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Research on Railway Train Space Position Correction Algorithm Based on GNSS Correction Model

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Abstract. The traditional railway train positioning methods mainly include three methods: speed sensor based, ground point responder response, and track circuit section occupancy detection. However, the traditional positioning method does not respond in a timely manner and is gradually being replaced by new positioning methods. With the development of high-speed rail in China, the Global Navigation Satellite System (GNSS) is gradually being implemented as a new positioning system for railway trains, and auxiliary technologies such as train accelerometers and odometry are integrated to ensure the safe operation of trains. However, GNSS can meet the positioning accuracy requirements in strong signal areas, but the positioning accuracy of trains is lower in weak signal or no satellite signal environments, resulting in certain positioning errors or noise, which cannot meet the needs of analysis and decision-making in geographic information systems. This paper uses the Unscented Kalman Filter algorithm to improve and design a GNSS based positioning correction model. Based on railway network GIS data, an electronic map spatial position correction matching method is proposed to improve and solve the problem of train positioning accuracy errors in weak signal environments. After experimental research, the GNSS positioning correction model and electronic map matching method designed in this paper can improve the fusion expression accuracy of train positioning on electronic maps, achieving the predetermined goal.

Keywords: train positioning, combined positioning, GIS, position correction

1 Introduction

As a strategic, pioneering and critical national major infrastructure, railroads are the arteries of the national economy, major livelihood projects and the backbone of the comprehensive transportation system, and their status and role in economic and social development are of paramount importance. The operational safety of railroads is the basis of all social activities. Train mainly includes passenger and freight transportation, is the main core of the main body of the railroad, so its train control and positioning plays an important role, the train control system includes the train running direction, running interval, running position and running speed control, is the train's "brain center".

High precision positioning of trains is crucial for modern railway transportation systems. It can provide accurate location information to help the dispatch center grasp the real-time operation status of trains, ensuring that trains run safely and on time according to the predetermined schedule and route. In emergency situations such as train malfunctions or accidents, high-precision positioning can quickly determine the position of the train, provide accurate guidance for rescue personnel, and ensure the safety of passengers. Therefore, high-precision positioning of trains is one of the key technologies to ensure the safety, efficiency, and reliability of railway transportation.

Traditional railway train positioning methods mainly include three approaches: speed sensor-based methods, balise response methods, and track circuit occupancy detection methods. In some early railway systems, the speed sensor-based method was widely used, which could estimate the train's position and speed by measuring the wheel speed [1]. The positioning of high-speed trains can be achieved through speed measuring devices and ground correction equipment. Pulse speed sensors (PSS) and speed measurement motors are traditional measuring devices. However, the positioning error of PSS is affected by wheel wear and slippage, which accumulates over time as the train operates [2]. Balise transponders are used in ETCS and CTCS systems. Positioning is achieved through a combination of transponder groups and odometer systems. However, there are issues such

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as the need for extensive maintenance of trackside equipment, accuracy affected by the spacing between transponders, only providing longitudinal position, reliance on known routes, potential false reporting during power outages, and lack of an absolute coordinate system reference. Continuous optimization is needed to improve its accuracy, stability, and reliability [3]. Due to the relatively small number of trains equipped with DIS and the experimental outline not allowing the installation of dedicated onboard equipment for testing, it is not possible to directly obtain objective data such as train speed curves or energy consumption to support subjective information. To overcome this dilemma, Delft University of Technology proposed using the available track occupancy time to reconstruct the train speed profile, which can be partially verified by measurements from electricity meters installed on several trains. The track circuit occupancy detection method uses the track as a conductive circuit to detect whether the rail is occupied by a train while sending signal information to check if the rail is broken [4]. Track circuits use wires laid under the tracks to detect changes in current and determine whether a section of track is occupied by a train, thus roughly estimating the train's position [5]. When a train enters a track circuit area, it changes the electrical characteristics of that area, triggering signal machines to display corresponding light signals to indicate whether subsequent trains can enter that area. However, with continuous advancements in railway technology and increased train operating speeds, traditional railway train positioning methods have gradually revealed their limitations. Firstly, the accuracy of track circuits is limited, only allowing rough positioning of trains, which cannot meet the needs for high-precision positioning. Moreover, the maintenance costs for track circuits and signaling systems are high, and they are susceptible to environmental factors (such as weather and humidity), leading to decreased system reliability. Additionally, as train density increases and transportation efficiency improves, traditional positioning methods struggle to handle multi-train tracking and real-time scheduling effectively.

With the intelligent development of global infrastructure and rail transportation system, railroad train positioning from the traditional transponder, trackside circuit, odometer, etc. gradually based on the global navigation system (GNSS), inertial navigation, multi-source speed sensors and other new types of train control system instead of the new train control system with on-board equipment integrity check function and ATO function [6], can meet the operational needs of general-speed wagons and high-speed trains. operation needs of the dynamic train sets. With the success of BeiDou3 satellite system network in 2020, accelerating the substitution and upgrading of the railroad train positioning system, the use of BeiDou, GPS satellites and other multi-source satellite positioning technology has gradually become an indispensable technology in the operation of railroad trains [7].

GNSS system is a major strategic infrastructure at the national level, which plays and occupies an important position in the national economic development. GNSS system has the characteristics of all-weather, all-day, high coverage, and has gradually become an important technical support for safe and stable transportation of railroads. However, GNSS system also has certain shortcomings in railroad operation, mainly in the ground in the open area or strong signal area, the positioning effect is obvious, high precision, to meet the needs of high-precision positioning of the column control, in the mountainous areas, long tunnels, or subject to interference in the region, the train positioning will be a certain deviation, resulting in the location of the data information loss or true. Therefore, researching how to improve the accuracy and reliability of GNSS positioning information has become a top priority in ensuring the safety of train operations. In view of this, many scholars and academics in various countries have conducted in-depth research on how to improve the GNSS positioning accuracy or position correction [8-9], H.J. Lee et al. designed a semi-automatic driving system using the GNSS system and the digital compass, which constantly corrects the traffic position information through the current position information and the heading angle to realize semi-automatic vehicle location Driving [10]; H. Yang et al. proposed an improved differential evolutionary algorithm based on the BeiDou navigation system, inertial navigation system and electronic map, this algorithm updates the individuals by changing the direction to multiple optimal values, and then composes a new combined localization algorithm [11]; Q.H. Luo et al. optimized and designed an improved SINS/DVL combined subsystem with a filtering gain compensation strategy, and proposed a USBL localization subsystem with Kalman-filtered acoustic signals, which finally resulted in a federal Kalman filter for fusing SINS/DVL combined positioning subsystem and USBL positioning subsystem positioning information [12]; J.F. Yang et al. analyzed the technical characteristics and advantages of BDS, GIS, and RS, and proposed a solution for the maintenance and monitoring of high-speed railroad infrastructure, and used a combination of vector and electronic map to achieve realizable display, and then realize remote monitoring, status query and management [13].

The Unscented Kalman Filter (UKF) is an algorithm used for state estimation in nonlinear systems, which employs sigma points to approximate the mean and covariance of nonlinear functions, thereby avoiding errors inherent in the linearization process. Since the concept of UKF was introduced in 1997, it has been widely applied in various fields [14]. M. Wu et al. have provided a detailed account of the application and methods of UKF in dealing with the identification of nonlinear structural systems, offering comprehensive guidance for the application of UKF in different scenarios [15].

In recent years, UKF has also found applications in the railway sector. Alex Cunillera and others have combined UKF with driving strategy calculators and post-processing modules, demonstrating that UKF can track speed and position measurements and estimate the parameters of running resistance modeled in dynamic equations [16]; Y.Y. Nazaruddin and others have utilized multi-sensor data fusion based on UKF to collect more accurate position measurement data during train travel [17]; D. Gao and others have proposed a fault diagnosis strategy based on an adaptive unscented Kalman filter to detect bias and drift faults in the pressure sensors of brake system equilibrium reservoirs [18]. In the realm of spatial data processing and cartography, the application of UKF has also been explored. Anoj K. Nambiar and others have developed a local sigma point unscented Kalman filter for ocean and atmospheric data assimilation, improving the performance of state estimation [19]; D. Rong and others have proposed an adaptive noise factor method based on the unscented Kalman filter that can adapt to time-varying measurement noise, enhancing the accuracy of spatial target tracking [20]; L. Yan and L. Zhao. have used the square root unscented Kalman filter to select sigma points based on the square root decomposition of the prior covariance, and then calculate the weighted mean and covariance for estimating the posture of a robot [21].

The research status of spatial matching methods for train positioning and electronic maps is a complex interdisciplinary field that is currently in a rapid development stage. With the continuous advancement of Global Navigation Satellite System (GNSS) technology, especially the widespread application of GPS, GLONASS, Galileo, and Beidou systems, train positioning technology has been greatly improved. However, due to the influence of complex environments such as urban canyons and tunnels, relying solely on GNSS for accurate train positioning still faces challenges. Therefore, researchers have begun to explore methods of integrating GNSS with various sensor data such as inertial navigation systems (INS), ground beacons, wireless communication networks, etc., to improve the accuracy and robustness of positioning. For examples, H. Jing et al. mainly focus on the integrity monitoring of GNSS and inertial navigation systems [22]; D. Liu et al. proposed a powerful train positioning system by integrating GNSS and INS into a tight coupling (TC) strategy [23].

In terms of electronic map matching, traditional map matching algorithms such as nearest neighbor method and probability statistics method have gradually been replaced by more advanced algorithms, such as dynamic Bayesian network methods based on Hidden Markov Model (HMM), Kalman Filter (KF), and Particle Filter (PF). These methods can better handle uncertain information and achieve real-time and accurate matching between train trajectories and electronic map paths. In addition, the development of deep learning technology has brought new possibilities for map matching. By constructing deep neural network models, complex nonlinear relationships can be learned, further improving matching accuracy.

In recent years, with the rise of big data technology and artificial intelligence technology, research on train positioning and map matching has begun to develop towards intelligence. By utilizing big data analysis techniques, historical positioning data can be deeply excavated to identify patterns and patterns of positioning errors, thereby guiding algorithm optimization. Meanwhile, by combining machine learning algorithms, the matching strategy can be automatically adjusted to adapt to the optimal solution in different scenarios. Like S. Wang et al. proposed a deep-learning based algorithm to recognize different types of rail profiles [24], while H. Song et al. applied data prediction and edge based information fusion to process real dynamic data and estimate the speed and position of trains [25].

In this paper, based on the pre-collected railroad train trajectory, using the traceless Kalman filter equation set, designing the improved GNSS correction model, and correcting and predicting the data of train positioning, and at the same time, based on the GIS spatial data of the railroad network, designing the method of spatial matching between train positioning spatial location and electronic map, realizing the correction, prediction, and matching of spatial location data information in the railroad geographic information system. The fusion of the trinity of correlation, and further improve the positioning accuracy of the railroad train in the weak signal area. Chapter 2 proposes a methodological model for spatial correction of position information of GNSS system. Chapter 3 proposes the GNSS position projection correction and data processing process for GIS e-maps. Chapter 4 validates and tests the algorithmic model and correction algorithms of GNSS system. Chapter 5 draws the conclusions of this test.

2 Position Correction Model Based on GNSS System

2.1 Establishment of Train Trajectory Operation Model

Trains are affected by various factors during operation, resulting in deviations between their actual position and GNSS measurement results. By establishing an accurate train trajectory model, these deviations can be effectively corrected and the accuracy of positioning can be improved. This model can comprehensively consider the topology of the line, the geometric characteristics of the track, and the dynamic characteristics of the train, so as to dynamically adjust the position of the train in real time, ensuring that its display on the GIS map is more accurate and reliable. During the operation of railway trains, a motion model is established based on their trajectory. The motion model of railway trains is shown in Fig. 1, where the world coordinate system with $\{O\}$, the train local coordinate system with $\{T\}$, the railroad train running the left side of the wheel's operating radius with R_L, the right side of the wheel's operating radius with R_R, θ is a moment in time the train around the arc of the running angle, the wheelbase of the left and right side of the railroad train with L. The general standard gauge on Chinese railroads is 1435mm.

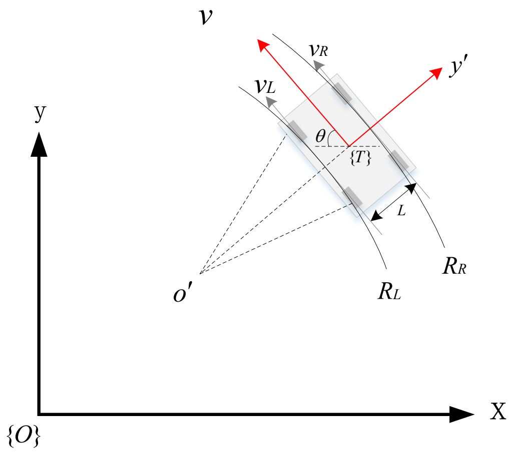


Fig. 1. Railway train motion model

Set the radius of the wheels of the railroad train for r, the angular velocity of the left and right wheels are U_R and U_L. From the geometric relationship in the figure, then it can be seen that the linear velocity of the left and right wheels of the train are:

$$\begin{cases} v_L = R_L \cdot U_L \\ v_R = R_R \cdot U_R \end{cases} \tag{1}$$

Since the wheelbase of the train is calculated through the left and right side wheels: $R_R - R_L = L$. The angular velocity of a railroad train rotating about the center of mass is given by the following relationship: $\theta = (v_R - v_L) / L$. The linear speed of the train, on the other hand, is generally calculated from the angular speeds of the wheels on the left and right sides, and the relationship given is calculated as follows:

$$v = \left(v_R + v_L\right) / 2 = \left(R_L \cdot U_L + R_R \cdot U_R\right) / 2 \tag{2}$$

Through formula (1) and (2), the trajectory equation of railway trains in the $\{T\}$ coordinate system can be derived:

$$\begin{cases} x = v \cdot \cos\theta \\ y = v \cdot \sin\theta \\ \theta = \left(v_R - v_L\right) / L \end{cases} \tag{3}$$

Further summarizing the above formulas, the railway train trajectory model can be obtained as follows. The model can determine the position and orientation of the train in the world coordinate system, which facilitates further prediction and correction of the train's position in the map.

$$\begin{bmatrix} \theta \\ x \\ y \end{bmatrix} = \begin{bmatrix} -r/L & r/L \\ r/2\cos\theta & r/2\cos\theta \\ r/2\sin\theta & r/2\sin\theta \end{bmatrix} \begin{bmatrix} u_L \\ u_R \end{bmatrix}. \tag{4}$$

2.2 GNSS System and Trajectory Prediction Fusion Positioning

GNSS systems usually require the capture of four satellites for positioning, so their positioning accuracy is high and the error is small in long-distance and strong signal areas, which can achieve precise positioning of trains. When the train enters a tunnel or strong interference area, due to insufficient satellite signals, less than 4 positioning satellites are usually captured and observed. Traditional GNSS positioning methods cannot provide sufficient satellite observation data, resulting in increased positioning errors and difficulty in meeting the precise positioning needs of the train. By integrating train trajectory inference algorithms, prior knowledge such as train operation history data, line topology information, and track geometry features can be utilized to predict and correct train positions. This method can infer the current position of the train by analyzing its motion state and travel path in the case of insufficient satellite signals, thereby improving positioning accuracy. The train trajectory estimation algorithm can effectively cope with signal loss or interference, ensuring accurate positioning even in harsh environments. This algorithm combines multiple sensor data and historical operating information to dynamically adjust the train position through a complex computational model, making the positioning results more reliable and accurate.

In this paper, the traceless Kalman filter algorithm is utilized to fuse the trajectory prediction model using GNSS system positioning, and then provide the accuracy of train positioning, in which the train trajectory prediction focuses on improving the region with poor signal strength to continuously improve the model of trajectory prediction. Setting the critical point of the train at the moment when the distance signal becomes weak as p, the moment of p point as t, and the coordinates of the train measured by the GNSS system at the moment of t as (x_t, y_t), the traceless Kalman state equation is derived as follows:

$$X_{t+1} = \begin{bmatrix} x_{t+1} \\ y_{t+1} \\ \theta'_{t+1} \\ v_{Lt+1} \\ v_{Rt+1} \end{bmatrix} = \begin{bmatrix} x_t + \left(r \cdot u_L \cdot \cos\theta/2\right) \cdot \Delta t + \left(r \cdot u_R \cdot \cos\theta/2\right) \cdot \Delta t \\ y_t + \left(r \cdot u_L \cdot \sin\theta/2\right) \cdot \Delta t + \left(r \cdot u_R \cdot \sin\theta/2\right) \cdot \Delta t \\ \theta'_t + r \cdot \left(u_R - u_L\right) \cdot \Delta t \\ r \cdot u_L \cdot \Delta t \\ r \cdot u_R \cdot \Delta t \end{bmatrix} + \begin{bmatrix} \omega_{t1} \\ \omega_{t2} \\ \omega_{t3} \\ \omega_{t4} \\ \omega_{t5} \end{bmatrix}. \tag{5}$$

where: ω_{t1-t5} is the prediction noise for each variable obeying a Gaussian distribution. The observation equation is:

$$Z_{t+1} = H \begin{bmatrix} x_{t+1} \\ y_{t+1} \\ \theta'_{t+1} \\ v_{Lt+1} \\ v_{Rt+1} \end{bmatrix} + \begin{bmatrix} \varepsilon_{t1} \\ \varepsilon_{t2} \\ \varepsilon_{t3} \\ \varepsilon_{t4} \\ \varepsilon_{t5} \end{bmatrix} \tag{6}$$

where: ε_{t1-t5} is the observation noise for each variable obeying a Gaussian distribution, and the expected observation noise is all 0; H is the transformation matrix of the state equation transformed to the observation equation.

3 Location Matching Method for Electronic Maps

3.1 Basic Data Production for Electronic Maps

After lossless Kalman filtering, the spatial position information of GNSS systems can basically meet the requirements. However, in railway geographic information systems, the high-precision positioning information provided by GNSS systems needs to be integrated and displayed with GIS electronic maps to achieve visual representation of basic maps and basic equipment and facilities along the railway [26]. In a 3D scene, electronic maps provide 3D models of railway bridges, tunnels, culverts, and station buildings These models typically use independent coordinate systems in railway design, construction, and other engineering projects. In order to integrate these data with GIS electronic maps, spatial transformation of the data is required through GIS processing clients [27].

Railroad geographic information system provides basic geographic information data, including vector data, DEM data, remote sensing imagery and three-dimensional models and other sources of data types, all types of data according to different analysis and display requirements for classification and production, of which vector data production is more complex, the main process for the railroad from the various construction units, collection of various types of ledgers, drawings, and other data, through the GIS professional client, all types of data cleaning, transformation, alignment, and data processing. Through the GIS professional client, all kinds of data are cleaned, transformed and aligned to form geographic information data with spatial location attributes, and then the professional electronic map is formed through the classification and assignment of all kinds of elements and cartography, and the two-dimensional geographic information data production process is shown in the following Fig. 2.

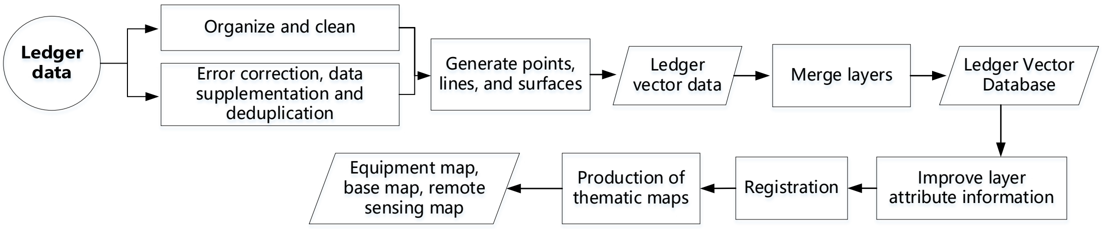


Fig. 2. Production process of 2D geographic information data

The production process of two-dimensional geographic information data is a systematic process, covering multiple stages such as data cleaning, feature generation, vector data creation, layer merging, and thematic map production, ensuring that the final generated data can meet practical application needs and provide accurate and reliable geographic information support. The organization and cleaning of data are fundamental steps, which involve error correction, data supplementation, and deduplication of raw data to ensure its integrity and consistency. Next, generate basic geographic features such as points, lines, and surfaces to form the foundation for subsequent analysis and application.

After generating the basic elements, the next step is to create vector data for geographic information. This process integrates different types of geographical features into a unified vector dataset. By integrating data layers from different sources and types, a comprehensive geographic information database is formed. This merging process not only improves the availability of data, but also provides a rich information foundation for subsequent analysis.

After merging layers, the data will be stored in a dedicated vector database for subsequent access and management. At this point, different types of maps such as equipment maps, base maps, and remote sensing maps will also be created, providing users with a multidimensional geographic information perspective. Furthermore, the production of thematic maps is aimed at meeting specific application needs, helping users better understand and utilize geographic information through further analysis and visualization of data.

The registration process ensures spatial consistency between different data layers, and by performing spatial registration on the data, all layers are analyzed in the same coordinate system. Improving layer attribute information can enhance data quality. By supplementing and refining attribute information, it ensures that data is not only spatially accurate, but also highly reliable in terms of attributes. Through this systematic process, users can obtain high-quality geographic information data, providing a solid foundation for decision-making and research.

Based on two-dimensional geographic information data, it is possible to construct and produce three-dimensional geographic information data in batches, including modeling of the monomer library and establishment of algorithm rules. The production process of 3D geographic information data is shown in Fig. 3.

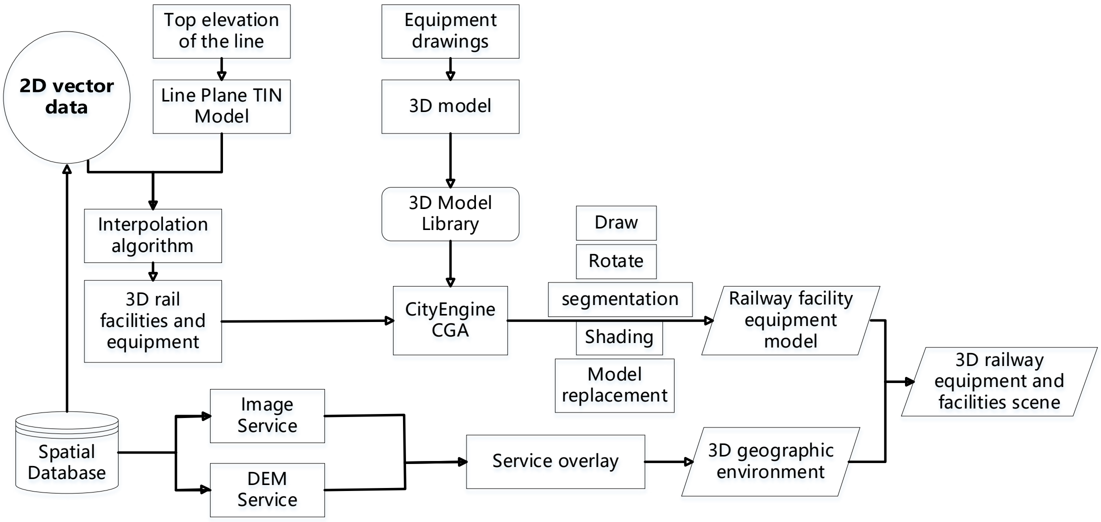


Fig. 3. Production process of 3D geographic information data

The production process of 3D geographic information data is a multi-step system engineering aimed at transforming 2D data into 3D models with spatial depth and realism. The starting point of the process is the acquisition of two-dimensional vector data, which typically includes information such as terrain, buildings, and transportation facilities. By analyzing these two-dimensional data, the highest point of the line and related equipment drawings are extracted, laying the foundation for subsequent 3D modeling.

In the process, interpolation algorithms are used to process two-dimensional data, generate a three-dimensional terrain model, and then construct a linear plane TIN (Irregular Triangular Network) model to better represent complex terrain features.

During the model construction phase, software such as CityEngine can be used to generate 3D models of buildings and facilities for drawing, rotating, and segmenting operations. Then, the generated 3D model is overlaid with existing geographic information to ensure that all elements are integrated in the same coordinate system. Digital elevation model (DEM) services and image services can be combined to provide richer background information for the 3D scene.

After a series of processing and integration, the final generated 3D geographic environment will include a complete scene of railway equipment and facilities. This scenario can not only be used for visual display, but also provide support for subsequent analysis and decision-making.

3.2 Fusion Positioning Based on GNSS System and Electronic Map

The fusion positioning based on Global Navigation Satellite System (GNSS) and electronic maps is a high-precision positioning technology that combines real-time location information provided by GNSS with detailed geographic data in electronic maps to achieve more accurate and reliable positioning. In railway geographic information systems, this fusion positioning method is particularly important because it can provide high-precision positioning information and integrate it with GIS railway thematic maps for visualization of basic maps and basic equipment and facilities along the railway. In a three-dimensional scene, electronic maps provide three-dimensional models of railway bridges, tunnels, culverts, and station buildings. They are generally used in railway design, construction, and other engineering projects as independent coordinate systems, which require spatial transformation of data through GIS processing clients to achieve high-precision positioning display and support analysis and decision-making for various railway business applications.

Through 2D and 3D map engines, data representation, analysis, and computation can be achieved. Commonly used 2D and 3D map engines such as ArcGIS API JS, Mapbox, Openlayers, and Leaflet can provide powerful spatial analysis capabilities and 2D visualization expressions [28]. These map engines can display geographic data in a graphical manner, allowing users to intuitively understand the spatial distribution and relationships of geographic information. At the same time, they also support various analyses and calculations of geographic data, such as overlay analysis, buffer analysis, network analysis, etc., to help users deeply explore the value of geographic data.

Cesium is commonly used three-dimensional visualization expression engine [29]. GNSS system is a collective concept GNSS system is a collective concept, which consists of GPS, GLONASS, GALILEO and BDS, GPS adopts WGS-84 coordinate system, GLONASS adopts PE-90 coordinate system of the former Soviet Union, GALILEO adopts ITRF-96 geodetic coordinate system, and BDS adopts BeiDou coordinate system, which is basically consistent with China’s CGCS2000 national geodetic coordinate system [30].

Electronic maps are generally two-dimensional planar maps, using the Mercator projection coordinate system, so different types of coordinate systems from the GNSS system need to be converted to the projection of the Mercator coordinate system, for example, from the BeiDou received a certain point of the coordinates of the CGCS2000 geodetic coordinate system $S_c(x',y')$, converted to the Mercator projection coordinate system under the coordinate system of $S_w(x'',y'')$, which is converted to the formula for:

$$\begin{cases} x'' = x' \cdot 20037508.34/180 \\ p = \log\left(\tan\left(\left(90 + y'\right) \cdot \pi/360\right)\right) \cdot \left(\pi/180\right) \\ y'' = p \cdot 20037508.34/180 \end{cases} \tag{7}$$

According to this formula, different types of coordinate systems of GNSS system can be transformed into web Mercator projection coordinate system to realize the fusion of positioning analysis with electronic maps.

3.3 Positioning and Correction Method Based on Electronic Map

In the process of map fusion, due to various factors, the train position sequence displayed on electronic maps often has some position information that deviates from the railway line. The schematic diagram of line position drift is shown in Fig. 4 below. For examples, due to obstacles such as buildings, trees, tunnels, etc., GNSS signals may be interfered with, resulting in inaccurate received location information; If the accuracy of the electronic map is not high enough or the update is not timely, the train position will deviate from the actual position; Changes in train speed and direction may also lead to errors in position information. These deviations are particularly evident when displayed on electronic maps at a scale of 1:1000, and require secondary correction to ensure accurate display of train position information on the electronic map.

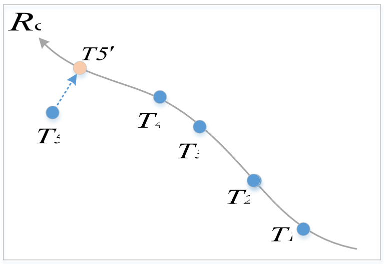


Fig. 4. Schematic diagram of line position drift

The position of the train can be corrected through geometric relationships, and the diagram of train correction projection calculation is shown in Fig. 5. R_C represents the centerline of the two tracks of the railroad, after the positioning through the GNSS system, the train position is displayed through the non-destructive Kalman filtering and fusion with the electronic map, T_1 to T_2 is the position of the train positioning, in which there is a deviation in the T_5 position, and it is necessary to carry out the corrective action of the train position, the corrective action is to use the way of the projection transformation to project a certain point to the railroad line, and to find out the coordinates of the coordinates on the railroad line.

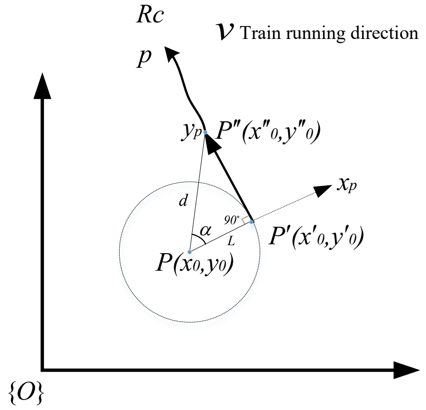


Fig. 5. Diagram of train correction projection calculation

R_C represents the centerline of the train running direction, where point p is the positioning point transmitted to the electronic map at the moment of t. It is known that the coordinates are $P(x_0,y_0)$, the projection point of point p on the railroad line is p', and the distance between p' and p is L. Then it satisfies:

$$L^2 = \left(x_0{}' - x_0\right)^2 + \left(y_0{}' - y_0\right)^2 \tag{8}$$

In addition, through the GNSS system its localization frequency time is very short, two adjacent points can be approximated as a straight line, then $PP' \perp PP''$, where $\angle PP'P'' = 90^\circ$, then:

$$\begin{cases} d^2 = \left(x_0'' - x_0\right)^2 + \left(y_0'' - y_0\right)^2 \\ \cos\alpha = L/d \\ \tan\alpha = \sqrt{\left(x_0'' - x_0\right)^2 + \left(y_0'' - y_0\right)^2 / L} \end{cases} \tag{9}$$

At the same time, by associating the above equations (8)(9), we can find the coordinates (x', y') of P'. The algorithm can be realized by using PostGIS, which is an extended spatial piece of the open source database PostgreSQL, and the middleware contains numerous spatial algorithmic functions, or we can write our own extended functions for spatial data processing.

4 Location Matching Method for Electronic Maps

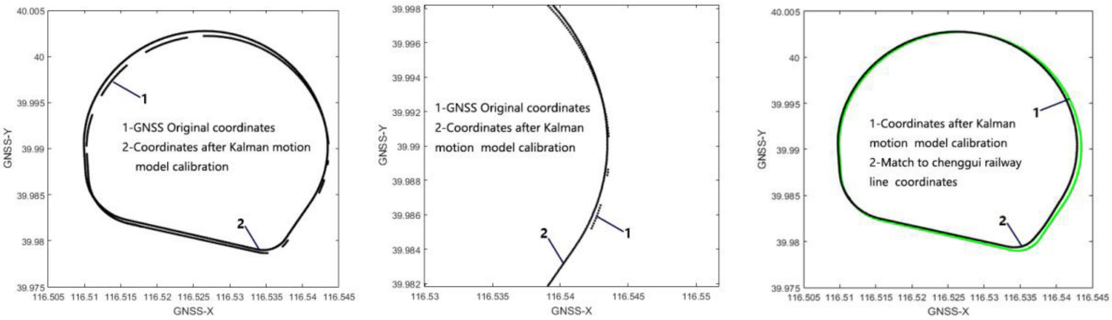
4.1 Analysis of Optimization Model Results for Train Operation Trajectory

The experiment conducted in this paper was a train test on the urban rail line of the circular railway experimental line in the eastern suburbs of the China Academy of Railway Sciences. This experimental line is the only railway comprehensive testing base in China and even Asia, with a total length of 38 kilometers of railway and scientific research laboratories, capable of conducting comprehensive testing on railway vehicles, urban rail transit vehicles, infrastructure facilities, communication signals, electrification technology and other aspects. The lines within the experimental line include the outer ring line, inner ring line, station yard line, triangle line, connecting line, and entrance ring line. The largest outer ring line is 9 kilometers long with a radius of 1852 meters and a total curve radius of 1432 meters. The inner ring line is approximately 8.5 kilometers long and consists of one straight line and three curves with half diameters of 350, 600, and 1000 meters. All circular lines are electrified. Install inertial group equipment on the train to collect position information, deviation angle, speed and other parameter information, as shown in Fig. 6(a) Inertial navigation installation position and Fig. 6(b) Laser velocimeter.

(a) Inertial guidance equipment (b) Laser tachymeter

Fig. 6. Inertial navigation equipment

In the process of train operation, only by the inertial guidance equipment collected by the train position data in the strong signal area of its position is more accurate, can truly reflect the trajectory of the train running situation, in the circular railroad tunnel inside, the results of the positioning of the poorer, and even will indeed positioning data, resulting in a distortion of the situation. In this paper, when combing the inertial guidance result data, some errors are obviously larger to be eliminated, using inertial guidance equipment to collect the train's northeastern sky speed, angle of deviation and other state posture data, to carry out the use of the traceless Kalman filtering prediction model, the train in the weak signal region for the state estimation and prediction. At the same time, through the inertial guidance for GNSS positioning of the original data after the filter can basically predict the train in the weak signal region of the trajectory, can see that the data and the original data there is a certain degree of error, the error can generally be corrected through the map correction method of the location of the projection, the final measured results and the predicted basic consistency. The GNSS result data fitting is shown in Fig. 7.



(a) Motion trajectory optimization (b) Motion trajectory optimization (local) (c) Projection correction

Fig. 7. GNSS data fitting

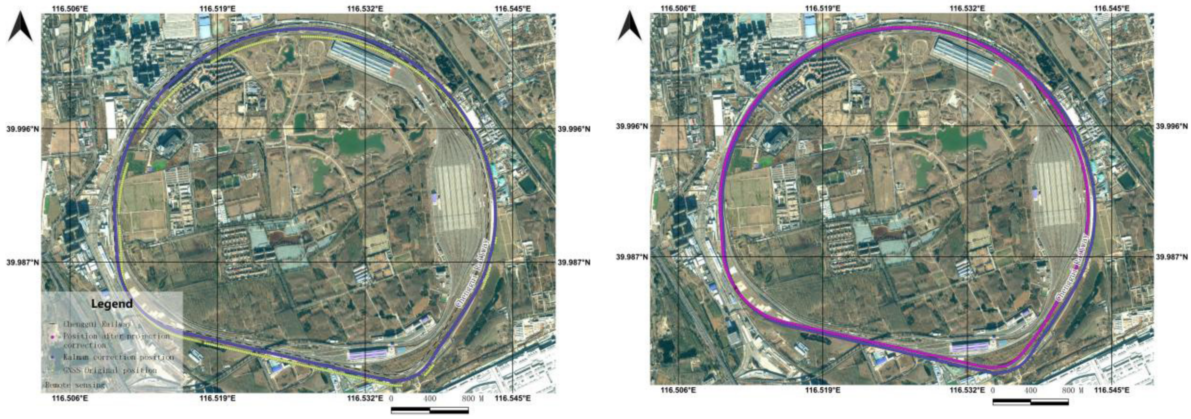
4.2 Analysis of GNSS Positioning and GIS Combined Positioning Matching Results

The fitting process of GNSS position data and remote sensing images is a complex and delicate task, involving multiple stages from data acquisition to final thematic map production. In this study, this article first collected the basic ledger information, design drawings, and construction drawings of the circular railway experimental line of the China Academy of Railway Sciences, which provided a basic framework for subsequent data processing. Subsequently, high-precision construction surveying technology was used to obtain the coordinates of CPIII pile points along the railway line, which are crucial for precise positioning of the railway line.

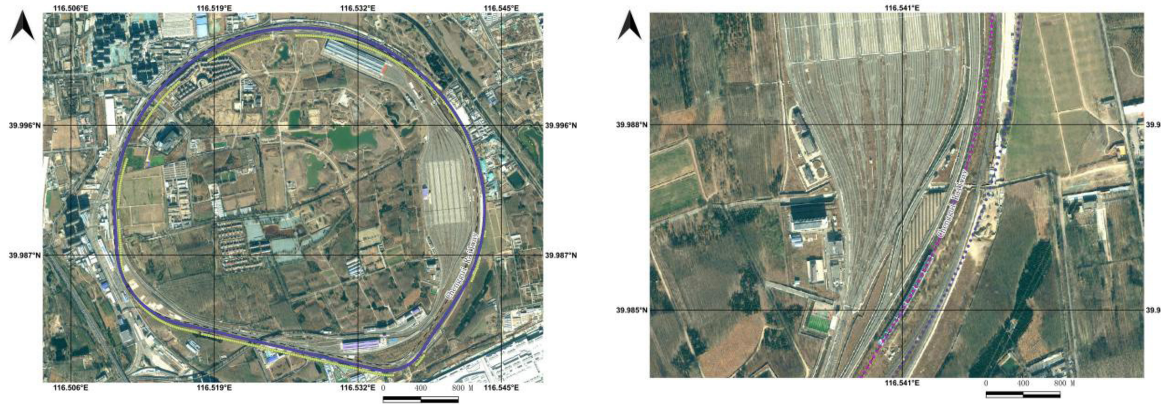
Using these high-precision CPIII pile point coordinates, we generated the mileage centerline along the line using professional GIS software. This step is crucial as it ensures that the locations of all subsequent railway equipment and facilities accurately correspond to their actual geographical locations. On this basis, this article further generates various railway equipment and facilities for the circular railway experimental line, including tracks, signal systems, power supply facilities, etc., which are important components to ensure the normal operation of the railway.

In order to improve the reliability and accuracy of the data, we fitted the generated GIS data with high-definition remote sensing images with a resolution of 0.5m from Google. Due to the high precision of both, the degree of agreement between them is very high, which provides a solid foundation for our data analysis. Through comparative analysis, GIS data and remote sensing images almost perfectly match in spatial location, which further verifies the accuracy of the data.

Finally, based on these precise data, we made and produced thematic maps. These thematic maps not only show the overall view of the circular railway experimental line, but also provide detailed annotations of the locations of various railway equipment and facilities, providing important reference for the design, construction, and maintenance of railways. The fitting of GNSS position data and remote sensing images is shown in Fig. 8.



(a) Comparison of GNSS original and kalman model corrected positions (b) Comparison of projected corrected position and kalman model corrected position



(c) Comparison of GNSS original and kalman model corrected positions-localization (d) Comparison of projected corrected position and kalman model corrected position-localized

Fig. 8. GNSS position data and remote sensing image fitting

In the experiment, the GNSS positioning information transmitted back by the train through the inertial navigation system was first collected. This information is generally analyzed as the actual positioning information of the train, but there are certain deviations that need to be corrected in practice. This article uses PostGIS algorithm to correct these positioning information. The corrected results show that the position of the train is very close to the marked position on the electronic thematic map, and the error is within an acceptable range. Further research and analysis can be conducted based on the positioning information. In the circular railway experimental line test, it was shown that the GNSS positioning information corrected by PostGIS algorithm can accurately reflect the actual position of the train, and the positioning accuracy of the train in weak signal areas can basically meet the requirements of analysis and research.

5 Conclusion

This paper proposes a GNSS positioning correction model based on the trajectory of railway trains and combined with the GNSS positioning system. In addition, by combining electronic map matching methods, the process of train position drift was studied and analyzed, and a train electronic map positioning correction algorithm was proposed to correct the position information. Inertial navigation was used to test train positioning prediction inside the circular railway experimental line tunnel.

This paper discusses the GNSS based train positioning correction model and its integration with electronic maps. It first establishes a train trajectory operation model, which uses a local coordinate system and parameters such as wheel radius, angular velocity, and wheelbase to describe the movement of the train.

Due to the limitations and inaccuracy of GNSS in areas with weak signals, such as tunnels, in order to improve positioning accuracy, this paper proposes the fusion of GNSS data and trajectory prediction algorithms, using an unscented Kalman filter to improve prediction in weak signal areas.

This paper also discusses the positioning accuracy challenges caused by environmental factors that may distort GNSS signals, analyzes the process of train position drift, and proposes a train electronic map positioning correction algorithm for correcting position information

Finally, this paper uses inertial navigation to test train positioning prediction inside the circular railway experimental line tunnel, and the obtained train position information meets the needs of electronic maps, proving the effectiveness of the proposed model and method. The results indicate that the GNSS positioning correction model and electronic map matching method can achieve satisfactory accuracy even in areas with weak signals, providing support for further analysis and decision-making in railway operations.

Although the train positioning correction method based on PostGIS algorithm has shown good performance in experiments, there are still some challenges that need to be addressed. The performance of this method is influenced by various factors, such as the quality of satellite signals and the accuracy of maps. Secondly, this method has a high computational complexity and requires a significant amount of computing resources. The safety and reliability of this method also need to be further improved. To overcome these challenges, future research can be conducted from the following aspects: firstly, optimizing the PostGIS algorithm to improve its computational efficiency; The second is to combine other sensor data, such as inertial measurement unit (IMU) data, visual sensor data, etc., to improve the accuracy and robustness of positioning; Thirdly, strengthen the security measures of the system to ensure the security of data transmission and processing; The fourth is to conduct large-scale on-site testing to verify the practicality and reliability of the method.

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