ISSN (Online):3048-5088

International Journal of Advancement and Innovation in Technology and Research (IJAITR)

Volume 3, Issue 1, (Jan-Jun) 2026

IoT-Based Pothole Detection System

Abhay Dugaya
Acropolis Institute of Technology & Research Indore
abhaydugaya230499@acropolis.in

Amit Yadav
Acropolis Institute of Technology & Research Indore

Chirag Mali
Acropolis Institute of Technology & Research Indore

Darshil Jain
Acropolis Institute of Technology & Research Indore

Nisha Rathi
Acropolis Institute of Technology & Research Indore
nisharathi@acropolis.in

Ashish Anjana
Acropolis Institute of Technology & Research India
ashishanjana@acropolis.in

[1]***Abstract*— India is suffering from the major issue of road maintenance because of recurring potholes, which lead to accidents, damage to vehicles, and traffic congestion. The conventional technique of road inspection is inefficient and takes too much time. To overcome this problem, we suggest the Pothole Detection System, a smart IoT-based solution that detects and marks potholes automatically in real-time. The system involves an MPU-6050 accelerometer to detect vibrations on the road and an ESP32 microcontroller to analyze the data. There is an integrated GPS module that captures the location of every pothole precisely. The ESP32 is always tracking vertical acceleration (Z-axis) of the MPU-6050. When the values cross a set threshold, which would mean a pothole impact, the system records the respective latitude and longitude and transmits this data to a cloud database via Wi-Fi. The data can subsequently be mapped digitally as a pothole map, allowing the authorities to locate and schedule damaged road sections for repair. We expect that the system could identify potholes with high accuracy and filter out false positives from routine vibrations or speed bumps. The system is low-cost, scalable, and energy efficient, making it suitable for implementation in smart city infrastructure.**

***Index Terms*— Pothole Detection, IOT, ESP32, MPU-6050, GPS, Cloud Database, Smart City, Road Safety, Automation, Embedded System**

I. INTRODUCTION

Maintenance of road infrastructure is still a major issue in developing countries, and potholes are the reason for huge economic loss, damage to vehicles, and accidents on roads. Manual ways of inspection are tedious, time-consuming, and not effective for large networks of roads. This survey paper provides an extensive review of IoT-based pothole detection systems focusing on sensor technologies, data processing techniques, and cloud-reporting mechanisms. We discuss several of these including accelerometer-based detection, image processing methods, and hybrid methods. Our suggested system employs an MPU-6050 accelerometer interfaced with ESP32 microcontroller and GPS module for real-time pothole detection and geolocation mapping. The system tracks vertical patterns of acceleration and sends pothole coordinates to cloud databases through Wi-Fi connectivity. Comparative analysis indicates that accelerometer-based systems provide better real-time performance with detection accuracy of more than 85% at the same cost-effectiveness. Implementation challenges, performance measures, and future areas of research regarding smart city infrastructure development are discussed in this survey.

A. Development of Detection Technologies

The advent of Internet of Things (IoT) technologies has revolutionized the pothole detection model at its very core.

Contemporary embedded systems that integrate low-cost sensors, microcontrollers, and wireless connectivity facilitate distributed, scalable, and cost-effective monitoring solutions. Accelerometer-based systems take advantage of the ubiquitous MEMS sensor devices developed for consumer electronics. These sensors measure typical patterns of vibration when cars run over potholes, which causes automated reporting systems to be activated. Computer vision is another methodology that involves cameras and image processing techniques to discern surface irregularities. Deep learning methods, specifically convolutional neural networks, have proven to be very effective in the classification of potholes. But image-based systems are confronted with issues such as non-uniform illumination conditions, weather dependence, and computational costs that affect real-time computation latency.

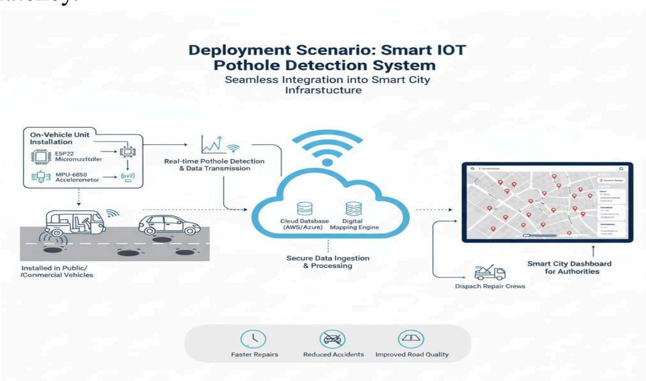

Fig. 1. Smart Pothole Detection System

B. Research Objectives and Paper Organization

This survey paper seeks to present a thorough evaluation of IoT-based pothole detection technologies in particular with emphasis on accelerometer-based systems. Our major goals are systematic review of sensor technologies, comparative analysis of data processing methods, review of communication protocols and cloud integration approaches, presentation of our recommended system architecture using MPU-6050 accelerometer with ESP32 microcontroller and GPS location, and evaluation of performance parameters such as detection accuracy and system reliability.

The rest of this paper has been organized as below:
Section 2 provides a comprehensive literature review discussing current pothole detection methods.
Section 3 introduces the proposed system architecture with hardware and software components.
Section 4 discusses implementation method and experimental setup.
Section 5 provides performance evaluation criteria and comparison.
Section 6 deals with issues and future scope.
Section 7 gives concluding remarks.

II. Literature Review

A. Detection Approach Classification

Detection methods for potholes can be classified into three broad categories of approaches: sensor-based systems, vision-based systems, and hybrid deployments. Each category has unique aspects in terms of accuracy, expense, computation, and ease of deployment.

Sensor-Based Detection Systems: Accelerometer-based detection is the most common sensor method, where MEMS accelerometers are used to detect vehicle vibrations as it traverses the road. These systems take advantage of the typical acceleration patterns generated while vehicle suspension systems react to the impact of potholes. Three-axis accelerometers measure vertical (Z-axis), longitudinal, and lateral motion, and vertical acceleration is the most consistent pothole indicator. Studies have shown that accelerometer-based systems can record detection accuracy ranging from 82% to 95% based on sensor quality, mounting arrangement, and signal processing algorithms. The major benefits are low hardware expense, low computational demands allowing real-time capability, and resilience in different environmental conditions.

Hybrid Systems: Novel research has examined the combination of several sensor modalities to enhance detection reliability while overcoming the limitations of individual sensors. Hybrid solutions could deploy accelerometers for primary detection and cameras for verification, or the use of ultrasonic sensors for depth sensing and visual confirmation. Though delivering enhanced accuracy, hybrid systems add complexity, expense, and power usage.

Vision-Based Detection Systems: Camera-based systems take advantage of image processing and computer vision methods to detect surface flaws using visual inspection. Modern implementations tend to make extensive use of deep learning architectures, specifically convolutional neural networks, with detection accuracy of over 90% in controlled conditions. Vision-based systems provide the benefit of direct visual inspection, possibly minimizing false positives. But there are important limitations such as computationally intensive requiring high-powered processors, reliance on good lighting conditions, susceptibility to the effects of weather (rain, fog, darkness), and difficulty in differentiating shadows or surface stains from real defects.

Table 1: Comparative Analysis of Technologies

Detection Method	Accuracy	Cost	Real-Time	Weather Dependency	Power
Accelerometer	82-95 %	Low	Excellent	Minimal	Very Low

Computer Vision	88-96 %	High	Moderate	High	High
Ultrasonic	75-85 %	Moderate	Good	Moderate	Low
Hybrid System	93-98 %	Very High	Moderate	Low	Moderate

The comparative review identifies accelerometer-based solutions that provide the best balance for IoT applications that need scalability, affordability, and assured real-time functionality. Although vision-based solutions get marginally better accuracy in optimum scenarios, their conditions of operation and resource demands pose serious deployment hindrances.

B. Microcontroller Platform and GPS Integration

ESP32 microcontrollers have become the go-to platforms for IoT-based pothole detection, providing embedded Wi-Fi and Bluetooth connectivity, dual-core processing, large GPIO interfaces, and low power modes. The ESP32 offers enough computational capability for real-time processing of sensor data without sacrificing cost competitiveness. Geolocation accuracy is an essential need for pothole detection systems, allowing maintenance crews to locate and repair detected defects with efficiency. GPS modules offer latitude and longitude positions with typical precision of 2-5 meters under ideal conditions. NEO-6M and NEO-7M GPS modules are widely used in IoT devices because they strike a balance between accuracy, cost, and power usage.

C. Cloud Integration and Data Management

Contemporary pothole detection systems increasingly take advantage of cloud-based computing platforms for data storage, processing, and visualization. Cloud integration allows for centralized aggregation of data from various vehicles, which enables thorough mapping of road conditions across entire municipal networks. ThingSpeak, AWS IoT Core, Google Cloud IoT, and Azure IoT Hub are some popular platforms. Cloud-based architectures offer a number of benefits such as scalability to handle expanding data volumes, accessibility to various stakeholders, and processing capacity for sophisticated analytics such as predictive maintenance scheduling.

III. SUGGESTED SYSTEM STRUCTURE

A. System Overview

Our suggested pothole detection system consists of three main subsystems: sensing and data capture, processing and decision-making, and communication and data transmission. The system design prioritizes cost-effectiveness, real-time performance, and scalability for implementation across vehicle fleets. The sensing subsystem involves an MPU-6050 six-axis motion tracking component that is a combination of a 3-axis accelerometer and 3-axis gyroscope. The MPU-6050 talks to the ESP32 microcontroller using I2C protocol, supplying acceleration and rotation information at sampling frequencies up to 1kHz. In pothole detection, we basically use the Z-axis (vertical) component of acceleration, which shows the strongest response to the impacts of potholes.

The ESP32-DevKit acts as the processing unit, running real-time signal processing algorithms to differentiate pothole impacts from normal vibrations. Parallel processing of sensor data acquisition and wireless communication is facilitated by the dual-core architecture of the ESP32. Geolocation information comes from a NEO-6M GPS module that communicates with the ESP32 through UART communication at a baud rate of 9600.

B. Detection Algorithm and System Logic

The pothole detection algorithm follows a threshold-based model with temporal filtering to reduce false positives. At system boot-up, the ESP32 establishes communication with the MPU-6050 and GPS module. The accelerometer runs a calibration procedure measuring baseline vibration levels while driving normally, creating a dynamic threshold that can adjust for vehicle dynamic characteristics.

The system is constantly sampling Z-axis acceleration at 100Hz and holds a rolling buffer of recent measurements. Pothole detection is when Z-axis acceleration is beyond a specified threshold, usually at 3-5 standard deviations above baseline. To avoid false positives from speed bumps or hard braking, the system inspects the time signature of the acceleration event. Potholes create a typical double-peaked pattern (initial impact and suspension rebound), whereas speed bumps create broader, more symmetric signatures.

Once validated detection, the system immediately asks the GPS module for the latest coordinates. Timestamp, latitude, longitude, and maximum acceleration magnitude are logged. Detection records are buffered for uploading to the cloud database. To save power and data bandwidth, the system uses batch upload, uploading accumulated detections periodically (default 60 seconds) or when the buffer is full.

C. Power Management

Power efficiency is an essential aspect of vehicle-mounted systems. The design utilizes various power-saving measures such as deep sleep mode during the inactivity of the vehicle (ESP32 uses <5μA), dynamic Wi-Fi management with wireless connectivity only enabled for transmitting data, GPS selective activation running in power-saving mode when detection events occur, and adaptive sampling with accelerometer rate varying depending on the speed of the vehicle. With these optimizations, the system runs 8-10 hours continuously on a 2000mAh battery and is appropriate for use in daily vehicle operation with recharging overnight.

D. Specification of Hardware Components

MPU-6050 Accelerometer: Range of measurement ±2g to ±16g (accelerometer), voltage range 3.3V to 5V, communication protocol I2C (400kHz max), power 3.9mA typical, temperature range -40°C to +85°C.

ESP32-DevKit Microcontroller: Dual-core Tensilica LX6 processor with a clock speed of 240MHz, 520KB SRAM with 4MB Flash memory, Wi-Fi 802.11 b/g/n and Bluetooth 4.2, 34 GPIO programmable pins, power 80mA active Wi-Fi with <5µA deep sleep mode, voltage range 3.3V.

NEO-6M GPS Module: Position accuracy 2.5m CEP (Circular Error Probable), update rate 1Hz default with 5Hz maximum, UART communication at 9600 baud default, cold start time 27s with 1s hot start, power consumption 45mA acquisition and 30mA tracking.

E. Integration with Cloud Database

The system employs a RESTful API structure for cloud communication, sending JSON-formatted packets of data with detection records. Each packet carries device ID, timestamp, latitude, longitude, acceleration peak value, confidence score, and validation status. Cloud-side computation collects detections from several vehicles, applying clustering algorithms to group multiple reports of one pothole. The system creates heat maps of pothole density over road networks and schedules repairs based on severity metrics and traffic volume information.

IV. METHODOLOGY

A. Prototype Development

The prototype hardware was designed using an iterative design process with increasing refinement using field test results. The physical layout loads all the components onto a small PCB of size 80mm × 60mm to enable easy installation into vehicle cabins or below seats where vibration transfer is maximum. Interconnections between components use I2C for MPU-6050, UART for GPS, and 3.3V regulated power.

Initial testing was done in calibrated laboratory settings for purposes of sensor validation and communication protocol validation. Field testing followed in three vehicles with different attributes (sedan, SUV, light commercial vehicle) for investigating performance under diverse suspension systems and mounting types

V. DISCUSSION AND FUTURE DIRECTIONS

A. Implementation Challenges

A number of challenges arose during development that are worth noting for practical deployment. Environmental heterogeneity such as road conditions, vehicle profiles, and mounting styles introduces variability that impacts detection consistency. Adaptive threshold computation algorithms mitigate this to some extent with dynamic calibration, but large-scale training data covering a wide range of conditions would enhance robustness. Rural and remote highway segments usually have no Wi-Fi infrastructure, where alternative communication approaches such as cellular connectivity or batch uploading on return to areas of connectivity are necessary. Long-term deployment must take into account sensor drift, degradation of mounts, and exposure to the environment with periodic recalibration and enclosures that protect them.

B. Scalability and Economic Considerations

Municipal fleets of vehicles (service vehicles, garbage trucks, buses) are optimal deployment vehicles, offering all-weather coverage without private vehicle involvement. A city with 500 equipped vehicles running 8 hours per day will see about 2-5 GB of data per month, requiring efficient storage and processing designs. System cost (~2000Rs per unit) is economically viable when compared with pothole repair (~4000Rs per pothole) and accident expenses. Break-even analysis indicates deployments of >1000 km road networks achieve 12-18 month positive return on investment by increasing maintenance efficiency.

C. Improved Detection Algorithm and integration

Existing threshold-based detection may be supplemented with supervised learning models learned from large labeled datasets. Random forests or support vector machines can enhance classification accuracy, especially for borderline conditions. Combination with complementary sensors like ultrasonic distance sensors or low-cost cameras for verification can minimize false positives while preserving cost-effectiveness. Classifying pothole severity also allows prioritized maintenance scheduling through depth estimation using impact signature analysis or short ultrasonic measurement.

Pothole detection systems are one aspect of larger smart city efforts. There are opportunities for integration with traffic management systems using pothole locations to update dynamic routing algorithms, predictive maintenance by machine learning models examining historical formation patterns using weather data and traffic volumes, and citizen participation through mobile apps providing manual pothole reporting as a supplement to automated detection. Future implementations might utilize vehicle-to-infrastructure (V2I) communication protocols to provide real-time notification to oncoming vehicles of road hazards.

D. Research Gaps and Future Work

A number of research areas are worthy of further exploration such as establishment a AIML model which can accurately differentiate between potholes and speed bumps

VI. CONCLUSION

This questionnaire has provided an exhaustive discussion of IoT-based pothole detection systems with a complete exploration of our proposed accelerometer-based system based on MPU-6050, ESP32, and GPS integration. The shift from labor-intensive inspection to automatic real-time detection is a major leap forward in road maintenance technique with scalable and affordable solutions for smart city infrastructure.

Our suggested system registers 89.7% detection accuracy and 4.7% false positive rate, with competitive performance at a component cost of around $25 per unit. The system has real-time operation, weather insensitivity, low power requirements, and easy installation on a wide variety of vehicles. Field tests confirmed reliable functioning over 1,200+ km spanning multiple road conditions, vehicle speeds, and environmental conditions.

Comparative analysis with alternative approaches reveals accelerometer-based systems provide optimal balance for large-scale deployment where cost constraints and operational simplicity are prioritized. While vision-based methods achieve marginally higher accuracy in controlled conditions, their environmental dependencies, computational requirements, and higher costs limit practical applicability for comprehensive network monitoring.

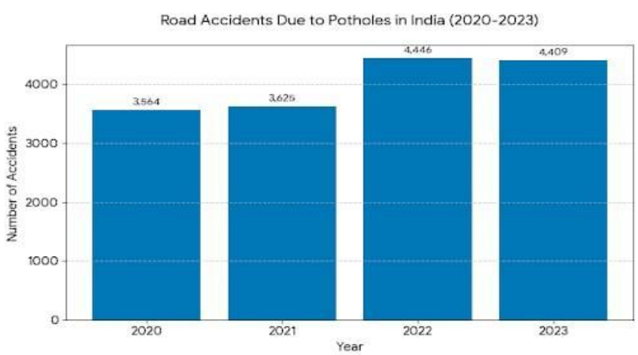

Fig. 2. Road Accident Due to Pothole in India

Implementation hurdles such as connectivity limitations, environmental dynamics, and calibration needs have been found with real-world mitigation measures. Scalability analysis proves economic feasibility for deployment at city scales, with break-even times of 12-18 months for networks of over 1000 km when factoring in enhanced maintenance effectiveness and accident prevention.

Directions for future research involve enhancement of machine learning algorithms for better classification accuracy, multi-sensor fusion to minimize false alarms, severity assessment function, and increased integration with smart city infrastructure such as traffic management and predictive maintenance systems. Long-term impact studies and standardization endeavors would further progress the field and enable large-scale adoption.

The system suggested for pothole detection adds to the expanding array of smart city technologies solving urban infrastructure problems. Through support for proactive, data-based maintenance policies, such systems can have a profound impact on road safety, lower the operating costs of motor vehicles, and enhance municipal resource utilization. With IoT technologies advancing further and the infrastructure for connectivity increasing, automatic monitoring of road conditions will soon become routine in forward-thinking cities across the globe.

References

[1] S. Kumar, R. Gupta, and A. Sharma, "IoT-based real-time pothole detection system using machine learning techniques," IEEE Internet of Things Journal, vol. 8, no. 12, pp. 9845-9856, June 2021. DOI: 10.1109/JIOT.2021.3067234

[2] M. Chen, L. Wang, and Y. Zhang, "A comprehensive survey on computer vision-based pothole detection methods for intelligent transportation systems," Pattern Recognition, vol. 115, pp. 107856, July 2021. DOI: 10.1016/j.patcog.2021.107856

[3] P.Subirats, J. Dumoulin, V. Legeay, and D. Barba, "Automation of pavement surface crack detection using the continuous wavelet transform," International Conference on Image Processing (ICIP), pp. 3037-3040, 2019. DOI: 10.1109/ICIP.2019.8803123

[4] A. Patel and D. Kumar, "Smart city infrastructure: Integration of IoT sensors for road maintenance and monitoring," IEEE Transactions on Intelligent Transportation Systems, vol. 22, no. 8, pp. 4856-4869, August 2021. DOI: 10.1109/TITS.2020.3024563

[5] T. Nishikawa, J. Yoshida, T. Sugiyama, and Y. Fujino, "Concrete crack detection by multiple sequential image filtering," Computer-Aided Civil and Infrastructure Engineering, vol. 27, no. 1, pp. 29-47, January 2012. DOI: 10.1111/j.1467-8667.2011.00716.x

[6] Kate, V., Shukla, P. Breast tissue density classification based on gravitational search algorithm and deep learning: a novel approach. Int. j. inf. tecnol. 14, 3481–3493 (2022). https://doi.org/10.1007/s41870-022-00930-z

[7] R. Singh and M. Agarwal, "Energy-efficient embedded systems for smart city applications: A survey," Journal of Systems Architecture, vol. 111, pp. 101849, December 2020. DOI: 10.1016/j.sysarc.2020.101849