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Development of track geometry inspection equipment for high-speed comprehensive inspection train in China

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Abstract

Purpose – This study aims to analyze the development direction of track geometry inspection equipment for high-speed comprehensive inspection train in China.

Design/methodology/approach – The development of track geometry inspection equipment for high-speed comprehensive inspection train in China in the past 20 years can be divided into 3 stages. Track geometry inspection equipment 1.0 is the stage of analog signal. At the stage 1.0, the first priority is to meet the China's railways basic needs of pre-operation joint debugging, safety assessment and daily dynamic inspection, maintenance and repair after operation. Track geometry inspection equipment 2.0 is the stage of digital signal. At the stage 2.0, it is important to improve stability and reliability of track geometry inspection equipment by upgrading the hardware sensors and improving software architecture. Track geometry inspection equipment 3.0 is the stage of lightweight. At the stage 3.0, miniaturization, low power consumption, self-running and green economy are co-developing on demand.

Findings – The ability of track geometry inspection equipment for high-speed comprehensive inspection train will be expanded. The dynamic inspection of track stiffness changes will be studied under loaded and unloaded conditions in response to the track local settlement, track plate detachment and cushion plate failure. The dynamic measurement method of rail surface slope and vertical curve radius will be proposed, to reveal the changes in railway profile parameters of high-speed railways and the relationship between railway profile,

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track irregularity and subsidence of subgrade and bridges. The 200 m cut-off wavelength of track regularity will be researched to adapt to the operating speed of 400 km/h.
Originality/value – The research can provide new connotations and requirements of track geometry inspection equipment for high-speed comprehensive inspection train in the new railway stage.

Keywords Track geometry inspection equipment, High-speed comprehensive inspection, Potential tapping requirements and technological direction, High-speed railway
Paper type General review

1. Introduction

In high-speed railway infrastructure, track regularity affects the safety and comfort of train operation. The track irregularity will exacerbate the interaction between track and vehicle and shorten the maintenance cycle and service life of key components of the vehicle track coupling system. Therefore, track regularity is one of the core contents of the research on the service status of high-speed railways (Li, Yang, & Ma, 2020; Niu, Liu, Xiao, & Xu, 2022). As the focus of China's high-speed railway technology development shifts from structural and functional design to operational safety assurance, improved operational quality and maintenance efficiency, how to maintain the high regularity of high-speed railway track service has also become one of the key scientific issues for the healthy development of high-speed railway technology (Wang, Zhang, Yang, Zuo, & Liang, 2019; Niu, Qu, Yang, & Liu, 2022). China's high-speed railways adhere to the maintenance and repair policy of "dynamic inspection as the mainstay, combined with static inspection." Based on the dynamic inspection data of a high-speed comprehensive inspection train with constant speed and load, combined with on-site static overlimit review, scientific operation guidance strategies are formulated.

The high-speed comprehensive inspection train is high-precision and cutting-edge mobile equipment in the field of railway infrastructure inspection. The track geometry dynamic inspection equipment for high-speed comprehensive inspection trains has played a huge role in ensuring safety warning and guiding on-site maintenance for high-speed railways. It provided technical support for promoting the implementation of precise maintenance, preventive maintenance and advanced safety prevention of track infrastructure. The track geometry dynamic inspection equipment for high-speed comprehensive inspection trains is an essential technical equipment to ensure the safe operation of high-speed railways. The development of high-speed comprehensive inspection train in foreign countries started earlier, but their related technologies had remained basically unchanged for 20 years (Xu, 2008; Li, Liang, & Wang, 2018). There are few references to foreign high-speed comprehensive inspection trains, and more literature focuses on the development of high-speed comprehensive inspection train in China (Li, Wang, Kang, & Li, 2014; Chen, 2017; Ma & Gao, 2020). The first developed "No. 0 high-speed comprehensive inspection train" has filled the gap in this field in China. The CRH380BJ-A high-altitude high-speed comprehensive inspection train based on the CRH380BG high-altitude Electric Multiple Units (EMU) technology platform developed in China has filled the gap in comprehensive inspection trains in high-altitude areas. The high-speed comprehensive inspection train based on the 500km/h "higher speed level test train" has been developed. The first "world-leading high-speed comprehensive inspection train" based on the Fuxing high-speed train technology platform in China has been developed. As the country with the longest operating mileage of high-speed railways, China currently has 16 high-speed comprehensive inspection trains of different speed levels, with a usage quantity ranking at the world's leading level. Since 2015, the annual inspection mileage of high-speed comprehensive inspection trains in China has exceeded one million kilometers. The first high-speed comprehensive inspection train developed by China with fully independent intellectual property rights exported to the

Jakarta–Bandung high-speed railway has further consolidated China's leading position in the world industry for high-speed comprehensive inspection trains (Wan, Yang, Liu, & Zhao, 2023). The high-speed comprehensive inspection train is also a brand of advanced manufacturing equipment in China. On the basis of summarizing the existing technologies and practical applications of high-speed comprehensive inspection trains, the "General Technical Conditions for High-Speed Comprehensive Inspection Trains" (Q/CR667-2018) has been formulated. Existing literature mainly discusses the overall architecture and functional indicators of high-speed comprehensive inspection trains in China. Some scholars briefly discussed the improvement direction of high-speed comprehensive inspection trains (Yao, Chen, Tao, Yang, & Wang, 2020). However, related scholars have not systematically reviewed the development of track geometry inspection equipment.

The organizational structure of this paper is arranged as follows: development characteristics of track geometry inspection equipment for high-speed comprehensive inspection trains are analyzed in Section 2, the proposed China's high-speed railway track geometry inspection requirements are given in Section 3 and Section 4 presents the investigation results discussion and conclusions.

2. Development characteristics of track geometry inspection equipment

According to the national conditions and high-speed railway plan, the track geometry inspection equipment for high-speed comprehensive inspection trains with Chinese characteristics has been developed for Chinese railways. In order to meet the needs of economic and social development, different emphases have been imposed on the development of track geometry inspection equipment in different periods of China's railway. The roadmap for the development of track geometry inspection equipment is illustrated in Figure 1. It constantly employs the inertial reference method, a globally predominant approach. Track geometry irregularities are delineated through the measurement of displacement of the car body or bogie in relation to the inertial reference. The evolution of track geometry inspection equipment in China can be delineated into three distinct phases, reflecting advancements in technology and operational requirements. The initial phase, designated as track geometry inspection equipment 1.0, was characterized by the use of analog signals. During this era, the primary focus was to fulfill the fundamental needs of China's railways, encompassing pre-operation joint debugging, safety evaluations

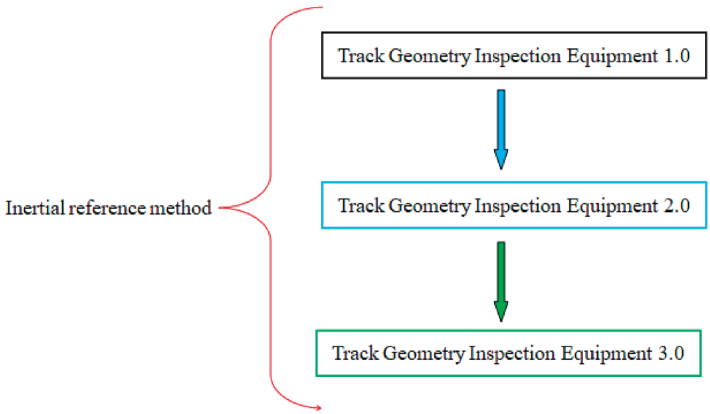

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Figure 1. Roadmap for the development of track geometry inspection equipment

and routine dynamic inspections, maintenance and repairs post-operation. Transitioning to the second phase, track geometry inspection equipment 2.0 marked the shift to digital signals. This period was pivotal in enhancing the stability and reliability of the equipment through hardware sensor upgrades and software architecture improvements. The third and most recent phase, track geometry inspection equipment 3.0, embodies the concept of lightweight design. At this stage, there is a concurrent development toward miniaturization, reduced power consumption, autonomous operation and a commitment to the green economy, all driven by evolving demands.

2.1 Track geometry inspection equipment 1.0 for high-speed comprehensive inspection train

Track geometry inspection equipment 1.0 is the stage of the analog signal. The first priority is to meet China's railways basic needs of pre-operation joint debugging, safety assessment and daily dynamic inspection, maintenance and repair after operation. It adopts new technologies such as high-speed image processing technology, photoelectric measurement technology, a gyroscopic platform, precise mileage positioning and high-speed computer real-time data processing to achieve the inspection of geometric irregularities such as track gauge, alignment, height, horizontal, curvature and triangular pits, as well as the inspection of significant ground features such as vehicle horizontal and vertical vibration acceleration, turnouts and bridges.

It can be seen from Figure 2 that track geometry inspection equipment 1.0 mainly consists of six parts: laser camera component, inertial measurement component, signal processing component, mileage positioning component, data processing component and mechanical suspension device (Wei, Liu, Zhao, Li, & Wang, 2011; Wei, Li, Zhao, & Chen, 2012).

The laser camera component consists of a machine vision measurement sensor that is installed on the inspection beam to provide machine vision measurement sensors for measuring the vertical and horizontal displacement of the bogie relative to the steel rail (Wang, 2018). It includes a high-speed camera module, a laser light source module, a front-end image processing module and a vibration damping sealing adjustment device.

The inertial measurement components are the core of inertial measurement technology, consisting of inertial sensors such as gyroscopes and accelerometers. Gyroscopes are used to establish a stable navigation coordinate system, while accelerometers are used to measure the acceleration signal of the carrier. After secondary integration calculation, the relative motion displacement of the carrier relative to the inertial reference coordinate system can be obtained. Inertial devices are used in measurements of height, orbit, horizontal, super elevation and triangulation.

The signal processing component includes a high-precision power pack, analog signal processing and monitoring module, laser camera control power supply, etc. Its main function is to provide power supply for sensors, analog signal processing board, temperature controller, time relay, etc. At the same time, it performs analog filtering, amplification, conditioning and other processing on the signal, measures the temperature of the camera and controls heating and cooling.

The mileage positioning component has multiple mileage source data collection and processing channels, which can publish unified positioning synchronization information in real-time for multiple clients, including driving direction, real-time mileage, increase and/or decrease mileage, real-time speed, time, etc. After receiving this information, the track inspection system integrates it with real-time inspection information to obtain inspection data containing accurate mileage information (Xia, Wang, Liu, & Zhang, 2017).

The data processing component is a vehicle-mounted local area network system composed of database servers, real-time processing computers, data application computers,

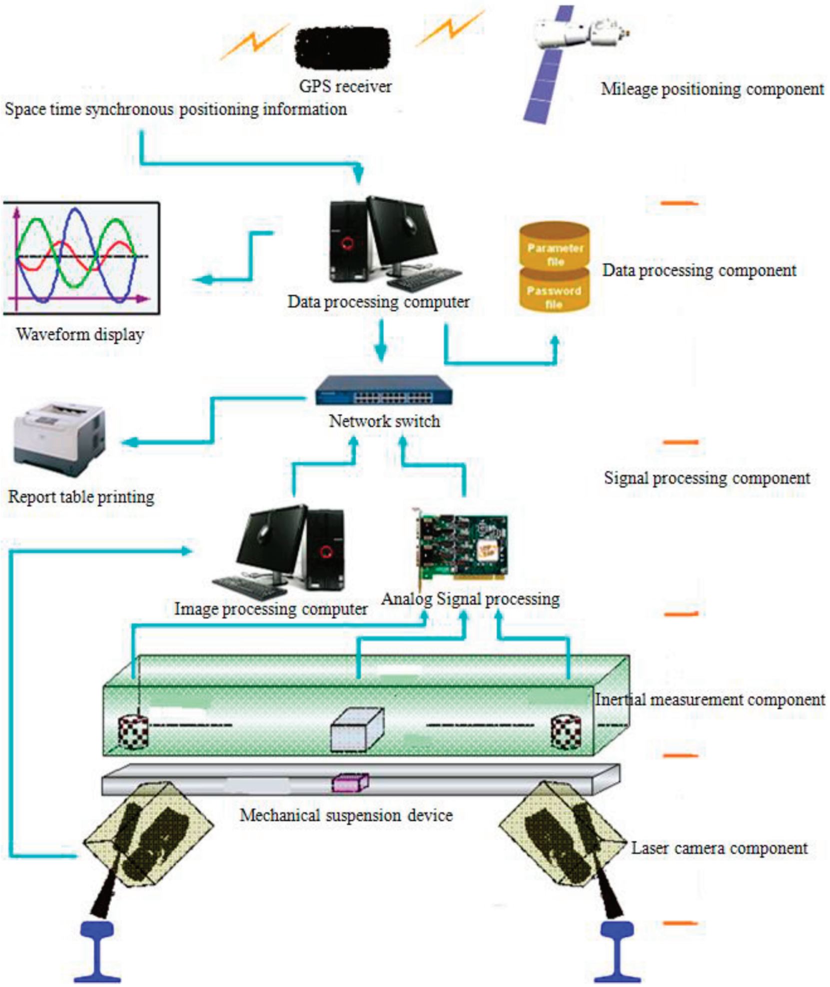

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Figure 2.
Architecture diagram of track geometry inspection equipment 1.0

network printers, switches and other equipment. Quantum NeXT (QNX) real-time multitasking operating system is installed on the real-time processing computer for track inspection run real-time data processing. This computer is equipped with a multifunctional interface board and an analog-to-digital (A/D) conversion board. The multifunctional interface board is mainly used to receive distance pulse signals, calculate the sampling interval time through an oscillator and counter, generate sampling interrupt signals and trigger the A/D conversion board to perform a data acquisition on all sensors. The track inspection data are transmitted to the database server through the network, and the data stored in the database include track geometry over limit data, track geometry waveform data, etc. All stored track inspection data are available for workstation applications to call and can extract the peak, length and position of detection items that exceed the standard. It can also edit and organize the out-of-limit locations and output an out-of-limit report table.

Data application computers can run applications such as over limit data browsing, waveform over limit browsing, waveform printing and over limit printing.

2.2 Track geometry inspection equipment 2.0 for high-speed comprehensive inspection train

Track geometry inspection equipment 2.0 is the stage of digital signal. At stage 2.0, it is important to improve stability and reliability of track geometry inspection equipment by upgrading the hardware sensors and improving software architecture. The track geometry inspection equipment was developed based on digital signal by using laser camera components and inertial components for digital signal transmission and collecting them into a computer through digital signal transmission for track geometry parameter synthesis calculation (Li, Yang, & Ma, 2020). It was called digital track geometry inspection equipment. It can be able to inspect basic track geometry items (such as gauge, left height, right height, left rail direction, right rail direction, super elevation, horizontal and triangular pit) and auxiliary evaluation indicators (such as track quality index and gauge change rate).

The digital signal transmission method is reliable and not easily affected by electromagnetic interference. The backend uses digital signal processing methods to filter and adjust the signal, improving system performance. The architecture of fully digital track inspection equipment based on digital sensors, digital signal transmission and digital signal processing was researched. The inertial component was installed in the inspection beam under the vehicle. The track geometry parameter calculation model and compensation and correction methods based on the relative position relationship between the inspection beam and the track were established. Using modern signal processing methods, data processing algorithms were designed and optimized to improve the accuracy of track geometry parameter inspection. The calibration method of digital signal track inspection equipment was different from that of the analog signal track inspection equipment. The gain-and-phase adjustment of the signal needs to be completed by software, and the calibration parameters can be automatically adjusted using fitting functions or table lookup methods, which has a certain effect on improving inspection accuracy.

The structure of digital track geometry inspection equipment was simple, as shown in Figure 3. The measurement sensors were installed on the inspection beam under the vehicle, and the onboard equipment was used to receive and process the sensor signals and output inspection results, while receiving mileage positioning information. The inspection beam was installed on the bogie under the vehicle, and laser camera components were installed on both sides of the inspection beam to provide lateral and vertical unilateral displacement. The inertial component inertial measurement unit (IMU) was installed in the middle of the inspection beam, which integrated three axial gyroscopes and three axial accelerometers. The digital automatic location detector (ALD) was installed in the middle of the inspection beam to detect ground signs (Liu, Gou, Cheng, & Cui, 2019). Digital accelerometers were installed in the vehicle to measure lateral and vertical acceleration. Geographical Positioning System (GPS) positioning was used for mileage reception. The onboard computer collected and processed these sensor signals. The track geometric parameters were finally obtained by the signal compensating, filtering and calculating based on the corresponding track geometric parameters model.

Comparing the track geometry inspection equipment 1.0 and 2.0, we can see the following differences.

The track geometry inspection equipment 1.0 uses all analog signal sensors, and analog filters are used for pre-processing sensor signals, which are completed by analog circuit boards such as capacitors and inductors. The structure of track geometry inspection equipment 1.0 is relatively complex, and the sensors used for measurement are distributed.

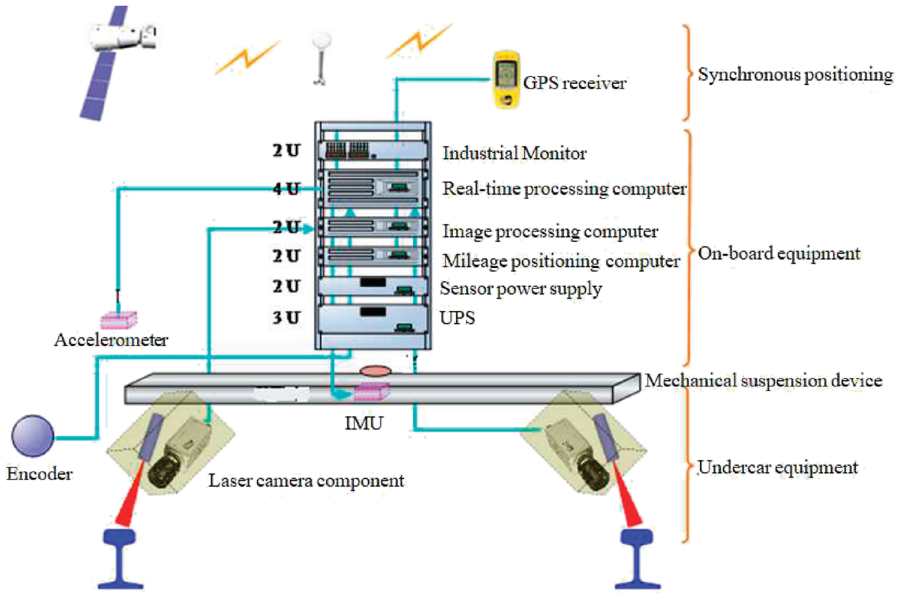

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Figure 3. Architecture diagram track geometry inspection equipment 2.0

Sensors are installed both on and off the vehicle, and the Compensated Assembly System (CAS) is installed in the middle of the vehicle. Vertical accelerometers and cable displacement sensors are installed on the left and right sides of the vehicle, respectively. The inspection beam is suspended on one side of the bogie end, and laser camera components are installed on both sides of the inspection beam to measure the track lateral displacement. The transverse accelerometer is installed in the middle of the inspection beam. The signal conditioning unit in the vehicle contains a hardware circuit board that simulates the filtering, conditioning and monitoring of signals. The sensor signal is collected by the A/D conversion board and enters the computer to calculate the track geometric parameters based on the corresponding mathematical model.

The sensors used in the track geometry inspection equipment 1.0 mainly include discrete gyroscopes and inclinometers, accelerometers, cable displacement sensors and laser camera components for measuring lateral displacement. The cable displacement meter reflects the deformation of the track directly below the wheel axle under dynamic loaded operation. The advantage of this displacement meter is that it has a large range, suitable for measuring large changes between the vehicle body and the frame, good resistance to environmental interference, low cost and easy installation. However, it also has the disadvantages of low frequency response, easy resonance or abnormal expansion and contraction and a high damage rate. The sensors of track geometry inspection equipment 1.0 are installed in three positions: axle box, bogie and vehicle body. The mathematical model of the 1.0 is relatively complex.

The track geometry inspection equipment 2.0 uses all digital signal sensors, which transmit signals through the controller area network (CAN) bus. After acquisition, the signal spectrum can be changed through software programming. It has high accuracy, strong electromagnetic interference resistance, high reliability and is not easily affected by environmental temperature. Digital filters are capable of time-division multiplexing and can simultaneously process multiple signals.

The track geometry inspection equipment 2.0 has a simple structure, with all sensors installed on the inspection beam at the end of the bogie. All accelerometers, gyroscopes and other inertial sensors are integrated into an IMU. Unlike the track geometry inspection equipment 1.0, the laser camera component of the track geometry inspection equipment 2.0 not only measures the lateral displacement of the steel rail but also the vertical displacement, without the need for loss-type sensors such as cable displacement sensors. All signals are transmitted to the computer through the CAN bus and calculated based on a mathematical model, making the mathematical model simpler. It has the advantages of strong anti-interference ability, few system failure points and easy maintenance.

The sensors used in the track geometry inspection equipment 2.0 mainly include three-axis acceleration and gyroscope integrated inertial component IMU and laser camera component. Both horizontal and vertical displacements in the 2.0 are captured by laser camera components through capturing rail section images, which are then processed through image processing algorithms such as binarization, refinement, coordinate rotation and feature point extraction before being output. Its advantages include high accuracy, high sensitivity, a wide frequency response range and a low loss rate. However, it is also susceptible to interference from rain, snow and sunlight. Currently, non-contact measurement methods using laser cameras are used at home and abroad.

2.3 Track geometry inspection equipment 3.0 for high-speed comprehensive inspection train

Track geometry inspection equipment 3.0 is the stage of light weight. At stage 3.0, miniaturization, low power consumption, self-running and green economy are co-developing on demand. The existing track geometry inspection equipment including 1.0 and 2.0 is scattered, and the size of the equipment is relatively large after assembly, as shown in Figures 3 and 4. After the opening of the Hainan East Ring Railway in 2012, the first set of track geometry inspection equipment based on operating high-speed EMU trains was developed in China. The track geometry inspection equipment has been simplified to meet

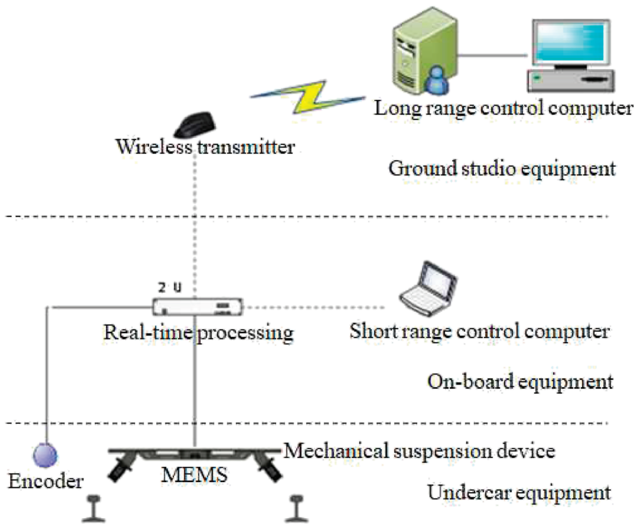

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Figure 4.
Architecture diagram track geometry inspection equipment 3.0

the urgent needs of track geometry inspection on the Hainan East Ring Line (Peng, Li, & Wei, 2017). However, there is still a big gap from lightweight. It can be seen from Figure 4 that track geometry inspection equipment 3.0 integrates functions such as control, acquisition, processing and analysis to form a small device unit inside the vehicle and a lightweight suspension device outside the vehicle. The size of the track inspection equipment's interior part is not more than 2U, and the weight of the exterior part is not more than 50kg, which is much lower than the size and weight of the existing track geometry inspection equipment. The processor within the device unit has comprehensive functions such as control, collection, processing, analysis, etc.

The existing track geometry inspection equipment (1.0 and 2.0) adopts X86 architecture processing boards, with each processing board consuming approximately 80-120W. Both continuous laser sources and traditional sensors have high energy consumption. Track geometry inspection equipment 3.0 is designed to use low-power devices such as pulse lasers, Micro-Electro-Mechanical Systems (MEMS) sensors, Advanced RISC Machines (ARM) processors, etc. to reduce the power consumption of the entire system to less than 100W.

Track geometry inspection equipment 3.0 has multiple operating modes, including short range control, long range control and automatic operation. Close range control is a traditional operating mode. It develops a remote control mode, which allows users to control and test the equipment on the vehicle in offices, data centers and other locations through network connections. The control content includes on/off, parameter settings, software upgrades, data uploading and downloading, etc. The automatic operation mode is set in advance to detect the automatic operation of the system without the need for manipulation.

3. China's high-speed railway track geometry inspection requirements

As of the end of 2023, China's railway operating mileage was 159,000 kilometers, including 45,000 kilometers of high-speed railway operating mileage, ranking first in the world. The railway projects among the 102 major projects identified in the Outline of the 14th Five-Year Plan of the country have been smoothly promoted. The Outline of the Leading Plan for a Strong Transportation Railway in the New Era clearly states that by 2035, the operating mileage of the national railway network will reach about 200,000 kilometers, including about 70,000 kilometers of high-speed railways. China has the world's largest high-speed rail operation network, with very complex operating scenarios and external environments. With the gradual accumulation of operating experience over the past decade and the exploration of safe operation rules for high-speed railway equipment, many new problems that were not encountered or studied in the past have gradually emerged. More and more urgent requirements have been put forward for the functions and applications of track geometry inspection equipment for high-speed comprehensive inspection trains.

With the extension of the service life of high-speed railway track infrastructure, hidden dangers and problems in the status of some high-speed railway track infrastructure are frequently emerging, such as local settlement, track slab detachment and pad failure. Some track infrastructure diseases lack efficient and reliable inspection methods. The research on effective dynamic inspection equipment for such diseases is of great significance for improving the safety guarantee capability of high-speed railway infrastructure. The track stiffness changes dynamic inspection will be studied under loaded and unloaded conditions in response to the track local settlement, track plate detachment and cushion plate failure. To reveal the changes in railway profile parameters of high-speed railways and the relationship between railway profile, track irregularity and subsidence of subgrade and bridges, a dynamic measurement method for rail surface slope and vertical curve radius based on an inertial measurement unit will be studied in response to the lack of dynamic inspection equipment for parameters of railway profile in China.

With the basic construction of China's high-speed railway network, the inspection cycle for large-scale operation of railway networks is becoming longer and longer. Further improving the speed of operational testing is a necessary means to enhance the efficiency of high-speed railway comprehensive train testing and meet on-site needs. At the same time, the design standards for high-speed railway with higher speed levels (400 km/h and above) are already being planned. The high-speed railway comprehensive inspection trains with higher speeds are important equipment to support the construction of high-speed railways with higher speed levels and meet the needs of joint debugging and testing of higher-level railways. The 200 m cut-off wavelength of track regularity will be researched to adapt to the operating speed of 400 km/h.

4. Conclusion

The development practice of track geometry inspection equipment for high-speed comprehensive inspection trains over the past 20 years has distinct characteristics in China. At the stage of analog signal, the first priority is to meet China's railways basic needs of pre-operation joint debugging, safety assessment and daily dynamic inspection, maintenance and repair after operation. At the stage of digital signal, it is important to improve stability and reliability of track geometry inspection equipment by upgrading the hardware sensors and improving software architecture. At the stage of lightweight, the miniaturization, low power consumption, self-running and green economy are co-developing on demand. Track geometry inspection equipment has evolved from 1.0 to 3.0, with significant improvements in both structure and performance. With the extension of the service life of high-speed railway track infrastructure, hidden dangers and problems in the status of some high-speed railway track infrastructure are frequently emerging. The ability of track geometry inspection equipment for high-speed comprehensive inspection trains will be expanded. The track stiffness changes dynamic inspection will be studied under loaded and unloaded conditions in response to the track local settlement, track plate detachment and cushion plate failure. The rail surface slope and vertical curve radius dynamic measurement method will be proposed to reveal the changes in railway profile parameters of high-speed railways and the relationship between railway profile, track irregularity and subsidence of subgrade and bridges. The 200 m cut-off wavelength of track regularity will be researched to adapt to the operating speed of 400 km/h.

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