Infact: Computer International Journal (ICIJ)
Vol.10, No.02, Agustus 2026
p-ISSN : 2527-8363, e-ISSN: 2829-0259
DOI:

Development of an IoT-Based Pothole Detection and Geolocation System Using ESP32-S3 and YOLOv8

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Submitted: 06/01/2026, Revision: 08/12/2026, Accepted : 08/15/2026

Abstract

Potholes are one of the most common forms of road damage that threaten transportation safety and reduce driving comfort. This study presents the development of an Internet of Things (IoT)-based pothole detection and geolocation system integrating an ESP32-S3 camera module, a GY-NEO8MV2 GPS receiver, battery voltage monitoring, and a cloud-based YOLOv8 object detection model. The proposed system automatically captures road images, records geographic coordinates, transmits data to a cloud server, and visualizes detection results through a monitoring dashboard. The YOLOv8 model was trained for 50 epochs and achieved a precision of 73.0%, recall of 71.2%, mAP@0.5 of 77.3%, and mAP@0.5:0.95 of 50.8% for pothole detection. Hardware evaluation showed reliable operation, with battery voltage measurement producing a relative error of 1.46% compared with a digital multimeter, while the GPS module maintained stable positioning with 12 connected satellites and an HDOP value of 0.65. Field experiments confirmed that the proposed system successfully detected potholes while simultaneously recording their geographic coordinates for visualization on a monitoring dashboard. These results demonstrate that the proposed IoT architecture is suitable for automated pothole monitoring and geospatial road condition reporting.

Keywords:
Potholes;
Object Detection;
YOLOv8;
GPS;
ESP32-S3;

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1. Introduction

Road infrastructure plays a crucial role in supporting economic activities, transportation systems, and regional development. However, road damage remains a significant national issue in Indonesia, including in Pontianak City. According to data from Badan Pusat Statistik (BPS), the total road length in Pontianak in 2020 reached 286.08 km, consisting of 200.46 km in good condition, 49.97 km in moderate condition, 19.93 km with minor damage, and 15.72 km with severe damage. These statistics indicate that a considerable portion of road infrastructure still experiences deterioration that can disrupt mobility and logistics distribution [1]. Moreover, damaged roads contribute significantly to traffic accidents, particularly in areas outside major urban centers [2], [3].

The Indonesian government has implemented various initiatives to improve road quality through routine and periodic maintenance programs [4], [5]. Nevertheless, major challenges remain in monitoring and inspection processes, which are still largely conducted using conventional methods [6], [7]. Manual inspection and survey-based assessments often result in slow data acquisition and inconsistent evaluations due to human subjectivity [8], [9]. Previous studies have reported that manual road condition surveys tend to be inefficient and lack systematic data collection mechanisms, limiting the accuracy of road damage information and delaying maintenance decision-making.

Several technological approaches have been introduced to improve road infrastructure monitoring. Systems such as Sistem Informasi Jalan dan Jembatan Indonesia (SIJJI) and other Geographic Information System (GIS)-based applications have been utilized for infrastructure management [10], [11]. Additionally, community reporting platforms such as Lapor! and Qlue allow citizens to report road damage incidents. However, these platforms generally rely on manual user reports and lack automated classification systems based on artificial intelligence [12]. As a result, many reports cannot be processed efficiently or prioritized according to the severity of road damage.

Recent advancements in computer vision and deep learning have introduced more effective solutions for automatic road damage detection. One widely used approach is the You Only Look Once (YOLO) algorithm, which enables real-time object detection using a single-pass neural network architecture [13]. Compared to earlier detection models such as Region-based Convolutional Neural Network (R-CNN) and Fast R-CNN, YOLO offers significantly faster processing speeds while maintaining high detection accuracy [14]. This capability makes it highly suitable for real-time monitoring applications in dynamic environments such as road surveillance.

Previous studies have demonstrated the effectiveness of YOLO-based systems in detecting road damage. Pramestya developed a YOLO-based digital image processing system for asphalt damage detection and achieved a classification accuracy of 99.25% with an average bounding box detection accuracy of 74.57% [15]. Similarly, a study employing YOLOv5 for pothole detection achieved a training precision of 96.6% [16]. Furthermore, Sucipto et al. developed a real-time pothole detection system using the ESP32-S3 Sense module integrated with YOLOv8, achieving an F1-score of 0.73 with an inference time of approximately 300–350 ms [17]. Despite these promising results, most existing systems still rely on external computers for processing or do not integrate spatial location information, limiting their practical implementation in autonomous field monitoring systems.

In addition to detection capability, integrating geographic positioning information is essential for infrastructure monitoring. The use of GPS modules enables automatic recording of road damage locations, allowing authorities to prioritize maintenance based on spatial distribution. The integration of GPS with detection systems can support real-time reporting and improve decision-making processes in infrastructure management [18], [19].

Based on these challenges, this study aims to develop a portable IoT-based pothole detection and geolocation system using an ESP32-S3 microcontroller integrated with a GY-NEO8MV2 GPS module and a cloud-based YOLOv8 object detection model. The proposed system automatically captures road images, records geographic coordinates, and visualizes pothole locations through a web-based monitoring dashboard to support road inspection and maintenance activities.

The main contributions of this study are summarized as follows:

a. Development of a portable IoT-based pothole detection system using an ESP32-S3 microcontroller integrated with a camera module and GPS receiver.
b. Integration of cloud-based YOLOv8 object detection with automatic geolocation and battery monitoring to support mobile road inspection.
c. Implementation of a web-based monitoring dashboard for visualization of pothole locations and detection results.
d. Experimental evaluation of the proposed system through hardware testing and field deployment using object detection performance metrics and GPS positioning.

2. Methods

The proposed system consists of three main stages: data acquisition, cloud-based object detection, and visualization. An ESP32-S3 microcontroller equipped with a camera module continuously captures road surface images. Simultaneously, a GY-NEO8MV2 GPS module records the latitude and longitude of each captured image, while a voltage sensor monitors the battery condition. The acquired data are transmitted to a cloud server via HTTP POST, where a YOLOv8 model performs pothole detection. The detection results, together with the geographic coordinates, are stored in a cloud database and displayed through a web-based monitoring dashboard. [20].

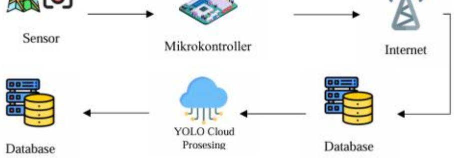

Fig. 1. Overall architecture of the proposed road damage detection system

The interaction between hardware components in the proposed system is presented in Figure 2. The system consists of several main components, including the ESP32-S3 microcontroller, camera module, GPS module, and a portable power supply unit. The camera module functions as the primary sensor to capture road surface images, while the GPS module provides spatial location information associated with the captured images. These components are controlled by the ESP32-S3 microcontroller, which processes the incoming data and prepares it for transmission. The system is powered by a lithium-ion battery configuration to support portable and autonomous operation during field deployment.

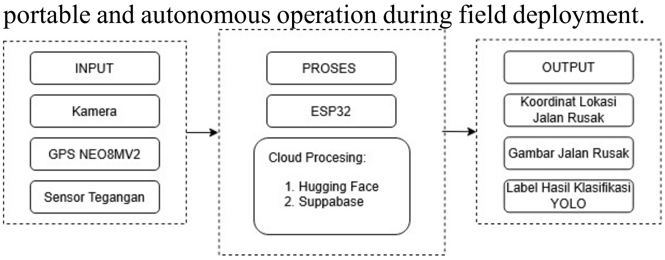

Fig. 2. Block diagram of the hardware components used in the system.

To ensure practical implementation in real-world conditions, the hardware components are integrated into a compact device prototype. The physical design of the proposed hardware system is shown in Figure 3, which illustrates the arrangement of the microcontroller, GPS module, power supply, and other supporting components within a protective casing. This design allows the device to be deployed in mobile scenarios, such as being mounted on a vehicle or carried for road monitoring activities. The compact structure also helps protect the internal electronic components from environmental disturbances while maintaining stable system operation.

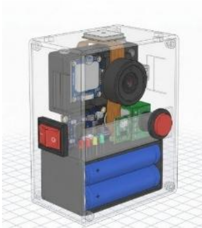

Fig. 3. Prototype design of the road damage detection hardware device.

During system operation, the camera continuously captures images of the road surface. Each captured image is compressed into JPEG format and combined with metadata such as GPS coordinates, timestamp, and battery status to form a single data payload. The payload is then transmitted to a cloud server using the HTTP POST protocol through an internet connection. Once the data are received by the server, the images are processed using the You Only Look Once (YOLO) deep learning algorithm deployed on a cloud computing platform. The YOLO model performs object detection and classification in a single inference process by analyzing visual patterns on the road surface. When road damage is detected, the system generates output consisting of bounding box coordinates, classification labels, and confidence scores that indicate the reliability of the prediction.

The detection results together with the associated metadata are stored in a cloud-based database to enable structured recording of road damage information. This stored data can later be accessed through a monitoring dashboard that visualizes the location and classification of detected road damage. By combining image-based detection with GPS location data, the system enables spatial monitoring of road conditions and supports more efficient infrastructure maintenance planning.

The operational workflow of the proposed system is illustrated in Figure 4. The process begins with system initialization, where all hardware components including the camera and GPS module are activated. The camera then captures images of the road surface while the GPS module records the corresponding geographic coordinates. The captured data are transmitted to the cloud server for processing using the YOLO detection model. If road damage is identified, the classification results and location information are stored in the database and displayed through the monitoring dashboard. This process is repeated continuously, enabling real-time monitoring and automated documentation of road damage conditions.

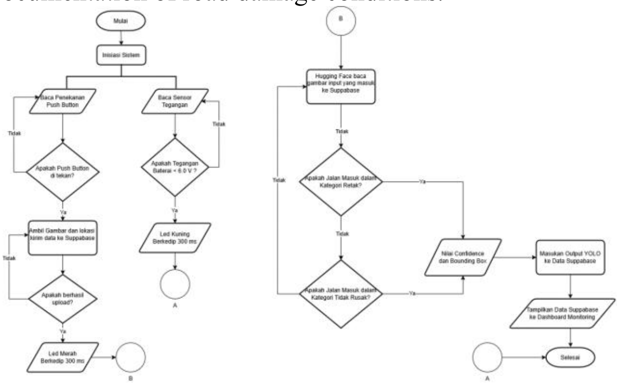

Fig. 4. Operational workflow of the proposed detection system.

3. Results and Discussion

This section presents the experimental results and analysis of the proposed road damage detection system. The evaluation includes hardware implementation, cloud-based detection performance, monitoring system visualization, and functional testing of system components.

The hardware prototype developed in this study integrates a camera module, GPS module, power supply system, and microcontroller into a single portable device. The implementation of the hardware system is illustrated in Figure 5, which shows the assembled device used to capture road images and transmit data to the cloud server. The system operates using the ESP32-S3 Sense as the main controller, which manages image acquisition and communication with external modules.

Fig. 5 Prototype Hardware System

The road damage detection process is performed using a cloud-based inference system utilizing the You Only Look Once (YOLOv8) algorithm deployed on a cloud computing platform. The captured images are transmitted to the server using an HTTP-based communication protocol, where the detection model performs object recognition and classification. The detection output generated by the cloud model is shown in Fig. 6, which illustrates the identification of road damage objects with bounding boxes and classification labels. The model produces prediction outputs including damage labels, confidence scores, and bounding box coordinates. The average inference time observed during testing ranged between 3–4 seconds, depending on image size and network conditions.

Fig. 6 YOLO Detection Output

The detection results are then automatically transmitted to a cloud database system, enabling real-time monitoring and visualization. A monitoring dashboard was developed to display the collected information in an accessible format for users. The dashboard interface is presented in Figure 7, which shows the main monitoring page containing key information such as damage classification results, GPS coordinates, and captured images from the detection system. This interface enables users to monitor road conditions and review detected damage events efficiently.

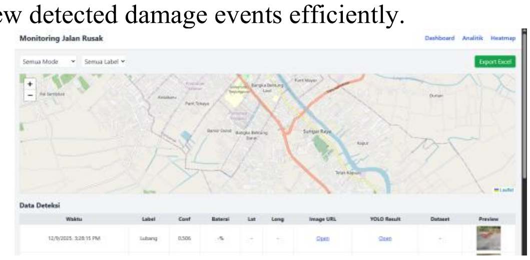

Fig. 7 Monitoring Dashboard Interface

To enhance spatial monitoring capabilities, the dashboard provides a geographic visualization feature that displays detected damage locations on an interactive map, as shown in Figure 8. Each marker on the map represents a detected road damage location based on the recorded GPS coordinates. This visualization allows users to identify damaged road areas and evaluate spatial patterns of infrastructure conditions.

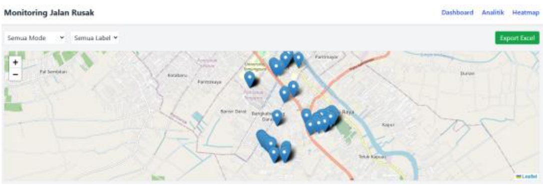

Fig. 8 Map Visualization of Detected Damage

In addition to spatial visualization, the system also includes an analytics module that summarizes the distribution of detected road damage categories. The analytical results are presented in graphical form, as shown in Figure 9, which provides an overview of the number and classification of detected road damage cases. This feature supports decision-making processes related to infrastructure maintenance by providing statistical insights into road condition patterns.

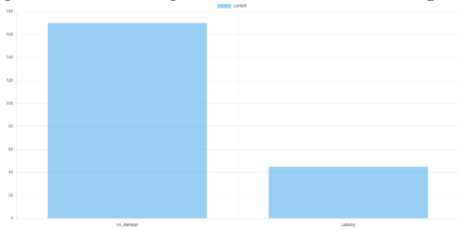
Fig. 9 Damage Classification Analytics

Furthermore, the dashboard includes a heatmap visualization feature that highlights the density of road damage occurrences across monitored regions. The heatmap representation, shown in Figure 10, provides an intuitive overview of areas with higher concentrations of detected road damage. Such visualization can assist authorities in identifying priority locations for maintenance and repair activities.

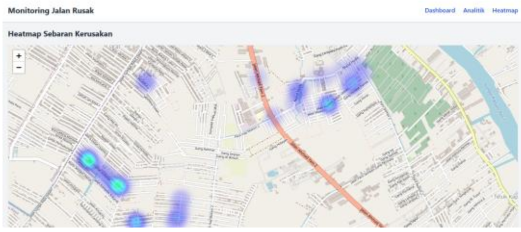

Fig. 10 Road Damage Density Heatmap

Several hardware components were also tested to evaluate system reliability. The camera module was configured with a 20 MHz clock frequency to ensure stable image acquisition. Images were captured in JPEG format with a resolution of 96 × 96 pixels to balance processing efficiency and detection requirements. The camera test results, shown in Fig. 11, demonstrate that the image capture process operates consistently under the configured system parameters.


Fig. 11 Camera Testing Result

The voltage monitoring subsystem was evaluated to verify the accuracy of the battery measurement circuit.The battery voltage was measured using a digital multimeter as a reference a 7.55 V. Subsequently the voltage sensor output was acquired through the microcontroller's analog-to-digital converter (ADC), a digital value used to estimate the battery voltage.

The comparison between the reference measurement and the calculated sensor output is presented in Figure 15. The sensor produced an estimated voltage of approximately 7.44 V, resulting in an absolute error of 0.11 V or a relative error of about 1.46%. These results indicate that the voltage sensor provides sufficiently accurate measurements for monitoring the battery condition during system operation.

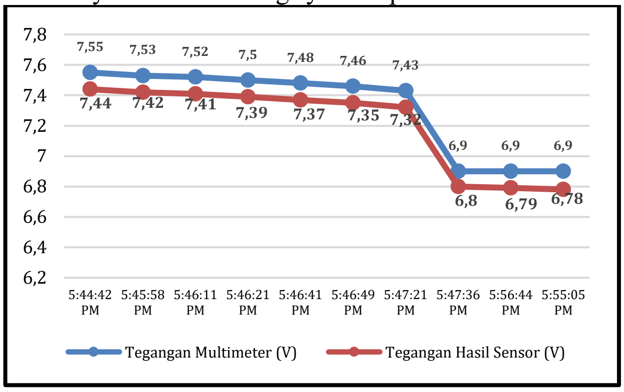

Fig. 13 ADC Sensor Voltage Measurement

Testing of the GPS module demonstrated reliable performance in determining the geographic location of the device. The test results presented in Figure 16 show that the GPS module successfully obtained valid latitude and longitude coordinates. During testing, the module was able to receive signals from multiple satellites, achieving stable positioning with a Horizontal Dilution of Precision (HDOP) value of approximately 0.65, indicating high positional accuracy.

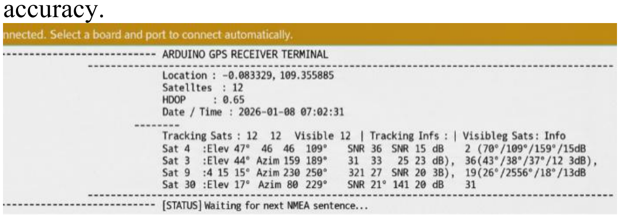

Fig. 16 GPS Module Testing Result

Finally, the performance of the road damage detection system was evaluated using field testing at several locations in Sungai Raya, West Kalimantan. The results of the detection experiments are summarized in Table 3, which presents the detected geographic coordinates, classification labels, and confidence scores generated by the YOLO model. The detected objects were primarily classified as potholes, with confidence values ranging between 0.33 and 0.70 depending on image conditions and object visibility. These results demonstrate that the proposed system is capable of detecting road damage objects and recording their geographic locations simultaneously.

Table 1. Road Damage Detection System Testing

No	Lintang, Bujur	Location	Label	Confidence YOLO	Output
1	−0.083567, 109.3788	Sungai Raya, Kabupaten Kubu Raya, Kalimantan Barat	Pothole	0.4 0.37 0.33	
2	−0.096436, 109.3596	Sungai Raya, Kabupaten Kubu Raya, Kalimantan Barat	Pothole	0.7	
3	−0.094557, 109.3536	Sungai Raya, Kabupaten Kubu Raya, Kalimantan Barat	Pothole	0.66	
4	−0.094493, 109.3520	Sungai Raya, Kabupaten Kubu Raya, Kalimantan Barat	Pothole	0.4 0.69	

Overall, the experimental results show that the integration of IoT-based image acquisition with cloud-based deep learning detection enables an effective system for automated road damage monitoring. The system successfully performs image capture, location tracking, object detection, and data visualization in an integrated framework, supporting real-time monitoring of road infrastructure conditions.

4. Conclusions

This study presented the design and implementation of an IoT-based road damage detection and monitoring system integrating the ESP32-S3 Sense platform with a cloud-based object detection model using You Only Look Once (YOLOv8). The experimental results demonstrate that the proposed system successfully performs integrated data acquisition, including image capture, battery voltage monitoring, GPS positioning, and data transmission to a cloud server for detection processing. The camera module operating in JPEG format with a resolution of 480 × 640 pixels was able to produce images suitable for the detection model, achieving confidence scores of up to 0.698 for pothole detection. Hardware testing also showed reliable subsystem performance, where the voltage monitoring circuit produced measurements with an average error of approximately 1.45–1.74% compared to multimeter readings, while the GPS module achieved stable positioning with 12 satellites and a Horizontal Dilution of Precision (HDOP) value of 0.65. Field experiments further confirmed that the system is capable of detecting pothole objects with confidence values ranging from 0.30 to 0.70, with cloud-based inference representing the dominant component of the overall processing time. These results indicate that the proposed architecture is feasible for automated road condition monitoring using IoT and deep learning technologies. Future research may focus on expanding the detection classes to include additional types of road damage, improving detection accuracy through higher-resolution imaging and larger training datasets, enhancing localization accuracy through advanced positioning techniques, and developing more comprehensive monitoring interfaces to support practical deployment in intelligent transportation infrastructure systems.

Acknowledgments

The author would like to express sincere gratitude to all parties who contributed to the completion of this research. Special appreciation is extended to the author's beloved parents, for their continuous prayers, love, encouragement, and moral support throughout the completion of this study.

The author is also deeply grateful to Mariana Syamsudin, Ph.D., and Medi Yuwono Tharam, S.T., M.T., as research supervisors for their valuable guidance, constructive suggestions, and continuous support throughout the research process.

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