International Global Navigation Satellite Systems Association

IGNSS Conference 2016

Colombo Theatres, Kensington Campus, UNSW Australia
6 – 8 December 2016

Seamless train localization based on BDS/INS/odometer/MM multi-sensor navigation system

Si-Rui Chen
School of Electronics and Information Engineering, Beijing Jiaotong University, P.R. of China
Email: 15120235@bjtu.edu.cn
Wei Jiang
School of Electronics and Information Engineering, Beijing Jiaotong University, Beijing Engineering Research Center of EMC and GNSS Technology for Rail Transportation, P.R. of China
Email: weijiang@bjtu.edu.cn
Bai-Gen Cai
School of Electronics and Information Engineering, State Key Laboratory of Rail Traffic Control and Safety, BJTU. Beijing Engineering Research Center of EMC and GNSS Technology for Rail Transportation, P.R. of China
Email: bgcai@bjtu.edu.cn
Jian Wang
School of Electronics and Information Engineering, Beijing Jiaotong University, Beijing Engineering Research Center of EMC and GNSS Technology for Rail Transportation, P.R. of China
Email: wangj@bjtu.edu.cn
Wei Shangguan
School of Electronics and Information Engineering, Beijing Jiaotong University, Beijing Engineering Research Center of EMC and GNSS Technology for Rail Transportation, P.R. of China
Email: wshg@bjtu.edu.cn

ABSTRACT

BeiDou Navigation Satellite System (BDS) has been widely applied in areas including communication and transportation, emergency rescue, public security etc., making remarkable benefit in social and economic aspects. The integration of BDS and Inertial Navigation System (INS) has meant that it gives greater access to a more consistent and accurate positioning capability than ever before. However, during the long BDS outages, the performance of the integration system degrades greatly because of the characteristics of the Inertial Measurement Unit (IMU) – the sensor error would be accumulated with time when it operates in a standalone mode. In this paper, a BDS/INS/odometer/Map-matching (MM) positioning methodology for train navigation applications is proposed and evaluated by the real test conducted in the western regions of China. This method is proposed to solve the problem of train positioning during BDS outages when the trains pass through the signal obstructed areas, like bridges, tunnels and valleys. The seamless

transition of the train operation in various scenarios can be therefore maintained. When the train operated in the open-sky environments, the BDS signals are available to provide accurate positioning, the BDS/INS are integrated to correct the INS errors by BDS measurements and calculate the velocity by odometer in navigation frame. Meanwhile, the integration system are also delivered accurate positioning measurements in high updated rate. In the case of BDS signals blocked, the integrated system can be seamless switched to the INS/odometer integration mode, the integrated system corrects the INS errors by using odometer measurements so as to provide continuous and acceptable positioning performance. In addition, MM technology is applied to improve the precise. In order to evaluate the proposed system, a real experiment was conducted in the western regions of China. The experimental results indicate that the proposed system can provide the accurate and continuous positioning service in both open-sky and BDS obstructed environments.

KEYWORDS: Beidou Navigation Satellite System; INS; odometer; map-matching; seamless train localization

1. INTRODUCTION

The scale of railway network has been further expanded in China in recent years. With the development of the implementation of the “Chinese Western Development Strategy”, which help accelerating the social and economic development of the whole western region, the center of Chinese railway construction has been moving to the western region. The railway network construction in western region is also under quick development.

Because of the vast territory and sparse population, the railways in Chinese western region have the characteristics of long mileage, small traffic volume and inadequate infrastructure. The majority of these lines are designed as single track railway, and defined as Low Density Lines (LDL). One representative LDL is Chinese Qinghai-Tibet railway, which locates in Chinese Tibet province and have more than 300 km depopulated zone at 4000 m above sea level. It is quite necessary to implement the train positioning methodology with high reliability and less maintenance for the low density lines like Qinghai-Tibet railway. The scene of Qinghai-Tibet railway is shown in left plot of Fig.1, and the right plot shows the example of tunnel in Qinghai-Tibet railway.

Figure 1. Qinghai-Tibet Railway

The Global Navigation Satellite System (GNSS) can improve the performance of the train positioning system, and has attracted increasing attention in recent years. It is able to reduce the

cost of the train positioning system greatly by decreasing the trackside equipments and the maintenance workload, and fulfil the special requirements for safety and efficiency.

As BeiDou Navigation Satellite System (BDS) has been able to fully cover the Asia-Pacific area, it has been applied in many fields including communication and transportation, emergency rescue, public security etc. in China, and making remarkable benefit in social and economic aspects (Soderholm *et al*, 2016). BDS has been applied to achieve accurate navigation and precise positioning as well. However, similar to Global Positioning System (GPS) system, BDS receivers must track more than four satellites in order to yield the precise coordinates. The more abundant resources of satellites, the better performance of positioning. Therefore the integration of BDS and INS is able to give greater access to a more consistent and accurate positioning capability than BDS applied standalone, especially at BDS-difficult area. BDS can constrain the increasing errors of INS, whereas INS also possesses excellent short-term precision, which can help mitigate the multipath effect and clock bias of BDS (Zhang and Xu, 2012).

BDS signals in good quality cannot be always maintained as there are BDS “dark territories” (like bridges, tunnels and valleys), the performance of the BDS/INS integration navigation system degrades greatly because of the characteristics of the Inertial Measurement Unit (IMU) – the sensor errors would be accumulated with time when it operates in a standalone mode. In order to obtain the real-time and precise positioning of the train, it needs some assistant technologies to improve the integrity and accuracy of BDS/INS navigation system, such as odometers, digital track maps, eddy-current sensors, Doppler velocity sensors (Acharya *et al*, 2011) and wayside transponders like RFID or Balises (Stadlmann, 2006). A common method to overcome the GNSS obstruction is to looking for a GNSS-alternative method, like fusing the odometer and IMU when in such area and applying a dead-reckoning principle. However a train position computing from dead reckoning by odometer may fail when worse adhesion occurs between train wheel and railway (Ernest *et al*, 2004).

Map-matching (MM) method plays an important role to enhance the accuracy. Based on the available track geometry and positioning data, a range of mathematical methods have been utilized in the MM algorithms (Quddus and Washington, 2015). MM method is mainly applied to identify the curves (Saab, 2000), when train runs across the non-turnout section, computing the projecting point on track map, so as to obtain the corrected train position. This method is able to help ensure the accuracy requirement of real-time positioning when successfully implemented. On another case, when train runs across the turnout section, it is necessary to determine the track number at the first time with curve-fitting method. The railway map database contains geometric coordinates which stored in discrete points, which could contribute to a cost consuming of the operation on regional railway lines with low traffic density (Gerlach and Rahmig, 2009). The railway map database is usually collected from various sources, such as a GNSS hand-held or extracted from aerial or satellite (Heirich, 2016).

In this paper, a positioning methodology based on BDS/INS/odometer/MM integration is proposed, which applying the data fusion algorithm for train navigation applications. This method is proposed to solve the problem of train positioning during BDS outages, the seamless transition of the train operation in various scenarios can be therefore maintained. When the train operated in the open-sky environments, the BDS signals are available to provide accurate positioning, BDS and INS are integrated to correct the INS errors. The INS gyroscope and accelerometer errors are constrained by BDS measurements and odometer calculates velocity in navigation frame. Meanwhile, the integration system also delivers accurate positioning parameters in high updated rate. In the case of BDS signals blocked, the integrated system can

be seamless switched to the INS/odometer integration mode, the integrated system corrects the INS errors by using odometer measurements so as to provide a continuous and acceptable positioning performance. Furthermore, with the shortest path search algorithm (SPSA) applied, the train position is projected to the digital track map to calculate the perpendicular distance, hence the corresponding 3D coordinates in the navigation frame could be further determined precisely.

In order to evaluate the proposed system, a real experiment was conducted in the western regions of China. The experimental results indicate that the proposed system can provide the accurate and continuous positioning service in both open-sky and BDS obstructed environments.

This paper is structured as follows. The navigation components of the proposed BDS/IMU navigation system odometer/IMU navigation system and MM technology are first introduced in Section 2. The proposed system operation in BDS open-sky and BDS-difficult scenarios and the seamless transition are discussed in Section 3. Finally, the seamless and accurate positioning experiment is described, including the system configuration and experiment design, and the test data analysis and evaluation are presented.

2. NAVIGATION COMPONENTS AND SYSTEM DESIGN

2.1 Algorithm development based on BDS/INS

The BDS/INS navigation algorithm generates position, velocity and attitude (PVA) solution with loosely-coupled Extended Kalman filter (EKF). PVA estimates are propagated forward in time based on IMU measurements, and errors are tracked and compensated by utilizing an error-state Kalman filter (Salmon and Bevly, 2014).

A. INS Update

Attitude information is maintained in the form of a transformation matrix C_b^n, relating the train body frame to the chosen navigation frame which is chosen north-east-down in this paper. The subscript “b”, “n”, “e”, “i” represent the body frame, navigation frame, earth fixed frame and inertial frame. The body coordinate frame is with the Euler rotation angles of (ϕ,θ,ψ),which means roll, pitch, and yaw in this paper. The initialization attitude matrix calculated by the three gyroscope measurements is as follows,

$$C_n^b=\begin{bmatrix} \cos\psi\cos\theta & \sin\psi\cos\theta & -\sin\theta \\ -\sin\psi\cos\phi+\cos\psi\sin\theta\sin\phi & \cos\psi\cos\phi+\sin\psi\sin\theta\sin\phi & \cos\theta\sin\phi \\ \sin\psi\sin\phi+\cos\psi\sin\theta\cos\phi & -\cos\psi\sin\phi+\sin\psi\sin\theta\cos\phi & \cos\theta\cos\phi \end{bmatrix} \quad (1)$$

The attitude matrix update is implemented using the quaternion approach. The equation is shown as,

$$\dot{q}=\frac{1}{2}\left[\omega_{nbq}^{b}\right]q \quad (2)$$

where q and $\dot{q}$ refer to the attitude quaternion and its rate, and ω_{nb}^{b} is the skew-symmetric

matrix of the angular-rate.

Accelerometer measurements can be converted from body frame to navigation frame and then used in (3) and (4) to update the position and velocity,

$$\dot{P}_n = V_n - \omega_{en}^n \times P_n \tag{3}$$

$$\dot{V}_n = f_n + g_n - \left(\omega_{en}^n + 2\omega_{ie}^n\right) \times V_n \tag{4}$$

where P_n and $\dot{P}_n$ are the position and position-rate vectors; V_n and $\dot{V}_n$ are the velocity and velocity-rate vectors; f_n is the accelerometer measurements; g_n is the gravity; ω_{en}^n is the angular rate vector of the navigation frame with respect to the earth fixed frame, resolved in the navigation frame ; ω_{ie}^n is the angular rate vector of the earth fixed frame with respect to the inertial frame, resolved in the navigation frame.

B. Extended Kalman Filter

The system state in the extended Kalman Filter is composed by eighteen states including attitude error (roll, pitch and yaw), position error (latitude, longitude and height), velocity error, gyroscopes' bias, accelerometers' bias and lever arm noise of BDS, respect to IMU center. These state variables could be defined as,

$$X = \left[\delta\psi \;\; \delta P_n \;\; \delta V_n \;\; \delta b_g \;\; \delta b_a \;\; \delta l_{BDS}\right] \tag{5}$$

where $\delta\psi$, δP_n , δV_n , δb_g , δb_a and δl_{BDS} are the attitude error, position error, velocity error, gyroscopes' bias, accelerometers' bias and the lever arm noise of BDS.

The Kalman filter includes time update process and measurement update process, the dynamic model and measurement model are shown in (6) and (7),

$$X = F * X + \omega \tag{6}$$

$$Z = H * X + \nu \tag{7}$$

where F is the state transition matrix, Z is the system measurement matrix, H is the computed Jacobian matrix, ω and υ are the process noise and measurement noise.

The Kalman filter time update process is to propagate the system state X , and the state covariance matrix P , shown in (8) and (9),

$$X = F * X \tag{8}$$

$$P = F * P * F^T + Q \tag{9}$$

where Q is the covariance matrix of the system process noise.

The INS navigation solution calculated during the time update is corrected in the measurement

update using the longitude, latitude, altitude whenever the BDS measurements are available. The Kalman measurement update process can be performed as seen in (10) – (12),

$$K = \frac{P * H^T}{H * P * H^T + R} \tag{10}$$

$$X = X + \frac{K}{Z - H * X} \tag{11}$$

$$P = \left(I_{18} - K * H\right) * P \tag{12}$$

The lever arm should be estimated and compensated as the BDS antenna is displaced from the IMU, and the navigation errors caused by the lever arm accumulate rapidly with time (Liu and He, 2002). Therefore, a compensation method should be taken into account to eliminate the disturbance force by the lever arm in the integration navigation system. The measurement matrix H, is calculated as,

$$H_{3\times18} = \left[\hat{C}_b^n\left(l_0^b \times\right) \quad I_{3\times3} \quad 0_{3\times3} \quad 0_{3\times6} \quad \hat{C}_b^n\right] \tag{13}$$

where l_0^b is the initial estimate of the lever arm.

System measurement Z, is calculated by comparing the position from BDS and predicted position derived from the INS, also the lever arm of BDS respect to IMU center should be considered. The Kalman filter measurement is shown as,

$$Z = \left[P_{INS} + l_{BDS} - P_{BDS}\right] \tag{14}$$

where P_{INS} is the INS position solutions, l_{BDS} is the estimated lever arm, and P_{BDS} is the BDS position solutions, respectively.

The covariance of the measurement noise R_{BDS}, is described as,

$$R_{BDS} = diag\left((0.15)^2 \quad (0.15)^2 \quad (0.05)^2\right) \tag{15}$$

where the unit of measurement noise variance is m^2.

2.2 Algorithm development based on INS/odometer

The use of odometer is particularly recommended when a LDL train localization system is implemented and there is the risk of BDS coverage failure, which is prone to happen when the train enters a tunnel or deep valleys (Hemerl and Schad, 2008).

The odometer is used to measure the train wheel speed and obtain the distance, and works together with the INS as dead-reckoning system to determine the position.

Odometer can provide absolute velocity as shown as,

$$V_{odo} = \frac{N_{odo}}{Q_{odo}} \cdot \pi \cdot d \tag{16}$$

where N_{odo} is the number of pulses per second counted by the odometer; Q_{odo} is the number of pulses when the wheel rotates a full turn; and d is the wheel diameter.

Combined with attitude matrix, the velocity in the navigation frame calculated by odometer parameter, which is,

$$V_n = C_b^n \times \begin{bmatrix} V_{odo} & 0 & 0 \end{bmatrix}^T \tag{17}$$

The INS/odometer navigation algorithm is set up in a similar manner to the BDS/INS navigation algorithm. Where the system state has 18 components, including attitude error (roll, pitch and yaw), position error(latitude, longitude and height), velocity error, gyroscopes' bias, accelerometers' bias and lever arm noise of odometer, respect to IMU center. Hence the state vector is defined as,

$$X = \begin{bmatrix} \delta\psi & \delta P_n & \delta V_n & \delta b_g & \delta b_a & \delta l_{ODO} \end{bmatrix} \tag{18}$$

where δl_{ODO} is the lever arm noise of odometer .

Measurement Z is calculated by comparing the position from odometer and predicted position derived from the INS, the lever arm of odometer respect to IMU center should also be considered. The odometer position is produced by multiplying the velocity in the navigation frame and cycle time of odometer. The measurement is shown as,

$$Z = \begin{bmatrix} P_{INS} + l_{ODO} - P_{ODO} \end{bmatrix} \tag{19}$$

where P_{INS} is the INS position solutions; l_{ODO} is the estimated lever arm of odometer; and P_{ODO} is the position calculated by the velocity of odometer and last train position information.

The covariance of the measurement noise R_{ODO} is described as,

$$R_{ODO} = diag\left((0.05)^2 \quad (0.05)^2 \quad (0.05)^2 \right) \tag{20}$$

where the unit of the measurement noise variance is m^2 .

2.3 Algorithm of map-matching

As the most part of railway lines are designed as single track railway, the precise train positioning by low-cost sensors and digital map is more suitable than conventional train positioning system with large number of balises installed along the track.

There is no doubt that the high precision track map database is crucial to the MM method. It

carries line information and plays an important role to improve train positioning accuracy (Saab, 2000).The digital track map is normally generated before the railway operation by a series precisely measured track points. The distance of any two is several meters. The track points are then processed by further optimization like smoothing, interpolation and reduction, to generate the formal rail track map.

The position of the train is normally between two consecutive track points. Based on the curvature radius of rail tracks, the trajectory between any two consecutive track points within the 1.5 m interval can be assumed to be a straight line (Zheng and Cross, 2012).Therefore, it is easy to obtain the train position by a linear mathematical model if the positions of the previous and post track points are known. Fig.2 shows an example of the processing strategy.

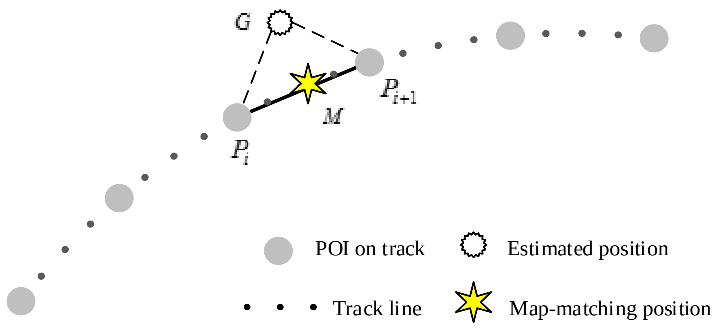

Figure 2. Example of MM procedure

The steps are as follows,

Step 1 According to the estimated position point $G(x, y)$, search the off-line track map and calculate the nearest point from the track point-of-interest (POI) database.

Step 2 Search the previous and post track points $P_i(x_i, y_i)$, $P_{i+1}(x_{i+1}, y_{i+1})$ from the track POI database which guarantee the train travels between them. If $x_i = x_{i+1}$, go to Step 3; if $y_i = y_{i+1}$, go to Step 4; otherwise jump to the Step 5.

Step 3 When $x_i = x_{i+1}$, the coordinates of MM position point is (x_i, y), go to Step 7.

Step 4 When $y_i = y_{i+1}$, the coordinates of MM position point is (x, y_i), go to Step 7.

Step 5 Calculate the slope k between the two track points, the function is shown as,

$$k = \frac{y_{i+1} - y_i}{x_{i+1} - x_i} \tag{21}$$

Step 6 Get the matching position point by perpendicular projection. The function is shown as,

$$M(x, y) = (\frac{x + ky - k(y_{i+1} - kx_{i+1})}{k^2 + 1}, \frac{kx + k^2 y + (y_{i+1} - kx_{i+1})}{k^2 + 1}) \tag{22}$$

Step 7 If a new point is received, go to step 1.

3. SYSTEM OPERATES IN BDS-AVAILABLE AND BDS-DIFFICULT SCENARIOS

The devices of train navigation system are installed in the driving cab, and collect redundant measurements from positioning sensors, including a BDS receiver, an IMU and an odometer. The information from these sensors generate the positioning result with assistance of track map database, which is stored in the on-board map server. Then, the location message is delivered to the main control unit. Fig.3 shows the structure of the train navigation system on-board equipments.

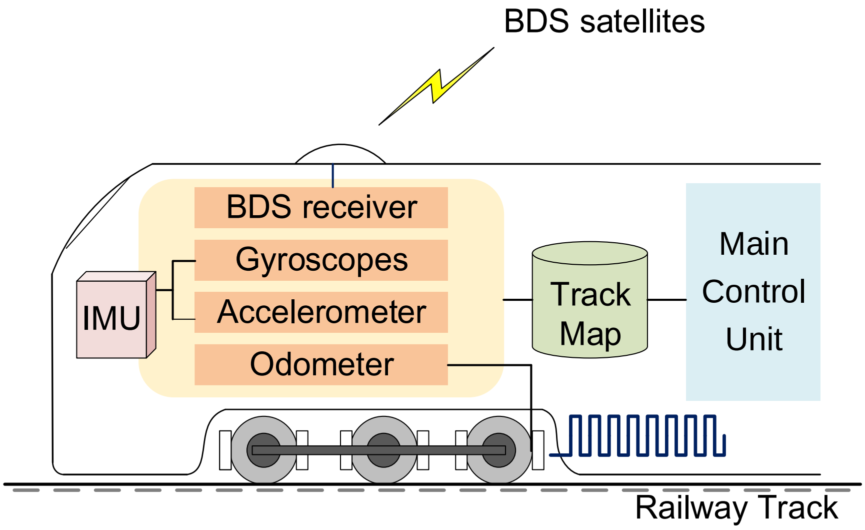

Figure 3. Structure of the train navigation system on-board equipments

At the beginning of the navigation system, the BDS measurements are available to provide accurate positioning service. The BDS/INS integration navigation system aims to utilize the advantages of the two individual systems and overcome their weaknesses. When BDS measurements are available, the integrated system can provide a complete navigation parameters, including position, velocity, acceleration, and attitude at high data rates. At the same time, the velocity obtained by odometer are combined with corrected attitude matrix and would be stored in the main control unit.

When train runs close or in the signal obstructed areas, like bridges, tunnels or valleys, the quality of BDS signal would decrease greatly. The train positioning systems detect the BDS availability and make the decision to switch the system to the INS/odometer integration mode immediately, and correct the INS errors by using odometer measurements so as to provide continuous and acceptable positioning performance. The seamless transition of the train operation in different scenarios can be therefore maintained.

The train positions estimated via EKF then combine the off-line digital track map data to obtain the corrected positions which should be on the railway track.

The scheme to fuse the BDS, INS, odometer and MM is shown in Fig.4.

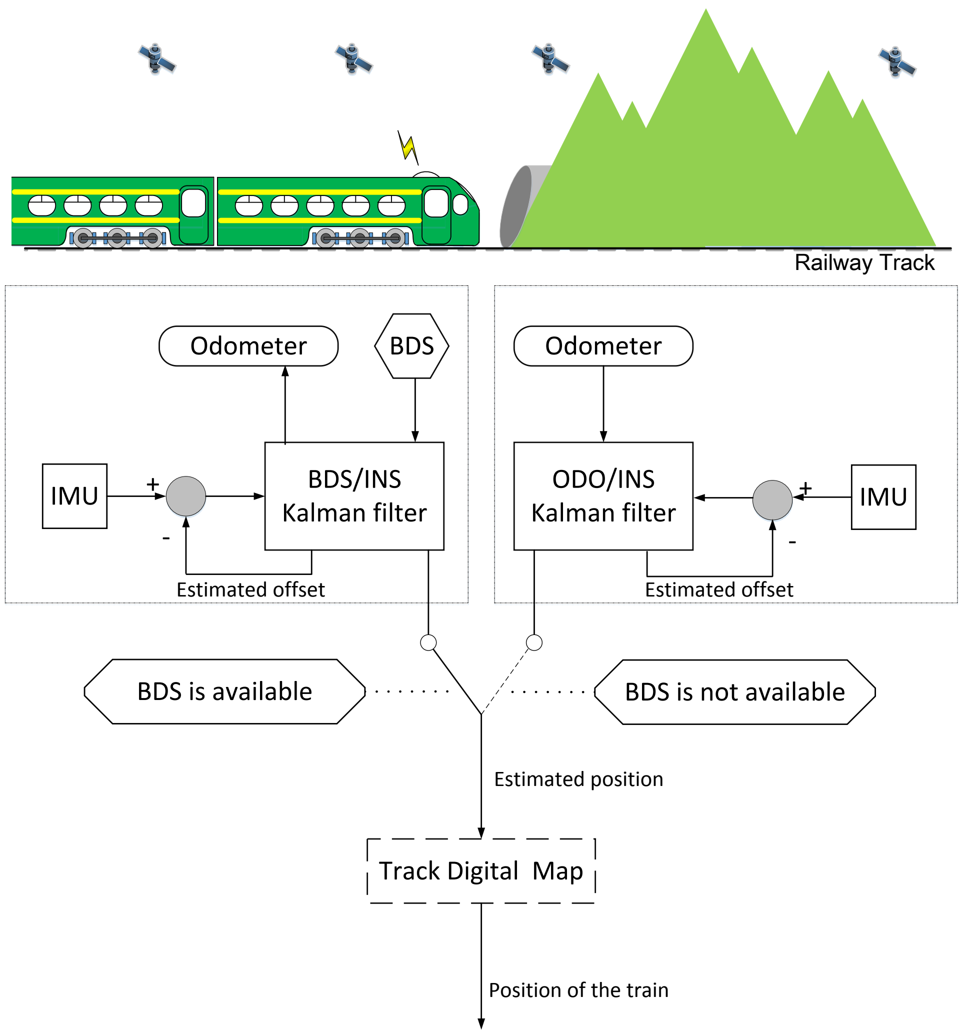

Figure 4. Train localization fusion scheme

There are two important points of the integration system.

1) The transition conditions: The number of visible satellites and the horizontal dilution of precision (HDOP) are considered to determine the operation scheme of the train positioning system, which are obtained from the BDS measurements. The greater the number of visible satellites and the smaller of HDOP, the better positioning performance could be achieved.

2) The threshold of MM: There should be a perpendicular distance threshold when applying the MM approach. The position of train is on the rail track, thus choosing a suitable threshold is the key problem. Firstly, calculate the perpendicular distance from estimated position to the railway track, then the MM processing is implemented when the perpendicular distance is less than the corresponding threshold. The proper threshold is related to the accuracy of BDS, to guarantee the effectiveness and accuracy of train positioning.

4. EXPERIMENT AND RESULT ANALYSIS

To evaluate the performance of the proposed navigation system, the field test was conducted in Qinghai-Tibet railway in April 2016. The experiment lasted for 25 minutes and the train run at

around 60 km/h. The test trajectory is shown in Fig. 5 where it run in the mount area environments, where BDS outages happened frequently. The test length was around 23.5 km.

The devices that were used in the test included one Unicore UB370 BDS receiver, one ADIS 16488 IMU, and one odometer installed connecting to the train wheel. The BDS positioning data and IMU raw data are obtained in 5Hz and 123Hz respectively, and the odometer output rate is 1Hz. The number of pulses when the wheel has rotated by a full turn is 1020. The track map data was previously generated and stored in the map server.

Figure 5. The trajectory of the rail test conducted on Qinghai-Tibet line

The on-board equipment is installed in the driving cab, to obtain the INS data, odometer data, and the BDS positioning data, then fusing the data with integrated method and MM technology. Finally, the train positioning report is delivered to the main control unit. The left plot of Fig.6 is the test train and the on-board equipment is shown in right plot.

Figure 6. The test train and the on-board equipment

The Fig.7 illustrates the positioning result computed by BDS, the zoom-in plot shows the trajectory on BDS-difficult period. The blue solid line indicates the real track data of map database, while the red line with "∗" is the BDS positioning results. It can be seen the BDS obstructed area is obvious. Fig.8 shows the offset between BDS positioning result and real track, it can be seen the offset is large, that is because the train run in mount area and the BDS position was processed in the single point positioning (SPP) mode with peudorange measurements.

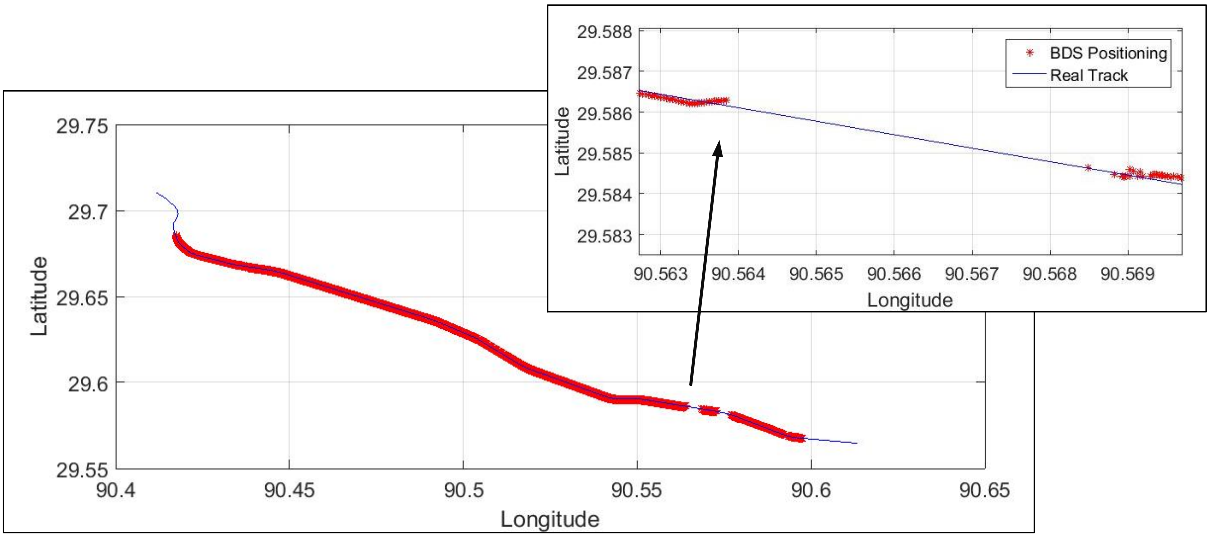

Figure 7. The positioning result computed by BDS

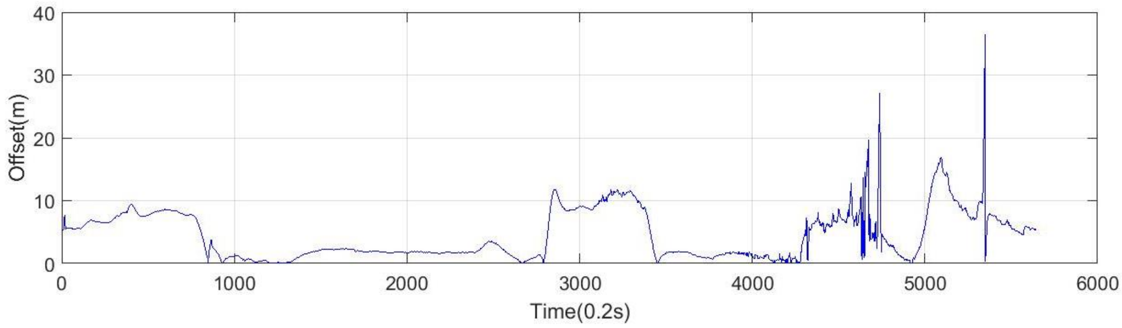

Figure 8. The offset between BDS positioning result and real track

Fig.9 shows the visible satellites number and HDOP of BDS positioning system. One can see the number of visible satellite dropped during the latter part of the test. At the same time, the HDOP increased correspondingly.

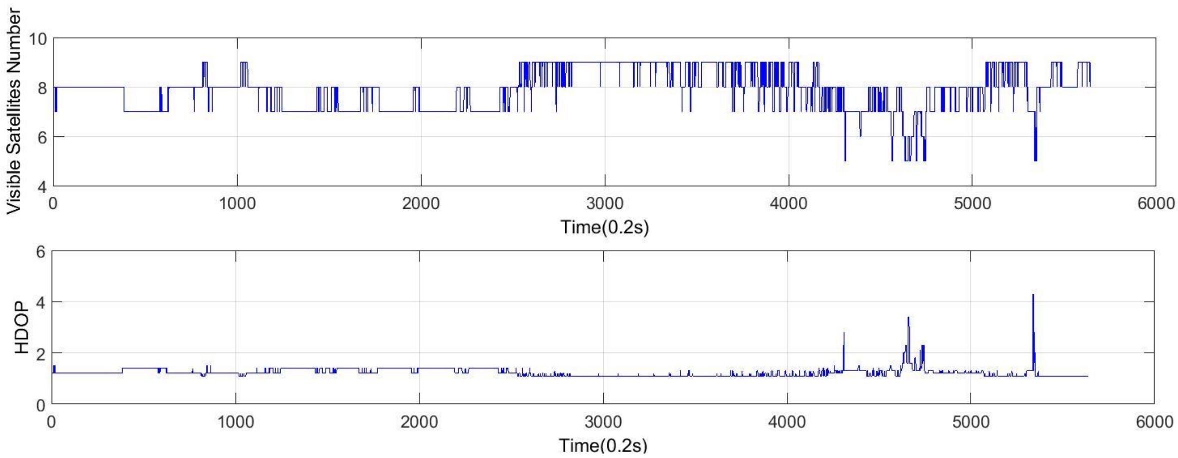

Figure 9. The visible satellites number and HDOP of BDS positioning system

In order to get the better performance of train positioning, the number of visible satellite is more than 6 and HDOP is lower than 1.5 are treated as the judging conditions of BDS availability. When the number of BDS visible satellite is less than 6 or the HDOP is more than 1.5, the BDS signals are treated as "unavailable", and vice versa. The perpendicular distance threshold of

MM is designed as 25m in this paper according to the BDS SPP accuracy.

Fig.10 shows the comparison of the positioning results of BDS/MM system and BDS positioning system. The blue solid line indicates the real track, the red line with "∗" is the BDS positioning results, while the green line with "Δ" is the integration positioning results of BDS and MM technology. According to this figure, the MM algorithm is effective when the system is able to receive the BDS signals, while the integrated system is not available when train runs into the BDS obstructed area.

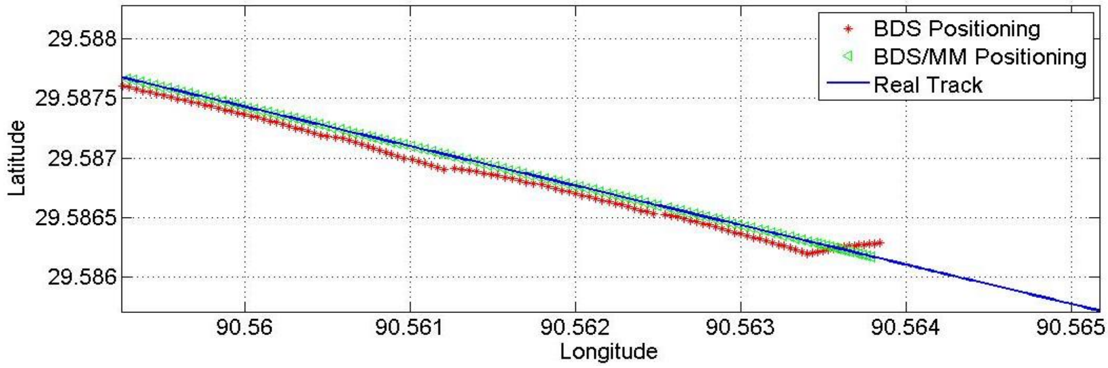

Figure 10. The comparison of BDS positioning and BDS/MM positioning results

Fig.11 compares the positioning performance of BDS/INS system and BDS positioning system. The blue solid line indicates the real track, the red line with "∗" is the BDS positioning results, while the green line with "Δ" is the integrated positioning results of BDS and INS. When the train operates in the open-sky environment, the BDS and INS integrate and deliver the accurate positioning solution in high updated rate. When the train runs into the tunnels, only the INS could work, the gyroscope and accelerometer bias accumulate with time quickly, which have a serious effect for the performance of train positioning, and result in an unacceptable positioning solution in very short time period.

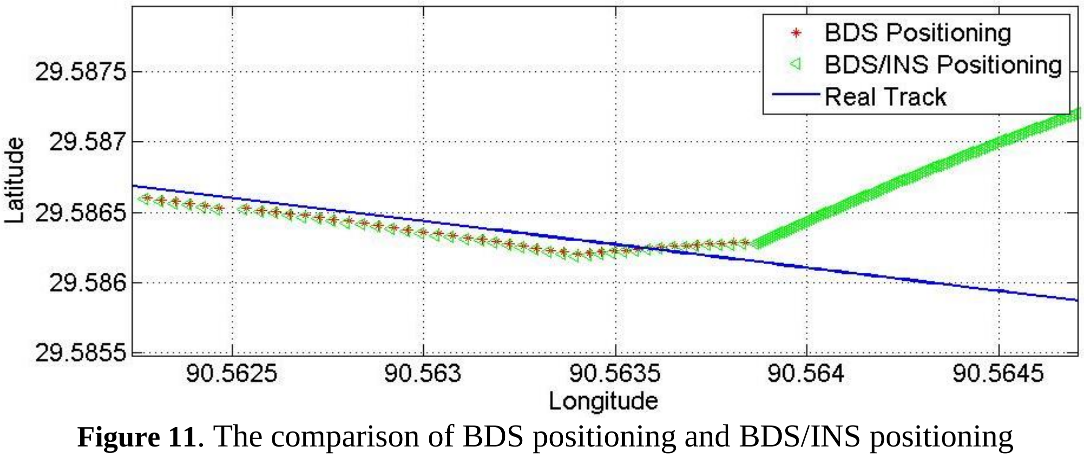

Figure 11. The comparison of BDS positioning and BDS/INS positioning

Fig.12 compares the positioning performance computed by the proposed BDS/INS/odometer/MM system and BDS positioning system. The blue solid line indicates the real track, the green line with "∗" is the BDS positioning result, while the red line with "o" is the BDS/INS/odometer/MM integration positioning results. When the BDS signals are available to provide positioning service, the BDS, INS and MM are integrated to obtain the integration position and at the same time, the velocity obtained by odometer combined with estimated attitude matrix are stored in the main control unit. When the train runs into BDS-

obstructed area, the INS and odometer can still work. In that case, the odometer and INS are integrated with the assistant of the MM to provide the continuous and seamless positioning service. The BDS/INS/odometer/MM integration positioning result shows the integrated system can be seamless switched to the INS/odometer/MM integration mode in the case of BDS signals blocked and the matching points are in good agreement with the real railway track.

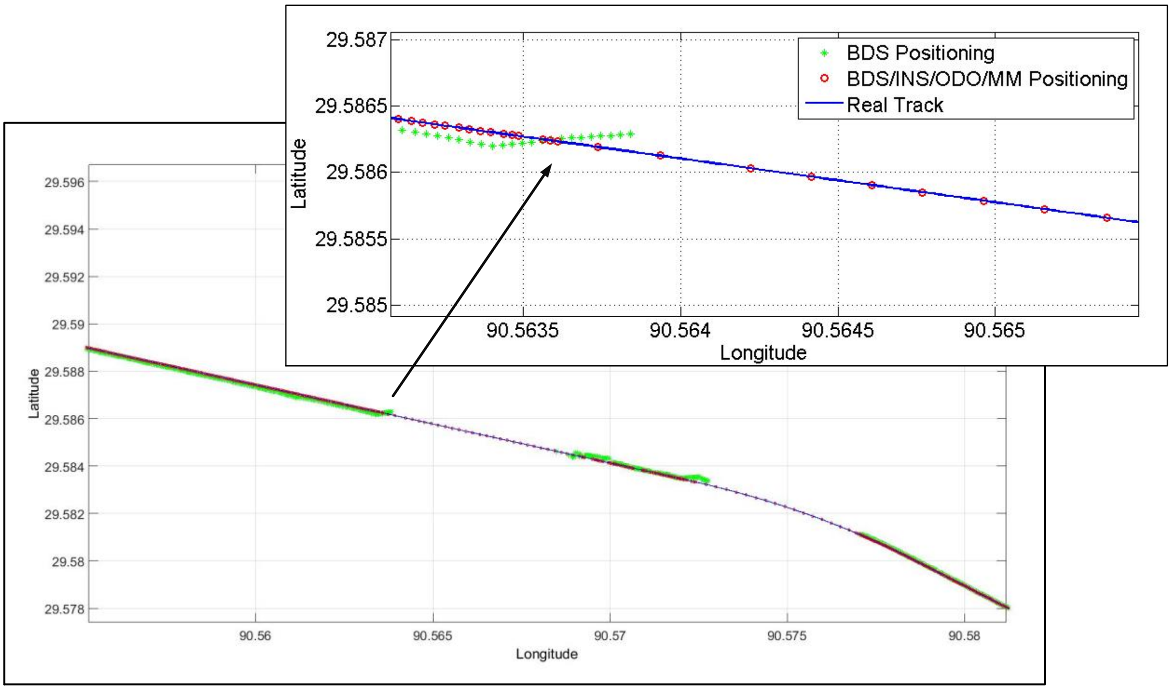

Figure 12. The comparison of BDS/INS/odometer/MM positioning and BDS positioning

5. CONCLUSIONS

This paper proposed an integrated navigation system based on BDS, INS, odometer and MM technologies in order to provide the continuous and reliable train positioning service in LDL railway. The proposed navigation system has two operating scenarios: open-sky and BDS obstructed environments. In the open-sky environment, the BDS signals are available to provide accurate train positioning, the BDS and INS are integrated to correct the INS sensor errors via EKF. On the other hand, the navigation system switch to the INS/odometer integration mode when the train runs close or enters a BDS-difficult area, like tunnel, valley, bridges or hillside, to ensure the reliability and accuracy of train real-time navigation. Furthermore, the algorithm of MM can significantly reduce the excessive errors of BDS SPP solution and help determine the train location on rail track. To evaluate the proposed navigation system, a real experiment was conducted on Qinghai-Tibet railway in the western region of China. The experimental results confirm that the proposed system can provide the seamless and continuous positioning service in both open-sky and BDS obstructed environments. Compared with a conventional BDS and BDS/INS navigation system, the proposed system shows improved system performance in different scenarios, especially on the BDS-difficult area.

ACKNOWLEDGEMENTS

This work was supported in part by the State Key Program of National Natural Science

Foundation of China under Grant 61490705 and U1334211, the National International Scientific and Technological Cooperation Project under Grant 2014DFA80260, and the Fundamental Research program for Central Universities under Grant 2016RC020.

REFERENCES

Soderholm S, Bhuiyan M, Thombre S, Ruotsalainen L, Kuusniemi H (2016) A multi-GNSS software-defined receiver: design, implementation, and performance benefits, *Annals of Telecommunications* 71(7-8):1-12

Zhang T, Xu X (2012) A new method of seamless land navigation for GPS/INS integrated system, *Measurement* 45(4):691-701

Acharya A, Smita S, Ghoshal T (2011) Train localization and parting detection using data fusion, *Transportation Research Part C* 19(1):75-84

Stadlmann B (2006) Automation of operational train control on regional branch lines by a basic train control, *Proc. IEEE Intelligent Transportation Systems Conference*, Toronto, Canada, 17-20 September, 50-54

Ernest P, Mazl R, Preucil L (2004) Train locator using inertial sensors and odometer, *Proc. IEEE Intelligent Vehicles Symposium*, Parma, Italy,14-17 June, 860-865

Quddus M, Washington S (2015) Shortest path and vehicle trajectory aided map-matching for low frequency GPS data, *Transportation Research Part C* 55:328-339

Saab S (2000) A map matching approach for train positioning part II: application and experimentation, *IEEE Transactions on Vehicular Technology*, 49(2):476-484

Gerlach K, Rahmig C (2009) Multi-hypothesis based map-matching algorithm for precise train positioning, *12th International Conference on Information Fusion*, Seattle, Washington, USA, 6-9 July, 1363-1369

Heirich O (2016) Bayesian train localization with particle filter, loosely coupled GNSS, IMU, and a track map, *Journal of Sensors*, 2016:1-15

Salmon D, Bevly D (2014) An exploration of low-cost sensor and vehicle model Solutions for ground vehicle navigation, *2014 IEEE/ION Position, Location and Navigation Symposium (PLANS 2014)*, Monterey, California, USA, 5-8 May, 462-471

Liu J, He X (2002) Analysis of lever arm effects in GPS/IMU integration system, *Transactions of Nanjing University of Aeronautics & Astronautics* 19(1):59-64

Hemerly E, Schad V (2008) Implementation of a GPS/INS/ODOMETER Navigation System, *ABCM Symposium Series in Mechatronics* 3:519-524

Saab S (2000) A Map Matching Approach for Train Positioning Part I: Development and Analysis, *IEEE Transactions on Vehicular Technology* 49(2):467-475

Zheng Y, Cross P (2012) Integrated GNSS with different accuracy of track database for safety-critical railway control systems, *GPS Solutions* 16(2):169-179