Current status and prospects of research on safety situation awareness of high speed railway operation environment

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Abstract

Purpose – The safety of high-speed rail operation environments is an important guarantee for the safe operation of high-speed rail. The operating environment of the high-speed rail is complex, and the main factors affecting the safety of high-speed rail operating environment include meteorological disasters, perimeter intrusion and external environmental hazards. The purpose of the paper is to elaborate on the current research status and team research progress on the perception of safety situation in high-speed rail operation environment and to propose directions for further research in the future.

Design/methodology/approach – In terms of the mechanism and spatio-temporal evolution law of the main influencing factors on the safety of high-speed rail operation environments, the research status is elaborated, and the latest research progress and achievements of the team are introduced. This paper elaborates on the research status and introduces the latest research progress and achievements of the team in terms of meteorological, perimeter and external environmental situation perception methods for high-speed rail operation.

Findings – Based on the technical route of "situational awareness evaluation warning active control," a technical system for monitoring the safety of high-speed train operation environments has been formed. Relevant theoretical and technical research and application have been carried out around the impact of meteorological disasters, perimeter intrusion and the external environment on high-speed rail safety. These works strongly support the improvement of China's railway environmental safety guarantee technology.

Originality/value – With the operation of CR450 high-speed trains with a speed of 400 km per hour and the application of high-speed train autonomous driving technology in the future, new and higher requirements have been put forward for the safety of high-speed rail operation environments. The following five aspects of

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work are urgently needed: (1) Research the single factor disaster mechanism of wind, rain, snow, lightning, etc. for high-speed railways with a speed of 400 kms per hour, and based on this, study the evolution characteristics of multiple safety factors and the correlation between the high-speed driving safety environment, revealing the coupling disaster mechanism of multiple influencing factors; (2) Research covers multi-source data fusion methods and associated features such as disaster monitoring data, meteorological information, route characteristics and terrain and landforms, studying the spatio-temporal evolution laws of meteorological disasters, perimeter intrusions and external environmental hazards; (3) In terms of meteorological disaster situation awareness, research high-precision prediction methods for meteorological information time series along high-speed rail lines and study the realization of small-scale real-time dynamic and accurate prediction of meteorological disasters along high-speed rail lines; (4) In terms of perimeter intrusion, research a multi-modal fusion perception method for typical scenarios of high-speed rail operation in all time, all weather and all coverage and combine artificial intelligence technology to achieve comprehensive and accurate perception of perimeter security risks along the high-speed rail line and (5) In terms of external environment, based on the existing general network framework for change detection, we will carry out research on change detection and algorithms in the surrounding environment of high-speed rail.

Keywords High-speed rail operating environment, Situation awareness, Meteorological disasters, Perimeter invasion, External environment

Paper type Research paper

1. Introduction

The safety of high-speed railway operation environment is an important guarantee for the safe operation of high-speed railway. The operating environment of high-speed railway is complicated, and the main factors affecting the safety of the high-speed railway operating environment include meteorological disasters, perimeter intrusion and hidden dangers of the external environment. In recent years, there have been a number of traffic safety accidents caused by an abnormal high-speed railway operation environment in China, such as high-speed rail trains being temporarily suspended due to being hit by color steel plates due to strong winds or foreign objects hanging on the contact network caused by strong winds, which have a direct impact on the safety of operation and the order of operation and jeopardize the lives of travelers and the safety of their properties. Railway technology workers have made efforts for many years.

After years of efforts, railroad science and technology workers have formed a safety monitoring technology system and system for high-speed train operation environment based on the technical route of "situational awareness-assessment and early warning-active control," and the safety monitoring system for high-speed train operation environment mainly includes natural disaster and foreign object intrusion monitoring system, high-speed railroad seismic early warning system, comprehensive video monitoring system, perimeter intrusion alarm system and perimeter intrusion alarm system. These systems have played a good role in the safe operation of high-speed trains. However, these systems are constructed independently, and the meteorological disaster early warning capability still needs to be strengthened; railroad operation has higher requirements for system security and the existing perimeter intrusion monitoring technology has low recognition accuracy under bad weather conditions, which cannot meet the application conditions of on-site all-weather monitoring; the external environmental hazard management is actively exploring the research and application of air-heaven and space-heaven fusion monitoring technology; research and development of air-heaven and space-heaven coordinated safety situational sensing, precise recognition, early warning assessment, active control, etc. are also underway. There is still much room for improvement in the research of air-air cooperative safety situational awareness, precise identification, early warning assessment and active control. With the operation of CR450 train sets with a speed of 400 km/h and the application of automatic driving technology for high-speed trains in the future, the safety situational

awareness and risk early warning of high-speed railroad operation environment will face new challenges.

At present, scholars at home and abroad have carried out research related to train operation safety under severe wind and high cold wind and snow environments, but there are fewer researches on theories and methods related to the accurate identification and assessment of perimeter intrusion and external environment safety hidden dangers, and there is a lack of in-depth research on theoretical and methodological studies on the safety situational awareness and early warning of high-speed train operation environment at the level of 400-km-per-hour speed. Therefore, it is urgent to carry out in-depth research on scientific issues such as multi-factor coupling disaster-causing mechanism in high-speed railway operation environment, air-heaven-air cooperative high-speed railway operation environment safety situation sensing mechanism and high-speed railroad operation environment safety intelligent early warning theory.

2. The mechanism and spatial and temporal evolution laws of the main factors affecting the safety of high-speed train operation environment

2.1 The mechanism and spatial and temporal evolution of strong winds and snowstorms on high-speed trains

A strong crosswind environment is one of the main meteorological factors leading to train accidents and affecting the safety of train operation and a lot of research has been carried out both at home and abroad on the safety of traveling in a severe wind environment. Countries such as Sweden, the UK and Japan have established regulations for train operation in windy environments and constructed windbreaks in places with severe wind damage (Diedrichs, Sima, Orellano, & Tengstrand, 2007). In China, the South Central University for China's Xinjiang region, the Tibetan Plateau and other unique strong wind environments and climatic conditions, on the causes of high wind disasters, the reasonable structure of the wind protection engineering and trainside wind stability and other issues, through numerical simulation and testing to carry out a lot of basic theories and application of technical research (Baker, 2014), analyzed the topography, wind speed level, the angle of the wind on the operation of the lateral stability of the vehicle law, the study of the complex alternating environment wind field, spatial-temporal wind field and the study of the complexity of the wind field. It has analyzed the influence of topography, wind speed level and wind angle on the lateral stability of running vehicles, studied the temporal and spatial evolution of wind fields in complex alternating environments and revealed the influence mechanism of strong side winds, high altitude and low air pressure on the safe operation of trains. However, in the CR450 high-speed operation scenario, the flow field around the train will be changed into a compressible flow field and the coupling effect of bad weather such as strong ambient winds, strong winds + strong rainfall and the compressible flow field around the train on the operation of the train will be more complicated, so it is urgent to carry out relevant research.

The cold and snowy environment causes a lot of snow and ice to accumulate in the bogie area of high-speed trains, which seriously jeopardizes the safety and comfort of train operation. At present, the developed high-speed railroad countries such as Scandinavia and Japan mainly adopt the methods of line snow removal and ice melting to alleviate the problem of serious snow accumulation in the bogie area (Liu, Chen, and Guo, 2020). Zhongnan University is the first to carry out research on snow accumulation in the bogie area of high-speed trains in China, and has constructed a perfect numerical simulation of wind and snow two-phase flow in the bogie area of high-speed trains and an experimental research system of two-phase flow in wind tunnels (Wang, Gao, Liu, Xie, & Zhang, 2019), revealed the spatial and temporal characteristics of wind and snow movement in the bogie area of high-speed trains,

revealed the snow formation mechanism in the bogie area of high-speed trains (Wang, Gao, Liu, Xie, & Zhang, 2018) and proposed a series of underfloor deflecting anti-snow flow control programs to realize the snow-rich environment of high-cold and snowy environment and to achieve a high speed and comfortable environment. It also proposes a series of underfloor deflector anti-snow flow control schemes, which realize that the snow accumulation in the bogie area of a high-speed train under the environment of high cold and abundant snow can be reduced by more than 50% (Wang *et al.*, 2018). When the running speed of high-speed train is increased to 400km/h and above, the air property of bogie area will be changed from incompressible to compressible flow state and the snow and ice accumulation characteristic of bogie area of high-speed train under the strong wind – blizzard coupling extreme weather is more complicated and the following and inertia of the snow particles in the compressible flow field will no longer be clear and the snow and ice accumulation on the surface of the bogie will also be changed, which will lead to the snow accumulation mechanism of bogie area. The snow accumulation mechanism in the bogie area is difficult to distinguish, and it is urgent to carry out related research.

The suddenness, unpredictability and irregularity of lightweight foreign objects along the railroad have a serious impact on the safe operation of high-speed trains. Most of the railroad foreign body intrusions are detected by machine vision, such as hidden Markov Kalman filtering for foreign body detection and tracking (Gao, Tian, Wang *et al.*, 2020), but there are few studies on the trajectory and attitude of lightweight foreign body intrusions along the railroad.

In order to investigate the effects of wind speed and direction of strong sustained and dynamic random crosswinds on both sides of a high-speed train, the author's project team firstly constructed a numerical simulation method for turbulent inflow and turbulence maintenance of a high-speed train and then, constructed a numerical simulation system of inflow turbulence by combining the IDDES (Enhanced Delayed Separation of Eddies) turbulence model with the synthetic eddy inlet turbulence generating method and then, investigated the mesh distribution, the format of the flow direction discretization, the degree of turbulence and turbulence integration scale of the inflow and the turbulence integration scale of the inflow. The project team has identified the grid distribution, convective discretization format, different incoming turbulence degrees and turbulence integration scale on the mechanism of turbulent kinetic energy flow attenuation. The project team has determined a turbulent inflow maintenance method with a grid scale of 1/5 or less of the turbulence integral scale combined with a hybrid MUSCL (monotonic upstream center of conservation law) third-order/center-difference discretization format and clarified the self-similarity behavior of the attenuation of the turbulent inflow.

In order to investigate the mechanism of snow and ice accumulation in the bogie area of high-speed trains, the project team has studied the spatio-temporal evolution characteristics of snow particle motion in the bogie area of high-speed trains, as shown in Figure 1, and investigated the causes of snow accumulation in the bogie area of high-speed trains. Based on the train aerodynamics theory and the wind and snow discrete phase theory, the project team has established the numerical simulation method of wind and snow two-phase flow in the bogie area of high-speed trains, established the wind tunnel test method of two-phase flow in the bogie area of scaled-down trains, clarified the strategy of setting up the boundary of the numerical simulation of wind and snow two-phase flow and determined the time threshold of the numerical simulation of wind and snow two-phase flow.

2.2 Mechanism and spatial and temporal evolution of heavy rainfall on high-speed railway infrastructure

The disaster caused by heavy rainfall on roadbed facilities depends on specific geology, disaster-conceiving environment, climate change and train vibration loading. And the

Source(s): Authors' own work

Figure 1.
The spatio-temporal evolution characteristics of snow particle motion in the bogie area of high-speed train

disaster-conceiving environment and the state of the roadbed project feed back each other and the state of the roadbed project leads to the deterioration of the disaster-conceiving environment and the change of the disaster-conceiving environment further feeds back and leads to the aggravation of the damages and destruction of the roadbed project, especially under the influence of external triggering factors such as heavy rainfall and train load, which can lead to the formation of the disaster-inducing facilities of the roadbed very easily.

The characteristics of a heavy rainfall disaster-conceiving environment are the key to the study of disaster-causing causes and prevention and control techniques for roadbed facilities. Under the coupling effect of heavy rainfall and train cyclic loading, the mutual feedback between disaster-conceiving environment and roadbed engineering leads to the evolution of the whole process from deterioration, damage and destruction of roadbed engineering. In the research on the mechanism of disaster-causing mutual influence of environment and roadbed facilities in the case of heavy rainfall, scholars at home and abroad have chosen different precipitation elements to study the possibility factors that cause heavy rainfall and flooding disasters. Luo, He, and He (2014) analyzed the impact of heavy rainfall and water damage on the stability of roadbed facilities, revealing the characteristics of the environment of heavy rainfall disaster; Chu (2023) studied the mechanism of typical heavy rainfall-induced highway infrastructure disaster mode; Guo *et al.* (2013) conducted an in-depth analysis of the influence of the train cyclic loading on the roadbed facilities under the condition of heavy rainfall disaster; Sun and Lv (2013) conducted an in-depth analysis of the interaction between environment and roadbed engineering under the conditions of heavy rainfall disaster. Although good research work has been carried out, the research on the disaster-causing mechanism and influence range of roadbed facilities under the action of network-type roadbed facilities, regional roadbed collapse, large-scale water damage of major single-point water damage and cyclic loading of trains under heavy rainfall conditions is still insufficient.

In recent years, the frequent occurrence of global regional heavy rainfall has led to the frequent occurrence of disasters on railroad roadbed facilities. In the research on the disaster

mechanism of railway infrastructure caused by heavy rainfall, Zhang, Su, Liu , Liu, & Sun (2014) have studied the disaster mechanism of railroad infrastructure caused by heavy rainfall, but the research on the disaster mechanism of railway infrastructure caused by heavy rainfall describes the phenomenon but reveals the connotation less, so it is urgent to carry out in-depth research on the disaster mechanism of railroad infrastructure caused by heavy rainfall.

In the research on the transformation mechanism of heavy rainfall-convergence disaster, many researchers have studied the transformation of heavy rainfall-water condition-disaster and have obtained some research results. Hastamuga, Cai, and Shi (2013) on the basin "rain → water" conversion process and law analysis, revealing the formation of flash floods; Liu, Zhou, Jia, and Wang (2017) used the domestic hydrological model to carry out distributed hydrological modeling application research to explore the establishment of rainfall runoff modeling and analysis methods.

At present, there is an urgent need to study the formation mechanism of small and medium-sized river floods and flash floods on railroads and the study of climate-geography-geology-engineering characteristics, to select typical railroads with high susceptibility to water damage on roadbase as the object of study and to study the disaster-bearing capacity assessment technology of railroad roadbase equipment.

In order to study the characteristics of precipitation in the national road network, the project team adopts the gamma distribution to classify the rainfall level; adopts the trend analysis of linear regression to analyze the temporal characteristics of rainfall along the railroads; adopts the Inverse Distance Weighted (IDW) interpolation method to study the spatial characteristics of rainfall and selects the large-scale atmospheric circulation in East Asia and the regional precipitation in China as the four main characteristics of rainfall. Four models of large-scale atmospheric circulation in East Asia and regional precipitation in China were selected, and the optimal integration of the models and the numerical analysis of power downscaling were carried out according to the three emission scenarios of high, medium and low greenhouse gases and the characteristics of the future changes of rainfall in China's road network area under the background of climate warming were studied.

2.3 Lightning's mechanism and spatial and temporal evolution of traction system and signal system

China's high-speed railway is mostly erected by elevated way, and the viaduct actually acts as the grounding device of the contact network. Lightning strikes on the contact network cause lightning failure of the traction system and signal system (Su *et al.*, 2022), which is the main reason for lightning affecting the safety of high-speed rail transportation. The current research on the lightning characteristics of HSR contact networks at home and abroad is based on two main ideas: one is to analyze the lightning strike rate and induced voltage of traction systems by drawing on the method of transmission line of power systems (Tlhabanyane and Gomes, 2021); the other is to establish the development mode of lightning pilots and study the lightning characteristics of the contact network and its influence on the system by analyzing the process of lightning and ground. Existing research results show that: the lightning resistance level of the T line of the contact network is higher than that of the F line, but both of them are less than 4kA, more than 90% of direct lightning strikes on the contact network will cause it to flashover and trip and the grounding system composed of steel reinforcement inside the viaduct has a good current dissipation ability. When the lightning intensity is relatively large or the falling lightning is very close to the contact network, the induced over-voltage generated by the lightning may lead to the flashover of the F line and the T line successively and the probability of the occurrence of this situation is less than 1%.

Lightning strikes on the contact network and nearby areas cause transient voltage rises on the viaduct (Xiang *et al.*, 2016), which are induced in the signal cables laid on the viaduct and then conducted to the equipment ports to cause failures. Traction, signaling system lightning transient over-voltage level determines the degree of damage, signaling system lightning transient intrusion paths, superimposed coupling mechanism is complex, the current domestic and foreign signaling system lightning electromagnetic transient coupling quantitative analysis of multi-path coupling research is insufficient and is only concerned about the equipment port, for the transient electromagnetic harassment generated by a lightning strike, how the space radiation, field-line coupling and crosstalk and other paths to the system equipment, such as indirect impacts, the relevant research is very little. Indirect impact on the system equipment through spatial radiation, field – line coupling, crosstalk and other channels, the relevant research is very little.

For a long time, many lightning protection technical measures have been put forward and widely applied to high-speed railways, and good results have been achieved, but these technical measures are basically based on the line of "passive lightning protection," and the research on active defense such as lightning monitoring and early warning for high-speed railways is slightly insufficient. The main high-speed railway operating countries in the world have carried out relevant research on lightning monitoring and early warning, and China's meteorological, electric power and petrochemical industries have also carried out research on the characteristics of lightning activities based on the lightning monitoring system, which has better solved the problem of lightning protection in their own industries. The research and application of lightning monitoring and spatial and temporal pattern of high-speed railway are less, Xiang and others have studied the lightning distribution characteristics of the line based on the grid method (Xiang, Gu, Chen, & etc, 2015), but only analyzed the density and frequency of ground flashes by using the method of grid statistics, and detailed research is needed for the monitoring of lightning along high-speed railway and prediction of lightning risk of the line.

In order to study the characteristics of spatial electric field along the high-speed railway, the project team establishes the physical model of electrified railroad and the electric field analysis model, adopts the calculation method of HJ24-2014 Technical Guidelines for Environmental Impact Assessment of Power Transmission and Transformation Engineering and carries out the simulation and analysis of electric field under the situation of no load on the contact network; establishes the coordinate matrix of the contact network of the viaduct, realizes the discretization of the contact network system of the viaduct and adopts the ultra-relaxed iteration method to solve the Laplace equation and calculate the discretization of the contact network system of the viaduct. The Laplace equation is solved by the ultra-relaxed iterative method, and the potentials of discrete points are calculated to realize the simulation analysis of the electric field under loaded conditions. The simulation results show that the higher the height of the viaduct is, the more obvious is the degree of distortion of the electric field around the F-feeding wires at the corners of the edge of the contact network system.

3. High-speed rail operating environment meteorological, perimeter and external environment situational awareness method

Situational awareness is a kind of environment-based, dynamic, overall insight into security risks, that, is based on security big data from a global perspective to enhance the discovery and identification of security threats, understanding and analysis, response and disposal capabilities and ultimately, for decision-making and control, is the embodiment of security capabilities, including perception, understanding and prediction of the three aspects.

At present, situational awareness technology has been applied to electric power (Wu, Ota, Dong, Li, & Wang, 2018), civil aviation (Nguyen, Lim, Nguyen, Gordon-Brown, & Nahavandi, 2019), highways (Zhu, 2020), network security (Tao, Liu, Zhao, Yang, & Wang, 2018) and other fields. However, in the field of safety of high-speed rail operation environment, the situational awareness model has not yet been established for meteorological disasters, perimeter intrusion and external environment safety hazards, and the research is still insufficient.

3.1 Meteorological hazard situation sensing along high-speed railways

The major high-speed railway operating countries in the world generally attach importance to the monitoring and early warning of meteorological disasters along the railroad and research work. They monitor the data of meteorological elements along the railroads by installing sensors for wind, rain, snow, etc. along the railroads, and at the same time, they actively cooperate with meteorological departments to carry out research and experimental work on forecasting and early warning technology. For example, the Shinkansen of Japan has installed wind speed and direction meters, rain gauges and snow gauges along the line to monitor the wind, rain and snowfall along the line, and has developed a strong wind warning system, which has been tested on some of the lines. At the same time, it cooperates with the Meteorological Bureau to carry out the early warning research of local gusts, for example, Fukuhara, Takami, and Araki (2020) proposed an algorithm to extract the strong wind area at the surface and realized the estimation of surface wind speed by the high altitude gust index through the existing meteorological radar observed echoes and the Doppler wind speed index in the high-altitude layer and combined with the historical meteorological data. Before the construction of the disaster monitoring system, the French railway cooperates with the meteorological department and carries out experimental verification for a period of 1.5–2 years. By laying wind test sensors along the line and combining them with the analysis of meteorological data, it carries out the work of gale forecast and warning, predicts the wind speed and wind direction for the next 10 min and combines them with the rules of the transportation organization to form the speed limitation rules.

China's high-speed railroad has built a high-speed railroad natural disaster and foreign object encroachment monitoring system, which monitors the wind, rainfall and snowfall along the line by installing wind speed and wind direction gauges, rain gauges and snow depth gauges along the line and provides operation and management suggestions for the dispatching and commanding. Based on the railway and meteorological monitoring data, some scholars have analyzed the characteristics of meteorological hazards along the railroad, for example, Li *et al.* (2021) analyzed the characteristics of wind conditions in Dashengguan and Yangcheng Lake along the Jiangsu section of the Beijing-Shanghai high-speed railway through the simulation of instantaneous wind speed. Sun, Zhang, and Ma (2019) analyzed the wind characteristics along the Jinqin High-Speed Railway based on the meteorological station data and the mesoscale model of the historical typical windy weather process from 2009 to 2018 and identified the sections along the railway that are seriously threatened by wind damage. In terms of forecasting and early warning, scholars have done a lot of research, especially in wind speed prediction. The prediction methods include the time series prediction method based on railroad wind monitoring data and the neural network prediction method. Liu, Li, and Duan (2019) from Central South University proposed a model based on RBF neural networks, wavelet packet decomposition-extreme learning machines and wavelet decomposition-support vector machines. He, Duan, and Yan (2023) proposed a short-term wind speed prediction method based on a deep auto-regressive model (DeepAR), which is validated by using measured wind speeds of Pingtan Straits Dual-purpose Railway Bridge

and Xihoumen Bridge. Aiming at the problems of delay and false alarms in high wind warning for high speed railways, Jin, Ye and Xiong (2021) proposed a combined prediction model based on adaptive noise with fully integrated empirical modal decomposition and long and short-term memory neural networks, which reduces the complexity of the prediction and improves the prediction accuracy of the model at the same time. The existing research mainly focuses on the prediction based on historical steady wind data and the research on the prediction of non-steady wind speed and the prediction of meteorological disasters coupled with time and space is insufficient.

In order to study the method of aerodynamic optimization of high wind monitoring points based on the aerodynamic performance of high-speed trains, the team first conducts large-scale simulation of wind field characteristics in a large area near the ground along the railroad line and preliminarily identifies the areas where the wind condition is more dangerous; then it conducts research on the small areas individually and simulates the wind field characteristics of the small areas by densely setting up the high wind monitoring points and adopting a more detailed discrete grid and calculation conditions and initially selects the high wind conditions in each small area. Then the small areas are studied individually and the wind field characteristics of the small areas are simulated by using a finer discrete grid and calculation conditions, so that the location of the gale monitoring point is selected initially in each small area and the layout of the wind speed monitoring equipment is determined initially by the location corresponding to the maximum wind acceleration factor and the wind direction. The location of the maximum value of the overturning moment of the first car is used as the site selection of the wind monitoring point and the reasonableness of the location of the initially selected monitoring point is verified and adjusted to realize the optimization of the wind monitoring point.

In order to study the wind speed prediction method along the railroad by integrating the residual correction multi-model, the team first obtains the wind speed monitoring data from the meteorological station of Lanzhou-Xinjiang High Speed Railway in a large sub-area, completes the null processing of anomalous values and the denoising processing of the filter with slight smoothing of the wind speed data, completes the derivation calculation of a single wind speed eigenvalue and lays a data basis for the establishment of the wind speed prediction algorithms in the following. We make full use of the advantages of traditional machine learning (Least Squares Support Vector Machine, LS-SVM), which has fewer parameters and faster convergence and neural networks (Gated Recurrent Unit, GRU), which has better generalization ability, to establish the residual modification model and weights by combining the XGBoost algorithm and the vulture search method.

3.2 Perimeter security risk situational awareness along high-speed railroads

In the field of perimeter security risk sensing along high-speed railways, the research in recent years mainly focuses on the identification and alarm technology of perimeter intrusion. Based on fiber optic sensing, visual recognition, microwave detection and other sensing technologies, many scholars have carried out a lot of research on railroad perimeter intrusion recognition algorithms and models (Ren, Yao, Huang, Yang, & Zhu, 2021). For the railroad boundary area, Tian, Shi, Guo, and Zhu (2022) and other vision-based detection methods, proposed a multi-scale foreign object detection algorithm based on zoom multi-scale enhancement feature fusion; the public dataset test demonstrated better performance; for the railroad perimeter intrusion monitoring, Sha, Chen, and He (2020) proposed a distributed vibration fiber-based railway perimeter intrusion monitoring algorithm, the fiber is laid along the railroad tracks, sensing the surrounding vibration and the detection algorithm analyzes the vibration signal to determine whether there is intrusion. However, the accuracy and reliability of single sensor technology in the recognition of bad weather conditions still need

to be improved, so multi-sensor fusion technology has become an important development direction to improve the accuracy and adaptability of recognition.

By integrating data from different sensors, multi-sensor fusion technology improves the sensing ability of perimeter security threats and can identify intrusion behaviors more effectively under different weather and environmental conditions. In recent years, many experts and scholars have conducted in-depth research on perimeter security of high-speed railways and proposed a recognition model based on the combination of multiple sensor technologies (Xie & Qin, 2019). For railroad perimeter monitoring, Wen, Peng, Lin, Gan, and Tan (2024) designed a camera and LiDAR sensor fusion strategy for complex weather and foreign object intrusion detection, which shows the robustness under rain and snow conditions. For railroad perimeter intrusion monitoring, Guo, Shi, Ma, and Wang (2024) proposed a millimeter-wave radar and video fusion monitoring scheme and designed a "linkage + tracking" fusion algorithm. These algorithms have significantly improved the coverage, applicable weather and recognition effect compared with the single-sensor technology (Wang, Liang, Liu, & Shi, 2020). However, these studies are still insufficient in the comprehensiveness and real-time perception of perimeter intrusion posture.

For the perimeter security risk sensing of high-speed rail, the team comprehensively analyzes the characteristics and scene adaptability of the current single technical defense means and puts forward the multi-sensor fusion monitoring technology scheme of millimeter-wave radar + video, LiDAR + video and vibrating fiber optic + video for the typical scenarios along the high-speed rail, such as the base section of the road, the bridge, the road rift valley and the tunnel entrance, which achieves the complementary monitoring ability and anti-interference ability. Meanwhile, in order to realize the accurate identification of bad weather and complex scenes, we study the video detection algorithm based on a bidirectional feature pyramid network, attention mechanism, sensory field module, research on point cloud segmentation and clustering algorithms, combined with a rain and fog interference filtering algorithm and a weather recognition algorithm, put forward the decision-making fusion algorithm based on the evaluation of the degree of confidence and set up the experimental simulation field to carry out a simulated intrusion test under rain and fog conditions. The results show that the millimeter wave radar + video fusion method can realize the effective monitoring of the intrusion of people within 200 m range under the conditions of good weather, dense fog and heavy rain and the LiDAR + video fusion method can realize the identification of the foreign objects with the edge length of more than 30 cm within 60 m range.

It is found through research that although there has been some progress in the field of perimeter security risk sensing along high-speed railways, the monitoring performance of the current monitoring means will be greatly reduced when passing through heavy rain, dense fog and other weather, so the research on reliable sensing and fusion technology of foreign object intrusion on railroads under adverse weather conditions should be increased in the future to improve the performance and adaptability of the railroad environmental security monitoring system. With the continuous improvement of computing power, it is still necessary to carry out research on artificial intelligence technology in perimeter intrusion identification and tracking technology so as to realize security risk situational awareness and improve the system's ability to monitor complex environments and different types of intrusion behaviors.

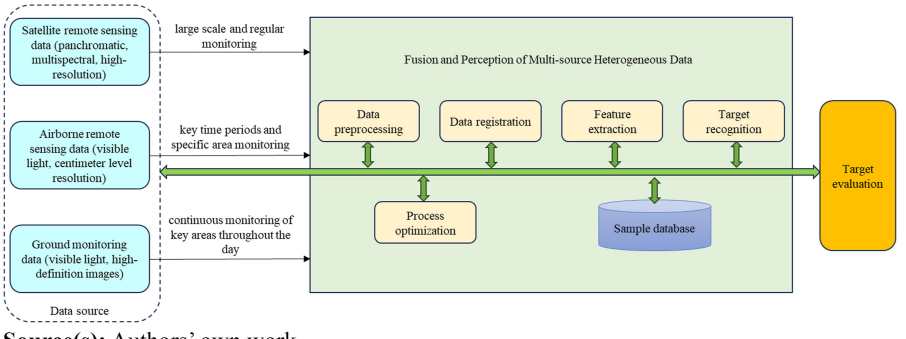
3.3 Situational awareness of safety hazards along high-speed railway lines

At present, most of the external situational awareness along the high-speed railway is based on remote sensing technology to monitor the external safety hazards of the railroad. With the research and development and application of China's high-resolution satellite data platform, the spatial resolution of remote sensing data has been significantly improved and the high spatial resolution multi-spectral remote sensing image data of the surface can be obtained at

meter and sub-meter levels through the high-resolution data platform. Therefore, it is possible to use multi-temporal high-resolution data to monitor the surface environment along the high-speed railway and study the corresponding high-resolution remote sensing monitoring program for the safety hazards of high-speed railway, as shown in Figure 2.

Using remote sensing data, various identification techniques for such hazards are proposed by exploiting features such as color, shadow, texture and geometric structure in remote sensing images. For example, Chen *et al.* (2021) proposed an optimal method combining morphological indexing and hierarchical segmentation to extract urban construction waste information in high-resolution images. By comparing the differences in spectral, geometric, texture and other features between the construction waste and the surrounding ground objects, a classification model based on knowledge rules is established to realize the fast and accurate extraction of construction waste information. Glanville and Chang (2015) compared the performance of algorithms for illegal waste disposal site identification and remote sensors for illegal waste disposal detection. Jiang *et al.* (2019) studied the monitoring technology of hard floating objects in the external environment of railroads based on high-resolution satellite images (0.5–1.0 m). Wang (2019) used Gaofen-2 remote sensing data as the data source and the improved multi-scale Forstner algorithm for feature point extraction to complete the spatial matching of different time-phase images. The SLIC super-pixel segmentation algorithm is used for image object segmentation, which transforms the image data from single pixel to feature objects and utilizes the NDVI, NDWI and brightness feature information of two time phases for regional classification, with an overall accuracy of up to 91%. Sun and Lv (2013) utilized the object-oriented optimal scale selection method and KNN classifier to extract high-speed railroad lines. Aiming at the semantic gap between the high-level semantics of images and the low-level visual features in the traditional building extraction method, Shen, Feng, Wang, and Dai (2018) proposed an automatic identification method of building hazardous areas along the high-speed railroad based on a convolutional neural network model in the framework of scene interpretation.

In the research of the air and space multi-source data fusion method, in order to realize the fusion of remote sensing data of different resolutions around the railroad and, at the same time, improve the quality of alternative data in the case of high-precision data affected by weather or clouds, the project team analyzes the status quo, characteristics and technical architectures of open source super-resolution reconstruction techniques and designs an attention-enhanced super-resolution reconstruction model VDSR based on convolutional neural network. By increasing the depth of the attention network module to strengthen the



Source(s): Authors' own work

Figure 2. High-resolution remote sensing change detection of safety hazards in the surrounding environment

model's ability to extract features of complex targets, the model reconstruction for dust nets, illegal buildings, public facilities and other targets, compared with the existing open source algorithms, to effectively realize the reconstruction of the details of the environmental safety hazards of the railroad targets, the complete restoration of the image of the color distribution and the boundary details, the research will be conducive to improving the identification of the environmental safety hazards of the railroad. This research will be helpful to improve the accuracy of the identification of hidden safety hazards in the railway surrounding environment.

As for the research on the construction method of the hidden danger sample library of the external environment of the railroad, the project team proposes a method of automatic labeling of hidden danger samples taking into account the characteristics of the railroad belt, which can adaptively adjust the digital linear map based on the mean drift segmentation algorithm and the Douglas–Peucker boundary refinement algorithm so as to build up the correspondence between the targets in the digital linear map and the remote sensing orthophotos. Meanwhile, by acquiring remote sensing images containing hidden targets in different environments, times and scales, the project team utilizes the sample migration algorithm to realize the sample augmentation of multiple types and attributes. The project team has initially constructed a database of hidden danger samples, which basically covers various types, providing a data basis for model training.

In the research of intelligent identification methods of hidden dangers in the external environment of railroads, the project team has enhanced the boundary information of hidden dangers by using super-resolution reconstruction, proposed an automatic identification algorithm of hidden dangers in the external environment based on the U-Net algorithm based on the sample library and proposed a GLA-STDeepLab network model combining the Transformer and CNN architectures for semantic segmentation, which has contributed to the development of the GLA-STDeepLab network model. At the same time, a GLA-STDeepLab network model combining Transformer and CNN architectures for semantic segmentation is proposed, which facilitates the interaction of feature maps at different scales, improves the accuracy of identifying the risk sources of the external environment of the railroad and the recognition rate of hard floating objects reaches 90%.

Deep learning-based remote sensing image change detection is a current research trend, but one of the main challenges of various deep learning networks is the comprehensive effectiveness of the training data. At present, the comprehensive coverage and accuracy of remote sensing image change detection for the environment around the high-speed rail need to be strengthened. Therefore, based on the existing general network framework for change detection, there is an urgent need to carry out research on algorithms and applications of fast recognition of small targets and unsupervised deep learning in the environment around the high-speed rail and to establish relevant labeled datasets.

4. Research prospect

In recent years, railroad scientists have carried out a lot of theoretical and technological research and development and application around the influence of meteorological disasters, perimeter intrusion and the external environment on the safety of high-speed railways, which have strongly supported the enhancement of railroad environmental safety guarantee technology. With the operation of CR450 train sets with a speed of 400 km/h and the application of automatic driving technology for high-speed trains in the future, new and higher requirements are put forward for the safety of high-speed railway operation environments. The following research is needed to be carried out on the mechanism of influencing factors of high-speed railroad operation environment safety and situational awareness:

(1) The mechanism and coupling relationship of the main influencing factors of high-speed railway operation environment safety

For the high-speed railroad with a speed of 400km/h and dynamic train sets, clarify the main influencing factors of the safety of the high-speed railway operation environment; explore the spatial and temporal evolution law of snow grain movement in the complex flow field at the bottom of high-speed trains under the alpine and abundant snow environment and study the mechanism of the role of the multi-factor coupling of extreme meteorological factors on the safety of high-speed trains; study the mechanism of the influence of the strong winds on the encroachment behavior of the typical light/hard foreign matter along the high-speed railway; study the disaster-causing mode and mechanism of the heavy precipitation on the high-speed railway roadbed facilities and establish the mechanism of the disaster-causing mode and the relationship of the strong precipitation on the roadbed facilities. It will study the disaster-causing mode and mechanism of heavy rainfall on the roadbed facilities of high-speed railways and establish the evolution model of rainfall-water condition-disaster condition around the roadbed of high-speed railways; it will study the characteristics of lightning strikes on the traction and signaling systems and reveal the intrusion characteristics and mechanism of lightning strike energy on the systems.

Various safety factors, such as meteorological disasters and external environmental safety, hidden dangers along the high-speed rail line are complicated and changeable. Therefore, it is necessary to apply the multi-scale coupling numerical characterization method of multiple environmental safety factors to clarify the time-space interaction characteristics of multiple safety factors, analyze the correlation between the evolution characteristics of multiple safety factors and the high-speed train safety environment and study the influence mechanism of multi-factor coupling on the safety of existing 350km/h and future 400km/h high-speed trains, so as to reveal the multi-factor disaster-causing mechanism of multi-factor coupling in multiple dimensions, such as time and space. Mechanism.

(2) The spatial and temporal evolution law of the main factors of high-speed rail operation environment safety

Research on multi-source data fusion methods and correlation characteristics covering disaster monitoring data, meteorological information, line characteristics and terrain features along the high-speed rail line; research on strong wind, heavy rainfall, snowstorm and lightning activities and characteristic evolution laws along the high-speed rail line; research on temporal and spatial characteristics of peripheral intrusion; research on temporal and spatial correlation rules between external environmental hazards and seasons, terrain features, etc. and reveal the temporal and spatial evolution laws of the main factors affecting the safety of the high-speed rail operation environment. Reveal the spatial and temporal evolution laws of the main factors affecting the safety of high-speed rail operation environments.

(3) In terms of meteorological disaster potential sensing method for high-speed railways

Analyze the spatial and temporal distribution patterns of wind speed, wind direction, rainfall and snow depth along the railroad line and the characteristics of atmospheric dynamics and thermodynamics and study the optimization methods of meteorological disaster monitoring points; study the methods of high-precision prediction of time series of meteorological information, such as wind speed, rainfall, snowfall, etc. along the high-speed railway line, set up coupled spatial-temporal prediction models of meteorological disasters along the high-speed railway line and study the realization of refined, small-scale, real-time, dynamic and accurate prediction of meteorological disasters along the high-speed railway line.

(4) Perimeter intrusion situational awareness method for high-speed railways

Aiming at the needs of all-weather and all-time intrusion monitoring at the perimeter of high-speed railways, research on reliable sensing technology under the interference of bad weather and complex environments, research on multi-modal fusion monitoring methods covering the typical scenes of high-speed railway operation, combine with artificial intelligence technology, construct an accurate identification model of intrusion at the perimeter of high-speed railways and research on real-time tracking technology of intrusion targets at the perimeter.

(5) Regarding the situational awareness method of hidden safety hazards in the external environment of high-speed railways

Research on the optimization layout method of the air-heaven-air cooperative sensor monitoring network; put forward the multi-dimensional feature portrayal method of remote sensing information of hidden safety hazards in the external environment of high-speed railways and construct the relevant marking data set. Establish the information fusion mechanism of a multi-source heterogeneous sensor network with air-heaven coordination and study the intelligent identification method of hidden safety dangers in the external environment of the high-speed rail and the evolution law of safety situation. Carry out research on the change detection and algorithm of the surrounding environment of the high-speed railway and conduct targeted research to realize the localization and tracking of key hidden dangers in the external environment.

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