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A Study on Autonomous Highway Surveillance Car

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ABSTRACT

As India is a rising country and the roads in India are developing rapidly one of the major challenges is to keep the reads safe and in proper condition. The objective of this study is to design and implementation of an "Autonomous Highway Surveillance Car" to operate without human intervention while continuously monitoring highway conditions in real time. The techniques like Robotics, embedded systems, machine learning, and Internet of Things (IoT) communication are integrated in this system to create an efficient road inspection solution. The vehicle is carrying an ultra- wide-angle camera that will capture road images continuously during movement. Then these images are processed using image processing techniques and trained machine learning models and identify road abnormalities such as potholes, surface damage, obstacles, and edge misalignment. As soon as the problem is detected, the system acquires its exact geographical location using a GPS module and then it sends the information to the concerned authorities through an IoT-based communication system for timely response and prompt action. Autonomous navigation is performed through multiple sensors, obstacle detection mechanisms, and basic path- planning algorithms, helping the vehicle to move safely along the highway without manual control. This system will drastically reduce the dependency on manual monitoring methods and improves response time for maintenance activities while reducing the error. Overall, the model demonstrates a practical, cost- effective, and scalable approach for intelligent highway surveillance and preventive road management.

***Keywords**: Internet of Things (IoT), Robotics, GPS, Intelligent Highway Surveillance, Machine Learning.*

Introduction

Transportation infrastructure forms the foundation of a nation's economic and social development by enabling the movement of goods, services, and people. To meet the demands of growing populations and urbanization in rapidly developing country like India, highway networks are expanding continuously as it serves a major connectivity routes that support trade, industry, and regional integration. However, as these networks expand, their maintenance and monitoring become very important and crucial. The large geographical coverage and traffic density make traditional manual inspection methods time-consuming, labor- intensive, and often insufficient for regular surveillance. Road surface quality plays an important role in ensuring traffic safety and vehicle efficiency and timely delivery of goods. Defects such as potholes, cracks, uneven surfaces, and edge deterioration can lead to vehicle damage, traffic congestion, and serious road accidents. Therefore, highway maintenance is not only important for operational efficiency but it is also a critical matter of public safety. Delays in detecting and repairing minor defects can result in more severe structural damage and increased risks in transportation. Advancements in Artificial Intelligence (AI), Internet of Things (IoT), and robotics offers new possibilities to address these issues through automation. The proposed project, "Autonomous Highway Surveillance Car," utilizes these technologies to develop an intelligent vehicle capable of continuously monitoring road conditions without human intervention. By integrating image processing, machine learning algorithms, sensor-based navigation, and real-time communication, the system detects road anomalies and transmits location-based alerts to the concerned authorities. This approach transforms traditional reactive maintenance into a proactive, data-driven infrastructure management system aimed at improving highway safety and operational efficiency.

Related Work

- **Paper Title: - Cost-Effective LiDAR for Pothole Detection & Quantification [15]**

  Summary: - The system was found to outperform camera-only approaches, particularly in scenarios with poor lighting or texture-less road surfaces. This confirms LiDAR's usefulness in autonomous road-health monitoring systems.

- **Paper Title: - Automated Road Defect Detection (Systematic Review) [18]**

  Summary: - The authors conclude that although significant progress has been made, major gaps remain in dataset diversity, model generalization, and severity estimation.

- **Paper Title: - Embedded Vision System for Anomaly Detection [30]**

  Summary: - The study concludes that classical computer vision techniques can be deployed on microprocessors for basic real-time detection but lack reliability in dynamic lighting and complex scenarios.

- **Paper Title: - Multi-sensor Fusion for Road Surface Assessment [32]**

  Summary: -The study concludes that fusing camera, IMU, and GPS data results in more stable and accurate pothole localization, especially during vehicle movement.

- **Paper Title: - Real-Time Pothole Detection Using Deep Learning [20]**

  Summary: -The study concludes that it stresses that deep learning models need careful optimization to run on resource-constrained hardware.

Problem Statement and Objectives

Although road construction technologies have advanced considerably, the monitoring of highway conditions still relies largely on traditional inspection methods. Manual surveillance typically involves patrol teams traveling along highways and visually examining the pavement, which is time-consuming, labor- intensive, costly, and dependent on human judgment. While CCTV systems are installed on many highways, they are primarily intended for traffic monitoring rather than detailed surface inspection, and their fixed angles and limited resolution restrict their ability to detect small defects such as cracks and potholes. Additionally, relying on public complaints to identify damaged roads is inconsistent and often lacks precise location information. As a result, there is no widely implemented low-cost, scalable, and fully autonomous system capable of continuously monitoring road conditions, leading to a significant information gap between the actual state of highways and the data available to maintenance authorities.

To address this issue, the proposed project introduces an Autonomous Highway Surveillance Car designed to operate along highway shoulders or designated lanes without human intervention. The vehicle integrates onboard sensors and a motor driver system to navigate a predefined path while maintaining lane alignment. A wide-angle camera continuously captures road images, which are processed using the MobileNetV2 architecture, a lightweight Convolutional Neural Network (CNN), to detect potholes and cracks in real time with high accuracy. When a defect is identified, the system records the anomaly type along with its precise GPS coordinates and transmits the information to a centralized cloud dashboard, enabling timely, data-driven maintenance decisions and reducing dependence on manual inspection methods.

System Architecture

The Autonomous Highway Surveillance Car is designed as a real-time mechatronic system that integrates embedded hardware, machine learning, and cloud communication. The architecture follows a modular approach in which high-level computational tasks such as visual perception and decision-making are separated from low-level control functions like motor actuation and sensor handling. The overall system is implemented as an edge-computing node, meaning that most of the data processing is performed directly on the vehicle. Unlike conventional IoT systems that transmit raw video streams to cloud servers for analysis resulting in high bandwidth consumption and network latency this design processes image data locally. Only the final result, such as detected road anomalies and related information, is transmitted to the cloud platform.

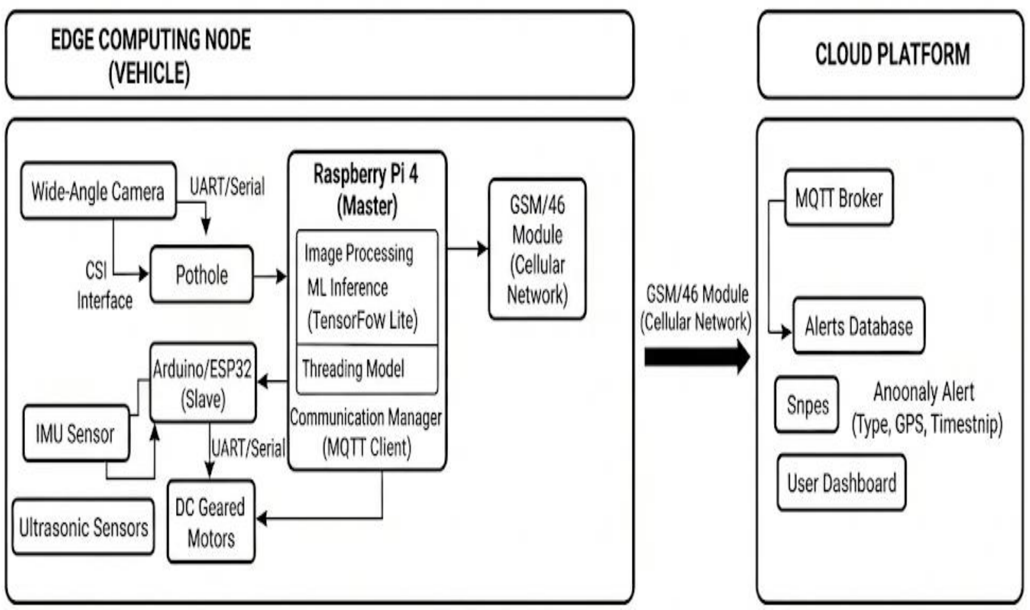

Fig. 1: Architecture of the proposed edge-based autonomous highway surveillance car

At the core of the system is the Raspberry Pi 4, which acts as the master controller. It is selected for its capability to handle multi-threaded operations and real-time image processing. The device runs the TensorFlow Lite inference engine to process video frames and detect road defects such as potholes and cracks. A structured threading model ensures that image processing, sensor data acquisition, and communication tasks operate concurrently without interrupting each other. The visual sensing subsystem consists of a wide-angle camera connected through the CSI (Camera Serial Interface) port to provide high-bandwidth and low-latency video input required for machine learning inference.

For low-level control and real-time responsiveness, an Arduino or ESP32 microcontroller is used as a slave controller. It communicates with the Raspberry Pi via UART/Serial interface and is responsible for motor control and sensor data collection. The microcontroller manages the DC geared motors for vehicle movement and gathers telemetry data from the IMU sensor for vibration monitoring and ultrasonic sensors for obstacle detection and distance measurement. Communication with the cloud is achieved using a GSM/4G module, enabling the system to operate independently of local Wi-Fi networks. The MQTT protocol is used for data transmission, where the Raspberry Pi functions as an MQTT client and publishes detected anomaly information to the cloud. On the cloud platform, an MQTT broker receives and routes the data to an alerts database, which stores details such as anomaly type, GPS coordinates, and timestamp. A user dashboard provides a graphical interface for authorities to monitor vehicle status and visualize detected road hazards on a map, allowing timely maintenance actions.

Hardware Block Diagram

The hardware design is around a Master-Slave configuration, utilizing two distinct processing units to maximize efficiency.

- The Processing Unit (Master Node): The Raspberry Pi 4 was selected due to its Quad-core Cortex-A72 processor, which provides sufficient computational power to run the TensorFlow Lite interpreter and OpenCV pipelines in real-time. Its dedicated CSI (Camera Serial Interface) port allows for high-speed video data transfer with lower latency compared to USB webcams.
- The Control Unit (Slave Node): While the Raspberry Pi is powerful, it is not a Real-

Time Operating System (RTOS). Precise timing required for PWM (Pulse Width Modulation) motor control and micro-second ultrasonic sensor readings is better handled by a dedicated microcontroller.

- Vision System: The camera is mounted on a 2-axis Pan/Tilt servo mechanism. This allows the software to actively stabilize the horizon or scan the surroundings independent of the vehicle's movement. A 160-degree wide-angle lens is used to capture the entire width of the lane and the shoulder, ensuring no anomalies are missed in the peripheral vision.

- Sensor Suite & Navigation: Connected via UART. It parses NMEA sentences to extract Latitude, Longitude, and UTC time. It has a ceramic antenna for better satellite lock in outdoor environments. Mounted on the front bumper. They operate on the time-of-flight principle to detect physical obstacles.
- Communication Module: This module provides cellular connectivity. It is controlled via AT Commands sent from the Raspberry Pi's UART interface. It is responsible for establishing the TCP/IP connection to the MQTT Broker.

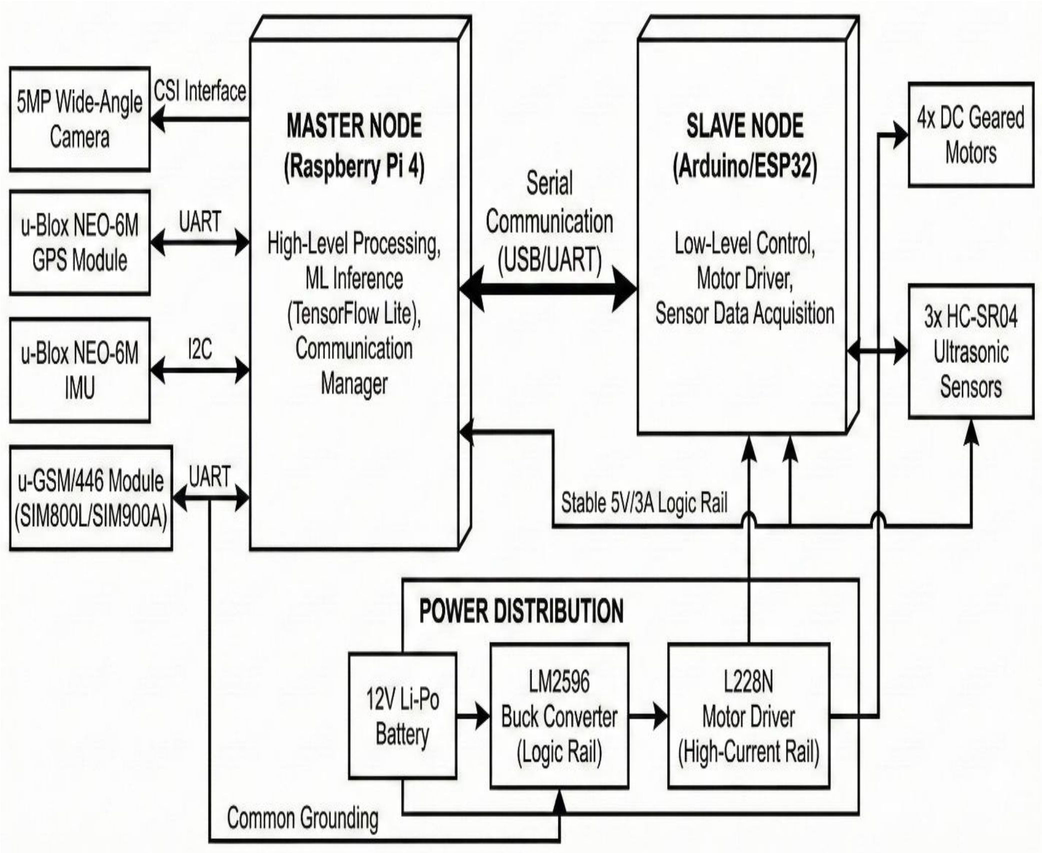

Fig. 2: Hardware block diagram of the Master-Slave Configuration.

Software Architecture

The software stack is built on Python 3 running on the Raspbian OS. The architecture is event-driven and multi-threaded to ensure that image processing does not block the navigation logic

- Threading Model: To achieve real-time performance, the software is divided into three concurrent threads:
- (Vision Loop): Captures frames, pre-processes them, runs the ML inference, and updates the global state variable current anomaly.
- (Control Loop): Reads sensor data, computes navigation logic (obstacle avoidance/lane following), and sends commands to the Arduino.
- (Communication Loop): Monitors the current anomaly state. If a new anomaly is detected, it fetches the latest GPS fix and publishes the alert to the cloud.
- Image Processing Pipeline: Resizing: The 1080p raw frame is downscaled to 224x224 pixels, which is the native input resolution for the MobileNetV2 model.

- Normalization: Pixel values (0-255) are normalized to a float range of (-1 to 1) to speed up convergence during inference.
- Region of Interest (ROI): The sky and peripheral distortions are cropped out to focus the model's attention solely on the road surface.
- Machine Learning Model Design: The core intelligence of the system is the MobileNetV2 Convolutional Neural Network (CNN).

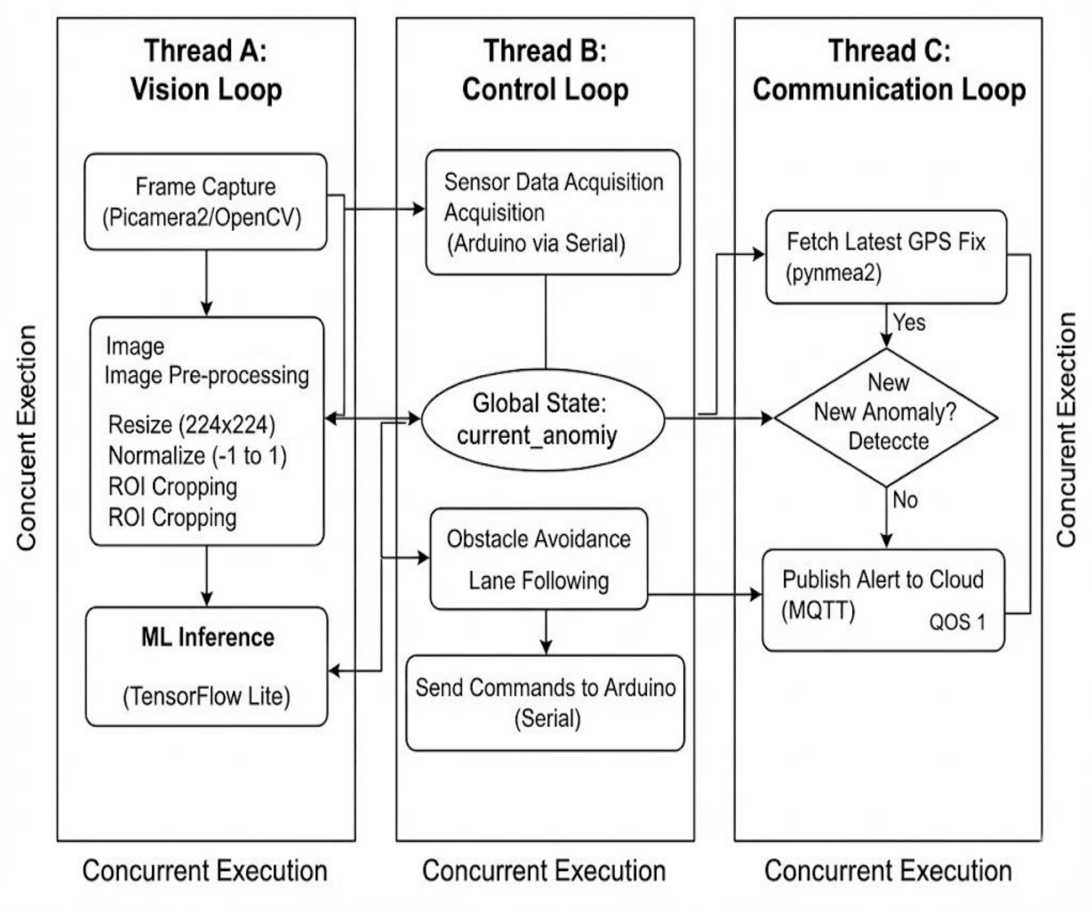

Fig. 3: Block diagram of Software Architecture

Data Flow and Communication Design

The system utilizes the MQTT (Message Queuing Telemetry Transport) protocol, which is the industry standard for IoT due to its lightweight nature and low bandwidth usage.

- GSM/4G Module: The hardware modem that connects the Raspberry Pi to the cellular network.
- MQTT Protocol: The system uses MQTT (Message Queuing Telemetry Transport), which is the industry standard for IoT because it is lightweight and works well on unstable mobile networks.
- MQTT Broker: This is a server (in the cloud) that acts as a "post office." It receives the alert from the car and holds it.
- QoS 1 (Quality of Service 1): The diagram notes "QoS 1," which is a setting that guarantees the message is delivered at least once. This ensures that even if the car goes through a tunnel or loses signal momentarily, the alert will eventually be sent.

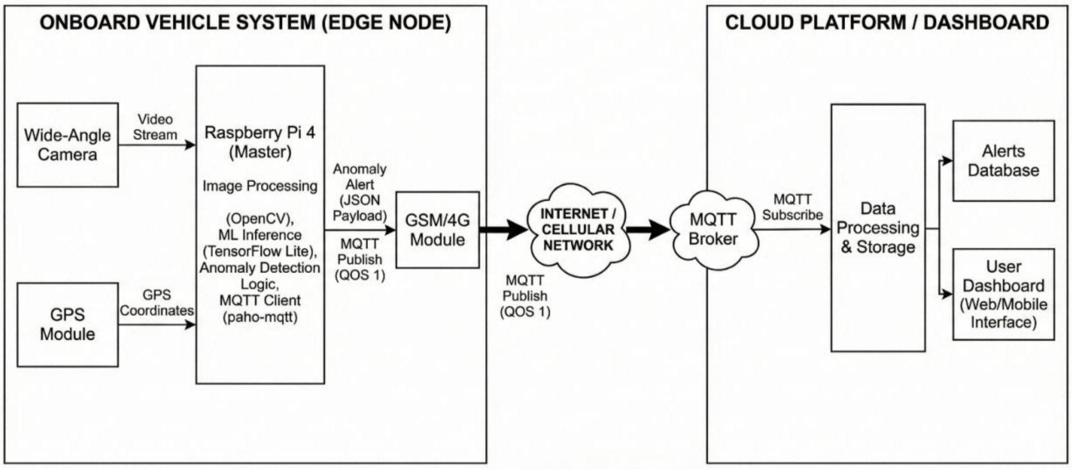

Fig. 4: Block diagram of Data Flow and Communication Design

- MQTT Subscribe: The dashboard constantly listens to the MQTT Broker. As soon as the Broker receives a new alert from the car, it instantly pushes it to the dashboard.

Performance Evaluation

- Optimized Edge Computing: The selection of MobileNetV2 as the core neural network validates that deep learning can be theoretically optimized for embedded devices. By processing video data locally on the Raspberry Pi 4, the design eliminates the latency and bandwidth costs associated with traditional cloud-based video streaming.
- Robust Control Architecture: The proposed Master-Slave configuration effectively decouples high-level cognitive tasks (vision processing) from low-level actuation (motor control). This separation of concerns is designed to ensure that the vehicle remains responsive and stable, even when the AI processor is under heavy load.
- Reliable IoT Communication: The integration of the MQTT protocol with QoS 1 guarantees that critical anomaly data—specifically geotagged pothole locations can be reliably transmitted to the cloud, even in the unstable network conditions typical of highway environments.

Conclusion

The "Autonomous Highway Surveillance Car" project has successfully established a comprehensive design framework for automating road infrastructure maintenance. Through rigorous literature survey and system analysis, this study confirms that the current reliance on manual, reactive inspection is inefficient and hazardous. The proposed solution addresses these challenges by designing a scalable, low-cost autonomous agent capable of real-time monitoring. In conclusion, while physical implementation is the subsequent phase, this project has laid a solid foundation for a smart maintenance rover. The design demonstrates that it is technologically feasible to digitize the physical state of roads using off-the-shelf components, offering a viable path toward predictive infrastructure management.

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