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Research article

Study on key technologies of GNSS-based train state perception for train-centric railway signaling

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ABSTRACT

The application of Global Navigation Satellite Systems (GNSSs) in the intelligent railway systems is rapidly developing all over the world. With the GNSS-based train positioning and moving state perception, the autonomy and flexibility of a novel train control system can be greatly enhanced over the existing solutions relying on the track-side facilities. Considering the safety critical features of the railway signaling applications, the GNSS stand-alone mode may not be sufficient to satisfy the practical requirements. In this paper, the key technologies for applying GNSS in novel train-centric railway signaling systems are investigated, including the multi-sensor data fusion, Virtual Balise (VB) capturing and messaging, train integrity monitoring and system performance evaluation. According to the practical characteristics of the novel train control system under the moving block mode, the details of the key technologies are introduced. Field demonstration results of a novel train control system using the presented technologies under the practical railway operation conditions are presented to illustrate the achievable performance feature of autonomous train state perception using BeiDou Navigation Satellite System (BDS) and related solutions. It reveals the great potentials of these key technologies in the next generation train control system and other GNSS-based railway implementations.

1. Introduction

The train control system plays a significant role in ensuring the safety of railway operation and improving the transportation efficiency. Chinese Train Control Systems (CTCSs), including CTCS level 2 and level 3, have been widely implemented in the high-speed railway system. Current CTCSs adopt the track circuit to realize the train occupancy examination and identification of train integrity, where the wheel speed sensor is adopted to obtain the train's speed and along-track location [1]. Under this architecture, the Balises are utilized to realize corrections to the accumulative position error, which requires a large number of track-side equipments and thus the expected cost efficiency for the maintenance operation cannot be achieved. At the same time, the fixed block operation mode for the trains constrains the possibility of improving the railway traffic density and operational efficiency. It can be seen that there has been a rapid growth of transport demand and the increasing urgency for the enhanced autonomy and intelligence of novel train control systems [2]. Thus, the improvement of transportation efficiency with reduced track-side equipments, construction cost and the maintenance burden has been highly concerned, with which the advanced train state perception and operation control systems with the train-centric design will be the core development direction in the near future.

To realize the novel train-centric control system architecture, the train state perception is an enabling issue in determining the control orders by the on-board sub-system. Different from the conventional positioning solutions based on the track-side facilities, autonomous train positioning using the GNSS (Global Navigation Satellite System) is highly concerned to reduce the Balises in position calibration [3], which is the foundation to achieve accurate and reliable perception of the train's running states. Through the rapid development and modernization of GNSSs, like GPS and Galileo, GNSS-enabled autonomous train state perception has been concerned and explored in many countries. Besides that, other train-borne positioning methods that have been utilized in the high-speed railway, like INS (Inertial Navigation System) and the Doppler radar, also show great potentials in realizing the

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autonomous train positioning with a low cost over the Balise-based solutions [4]. However, it can be found that the single-sensor-based solution cannot satisfy the requirement of the train control system due to specific limitations and disadvantages in practical scenarios [5]. How to explore the capabilities of multiple perception sensors and break through the application-demand-oriented information fusion processing technology is the key to realize the satisfaction of novel train control systems with the train-centric design. Hence, it is important to overcome the key technologies of autonomous train positioning based on the fusion of GNSS and assistant sensors. By developing a novel train control system with dynamic configuration of the trains' interval, reduced involvement of track-side equipments, and enhanced maintainability of the on-board train positioning system, the advantages of the train-centric mode will be practically reflected and utilized for specific railway lines. In this paper, key technologies of the novel train control system with GNSS-based autonomous perception are investigated and demonstrated in the practical environment, which illustrate the necessity and advantages of the utilization of GNSS, especially BDS (BeiDou Navigation Satellite System), in future safety-related railway systems in China.

2. Multi-sensor data fusion

In existing railway signaling systems, the track occupancy of the train is determined by the track circuit, and the exact along-track location of the train is calculated by integrating both the train-borne odometer (or Doppler radar) and track-side Balises. The novel train-centric signaling system determines the track occupancy and train location without relying on those track-side facilities. Thus, raw measurements from multiple train-borne sensors will be integrated to achieve the required accuracy level, reduce the uncertainty and enhance the dependability.

2.1. GNSS/INS/Odometer sensor data fusion

The ODO (Odometer) is the most commonly used train positioning method in existing train control systems. Wheel slide and slip during the train operation, as well as wheel diameter wear, may result in errors in the train speed measurement, and lead to error accumulation in the along-track location calculation results. Such errors will be brought into the INS/ODO integrated positioning system. The train positioning error by INS/ODO drifts over time until the position calibration results are available. Different from the Balises, results of GNSS positioning can provide the correction without relying on the track-side. Performance of a GNSS/INS/ODO integrated positioning system will be determined by the reliability and accuracy of GNSS. When the GNSS performance decreases or the GNSS signal is blocked for a long time, the result of INS will not be guaranteed effectively [6]. Therefore, the availability and observation quality of GNSS greatly affect the precision and effectiveness of train positioning using INS and ODO.

The key issue in realizing the multi-sensor integrated train positioning is the sensor fusion logic. It is in charge of combining the measurements from multiple sensors, improving the reliability and fault tolerance of the integrated system, providing suitable auxiliary information for the existing location determination system, and simplifying the system complexity over those track-side-relied solutions. Among different sensor fusion algorithms, Federated Kalman Filter (FKF) is a distributed cascaded integrated sensor fusion method and widely considered in applications because of its flexibility, low computational effort, and excellent fault tolerance capability. FKF consists of several local filters and a main filter, in which the system information is allocated in the local filters and then fused in the main filter. For the GNSS/INS/ODO integrated train positioning system based on the FKF, INS is integrated due to its advantages in high output rate, autonomy and reliability. Considering the INS-related local filtering structures, two local filters for GNSS/INS and INS/ODO can be established, as shown in Fig. 1. These two local filters operate in parallel to obtain local estimations through the measurements $\mathbf{z}_1$ and $\mathbf{z}_2$. Once the requirements of the main filter are satisfied, the global estimation will be performed in the main filter, which will be fed back to the local filters for future iterations.

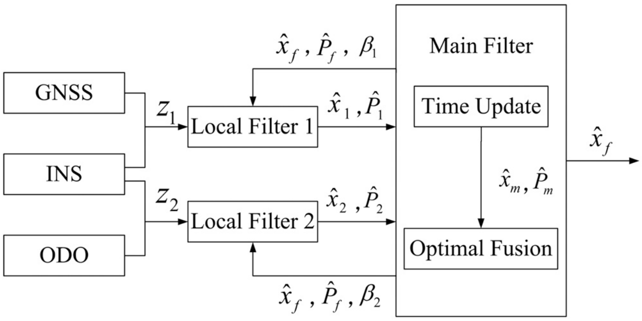

Fig. 1. Architecture of GNSS/INS/ODO sensor data fusion for integrated train positioning.

2.2. Trackmap-enhanced data fusion

Considering the constraint of the train's trajectory, priori information about the spatial characteristics of the train position can be obtained through the trackmap database with a high precision level through precise measuring and data processing. Using the map matching logic, the raw sensor fusion-derived coordinates can be calibrated according to the known track information. At the same time, the along track travelling distance over the corresponding referencing point can be calculated to describe the one-dimensional train location.

A variety of map matching algorithms already exist. For single line railways, the vertical projection method can efficiently derive the map matched train position. Principle of the vertical projection for map matching is shown in Fig. 2, where the dark gray curve represents the railway line, the light gray "○" represents the discrete points in the trackmap, the red "○" denotes the estimated train position obtained by the on-board positioning system, the yellow "○" indicates the track position after map matching, and the black dotted line between the red and yellow "○" represents the residual between the sensor fusion derived train position and the candidate target track segment.

When the train is operating in the throat area of a railway station and the route information of the train is unknown to the train positioning system, there will be a hesitation area when the train passes through the switch point. The projection point on the main line will be calculated by map matching so that the mileage of the train can be acquired. However, the track discrimination has to be realized to describe the track occupancy when the accuracy of positioning is sufficient. When the train is not running through the switch area, track occupation will be identified and the candidate track piece will be locked before the corrected train position is calculated by vertical projection.

From Fig. 2, it can be found that the residual error of map matching illustrates the lateral error of the positioning result by sensor fusion. It allows us to evaluate the quality of sensor fusion and protect the map matching from faulty or biased positioning results. The map matching residual error will be examined with a pre-defined threshold. When the residual exceeds the threshold, the map matching results will not be adopted to generate train position output to the train control kernel, and an alarm will be triggered to indicate the failure in the map matching operation. The residual threshold is an important decisive factor to control the quality of residual examination. It is determined considering the accuracy level of GNSS. A reasonable threshold that matches the GNSS quality level can ensure the accuracy and availability of train positioning and avoid incorrect map matching operations.

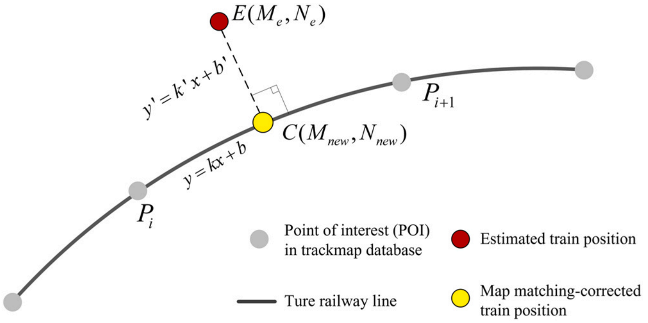

Fig. 2. Principle of map matching using the vertical projection logic.

2.3. Integrity monitoring at the sensor fusion level

To effectively improve the integrity level of train positioning considering the safety requirement of the railway signaling system, the IM (Integrity Monitoring) is of great necessity. The user-level IM method only uses redundant sensor measurements for consistency verification. Since it does not rely on external integrity enhancement auxiliary systems, the user-level IM strategy is adopted in the train control applications that emphasize the autonomous capability of the on-board system. Once the fusion filtering and map matching are completed with the trackmap database, the derived results will be utilized to evaluate the HPE (Horizontal Position Error) with the ground truth from the reference system. With the pre-define HAL (Horizontal Alert Limit) based on the system requirements, HPE will be compared with the HAL to identify the fault state of the positioning system.

To specify whether the train localization output satisfies the application requirements, a decision can be made on the integrity status before generating the location report. The HPL (Horizontal Protection Level) that is calculated with the sensor fusion filter and map matching operations, the HPE between the positioning result and the reference information, and the pre-defined HAL, will be considered at the same time to identify the train positioning integrity status. Under the normal condition with a reliable estimation to the HPE, HPL should cover HPE to realize an effect error envelope. An alarm is required to be activated when HPL exceeds HAL. However, the relationship among HPE, HPL and HAL does not always fall into the normal situation due to faults or failures by the effect of various factors. Hence, different integrity status cases may be obtained in the examination as shown in Fig. 3. In the figures, the HPL and HAL values are represented by the radius of the circles, and the HPE can be evaluated by the distance from the coordinate origin to the point represented by the HPE.

Five cases shown in Fig. 3 can be described as follows.

1) Normal with (HAL > HPL > HPE). The positioning error meets the application requirements and fault is not detected in this case.
2) Dangerous Detected (DD) with (HPL > HAL) ∩ (HPE > HAL). When HPE exceeds the limit HAL under the situation HPL > HAL, the fault occurrence can be detected and an alarm will be activated. In addition, it is not necessary to distinguish the two situations with HPE > HPL and HPE ≤ HPL since the fault is always detectable.
3) Safe Detected (SD) with (HPL > HAL > HPE). The train position error does not exceed the limit HAL but it is determined that the fault exists at the current instant. Although the corresponding alarm will be triggered, it is not harmful to the normal operation of the train control system.
4) Dangerous Undetected (DU) with (HPE > HAL > HPL). It indicates the situation where the train position error exceeds the threshold but it is not detected. It will not trigger an alarm under the dangerous situation. If this status continues for a long time, it will seriously affect the normal operation of the location-based applications because the potential danger cannot be recognized by users and the corresponding protective measures will not be taken.
5) Safe Undetected (SU) with (HAL > HPE > HPL). The train position error does not exceed the limit HAL, but HPL fails to bound the HPE. Although this status is still within the safe operation domain, the risk of the DU status still exists when the error keeps increasing.

Based on the above analysis to the integrity monitoring status, the fault status of the train positioning system can be determined according to the decision space as Table 1.

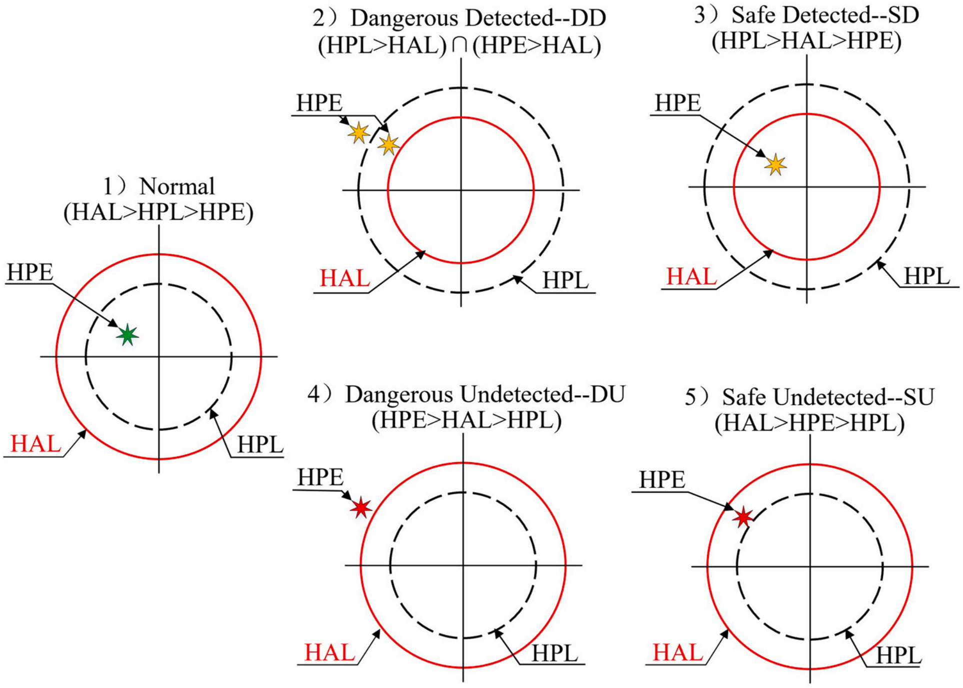

Fig. 3. Different integrity status cases by comparison of HPE, HPL and HAL.

Table 1
Principle of integrity status identification.

No.	Fault detection result	Determination condition
1	Normal	HAL > HPL > HPE
2	NGO	No GNSS output
3	Dangerous Detected (DD)	(HPL > HAL) ∩ (HPE > HAL)
4	Safe Detected (SD)	HPL > HAL > HPE
5	Dangerous Undetected (DU)	HPE > HAL > HPL
6	Safe Undetected (SU)	HAL > HPE > HPL

3. Virtual Balise

The concept of VB (Virtual Balise) can effectively integrate the satellite positioning technology into existing train control system frameworks without modification to the specifications [7,8]. VB capture is acknowledged by matching the train position and the preset VB reference position along the track [9]. Within a specific distance limit, a success matching will enable the determination of the time instant when a train passes through the target VB. Then, the VB telegram can be extracted and transmitted to the ATP (Automatic Train Protection) system kernel. Based on the existing VB capture mechanism, a pre-capture decision logic is necessary to effectively reduce the risk of missed VB capturing. A VB capture recognition method based on the forward search strategy is proposed to accurately determine the position and time of VB capture, which improves the VB capture performance over conventional solution requires a pre-defined capture interval.

3.1. Pre-capture decision logic

With the aid of the train state prediction method, the NVB (Next Virtual Balise) pre-capture decision is made according to the relative position relationship between the train and the NVB. By comparing the predicted mileage $\varDelta S'_{t+1}$ per unit time with the distance $\varDelta S_{\mathrm{NVB}}$ between the train and the NVB at instant t, the following principles are used to realize the NVB pre-capture.

$$VBState_i = \begin{cases} 1, \begin{cases} (\varDelta S_{\mathrm{NVB}} - \varDelta S'_{t+1}) \le 0 \\ (\varDelta S_{\mathrm{NVB}} - \varDelta S'_{t+1} - DCI_t) \le 0 \end{cases} \\ 0, (\varDelta S_{\mathrm{NVB}} - \varDelta S'_{t+1} - DCI_t) > 0 \end{cases} \tag{1}$$

where i is the VB ID number, DCI is the fitting value of the train position prediction error by the LS (Least Squares) method based on the historical state information, which changes dynamically with the train speed; $VBState$ is the result of the NVB pre-capture decision.

As shown in Fig. 4, it can be found that the sub-figure (a) shows that the predicted train position does not pass the NVB at instant $(t+1)$. Since the predicted train position is still far from the NVB, the VB capture and recognition will not be activated under this situation and the VB capture logic will have to continue the train state monitoring ($VBState = 0$). The sub-figure (b) shows two successful cases of NVB pre-capture recognition ($VBState = 1$), indicating that the predicted train position falls into the pre-capture range and thus the VB capture identification will be triggered in the following unit cycle time $\varDelta T$. It is obvious that the involvement of DCI allows us to prevent the missed VB capture when there is a relatively large train position prediction error.

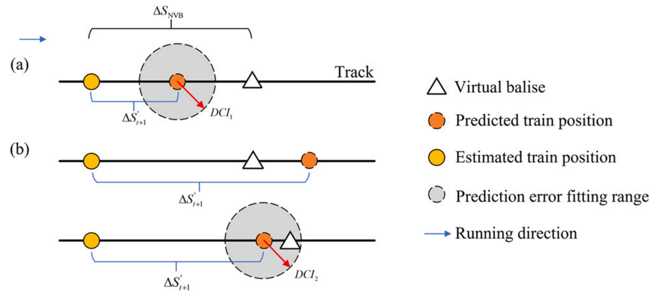

Fig. 4. Different situations of VB pre-capture decision logic.

3.2. VB capture identification

In the train position prediction for pre-capture, the IMM (Interactive Multiple Model) algorithm has been adopted to constrain the prediction error considering different kinematical models of the train, including Constant Stop (CS), Constant Velocity (CV), Constant Acceleration (CA) and Constant Turn (CT). According to the probability evaluation results of each sub-model, it is considered that the model F_i with the largest probability may effectively represent the current running characteristics of the train. To exactly determine the VB passage instant, the cycle time for pre-capturing is divided into $(N-1)$ equal intervals. When the pre-capture is identified, the microscope forward recursion of the train location within the following cycle interval $(t, t+\varDelta T)$ will be carried out according to Eq. (2) to predict the train's state, and each recursion is carried out based on the previous recursion result. By calculating the traveling distance of the train within the interval $(t, t+\varDelta T)$, the exact moment when the head of the train passes through the NVB can be calculated, so as to determine the location with the NVB capture identification. Fig. 5 shows the principle of VB capture identification within the interval $(t, t+\varDelta T)$ when the pre-capture has been identified at instant t.

$$X_{t+j\delta t} = FX_{t+(j-1)\delta t}\,(j = 1, 2, \ldots N-1) \tag{2}$$

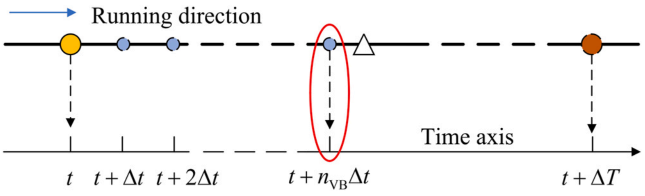

Fig. 5. Principle of VB capture identification.

4. Train integrity monitoring

The connection mode between the train carriages is a rigid connection. When the train is grouped, the length of the train will be fixed covering the length of all the locomotives and carriages (or EMUs for the high-speed railway) [10,11]. In the practical operation, a normal train integrity state indicates that the relative speed of the HOT (Head-of-Train) and EOT (End-of-Train) is zero and the projected HOT-EOT interval equals to the nominal train length. When decoupling occurs, the train will be in an incomplete state, the thus the EOT will lose the traction force and decelerate until the speed falls to zero. An abnormal integrity status will result in an increased HOT-EOT relative speed, leading to an increasing HOT-EOT distance. Therefore, the train integrity state can be identified by evaluating the HOT/EOT relevant state and the train length.

4.1. Train integrity monitoring based on GNSS and trackmap

Through the monitoring of along-track position, speed and direction of the HOT and EOT with the aid of the trackmap database, the train integrity status can be determined through the dynamic evaluation of the train length.

Based on the POI (Point-of-Interest) set $MAP_{84} = \{P_1, P_2, \ldots, P_i, \ldots, P_m\}$, $P_i = (B_i, L_i, H_i, S_i)$ from the trackmap, where (B_i, L_i, H_i, S_i) represent latitude, longitude, altitude and mileage of the POI, map matching can be carried out to determine the along-track location (1D mileage that is not affected by the curve shape of the railway line) of HOT and EOT for train length (L_{matching}) evaluation, which means

$$L_{\mathrm{matching}} = |S_{\mathrm{HOT}} - S_{\mathrm{EOT}}| \tag{3}$$

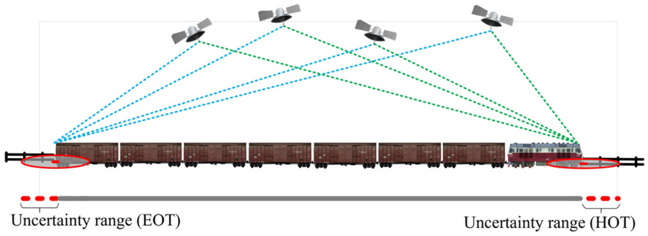

Fig. 6. Principle of length-based train integrity monitoring based on GNSS and trackmap.

Due to the existence of positioning error, especially the uncertainty of EOT positioning resulted by the constrained satellite visibility, the uncertainty of the derived train length has to be concerned [12]. As shown in Fig. 6, an uncertainty buffer has to be added to the estimated HOT and EOT position to form an enhanced "envelope" for the train integrity determination purpose. A conservative evaluation of the uncertainty ranges is necessary due to the safety assurance target, and thus several factors related to the positioning performance have to be investigated, including the measurement noise, state estimation error and the potential fault(s) and failure(s). With this consideration, the derived train length would be larger than truth, and thus the threshold for train integrity identification has to be effectively determined to avoid false alarm to the abnormal train integrity events.

The uncertainties in HOT and EOT positioning results lead to the estimation deviation of the train length. When the quality of GNSS positioning degrades with the change of the observation condition, the deviation of train length estimation would be large and thus the failure of accurate train integrity monitoring may occur. Therefore, the consistency evaluation of the HOT/EOT relative speed can be involved to consolidate the integrity status identification through multiple information resources.

Considering the errors in position and speed measurements of the both ends, it would be necessary to constrain the errors through the filtering operation. It can be found that there are mainly two specific trends to the monitoring variables, including relative static and relative acceleration according to the HOT-EOT-based train length and relative speed estimation. Therefore, a sliding window strategy can be involved for mean filtering, and then the filtered data in the window can be fitted by LS-based linear fitting. According to the fitting results, the qualitative trend of the data in the sliding window can be recognized to analyze the changing status of the HOT/EOT relative speed and the estimation deviation of the train length.

4.2. Safe train envelope estimation

For GNSS-based train positioning and train integrity monitoring, the uncertainty in state estimation has to be concerned to ensure the safety and efficiency of train operation by utilizing the integrity monitoring result. Under the moving block train control scheme, where the occupancy of the track segments is determined by the practical length of the train, it is necessary to add a reasonable margin to the raw HOT and EOT location to form a safe occupancy range [13]. The safe train position has to cover the most unfavorable conditions. With this consideration, the margin should be sufficiently large to realize a high possibility to protect the unsatisfied situations. However, an excessive margin will lead to unreasonable identification of track occupancy, which may greatly affect the operational efficiency. To realize the expected balance level between the safety and efficiency characteristics, a constrained safe margin has to be adopted on the basis of safety and rationality, so as to reduce the train tracing interval and improve the system efficiency.

The essence of the safe train envelope is to realize the safety assurance of train control by describing the reliability of train positioning. The safe train envelope extends the positioning output based on the evaluation of the uncertainty of positioning errors, and provides a safe overlay to the most possible position derived by the HOT/EOT positioning unit. The safe margin consists of the HPL by integrity monitoring result and the confidential interval of the positioning error.

The HPL, which indicates the radius of a circle in the horizontal plane with its center being at the true position to describe the region assured to contain the indicated horizontal position, is usually regarded as the safety boundary of positioning result by GNSS. However, the existence of the integrity risk may lead to an unbounded position error that exceeds the HPL. Without the high-level referencing system during the dynamic operation, it is difficult to accurately evaluate the reliability of the safety boundary by HPL. In order to guarantee the credibility of the safe margin for envelope evaluation, it is necessary to estimate the possible range of the positioning error by a specific error confidence interval strategy. Considering the track-constrained along-track operation of railway trains, the error confidence interval indicates a one-dimensional along-track interval that can be represented by the uncertainties in state prediction, measurement update and the trackmap-based location determination, which means

$$[\delta_{\text{low}}(k),\, \delta_{\text{up}}(k)] = f(\boldsymbol{z}_k,\, \hat{\boldsymbol{x}}_k^-,\, \boldsymbol{g}) \tag{4}$$

where $\delta_{\text{low}}(k)$ and $\delta_{\text{up}}(k)$ represent the lower and upper limits of the confidence interval at instant k, $\boldsymbol{z}_k$ indicates the user measurement result, $\hat{\boldsymbol{x}}_k^-$ denotes the prediction result, and $\boldsymbol{g}$ represents the prior geographic information from the trackmap database.

Based on the lower and upper limits, the error confidence interval can be evaluated by the range of the two limits as $LCI(k) = \delta_{\text{up}}(k) - \delta_{\text{low}}(k)$ and is updated with time. Thus, the safe train envelope $S_{\text{envelope}}(k)$ can be calculated by combining the HPL and error confidence interval as

$$S_{\text{envelope}}(k) = HPL(k) + LCI(k) \tag{5}$$

5. State perception performance evaluation

5.1. RAMS architecture for railway signaling

The performance indices of GNSS-based positioning are different from the requirements of railway systems, especially for the safety-related railway applications. With the EN50126 standard definition, the RAMS (Reliability, Availability, Maintainability & Safety) architecture is presented with different requirements to specific railway systems and functions.

1) Reliability. It refers to the ability of a product or a system to perform a specified function under specified conditions and within a specified time period. The evaluation indicators with respect to the reliability include failure rate, MTBF (Mean Time Between Failure) and MUT (Mean Up Time).

2) Availability. It refers to the extent to which a product or a system is in a workable or usable state at any moment when the required external resources are met or when it starts to perform its tasks. The availability of a product is a composite representation of its reliability and maintainability.

3) Maintainability. It refers to the ability of a product or a system to perform specified maintenance work under the specified conditions and within the specified time using the specified procedures and resources for maintenance.

4) Safety. It refers to the ability to not incur risks that may cause damage. The safety requirements of the GNSS autonomous positioning-based train control system include functional safety requirements and other safety requirements. Among them, functional safety requirements are described by SIL (Safety Integrity Level), and different SIL levels are defined by the THR (Tolerable Hazard Rate).

For a novel train control system based on autonomous perception using GNSS, the RAMS indices also have to be considered in the design and operation phases. The relationship of RAMS indices in the railway domain is shown in Fig. 7. If the reliability and maintainability are met, and long-term maintenance and control are performed according to the environment in which the system is located, the safety and availability of the system can also be met.

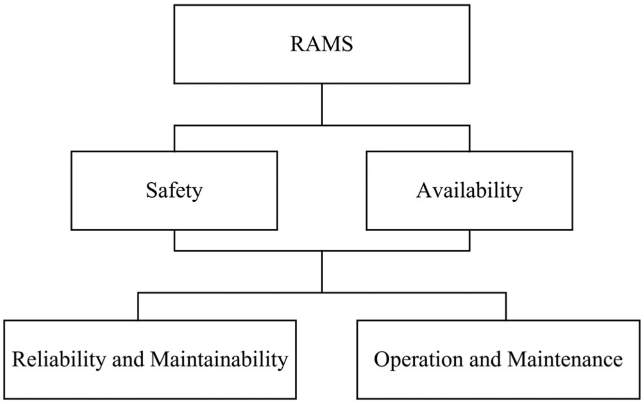

Fig. 7. Relationship of different indices in the RAMS architecture.

5.2. *Indices of integrated train state perception*

It can be found that the GNSS-enabled train state perception can be evaluated using different indices from the railway-specified RAMS architecture. The relationship between GNSS-related performance index system and the RAMS definitions has to be investigated to achieve effective evaluation of the GNSS-based applications in the railway domain. The performance indices corresponding to GNSS are summarized as follows.

1) Accuracy. As the most essential evaluation indicator for the GNSS-enabled train positioning, the concept of accuracy mainly includes static accuracy and dynamic accuracy. Accuracy can be divided into two parts, including correctness and precision. As described in Table 2, it can be expressed by the position error and the degree of confidence, respectively.

2) Integrity. Integrity status identification of GNSS-based train state perception can be performed by combining fault detection at different information processing stages. Only horizontal position results are considered in the railway applications, the integrity of an integrated train positioning solution like the GNSS/INS integrated mode can be defined as “the ability of the train positioning unit to alert the train control system if it cannot provide available horizontal position results”.

The evaluation of the integrity status is different from the accuracy since it concerns more about the behaviors of the perception logic against the critical conditions with fault(s) or failure(s). It can be described by the false alarm rate, missed detection rate, HPE, HPL, HAL and TTA (Time to Alert), which are summarized in Table 3.

For the train positioning integrity assessment aiming at train positioning status identification, the output parameter is the train positioning output result integrity status. In the train positioning integrity state, in addition to the normal state, there are three non-normal states: alarmed non-hazardous state, alarmed hazardous state and no alarmed hazardous state.

For the integrity assessment aiming at the identification of train positioning status, the “integrity state” will be identified as the output of the assessment, which is defined as status of the train positioning output results obtained with the integrity assessment input parameters. It can be classified as normal, safe alarmed, dangerous alarmed, and dangerous un-alarmed.

3) Availability. According to the definition of availability in EN50126, availability of an integrated train positioning system like GNSS/INS mode is defined as “the extent to which the train positioning is available at any given moment”. The required parameters for the availability assessment mainly include the integrity status, hardware failure rate, and environmental scene parameters, which can be described as Table 4.

The availability evaluation results can be reflected by the instantaneous availability and steady-state availability. The instantaneous availability $A(t)$ evaluates the probability that a train positioning unit normally provides the reliable location service at a certain moment. Under the normal circumstances, the train positioning unit is able to provide location information at a fixed frequency f_{N}. If the train location unit is able to provide the reliable location service normally at instant $t_{1,}$ it is considered to be available in the period from $t_0 = t_1\text{-}1/f_{\mathrm{N}}$ to t_1, denoted as $A(t_1) = 1$. Otherwise, it is considered to be unavailable at this instance, which means $A(t_1) = 0$. Different from the instantaneous availability, the steady-state availability A illustrates the probability that a train positioning unit provides the location service correctly after reaching a steady

Table 2
Parameters in accuracy evaluation.

Parameter	Symbol	Description
Position error	e	Deviation of the measurement result from the truth.
Degree of confidence	$1\text{-}\alpha$	Degree of agreement of the measurement results, which can be measured by the dispersion of the measurement results; the length of the region where the overall parameter lies within a certain confidence level is called the confidence interval

Table 3
Parameters in integrity evaluation.

Indicator	Symbol	Description
Horizontal position error	*HPE*	The difference between the measured position of the train at a certain moment and the reference value output by the reference system in the horizontal direction. The reference system is able to achieve a higher accuracy installed at the same location as the current train positioning unit.
False alarm rate	P_{fa}	Required parameters for fault detection, fault isolation and horizontal protection level calculation. In practice, the settings should be defined concerning the requirements of specific railway lines with different traffic densities.
Missed detection rate	P_{md}	Required parameters for fault detection, fault isolation and horizontal protection level calculation. In practice, the settings should be defined concerning safety requirements and the tolerable risk raised by the positioning unit.
Horizontal protection level	*HPL*	The position output thresholds obtained on the basis of false alarm rate and missed detection rate. The HPL should effectively bounds the HPE under normal conditions.
Horizontal alert limit	*HAL*	The maximum horizontal position error value that does not activate the alarm. It is related to the practical requirement of the train control system and the environmental factors of specific railway lines.
Time to alert	*TTA*	The maximum time interval permitted from the time when the fault information is collected until the user receives an alarm. The determination of the TTA is also related to the operational requirements. An integrity event should not be considered as such unless it lasts for longer than the TTA without an alarm being raised.
Environmental scene parameter	S_{c}	The results of environmental scene clustering classification based on a priori information. It is used to improve the filter estimation quality to further ensure the accuracy and integrity of GNSS-based perception.

Table 4
Inputs of availability evaluation.

Parameter	Symbol	Description
Integrity state	S_i	Obtained through the integrity assessment.
Hardware failure rate	λ_H	Probability of hardware failure for the sensor(s) or the data processing module in the train positioning unit.
Environmental scene parameter	S_c	Clustering result of environmental scenes based on a priori information, which is used to implement state transfer analysis and availability assessment of sub-environmental scenes.

Table 5
Definition of different SILs according to the THR.

Tolerable Hazard Rate (per hour, per function)	SIL level
$10^{-9} \leqslant THR < 10^{-8}$	4
$10^{-8} \leqslant THR < 10^{-7}$	3
$10^{-7} \leqslant THR < 10^{-6}$	2
$10^{-6} \leqslant THR < 10^{-5}$	1

state over a longer period of operation. Thus, the relationship between the two availability parameters can be described as

$$A = \lim_{t \to \infty} A(t) \tag{6}$$

4) Safety. Safety stands for the ability to eliminate the risk of unacceptable damage to a positioning unit. The railway sector uses safety integrity level to describe the likelihood that a system achieves the required safety function within a specified time under all specified conditions. The SIL specifies the safety integrity requirement for the safety functions assigned to the safety-related systems. Different SIL levels can be described in Table 5.

The risk assessment needs to be performed for the safe design of train positioning architecture for the railway signaling applications. The risk assessment results can be classified as risky and the risk-free cases. Therefore, the output of safety assessment can be defined as the frequency of risky event P_{risk}.

It has to be noted that the above-mentioned indices considering both the RAMS and GNSS systems are closely correlated, which means that performance evaluation is carried out based on a systemic measure. The relationship among the performance indicators for GNSS-based train positioning and state perception can be described as Fig. 8.

6. Field demonstration and analysis

Based on the development of the novel train control system, an advanced train positioning unit for the railway train control application was designed and developed. The unit is realized based on the safe platform with a 2-out-of-2 (2oo2) redundant architecture. Under the safe platform architecture, the sensor data collection boards and communication boards are designed independently. Two sensor data collection boards are involved to independently collect raw measurements from the GPS/BDS receivers, INS sensors and the odometer. The communication boards are designed for information interaction between the train positioning unit and the ATP kernel. The core position calculation unit realizes the sensor data fusion and location determination using the presented technologies in this paper. In 2021, a field test was carried out at the Haergai-Muli railway. The test section is more than 120 kilometers with a high altitude between 3200 and 4200 m. Five stations are involved in the field test section, including Huancang, Chaidaer II, Chaidaer I, Wailihada and Jiangcang. Trackmap database of the test section was measured and generated before the field demonstration. Specific track-side GPS/BDS differential stations were developed and installed to enhance the performance of train-borne receivers. Field data collection for trackmap generation and the equipment deployment status in the field test are shown in Fig. 9.

In the field test, the whole train control system, including on-board equipments, track-side facilities, train control center and the integrated communication subsystem, were involved to validate the novel train control mode under the moving block scheme with the state perception by BDS. According to the operation plan for validating the train position and route resource management capabilities, the on-board equipments of three test trains independently

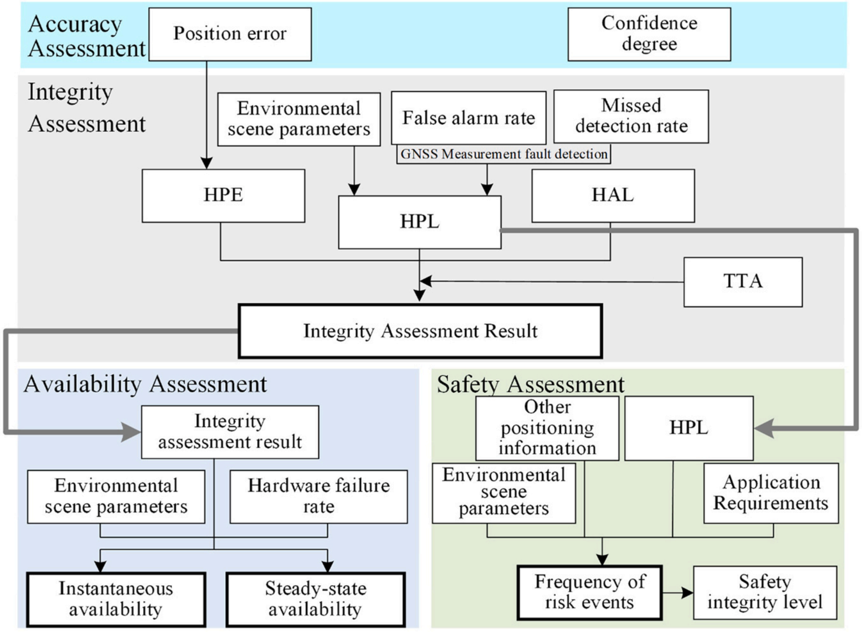

Fig. 8. Relationship of the performance indicators for GNSS-based train perception.

Fig. 9. Trackmap generation and equipment deployment in field test in Haergai-Muli railway.

Table 6
Train positioning errors under different modes in field test (meters).

Positioning mode	Mean	STD	95 % probability error
Static positioning	1.53	0.38	2.59
Dynamic positioning (single-mode GNSS)	3.09	0.88	4.67
Dynamic positioning (dual-mode GNSS, BDS + GPS)	1.59	0.87	3.20
Dynamic positioning (GNSS/INS/ODO fusion)	1.49	0.81	3.02
Dynamic positioning (differential GNSS and sensor fusion)	1.42	0.26	1.76

realized the track resource allocation, route establishment and resource release operations. The position of the leading train, within a tracing train couple, can be identified by the train-to-train communication, with which the on-board equipment of the following train was able to independently calculate the MA (Moving Authority) considering both the operation plan and the route resource application status. The trackmap database was designed and generated effectively with a reduced data volume, which releases the requirement to the train-ground communication and the complexity of system interfaces for trackmap verification. Through the integration of static trackmap information, sensor data fusion for BDS/GPS receivers, INS sensors and the odometer measurements were realtimely achieved with a high availability level under the complex and time-changing operation environment. Both the static and dynamic test cases were involved in the field demonstration. Table 6 summarizes the accuracy results of train positioning under different system modes.

The results from field demonstration illustrate that involvement of the presented key technologies, including the safe platform and multi-source sensor fusion mechanism, effectively guarantees the performance of GNSS-based autonomous train positioning and state perception even under complex and time-varying operational conditions. The utilization of the differential GNSS technology and the integrity monitoring logic makes it possible of achieving the high accuracy and robustness against the possible difficult or even critical conditions. The field test results demonstrate the feasibility and the advantages of utilizing BDS in realizing a novel autonomous train control system with a train-centric design, which is of great significance in the future high-speed and plateau railway applications with the enhanced environmental flexibility and whole life cycle cost efficiency.

7. Conclusion

The application of GNSS technology is one of the representative characteristics of intelligent railway systems in the future. However, there are specific requirements to the GNSS-based train positioning and state perception in the railway signaling applications due to the critical requirement to the safety. Thus, the utilization of GNSS has to be enhanced by the specific technical solutions. The sensor data fusion technique is of great significance to enhance the service availability under degraded or even a critical GNSS observing condition. To ensure the compatibility to the existing system specifications, the VB technology enables the integration of the GNSS capabilities into the train control system and meanwhile the train integrity monitoring logic allows the opportunity to realize moving block-based train operation control through the dynamic identification of the track occupancy and safe envelope of the train. By investigating the relationship between the GNSS performance system and the RAMS specification, the performance evaluation of the GNSS-based train positioning can be effectively realized. It can be found that the involvement of these key technologies consolidates the autonomy and capabilities of the train-borne system, which releases the requirement to the track-side facilities like track circuit and Balises. The field demonstration further validated the effectiveness of the presented key technologies under the complex real environment. With the development of the global BDS-III system, it can be expected that more GNSS-based applications will be promoted in the intelligent railway systems in the future.

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