

Vision-Based Smart Pothole Detection and Alert System using ESP32

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Abstract— Road damage and potholes are one of the major causes of vehicle accidents and traffic disruptions. Traditional pothole detection methods rely on manual inspection, which is inefficient and time-consuming. This project proposes a Smart Pothole Detection and Alert System using ESP32 that utilizes computer vision and sensor-based detection to identify potholes and automatically control vehicle speed.

In the proposed system, a web camera connected to a laptop captures road images periodically. The captured images are compared with a predefined reference image using Python-based image processing techniques. If the similarity between images falls below a threshold, the system identifies the presence of a pothole or road anomaly. The detection result is then transmitted to an ESP32 microcontroller through wireless communication.

Once the ESP32 receives the signal, it activates the ultrasonic sensor (HC-SR04) to measure the depth of the pothole. Based on the measured depth, the motor speed is automatically reduced using the L293D motor driver controlling BO motors. This helps simulate a smart vehicle system that slows down when a pothole is detected.

The proposed system demonstrates how computer vision, IoT, and embedded systems can be integrated to create an intelligent road safety solution.

I. Introduction

Road networks play a crucial role in modern transportation systems, influencing economic growth, public safety, and daily mobility. However, road surface deterioration remains a significant challenge in many countries, especially in rapidly growing urban areas. Among various road defects, potholes are one of the most common and dangerous problems affecting road quality.

Potholes are depressions formed on road surfaces due to repeated traffic loads, water infiltration, temperature fluctuations, and inadequate maintenance. These surface irregularities pose serious risks to vehicles and drivers. Sudden encounters with potholes can cause loss of vehicle control, unexpected braking, and accidents. Additionally, potholes lead to mechanical damage such as tire punctures, suspension failures, and wheel misalignment, increasing maintenance costs for vehicle owners. Poor road conditions also contribute to traffic congestion, increased fuel consumption, and reduced travel efficiency, leading to economic losses on a larger scale.

Traditionally, pothole detection and road condition monitoring rely on manual inspection methods carried out by municipal

authorities. These inspections are often based on field surveys, visual observations, or citizen complaints. Such approaches are time-consuming, labour-intensive, and inefficient, especially in large urban road networks. Furthermore, manual inspection lacks real-time monitoring capability, which results in delays between pothole formation and repair. These delays increase the risk of accidents and further road deterioration. Therefore, there is a growing need for automated systems that can detect potholes efficiently and assist in improving road safety.

Recent advancements in computer vision, embedded systems, and Internet of Things (IoT) technologies have enabled the development of intelligent monitoring systems capable of analysing road conditions automatically. Computer vision techniques allow systems to process and analyse images of road surfaces to identify irregularities such as potholes or cracks. When integrated with embedded microcontrollers and sensors, these technologies can create smart systems that detect hazards and respond accordingly.

In this context, the proposed project presents a Smart Pothole Detection and Alert System using ESP32. The system integrates computer vision-based image analysis with sensor-based depth detection and motor control mechanisms. In the proposed architecture, a web camera connected to a laptop captures images of the road surface at regular intervals. These captured images are processed using Python-based image processing techniques with libraries such as OpenCV, PIL (Python Imaging Library), and NumPy.

The captured image is compared with a predefined reference image representing a normal road surface. Image comparison is performed using pixel difference analysis, which calculates the similarity percentage between the reference image and the live image. If the similarity falls below a predefined threshold, the system identifies the presence of a pothole or road surface anomaly.

Once a pothole is detected, the detection result is transmitted from the laptop to an ESP32 microcontroller through serial communication. The ESP32 then activates an HC-SR04 ultrasonic sensor to measure the depth of the detected pothole. Based on the measured distance, the system adjusts the speed of BO motors using an L293D motor driver, effectively reducing the speed of the prototype vehicle when a pothole is detected.

The proposed system demonstrates how computer vision techniques combined with embedded hardware and sensors can be used to create a smart road safety prototype. By automatically detecting potholes and adjusting vehicle movement, the system aims to simulate an intelligent driver assistance mechanism that can help prevent vehicle damage and improve road safety.

The primary objective of this research is to design and implement a low-cost pothole detection system that integrates image processing, embedded microcontrollers, and ultrasonic sensing. The proposed solution highlights the practical application of computer vision and IoT-based technologies in intelligent transportation systems and smart infrastructure monitoring.

II. Problem Statement

Road potholes have become a major infrastructure problem that negatively affects transportation safety, vehicle durability, and overall travel efficiency. Potholes can cause sudden vehicle instability, loss of control, accidents, and severe damage to vehicle components such as tires, suspension systems, and wheel alignment. In addition, potholes contribute to traffic congestion, increased fuel consumption, and higher maintenance costs, creating economic burdens for both individuals and transportation authorities.

Conventional pothole detection methods mainly rely on manual road inspections conducted by municipal authorities or on complaints reported by road users. These traditional approaches are time-consuming, labor-intensive, and often inefficient, especially in large urban road networks. Manual inspection also lacks continuous monitoring capability, which causes delays between pothole formation and detection. Such delays increase the risk of accidents and allow road conditions to deteriorate further before maintenance actions can be taken.

Although some automated pothole detection systems have been proposed, many of them rely on expensive sensors, complex hardware configurations, or computationally intensive machine learning models. These approaches often require high processing power and specialized equipment, making them difficult to implement in low-cost prototype systems or small-scale applications.

Therefore, there is a need for a simple, low-cost, and practical pothole detection system that can detect road surface irregularities using easily available hardware and software tools. The system should be capable of identifying potholes through image analysis and generating a response that can help prevent potential vehicle damage.

The core problem addressed in this project is the lack of an affordable and efficient system that can automatically detect potholes using computer vision techniques and respond through an embedded control mechanism. The proposed solution integrates webcam-based image capture, Python-based image comparison, an ESP32 microcontroller, an ultrasonic sensor for depth measurement, and motor speed control using a motor driver. This integrated approach demonstrates a prototype model for intelligent pothole detection and vehicle safety response.

III. Literature Review

Road surface monitoring and pothole detection have become important research areas in the field of intelligent transportation systems due to the increasing number of road accidents and vehicle damages caused by poor road conditions. Potholes significantly affect driving safety, traffic efficiency, and vehicle performance. Traditional road inspection methods are mainly based on manual surveys and physical inspections performed by road maintenance authorities. These methods are time-consuming, labor-intensive, and unable to provide continuous monitoring of road conditions. As a result, potholes often remain undetected for long periods, increasing the risk of accidents and infrastructure deterioration.

To overcome these limitations, researchers have explored automated pothole detection techniques using computer vision and sensor-based systems. Computer vision techniques allow the analysis of road surface images to identify irregularities such as potholes, cracks, and surface depressions. Image processing algorithms can detect differences between normal road surfaces and damaged areas by analyzing features such as texture, pixel intensity, and surface patterns. These methods reduce the dependency on manual inspections and enable automated monitoring of road conditions.

Several studies have implemented pothole detection using cameras mounted on vehicles. In these systems, images of the road

surface are continuously captured and processed using image analysis techniques. By comparing the captured images with reference images of normal road surfaces, surface anomalies can be detected. Image comparison techniques based on pixel difference and similarity measurement provide a simple and computationally efficient approach for identifying pothole-like irregularities. Such methods are suitable for prototype systems and real-time applications where complex processing is not required.

In addition to vision-based approaches, sensor-based techniques have also been widely used for pothole detection. Sensors such as ultrasonic sensors, accelerometers, and vibration sensors can detect sudden changes in distance or motion when a vehicle encounters a pothole. Ultrasonic sensors are particularly useful for measuring the distance between the sensor and the road surface, allowing the system to estimate pothole depth. When combined with image processing techniques, sensor data can improve the reliability of pothole detection systems.

Embedded systems play an important role in implementing such automated detection mechanisms. Microcontrollers such as the ESP32 provide a compact and efficient platform for integrating sensors, communication interfaces, and control mechanisms. The ESP32 supports wireless communication and real-time data processing, making it suitable for embedded control applications. By connecting sensors and motor control modules to the microcontroller, it is possible to design intelligent systems that respond automatically when road anomalies are detected.

Despite the various approaches proposed in previous research, many existing solutions rely on complex hardware configurations or computationally intensive algorithms. These systems may not be suitable for low-cost prototype development or educational applications. Therefore, there is a need for a simple and cost-effective system that integrates computer vision techniques with embedded hardware to demonstrate automated pothole detection and response mechanisms.

The proposed system addresses this need by combining webcam-based image capture, Python-based image comparison, an ESP32 microcontroller, an ultrasonic sensor for depth measurement, and motor speed control using an L293D motor driver. The system captures road images using a webcam connected to a laptop, compares them with a reference image to detect potholes, and sends the detection result to the ESP32. The microcontroller then measures the pothole depth using the ultrasonic sensor and adjusts the speed of the BO motors accordingly. This integrated approach provides a practical demonstration of how computer vision and embedded systems can be used to develop intelligent road safety solutions.

IV. Proposed System

The proposed Smart Pothole Detection and Alert System using ESP32 is designed as a low-cost prototype that combines computer vision, embedded systems, and sensor-based detection to identify potholes and respond accordingly. The system aims to demonstrate an automated mechanism for detecting road surface irregularities and controlling vehicle movement to prevent potential damage.

Unlike conventional systems that rely on expensive sensors or complex machine learning models, the proposed system uses simple image comparison techniques and affordable hardware components. The system captures images of the road surface using a web camera connected to a laptop, where the images are processed using Python-based image processing techniques. When a pothole is detected, the system sends a signal to an ESP32 microcontroller, which measures the pothole depth using an ultrasonic sensor and accordingly reduces the speed of the vehicle using a motor driver and BO motors.

This approach demonstrates how computer vision and embedded control systems can be integrated to create a smart road safety prototype.

A. System Components

The proposed system consists of the following main

components:

Web Camera

A USB web camera connected to the laptop captures images of the road surface at regular time intervals. These images are used as input for the pothole detection process.

Laptop with Image Processing Software

The laptop performs image processing using Python programming. Libraries such as OpenCV, PIL (Python Imaging Library), and NumPy are used to capture images, compare them with a reference image, and calculate similarity between images.

ESP32 Microcontroller

The ESP32 acts as the main embedded controller in the system. It receives detection signals from the laptop through serial communication and controls the ultrasonic sensor and motor driver accordingly.

Ultrasonic Sensor (HC-SR04)

The ultrasonic sensor measures the distance between the sensor and the road surface. When a pothole is detected, the sensor helps estimate the depth of the pothole.

Motor Driver (L293D)

The L293D motor driver controls the speed of the BO motors based on commands received from the ESP32.

BO Motors with Wheels

BO motors are used to simulate the movement of a vehicle prototype. When a pothole is detected, the motor speed is reduced to prevent sudden impact.

Power Supply

A battery or power bank supplies electrical power to the ESP32, sensors, and motors, allowing the system to operate as a mobile prototype.

B. Working Principle

The proposed system operates using a combination of image comparison and sensor-based depth measurement.

Initially, a reference image of a normal road surface is captured and stored in the system. During operation, the web camera continuously captures live images of the road surface at regular intervals.

The captured image is then processed using Python image processing techniques. The system compares the live image with the stored reference image by calculating the difference between their pixel values. Based on this comparison, the system calculates a similarity percentage between the two images.

If the similarity value falls below a predefined threshold, the system identifies the presence of a pothole or road surface anomaly.

Once a pothole is detected, the laptop sends a command signal to the ESP32 microcontroller through serial communication. After receiving the signal, the ESP32 activates the HC-SR04 ultrasonic sensor to measure the distance between the sensor and the road surface. If a significant depth variation is detected, the ESP32 reduces the speed of the BO motors using the L293D motor driver.

This mechanism simulates a smart vehicle system that slows down automatically when a pothole is detected.

C. System Architecture

The proposed system architecture consists of three main

modules:

Image Processing Module

The image processing module runs on the laptop and performs the following tasks:

Capturing images using the web camera
Comparing the live image with the reference image
Calculating similarity percentage

Detecting potholes based on image differences
Sending detection signals to the ESP32 microcontroller

Embedded Control Module

The embedded control module consists of the ESP32 microcontroller. It performs the following tasks:

Receiving detection signals from the laptop

Activating the ultrasonic sensor
Measuring pothole depth

Controlling motor speed through the motor driver

Mobility and Response Module

This module consists of the BO motors and motor driver. When the ESP32 detects a pothole condition, it reduces the motor speed to simulate a vehicle slowing down before hitting a pothole.

The overall architecture of the proposed Smart Pothole Detection and Alert System is illustrated in Fig. 1.

Smart Pothole Detection and Alert System using ESP32

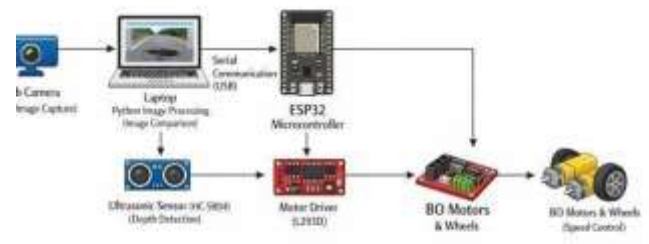


Fig. 1. Block Diagram of Smart Pothole Detection and Alert System using ESP32

D. Data Flow of the System

The overall data flow of the proposed system can be summarized as follows:

The web camera captures a live image of the road surface. The captured image is sent to the laptop for processing.

The system compares the live image with the reference road image. If the similarity is below the threshold, the system detects a pothole. The laptop sends a command signal to the ESP32 microcontroller.

The ESP32 activates the ultrasonic sensor to measure pothole depth.

Based on the depth measurement, the ESP32 controls the motor driver.

The motor speed is reduced to simulate safe vehicle movement.

This integrated system demonstrates how computer vision and embedded control systems can work together to detect potholes and respond automatically, improving road safety and preventing vehicle damage.

V. Methodology

The methodology of the proposed Smart Pothole Detection and Alert System using ESP32 describes the procedure followed for capturing road surface images, processing visual data using computer vision techniques, detecting potholes, and controlling vehicle movement accordingly. The system integrates image processing performed on a laptop with embedded control through an ESP32 microcontroller, along with sensor-based depth measurement and motor speed control. The following steps describe the operational workflow of the system.

Step 1: System Initialization

When the system is powered on, all hardware and software components are initialized. The laptop establishes a connection with the USB web camera, and the Python environment loads the required image processing libraries such as OpenCV, PIL (Python Imaging Library), and NumPy.

At the same time, the ESP32 microcontroller initializes the ultrasonic sensor (HC-SR04), motor driver (L293D), and BO motors. Serial communication between the laptop and ESP32 is also established to enable data transfer.

Step 2: Reference Image Capture

Initially, the system captures a reference image of a normal road surface using the web camera. This reference image represents a road without potholes and is stored in the system memory. It serves as the baseline image for comparison during pothole detection.

Step 3: Live Image Acquisition

During system operation, the web camera captures live images of the road surface at regular intervals. The captured images are stored temporarily in the system and passed to the Python image processing module for analysis.

Step 4: Image Comparison Process

The captured live image is compared with the previously stored reference image using an image difference technique. Both images are converted into a comparable format, and pixel-level differences between the two images are calculated.

The Python program computes the number of pixels that differ between the reference image and the captured image.

Step 5: Similarity Percentage Calculation

After computing the image difference, the system calculates the similarity percentage between the reference image and the live image using numerical analysis.

A higher similarity value indicates that the road surface is normal, while a lower similarity value suggests the presence of a pothole or irregular surface condition.

Step 6: Decision Making and Signal Transmission

A predefined threshold value is used to determine whether a pothole is present. If the similarity value falls below the threshold, the system identifies the road surface anomaly as a pothole.

Once a pothole is detected, the Python program sends a control signal through serial communication to the ESP32 microcontroller.

Step 7: Depth Measurement Using Ultrasonic Sensor

After receiving the signal from the laptop, the ESP32 activates the HC-SR04 ultrasonic sensor to measure the distance between the sensor and the road surface.

The ultrasonic sensor helps determine the depth of the pothole, providing additional confirmation of the detected road defect.

Step 8: Motor Speed Control

Based on the depth measurement, the ESP32 controls the L293D motor driver to adjust the speed of the BO motors.

When a pothole is detected, the system reduces the motor speed to simulate a vehicle slowing down before encountering the pothole. This mechanism demonstrates a smart vehicle response to road

surface irregularities.

Step 9: Continuous Monitoring

The system continuously repeats the image capture, comparison, and detection process as long as the system remains operational. This allows the system to monitor road conditions in real time and respond automatically when potholes are detected.

The working procedure of the proposed system is illustrated in Fig. 2.

Flowchart of Smart Pothole Detection and Alert System using ESP32

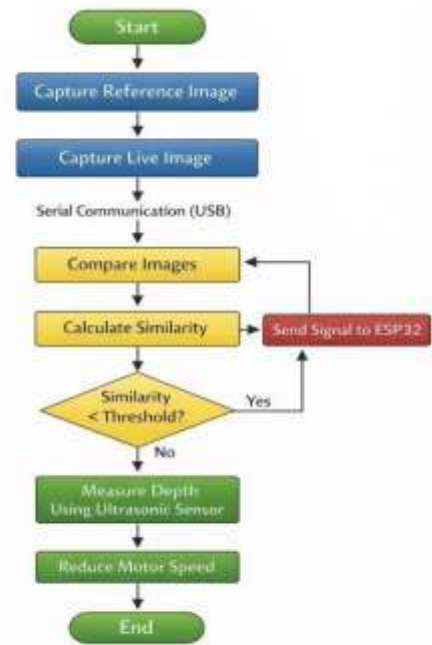


Fig. 2. Flowchart of Smart Pothole Detection and Alert System using ESP32

VI. Implementation

The proposed Smart Pothole Detection and Alert System using ESP32 was implemented as a hybrid system combining computer vision processing on a laptop with embedded hardware control using an ESP32 microcontroller. The system detects potholes by comparing real-time images captured through a webcam with a reference road image. Based on the detection result, commands are transmitted to the ESP32 through wireless communication, which then measures road depth using an ultrasonic sensor and adjusts the motor speed accordingly.

The prototype was designed using low-cost and easily available hardware components, ensuring portability and feasibility for practical road monitoring applications.

A. Hardware Setup

The hardware architecture of the system consists of the following main components:

ESP32 Microcontroller

The ESP32 microcontroller acts as the central embedded controller responsible for receiving commands from the laptop via Wi-Fi communication. It processes the received signals and controls the ultrasonic sensor, motor driver, and LED indicators.

Webcam

A USB webcam connected to the laptop (USB 2.0 interface) is used for capturing images of the road surface. The webcam continuously captures images that are processed using computer vision algorithms implemented in Python.

Ultrasonic Sensor (HC-SR04)

The HC-SR04 ultrasonic sensor is used to measure the distance between the system and the road surface. When a pothole is detected through image comparison, the ESP32 activates the ultrasonic sensor to measure the depth of the road depression. This additional sensing improves the reliability of pothole detection.

Motor Driver (L293D)

The L293D motor driver is used to control the speed and direction of the BO motors. The ESP32 sends control signals to the motor driver to adjust the speed of the mobile platform when potholes are detected.

BO Motors and Wheels

The system is mounted on a mobile chassis with BO motors and wheels. These motors allow the platform to move along the road surface for continuous monitoring and scanning of road conditions.

Power Supply

A battery or power bank is used to supply power to the ESP32, ultrasonic sensor, motor driver, and motors, enabling standalone operation.

B. Software Development Environment

The software implementation of the system consists of two parts:

Computer Vision Processing (Laptop)

Embedded Control System (ESP32)

The computer vision module was developed using Python programming language with OpenCV and PIL libraries for image capture and image comparison. The embedded control system was programmed using Arduino IDE with Embedded C/C++, which controls the ESP32 hardware components.

C. Reference Image Capture

At the beginning of the system operation, a reference image of a normal road surface is captured using the webcam. This image acts as the baseline for comparison.

A Python program using OpenCV captures the image from the webcam and saves it as a reference file. The reference image represents a road surface without potholes.

This step is important because the system later compares live images with this reference image to detect road surface anomalies.

D. Live Image Capture and Processing

During operation, the webcam continuously captures images of the road surface at regular intervals. The Python program captures a new image every few seconds using the OpenCV library.

The captured image is then compared with the reference image using image difference techniques implemented with the Python Imaging Library (PIL). The program calculates the similarity percentage between the reference image and the live image by computing the difference between pixel values.

If the similarity value falls below a predefined threshold, the system identifies the presence of a pothole or road anomaly.

E. Communication with ESP32

Once the pothole detection decision is made by the Python program, the laptop sends a command to the ESP32 using serial communication over Wi-Fi.

Two different signals are transmitted:

'S' (Stop / Slow) → indicates pothole detected 'N'

(Normal) → indicates normal road surface

The ESP32 receives this signal and performs further processing based on the received command.

F. Ultrasonic Depth Measurement

When the ESP32 receives the pothole detection signal, it activates the HC-SR04 ultrasonic sensor to measure the distance between the sensor and the road surface. If a significant depth variation is detected, it confirms the presence of a pothole. This step helps improve detection accuracy and reduces false detections caused by shadows or lighting variations.

G. Motor Speed Control

After confirming the pothole detection, the ESP32 sends control signals to the L293D motor driver. The motor driver then reduces the speed of the BO motors, allowing the mobile platform to slow down when approaching a pothole. This mechanism simulates a safety response system that can help prevent vehicle damage in real-world scenarios.

H. System Testing

The prototype system was tested on different road-like surfaces with artificial potholes and depressions. During testing, the webcam successfully captured road images, and the Python program detected surface anomalies using image comparison techniques.

The ESP32 received commands from the laptop and correctly activated the ultrasonic sensor to measure depth. The motor speed

was successfully reduced through the motor driver when potholes were detected.

The experimental results demonstrate that the proposed system can effectively detect potholes and generate alerts using a combination of computer vision and embedded sensing techniques.

VII. Results and Discussion

The proposed Smart Pothole Detection and Alert System using ESP32 was experimentally evaluated to analyze its detection capability, system response, and reliability under different road surface conditions. The testing process involved capturing road surface images using a USB webcam connected to a laptop and processing the images using a Python-based computer vision program. The processed results were then transmitted to the ESP32 microcontroller to trigger alerts and control motor movement.

The experiments were conducted on three types of test surfaces: smooth road surfaces without defects, surfaces containing small potholes or shallow depressions, and surfaces containing larger potholes. Artificial depressions were created on flat surfaces to simulate real road damage conditions.

During the testing phase, the webcam continuously captured images of the road surface at regular intervals. The captured live images were compared with a previously stored reference image representing a normal road surface. The comparison was performed using a Python-based image processing program that calculated the similarity percentage between the two images by analyzing pixel differences.

When the similarity value between the reference image and the live image decreased below a predefined threshold, the system identified the presence of a pothole or road anomaly. Based on this detection result, the laptop transmitted a command signal to the ESP32 microcontroller through serial communication.

Upon receiving the pothole detection signal, the ESP32 activated the HC-SR04 ultrasonic sensor to measure the distance between the sensor and the road surface. This depth measurement provided additional verification of the pothole. If the sensor detected a noticeable depression, the ESP32 confirmed the pothole condition. Once the pothole was confirmed, the ESP32 triggered the LED indicator to provide a visual alert and simultaneously reduced the speed of the BO motors using the L293D motor driver. This response mechanism simulates a safety system where a vehicle slows down when encountering a pothole.

The system performance was evaluated based on three major parameters: detection capability, response time, and operational reliability. Experimental observations showed that smooth road surfaces produced very small differences between the reference and live images, resulting in high similarity percentages and no pothole alerts. In contrast, surfaces containing potholes showed larger image variations, reducing the similarity value and triggering the detection mechanism.

The average response time from image capture to motor speed adjustment was observed to be within a few seconds, indicating near real-time operation suitable for practical road monitoring systems. The integration of the ultrasonic sensor improved detection reliability by verifying the physical depth of the road surface, thereby reducing false detections caused by shadows or lighting variations.

Smooth Road Surface:

The experimental observations can be summarized as follows: High similarity between reference and live images; no pothole detected; LED remained off and motors continued at normal speed. Small

Potholes or Shallow Depressions:

Moderate variation in image comparison; potholes detected in most cases; LED indicator activated and motor speed slightly reduced. Large

Potholes: Significant difference between reference and live images; consistent pothole detection; LED activated immediately and motor speed reduced effectively.

Although the system demonstrated promising results, some limitations were observed during testing. Detection accuracy was affected under poor lighting conditions, strong shadows, or reflective surfaces. Additionally, very small cracks or minor surface irregularities sometimes produced insufficient image variation for

reliable detection.

Overall, the proposed system successfully demonstrated an effective low-cost pothole detection mechanism by combining computer vision processing on a laptop with embedded sensing and motor control using ESP32. Compared to traditional manual road inspection methods, the proposed system provides automated detection, faster response, and reduced human intervention. These results indicate that the system has the potential to support intelligent road monitoring and smart transportation infrastructure applications.

VIII. Advantages

The proposed Smart Pothole Detection and Alert System using ESP32 provides several advantages compared to traditional manual road inspection methods. The system is developed using low-cost hardware components such as the ESP32 microcontroller, USB webcam, ultrasonic sensor, BO motors, and an L293D motor driver. This makes the system economically feasible and suitable for experimental deployment or prototype development for intelligent road monitoring applications.

One of the key advantages of the system is the use of computer vision techniques implemented on a laptop using Python and OpenCV. The webcam captures real-time images of the road surface, which are then compared with a reference image to identify possible road anomalies. This approach enables automatic pothole detection without requiring expensive sensors or complex hardware.

Another important advantage is the integration between image processing and embedded control. Once a pothole is detected through image comparison, the laptop sends a signal to the ESP32 microcontroller. The ESP32 then activates the ultrasonic sensor to measure the depth of the road surface and verify the presence of a depression. This additional sensing layer improves the reliability of the detection system.

The system also includes a motor control mechanism, where the ESP32 controls the speed of BO motors through the L293D motor driver. When a pothole is detected, the motor speed is automatically reduced, simulating a safety response that can help prevent vehicle damage in real-world applications.

The use of a modular architecture combining computer vision and embedded systems makes the system flexible and easy to modify for future improvements. Additional sensors, wireless communication modules, or cloud connectivity can be integrated to enhance system functionality.

Furthermore, the system operates using portable power sources, making it suitable for mobile monitoring platforms and prototype testing environments. By enabling automated pothole detection and alert generation, the system reduces the need for manual inspection and demonstrates a practical approach toward improving road safety and intelligent transportation monitoring.

Overall, the proposed system highlights the potential of combining computer vision, embedded control, and sensor-based verification to create a low-cost and effective pothole detection solution.

IX. Future Scope

The proposed Smart Pothole Detection and Alert System using ESP32 provides a basic framework for automated road surface monitoring and can be further enhanced through several technological improvements. Although the current prototype successfully demonstrates pothole detection using webcam-based image comparison and embedded control, additional features can significantly improve its functionality, accuracy, and scalability.

One possible enhancement is the integration of a GPS module with the ESP32 microcontroller. This would allow the system to record the geographical location of detected potholes. Such location data could help municipal authorities identify damaged road segments and plan maintenance activities more efficiently.

Another improvement could involve wireless data transmission to cloud platforms or centralized servers. Instead of operating only

between the laptop and ESP32, future systems could send pothole detection data to an online database. This would enable long-term road condition monitoring, data analysis, and easier reporting for large road networks.

The system can also be improved by developing a mobile or web-based monitoring interface that displays pothole detection results in real time. Such an interface could allow road maintenance teams or city authorities to visualize detected road defects and respond quickly to repair requirements.

To improve detection accuracy, future versions may incorporate advanced machine learning or deep learning algorithms for image classification. These algorithms could better distinguish potholes from other road irregularities such as shadows, stains, or minor surface textures. However, such techniques would require more computational resources and optimized hardware support.

Another potential enhancement is the use of better camera modules or night-vision cameras, which would allow reliable detection under low-light or nighttime conditions. Additional sensors such as accelerometers or vibration sensors could also be integrated to improve detection reliability through multi-sensor data fusion.

Furthermore, the mobility system could be enhanced with autonomous navigation features, allowing the monitoring unit to automatically scan larger road areas without manual control.

With these improvements, the proposed system could evolve into a more advanced intelligent road monitoring platform, capable of supporting smart city infrastructure and improving road safety through automated pothole detection and reporting.

X. Conclusion

This research presented the design and implementation of a Smart Pothole Detection and Alert System using ESP32, developed to address the increasing problem of road surface deterioration and the limitations of traditional manual inspection methods. Potholes significantly affect road safety, cause vehicle damage, and lead to economic losses, which highlights the need for an automated and efficient monitoring solution.

The proposed system integrates computer vision and embedded systems to detect potholes in real time. A USB webcam connected to a laptop captures road surface images, which are processed using Python and OpenCV libraries. The captured images are compared with a reference road image using an image comparison technique to determine the similarity between the two images. When a significant difference is detected, the system identifies the presence of a pothole.

After pothole detection, the laptop communicates with the ESP32 microcontroller, which further activates the ultrasonic sensor (HC-SR04) to measure the depth of the road surface. Based on the detected condition, the ESP32 controls the motor driver (L293D) to reduce the speed of the BO motors, thereby simulating a safety response for the moving platform. This combination of image processing and sensor-based verification improves the reliability of pothole detection.

Experimental testing demonstrated that the prototype system successfully captured road images, compared them with the reference image, detected surface anomalies, and generated appropriate control responses. The system proved capable of performing automated pothole detection using low-cost hardware components and simple image processing techniques.

Overall, the proposed system demonstrates a practical and cost-effective approach for intelligent road monitoring. By combining computer vision, embedded control, and sensor-based verification, the system provides a foundation for future smart road monitoring technologies that can contribute to improved road safety and efficient infrastructure maintenance.

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