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Vision-Based Adaptive Traffic Signal System with LoRa Emergency Vehicle Priority

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Abstract: ***Rapid urbanization and the increasing number of vehicles have led to severe traffic congestion and inefficient traffic management systems. Conventional traffic signals operate using fixed timing mechanisms, which fail to adapt to real-time traffic conditions and emergency situations. This research proposes SmartFlow, a vision-based adaptive traffic signal management system integrated with LoRa communication for emergency vehicle prioritization. The system utilizes a Raspberry Pi with a camera module to analyze real-time traffic density using computer vision techniques. Based on detected vehicle density across multiple lanes, signal timings are dynamically adjusted to optimize traffic flow. Additionally, LoRa-enabled communication allows emergency vehicles to transmit priority signals to intersections, ensuring faster clearance and reduced response time. The proposed system enhances traffic efficiency, minimizes congestion, reduces waiting time, and improves emergency response performance.***

Keywords: Smart Traffic System, Computer Vision, LoRa Communication, Emergency Vehicle Priority, Raspberry Pi, Intelligent Transportation System.

I. INTRODUCTION

Traffic congestion has become a major challenge in modern urban environments due to population growth and increasing vehicle density. Traditional traffic signal systems rely on predefined timing schedules that do not consider real-time traffic conditions, resulting in inefficient traffic flow and unnecessary delays.Recent advancements in Intelligent Transportation Systems (ITS) have enabled the development of smart traffic control solutions using artificial intelligence, computer vision, and wireless communication technologies. Vision-based traffic monitoring provides accurate vehicle density estimation, while long-range wireless communication technologies such as LoRa enable reliable communication over large distances with low power consumption.

This research introduces SmartFlow, an adaptive traffic signal management system that integrates computer vision with LoRa communication to dynamically control traffic signals and provide priority access for emergency vehicles such as ambulances and fire trucks.

Problem Statement

Existing traffic signal systems have several limitations, including fixed signal timing that does not consider real-time traffic density, leading to increased vehicle waiting times at intersections. These systems also lack mechanisms to prioritize emergency vehicles and often result in inefficient use of road infrastructure. Consequently, unnecessary fuel consumption and increased pollution occur, highlighting the need for a smart traffic management system capable of real-time monitoring and adaptive signal control.

II. LITERATURE REVIEW

Several researchers have proposed intelligent traffic management systems to overcome the limitations of conventional fixed-time traffic signals[1]. Early systems relied on sensors and IoT devices to monitor traffic flow; however, these approaches required expensive infrastructure and maintenance. Recent studies introduced computer vision techniques for vehicle detection and traffic density estimation using image processing, which improved traffic efficiency by enabling adaptive signal control. Some works also implemented RFID-based or wireless communication systems to provide priority for emergency vehicles[4], but these solutions were limited by short communication range and scalability issues. Although AI-based traffic systems achieved accurate traffic analysis, they often required high computational resources. Therefore, there remains a need for a cost-effective system that integrates real-time vision-based traffic monitoring with long-range emergency communication[2].

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The proposed SmartFlow system addresses this gap by combining computer vision with LoRa technology to enable adaptive traffic control and efficient emergency vehicle prioritization.

III. METHODOLOGY

The proposed Vision-Based Adaptive Traffic Signal System with LoRa Emergency Vehicle Priority operates by combining computer vision, embedded processing, and wireless communication to dynamically manage traffic signals based on real-time road conditions. Initially, a camera module installed at the traffic intersection continuously captures live images of each lane. These images are transmitted to a Raspberry Pi, which acts as the central processing unit of the system. To estimate traffic density accurately, each road lane is divided into multiple sections (L0, L1, and L2). The system compares real-time images with reference images of an empty road to detect vehicle presence in each section[5]. The following block diagram shows that,

A. Block Diagram

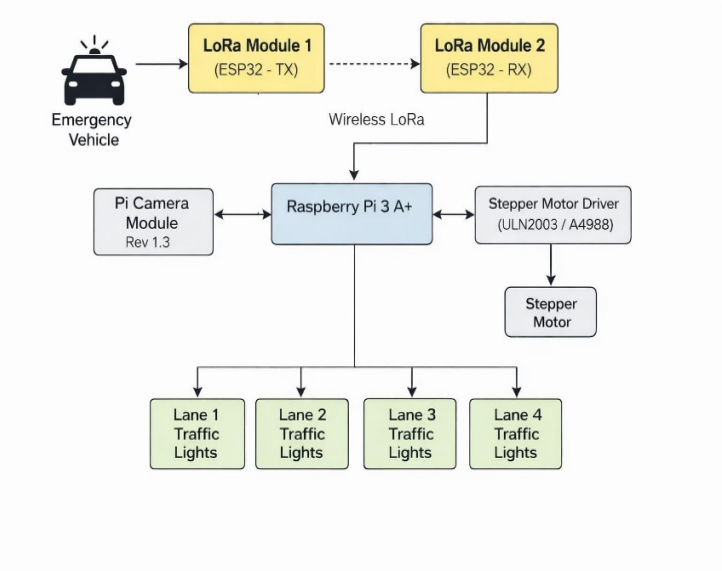


Fig.1 Block Diagram

B. Working

1) Emergency Vehicle Detection & Transmission

An emergency vehicle is equipped with a LoRa Module connected to an ESP32 transmitter. As the vehicle approaches a traffic junction, the system automatically sends a priority signal through wireless communication [5].

2) LoRa Communication

The transmitted priority signal is received by another LoRa module connected to an ESP32 receiver installed at the traffic junction. LoRa technology is selected due to its long-range communication capability, low power consumption, and reliable data transmission even in urban environments [3].

3) Traffic Monitoring using Vision System

A Pi Camera Module continuously captures live traffic footage at the intersection. The camera is connected to a Raspberry Pi 3 A+, which processes the captured images in real time [7].

4) Decision Processing using Central Controller

The Raspberry Pi operates as the central processing unit of the system. It integrates traffic density information obtained from the vision system with emergency alerts received through LoRa communication [9].

5) Emergency Vehicle Priority Mechanism

Upon receiving an emergency signal, the system overrides the standard traffic control algorithm. The Raspberry Pi immediately assigns priority to the lane corresponding to the emergency vehicle by activating the signal control mechanism through a servo motor [2].

6) Adaptive Traffic Signal Control

The Raspberry Pi manages traffic signals across all four lanes of the intersection. Signal transitions are dynamically adjusted according to real-time traffic analysis and system decisions [10].

IV. HARDWARE

1) RASPBERRY PI 3A+

The Raspberry Pi 3A+ functions as the central control unit of the system, managing all input and output operations for intelligent traffic control. It integrates data from sensors and LoRa communication to make real-time decisions [4]. Emergency vehicle signals received via UART communication trigger priority signal changes. The Raspberry Pi also controls a relay board that operates the LED-based traffic lights (Red, Yellow, and Green) at the intersection[9].

2) LORA MODULE

In addition to traffic density analysis, an emergency vehicle detection mechanism is implemented using a LoRa module [2]. When an emergency vehicle equipped with a LoRa transmitter approaches the junction, a signal is sent to the Raspberry Pi receiver. On reception, the controller overrides the normal sequence and immediately turns the corresponding lane's signal green for 30 seconds [10].

3) RASPBERRY PI CAMERA REV 1.3

In the proposed Vision-Based Adaptive Traffic Signal System, the Raspberry Pi Camera Module v1.3 is used as the primary image acquisition device for real-time traffic monitoring. The camera captures live video streams of road intersections, which are processed by the Raspberry Pi to analyze vehicle density and traffic flow conditions [2].

4) ESP-32

The ESP32 is a low-power microcontroller with built-in Wi-Fi and Bluetooth capabilities, used for wireless communication and control in embedded systems. In this project, the ESP32 interfaces with the LoRa module to transmit and receive emergency vehicle signals between the vehicle and the traffic junction. Its high processing speed, multiple GPIO pins, and reliable connectivity make it suitable for real-time data transmission and smart traffic management applications [3].

V. FUTURE SCOPE

The proposed Vision-Based Adaptive Traffic Signal System can be further enhanced by integrating advanced deep learning models for more accurate vehicle classification and traffic prediction. Future improvements may include cloud-based data analytics for city-wide traffic optimization, integration with IoT smart city infrastructure, [2] and deployment of multiple interconnected intersections for coordinated signal control. Additionally, incorporating automatic incident detection and enhanced emergency vehicle recognition can further improve traffic efficiency and public safety [8].

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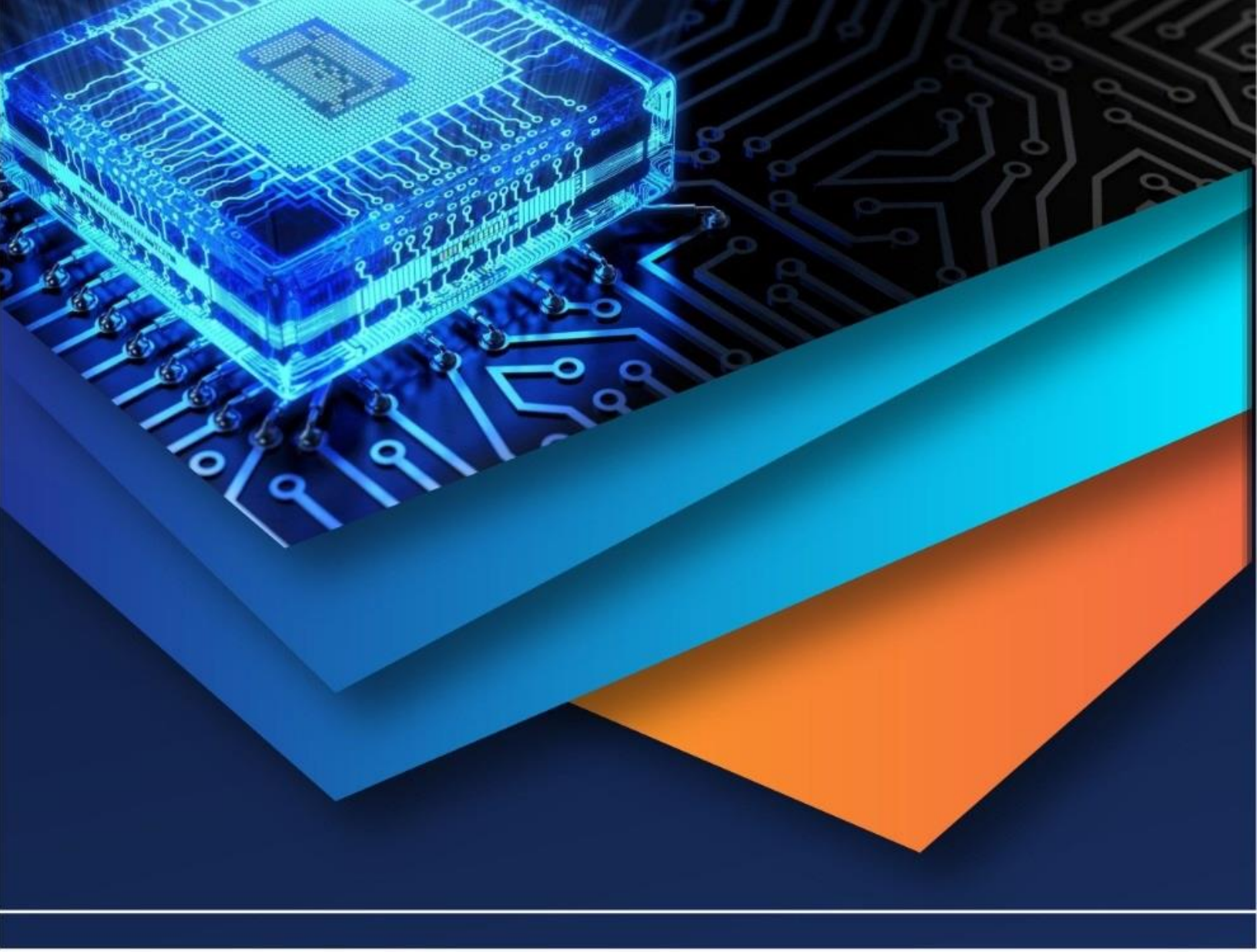
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