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Automated vision inspection of rail surface cracks: A double-layer data-driven framework☆

Li Zhuang[a], Long Wang[a,b,c], Zijun Zhang[a,*], Kwok Leung Tsui[a]

[a] P6600, 6/F, Yeung Kin Man Academic Building, Department of Systems Engineering and Engineering Management, City University of Hong Kong, Hong Kong
[b] School of Computer and Communication Engineering, University of Science and Technology Beijing (USTB), Beijing 100083, China
[c] Beijing Key Laboratory of Knowledge Engineering for Materials Science, Beijing 100083, China

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ABSTRACT

A double-layer data-driven framework for the automated vision inspection of the rail surface cracks is proposed in this paper. Based on images of rails, the proposed framework is capable to detect the location of cracks firstly and next automatically obtain the boundary of cracks via a feature-based linear iterative crack aggregation (FLICA). Extended Haar-like features are applied to develop significant features for identifying cracks in images. Built on extended Haar-like features, a cascading classifier ensemble integrating three single cascading classifiers with a major voting scheme is proposed to decide the presence of cracks in the image. Each single cascading classifier is composed of a sequence of stage classifiers trained by the LogitBoost algorithm. A scalable sliding window carrying the cascading classifier ensemble is applied to scan images of rail tracks, which is identified by the Otsu's method, and detect cracks. After completing the crack registration in the first layer, the FLICA is developed to discover boundaries of cracks. The effectiveness of the proposed data-driven framework for identifying rail surface cracks is validated with the rail images provided by the China Railway Corporation and Hong Kong Mass Transit Railway (MRT). Six benchmarking methods, the Otsu's method, mean shift, the visual detection system, the geometrical approach, fully convolutional networks and the U-net, are utilized to prove advantages of the proposed framework. Results of the validation and comparative analyses demonstrate that the proposed framework is most effective in the rail surface crack detection.

1. Introduction

As one of the public transportation systems, the railway historically offered a major contribution into the worldwide economic and cultural exchange (Ning et al., 2011). In recent years, a rapid development in the speed and load of trains has led to more intense bending and shear stresses which largely increase the risk of damages into rail tracks and subsequently result in the derailment as well as other service disruptions (Li et al., 2014a). Thus, due to the advancement of trains, enhancing the rail track inspection and maintenance techniques has become a major concern in railway transportation services (Bocciolone et al., 2007; Ghofrani et al., 2018). Meanwhile, the railway industry presents a high interest in the early detection of newly developed defects on rail surfaces which could lead to other severer defects. Therefore, advanced nondestructive testing (NDT) techniques which offer the more

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[*] Corresponding author.

E-mail address: zijzhang@cityu.edu.hk (Z. Zhang).

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efficient and insightful inspection performance are developed and applied to facilitate the manual inspection of rail track defects including surface defects (Clark, 2004).

Recently reported railway NDT techniques deployed various additional sensors in the inspection which did not impair inspected parts. Papaelias et al. (2008) presented a review of NDT techniques for detecting rail defects including the ultrasonic inspection, magnetic flux leakage (MFL) based inspection, pulsed eddy-current (PEC) based inspection, etc. An innovative ultrasound technique was proposed to detect the railway wheel-flat (Brizuela et al., 2011). A variety of more advanced inspection methods based on ultrasonic signals, such as the electromagnetic acoustic transducer (EMAT) (Petcher et al., 2014) and guided wave inspection (Loveday, 2012), were further developed. The MFL was applied to inspect shapes and orientations of multiple cracks on railways (Gao et al., 2015). The advanced rectangular PEC was developed to identify surface and structural defects based on different directions of sensor scanning (He et al., 2010). Although all reported NDT techniques proved feasibility in detecting rail surface defects, their real implementations are limited to skillful technicians, specific inspection conditions, and potential radiation hazards. Moreover, additional sensors and maintenance services required in the implementation of presented inspection methods will raise an extra demand of the capital investment.

The technique of inspecting surface defects has been enhanced with the development of computer vision theories and the upgrade of infrastructure monitoring equipment. The process of implementing a typical vision inspection system (VIS) was illustrated by four sequences of steps as discussed in Malamas et al. (2003): (1) the acquisition of surface images/videos of an object via digital cameras mounted on the testing equipment; (2) the image processing for improving the quality of images/videos; (3) the feature extraction based on computer vision algorithms; and (4) the decision-making process for producing detection results. The research of VIS focused on developing effective methods for teaching machines to identify surface defects of interested objects based on visual data. Li et al. (2014b) applied a back propagation neural network to automatically identify pavement defects from image. Oliveira and Correia (2013) reported the characterization of cracks on the road based on the unsupervised learning method. Prasanna et al. (2016) presented a spatially tuned robust multifeatured classifier to identify cracks on the bridge. Gibert et al. (2014) proposed a discrete shearlet transform method based on GPU to detect cracks on the texture image. Compared with other NDT technologies, unique features of the VIS include the automated inspection process, high inspection flexibility, low hardware investment, etc.

The application of the VIS in the rail surface crack inspection has recently been a sweet-spot in the railway condition monitoring research. The model-based approaches and data-driven approaches are two categories of techniques majorly discussed in the literature of inspecting rail cracks with the VIS. In the model-based approaches, explicit models including thresholding and texture models were applied to handle the image segmentation and analysis. Li and Ren (2012) introduced a local Michelson-like contrast approach to enhance the image quality and a proportion emphasized maximum entropy thresholding method to identify cracks on the rail surface. Sambo et al. (2016) adopted an adaptive thresholding to detect the rolling contact fatigue damage on the rail surface based on binary images. Jie et al. (2009) applied a geometrical defect locating method to detect rail head surface cracks through analyzing the gray-level histogram curve generated from rail images. In the category of data-driven approaches, a classifier was developed to locate defects based on images. Mandriota et al. (2004) introduced Gabor filters to extract the texture features of the rail surface and applied the *k*-nearest neighbor classifier to determine the presence of the corrugation. Xia et al. (2010) applied the Haar-like feature to extract features of the fastener and identified the fastener state in images by an AdaBoost algorithm. Faghih-Roohi et al. (2016) utilized the deep convolutional neural networks to detect the rail surface defects. Gibert et al. (2017) presented a multi-task learning framework to inspect railway track components using deep convolutional networks. The computer vision inspection of rail surface defects in Faghih-Roohi et al. (2016), Gibert et al. (2017), Jie et al. (2009), Li and Ren (2012), Mandriota et al. (2004), Sambo et al. (2016) and Xia et al. (2010) were all studied based on a large number of images collected by testing trains. The model-based approach for detecting rail surface defects based on images was simple to implement while data-driven approaches were more robust to images containing more noises. However, the main feature of reported two categories of methods is the identification of the defect presence while discovering more details of defects including their boundaries is rarely discussed. Although the boundary of the defect on railway ties and fasteners can be detected based on deep learning (Gibert et al., 2017), training high quality deep learning-based models desires a large amount of available data and rich experiences in model parameter tuning. The automatic detection of the presence and boundaries of cracks is beneficial to significantly facilitate the visual diagnosis process. Thus, it is meaningful to investigate more advanced approaches which can successfully identify the presence and boundaries of cracks.

This paper proposes a bi-layer data-driven framework for identifying rail surface cracks and discovering their boundaries based on images. In this framework, extended Haar-like features (Lienhart and Maydt, 2002) are applied to extract effective features to depict characteristics of cracks in images. Next, based on selected extended Haar-like features, a cascading classifier ensemble is developed by integrating individual cascading classifier built via the LogitBoost algorithm (Friedman et al., 2000) with a bootstrap aggregation (Breiman, 1996). Locations of cracks are identified by the developed cascading classifier ensemble deployed in a scalable sliding window for scanning over the rail track extracted from raw images. After identifying locations of cracks, the crack region is enlarged for deriving boundaries of contained cracks. A feature-based linear iterative crack aggregation (FLICA) method is proposed to precisely determine boundaries of cracks and highlight them in the image. Six benchmarking algorithms, the Otsu's method (Otsu, 1979), mean shift (Comaniciu and Meer, 2002), the visual detection system (VDS) for rail surface defects (Li and Ren, 2012), the geometrical approach for rail head surface defect detection (Jie et al., 2009), as well as two automatic segmentation methods, the fully convolutional networks (Long et al., 2015) and the U-net (Ronneberger et al., 2015), are employed to validate the effectiveness of the proposed framework. The Rail images utilized in this study are provided by the China Railway Corporation and MTR. The proposed data-driven framework is applicable to develop high quality models serving as the intelligence of detecting rail track surface cracks via analyzing images collected manually or by automated imaging systems. Moreover, the proposed framework is capable to accurately detect cracks given a limited number of training images. The image-based crack detection function offered by the proposed framework is beneficial to boost the efficiency of railway system health condition monitoring and assessment process as well as

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