Research on the Present Situation and Development Trend of Subway Tunnel Inspection Vehicle

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Abstract. For the operational subway tunnel, the manual inspection accounts for the majority in terms of detecting the diseases and damage of tunnel. The accuracy of manual inspection mainly depends on the professional level of the detection personnel, and the whole detection process always is inefficient, which cannot meet the needs of actual tunnels. To address this issue, the intelligent mobile tunnel detection vehicle emerges as the times require. By using advanced technologies such as laser scanning and high-speed camera array, the subway tunnel detection vehicle has achieved the advantages of simple operation, comprehensive function and automatic detection. However, the current subway tunnel detection vehicle mainly realizes the scanning detection of tunnel surface diseases, and the detection of tunnel structural diseases is less involved. Based on the track and tunnel detection requirements, this study analyzes the current situation and existing problems of subway tunnel detection comprehensively, puts forward the development direction of tunnel structure detection, and the application prospect of intelligent detection vehicle in subway tunnel is prospected.

1. Introduction

Long-term operation of subway tunnels under wheel-rail friction, vibration, impact and other conditions will cause different levels of damage to the track, such as deterioration of track geometry, rail wear or fracture, loose or missing fasteners, settling of the track bed, cracking of sleepers and so on. Failure to discover and deal with them in time will seriously affect driving safety. In addition, the environment of the subway tunnel is complex and changeable. Under the action of various factors such as the surrounding ground pressure, nearby construction disturbance, and dynamic vehicle load, the tunnel structure will also be destroyed [1-3]. Diseases such as tunnel settlement, deformation, lining cracks, spalling, falling blocks, surface leakage and misalignment of pipe segments will directly pose a serious threat to the safe operation of subway tunnels.

It is necessary to strengthen the detection of subway tunnel diseases. Traditional detection methods mainly include fixed sensor monitoring and manual inspection. In the current traditional detection methods, fixed monitoring mainly uses fixed sensors to monitor the tunnel. This mode is suitable for specific local areas and has a high cost of use, and generally cannot cover the entire line; Among the
fixed sensors, there is a distributed optical fiber sensor based on Brillouin scattering, which can achieve full range and high-density measurement points, which is the mainstream direction of the development of fixed sensors [4]. Use distributed optical fiber sensors to measure the strain of the structure, and then select the appropriate algorithm to infer the health of the structure through the strain data [5, 6]. Manual inspections mainly rely on manual and hand push (handheld) tools for data collection, such as static inspection and manual inspection, have slower speed, lower efficiency, high pressure of missed inspection, harsh working environment, aging of inspectors and prominent problems in recruitment. As the operating pressure increases and the skylight period continues to be compressed, the existing detection technology level of subway tunnels has become increasingly unable to meet the actual requirements for operational safety, and there is an urgent need to adopt advanced and efficient detection methods.

With the advancement of science and technology, especially the advancement of cutting-edge technologies such as robotics, artificial intelligence, big data, cloud computing, Internet of Things, unmanned driving, and 5G communications, it has provided a technical foundation for intelligent detection of subway tunnels. This article discusses the future application trend of the subway tunnel intelligent inspection vehicle by analyzing the current situation of subway tunnel inspection technology, the new inspection technology and the existing problems in the current inspection methods.

2. Status Quo of Metro Tunnel Inspection Technology
The main problems currently existing in subway tunnels are: longitudinal settlement of the tunnel, lateral convergence, horizontal deformation, insufficient thickness and strength of the lining concrete, voids and imperfections behind the lining, cracks, falling blocks or spalling on the lining surface, water leakage, and segmental linings. Mistakes, track defects, etc [7].

2.1. Tunnel longitudinal settlement, lateral convergence, horizontal displacement detection
Mainly manual inspections are used to measure the longitudinal settlement of the tunnel through the use of leveling, static level measurement, etc.; use the convergence ruler, laser ranging, and total station to measure the lateral convergence of the tunnel; use the total station to measure the level of the tunnel Displacement.

2.2. Lining and floor quality and back cavity inspection
For the detection of tunnel lining and floor quality and the cavity behind it, the detection method of tunnel lining quality and disease at home and abroad is mainly ground penetrating radar method. In recent years, the ground penetrating radar method has been widely used in the inspection of existing lines and newly built subway tunnels. The traditional method is to use a hand-held antenna close to the lining survey line for inspection [8]. A few use hydraulic systems to support the antenna close to the lining and encounter contact nets. The fixed pole needs to lower the antenna, and only one longitudinal section can be detected at a time. It takes 6 skylights to detect a 2 km long tunnel. During the inspection, power outages during the maintenance of the sunroof are required, transportation needs to be interrupted, and the contact network is affected. The detection of the tunnel floor also uses the way that the ground penetrating radar is close to the ground.

2.3. Lining and floor strength testing
The concrete strength testing of lining and base plate is mainly divided into destructive testing and non-destructive testing. The early drilling method commonly used is destructive testing. Although it can directly detect the quality of the lining, it destroys the integrity of the tunnel's waterproof and drainage system and the lining structure. Commonly used non-destructive testing methods include rebound method, ultrasonic method, and ultrasonic rebound method [9]. The rebound method uses a rebound meter to test the concrete strength of a certain range of the surface of the lining or the bottom plate, and the test results have certain limitations. Ultrasonic method can reflect the internal strength of concrete, but it is still affected by the material itself such as the particle size of concrete aggregates. The ultrasonic
rebound integrated method combines the advantages of the first two methods, makes up for the shortcomings of the single rebound method and the ultrasonic method, has the advantages of high test accuracy and relatively simple operation, so it has been widely promoted at home and abroad.

2.4. Tunnel boundary detection
The subway tunnel boundary, that is, the building boundary, is an extreme cross-sectional profile perpendicular to the centreline of the line. Within this outline, except for rolling stock and equipment interacting with rolling stock, other equipment or buildings are not allowed to invade [10]. Tunnel boundary detection mainly uses tunnel boundary detection vehicles, boundary measuring instruments or total stations to detect a small number of sections that may be structurally deformed.

2.5. Detection of lining cracks, falling blocks, spalling, water leakage, and pipe piece misalignment
Rail inspection is divided into flaw detection, appearance, surface damage and wear inspection. Rail flaw detection uses rail flaw detectors and flaw detectors for regular inspections, and the flaws detected by rail flaw detectors should also be rechecked with flaw detectors. The inspection of rail appearance and surface damage is mainly carried out by manual inspections. When rail scratches, fish scale cracks, abrasion, rust and other damages are found, rechecks will be carried out. Rail wear is mainly detected manually by rail profile (wear) measuring instruments and other testing instruments.

In summary, it can be seen that the existing subway tunnel disease detection methods are mainly manual, that is, relying on human eye detection and manual instrument detection. The advantages of these two methods are that the technology is mature and reliable, but at the same time there are higher requirements for the inspectors. The shortcomings that it is difficult to guarantee the safety of the inspectors, there are safety uncertainties, and the manual inspection has a large subjectivity, even experienced inspectors can hardly guarantee the completeness and accuracy of the test results. With the continuous increase of the current testing workload, this manual method of adding instruments becomes more and more difficult to meet the testing requirements, the time required to complete all the testing is also getting longer and longer, and the safety of the testing personnel cannot be guaranteed.

3. New technology of subway tunnel inspection
With the aging of a large number of existing subway tunnel operating lines, new tunnel diseases continue to appear, posing a great threat to the safety of subway operation. Some diseases may already exist when they are constructed. Regular and accurate detection of tunnels is carried out to detect diseases early. Targeted remediation of serious diseases can save maintenance costs and is also an important means to ensure the safety of subway operations [11]. Because traditional tunnel detection relies on manual operation, it is time-consuming and difficult to comprehensively and accurately detect. The new technology of high-efficiency, automatic and intelligent tunnel state detection is an important means and an inevitable trend to solve this problem.

3.1. New technology for detecting lining surface diseases
Industrial CCD cameras are widely used at home and abroad to collect disease image information such as cracks, water leakage, and spalling on the lining surface. The laboratory of Hanyang University in South Korea uses a linear CCD camera, which can detect cracks with a width of more than 0.3 mm and a speed of 5 km/h. Japan Inspection and Survey Co., Ltd. also uses CCD cameras, which can detect cracks with a width of 0.1 mm at a speed of 5 to 50 km/h. The Swiss tunnel detection equipment tCrack [12], the crack detection accuracy is 0.3 mm, and the speed is about 2.5 km/h.

In 2012, Wang Rui and Qi Taiyue [13, 14] of Southwest Jiaotong University used high-precision line-scan cameras to detect cracks, which can identify 0.2 mm cracks and the detection speed is 13 km/h. In 2014, the subway tunnel structural disease detection equipment system MTI-100 developed by Tongji University Huang Hongwei is a walking detection platform composed of 6 linear array CCD cameras and light sources, which can detect cracks, water leakage, falling blocks and other disease information.
3.2. New technology of tunnel boundary detection
Laser scanning technology uses the principle of laser ranging to measure three-dimensional data. Its main advantage is that it can quickly, high-density, and high-precision obtain three-dimensional data, that is, point cloud data [15]. The system accuracy of 3D laser scanning technology is related to point cloud density, detection speed, ground base station layout, etc. The inner contour deformation can be obtained by comparing the three-dimensional data of the tunnel structure detected before and after [16].

The GPR5000 mobile measurement system produced by the Swiss AMBERG company is equipped with a two-dimensional laser scanner [17], which can detect and analyze the overall state, disease, boundary, misalignment, deformation, and convergence of the subway structure. When the walking speed is less than or equal to 1.5 km/h, a crack with a width of 0.3 mm can be identified; when the walking speed is less than or equal to 6 km/h, a crack with a width of 1.5 mm can be identified.

3.3. New technology for track defect detection
The full-section integrated testing equipment for urban rail transit tunnels developed by Beijing Urban Construction Survey and Design Institute can detect the fastening status of the fastener system; fastener integrity; fastener abnormality; thickness of under-rail pad; geometric relationship between rail and rail platform. The orbital geometric parameters include five items: gauge, level, orbit, height, and twist. The line structure laser at both ends of the moving three-dimensional laser scanning system is used to collect the inner profile of the rails on both sides of the track to calculate the gauge. Extract the rail profile waveform from the cross-sectional data, compare it with the reference rail waveform, find the abnormal
position, then analyze the abnormal value distribution of the continuous rail section, determine the type of damage and calculate the area of the damage to evaluate the damage degree.

![Line structure laser inspection equipment detects track diseases](image)

**Figure 3.** Line structure laser inspection equipment detects track diseases

### 3.4. Other new detection technologies

(1) Detection data automatic processing technology

With the continuous upgrading of detection equipment and technology, the detection speed has been greatly improved, and the efficiency of manual identification processing is extremely low, the effect is poor, and the actual overall efficiency is difficult to improve. The automatic processing of inspection data is realized through deep learning, which effectively solves the problem of massive inspection data processing. For example, to process image data of cracks on the lining surface, a large number of neural network trainings are carried out using the crack image sample database to obtain a mature system algorithm that can be used to discriminate and process data, and use the system to identify, classify, count, and extract cracks, etc. Complete automatic processing of test data [18].

(2) Tunnel health management big data platform

Tunnel quality inspection only completes the collection of disease data. As the health status data of the tunnel in different periods continues to accumulate, a comprehensive grasp of the tunnel structure is achieved through the establishment of a tunnel disease analysis model, a disease development prediction model, structural safety status assessment, and structural safety early warning. Safe state, give full play to the value of big data of tunnel health state.

### 4. Introduction of comprehensive inspection vehicles for domestic and foreign tunnels

With the maturity of tunnel inspection technology and the development of new sensing technologies, comprehensive inspection vehicles integrating multiple inspection technologies have emerged at home and abroad. Highly integrated equipment can save tunnel comprehensive inspection time, improve inspection accuracy, and greatly reduce inspection costs.

(1) Wuda Zhuoyue Technology Co., Ltd. is relatively mature in detection technology, and developed the ZOYON-TFS tunnel rapid measurement system [19]. The system adopts the LED lamp group to illuminate the high-definition area array collection method. It is equipped with a total of 34 LED lights and high-speed cameras. There are 32 sets of high-precision laser scanners, one of which has a higher speed, producing 1016000 points per second, and is equipped with GPS and some extended detection modules. It can be seen that the system has complete equipment and high-precision instruments. At the same time, the system can also cover more detection indicators, and can quickly detect diseases such as tunnel openings, portals, cracks, water leakage, stratification, spalling, and overhaul roads. The data accuracy is high, and the positioning accuracy is ≤1m. The crack detection accuracy is up to 0.2mm, and the deformation detection accuracy is up to 0.2mm, which avoids the error caused by the traditional detection method due to man-made cables, and has been put into actual tunnel detection in many places. It was delivered domestically, breaking the foreign monopoly.
(2) The TDV-H2000 highway tunnel rapid inspection vehicle independently developed by Shanghai Tongyan Civil Engineering Technology Co., Ltd [20], and Tongji University. The rear of the vehicle body is equipped with image acquisition equipment and power supply devices. The upper part is equipped with a laser point cloud. The operator is in the box. Working inside the body, it can detect the two parts of tunnel structure disease and tunnel outline, and can automatically perform data analysis, spread map splicing, disease identification, three-dimensional modeling and data management. Its tunnel inspection vehicle is characterized by two-lane inspection, which realizes automatic control of tunnel inspection data collection, with a crack width identification accuracy of 0.2mm, and constructs a three-dimensional point cloud model of the tunnel.

(3) The integrated full-section intelligent tunnel disease detection track running equipment developed by Beijing Urban Construction Survey and Design Institute was officially put into operation before the operation of Suzhou Metro Line 5. The equipment is equipped with mobile 3D laser detection devices and high-speed line array camera detection equipment. Line structure laser inspection equipment. The device has a high degree of integration and a wider detection range. It can realize the subtle synchronization control of multi-sensor under high dynamic conditions. The inspection vehicle uses the precise change detection of the structural profile based on three-dimensional fine representation and the intelligent identification of typical diseases, which realizes the accurate calculation of the millimeter-level deformation parameters of the structural profile, the detection of the track geometry, the detection of the rail damage, the detection of the fasteners, and the supporting equipment at the same time. A data management platform has been developed to facilitate the storage, analysis and display of the collected data.
Figure 6. Metro tunnel inspection vehicle of Beijing Urban Design Institute

(4) The Japanese MIMM-R inspection vehicle is equipped with air-coupling radar, 20 industrial CCD cameras, laser scanners and other equipment, which can detect the thickness of the lining and the back cavities, cracks and water leakage, inner contour deformation, etc. During detection, the distance from the radar to the wall can reach 3 m, within a certain range, the error of the lining thickness is ±5 cm, and the error of the back cavity diameter is ±10 cm; when detecting at a speed of 70km/h, it can identify cracks with a width of 0.2 mm. The contour deformation detection accuracy is 1.0 mm.

Figure 7. Japan MIMM-R tunnel inspection vehicle

In summary, although some different types of tunnel inspection vehicles have been developed at home and abroad, there are still some problems as follows: (1) Most of the inspection vehicles have single and incomplete disease detection indicators. Moreover, the current inspection vehicle mainly detects tunnel surface diseases, and does not involve too much of tunnel structural diseases, such as tunnel lining strength, cavities behind the lining, etc., tunnel structural diseases still rely on manual detection methods, and the detection efficiency is low; (2) The degree of automatic identification is low, and automatic identification and manual correction are required; (3) The detection speed is slow, which cannot meet the needs of a large number of tunnel inspections in our country; (4) Most of the current inspection vehicles are inspection vehicles for road tunnel diseases. The research and development of inspection vehicles for subway tunnel inspection is relatively small.
5. Future development trend of subway tunnel inspection vehicles

Summarizing the development of tunnel structural disease detection technology in recent years, the following four trends can be seen: 1) Detection automation, various sensors and automatic detection equipment are increasingly used in disease detection, and the method of disease detection tends to change from traditional manual detection to Semi-automatic detection and full-automatic detection; 2) Real-time detection, due to the development and popularization of sensor equipment, especially the research and development of fully automatic monitoring equipment, the detection frequency tends to be real-time monitoring instead of timing detection; 3) The detection is integrated, and the detection tool is changed from a single Disease detection instruments tend to be integrated disease detection systems, which can detect multiple diseases at once with one device. 4) Comprehensive testing. Tunnel testing should not only be limited to the detection of surface diseases. Future development should focus on the structural diseases of the tunnel. Structural diseases are difficult to find, but the harm to the tunnel is huge, so we should devote ourselves to research and development. High-efficiency testing is performed on the equipment to ensure the safe operation of the tunnel structure.

6. Conclusions

This article summarizes and analyzes the existing subway tunnel inspection technologies, briefly introduces a variety of new inspection technologies represented by high-speed array cameras to collect lining surface images, three-dimensional laser scanning to detect tunnel contour deformation, etc. At the same time, this paper introduces different types of comprehensive inspection vehicles at home and abroad. It points out the current problems of detection technology and the development trend of tunnel detection technology, and provides ideas for the development of subway tunnel detection vehicles.

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