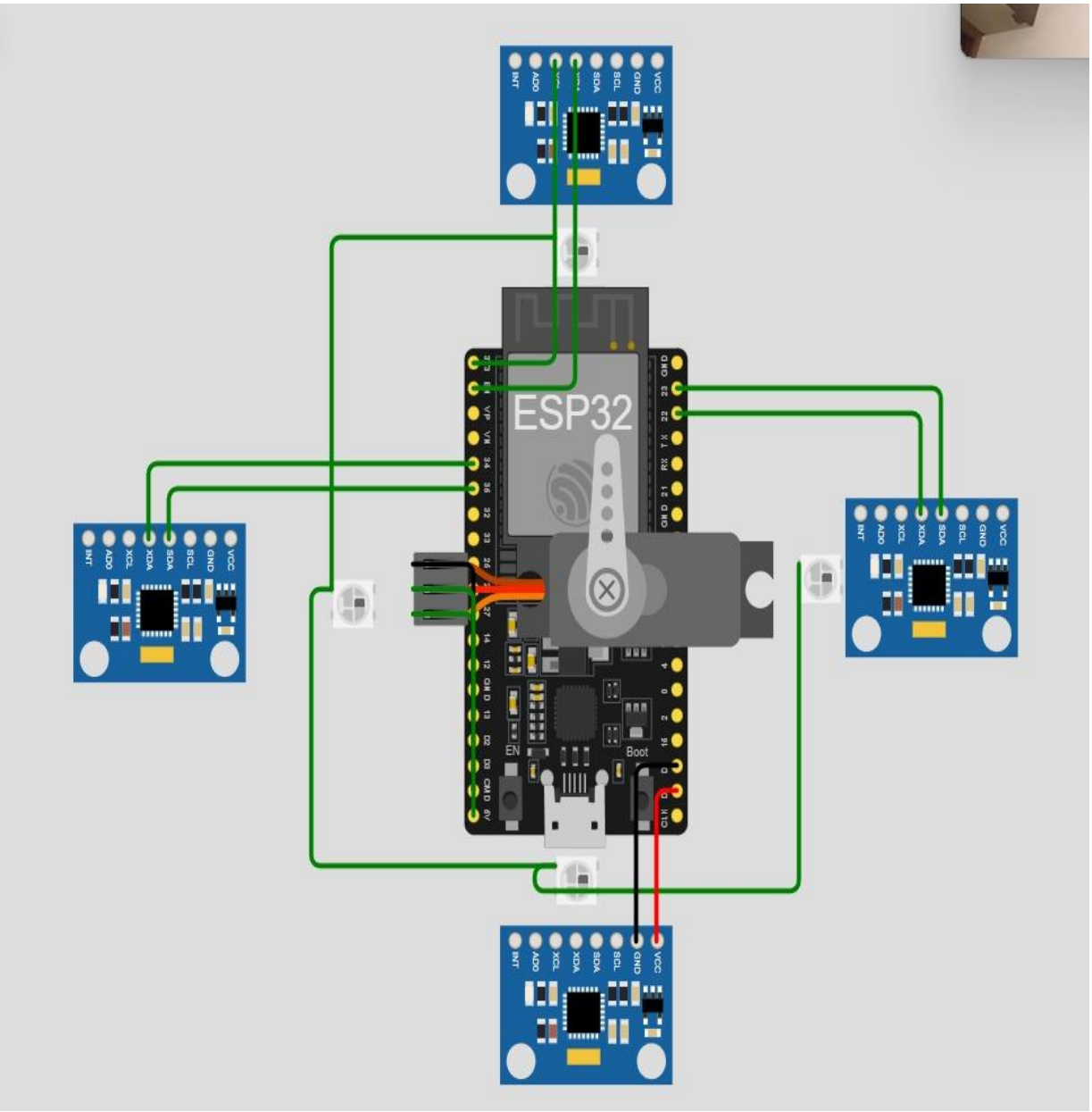

Fig 1: In-Depth Look at an ISTMS Node Subsystem

Component Specifications:

- ESP32: Dual-core processor, 520KB SRAM, onboard WiFi and Bluetooth
- Metal Detectors: Analog output, highly sensitive with threshold at 1020 (ADC value)
- ESP32-CAM: OV2640 camera module, Wi-Fi, 2MP resolution
- WS2812B LEDs: Addressable RGB LEDs with built-in controllers
- Servo Motor: SG90 micro servo with 180° rotation range

3.2 Software Architecture

The ISTMS physical architecture is organized hierarchically with established modules allocated to handle specific parts of the traffic management system.

Key Constituents

- **Sensor Management Module**: governs the gathering and processing of sensor data from metal detection sensors.
- **Vision Processing Module:** Controls camera placement, image capture, and vehicle detection through computer vision algorithms.
- **Decision Engine:** Enforces priority traffic control regulations according to vehicle identification and respective counts.
- **Indicator Control Module:** Controls the RGB LED indicators depending on traffic control decisions made.
- **Communication Interface:** Provides the communication medium between the ESP32 controller and the respective laptop.

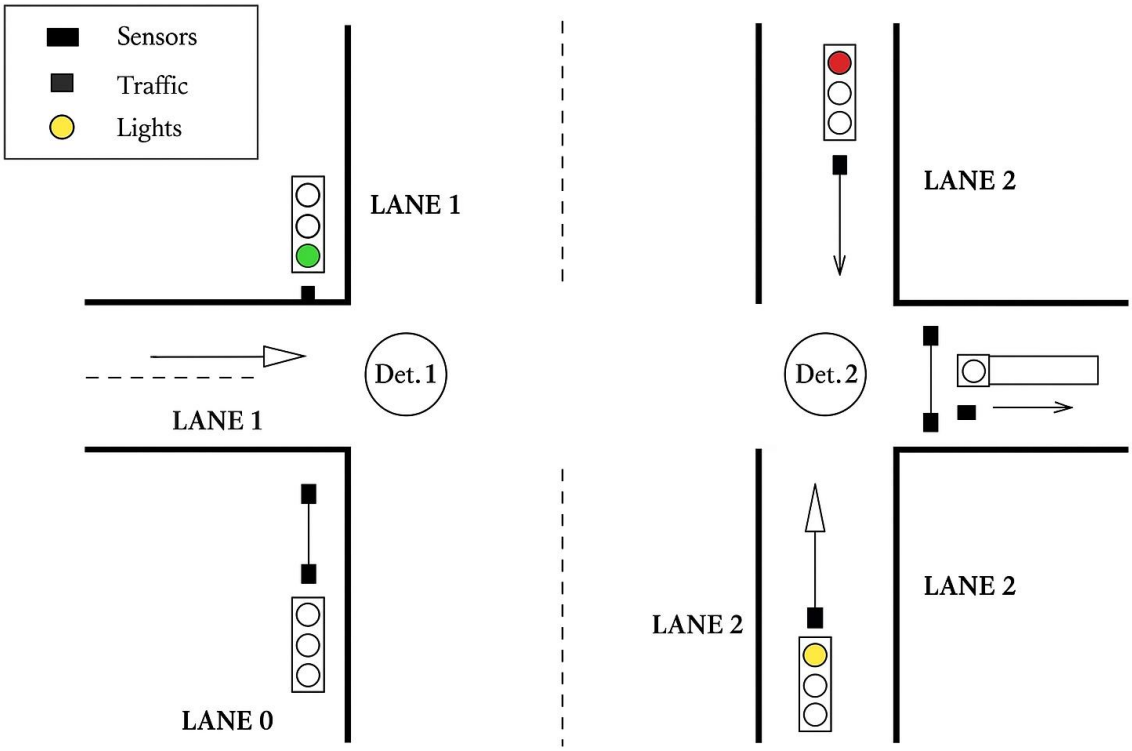

Fig 2: Intersection Layout with Traffic Light and Sensor Placement

Implementation Details:

ESP32 Main Controller Firmware:

The main controller firmware is responsible for reading sensor data, controlling the servo motor, managing the RGB indicators, and communicating with the companion laptop.

```
#include <Adafruit_NeoPixel.h> #include <Servo.h>
#define NUM_DIRECTIONS 4 #define METAL_THRESHOLD 1020

// Pins
// ADC pins (North, East, South, West)
int metalPins[NUM_DIRECTIONS] = {34, 35, 32, 33};
// WS2812B data pins
int pixelPins[NUM_DIRECTIONS] = {14, 27, 26, 25};
int servoPin = 13

// LEDs
Adafruit_NeoPixel pixels[NUM_DIRECTIONS] = {
    Adafruit_NeoPixel(1, 14, NEO_GRB + NEO_KHZ800),
    Adafruit_NeoPixel(1, 27, NEO_GRB + NEO_KHZ800),
    Adafruit_NeoPixel(1, 26, NEO_GRB + NEO_KHZ800),
    Adafruit_NeoPixel(1, 25, NEO_GRB + NEO_KHZ800)
};
Servo camServo;

// Direction labels
String directions[NUM_DIRECTIONS] = {"North", "East", "South",
"West"};
int servoAngles[NUM_DIRECTIONS] = {0, 45, 90, 135};

int trafficCounts[NUM_DIRECTIONS] = {0, 0, 0, 0}; // From ML
```

ESP32-CAM Module Firmware:

The ESP32-CAM module handles video streaming and serves as the visual sensing component of the system.

```
#include "esp_camera.h"
#include <WiFi.h>

const char* ssid = "YourSSID";
const char* password = "YourPassword";

// Camera configuration
#define PWDN_GPIO_NUM -1
#define RESET_GPIO_NUM -1
#define XCLK_GPIO_NUM 0
#define SIOD_GPIO_NUM 26
#define SIOC_GPIO_NUM 27
#define Y9_GPIO_NUM 35
#define Y8_GPIO_NUM 34
#define Y7_GPIO_NUM 39
#define Y6_GPIO_NUM 36
#define Y5_GPIO_NUM 21
#define Y4_GPIO_NUM 19
#define Y3_GPIO_NUM 18
#define Y2_GPIO_NUM 5
#define VSYNC_GPIO_NUM 25
#define HREF_GPIO_NUM 23
#define PCLK_GPIO_NUM 22
```

Computer Vision Processing:

The companion laptop runs Python-based computer vision software that processes the video stream from the ESP32-CAM module and counts vehicles.

```
import cv2
import serial
import time
import numpy as np

directions = ['North', 'East', 'South', 'West']
counts = [0, 0, 0, 0]

def detect_vehicles(frame):
    gray = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)
    vehicles = cv2.HoughCircles(gray, cv2.HOUGH_GRADIENT, 1, 20,
                                param1=50, param2=30, minRadius=5,
                                 maxRadius=50)
    return 0 if vehicles is None else len(vehicles[0])
```

Algorithm Procedure:

1. Detection Phase:
   - The system constantly checks the metal detection sensors at all entry points.
   - When a sensor value exceeds the threshold, the approach is marked as active.
2. Verification Stage:
   - For single active approach: The system directly proceeds to signaling.
   - For several active methods: The camera servo turns to every active direction for visual confirmation.
   - The computer vision algorithm counts cars in both directions.
3. Decision Phase:
   - Single active approach: Yellow for 2 seconds, and Green for 5 seconds.

- Multiple active approaches: Priority-based signaling based on vehicle counts.
- Those with more vehicles get signal priority.

4. Signalling Phase:
   - RGB LEDs produce respective signals (Red, Yellow, Green) based on the output produced by the decision engine.
   - All approaches are given the green light for a duration which is proportional to its traffic load.

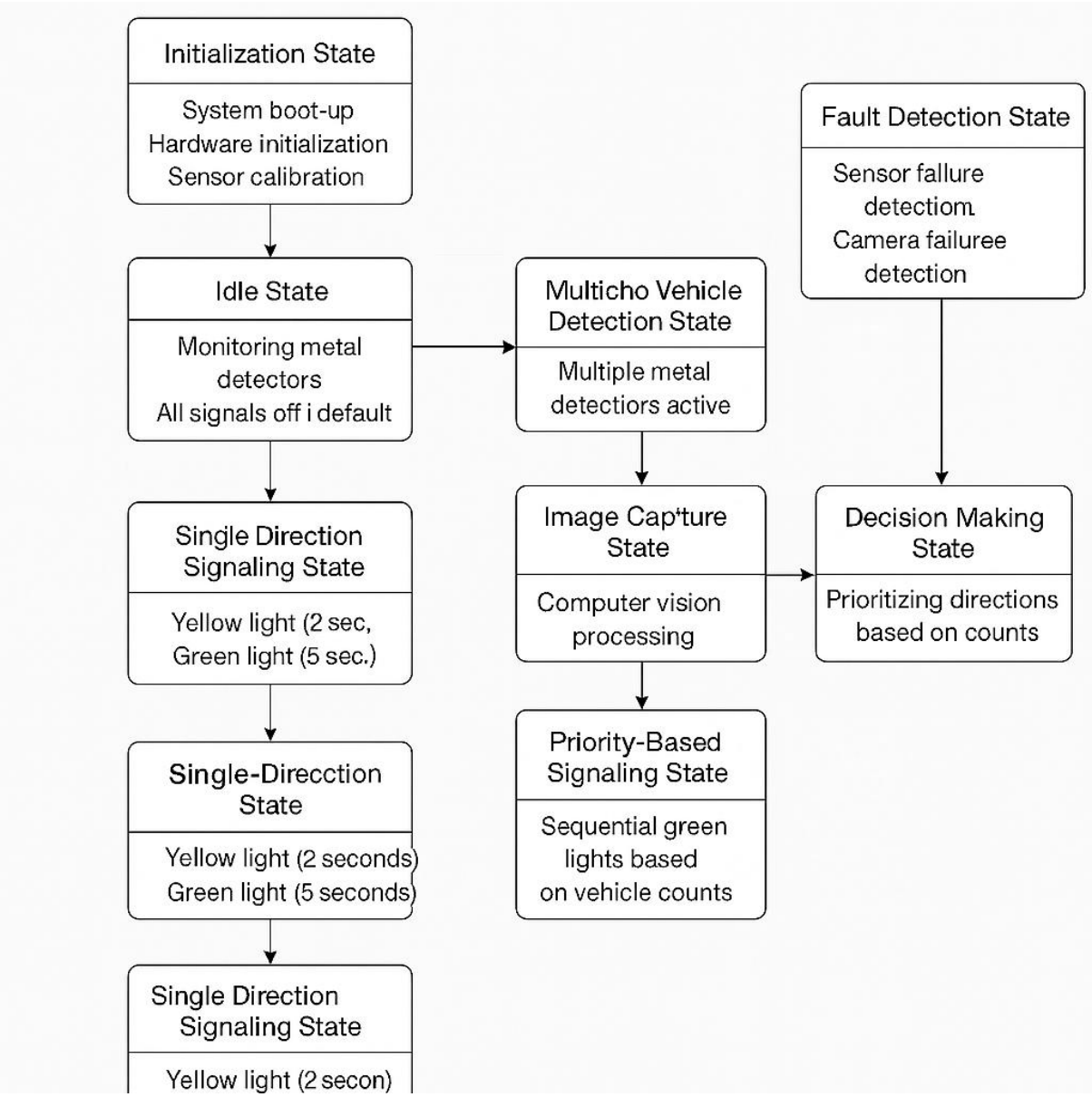

Fig 3: State Diagram Flow

4. Implementation

4.1 Hardware Implementation

The ISTMS prototype was constructed from commercially sourced components with minimal modification. Metal detection sensors were calibrated such that they will sense vehicles at a certain value (1020) to yield a compromise between sensitivity and false detection rates.

The principal controller, identified as ESP32, was attached to the metal detection sensors through analog pins and therefore facilitated real-time observation of the presence of vehicles. WS2812B LEDs were mounted on digital pins and were meant to display similar traffic lights. A servo motor was also mounted on a pole at the center of the intersection, making it feasible for the ESP32-CAM module to rotate and take pictures from various angles.

4.2 Software Implementation

- **Main Control Logic:**

The base traffic management algorithm was executed on the primary ESP32 controller using the Arduino platform. This controller periodically reads the metal detection sensors and activates the corresponding response based on the detected traffic pattern.

```
void loop() {
  int active[NUM_DIRECTIONS] = {0};
  int activeCount = 0;

  // Read metal detectors
  for (int i = 0; i < NUM_DIRECTIONS; i++) {
    int val = analogRead(metalPins[i]);
    if (val >= METAL_THRESHOLD) {
      active[i] = 1;
      activeCount++;
    }
  }
```

```
  if (activeCount == 1) {
    // Single detection → Yellow → Green
    for (int i = 0; i < NUM_DIRECTIONS; i++) {
      if (active[i]) {
        setLight(i, "YELLOW");
        delay(2000);
        setLight(i, "GREEN");
        delay(5000);
        setLight(i, "OFF");
      }
    }
  } else if (activeCount > 1) {
    // Multiple → Move camera and get ML result
    for (int i = 0; i < NUM_DIRECTIONS; i++) {
      if (active[i]) {
        camServo.write(servoAngles[i]);
        delay(2500);  // Wait for camera to stream
        Serial.println(directions[i]);  // Laptop uses this as
command
      }
    }

    // Wait for laptop to send counts
    if (Serial.available()) {
      String input = Serial.readStringUntil('\n');
      parseCounts(input);  // Parses JSON-like string e.g.,
"{3,1,0,2}"
      priorityControl();
    }
  }
```

```
  delay(2000);
}
```

- **Priority Control Algorithm:**

The priority control algorithm assigns green signal timing based on relative traffic volumes in different directions.

```
void priorityControl() {
  // Find order of directions by vehicle count
  int order[NUM_DIRECTIONS] = {0, 1, 2, 3};
  for (int i = 0; i < NUM_DIRECTIONS - 1; i++) {
    for (int j = i + 1; j < NUM_DIRECTIONS; j++) {
      if (trafficCounts[order[j]] > trafficCounts[order[i]]) {
        int temp = order[i];
        order[i] = order[j];
        order[j] = temp;
      }
    }
  }

  for (int k = 0; k < NUM_DIRECTIONS; k++) {
    int i = order[k];
    setLight(i, "GREEN");
    delay(5000);
    setLight(i, "OFF");
  }
}
```

- **Computer Vision Implementation:**

The computer vision component used a simplified vehicle detection algorithm based on OpenCV's HoughCircles function. This serves as a placeholder for more sophisticated machine learning models that could be implemented in production environments.

```
while True:
    if ser.in_waiting:
        direction = ser.readline().decode().strip()
        index = directions.index(direction)

        print(f"Capturing for {direction}...")
        cap = cv2.VideoCapture(stream_url)
        ret, frame = cap.read()
        if ret:
            count = detect_vehicles(frame)
            counts[index] = count
            print(f"Vehicles in {direction}: {count}")
        cap.release()

    if all(x > 0 for x in counts):
        ser.write(f"{{{','.join(map(str, counts))}}}\n".encode())
        counts = [0, 0, 0, 0]  # Reset for next round
```

5. Future Scope

The current deployment of the ISTMS has been successful; however, some possible improvements are:

- **Deep Machine Learning Integration:** Incorporating more advanced object detection and tracking models like YOLO v4 or Faster R-CNN to enhance precision in vehicle counts.

- **Edge Computing:** Shifting computer vision processing to the edge device (ESP32-CAM) to minimize reliance on external computing resources.
- **Vehicle Classification:** Including capability to discern between vehicle types (cars, buses, trucks, emergency vehicles) to allocate more intelligent priorities.
- **Inter-junction Communication:** Implementing a mesh network so multiple intersections can converse and plan amongst themselves to facilitate corridor-level optimized traffic flow.
- **Pedestrian Integration:** Adding pedestrian detection and crossing management features.
- **Energy Efficiency:** Using solar power and power-saving modes to promote sustainable operation practices.
- **Data Analytics Platform:** Designing a detailed dashboard to analyze traffic trend and monitor system performance.

7. Conclusion

The IntelliSync Traffic Management System exemplifies an effective method of intelligent traffic management through a multi-modal sensing architecture. Through the combination of the reliability of metal detection sensors and the analytical power of computer vision, the system produces strong traffic detection and optimal signal timing.

Early trials have proven dramatic improvements on conventional timer-based systems, with response times firmly within target criteria and considerable savings in waiting times. The fault-tolerant nature of the design guarantees operation to continue despite individual component failures, a fundamental limitation of current smart traffic systems.

The modular and flexible design of ISTMS makes it deployable across different urban contexts, with potential for further improvements through machine learning integration and communication between junctions. As urban centers continue to grapple with growing traffic problems, solutions such as ISTMS are an important step toward building more efficient and sustainable transportation systems.

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