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AUTOMATED POTHOLE DETECTION AND ROAD QUALITY MONITORING USING NODEMCU AND MQTT

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ABSTRACT: Road safety is influenced by various factors, including driving habits, weather conditions, and the quality of road infrastructure. Ensuring a smooth traffic flow and safety requires continuous monitoring of road conditions; however, poorly maintained roads can lead to vehicle damage, driver discomfort, and increased accident risk. Traditionally, road inspections are carried out manually, a process that is time-consuming and costly, posing challenges for transport authorities in maintaining road networks efficiently. To address these limitations, this study proposes the development of an automated pothole detection system. The system collects road condition data and utilizes the Message Queuing Telemetry Transport (MQTT) protocol for efficient transmission of data to a central server. Haar Cascade algorithm integrated into the NodeMCU devices assesses road quality parameters, enabling real-time detection of potholes. Data collected by the system is transmitted via MQTT to a central server for analysis and reporting. Experimental results demonstrate that the system successfully detects potholes, automatically sending alerts to the central server to enable prompt road maintenance. The automated pothole detection system provides a cost-effective, automated solution for monitoring and improving road conditions, offering transport authorities a more efficient, data-driven approach to road maintenance.

Keywords: Pothole detection, Road quality, NodeMCU, MQTT, Haar Cascade

1. INTRODUCTION

The quality of road infrastructure is a critical factor in ensuring safe and efficient transportation. Well-maintained roads provide a stable driving environment, reducing the likelihood of accidents and vehicle damage [1]. However, poor road conditions, particularly the presence of potholes, significantly compromise road safety. Potholes are structural failures on road surfaces, typically caused by water erosion and repeated stress from vehicular traffic [2-4]. These defects often go unnoticed by drivers until they pose a direct risk, making pothole detection and repair essential for maintaining road quality.

Potholes present several challenges for drivers, especially when encountered at high speeds. Hitting a pothole can lead to a loss of vehicle control, damage to tires, and suspension systems [5]. In severe cases, it can lead to accidents, placing both the driver and other road users at risk. Additionally, pothole-related damages impose significant repair costs on vehicle owners and contribute to traffic congestion. Therefore, timely identification and repair of potholes are essential to minimize these risks and enhance overall traffic safety.

Traditionally, road inspection processes rely on manual and visual assessments, where personnel physically inspect road conditions to identify damage [6-7]. While this method has been the standard for many years, it is not without limitations. Manual inspection is time-consuming, labor-intensive, and prone to human error. The subjective nature of visual assessments means that the identification of potholes can vary based on the inspector's experience and judgment, leading to inconsistencies in detection accuracy [8]. This creates a need for more reliable and efficient methods to assess road conditions.

With recent advances in artificial intelligence (AI) and machine learning technologies, automated systems for road condition monitoring are emerging as a more effective alternative. This paper proposes a system for detecting potholes using the Haar cascade algorithm, capable of real-time detection and reporting. The system leverages NodeMCU hardware integrated with the Message Queuing Telemetry

Transport (MQTT) protocol to transmit data to a central server, facilitating immediate action by road authorities. By automating the pothole detection process, the system aims to deliver a faster, more accurate, and cost-effective solution for monitoring and maintaining road quality.

The remainder of this paper is organized as follows. Section 2 reviews related work on road quality monitoring, while Section 3 discusses previous studies on the MQTT protocol and NodeMCU implementation. The proposed pothole detection system for road quality assessment is presented in Section 4. Section 5 elaborates on the results and discusses the findings. Finally, Section 6 concludes the study and provides recommendations for future research.

2. ROAD QUALITY MONITORING

Pothole detection technology has recently advanced from basic methods, like initial image processing techniques, to sophisticated machine learning approaches. Many researchers have explored ways to improve upon the limitations of traditional pothole detection methods. For instance, one study [9] integrated laser line deformation with image processing to enhance accuracy. This method, although innovative, was highly susceptible to environmental variations and noise, necessitating controlled conditions that limited its practical application in real-world settings. Similarly, another approach by [10] used ultrasonic sensors combined with inter-vehicle communication to detect large road damage with high accuracy. However, this method encountered difficulties in identifying smaller road imperfections and adapting to different infrastructure constraints.

Research interest in pothole detection remains strong. Jo and Ryu [11], for example, utilized embedded systems in black-box cameras for road defect identification, prioritizing computational efficiency to filter out irrelevant objects. Despite demonstrating robust sensitivity and accuracy, this system struggled to maintain efficiency for precise detection in varied road environments where lighting and surface conditions differed significantly.

Further studies, such as those by Madli et al. [12] and Ryu et al. [13], developed real-time road defect detection systems using GPS and optical sensors, providing practical alerts to drivers about potential hazards. However, limitations such as GPS precision and weather-related challenges for optical sensors affected their results. Similarly, [14] faced challenges when applying a laboratory model to real-world conditions, as it was built on the assumption of uniform road surfaces, underscoring the need to accommodate surface diversity in detection systems.

Jeng et al. [15] presented a road monitoring system that used smartphone sensors and relied on community participation to increase coverage. While it provided valuable data on road conditions, the method faced issues with data consistency and uneven sensor accuracy, emphasizing the need for standardized data collection methods across different regions.

Machine learning has recently yielded promising results, especially through models like YOLOv8 for urban pothole detection [16]. This model outperformed methods like Faster R-CNN and SSD in terms of mean Average Precision (mAP) and recall, making it recognized for its potential in improving road safety and reducing maintenance costs. Improvements, such as expanding dataset sizes and optimizing training, have further boosted YOLOv8’s efficiency for real-time use, though certain limitations still need to be addressed in future research.

Additionally, a lightweight detection system based on Full Convolution One-Stage Object Detection (FCOS) [17] was optimized to achieve high accuracy with low computational demand. By leveraging Canny edge detection and a G-GhostNet backbone to minimize model parameters, along with an SCConv module for feature extraction, this approach proved effective, requiring minimal hardware resources. However, the system encountered challenges with false detections under low-light conditions, indicating the need for further improvements to enhance adaptability, reduce hardware dependency, and integrate multi-sensor data for broader and more robust pothole detection.

3. MQTT PROTOCOL AND NODEMCU IMPLEMENTATION

Integrating the MQTT protocol with NodeMCU in Internet of Things (IoT) systems offers substantial potential to improve real-time data sharing and reporting across various applications. A. Zanella et al. (2014) illustrated the effectiveness of MQTT in enabling device-to-device communication within smart cities, giving both authorities and citizens access to urban data. This approach enhanced public involvement and increased responsiveness to city needs through live data. However, a significant challenge was achieving compatibility among diverse IoT systems and older infrastructure. As cities adopted devices from various manufacturers, ensuring that MQTT could integrate with established communication protocols was crucial for seamless and efficient operations.

Research conducted by R. A. Atmoko, R. Riatini, and M. K. Hasin (2017) [19] found that MQTT outperforms HTTP in rapidly gathering data from temperature and humidity sensors in IoT applications. They demonstrated that MQTT's speed and efficiency in transmitting sensor data made it ideal for time-sensitive applications. However, they also emphasized the need to improve data quality and ensure secure communication as IoT networks continue to expand. As more devices join the network, maintaining stability and security becomes essential. Future large-scale networks require enhanced MQTT protocols with strong encryption to safeguard data security.

The study by M. Kashyap, V. Sharma, and N. Gupta (2018) [20] identified MQTT and NodeMCU as practical solutions for IoT communication, although challenges in scalability and security persisted. As IoT systems expanded into sectors such as healthcare and transportation, the demand for secure data transmission and privacy protection increased. Future research should focus on enhancing MQTT's security features and exploring how artificial intelligence (AI) and machine learning (ML) can optimize data flow. With AI-driven algorithms, MQTT-based IoT systems could become more responsive to real-time information, providing predictive insights to support decision-making processes.

C. D'Ortona, D. Tarchi, and C. Raffaelli (2022) [21] applied MQTT in smart city settings to monitor vulnerable road users via wearable devices, demonstrating the framework's potential for expansion and customization. However, the challenge remained in preserving security while scaling open-source solutions. Future upgrades need to balance adaptability with strong security measures to ensure safe data exchanges as smart city infrastructures develop.

Hence, this paper develop a pothole detection, combining MQTT protocol with NodeMCU offers a powerful solution for real-time monitoring and maintenance. MQTT enables fast transmission of sensor data, allowing IoT systems to detect potholes and notify relevant authorities promptly. NodeMCU's Wi-Fi capability facilitates smooth data collection from road sensors, while MQTT's lightweight design ensures stable communication, even over low-bandwidth connections. This setup can reduce delays in pothole repairs, enhancing safety and efficiency in urban road maintenance. The streamlined communication provided by MQTT and NodeMCU could redefine how cities manage road maintenance and infrastructure challenges.

4. **Pothole Detection for Road Quality**

The automated system for detecting potholes uses video capture and machine learning, with Internet of Things (IoT) communication protocols like MQTT to improve reporting efficiency. The framework and flowchart offer a detailed view of how data flows from video capture to the transmission of pothole detection alerts to relevant authorities. This system combines key technologies, such as video preprocessing, machine learning-based detection, and real-time communication, creating an efficient solution for monitoring road quality.

As shown in Figure 1, the framework is designed to handle several tasks, beginning with the capture of road condition video footage. Videos are resized and converted to grayscale to simplify processing. Grayscale conversion effectively reduces data complexity without compromising the essential features needed for identifying potholes. Additionally, the framework extracts Haar features, known for their simplicity and efficiency in object detection, to identify key characteristics that indicate potholes.

After feature extraction, positive images are annotated with bounding boxes, and sample images are created to train a classifier model with the OpenCV cascade classifier method. This enables the system to distinguish potholes from other road features. The framework's scalability and modularity make it adaptable for future enhancements, such as adding new sensors or refining machine learning algorithms.

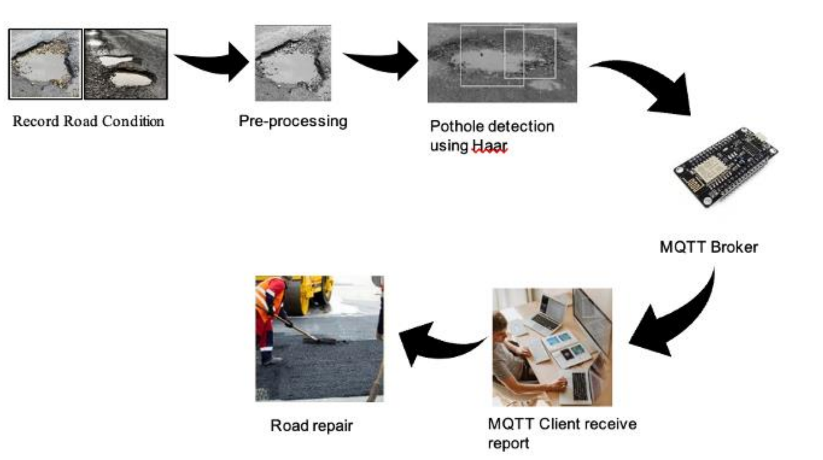

Figure 1: Pothole Detection Framework

Meanwhile, Figure 2 shows a flowchart that outlines the operational steps of the proposed system, combining video capture, machine learning, and IoT-based communication through NodeMCU and the MQTT protocol for pothole detection and reporting. This flowchart breaks down each step, beginning with system setup and ending with a pothole detection message, facilitating a seamless real-time monitoring system. The process starts with the NodeMCU microcontroller initializing and establishing a connection to the MQTT broker. The NodeMCU, an open-source IoT platform with built-in Wi-Fi, is ideal for applications like this. Once initialized, it connects to an MQTT broker, which acts as a central point for data exchange, managing all incoming and outgoing messages related to pothole detection and ensuring the system is ready for data transmission. After connecting, the NodeMCU subscribes to a specific MQTT topic for pothole alerts. By subscribing, the NodeMCU can listen for or send messages under that topic, ensuring that only relevant devices or authorities receive the alerts, thus focusing communication and ensuring real-time delivery to the right stakeholders.

With the setup complete, the video capture process begins, continuously recording road conditions as input for pothole detection. Each video frame is extracted and analyzed in real-time to monitor road conditions and identify any irregularities continuously. Once a frame is captured, the system employs the Haar Cascade classifier, a machine learning algorithm for object detection. The classifier examines each frame for features that resemble potholes, such as edges, textures, and shapes, identifying the presence of potholes in the frame. The classifier is calibrated to reduce both false positives and negatives, achieving accurate detection. When the system identifies a pothole, the NodeMCU triggers a message via the MQTT broker. The broker then posts this message to the specific MQTT topic, enabling any connected clients, such as road maintenance authorities, to receive real-time alerts. This timely communication ensures that road conditions receive prompt attention.

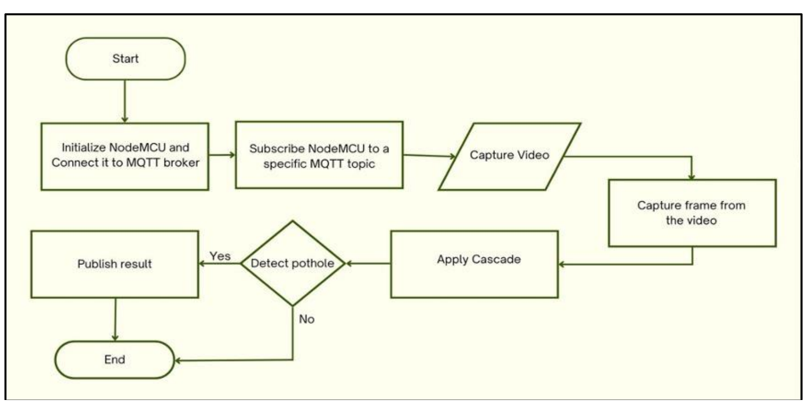

Figure 2: Operational Steps of Pothole Detection Flowchart

5. Results and Discussion

This section presents the results of the detection process, detailing the accuracy and performance of the Haar Cascade algorithm in identifying potholes, as well as the configuration of the NodeMCU with MQTT for reliable data transmission. As depicted in Figure 3, several potholes on a rural road are clearly marked with bounding boxes, showcasing the system's ability to accurately identify and localize these road defects. The bounding boxes serve as visual indicators of the algorithm's detection, confirming its effectiveness in analyzing video footage and pinpointing areas of concern.

This figure demonstrates the system's real-time detection capabilities, highlighting its practical use in monitoring road conditions and identifying potential hazards. By accurately marking potholes, the system offers a reliable solution for early detection, which can inform prompt road maintenance and repair efforts. The bounding boxes not only confirm the system's detection performance but also emphasize its ability to analyze video data efficiently in diverse environments, such as rural roads where surface irregularities are common.

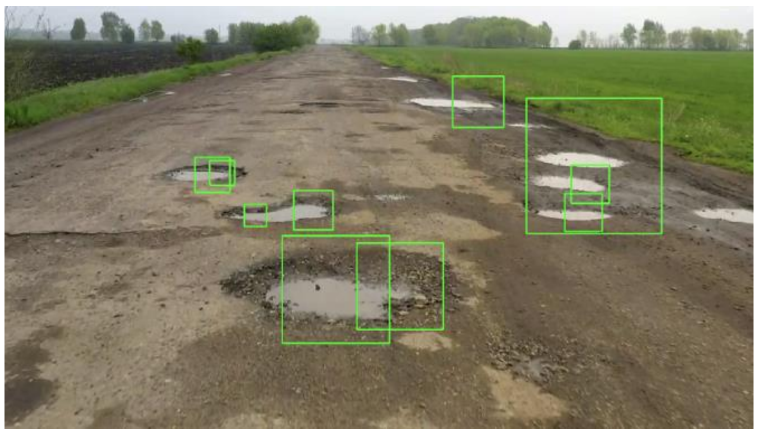

Figure 3: Pothole detection

The NodeMCU is successfully configured to use the MQTT protocol for data transmission. The process involves setting up the NodeMCU with appropriate sensors and programming it to publish messages to an MQTT broker. The system is tested in various environments to ensure reliable data transmission. Challenges such as network connectivity issues and power management are addressed by optimizing the NodeMCU settings and using a stable MQTT broker. Figures 4 through 7 illustrate how the detected pothole message can be seamlessly passed from NodeMCU, published by the MQTT broker, to the MQTT client. Figure 4 illustrates the connection between NodeMCU and a laptop, utilizing a Type-C cable.

Figure 4: NodeMCU connected to laptop

When a pothole is detected, it triggers a message “pothole detected”. In the video, six potholes are detected, and it sends six corresponding messages. As shown in the output terminal of Figure 5 there are six messages saying that “pothole detected, message sent to MQTT broker”.

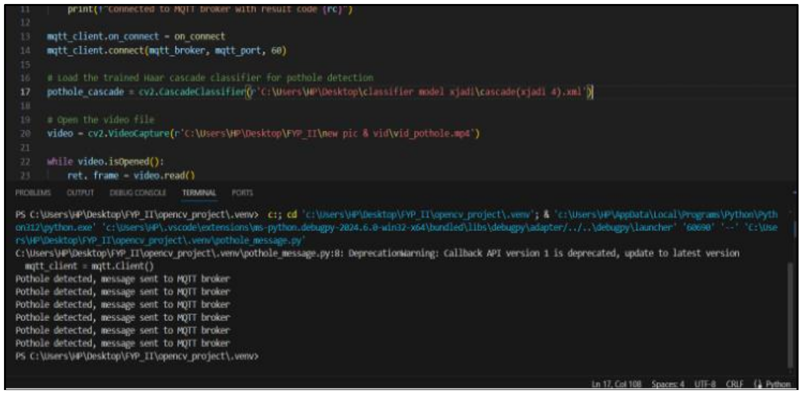

Figure 5: The outputs in the terminal

Arduino is the software used for uploading code to the NodeMCU. In the Serial Monitor of the Arduino, as shown in Figure 6, messages under the topic road/quality have successfully arrived.

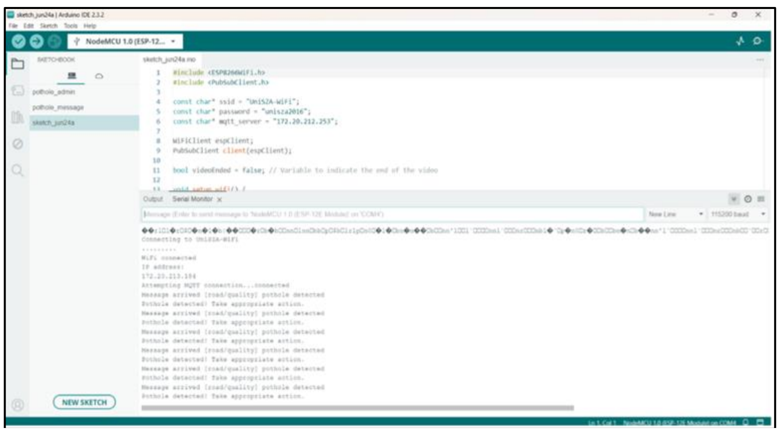

Figure 6: The Serial Monitor messages

MQTT Explorer is a graphical interface for managing and monitoring communication between MQTT clients and the broker. Figure 7 shows that six messages have arrived under the topics’ road’ or ‘quality’.

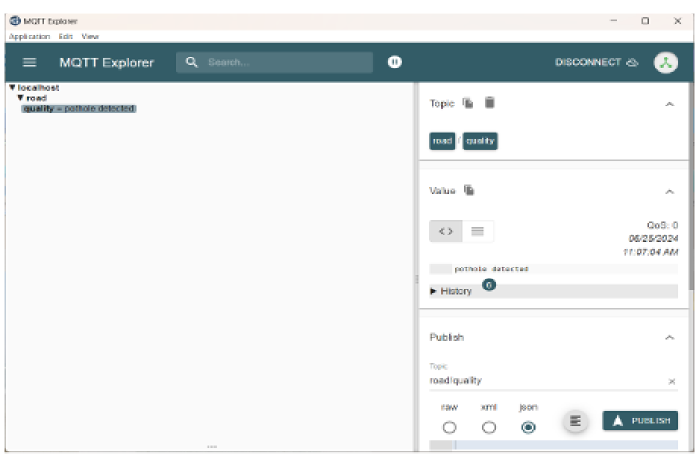

Figure 7: The MQTT client receives six messages

The proposed system for pothole detection encountered challenges, particularly with false positives and negatives in the detection process and network connectivity issues with MQTT. The Haar Cascade algorithm sometimes misidentified shadows or debris as potholes, leading to detection inaccuracies. Network issues were addressed by optimizing the NodeMCU and using a more reliable MQTT broker to ensure stable communication. However, these challenges highlighted the need for more sophisticated detection methods and improved communication stability.

To enhance the system, future improvements could involve integrating advanced algorithms such as YOLO or deep learning-based methods to significantly reduce false positives and improve detection accuracy in complex environments. Expanding the system's hardware capabilities and coverage, along with implementing data encryption and exploring alternative communication protocols, would further boost performance and security, especially for large-scale implementations. As the system scales, incorporating solutions such as message queuing or load balancing may also be necessary to manage increased traffic efficiently and minimize delays.

Additionally, relying on continuous video capture and central processing poses a challenge for scalability. Incorporating edge computing to offload some processing tasks to the NodeMCU could reduce communication overhead and enhance efficiency. Overall, the system provides a solid foundation but would benefit from further enhancements in machine learning, scalability, and hardware optimization to ensure more accurate and reliable road quality monitoring in large urban areas.

6. CONCLUSION

This work effectively demonstrates how integrating NodeMCU with the MQTT protocol and Haar Cascade detection can enhance pothole detection and road monitoring. The system's ability to accurately identify potholes in video footage and send notifications to relevant authorities represents a significant advancement in road maintenance technology. This approach not only enhances the efficiency and precision of road condition assessments but also provides a cost-effective solution for continuous monitoring, potentially reducing road hazards and improving transportation safety. Although challenges such as false positives in detection and occasional network connectivity issues were encountered, the project highlights the potential for further advancements. Future work could focus on implementing more sophisticated detection algorithms and extending the system's reach to monitor larger road networks. By addressing these aspects, the system could become an increasingly reliable tool for maintaining road infrastructure, ultimately.

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An AI-generated application was utilized in writing this paper. This tool was used to enhance sentence fluency and improve readability.

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