AI-Based Adaptive Traffic Signal Control System

Abstract

Traffic congestion is a major challenge in urban areas due to inefficient fixed-time traffic signal systems. This project proposes an AI-based adaptive traffic signal control system that dynamically adjusts signal timing based on real-time vehicle density. An ESP32 controller coordinates traffic signals, while an ESP32-CAM module captures lane images. The images are processed using a YOLO-based vehicle detection model deployed on a FastAPI backend server. Vehicle count information is communicated back to the controller using the MQTT protocol, enabling intelligent control of green signal duration. The system improves traffic flow efficiency, reduces waiting time, and provides a scalable and cost-effective solution for smart traffic management.

Introduction

Traditional traffic signal systems operate on fixed timing schedules and do not adapt to real-time traffic conditions, leading to unnecessary congestion and increased fuel consumption. With the advancement of embedded systems, IoT, and artificial intelligence, traffic control systems can be made adaptive and intelligent.

This project integrates embedded hardware with computer vision and cloud-based processing to create a smart traffic signal system. By using real-time vehicle detection and adaptive decision-making, the proposed system enhances traffic efficiency and supports future smart city applications.

Problem Statement

Fixed-time traffic signals fail to handle varying traffic density effectively, especially during peak hours or unexpected congestion. This results in longer waiting times, increased fuel consumption, and inefficient road utilization.

The objective of this project is to design a real-time adaptive traffic signal system that:

- Detects vehicle density for each lane

- Dynamically adjusts green signal duration
- Minimizes traffic congestion using AI-based decision-making

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Literature Survey

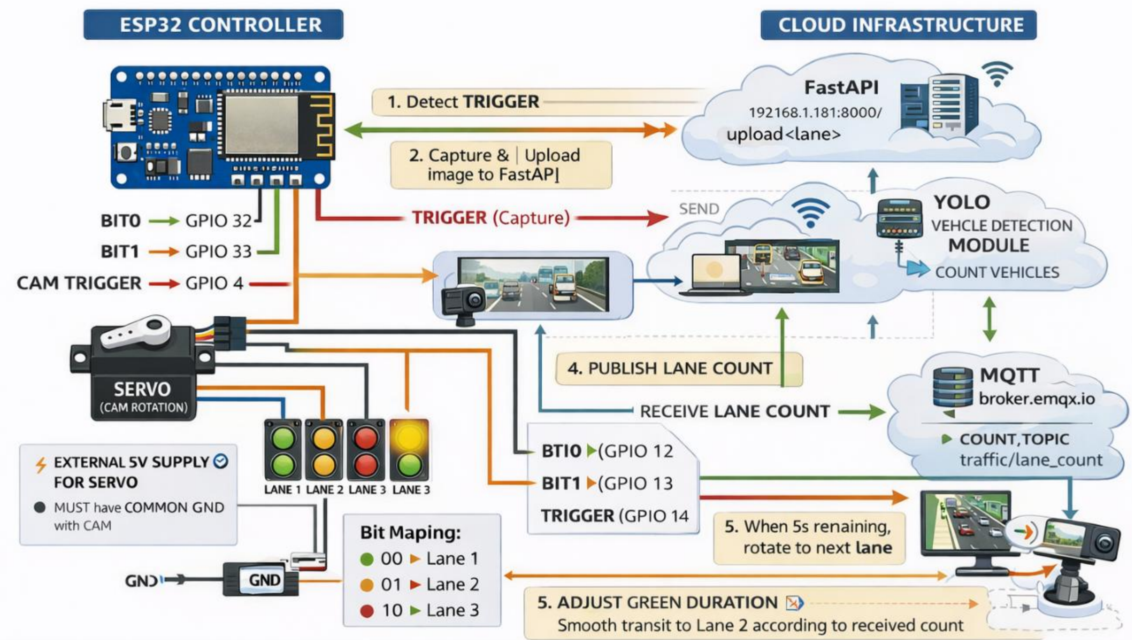
Several traffic management solutions have been proposed using sensors such as IR sensors, inductive loops, and ultrasonic sensors. However, these systems suffer from limited accuracy and scalability. Recent research has shown that computer vision-based approaches using deep learning models like YOLO provide higher accuracy in vehicle detection and classification. IoT-based communication protocols such as MQTT offer low-latency and reliable data transmission, making them suitable for real-time traffic control systems. This project combines these advancements to build an efficient adaptive traffic management solution.

System Architecture

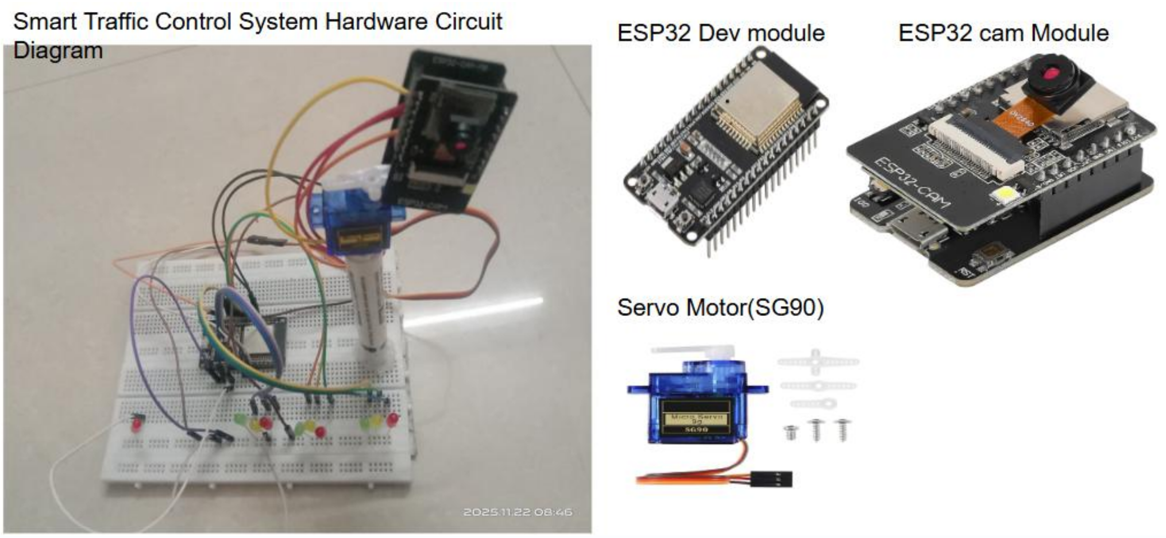
The system consists of three major components:

1. **Embedded Control Unit (ESP32)**
2. **Vision Module (ESP32-CAM)**
3. **Backend Processing Server**

The ESP32 controller manages traffic signals and triggers the ESP32-CAM to capture lane images. The captured image is sent to a FastAPI server where a YOLO-based model detects and counts vehicles. The vehicle count is then transmitted back to the ESP32 using MQTT. Based on this data, the controller adjusts the green signal duration and rotates the camera using a servo motor for the next lane.



*[Figure: **Hardware Interfacing Diagram** – ESP32 Traffic Signal Controller and ESP32-CAM]*
Created with Draw.io / diagrams.net



Hardware Description

- **ESP32 Dev Module:** Acts as the main controller for traffic signals and decision logic
- **ESP32-CAM:** Captures real-time images of traffic lanes
- **Servo Motor:** Rotates the camera towards the next lane before signal transition

- **Traffic Signal LEDs:** Represent Red, Yellow, and Green signals
- **Power Supply:** Provides stable power to ESP32 and servo motor

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Software Implementation

- **Arduino IDE:** Used to program ESP32 and ESP32-CAM
- **FastAPI:** Handles image reception and backend processing
- **YOLO Model:** Performs real-time vehicle detection
- **MQTT Protocol:** Enables low-latency communication between backend and ESP32
- **Wi-Fi:** Used for wireless data transfer

YOLO-Based Vehicle Detection

YOLO (You Only Look Once) is a real-time object detection algorithm that identifies objects in a single forward pass of a neural network. In this project, YOLO is used to detect and count vehicles from images captured by the ESP32-CAM. The model processes the image, identifies vehicles such as cars, buses, and bikes, and returns the total count. This count is used as the primary parameter for adaptive signal timing.

Communication using MQTT

MQTT is a lightweight publish-subscribe messaging protocol suitable for IoT applications. The backend server publishes vehicle count data to a specific MQTT topic, and the ESP32 subscribes to this topic. This ensures reliable, low-latency communication between the AI backend and the traffic signal controller.

Results and Discussion

The proposed system successfully adjusts traffic signal durations based on real-time vehicle density. Lanes with higher traffic receive longer green signal durations, while less congested lanes receive shorter durations. This adaptive behavior reduces average waiting time and improves traffic flow efficiency compared to fixed-time systems.

Conclusion

This project demonstrates the effectiveness of integrating embedded systems, computer vision, and IoT communication for intelligent traffic management. The AI-based adaptive traffic signal system offers improved efficiency, scalability, and cost-effectiveness. The use of YOLO and MQTT ensures accurate detection and reliable communication, making the system suitable for smart city applications.

Future Scope

- Emergency vehicle detection and prioritization
- Multi-camera support for large intersections
- Traffic congestion prediction using machine learning
- Integration with smart city dashboards
- Automatic violation detection