# Overview of Tunnel Detection Technology

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**Abstract.** Due to limited land resources, there are more and more tunnel projects around the world, such as subways, mountain tunnels, undersea tunnels and high-speed railway tunnels. Being independent of their purpose, such underground construction environment is sinister and complex. With the long-time use of tunnels, it is necessary to detect and diagnose quality defects to avoid accidents, such as geological environment, lining cavity, concrete strength, lining thickness, seepage water, section deformation, crack and so on. This paper provides a comprehensive overview of geological exploration before the completion of tunnels, the analysis and control of quality defects during the structure construction as well as the continuous monitoring and diagnosis of tunnel faults after establishment. Finally, challenges and future tunnel inspection directions are discussed.

**Keywords:** Tunnel fault · Monitor and diagnosis · Detection methods

## 1 Introduction

A large number of tunneling was performed during the last few decades and also will be continued constructed in the future. By the end of 2018, there are 15,117 railway tunnels in operation, with a total length of 16,331 km in China [1]. In addition, it is estimated that the total number is expected to reach 1700 and the total length will exceed 20000 km by the end of 2020. And the structure is also considerable designed to run for as many years as possible, take the Gotthard Tunnel which is the longest railway tunnel in the world for example, it is expected to use for 100 years. But once the project is completed and put into operation, various diseases will inevitably occur due to the influence of engineering, hydrogeology and other factors under long-term use, such as lining leakage, cracking, peeling, arch cavity, concrete strength deterioration, pavement cracking, etc. These issues is getting worse as time goes by and will eventually reduce the strength and life of the tunnel which will cause great security risks. Therefore, in order to maintain the tunnels' safety, periodic detection, repair [2], and tunnel asset management [3, 4] and monitor [5] is required.

Currently, tunnel inspection is mainly performed manual and the inspector employ various sensors to detect and record the tunnel diseases for analysis, so the detection are highly depended on the personal experience and the results are subjective and unreliable. In addition, the manual slow detection speed and low efficiency consumes lots of manpower and material resources, resulting in higher comprehensive costs. Moreover,

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manual detection needs close the traffic lane to guarantee the safety of inspectors which often obstructs the tunnel traffic. Furthermore, the tunnel environment is lack of light and bad air [6], such environment may be seriously harming the inspector's body. Finally, it is very difficult to detect the tunnel at any time when need and often conduct once a year which can't meet the requirement, besides, it is also hard to keep and analysis the records over time. Therefore, researches on automatic tunnel detection technology have received great attention and some related area have also achieved breakthroughs. Multi-sensor fusion and various techniques have been conducted to complete these task.

This paper will describe the main tunnel inspection robots and key methods. The remainder is structured as follows: Sect. 2 gives an overview of the main tunnel inspection robots and the inspection system. Section 3 describes the inspection methods developed with various sensors application. Finally, the conclusions are included in Sect. 4.

## 2 The Tunnel Detection Robots and Systems

Due to the drawbacks of manual inspection and the background of more and more tunnels are put into use, the demand for tunnel inspection robots and inspection system is increasing. With the continuous development of computers, CCD sensors, radar technology, laser scanning and information fusion, the tunnel detection technology has also been improved and basically realized automatically. Infrared thermography (IRT), ground penetrating radar (GPR), and ultrasonic tomography (UST) techniques were used to inspect the structure underneath the surface [7]. L.Y. Ding et al. constructed a multi-dimensional model management system to integrate all the information from the visual working unites for the effective information exchange and monitor [8].

### 2.1 The Railway and Road Tunnel Inspection System

The portion of tunnels in Japan is among the highest in the world, therefore, in the early 1980s, Japan established the technical standards to evaluate the life of tunnel linings and improved emergency facilities for preventive maintenance work [9, 10]. The early Japanese representative tunnel inspection vehicle is Komatsu, composed of three parts: data acquisition, data storage and image processing, which significantly promoted the development of automatic tunnel detection [11].

In order to inspect and monitor tunnel more efficient and precise without traffic restrictions, the motion-blur-compensated visual system was developed which consisted of a mirror, a high-speed camera, an illumination unit, a lens and a PC (see Fig. 1). The experiments verified that this system was effective when the speed was 24 km/h, 30 km/h, 40 km/h, 50 km/h, 56.5 km/h [12].

The European Commission has funded the ROBO-SPECT European project with the main target of providing an automated solutions for tunnel inspection of cracks and other defects [13, 14, 15, 16]. Figure 2 (a) shows the final ROBO-SPECT robotic system with a designed ultrasonic sensors to measure the width and depth of cracks. This platform is constructed from an autonomous vehicle and the robotic arm, while the visual depiction consisted with cameras, a 3D laser profiler and lighting system (see Fig. 2(b)).

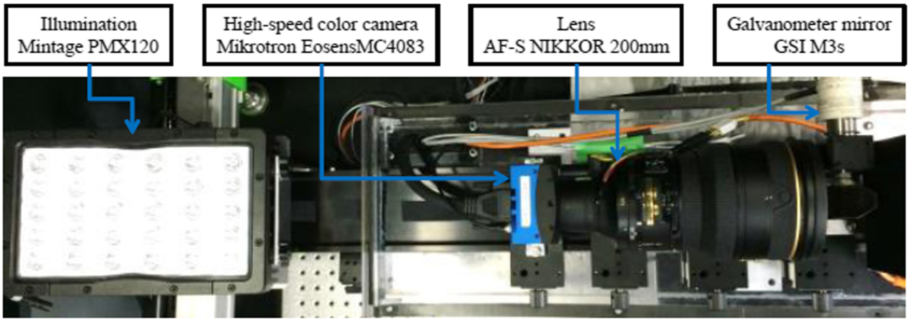

**Fig. 1.** The motion blur compensation system.

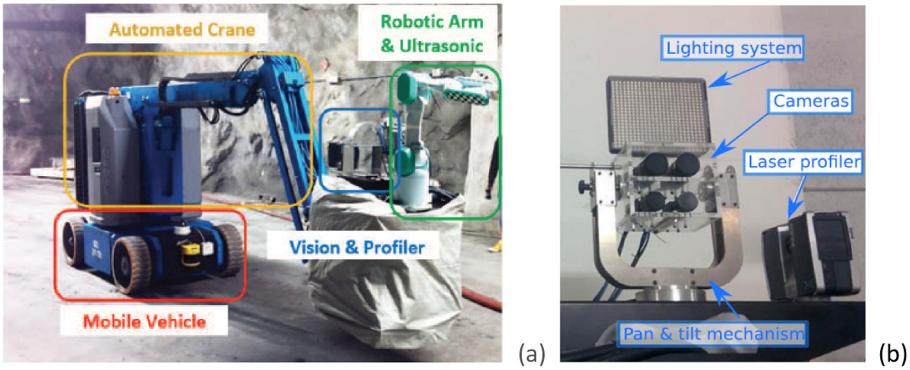

**Fig. 2.** The ROBO SPECT robotic system. (a) Outlook of the robotic system. (b) The ROBO SPECT vision system

In 2018, it was reported that Japan developed a tunnel cross-section detection system [17]. This system is based on a mobile protect bracket which can be adjusted with the range of 6.36 m to 9.56 m according to different tunnel width. Since the bracket is in a cross-road shape, the vehicles can pass under it (see Fig. 3). In addition to the vision detection techniques, the impact sound diagnosis system is present [18]. It has been verified that this detection unit can detect 100% of abnormal tap position that can be inspected manually.

## 2.2 The Subway Tunnel Inspection System

The MTI-100 (Moving Tunnel Inspection) was designed for subway inspection and was suitable for 5.5 m in diameter constituted by the image acquisition system, control system and moving control system (see Fig. 4) [19]. Taking the lighting and vibration into consideration, the image acquisition system uses high-resolution line-scan CCD cameras and lighting. It is said that the equipment can reach 0.3 mm/pix at the range of inspection approximately 290°, but the average movement speed is just 5 km/h.

**Fig. 3.** cross-section detection system.

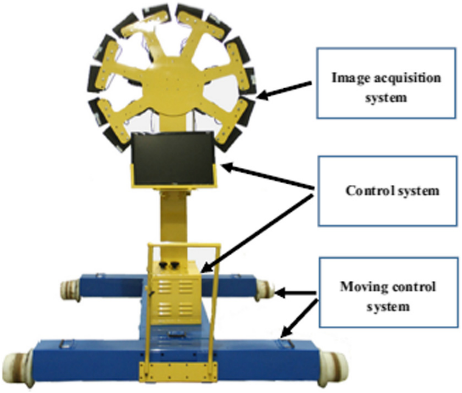

**Fig. 4.** Outlook of MTI-100

Amberg Clearance IMS 5000 [20], as shown in Fig. 5, is the new way of railway infrastructure scanning and measuring trolley consisting of precision sensors of gauge, super elevation and distance as well as ruggedized notebook. Its laser scanner can acquit high accurate 3D point cloud of complete infrastructure for measurement and calculation of track parameters like horizontal, vertical versions, curvature, radius, gauge, super elevation and twist. The typical measuring speed is 3.5 km/h, and the system profile accuracy is about ±3 mm. Amberg Clearance IMS 5000 has been used for railway tunnel inspection in China [21, 22].

## 3 Tunnel Inspection Methods

### 3.1 The Ultrasonic Reflection Methods

Ultrasonic tomography (UST) reflection method is the first nondestructive testing method created for testing concrete based on emitting the ultrasonic waves and receiving the reflection [23]. The ROBINSPECT project developed the ultrasound-based crack analysis method combination with commercial piezoelectric ultrasonic transducers reported in

**Fig. 5.** Amberg IMS 5000

Fig. 6 for measure the crack depth. The device is constituted by a polymeric, low-finesse Fabry-Perot interferometer manufactured. When the incoming ultrasonic wave hit the polymer spacer, the change of the polymer thickness consequently leads to variations of reflected optical intensity, such tunnel cracks can be measured [16].

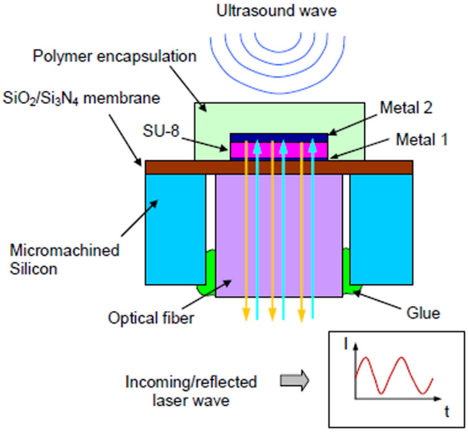

**Fig. 6.** Acousto-optical ultrasound detector

### 3.2 Ground Penetrating Radar(GRP) for Tunnel Detection

Ground penetrating radar (GRP) can be used for mapping tunnel lining condition and locating the concrete deterioration [24]. In order to keep the normal operation of the tunnel, GRP systems [25-27] is used to detect the tunnel damage in many cases, but their performance changes according to the types of soil, subsurface features and so on. Paper [28] designs the systematic and effective GRP system for tunnel detection shown in Fig. 7 . It illustrates that the tunnel defects could be recognized from the received power as the propagation loss and scattering differs due to different medium.

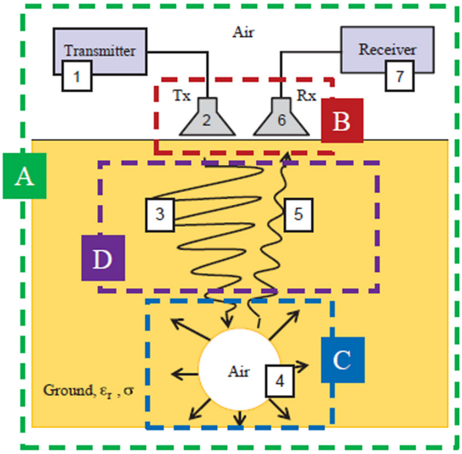

**Fig. 7.** GRP principle for tunnel detection

### 3.3 Vision Inspection System

The early detection of any visual changes in the tunnel surface, such as the leakage, cracks and corrosion is a critical requirement for failure prevention. Paper [29] presented an automated system for detecting the visual defects on the tunnel linings. Due to the spatial range and field of view of railway tunnel measurements are quite large, it is a challenge to inspect the 3D clearance. Automated system for detecting, localizing, clustering and ranking changes on tunnel surface is conducted [30]. The multiply vision measurement system is illustrated in Fig. 8 [31], including multi-camera and structured-light vision system (MSVS), a high-speed image acquisition block, an odometer, a vibration compensation component and an image processing computer. The MSVS installed at the frontal-side of the vehicle body gets the complete field of view of the tunnel cross-section when the vehicle are moving. Since the laser strips could capture the depth information of the railway tunnel surface, this system is able to reconstruct the 3D metric surface model.

As we know the tunnel full cross section is not normal circle and the system always just get the information from the multiple distorted images, such we need to calibrate the images and remove the image fluctuation [32] to get a high level of accuracy. Hayakawa T et al. [12] developed a motion-blue-compensated visual inspection system installed on an vehicle for tunnels. It was tested that the system could compensate for motion blur when the target height was 5m at the speed of 40km/h, Krisada Chaiyasarn et al. [33, 34, 35] proposed a novel mosaicing system that can create an almost distortion-free mosaic image of tunnels. This system removed distortion through structure from motion that could create a 3D point cloud of the tunnel surface from uncalibrated images and enabled the system to cope with images with a general camera motion. All the 3D points and the calibration matrix are used to initialize the Bundle Adjustment (BA) algorithm and the Support Vector Machine (SVM) classifier is applied to discriminate the tunnel surface points [18].

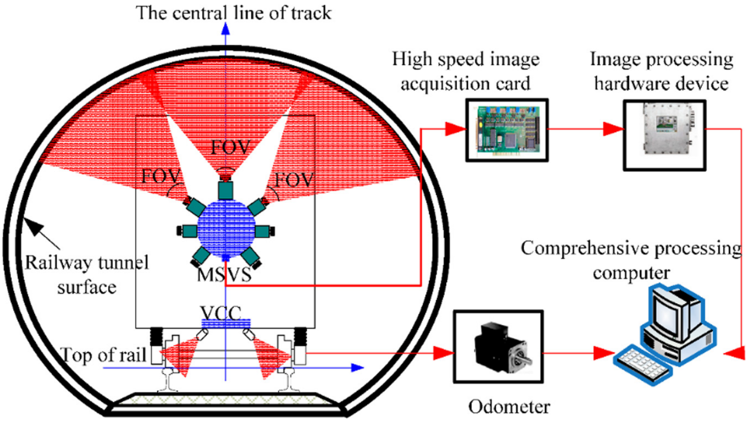

**Fig. 8.** The railway tunnel vision measurement system.

### 3.4 3D Reconstruction from Point Clouds

Terrestrial Laser Scanners (TLS) have become systems frequently used in tunnel inspection to build the 3D models from the point clouds [36, 37, 13], but the distance to the object and angle of incidence are the two factors affect measurement errors. A methodology to build an error model o analysis the influence of range and angle of incidence of terrestrial laser scanning is proposed [38]. Figure 9 shows, on the left, a point cloud simulated by using its procedure, and the image on the right is a perspective view of the point cloud. It was obtained considering that the laser scanner is located in the center of a tunnel with a circular cross-section of radius R = 5 m.

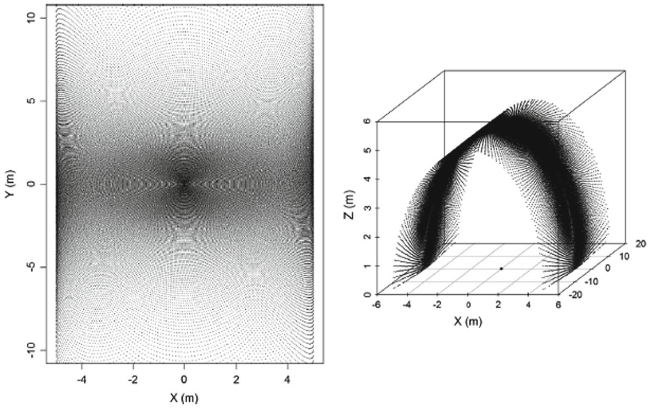

**Fig. 9.** View of the point cloud plant (left) and 3D represents (right) of the tunnel

# 4 Conclusion

In this paper we have presented the recent research works about tunnel detection systems and methods. The four most commonly nondestructive detection methods that the ultrasonic tomography reflection method, the ground penetrating radar, the vision inspection system and the 3D tunnel construction based on the terrestrial laser scanners are discussed in the paper. It can be seen that although it has achieved some breakthrough in recent decades, there are still a lot of work to be done to realize automatic tunnel detection in the future.

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