Revolutionizing Road Maintenance: A Data Fusion and AI-Based Approach

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ABSTRACT

The deterioration of pavement conditions over time can lead to significant costs for rehabilitation once the pavement conditions fall below a certain level of deterioration. To mitigate these costs, it is possible to extend the service life of pavement through periodic maintenance at a relatively low cost. To increase the frequency of inspections and enhance the effectiveness of maintenance activities, this study proposes a crowdsourcing-based inspection system for autonomous road condition assessment that can be mounted on multiple vehicles. The proposed inspection system can evaluate the pavement condition based on the Pavement Surface and Evaluation Rating (PASER) system. Vehicles equipped with this data acquisition system are driven over the road through the cities twice per week, thus comprehensive RGB-D data of the road surface are collected timely and widely. The system can detect various defects, including transverse cracks, longitudinal cracks, alligator cracking, and 3D defects such as rutting and potholes through a trained deep learning-based classification model. Furthermore, the proposed autonomous road inspection system can monitor the evolutionary changes of defects such as cracks and potholes to enable damage prognosis.

INTRODUCTION

Over 40% of roads are in poor or mediocre conditions in the United States according to the latest ASCE report card released in 2021 [1]. This low-grade pavement condition costs a huge amount of money for repair. Conversely, the pavement can be rehabilitated

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with a small amount of money if it receives periodical maintenance at the early stage of the deterioration with frequent inspections. Therefore, road condition assessment is a crucial task for ensuring the functionality of transportation infrastructure. It is essential to monitor the deterioration of the pavement systemically and frequently. In general, the most common approach is to send trained raters to the field to inspect and evaluate the road condition. However, this manual-based inspection is time-consuming and dangerous [2]. To have effective and more accurate surveys as well as ensure the safety of survey crews, several automatic data acquisition vehicles are adopted by the Department of Transportation all over the country. For example, Autonomous Road Analyzer Vehicle (ARAN) is a high-speed and multi-functional vehicle equipped with a precise survey system to measure pavement conditions and collect data. However, the major disadvantage of this type of automated vehicle is the expensive equipment cost.

Various methods have been developed to assess road conditions effectively, including the use of different sensors. Therefore, a few studies have attempted to develop various automated pavement condition assessment methods using affordable sensors. Vibration-based data has been widely employed in several studies for pavement condition rating and ride quality evaluation, leveraging sensors such as accelerometers and gyroscopes to measure the motion and rotation of the vehicles. Souza proposed a simple and low-cost approach for asphalt pavement evaluation using the three-axis acceleration data obtained from the smartphone [3]. This approach incorporates the utilization of accelerometers and gyroscopes to effectively measure the motion and rotation of vehicles, enabling the accurate evaluation of pavement conditions and the assessment of ride quality. However, the disadvantage of this approach is noisy data. Moreover, it only considers the conditions at the wheel path. In recent years, vision-based data has emerged as an alternative and complementary approach to road condition assessments. Several studies have been conducted, applying different methodologies such as deep learning. Majidifard et al proposed a new asphalt pavement condition index using a deep learning-based approach [4]. The authors collected pavement data from Google Street View and developed a deep-learning framework for pavement condition rating. However, the road condition from Google Street View may be outdated and cannot reflect the immediate road conditions. Guan et al. proposed an approach for automated pavement distress detection using stereo vision and deep learning [5]. The authors developed a stereo vision system that captures images of pavement surfaces from three cameras and implemented a 3D reconstruction of the pavement surface. Then, a deep learning convolutional neural network (DCNN) was applied to detect and quantify pavement distress, including cracks and potholes. However, the performance of the proposed system can be compromised due to the quality of the RGB images such as poor illumination conditions. Mahlberg et al proposed a novel approach for pavement quality evaluation using connected vehicle data [6]. A data acquisition system composed of connected vehicles equipped with multiple sensors such as an accelerometer, GPS system, and LiDAR to estimate pavement roughness, which is a key indicator of pavement quality. However, the major disadvantage of this type of connected vehicle is the expensive equipment cost.

The present research endeavors to design an autonomous end-to-end system for evaluating and rating pavement surface conditions using cost-effective RGB-D sensors. The Pavement Surface Evaluation and Rating (PASER) technique is a widely recognized approach for assessing road conditions, which traditionally involves visual inspection conducted by trained personnel [7]. The proposed methodology incorporates the outcomes of trained Deep Convolutional Neural Networks (DCNNs) and Global Positioning System (GPS) coordinates to automate the assignment of PASER scores to individual road segments. In addition, the developed data acquisition system is amenable to being installed on multiple vehicles, enabling the collection of RGB-D road surface data and offering the potential for crowd-sourced and Internet of Things (IoT) data generation.

DATA COLLECTION AND PREPARATION

Recently, there has been an increasing interest in utilizing depth data. RGB and Depth data can complement each other to enhance the performance of segmentation. The aim of this paper is to evaluate the road conditions using RGB and depth data. The data can be categorized into 2D color images and 3D spatial depth data. To enhance the autonomy of road condition assessment, an autonomous system for road condition assessment using consumer-grade RGB-D sensors that can be mounted on various vehicles is developed. The developed data acquisition system is composed of two RGB-D sensors that can capture the 3D information of the complete lane width. Figure 1 displays the developed data acquisition system. Two RGB-D sensors are connected to a power-efficient NVIDIA Jetson TX2 edge computing device. In addition, a GPS sensor is connected for temporal and spatial frame registration. Robotic Operating System (ROS) [8] which is an open-source freeware that facilitates the programming of robots for inter-process communication is used to interconnect the hardware components and provide an interface for top-down control in the system. Vehicles equipped with this data acquisition system are routinely driven over roads at speeds of 30-40 mph in the city to collect RGB-D pavement surface data. The resolution of the collected RGB and depth image is 640×480 pixels. A portable 1-TB USB SSD device is used to archive a high volume of images. RGB and depth images are stored in JPEG and PNG format, respectively. The trajectory of each vehicle and the corresponding coordinate from the global positioning system (GPS) is recorded.

Figure 1. Data collection system configuration. The proposed data acquisition system includes two RGB-D sensors, one edge computing device, and a GPS sensor. All sensors are integrated through Robotic Operating System. The system can be easily mounted on a bike rack at the trunk.

ROAD DEFECTS IDENTIFICATION AND CLASSIFICATION

The Pavement Surface and Evaluation Rating (PASER) system is a widely used visual-based inspection system for assessing the condition of pavement on a scale of 1 to 10, where a score of 1 represents the worst condition, and 10 represents the best condition. In the present study, an autonomous end-to-end rating approach is proposed to assign the PASER score for each road segment using several neural networks for defect classification and segmentation. Initially, a convolutional neural network is trained for defect classification to assign PASER scores for different pavement conditions. As depicted in Figure 2, pavement surface data can be categorized into 8 different types of distresses, including healthy surface, open joint, manhole, crack sealant, transverse crack, longitudinal crack, alligator crack, and pothole, based on the PASER guidelines. The network was trained for 30 epochs using the Adaptive Moment Estimation (Adam) optimizer with a learning rate of 0.0001 and a batch size of 16. The trainable parameters were fine-tuned from a pre-trained ResNet152 network [9], which was previously trained on the ImageNet dataset [10].

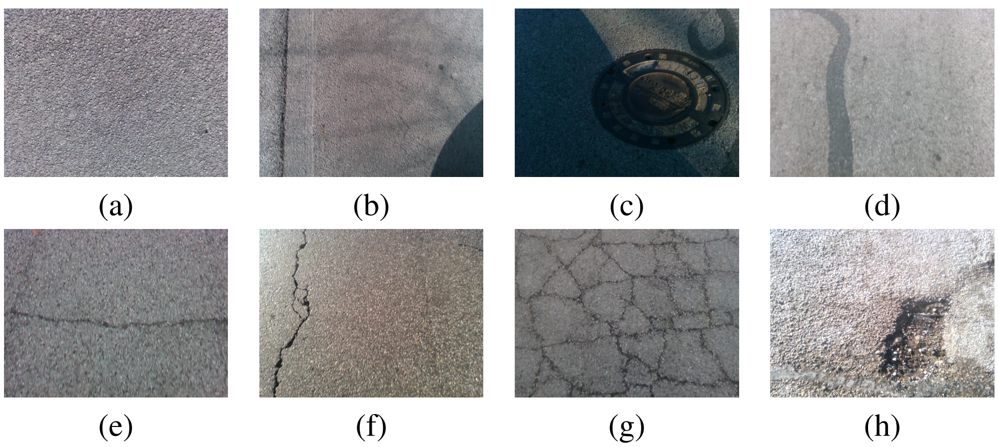

Figure 2. Sample images of each class: (a) Healthy, (b) Open joint, (c) Manhole, (d) Sealant, (e) Transverse crack, (f) Longitudinal crack, (g) Alligator cracking, and (h) Pothole.

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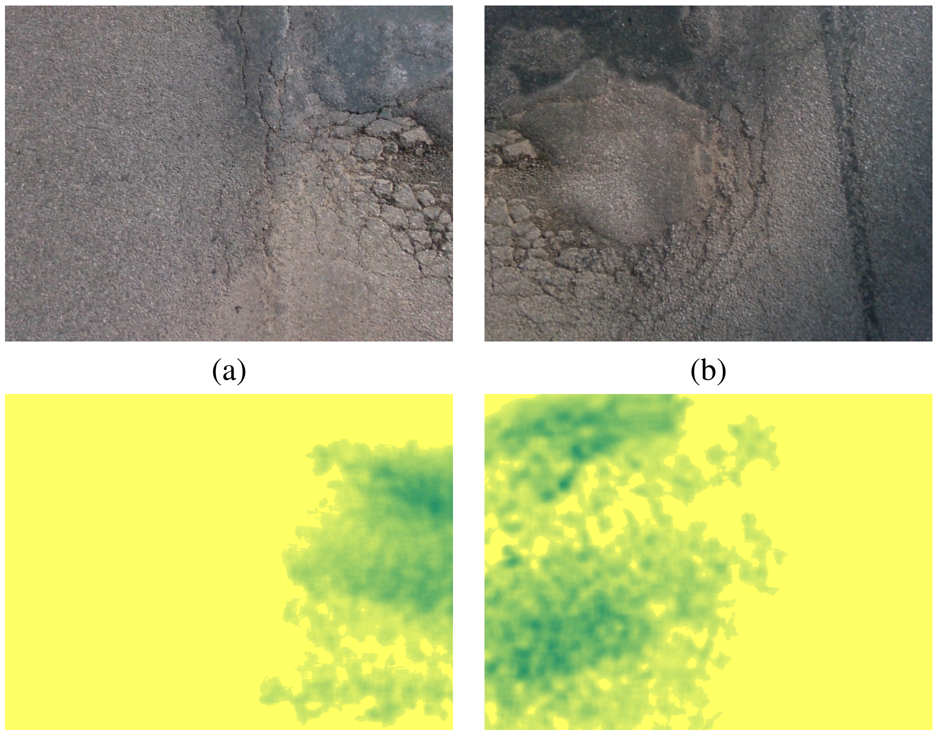
With the classification results, an autonomous end-to-end rating approach is developed to assign the PASER score for each road segment. Following the classification of pavement surface data, the proposed system adheres to the Asphalt PASER standard to assign a score. To improve the reliability of the rating, the depth data is also incorporated into the end-to-end system. As illustrated in Figure 3(a) and (b), the trained network classifies the RGB images as exhibiting alligator cracking, while neglecting the depth information. Nonetheless, upon inspection of the depth data, these defects are found to be severe rutting which is shown in Figure 3(c) and (d). This example highlights the complementary role of 3D information in conjunction with 2D color images for accurately assessing road conditions. As shown in Figure 4, the final PASER score from the proposed end-to-end system is displayed on the map through different colors, where red signifies the poor condition, blue denotes fair condition, and green designates the good condition. Moreover, as shown in Figure 5, the developed data acquisition system allows monitoring of the progression of defect deterioration. It is shown that the area of the defect has been expanded through RGB images and the depth of the defect also increased shown in the depth image.



(a) (b)

(c) (d)

Figure 3. Example images of rutting: (a) RGB image from the right camera, (b) RGB image from the left camera, (c) The corresponding depth image of the right RGB image, and (d) The corresponding depth image of the left RGB image.

Figure 4. An example of data collection route. The color of the path corresponds to distinct conditions of the PASER, where red signifies the poor condition, blue denotes the fair condition, and green designates the good condition. The total length of this route amounts to 1.4 miles.

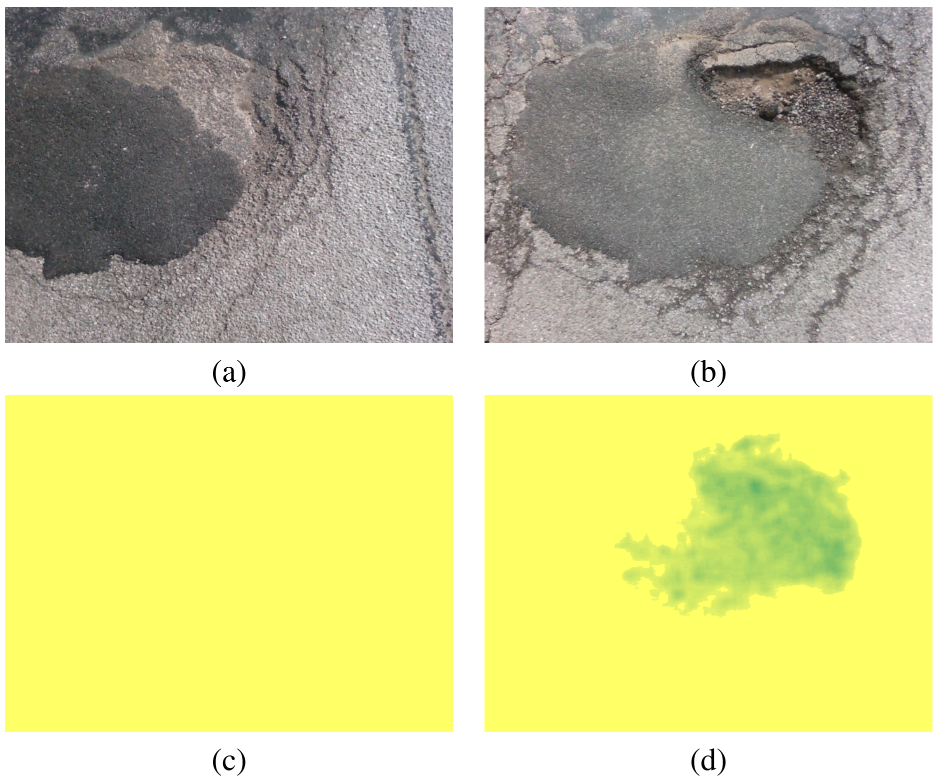


Figure 5. Sample RGB-D images collected at different dates show the deterioration of a pavement defect within a few days. (a) RGB image collected on February 26, (b) RGB image collected on March 5, (c) Depth image collected on February 26, and (d) Depth image collected on March 5.

CONCLUSIONS

To enhance the efficiency of pavement inspection and extend the service life of the pavements, proposes an autonomous end-to-end system for evaluating and rating pavement surface conditions using cost-effective RGB-D sensors. The system incorporates trained neural networks and GPS coordinates to automate the assignment of PASER scores to individual road segments. In addition to the PASER score assignment, depth data of the pavement defects would help to establish a further understanding of pavement deterioration evaluation through defects quantification. The proposed methodology has the potential for crowd-sourced and IoT data generation. Furthermore, the proposed system enables time-based tracking of defects to evaluate the rate of their deterioration. In the future, the proposed solution can be scaled up where it is applied to a large number of roads and multiple vehicles to form a dense mobile sensor network to obtain IoT-generated data for crowdsourcing. With this system, decision-makers will have more frequent updates about the condition of a section of the road, which will lead to more informed decision-making regarding inspection optimization, maintenance prioritization, estimation of remaining useful life, etc.

REFERENCES

1. ASCE. 2021. "2021 infrastructure report card–A comprehensive assessment of America's infrastructure," .
2. Attoh-Okine, N. and O. Adarkwa. 2013. "Pavement Condition Surveys – Overview of Current Practices," Report, Delaware Center for Transportation.
3. Souza, V. M. 2018. "Asphalt pavement classification using smartphone accelerometer and Complexity Invariant Distance," *Engineering Applications of Artificial Intelligence*, 74:198–211, ISSN 0952-1976, doi:https://doi.org/10.1016/j.engappai.2018.06.003.
4. Majidifard, H., Y. Adu-Gyamfi, and W. G. Buttlar. 2020. "Deep machine learning approach to develop a new asphalt pavement condition index," *Construction and building materials*, 247:118513.
5. Guan, J., X. Yang, L. Ding, X. Cheng, V. C. Lee, and C. Jin. 2021. "Automated pixel-level pavement distress detection based on stereo vision and deep learning," *Automation in Construction*, 129:103788.
6. Mahlberg, J. A., H. Li, B. Zachrisson, D. K. Leslie, and D. M. Bullock. 2022. "Pavement Quality Evaluation Using Connected Vehicle Data," *Sensors*, 22(23):9109.
7. Walker, D., L. Entine, and S. Kummer. 2002. "Pavement surface evaluation and rating. Asphalt PASER manual," *Transportation Information Center, University of Wisconsin–Madison, US*.
8. Quigley, M., K. Conley, B. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, A. Y. Ng, et al. 2009. "ROS: an open-source Robot Operating System," in *ICRA workshop on open source software*, Kobe, Japan, vol. 3, p. 5.
9. He, K., X. Zhang, S. Ren, and J. Sun. 2016. "Deep residual learning for image recognition," in *Proceedings of the IEEE conference on computer vision and pattern recognition*, pp. 770–778.
10. Deng, J., W. Dong, R. Socher, L.-J. Li, K. Li, and L. Fei-Fei. 2009. "Imagenet: A large-scale hierarchical image database," in *2009 IEEE conference on computer vision and pattern recognition*, IEEE, pp. 248–255.