REAL-TIME ADAPTIVE TRAFFIC SIGNAL CONTROL BASED ON TRAFFIC DENSITY ESTIMATION USING OPENCV AND ESP32-CAM

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Abstract
As urbanization has increased rapidly, and the number of vehicles on roads has increased exponentially, conventional traffic management systems have become inefficient, rigid, and incapable of responding dynamically to real-time traffic conditions. The fixed-time traffic signals, which are based on pre-set timers without considering the actual traffic density, often result in unnecessary congestion, increased waiting time, excessive fuel consumption and higher emission of greenhouse gases. To overcome this, intelligent and adaptive traffic control systems capable of Monitoring real-time road conditions and adjusting signal timing are required. The proposed system, Smart Traffic Signal using Two ESP32-CAM, ESP8266, Python and Open CV, aims at providing a low-cost, scalable, and efficient solution for real-time traffic density analysis and signal automation.
Keywords: *Smart Traffic Signal, Intelligent Transportation System, ESP32-CAM, ESP8266, Computer Vision, Open CV, Python.*

1. Introduction

Traffic congestion has become one of the most critical challenges in modern urban environments. With the increasing population and rapid growth in vehicle ownership, traditional traffic management systems are no longer capable of handling the dynamic and unpredictable nature of road traffic. Fixed-time traffic signals, which operate based on pre-programmed timing sequences, do not consider real-time traffic density and often result in inefficient traffic flow. Vehicles are forced to wait at signals even when there is no traffic on the opposite lane, leading to unnecessary delays, fuel wastage, driver frustration, and environmental pollution.

The concept of intelligent traffic management has emerged as a key component of smart city development. A smart traffic signal system is designed to monitor real-time traffic conditions, analyze congestion levels, and dynamically adjust signal timings to optimize traffic flow. The integration of embedded systems, wireless communication, and computer vision technologies has made it possible to design low-cost and highly efficient traffic control solutions.

The proposed system utilizes two ESP32-CAM modules for capturing real-time images of traffic from different lanes. The ESP32-CAM is a powerful and cost-effective microcontroller with an integrated camera and Wi-Fi capability, making it ideal for IoT-based image acquisition applications. The captured images are transmitted wirelessly to a central processing unit where Python and Open CV are used for image processing and vehicle detection. Open CV, being an open-source computer vision library, provides robust tools for object detection, motion analysis, and image segmentation.

The ESP8266 microcontroller is used as the control unit for traffic signal operation. It receives commands from the processing system and controls the LED-based traffic lights accordingly. This wireless

communication-based architecture eliminates complex wiring and allows flexible deployment.
The main objective of this project is to develop a real-time, adaptive traffic signal system that:

- Reduces traffic congestion
- Minimizes vehicle waiting time
- Optimizes signal timing dynamically
- Provides a low-cost and scalable solution
- Supports smart city infrastructure

The system also serves as an educational model for students and researchers to understand the integration of IoT, embedded systems, and computer vision in real-world applications.

2. Problem Statement

Conventional traffic signal systems are based on fixed timing mechanisms that do not adapt to real-time traffic conditions. These systems assume equal traffic flow in all directions, which is rarely the case in real-world scenarios. During peak hours, some lanes experience heavy congestion while others remain relatively empty. However, the signal timing remains unchanged, resulting in inefficient utilization of road infrastructure.
Major problems in existing systems include:

- Increased vehicle waiting time
- Traffic congestion at busy intersections
- Fuel wastage due to unnecessary idling
- Higher air pollution
- Lack of real-time monitoring
- No priority for emergency vehicles

In developing countries, the installation of advanced sensor-based traffic systems is expensive and requires significant infrastructure changes. There is a need for a low-cost, intelligent, and easily deployable traffic management system that can adapt dynamically to traffic density.
The proposed system addresses these challenges by using camera-based vehicle detection and wireless communication for signal control.

3. Related Work

Many researchers have proposed intelligent traffic management systems using various technologies such as:

- Inductive loop sensors
- Infrared sensors
- RFID-based systems
- Wireless sensor networks
- Machine learning algorithms
- Deep learning-based vehicle detection

Sensor-based systems require physical installation on roads, which increases cost and maintenance complexity. RFID-based systems are effective for vehicle identification but require RFID tags in all vehicles.
Recent advancements in computer vision have enabled camera-based traffic monitoring systems. These systems use image processing techniques for vehicle detection, traffic density estimation, and violation monitoring.
However, many existing solutions rely on high-cost hardware, cloud-based processing, or complex deep learning models that require powerful GPUs.
The proposed system differs by:

- Using low-cost ESP32-CAM modules
- Performing efficient image processing using Open CV
- Using ESP8266 for real-time signal control
- Providing a scalable and affordable solution.

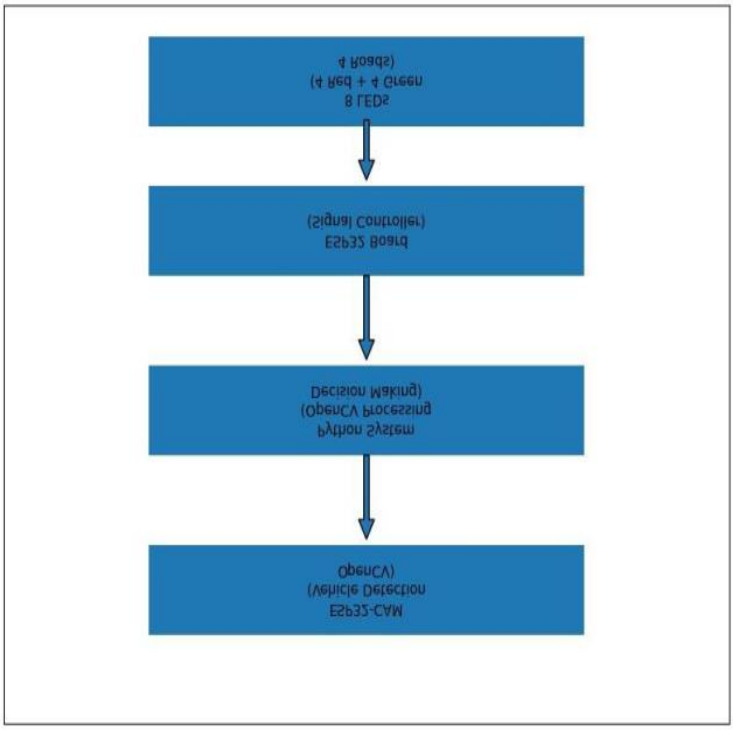
4. Methodology

The methodology of the proposed system is divided into multiple stages:
1. Image Acquisition :- Two ESP32-CAM modules capture real-time images from different traffic lanes and transmit them via Wi-Fi.
2. Data Transmission :- The captured frames are sent to a local server or computer using HTTP or streaming protocol.

3. Image Processing:-Python and OpenCV are used for:
- Grayscale conversion
- Background subtraction
- Contour detection
- Vehicle counting
- Traffic density calculation

4. Decision Making :- The lane with higher vehicle count is given longer green signal duration.
5. Signal Control :- ESP8266 receives commands and controls traffic LEDs accordingly.

5. BLOCK DIAGRAM



6. System Architecture

The system consists of:

6.1 Hardware Components
- Two ESP32-CAM modules
- One ESP8266
- Traffic signal LEDs
- Power supply

6.2 Software Components
- Python
- OpenCV
- Embedded C for ESP modules
- Wi-Fi communication protocol

6.3 Working Flow
- Capture image →
- Send to server →5
- Process using OpenCV →
- Calculate density →
- Send signal command →
- Control traffic light.

7. Conclusion

The Smart Traffic Signal system using ESP32-CAM, ESP8266, Python, and OpenCV provides an efficient and low-cost solution for real-time traffic management. The system dynamically adjusts signal timing based on actual traffic conditions, reducing congestion and improving road utilization.

The use of computer vision eliminates the need for expensive road sensors, making the system suitable for developing regions. The wireless architecture ensures easy installation and scalability.

Future enhancements may include:

- Emergency vehicle detection
- Cloud-based monitoring
- AI-based vehicle classification
- Integration with smart city platforms

This system demonstrates how IoT and computer vision can be combined to solve real-world transportation problems effectively.

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