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Inspection equipment study for subway tunnel defects by grey-scale image processing

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ABSTRACT

In recent years, much attention has been paid to Machine Vision-Based (MVB) technology for tunnel main defect (leakage and crack) inspection as an innovative technology. Based on the principle of MVB technology, various researchers have developed tunnel inspection equipment, but most of them need either a trailer or an external power supply, which cannot meet the demand of subway tunnel inspection in China. The limited inspection time, high demand for precision, rigid requirements of operational management and high cost of the equipment restrict the application of this method in China. MTI-100 (Moving Tunnel Inspection) was developed under these circumstances. To capture stable, high-quality images of the lining surface as the raw data of inspection, an image capture system is well designed based on CCD (Charge-coupled Device) camera scanning. Additionally, equipment optimization design of the mechanism and electricity requirements for the inspection accuracy of subway tunnel inspection is investigated. The maximal size and weight of equipment elements determined the convenience of inspection, which is primarily conditioned by these designs. The effects of lighting and vibration have been considered. A method to calculate the image shift caused by vibration is proposed. The software network is another core component of the equipment, which connects the image acquisition, image storage and defect recognition. The famous Otsu method is used for leakage recognition. A new algorithm based on the features of the local image grid is developed to recognize cracks. A comparative study shows its high accuracy for crack recognition. Finally, a simulative tunnel test and field inspection are undertaken to verify the performance of the non-destructive subway tunnel inspection equipment. Through these tests, the accuracy, stability, repeatability, labor intensity and efficiency of the equipment have been verified. A real project test certified that the developed MTI-100 is quite suitable for practical tunnel inspection.

1. Introduction

With the rapid development of the urban railway system in China, more than 20 cities' urban railway systems have come into service in recent years. From 2005 to 2014, the total length of urban railway system growth was 231.8 km per year, among which more than 70% was subway tunnel growth. The total length of urban railways exceeded 3000 km as of 2015, and the length of subway tunnels accounts for 74.4 percent of all mileage [1,2]. This quick increase and the long total distance are two characteristics of Chinese subway tunnels that have led to the focus on operational safety. The increasing construction of subway tunnels is accompanied by a shortage of skilled workers and neglected construction quality supervision, which have led to the original existence of the defects in tunnels. As the main structural defects in subway tunnels, leakage and cracks threaten the safety of tunnel structures [3,4]. For example, according to the inspection results, leakage can be generally found in Shanghai line one, and the total length of cracks has reached 300 m [5]. Due to this reason, tunnel inspection is the foundational work that connects with the safety management of metro operation, which includes crack and leakage inspection.

Manual vision-based inspection is the traditional way to inspect the cracks and leakage of subway tunnels [6,7]. For now, to satisfy the plentiful inspection work in the Shanghai Metro, more than 50 inspectors walk along the tunnel every day to cursorily observe the lining surface and record the position and severity of defects using digital cameras based on the experience of the inspectors. Due to the limited time for inspection, they do not have time to scrutinize the tunnel, which leads to the omission of imperceptible defects

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and cannot guarantee the inspection results. Sometimes, inspectors cannot finish the inspection in the limited amount of time. Another problem of the manual vision-based inspection is the difficulty of measuring the defects. On account of most of the cracks being at the top of subway tunnels, inspectors need to climb on a scaffold to measure the width of cracks using a crack width measure instrument, which causes safety problems for inspectors [7]. The inefficiency, subjectivity, unreliability and insecurity of traditional methods has led to the urgent need for a new method to be developed to enhance the tunnel inspection method.

In this decade, a MVB (machine vision-based) method has been used in surface inspection as a non-contact detection technology that can effectively track the dynamic information of the object surface [8,9]. This method uses the collected images captured by the camera to calculate the dimensions of the targets [10]. The grey level of every pixel in the image represents the strength of the light reflected from the surface of the measured object. The pixels of an image correspond one-to-one with points on the surface of the object and can be used to calculate the positions of defects. This method has been applied as a novel method for inspecting the surface defects of tunnels.

After many years of research, many countries have developed tunnel inspection equipment based on MVB method [11–15], such as Japan [16] and China [17,18], for road tunnels, and Switzerland [19], for railway tunnels (Fig. 1). Swiss tCrack [19] uses several CCD (Charge-coupled Device) cameras and lights that can recognize cracks of more than 0.3 mm in width, and its full speed is approximately 2.5 km/h. Japanese Keisokukensa.co launched MIMM-R for tunnel inspection. It combines CCD cameras, a laser scanner and Ground Penetrating Radar (GPR), which gives it the ability to inspect cracks, leakage and also tunnel deformation and tunnel lining cavities. As its main function, it can detect cracks and leakage with 0.2-mm resolution at 70 km/h. However, the equipment above needs either a trailer or power supply, which cannot be provided or is too expensive for the tunnel inspection and maintenance department in China. The EURO project also focused on this area, which results in ROBOSPECT [20–22]. This equipment can work in all kinds of working conditions especially tunneling to inspect the crack at the surface of the lining. The equipment uses the laser to construct the 3D image of tunnel and the area-scan camera to obtain the details of the defects. However, finishing the inspection with the full face of tunnel lining is difficult.

Subway tunnel inspection has several characteristics that differentiate it from road tunnel and railway tunnel inspection. Firstly, the inspection time is limited to 2–3 h per day during the nighttime to guarantee the daily operation of the metro. Working before dawn will always decrease the attentiveness of inspectors and lead to inspectors feeling tired. Secondly, the inspection work's intensity is high. There is plenty of work that needs to be finished in a short period of time, including crack and leakage inspection over a long distance, with at least two sections of nearly 3 km per night for subway tunnel inspection. In addition, the requirements on the precision and accuracy of inspection are rigid, i.e., even hairline cracks need to be found. Another characteristic is that the equipment cannot be stored in the subway tunnel for safety reasons. China also cannot provide the train or power source for inspection, different from Japan and Europe. As a result of these characteristics in subway tunnel inspection, efficiency, high precision, an autonomous power supply and the ability to be transported are necessary attributes for inspection equipment.

For these reasons, the existing tunnel inspection equipment cannot be applied to subway tunnel inspection in China. The subway tunnel maintenance department in China has waited for high-efficiency, cost-beneficial and high-performance tunnel inspection equipment to help them finish the inspection work. To meet the requirements of subway tunnel inspection, this project has focused on developing novel subway tunnel inspection equipment by applying MVB technology, including the hardware system and software system. The research also strived to enhance the captured image's quality and reduce the weight of the equipment, which affect the precision and efficiency of the equipment. The influence of lighting and vibration on image quality was discussed to guarantee that the inspection work could be well finished. A unit equipment test and simulative tunnel experiment were undertaken to verify the feasibility and precision of the equipment, and a field test was conducted at Shanghai metro tunnel to verify the performance of the equipment. The method for the design and optimization of inspection equipment mentioned in this paper can be adopted for similar equipment as well.

2. The determination of design parameters for a hardware system

The most widely used machine vision sensors for tunnel inspection are (line-scan or area-scan) charge coupled device (CCD) cameras or laser scanners [23]. Compared with a laser scanner, using a CCD camera to capture the images of tunnel lining is faster and always has higher precision [24]. Image distortion is an inevitable problem when using an area-scan CCD camera; researchers always need to use a checkerboard plane to calibrate the camera before image capture. An additional image processing method needs to be applied to rectify distorted images. This will increase the complexity of the image processing method and the time-consumption. Different from area-scan cameras, line-scan CCD cameras can obtain more stable images of different surfaces, but lighting and vibration must be considered to guarantee the quality of the images. On the basis of the different characteristics of sensors, the line-scan CCD camera was chosen as the kernel element in this project.

The traditional task for a line-scan CCD camera is the use of a fixed camera to measure a moving object with a constant speed.

Fig. 1. Typical inspection equipment in subway tunnels.