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Deep learning based image recognition for crack and leakage defects of metro shield tunnel

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ABSTRACT

The performance of traditional visual inspection by handcrafted features for crack and leakage defects of metro shield tunnel is hardly satisfactory nowadays because it is low-efficient to distinguish defects from some interference such as segmental joints, bolt holes, cables and manual marks. Based on deep learning (DL), this paper proposes a novel image recognition algorithm for semantic segmentation of crack and leakage defects of metro shield tunnel using hierarchies of features extracted by fully convolutional network (FCN). The defect images in training dataset and testing dataset are captured via a self-developed image acquisition equipment named Moving Tunnel Inspection (MTI-200a). After the establishment of image datasets, FCN models of crack and leakage are separately trained through several iterations of forward inference and backward learning. Semantic segmentation of defect images is implemented via the corresponding FCN models using two-stream algorithm, i.e. one stream is used to recognize the crack by sliding-window-assembling operation and the other is adopted for the leakage by resizing-interpolation operation. Compared with two frequently-used traditional methods, i.e. region growing algorithm (RGA) and adaptive thresholding algorithm (ATA), great superiority of the proposed method in terms of recognition results, inference time and error rates is shown based on four typical types of defect images which are crack-only image, leakage-only image, two-defect-nonoverlapping (TDN) image, two-defect-overlapping (TDO) image. The proposed method using DL can be employed to rapidly and accurately recognize defects for structure health monitoring and maintenance of metro shield tunnels.

1. Introduction

Metro shield tunnel is wildly used in urban underground railway transit system in the world. For the reason that lining structure of a tunnel usually suffers attacks from environmental actions, crack and leakage are commonly observed on the surface of shield tunnel lining (Yuan et al., 2013). To ensure the safety of such structure, periodic inspections have been conducted via non-destructive evaluation (NDE), especially vision-based methods (Haack et al., 1995; Richards, 1998; Asakura and Kojima, 2003; Delatte et al., 2003; Lee et al., 2013; Dawood et al., 2017; Wu et al., 2017). Traditional visual inspection of these defects is implemented by human inspectors walking along the surface of shield tunnel with their naked eyes. However, it is very time-consuming, tedious and even more labor intensive, which is really a challenge for tunnel operators. Furthermore, inspecting metro tunnels is usually carried out at midnight with limited time, e.g. a net 2 working hours (Ai et al., 2015; Huang et al., 2017a). During this severe working condition, manual recognition is prone to make mistakes inevitably. In view of this limitation, robot-based automatic visual inspection has been developed to reduce labor requirements and improve the safety of both inspectors and operating structures (Sasama, 1994; Haas et al., 1995; Ukai et al., 1996; Sasama et al., 1998; Ukai, 2000; Lee et al., 2007; Ukai, 2007; Gavilan et al., 2013; Montero et al., 2015; Lattanzi and Miller, 2017). In applying the robot-based automatic visual inspection technique, the current bottleneck problem is the recognition speed and accuracy, as most current algorithms of computer vision are constructed using handcrafted image features which are designed by experienced human engineers but are inevitably sensitive to some interference on metro tunnel lining, i.e. segmental joints, cables, brackets, manual marks and bolt holes (Sohn et al., 2005; Yu et al., 2007; Victores et al., 2011; Nishikawa et al., 2012; O'Byrne et al., 2013; O'Byrne et al., 2014; Zhang et al., 2014; Huang et al., 2017b; Yu et al., 2017; Zhang et al., 2018).

Recently, a novel powerful machine learning technique named deep learning (DL) has been proposed in the field of artificial intelligence (AI) in line with significant advancements on data acquisition and computational hardware, i.e. graphics processing units (GPUs) (Hinton and Salakhutdinov, 2006; LeCun et al., 2015). DL reveals intricate

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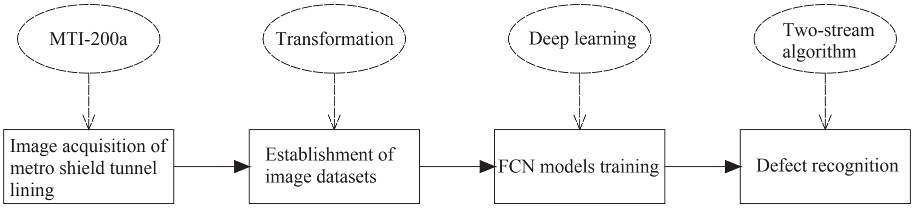

Fig. 1. Flowchart of the proposed method.

image features in large datasets by using the back-propagation algorithm to indicate how a model should change its internal parameters that are used to compute the representation in each layer from the representation in the previous layer. The key advantage of DL is that multiple layers of features are not designed by human engineers but through a general-purpose learning procedure. DL was selected as one of 10 breakthrough technologies by MIT technology review in 2013. Some famous DL frameworks like Caffe (Jia et al., 2014) and TensorFlow (Abadi et al., 2016) are developed to implement DL algorithms conveniently, which further promotes the progress of techniques in the field of DL powerfully. Convolutional neural network (CNN), a DL-based architecture with large learning capacity, has fewer connections and parameters and is easier to train compared to standard feed-forward neural networks with similarly-sized layers (Lecun et al., 1998; Krizhevsky et al., 2012; Gu et al., 2015; Schmidhuber, 2015). Interestingly, the DL technique has been adopted for the inspection and maintenance of civil infrastructure and proved to be a very effective method (Makantasis et al., 2015; Protopapadakis and Doulamis, 2015; Zhang et al., 2016; Cha et al., 2017; Xu et al., 2017). However, these methods using DL, especially CNN, are merely focused on image classification which is unable to locate defect boundaries effectively due to the coarse results.

In order to precisely separate defect regions from background regions, semantic segmentation of defect images is needed (Garcia-Garcia et al., 2017). Fully convolutional network (FCN), one specific CNN, is firstly proposed by Long et al. (2015) to conduct semantic segmentation of images. Compared to normal CNN, FCN can take input of arbitrary size and produce correspondingly-sized output with efficient inference and learning. FCN has been used to solve difficult problems in many areas and has achieved remarkable outcomes (Kruthiventi et al., 2017; Tarolli et al., 2017; Yuan et al., 2017). However, there are quite few researches on the application of FCN into semantic segmentation of defect regions in the field of civil engineering. As far as metro shield tunnel is concerned, it has to be noted that the defects such as crack and leakage are often physically related and can be observed close to each other on-site, which means regions of crack and leakage might be overlapped. Current researches have few attentions on this practical difficulty for the DL-based image recognitions.

In view of the above current limitations, a novel DL-based algorithm is proposed in this paper using FCN to implement semantic segmentation of crack and leakage more precisely from inner surface images of metro shield tunnel lining which are captured by a self-developed image acquisition equipment based on continuously scanning. In the proposed algorithm, crack model and leakage model are trained by FCN after several iterations of inference and learning, respectively. Semantic segmentations of crack and leakage are separately carried out via crack model and leakage model for the reason that the pixel attributes are conflicted when pixels belong to crack and leakage simultaneously. Metro shield tunnels have some kinds of interference such as segmental joints, bolt holes, cables and manual marks on the lining surface, which pose great challenges to carry out image recognition of lining defects. The aim of this study is to build a robust recognizer that is less influenced by noises and interference for semantic segmentation of crack and leakage defects of metro shield tunnel, which will be beneficial for the maintenance of metro shield tunnel and other civil infrastructure. The content of this paper is described as follows. Section 2 presents a flowchart of the proposed method with a detailed description of the procedure to build a recognizer for inspecting crack and leakage defects. Section 3 demonstrates experimental evaluation by comparing with traditional frequently-used methods. Section 4 discusses the effect of hierarchies of image features and the difference between crack and leakage recognition. Finally, Section 5 concludes this article.

2. Framework to build recognizer for crack and leakage defects

The proposed method to recognize crack and leakage defects for metro shield tunnel is summarized into four phases, as shown in Fig. 1. Firstly, high-definition images of inner lining surface of metro shield tunnel are captured by a continuously scanned image acquisition equipment named Moving Tunnel Inspection (MTI-200a) which is self-developed by the authors. Then, in order to establish image datasets which consist of crack dataset and leakage dataset, label-preserving transformations are used to augment the number of defect images and solve class imbalance problem by rotating, sliding window and splitting based on manually labelled images. Thirdly, after the establishment of image datasets, DL-based training of FCN models is performed to produce crack model and leakage model through several iterations of forward inference and backward learning. Finally, a two-stream algorithm using FCN models for image recognition of crack and leakage defects is implemented with considering regions of crack and leakage will be overlapped. Details of these four steps are discussed as below.

2.1. Image acquisition of metro shield tunnel lining

Metro shield tunnel is a tubular underground structure of which lining surface has a certain curvature in weak light environment. In order to capture inner surface images of shield tunnel lining, the novel equipment MTI-200a is updated from the previous version of MTI-100 (Huang et al., 2017b). MTI-200a consists of linear sensor cameras (6 units, GigE version), light source (19 units, white LED), computer, monitor, encoder, battery etc. The used camera has a single line of photosensitive sensors which are monochrome complementary metal oxide semiconductor (CMOS). The total number of photosensitive sensors is 8192 and the sizes of them are all 7.04 μm × 7.04 μm. Focal length of the lens is 60 mm. The technical specifications of MTI-200a are shown in Table 1. The sketch map and working scene of MTI-200a are shown in Fig. 2. There are some objects on the surface of metro tunnel lining, including LED lighting, pipes, cables etc., which is quite different from other civil works. Metro shield tunnel has many

Table 1
Technical specifications of MTI-200a.

Index	Value
Image resolution	0.2 mm/pixel
Inspection speed	0–10 km/h
Image format	8 bit, monochrome, bmp
Line rate	0–13 kHz
Diameter of the tunnel	5.5 m
Inspection range	270°
Time for assembly/disassembly	5 min/3 min
Max weight for a single part	25 kg
Total weight	140 kg