www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

Electronic Track Map Building for Satellite-based High Integrity Railway Train Positioning

[1]Liu Jiang, [2]Cai Baigen, [3]Wang Jian

[1] School of Electronic and Information Engineering, Beijing Jiaotong University, and School of Transportation Science and Engineering, Beihang University, Beijing, China

[2] School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing, China

[3] State Key Laboratory of Rail Traffic Control and Safety, and School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing, China

Emails: jiangl@m.bjtu.edu.cn, bgcai@bjtu.edu.cn, wangj@bjtu.edu.cn

Submitted: Feb. 12, 2013 ***Accepted: Mar. 27, 2013*** ***Published: Apr. 10, 2013***

Abstract- The concept of electronic track map has been introduced and researched in many satellite-based railway train positioning and location-based railway systems. It should characterize the railway tracks and their key objects and facilities with a satisfied accuracy and completeness. Based on the application requirements, design and building of the electronic track maps should be in accordance with the map matching approach, and moreover, considering the integrity effect that is decisive to safety. This paper introduces a paradigm for electronic track map design and generation. According to the satellite-base train positioning scheme, the architecture of the electronic track map and its coupling in the train-borne systems is investigated. Detailed track map generation method is summarized as a

five-step process, including raw measurement collection, rejection of abnormal measurement, feature points extraction, track interpolation, and topographic property supplement. Following this approach, the map matching with high integrity is discussed where the statistics of matching residual is adopted to improve the direct error analysis. Practical measurements and field test results demonstrate the capability of the presented track map building and integrity monitoring approaches. That provides great potential to implementation of satellite navigation in railway applications and services.

Index terms*:* Electronic track map, railway train positioning, Global Navigation Satellite System (GNSS), multi-sensor integration, high integrity.

I. INTRODUCTION

Due to rapid and widely development of GNSS (Global Navigation Satellite System) techniques all over the world, railway signaling and train control systems are about to experience a major change. Integration of GNSS in the specific railway systems may provide great benefits such as the lower initial costs, less maintenance demand and potentiality of increasing the capability of railway lines for both freight and passenger trains. It is being expected to constitute an attractive complement or even a replacement for existing techniques, though it has received little attention so far [1][2]. However, GNSS suffers from line-of-sight (LOS) problems especially in the low satellite visibility environment such as the deep cuttings, forest, urban canyons and tunnels, which would cause lack of availability and integrity. Since the satellite geometry is a primary requirement for railway, the stated limitations of GNSS are unacceptable for safety-critical railway applications. Besides, uncertainties in sensor measurement should be highly concerned in prevent risk issues [3]. Hence, the integration of GNSS with additional sensors is regarded as effective solution that significantly improves the performance of train positioning, where the multiple sensor fusion method plays a major role in application [4]. Moreover, the accurate and reliable railway track map database is of great significance. As a core element in a Satellite-based Train Positioning System (STPS), the electronic track map provides a complete description to the topological information of railway tracks, and it can be used as reference to calibrate the position estimation error and make the position result be identified within the track-defined one-dimensional location coordinate. Although the electronic track map cannot fully compensate LOS weakness of GNSS, it is capable of improving the positioning performance and support train operation monitoring, output validation, fault detection and positioning integrity [5][6].

For building electronic track maps for high integrity train positioning and other related railway applications, it is usually difficult and not cost-effective by satellite image-based remote sensing approach, which has been widely used in many specific applications [7]. High precision GNSS-based track measuring is an efficient method to obtain the fundamental information of railway tracks, and map building can be achieved by post-processing of the raw measurement. Switzer Pushcart was used in WCRM (West Coast Route Modernization Program) to realize the track data collection, where both incorrect and multiple measurements synthesis were considered [8]. The ITCS (Incremental Train Control System) describes rail tracks by approximation with reduced polyline or circle curve, which has been successfully applied in Qinghai-Tibet Railway in China since 2006 [9]. Gomm (2002) made some research on generation of track database and development of corresponding standard in the LOCOPROL project [10]. Gao (2006) developed a multi trajectory fusion based method to generate accurate track map database from the huge measurements in the railway shunting operation [11]. Hensel (2010) proposed a probabilistic rail train locating method, which chose the switches as the landmarks for generation the simple rail topological map [12]. Chen (2010) developed a nonlinear combinatorial data reduction model for a large amount of railway GPS data to decrease the memory space of map database [13]. Gikas (2012) described a novel approach for extracting centerline geometry of railway tracks in the form of traditional design elements (i.e. the straight lines, circle arcs, and clothoids), which uses a series of specific filters that fully adhere to fractal properties of the centerline location for building a map database [14].

With a track map database, train positioning can be assisted by various integration approaches at different coupling levels, and map matching (MM) is considered as a relatively low-cost and effective choice. Since the map matching logic enhances the structure of the STPS, relevant factors from the MM process should also be covered to evaluate and improve positioning integrity, which is meaningful to the assurance of safety for those location-based railway application systems and services. Quddus (2006) summarized and studied the high-integrity map matching algorithms for transport applications, and analyzed the factors affecting the integrity of a MM approach [15]. Gerlach (2009) presented the multi-hypothesis solution to enhance correctness of occupied track segment identification and achieve effective map matching [16].

Jana (2009) proposed the discrete PIM (Position Integrity Monitoring) algorithms to imply the integrity level of the GNSS position results and the track matching process by a multivariate statistical analysis-based solution [17].

Current researches on specific railway electronic track maps mainly concern management of railway GISs (Geographic Information Systems) which are performed for construction and maintenance of the infrastructure. There are not sufficient efforts on the design and utilization of electronic track maps for performance optimization of train positioning when using the satellite navigation resources (especially Beidou Navigation Satellite System). Particularly, it should be highly concerned to enhance the integrity of corresponding MM solution for certain maps for satellite-based safety-critical railway applications, i.e. train control and collision early warning. In this paper, based on the requirements analysis of high integrity train positioning using GNSS, a design of electronic railway track map is presented, and solution for map building is analyzed with validation of train positioning and map matching by practical field measurements.

II. ARCHITECTURE DESIGN

A satellite-based train positioning system always takes a multi-sensor integration-based architecture to avoid risks of GNSS, including unavailable SIS (Signal-In-Space), multi path effects and EMI, etc. Inertial sensors are promising choices for most of road transportation applications, and they are also proved suitable for railway trains. If available, the differential satellite positioning can provide meter-level accuracy which might be more effective to determine the train's position, velocity and other required state descriptions. Within the GNSS/INS enhances odometer scheme, an architecture solution of the satellite-based train integrated positioning system can be illustrated as shown in Fig. 1, where a OBC denotes on-board computer, and IMU is the inertial measurement unit. For purpose of assisting the train control system by GNSS, the presented positioning system is designed with interface to the on-board ATP (Automatic Train Protection) equipment.

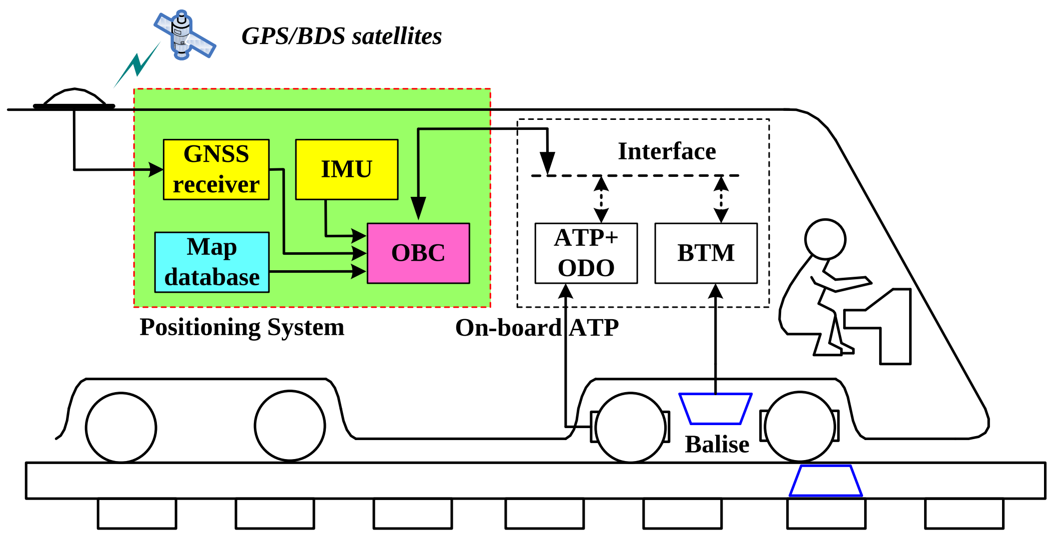

Figure 1. Architecture of train positioning system

Generally, railway lines are composed by tracks and their subsidiary facilities. The electronic track map is designed, generated and stored as static data source representing the covered railway lines. As the most important part, track data are fundamental elements to fill the database and describe practical railway lines in different scales. There are always three parts to form the track database, including key information, track data and the topographic data. Structure of the electronic track map is as shown in Fig. 2.

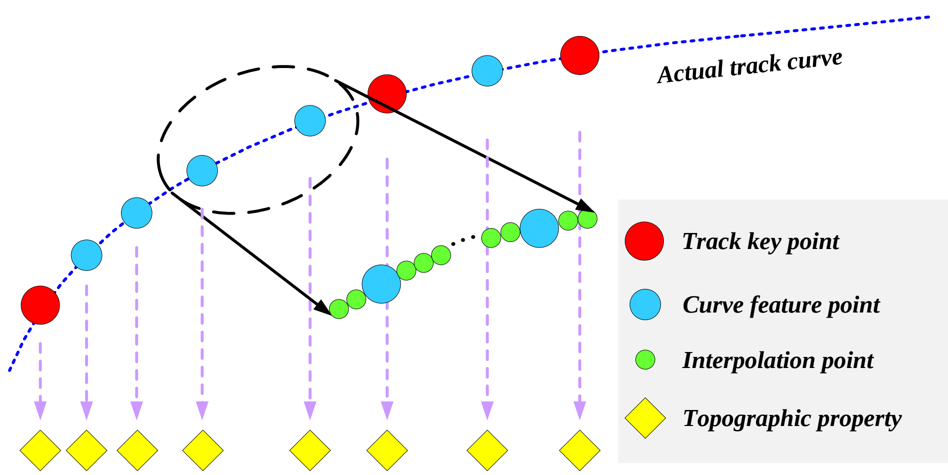

Figure 2. Structure of the electronic track map

The key track points dedicated to satellite-based train positioning process, marks and describes the crucial feature properties of track location such as signaling controllers, switches, station centers, etc.

The curve feature points provide track geometry descriptions to actual rail tracks that are abstracted as essential curve elements. The feature points can be divided into two levels, where reduced feature point set can be formed to approximate real tracks on low scales, and a high scale refers to supplement of interpolation data to refine the description.

The topographical properties refer to positioning related environmental factors along train operation, including surrounding characters (tunnels, hills, and forests), meteorological conditions, etc.

III. TRACK MAP BUILDING METHOD

Raw track measuring data are collected by high precision GPS receiver from rail lines and stations. As the demand for track map database according to the given structure, procedure for building the track map database is divided into five steps as follows.

(1) Raw measurement collection

High precision GPS (usually the differential GPS) receiver is taken to measure the track curves and determine position of the POIs (Points-Of-Interests) along tracks. Ideally, for the static measuring, there should be an error bound achieved better than 1m. For the dynamic process there should be continuous, uniform and precise (with an error bound less than 2.5m) measuring as the track geometry.

(2) Rejection of abnormal measurement

Table 1: Abnormal mode description and the rejecting strategies

Mode	**Rejecting strategy**
Non-uniform	Inspect the distance between adjacent points, only points satisfy the upper and lower limit will be reserved.
Intermittent	Inspect the distance between adjacent with an upper limit, take supplementary measuring or data interpolation
Gross error	Inspect by filtering or smoothing with residual statistics, replace abnormal data by state estimation

With uncertainties and limitations from operation conditions, there may be abnormal data in the raw measurements due to unavailability of the receivers, unreasonable mapping routes or certain challenging environment factors. Primary modes of abnormal measurement and corresponding rejecting strategies are listed in Table 1. Fig. 3 presents a case where abnormal data are detected and rejected by presented strategies.

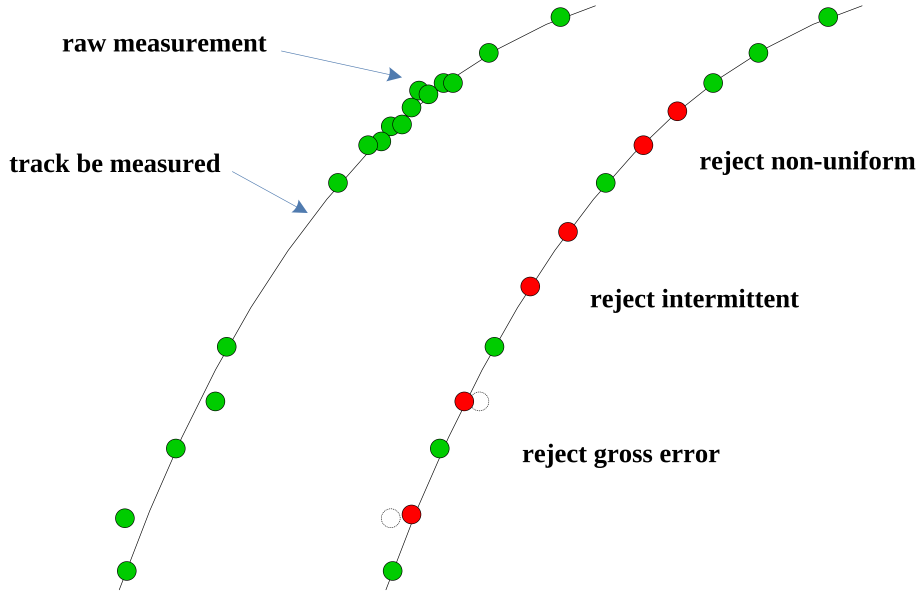

Figure 3. Abnormal mode and the rejecting results

(3) Feature points extraction

In order to describe topological properties of the track curves with only a few feature points, proper measures should be taken for the feature extraction with data validated by abnormal mode inspection. Among those feature extraction algorithms in GIS field, the Douglas-Peucker (DP) algorithm [18] is a classical method and regarded suitable for many applications. However, traditional DP method takes disadvantage of the fixed limit error, which leads to insufficient adaptability to varieties from uncertain conditions. In this research, we calculate angular rate for every measured map fix and validate it with a predefined threshold ε_ρ as the criterion

$$\rho(k) = \left|\theta(k) - \theta(k-1)\right| / d(k) > \varepsilon_\rho \tag{1}$$

where $\theta(k)$ denotes the attitude from the k th map fix to the $(k+1)$ th along a current track, and $d(k)$ represents the distance between the current map fix to the former one. Since distance between adjacent measuring fixes cannot be controlled as a constant value, we use an angular rate $\rho(k)$ to the moving distance to evaluate the variation. If distance-based variation $\rho(k)$ exceeds the predefined threshold ε_ρ, it may indicate a extreme point to represent the curvature of a track curve that cannot be reduced. With the extracted extreme points, an original track curve is divided into several pieces. The principle is shown in Fig. 4.

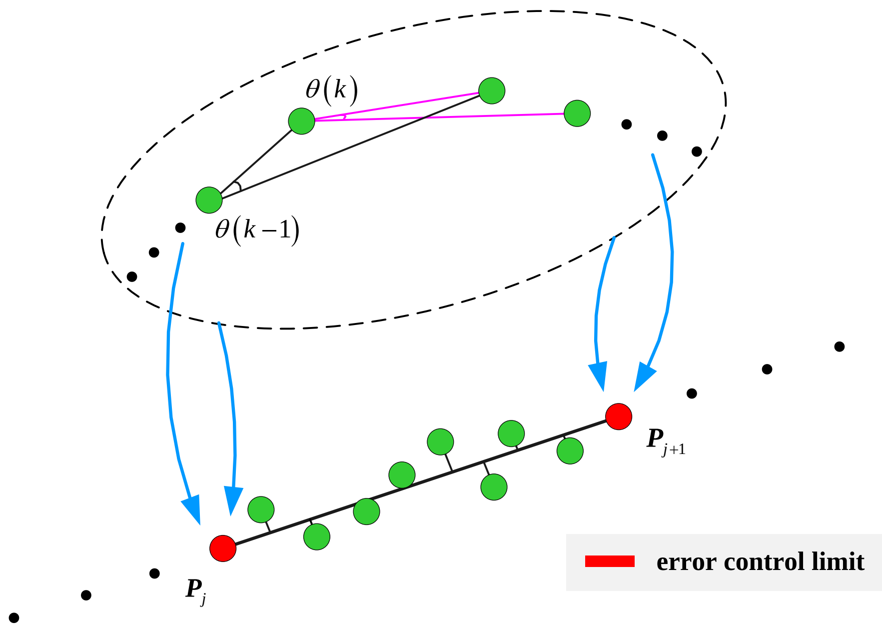

Figure 4. Principle of the feature point extraction

For the divided track pieces, we use a piecewise validation method with vertical distance to inspect all the explored feature points $\boldsymbol{P}_j$, which contains the coordinate location and feature marks. Different from traditional approach, an adaptive error control limit based strategy is adopted according to a given parameter ω_j that fulfills $\omega_j \in (0,1]$. The criterion for validating the feature points is written as follow

$$\max_k \{d(k)\} \le \omega_j \bar{d}, k \in 1, \cdots, n_j \tag{2}$$

where $\bar{d}$ is a predefined vertical distance limit that is scaled by ω_j when considering the baseline from $\boldsymbol{P}_j$ to $\boldsymbol{P}_{j+1}$, and n_j denotes the number of candidate map points between the two feature vertex points. If criterion (2) is satisfied for all the n_j points, they will be reduced and not included into the database to represent the current track. Otherwise, validation will be continued for the re-divided pieces, where that point with a maximum distance $\max_k \{d(k)\}$ will be considered as another curve feature point. The detailed feature point extraction procedure is presented in Algorithm 1.

Since the extreme points reflect variation of track curves, we can use them to represent the tracks in a relatively low scale.

Algorithm 1 Feature point extraction

Require Track measurement point set $\{\boldsymbol{P}_k\}$ after abnormal mode inspection.

1: Compute angular rate $\rho(k)$ and determine the extreme points for piece division as (1).

2: Divide a track into n_j pieces with selected extreme points.

3: Take endpoints of piece j to update the $\boldsymbol{P}_j$ and $\boldsymbol{P}_{j+1}$, and calculate the control limit.

4: Inspect every point as criterion (2). If the criterion is not satisfied for $\hat{\boldsymbol{P}} = \arg\max_k \{d(k)\}$, $\hat{\boldsymbol{P}}$ is taken as a new extreme point to re-divide piece j, and repeat step 3 until all the points between the $\boldsymbol{P}_j$ and $\boldsymbol{P}_{j+1}$ is within the bound as (2).

5: $j \leftarrow j+1$, repeat step 3, until all the pieces complete the inspection.

(4) Track data interpolation

In order to meet critical requirement of position accuracy and improve efficiency of map matching in high speed train operation process, map database containing the high scale track curve description by interpolation data is necessary, and that may enable the point-to-point MM logic and reduce calculation cost of the on-board computer. The railway tracks mainly consist of line segments, circular curves and transition curves. The obtained track feature points control the curvature to track representations. With constraint from these feature points, interpolation can be performed as a required resolution indicator γ. The cubic B-spline is suitable for approximating the actual tracks by interpolating with the extracted feature points.

By calculating the control vertices, interpolation can be carried out to generate detailed track feature information in high resolution. Determination of the indicator γ is important if the point-to-point MM logic is adopted by limiting the accuracy of matched results. Usually, a small γ indicates a large volume of a high-resolution map database but more desired map matching precision level. That depends on the practical application of the track map.

(5) Topographic property supplement

With those previous steps, we can obtain reduced map feature points and the interpolation, thus the essential structure description of the actual railway tracks has been achieved. However, considering the practical contribution of a track map database in the multi-dimensional satellite-based train positioning, specific one-dimensional track coordinate requires suitable solution for the coordinate transformation. Accordingly, the mileage information provides the effective solution to supply topographic properties to the track descriptions and directly used in MM.

Since there may be multiple parallel tracks in the station areas, misleading may exist in the position fix of sidelines for different paths by which a train can pass the station. Hence, a unified principle is employed to take mileage in mainline as reference, where the sideline fix uses its projection to the main line to determine the corresponding mileage. Offset to the mainline will be used to indicate the relativity. Principle of the projection is shown in Fig. 5.

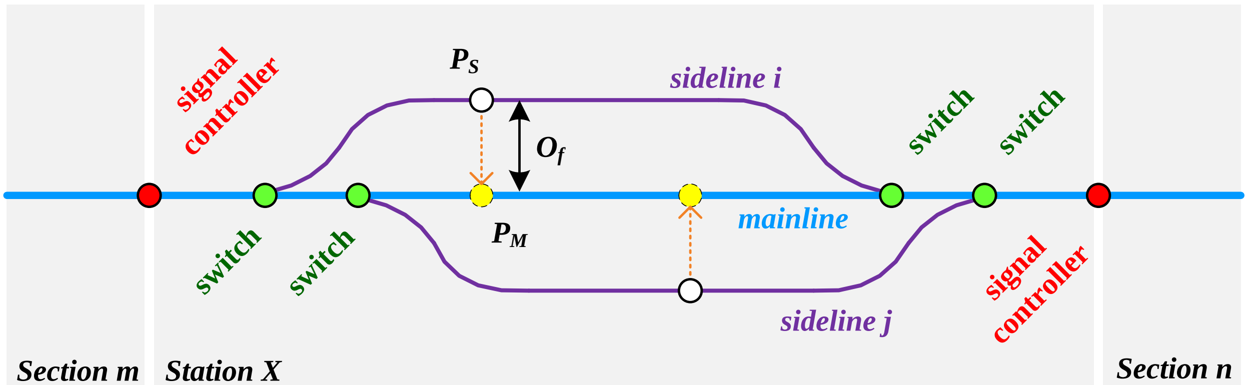

Figure 5. Principle of mileage projection

Table 2: Data format with property supplement

No.	Content	Description
1	index num.	to index this point within the area limit of this file
2	coordinate location	the longitude and latitude of this map fix
3	altitude	value from raw GPS measuring or interpolation
4	mileage	km
5	area type	station or the track section
6	area name	section index or station name
7	track type	mainline or sideline
8	track index	track number indexed in the station, if a sideline
9	track offset	track offset distance to the corresponding mainline
10	direction	up link or down link, if in the mainline
11	feature type	feature point or interpolation point
12	specific type	switch, signal controller, insulated joint, etc
13	object name	name of the specific object

Besides the mileage, some additional information will be coupled to precisely and completely define every map fix, including the area indicator, track information and object description, etc. One of the feasible data format using to describe the map fixes is listed in Table 2.

With this five-step procedure, the electronic track map data is completely prepared and the database can be built accordingly. The results are capable of being stored and integrated for satellite-based train positioning and integrity monitoring.

IV. HIGH INTEGRITY TRAIN LOCATING

Integrity of train positioning is one of the key performance indices to evaluate the trust level that can be given to the derived positioning results, and that is of great significance to some safety critical applications [19][20]. In specific satellite-based train operation control system, integrity indicators are important references to update the safety buffer for both ends of a target train and determine the precise boundaries of speed-distance curve. Since the map matching is the final stage to decide the train position with the track coordinate, it is necessary to monitor the integrity performance of the MM calculation in real-time.

In a loose coupled sensor integration frame, map matching is activated by the sensor fusion filtering result in every calculation cycle. Assuming $\hat{\boldsymbol{X}}_k$ is the state estimation from a Kalman filter that fuses the measurement from the satellite receiver and the inertial sensors at instant k, the map matched result is updated to $\boldsymbol{M}_k$, and these vectors are written as

$$\hat{\boldsymbol{X}}_k = \begin{pmatrix} x_k & y_k & l_k \end{pmatrix}^{\mathrm{T}} \tag{3}$$

$$\boldsymbol{M}_k = \begin{pmatrix} x_k^{\mathrm{m}} & y_k^{\mathrm{m}} & l_k^{\mathrm{m}} \end{pmatrix}^{\mathrm{T}} \tag{4}$$

where x_k, y_k are longitude and latitude of a current location, l_k is its mileage, and the mark m denotes the map related values. With a sliding-window with fixed length W, the candidate track map point set $\{\boldsymbol{P}_j\}$, $j = 1, 2, \ldots, W$ is determined along a given $\hat{\boldsymbol{X}}_k$ according to a candidate center searching logic by considering previous matching result. The matching probability $\phi(\boldsymbol{P}_j \mid \hat{\boldsymbol{X}}_k)$ for every candidate map fix is estimated according to a distance-based Gaussian density. An end vertex $\boldsymbol{P}_{\mathrm{F}}$ of a minimum candidate segment is determined by

$$\boldsymbol{P}_{\mathrm{F}} = \arg\max_{j} \phi(\boldsymbol{P}_j \mid \hat{\boldsymbol{X}}_k) \tag{5}$$

Another end vertex $\boldsymbol{P}_{\mathrm{S}}$ can be selected from the two neighborhood points using the same principle. With this minimum candidate segment from $\boldsymbol{P}_{\mathrm{F}}$ to $\boldsymbol{P}_{\mathrm{S}}$, the matching position constrained by track map will be derived as a maximum similarity criterion

$$\boldsymbol{M}_k = \arg\max_{i} \lambda\left(\boldsymbol{P}_i \mid \left(\boldsymbol{P}_{\mathrm{F}}\boldsymbol{P}_{\mathrm{S}}\right), \hat{\boldsymbol{X}}_k\right), \boldsymbol{P}_i \in \left(\boldsymbol{P}_{\mathrm{F}}\boldsymbol{P}_{\mathrm{S}}\right) \tag{6}$$

where $\boldsymbol{P}_i$ denotes the object location belongs to the line segment $\left(\boldsymbol{P}_{\mathrm{F}}\boldsymbol{P}_{\mathrm{S}}\right)$ or an interpolation set, and the function $\lambda(*)$ is similarity function. The presented track map matching method is as shown in Fig. 6.

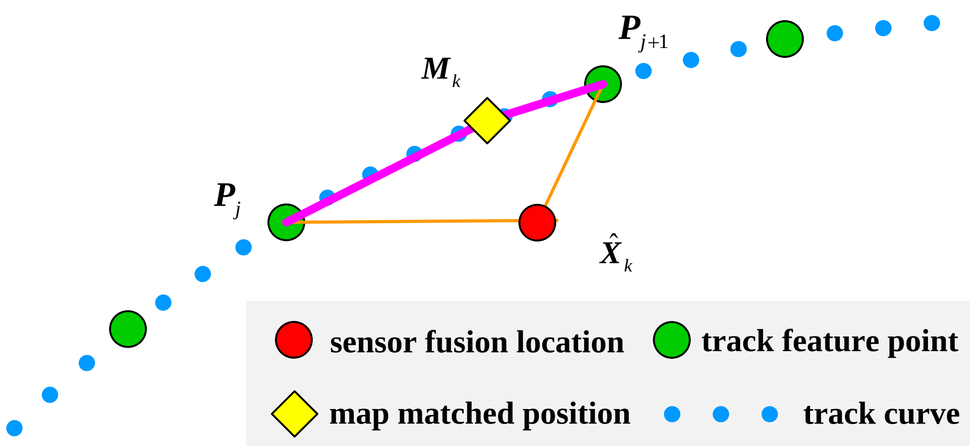

Figure 6. Principle of map matching calculation

Integrity monitoring is real-timely carried out by validating statistical characters of map matching residual error $\boldsymbol{e}(k)$, which is computed as

$$\boldsymbol{e}(k) = \boldsymbol{M}_k - \hat{\boldsymbol{X}}_k \tag{7}$$

A test statistic is built based on the residual error. It should be followed that

$$\mathrm{T}_{\mathrm{e}} = \boldsymbol{e}(k+1)^{\mathrm{T}} \boldsymbol{W}_k^{-1} \boldsymbol{e}(k+1) \sim \frac{\chi_2^2}{\chi_{k-1}^2} = \frac{2}{k-1} F_{2,k-1} \tag{8}$$

where the matrix $\boldsymbol{W}_k = \sum_{i=1}^{k} \boldsymbol{e}(i)\boldsymbol{e}(i)^{\mathrm{T}}$ associates with positioning result up to time k. For the given test significance level α, the above test statistic forms an indication to integrity stage satisfaction. It helps a TPS with map assistance be aware of its operation state and sensitive to possible faults or failures in filter estimating or map matching. The precision related to map database building process is another factor which is also a potential cause to affect the statistics feature of matching residual error.

V. FIELD TEST ANALYSIS

The presented map database building method is used in field works in Qinghai-Tibet Railways. The test was carried out with an experimental mapping system including a SBAS-aided high precision differential GPS receiver and the developed specific software. Raw collection sets were stored and off-line processed. The measuring equipments in field works are as illustrated in Fig. 7, and the results have been applied in practical railway engineering application.

Figure 7. Field test in practical railway lines

For an experimental track with a length over 1000m, data reduction and feature points extraction were performed with different parameters. Also, the high resolution map was considered by interpolation via the explored curve feature points. In Fig. 8 and Fig. 9, two different results of track map representation are demonstrated respectively, where the red marks are track feature points and those green marks stand for the interpolation with more details.

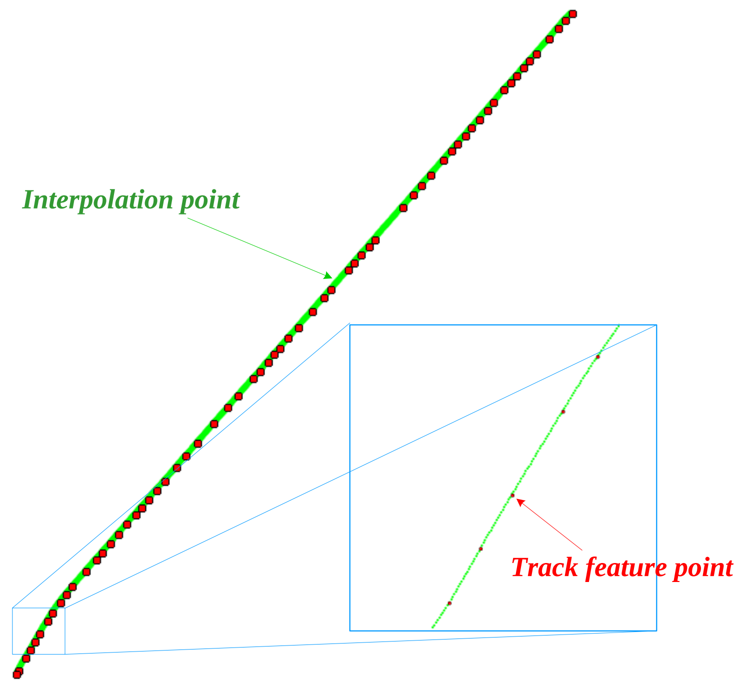

Figure 8. Generated map of the test track

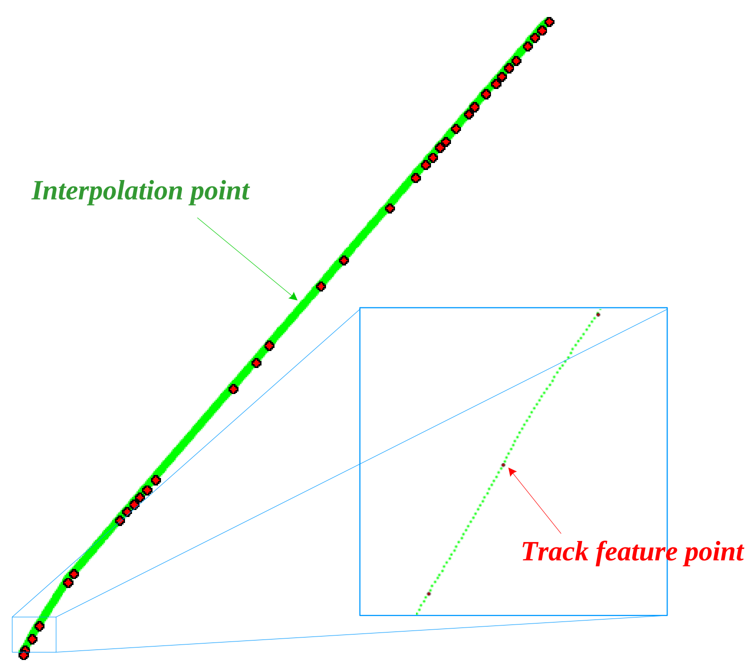

Figure 9. Generated map with different parameters

Since the track feature points are considered the decisive factors that correspond to description and quality of the map, it is crucial to choose suitable parameters in criterion (2). The angular rate limit ε_ρ greatly affects the precision level and the efficiency of the derived map database. As shown in Fig. 8, we use a relatively small value $\varepsilon_\rho = 3$. As a result, there are 65 feature points extracted over 1100 frame raw GPS measurements, which means 94.1% of them have been reduced in track representation. Based on the presented B-spline interpolation principle, totally 1939 points are generated to refine the description of the track curves, which indicates 30 map points on average are taken for supplement between two adjacent feature points, with an average distance of 0.51m. For the test results shown in Fig. 9, the control limit is set with a larger value $\varepsilon_\rho = 8$. Since a relatively critical limit is used, the feature points are reduced to 35, which indicate that 96.8% of the raw data is rejected to be included in a low-resolution database. There are 1924 points generated to enhance the density of track map and it is with a similar average space interval 0.52m as shown in Fig. 8. To compare and analysis the sensitivity of the presented feature point extraction method to a specific ε_ρ, different value of the threshold ε_ρ with a range from 1 to 8 is tested and listed in Table 3.

Table 3: Comparison of feature point extraction results with different ε_ρ value

Angular rate threshold	**Number of extracted map points**	**Reduction ratio**	**Number of interpolation map points**	**Average space interval (m)**
1	76	93.2%	1934	0.517
2	68	93.9%	1941	0.515
3	65	94.1%	1939	0.516
4	60	94.6%	1939	0.516
5	52	95.3%	1940	0.516
6	39	96.5%	1934	0.517
7	37	96.7%	1925	0.520
8	35	96.8%	1924	0.520

From the results it can be found that the presented method is with tolerance to the limit threshold of angular rate, and the interpolation of map points is adaptive to the feature point set with the constraint from the resolution indicator. The track feature representation capability and resolution adaption of the map building method is illustrated to fulfill the requirements and expectations.

To validate the function of integrity monitoring with respect to the map matching calculation based on the provided track map data, the MM algorithm is considered and field data are used to compute the train location within the track coordinate. When the criterion in (8) is not satisfied, the coupled GNSS location or filter estimation will be identified and marked as the position should be alerted. Fig. 10 shows the global and local results of the map matching logic and the identifications in the map view. Since there may be faults, failures or some uncertainties in original sensor measurement and the information processing process, while map precision and reliability of the track data are decided by many factors, it is difficult to locate the actual cause and evaluate the performance anomalies precisely. Hence, from the view of system output, map matching provides an effective stage to monitor and explore the integrity level of the STPS.

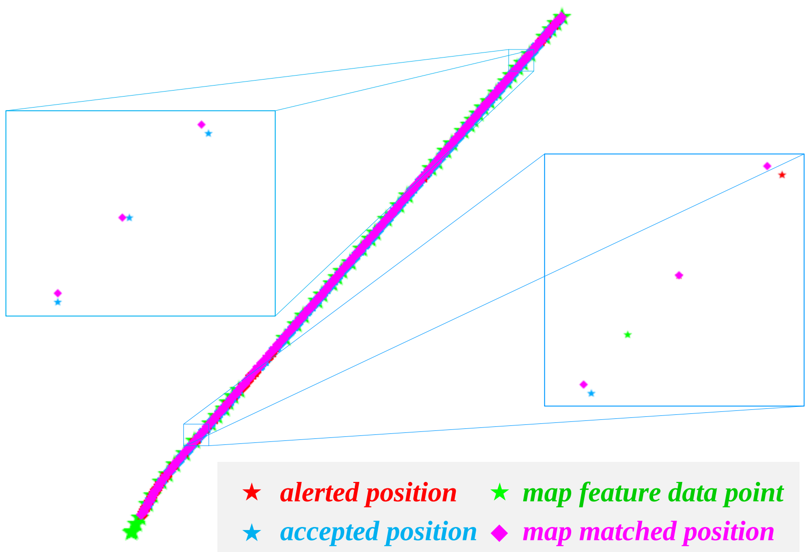

Figure 10. Map matching results in the map view

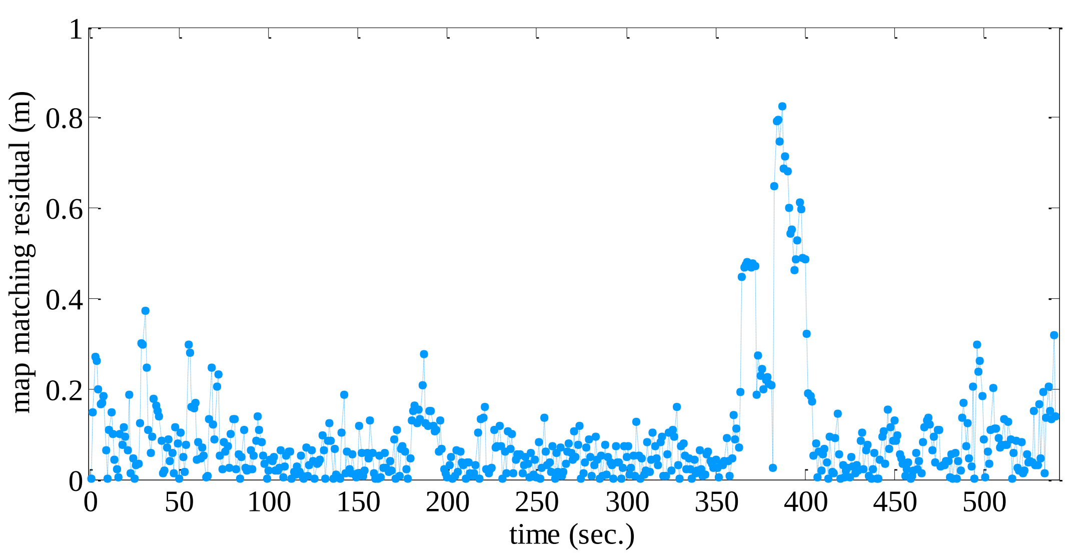

Figure 11. Residual error of map matching

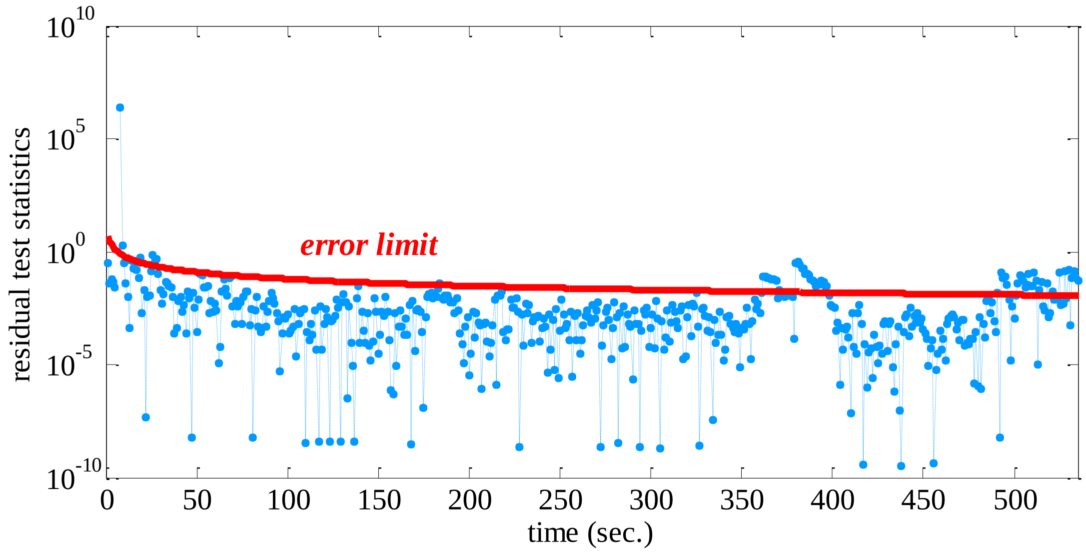

Figure 12. Integrity monitoring of the map matching

The map matching residual error gives a direct expression for deviation from measurement (or information integration) to track reference as shown in Fig. 11, where the point-to-curve map matching strategy is adopted by using the track feature information. Although it implies some apparent anomalies which generate fluctuations in residual, it still encourages us to perform more deep explorations to imply the inner states and potential trends for service capability of an actual STPS. Here we consider the statistical properties of the residual by constructing the test statistics as equation (8). As shown in Fig. 12, besides the obvious increase of residual error from 365 to 400 which can also be clearly located in Fig. 11, the presented statistical method expands that identification with its control limit, where 63 of 540 measurements (over 11.66%) are confirmed with integrity alerts and will not be considered to be valid for effective location report generation.

Table 4: Comparison matching integrity monitoring with different map set

Number of track points	**Alerting matching point**	**Ratio of alerting identification**	**Average residual error (all)**	**Average residual error (valid only)**
68	56	10.37%	0.063	0.052
60	47	8.7%	0.065	0.056
52	85	15.74%	0.114	0.066
37	88	16.3%	0.174	0.094

Four map data sets as described in Table 3 are selected to analyze the coupling between map data reference and the matching integrity monitoring. As the results shown in Table 4, when the track data set is large, the matching residual error is at a relatively lower level, and deviation between general average error and that from valid matching process is unconspicuous. While the reduction of track points is serious, decrease of extracted track feature points leads to more uncertainties in track representation. Thus, there will be more invalid map matching results identified by integrity monitoring logic. Because of the constraint from the adopted integrity strategies, the accepted map matching result holds a lower average match residual error, which makes contribution to the performance of train positioning. Based on that, the integrity monitoring logic will be more sensitive to existing, forthcoming and potential integrity events in map matching process in the map-assisted train positioning process, and therefore, greatly enhance monitoring effectiveness and improves the safety level for many practical railway applications.

VI. CONCLUSION

In this paper, with the consideration of electronic track map for satellite-based train positioning and its application in railway applications and services, based on the requirement of integrity for the safety, a complete track map database generation approach has been proposed. This approach relies on a curve representation scheme that requires describing the tracks using the correct, uniform and effective key points derived from sensor measurement. Moreover, this approach can handle different applications with requirements to the map resolution, which enables different map matching strategies according to the actual demands and operation conditions. The high resolution map is achieved by interpolation based on track representations in low resolution. Besides, high integrity map matching scheme is investigated by monitoring the match residual statistics using the generated map data. The integrity capability may contribute a lot to the safety aspects that should be highly concerned in satellite-based railway location applications and services.

The future research will focus on more detailed performance analysis of the generated map database. Uncertainty originated form information processing in map building will be described more accurately and completely. In addition, field test of map-aided STPS in different operation scenarios is necessary.

VII. ACKNOWLEDGEMENT

This research was supported by the Specialized Research Fund for the Doctoral Program of Higher Education (20120009110029), National Natural Science Foundation of China (61104162, 61273897), China Postdoctoral Science Foundation funded project (2011M500219, 2012T50037), Technological Research and Development Programs of the Ministry of Railways (2012X010-F).

REFERENCES

[1] G. Barbu, “GNSS / GALILEO certification for rail safety applications Railway requirements and the strategic position of UIC”, Proceedings of World Congress on Railway Research 2008, Seoul, 2008, pp. 1-9.

[2] Y. Zheng, “Improving Positioning Accuracy and Integrity in Rail Safety-Critical Applications Through the Integration of GNSS with a Track Data Base”, Proceedings of 20th International Meeting of the Satellite Division of The Institute of Navigation, Fort Worth, 2007, pp. 1456-1465.

[3] X. Xu, Z. Zhou, C. Wen, “Data Fusion Algorithm of Fault Diagnosis Considering Sensor Measurement Uncertainty”, International Journal on Smart Sensing and Intelligent Systems, Vol.6, No.1, 2013, pp. 171-190.

[4] T. K. Dakhlallah, M. A. Zohdy, “Type-2 Fuzzy Kalman Hybrid Application for Dynamic Security Monitoring Systems based on Multiple Sensor Fusion”, International Journal on Smart Sensing and Intelligent Systems, Vol.4, No.4, 2011, pp. 607-629.

[5] A. Filip, J. Taufer, H. Mocek, et al, “The high integrity GNSS/INS basedtrain position locator”, Proceedings of the 9th International Conference on Computer System Design and Operation in Railways and other Transit Systems, Dresden, 2004, pp. 495-506.

[6] Y. Zheng, P. Cross, M. Quddus, “The Effects of Railway Track Database Quality on the Performance of Tightly Coupled GNSS/Track Database Train Positioning System”, Proceedings of 22nd International Meeting of the Satellite Division of The Institute of Navigation, Savannah, 2009, pp. 2146-2155.

[7] S.R. Lee, “A Coarse-to-Fine Approach for Remote-Sensing Image Registration Based on a Local Method”, International Journal on Smart Sensing and Intelligent Systems, Vol.3, No.4, 2010, pp. 690-702.

[8] R. Glaus, G. Peels, U. Muller, el al. “Precise Rail Track Surveying”, GPS World, Vol.12, No.2, 2004, pp. 76-78.

[9] D. Chen, Y. Fu, B. Cai, Y. Yuan, "Modeling and Algorithms of GPS Data Reduction for the Qinghai–Tibet Railway", IEEE Transactions on Intelligent Transportation Systems, Vol.11, No.3, 2010, pp. 753-758.

[10] H. Gomm, "Data Format Specification for the Track database", Technical Report Document, Issue: 0.0.3, LOCOPROL, 2002.

[11] G. Gao, B. Cai, "Research on Automatic Electronic Map Generation Algorithm for the Train Supervision System", Journal of the China Railway Society, Vol.28, No.1, 2006, pp. 63-67.

[12] S. Hensel, C. Hasberg, "Probabilistic Landmark Based Localization of Rail Vehicles in Topological Maps", Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, 2010, pp. 4824-4829.

[13] D. Chen, Y. Fu, B. Cai, Y. Yuan, "Modeling and Algorithms of GPS Data Reduction for the Qinghai-Tibet Railway", IEEE Transactions on Intelligent Transportation Systems, Vol.11, No.3, 2010, pp. 753-758.

[14] V. Gikas, J. Stratakos, "A Novel Geodetic Engineering Method for Accurate and Automated Road/Railway Centerline Geometry Extraction Based on the Bearing Diagram and Fractal Behavior", IEEE Transactions on Intelligent Transportation Systems, Vol.13, No.1, 2012, pp. 115-126.

[15] M. Quddus, W. Ochieng, R. Noland, "Integrity of Map-Matching Algorithms", Transportation Research Part C, Vol.14, No.3, 2006, pp. 283-302.

[16] K. Gerlach, C. Rahmig, "Multi-Hypothesis Based Map-Matching Algorithm for Precise Train Positioning", Proceedings of the 12th International Conference on Information Fusion, Seattle, 2009, pp. 1363-1369.

[17] H. Jana, "GNSS Train Position Integrity Monitoring by the Help of Discrete PIM Algorithms", Journal of Applied Mathematics, Vol.2, No.3, 2009, pp. 73-80.

[18] D.H. Douglas, T.K. Peucker, "Algorithms for the reduction of the number of points required to represent a digitized line or its caricature", Canadian Cartographer, Vol.10, No.2, 1973, pp. 112-122.

[19] I.V. Nikiforov, F. Choquette, "Integrity Equations for Safe Train Positioning Using GNSS", Proceedings of the European Navigation Conference, Graz, Austria, 2003, pp. 22-25.

[20] J. Marais, M. Berbineau, O. Frimat, J.P. Franckart, "A New Satellite-Based Fail-Safe Train Control and Command for Low Density Railway Lines", Proceedings of the TILT Seminar (Technological Innovations for Land Transportation), Lille, France, December 2003.