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Rail Detection Research Status of Multi -Sensing Technology

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Abstract:

Traditional rail inspection methods, primarily relying on manual inspection and basic equipment, face significant challenges including low efficiency, poor accuracy, and susceptibility to human error. This paper presents a comprehensive review of the current research status and future trends in multi-sensor rail transit inspection vehicles. The focus is on the integrated application of various sensing technologies, particularly inertial systems and visual sensing, to achieve high-precision and efficient measurement of rail geometrical parameters. An in-depth analysis of key technologies and challenges in railway track inspection is provided, exploring how advanced sensing methods can overcome the limitations of traditional approaches. The paper also examines the market prospects for rail transit inspection, highlighting the growing demand for more sophisticated and reliable inspection systems. Furthermore, potential future research directions in this field are outlined, including the development of AI-powered data analysis, real-time defect detection algorithms, and the integration of emerging technologies such as LiDAR and thermal imaging. This review aims to provide valuable insights for researchers, engineers, and industry professionals working on advancing rail inspection technologies.

Keywords: Multi -sensing technology; rail detection; inertial sensor; visual sensing.

1. Introduction

With the growing global transportation network and the popularity of high-speed trains, the safety and stability of the track has become a key factor in ensuring the overall transportation safety. The basis of locomotive and vehicle operation depends on the railway track, the wheels directly support the locomotive and the vehicle, the stability, comfort and safety of the train operation will be directly affected by the geometric state of the track, even a small orbital deformation can bring a

lot of wheel-rail forces, affect the safety of driving, limit the driving speed. In order to ensure that the rail safety of the operating period is necessary to adjust to the smooth state of the design, the basic premise is to accurately determine the position and the size of the orbital deformation. In order to effectively do the rail maintenance work, it is essential to quickly and accurately measure the system. The precise measuring rail geometry is of great significance for the repair of the entire track.

Traditional rail testing methods mostly depend on artificial inspections, not only low efficiency, but also difficult to cope with the complex and varied track environment. At the same time, due to the limited maintenance time of high -speed rail maintenance, the maintenance tasks are very arduous.

The measurement of high -precision rail testing is essentially determining the three -dimensional position coordinates of the rail and the relative relationship between the two rails. The precision measurement of the rail geometry is urgent. It can quickly and accurately measure the orbit in a short time, and at the same time, it meets the requirements of two aspects: efficiency and accuracy. This is an urgent need to solve engineering technology and method issues. Therefore, the development of an intelligent rail detection vehicle that can automatically, efficient, and accurately detects the rail state is of great significance for improving rail maintenance levels and ensuring the safe operation of train trains. Based on the in -depth analysis of existing literature, this article combines the author's own thinking, and aims to in -depth discussion of inertia sensor and visual sensor [1][2]. How to achieve comprehensive, high -precision and real -time monitoring of the track status, so as to be rail transit The formulation of fine adjustments, efficient maintenance, low cost, and intelligent management strategies of the system provides a solid theoretical foundation and practical reference.

2. The application of multi -sensing technology in rail detection

2.1 Inertia sensor technology

2.1.1 Definition and function of inertial sensor

The inertial sensor is a sensor that can measure and perceive the motion of the object (such as acceleration, angle speed, etc.). Inertial sensors work by using built-in sensitive elements to sense the movement of an object in inertial space, and then convert these changes into measured and processed electrical signal outputs.

Inertial sensors have many functions in real physical scenarios, due to their internal characteristics, inertial sensors can monitor the acceleration of objects, angular velocity and other motion state parameters in real time, and also have the role of motion monitoring, and are essential for systems that need to accurately control the trajectory or attitude. Inertial sensors can provide an important basis for evaluating the dynamic performance of objects, because they can directly measure the dynamic parameters of acceleration and angular velocity of objects, which provides an important basis for evaluating the dynamic performance of objects, and it is of great significance for optimizing system design and improving operation efficiency and stability.

Secondly, the navigation and positioning effect. In the absence of external reference signal support, inertia sensors can independently and real time provide the position, speed, and direction information of the objects in real time, thereby achieving the ability of independent navigation. Although running independently may accumulate a certain error for a long time, this limitation can effectively make up for the organic combination with other advanced navigation systems (such as GPS global positioning system GPS), which can significantly improve the accuracy and positioning of navigation and positioning Reliability [3].

2.1.2 Application of inertial navigation in rail detection

Inertial sensor technology and rail testing are two important aspects in modern transportation. Their deep integration shows unique value in the maintenance of transportation infrastructure. The domestic single-axis fiber gyroscope demonstrates high accuracy, particularly in its exceptional zero bias stability [4]. These technical characteristics have planted the indispensable seeds for the application of inertial navigation systems in orbit detection. It cleverly uses gyroscope to capture the instantaneous angular velocity of the car during driving, analyzes the angle of the car in real time through the precise location, and combines the mileage data with the results of the angle point to build an efficient data processing mechanism, and the detailed track coordinates can be accurately calculated through this data fusion method, which not only reflects the data processing ability brought by technology fusion, but also ensures the comprehensiveness and accuracy of the track position information.

If the data of inertial sensing and the coordinate information from the total station are fused, the limitation of single-point detection can be overcome and accurate trajectory positioning can be achieved within the overall line design coordinate system. This innovative integrated application not only improves the accuracy and efficiency of track inspection, but also provides strong technical support for the safe operation and efficient maintenance of the railway transportation system, which has important practical significance and broad development prospects [5]. Well, in terms of track detection, to understand how the system works, it is important to consider the basic structure of the railway line: in the plane, the railway line is mainly composed of straight segments, transition curves and circular curves, in which the increase in the value of lateral deviation is theoretically zero. The use of a cars combined with high -precision optical fiber gyroscope to achieve accurate calculation of the three -dimensional coordinates of the track. It does not need to rely on the control network, which greatly improves maintenance efficiency and reduces costs. Among them, the inertial sensor can not only use the angular velocity data provided by the gyroscope to determine the orientation and inclination of the track, but also monitor the displacement between the equipment and the track and evaluate the straightness of the track. Compared with the detection efficiency of traditional GNSS and full station instruments is low, the steps are cumbersome, and the cost is high.

2.2 Visual sensing technology

2.2.1 Principles and function of visual sensing technology

The working principle of visual sensing technology is to capture the light information in the environment through optical devices such as cameras to form an image, and then use the image processing algorithm to analyze and process the image, and at the same time refine the useful information such as the shape, size, and position of the target, and summarize the extracted information according to the above, and the machine can make corresponding decisions and control to realize the interaction with the environment or the target object. The camera and the image processing system camera constitute the core components of the vision sensor: among them, the camera, as the “eye” of the visual sensor, is responsible for capturing the light information in the environment, converting it into electrical signals, and finally forming an image, and the quality of this part of the image will be directly affected by the performance of the camera; Second, the image processing system consists of two parts: hardware and software, which are mainly responsible for processing and analyzing the images captured by the camera, the hardware part, such as the image processor, which is responsible for the processing and conversion of image signals, and the software part contains various image processing algorithms for extracting useful information from the images [6].

Visual sensing technology is characterized by high-precision, high-resolution imaging, which can capture subtle changes and rich details of images, providing the basis for subsequent image recognition, processing, and analysis, which has proven its value in a variety of applications. This technology also has excellent real-time performance, which can quickly capture and process image information, and meet the needs of rapid response and instant feedback in dynamic environments. And this sensing technology is widely used in real-time monitoring, dynamic tracking and other visual sensing technology fields to ensure that the system can maintain a stable and efficient operation state in a complex and changeable environment.

2.2.2 The application of visual sensing technology in rail detection

Building on the inertial sensing techniques discussed earlier, the integration of visual sensing techniques into rail inspection offers significant advantages. If the vision sensor captures the detailed image data of the track at the same time, the inertial sensor simultaneously tracks the real-time dynamic changes of the track detection equipment, then a comprehensive monitoring system is formed. The two sensors maintain a specific rotation and migration relationship in space, and accurate calculations enable the efficient fusion of visual and inertial sensor data. Therefore, the precise emission of the relative position of visual sensing technology and inertial sensing technology is of great significance for the fusion of information between the two. This fusion technology not only improves the accuracy and efficiency of rail inspection, but also provides strong support for the application of modern robotics in the field of rail inspection [7]. In this report, this paper use binocular stereo vision technology, which is a method that uses two cameras to capture images of the measured object from different positions, and calculates the spatial three-dimensional coordinates of physical points by calculating the positional deviation between individual image points in different images of the same physical point. This process is shown in Fig. 1.

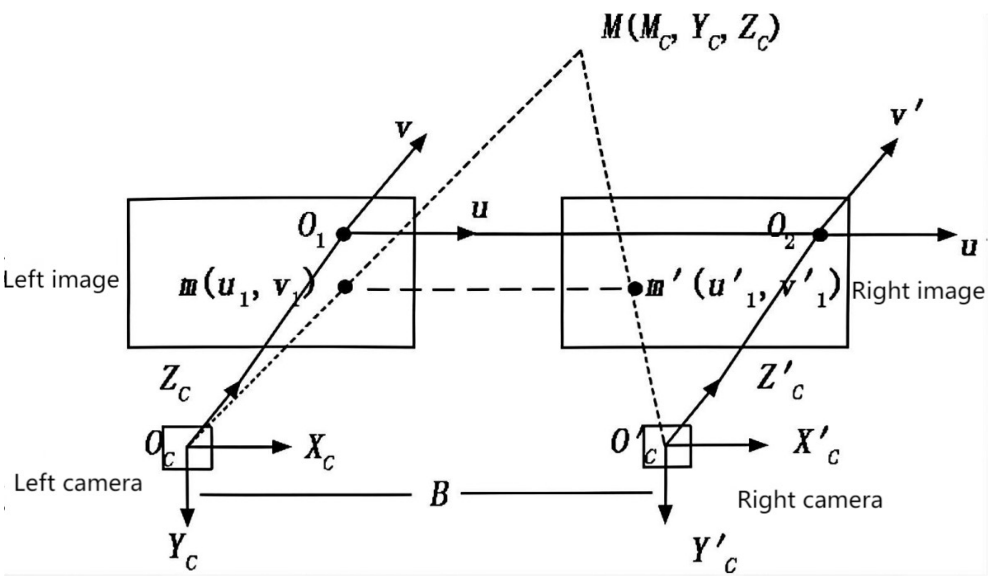

Fig. 1 Schematic diagram of the binocular vision system [7].

The vision sensor can not only capture the image of the track through the camera, analyze the geometry of the track (such as straight lines and curves), but also identify special marks, cracks and other defects on the track, and finally obtain visual information about the surrounding environment to provide reference for the surrounding conditions of the track.

2.3 Multi -sensor technology fusion

In rail detection, the visual sensing and inertial sensing can be effectively fused through the following methods: the system consists of a double -eyed visual system and an inertial measurement unit containing the gyroscope and the acceleration meter, and the two are fixed on the same motion carrier. Early rail inspection vehicles were primarily of the mechanical contact type, characterized by low detection speeds and limited inspection capabilities. Subsequently, the expansion Carman filtering algorithm combined the predictive values of the inertial measurement unit with the observation value of the visual vision, the extended Kalman filter algorithm achieves optimal estimation by predicting and updating the system state (position, attitude) and error state. The binocular vision measurement value is used as the prediction and the gyroscope measurement value is used as the observation, and the systematic error estimate is obtained through the filtering algorithm, which is fed back to the binocular vision system for status update, and the real -time update attitude matrix and error feedback were corrected, and the high -precision motion carrier space positioning information was finally obtained [8]. Fig. 2 shows the data fusion method, Fig. 3 shows the combination of gyroscope and vision sensors in orbit detection

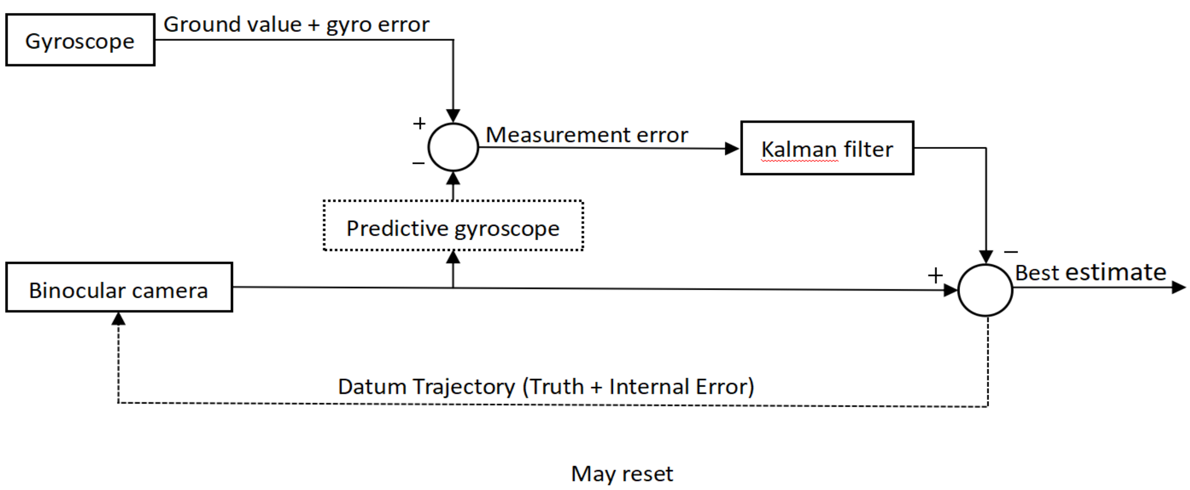

Fig. 2 A data fusion model based on the extended Kalman filter [8].

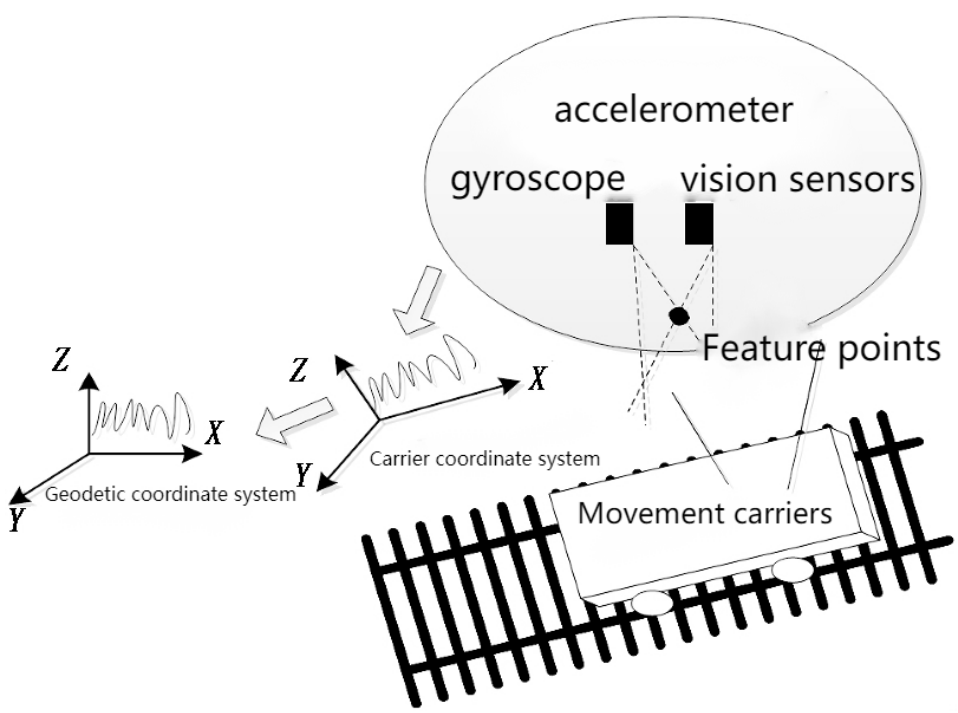

Fig. 3 Multi-sensor fusion detection system [9].

The detection method based on multi-sensor information fusion exhibits rich internal characteristics and has the effect of significantly improving the detection accuracy. The smoothness of the track line is guaranteed by fusing data from the binocular vision and inertial measurement units, which plays a crucial role in the safety and stability of train operation. The method's precise alignment in three-dimensional space covers its core parameters such as position, orientation, and shape.

If the specific content of the inspection is refined, the lateral, longitudinal, and vertical displacement of the track is accurately measured, and the possible deformation of the track such as tilt and distortion is analyzed in depth, then the geometric state of the track can be ensured to meet the safety and operation requirements, and the track diseases can be found and repaired in time, prolonging the service life of the track and providing strong support for the sustainable operation of the track [10]. In addition, the method also optimizes the train trajectory and speed control strategy, and also improves the operation efficiency of the train, which is of great significance for improving the overall efficiency of railway transportation. Finally, the development of intelligent trajectory detection technology is promoted through the method of multi-sensor fusion detection, which lays a solid foundation for the automation and intelligent transformation in the field of trajectory detection in the future.

3. Conclusion

This review of the track detection technology report based on multi-sensor technology provides an effective solution to the problems of low efficiency and poor accuracy of manual inspection in track detection, and realizes the high-precision and high-efficiency integrated measurement of track geometric parameters through the integrated application of multi-sensor technology, which provides a solid guarantee for the safe and efficient operation of rail transit. The application of multiple sensing technology in rail detection is constantly being applied. Its high precision, high efficiency and automation level have become an important trend in the future development of rail transit maintenance. According to the current research status, the future development direction of rail inspection technology can focus on the following aspects:

Develop a system based on cloud computing and big data platform to realize continuous monitoring and real-time feedback of railway status to improve safety and maintenance efficiency, and its system can quickly identify abnormal tracks and predict potential faults, provide scientific decision-making support for track maintenance, and realize the transformation from “in-event-in-event-maintenance” to “predictive maintenance”.

In the technology of inertial sensing and visual sensing technology, through the integration of satellite navigation, visual positioning and other technologies, high-precision orbit positioning and three-dimensional map construction system are developed to complete more efficient and intelligent orbit detection.

Develop a fully operational rail inspection vehicle and unmanned aerial vehicle inspection system, whose highly automated and intelligent rail inspection equipment can minimize human intervention, improve operational safety and efficiency, and enable it to perform efficient and accurate track inspection tasks in complex environments.

With the future progress of science and technology, rail transit detection will be promoted to the direction of more intelligent, automated and real-time capabilities, so as to make a significant contribution to the sustainable development of the rail transit industry, and at the same time, this paper should also pay attention to the challenges and constraints of technology application, and meet the growing demand for rail transit maintenance through continuous optimization and improvement.

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