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Recognition, location, measurement, and 3D reconstruction of concealed cracks using convolutional neural networks

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HIGHLIGHTS

- Project presents an application of convolutional neural networks (CNN) in cracks.
- Different CNNs are established by the processes of structure design, training and testing.
- The crack feature points are extracted by feature extraction CNN to establish 3D model.
- CNN is able to recognize concealed cracks from other damage in GPR images with zero error.
- CNNs could be accurately used for the recognition, location of concealed crack of asphalt pavement.

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ABSTRACT

Concealed cracks in asphalt pavement are the cracks that originate below the surface of the pavement. These cracks are a major contributing factor to pavement damage, in addition to being a major contributing factor to the formation of reflection cracks. The detection of a concealed crack is considered challenging because the location of the crack is, by definition, difficult to find. Therefore, the research on the utilization of ground penetrating radar (GPR) to locate concealed cracks has gained significant interest in recent years. However, the manually processed GPR image used for the recognition, location, and measurement of concealed cracks is inefficient and inaccurate. This project presents an application of convolutional neural networks (CNNs) to GPR images that automatically recognizes, locates, measures, and produces a 3D reconstruction of concealed cracks. In this project, three different CNNs (recognition, location, and feature extraction) were established to accomplish the aforementioned tasks automatically. Each CNN is developed through processes of structural design, training, and testing. The recognition CNN was designed to distinguish concealed cracks from other types of damage in a GPR image, the location CNN determined the location and length measurement of concealed crack images based on the results provided by the recognition CNN, and crack feature points were extracted by the feature extraction CNN to establish the 3D reconstruction models of the concealed cracks. The 3D reconstruction models were then used to calculate crack volume and predict the growth tendency of cracks. The results indicated that the recognition CNN is able to distinguish concealed cracks from other types of damages in 6482 GPR images with zero errors. In addition, the length recognition results calculated from the location CNN possess a 0.2543 cm mean squared error, a 0.978 cm maximum length error, and a 0.504 cm average error in the test samples. Meanwhile, the feature extraction CNN is able to provide feature points for a 3D reconstruction model. The results of this study suggest that the CNNs could be accurately used for the recognition, location, and 3D reconstruction of concealed cracks in asphalt pavement in real-world applications.

1. Introduction

The semi-rigid base in an asphalt pavement structure is the most popular structure in Chinese highways because of its two main advantages: low investment cost and straightforward manufacturing process. Therefore, more than 950,000 km of highway were

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built using semi-rigid base in China until 2015, which perfectly meets the status of China's economic capability, which is that of a developing country. After decades of operation, a consensus has been reached in China, that the cracking of semi-rigid base structures is inevitable. Reflection cracks are the most common cracks in semi-rigid bases in China, and they always occur in either the semi-rigid base itself or in sub-bases before propagating to the surface. The formation of these cracks is the result of dry environments and temperature decrease in the semi-rigid bases and sub-bases. Reflection cracks can be visually observed, unlike concealed cracks. To prevent highway reflection cracks, it is necessary to detect them before they propagate to the surface. The cracks that occur in semi-rigid bases or sub-bases but have not yet transitioned into reflection cracks are called concealed cracks. Therefore, concealed cracks are the intermediate states of reflection cracks. If effective measures are taken to detect concealed cracks early, the formation of reflection cracks may be prevented. However, the detection of concealed cracks has proved to be very challenging, mostly because of their location below the pavement.

Ground penetrating radars (GPRs) have advantages such as high efficiency, safe operation, nondestructive operation, and high anti-interference [1–4], and therefore, are widely used in highway detection. In recent years, significant progress has been made in the utilization of GPRs for detecting concealed cracks in semi-rigid base and sub-base structures. However, there are several obvious disadvantages to this technology; namely, its dependency on other auxiliary instruments for damage recognition, complicated data preprocessing requirements, the difficulty in location automatically, and complicated 3D reconstruction operations [5–9]. Solla et al. [5] used GPR images to detect concealed cracks and successfully extracted their geometric features, but this method requires the assistance of infrared thermometers. In addition, Lu et al. [6] completed the recognition and location of concealed cracks in asphalt pavements, but the data preprocessing required to do so is complex. Xu et al. [7] successfully detected voids and cracks under the pavement using GPR, while the processes of category, location, and feature extraction of different types of damage all rely on artificial. Gracia et al. [8] analyzed GPR reflected waves to extract information on damage characteristics. Because different cracks have different specificities, the analysis workload is significant. Szymczyk et al. [9] used an S-transformation to successfully develop a three-dimensional reconstruction of GPR signals by using a complex conversion process. Obviously, these methods may not be able to automatically detect concealed cracks efficiently for their complex manual processes. Therefore, concealed crack detection should focus on the development of an automatic damage analysis system in GPR. The combination of GPR images and CNN may provide a potentially novel method for concealed crack detection.

The convolutional neural network (CNN) has advantages in the field of image recognition [10–13]. The CNN can be considered a type of highly nonlinear mapping that outputs the target features in a specified form based on the input image. The CNN is a type of artificial neural network whose structure of shared weights reduces the complexity of the network models, and the structure is similar to that of biological neural networks [14,15]. Images are used as the input data, which directly avoids the complex traditional recognition algorithm used in feature extraction and data reconstruction. The network structure has high invariance in the transformation of translation, scaling, tilting, and so on. This property can be used to analyze the complex shape changes of pavement cracks or voids [16–18]. Therefore, the introduction of CNN to the field of the concealed crack detection, combined with the use of GPR images instead of manual measurements, significantly improves the accuracy of the detection results and the efficiency of the detection processes. This is achieved without the use of high-performance hardware and personnel requirement, thereby reducing the associated costs.

In this research, attempts have been made to employ CNN to provide appropriate models for the automatic recognition, location, length measurement, and 3D reconstruction of concealed cracks in batches using GPR images of asphalt pavements. The technical outline of this study is organized as shown in Fig. 1. The preparation section presents the acquisition method of the GPR damage images. The experimental section details features of the proposed method, including the recognition CNN, the location and length CNN, and the feature extraction CNN. Then, the experimental results and discussions are presented.

2. Acquisition and preprocessing of GPR images

2.1. Collection device and method

A high-quality GPR image of a concealed crack is required to establish CNN models. However, the image quality is often influenced by the acquisition equipment and pavement structure. Therefore, the antenna type and frequency used should be selected according to the pavement structure to be examined. In this study, a LTD-2000 GPR (made in China) was adopted to capture images. The parameters of the LTD-2000 GPR include a 500 MHz shielding antenna (size: 30 cm × 30 cm × 14 cm), and a 20 cm transmitting-receiving antenna distance. The vertical and horizontal resolution ranges of the 500 MHz antenna were 0.15–0.27 cm and 3.0–5.2 cm, respectively, which were slightly influenced by the dielectric constants of the highway materials. The vertical resolution of the 500 MHz antenna could meet the engineering demands [19], but the horizontal resolution could not. Therefore, the widths of the concealed cracks could not be correctly reflected in the GPR images, and a revision should be made to calculate the actual values of the crack widths in the follow-up work for feature extraction.

The GPR image collection method also has an effect on image quality, especially the sharpness. The optimal collection method should utilize a reasonable detection point distance in order to guarantee high-quality images of damage. Therefore, the distances between checkpoints should be chosen based on the geometric features of the highway damage. Generally, the width of a concealed crack is less than 8 mm [20–22]. Based on the research of Lu et al. [6], a concealed crack can be detected by at least four echo signal records. Therefore, the checkpoint distances were selected to be 4 cm (L/5) apart in this research. A 4 cm (L/5) distance can guarantee that the GPR scans and records more than four echo signals from topmost point of the crack The scanning and recording of one echo signal is shown in Fig. 2. The antenna is activated to record an abnormal crack signal as its position is moved from location 1 to location 2. The distance between locations 1 and 2 was L/5. One effective concealed crack image included the four previously mentioned records. Then, denoising, wavelet analysis, and the detection results of GPR images were performed automatically by LTD-2000 systems based on the collected GPR data. Considering the influence of electromagnetic wave scattering and the origination point of the concealed cracks in the sub-bases, only the ranges from sub-bases to upper layers remained in the GPR images. This meets the requirements for highway detection [19]. In this method, the influence of all types of damage described previously were shown in the GPR images. The core sampling method shown in Fig. 3 was used to determine the types of disasters that occurred after GPR scanning.

2.2. GPR datasets

A typical GPR image of a concealed crack gathered using the above method is shown in Fig. 4a. The shape of the concealed crack