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Kinematic Measurement of the Railway Track Centerline Position by GNSS/INS/ Odometer Integration

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ABSTRACT Accurate absolute measurement of existing lines is a task of fundamental importance to provide scientific basis for reconstruction. Traditional railway track survey methods in combination with classical geodetic surveying apparatus such as total stations cannot meet the requirements of surveying efficiency. Accurate, reliable and fast existing railway surveying applications call for an innovative method that can obtain high-precision, continuous and uniform railway track axis position in short time without interrupting the railway traffic. This paper provides an innovative solution to track axis surveying based on the integrated technique of global navigation satellite system (GNSS), inertial navigation system (INS) and odometer. GNSS/INS/odometer system does not depend on a high-precision track control network, which can operate in mobile surveying mode and significantly improve the measuring speed from 0.15 km/h to 5 km/h compared to conventional methods. Compared with satellite surveying methods, this solution for the measurement of existing line axis can obtain continuous and high-precision results in the absence of satellite signals. The results of field tests on the Zhengzhou-Xuzhou high-speed railway track show that the measurement errors are less than 0.6 cm and 1.1 cm in horizontal and vertical directions, respectively, and this measuring system is able to maintain high precision of 5 cm with a GNSS outage of 700 s, which can meet the accuracy requirements of China Specifications for Survey Engineering of High-speed Railway and serve visualization, assessment and design process of existing railways.

INDEX TERMS GNSS/INS/odometer, railway track, absolute measurement, accuracy assessment.

I. INTRODUCTION

Railways are essential components of the global economy and infrastructure. Throughout the life cycle of railway, rail operators demand efficient surveying methods to provide database for planning, constructing, operating and expanding the railway track and its auxiliary buildings. With the rapid growth in the operational mileages of railways, how to carry out the survey of existing railways efficiently and accurately is an urgent problem to be solved at present. After several years running, the existing lines often lack of relevant and integrated data for timely monitoring, expansion and reconstruction. Systematic surveys and evaluations are greatly needed to acquire uniform, scientific and complete track map and database. The precise measurement of the absolute position of track centerline in 3D space is the foundation for railway line restoration and speed-up [1]–[3]. Therefore, obtaining the railway track axis position is of great significance for the renovation, betterment and redesign of existing lines.

As for the existing railways, rail operators need a productive rail measuring system to make accurate surveys on existing track in their daily work. Because technical maintenance and reform of railway demand accurate information, it is practically required to survey the track centerline with an absolute position accuracy of 5 cm relative to the track control network, which can meet the accuracy requirements of China Specifications for Survey Engineering of High-speed Railway and be utilized in practical track axis absolute measuring application. These collected data of recorded railway track form the basis for redesign and quality control of the track,

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which can be used for railway track location, renovation and reconstructing to improve the line running speed. In addition to the accuracy requirement, time efficiency is another critical demand for existing track survey. Due to the busy railway traffic service, the skylight time or time slot permitted for line monitoring and measurement is limited. Finishing the surveying process of the railway track position as fast as possible is essential to avoid interrupting the railway traffic [4]–[6]. Therefore, accurate, continuous and uniform measurement of the track absolute coordinates is a task of fundamental importance for existing line survey.

Currently, the overall railway track centerline position coordinates of an existing line are obtained by the absolute geodetic surveying method, such as total station. In previous work, a high-precision total station is widely used for surveying absolute track axis position of existing lines. The measurement personnel sets up the total station on the control points along the railway track and survey the 3D coordinates of a prism placed on the rail or track inspection trolley. The 3D position of the track centerline can be determined by using the prism coordinates with an absolute position accuracy of 1 mm relative to the track control network. However, this method has two fatal shortcomings for absolute measurement of existing lines. The first one is inefficiency. Because the total station system uses the stop-and-go mode and the line of sight is shorter than 70 m in the surveying process, only 150 m of track can be measured by this method each hour [5]–[8]. Thus, the skylight time cannot satisfy the measurement task in high traffic volumes. The second disadvantage is that this universal geodetic method with the total station depends heavily on a dense control point network, which is often destroyed or not well maintained along exiting lines after a long time of railway running.

The development of satellite geodetic techniques, together with the increase of GNSS surveying precision, leads to the tentative application for the purpose of railway track surveying based on the GNSS technology [9]. This method measures the 3D coordinates of the GNSS antenna center by installing the GNSS receiver on the track measuring trolley in kinematic surveying mode. The absolute position of the track centerline can be calculated by projecting GNSS coordinates onto the track axis. The GNSS absolute surveying system is widely used to achieve centimeter-level measurement accuracy in the post-processing kinematic (PPK) mode, and this accuracy can satisfy the maintenance, renovation and redesign of existing railway lines [4], [10], [11]. Compared with the conventional total station measurement system, the mobile surveying mode based on GNSS has high efficiency and independence, and this mode needs a small number of control points and can significantly improve the speed from 0.15 km/h to 5 km/h. However, the GNSS receiver cannot be continuously used for the existing line survey due to the loss of satellite signals by obstructions from buildings, tunnels or trees along the railway, which lead to low position accuracy of GNSS in a complex environment. Therefore, the surveying mode based on GNSS positioning technology is unreliable for the railway track survey under harsh GNSS environments.

As for the absolute measurement of existing railways, conventional optical methods based on the total station and GNSS technology both have their own shortcomings, and neither method can satisfy the fast, precision and continuous surveying requirement. In this case, a reliable, flexible and rapid railway measurement method for completing a precision surveying task within a short time is greatly needed. Therefore, we propose a method based on the inertial navigation system (INS), GNSS, odometer and gauge sensors to survey the precise track centerline position by using multi-sensors and multi-sources information fusion.

In this paper we propose to survey existing lines with GNSS/INS/odometer integrated technology to obtain continuous, reliable and highly precise track centerline position and analyze the measurement accuracy of the kinematic surveying method. Combined with kinematic measurement, the GNSS/INS/odometer integrated system uses an inertial high-performance mode with centimeter precision, which can provide continuous and high-efficiency measurement of the track axis 3D coordinates in mobile surveying mode with a measuring speed of 5 km/h. This mobile surveying solution allows operators to finish the actual work of existing line survey in all kinds of weather and harsh GNSS conditions. This paper presents a data fusion method of multi-source information disposing and a suitable coordinate transformation method to obtain accurate railway track axis position. Because the fast precision measurement method for existing railway survey based on the GNSS/INS/odometer integrated system and other sensors is a new technology, the architecture, workflow, data processing and test accuracy assessment are introduced emphatically, which will facilitate the following research on the absolute measurement of existing lines by using multi-sensors and multi-sources information fusion. This paper is organized as follows. Section 2 presents the measurement principles of the GNSS/INS/odometer integration. Section 3 introduces the key points of the algorithm during data post-processing. Section 4 concentrates on the experimental description and detailed accuracy assessment.

II. ABSOLUTE TRACK MEASUREMENT BASED ON GNSS/INS/ODOMETER

A. MEASUREMENT PRINCIPLE

A track centerline can be considered as a 3D curve which is described based on its absolute position information in the reference geodetic frame. According to the 3D coordinates of the track centerline and gauge information of the railway, the existing line absolute position in 3D space can be uniquely determined. If the track axis coordinates, attitudes and gauge can be surveyed accurately, the actual track position can be calculated with high-precision solutions [12], [13]. The definition of the track position is expressed as the horizontal and vertical coordinates in the reference geodetic frame.

The railway track axis measurement system integrates INS, GNSS, odometer and gauge sensors on a lightweight track

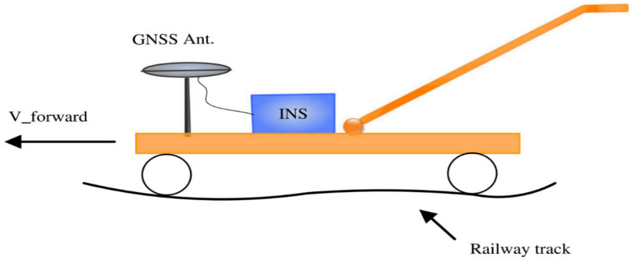

FIGURE 1. **Illustration of the integrated measurement system used for track absolute surveying.**

trolley to obtain accuracy position and attitude in kinematic surveying mode. The GNSS surveying system can realize centimeter absolute positioning accuracy in mobile surveying mode based on PPK technology. When GNSS mode is unreliable for continuously surveying railway track under harsh GNSS environments, INS and odometer sensor can provide the reference of a high-accuracy position during GNSS outage time. The INS is well known to provide extremely high accuracy position and attitude measurements in a short time and the proposed surveying system can obtain velocity data from the odometer. GNSS/INS/odometer integrated system takes advantage of GNSS position and odometer velocity measurement as update information to compensate for the error accumulation of INS in a well-designed Kalman filter and obtains continuous high-precision coordinates of the track in a long time range [14]–[17].

During railway track measurement process, the track trolley can keep continuous contact with the track in the both horizontal and vertical directions without suspension, linking the integrated measuring system and rails mechanically to capture the absolute position information of the rails accurately. The GNSS/INS/odometer/gauge integrated system captures the 3D position, velocity, attitudes and gauge of the measured track accurately, continuously and simultaneously as shown in Figure 1. The existing lines axis position sequences can be accurately calculated by using multi-sensors outputs with the method of multi-sources information fusion and coordinate transformation model.

B. INSTRUMENTATION OF TRACK MEASURING SYSTEM

The railway track absolute measurement system based on GNSS/INS/odometer introduced in this paper mainly consists of a lightweight track trolley, high-precision GNSS/INS integrated system, odometer and gauge measuring sensor, as shown in Figure 2. The mobile surveying mode designed to capture the absolute position of the track centerline in 3D space records different sensor measurements and accomplishes the time synchronization between these sensor outputs inside the recording system. The data reception, storage, and time synchronization are implemented based on the recording system. All the data from different sensors are recorded in an identical time frame to realize time synchronization. In the following subsections, the basic modules and their functions of the measuring system are presented, including track trolley, GNSS/INS integrated system, odometer and gauge sensor.

FIGURE 2. **The railway track absolute measuring system (top) and its typical structure (bottom), including the track trolley, measurement sensors and data recording system.**

1) TRACK TROLLEY

The track trolley is a rigid platform carrying the GNSS/INS integrated system, odometer and gauge sensor. During the existing line survey operation process, the track trolley can be pushed forward and backward on the railway track lightly with the push rod by only one operation worker. Conforming to normative railway standards, the three wheels of track trolley can maintain continuous, rigidly and reliable contact with rails during mobile measuring process. Therefore, those sensors mounted on the trolley platform can incessantly and accurately capture the response signs of the measured track from moving trolley on the rails. The designed top speed of the trolley is 10 m/s moving on the railway track. Under this speed, the trolley does not jump off the rails and can be rigidly in continuous contact with the track in mobile surveying mode.

It should be noted that the mounting positions of different sensors are distinct on trolley platform, which need to be accurately calibrated based on the high-precision rule or the total station before data processing. The distances between those sensors are defined as the lever arm vectors, which are the indispensable information for data fusion process. During the integrated navigation computation process, the lever arm compensation between the inertial measurement unit (IMU) center and the GNSS antenna phase center is necessary to obtain high-precision navigation solutions. In order to project the coordinates from the IMU center to the measured track axis, the track trolley lever arm parameter between the IMU center and the upper surface of the rails in contact with the trolley wheels needs to be calibrated accurately.

2) GNSS/INS INTEGRATED SYSTEM

The IMU is the core sensor of the whole integrated surveying system, which is mainly used for providing high-precision position, velocity and attitude results of trolley and bridging the position gap of the GNSS under a harsh GNSS environment during the mobile surveying process. The choice of IMU type is up to the accuracy requirement, and a navigation grade IMU, POS830, which is manufactured by Wuhan MAP Space Time Navigation Technology co..LTD, can meet the precision requirement of existing line survey. This IMU consists of a linear quartz accelerometer triad and a ring laser gyroscope triad, which can output continuous, accurate and reliable acceleration and angular velocity of IMU center at 200 Hz in three mutually orthogonal directions. A NovAtel OEMV-2 GNSS receiver is built in POS830 system to provide raw GNSS observations.

GNSS can provide absolute positions with centimeter precision in the global coordinate frame by using PPK technology based on carrier phase measurement. During the measurement process, the NovAtel OEMV-2 GNSS receiver build-in the POS830 works as a rover, and the GNSS reference station as a master should be located at one control point of the railway control network for carrier phase based differential GNSS processing. The rover and master GNSS receivers simultaneously record raw GNSS observations at a 1 Hz sampling rate, and the baseline length between the rover and master stations is usually less than 20 km to ensure centimeter accuracy. The GNSS position is the primary choice for the existing line survey to obtain 3D coordinates of measured track with centimeter precision in global coordinates whenever GNSS signals are available. When the GNSS signals are inevitably weakened and even blocked, the measuring system needs to continuously work using the IMU and other sensors.

It has been widely proved that the benefits and shortcomings of INS and GNSS are complementary, and the advantages of both modules can be combined to give a continuous, high-efficiency and complete surveying solution during both the short and long term. In the GNSS/INS integrated system, GNSS module position results can prevent inertial solution drifting, while INS module outputs can correct the GNSS solutions and bridge GNSS signal outages. Based on a well-designed loosely-coupled algorithm, the GNSS/INS integration system can provide high-frequency positioning and attitude solutions of the IMU, which is the foundation to gain the accurate 3D coordinates of the measured track.

3) ODOMETER

The odometer mounted on the wheels of the trolley platform is applied to measure the longitudinal velocity along the rails by the track trolley. Time tags from GNSS/INS integrated time are attached to each epoch of odometer outputs to realize the time synchronize. The longitudinal velocity of trolley from odometer is an important observed value for multi-data fusion process, which can be regarded as the 3D velocity update combined with non-holonomic constrain (NHC). The 3D velocity constraint including odometer auxiliary and non-holonomic constraints (NHC) determines the trolley velocities in the along-track and two cross-track directions, which can correct the INS drift errors effectively and improve the integrated navigation accuracy when GNSS signals are interfered or blocked. When GNSS signals are interrupted, the application of odometer outputs with NHC is helpful for maintaining the navigation precision to collect continuous, reliable and accurate measurements on track absolute position.

4) GAUGE SENSOR

Track gauge is defined as the distance between the left and right tracks of a railway, which is measured using a high-precision mechanical distance measurement system. The gauge measurement determines the trolley platform lever arm parameter between the IMU measurement center and the rail top surface of the railway in contact with the trolley wheels. Since the accurate navigation position results of IMU center need to be projected to the measured rails, gauge values play a foundational role in the coordinate transformation process. The actual track can be calculated with high precision if the coordinates of IMU center and gauge can be surveyed accurately. In addition, the gauge measurements should be synchronized with the integrated measuring system in real time by adding time tags from GNSS/INS system.

III. DESCRIPTION OF THE DATA PROCESSING ALGORITHM

The synchronized data from the measuring sensors mounted on the track trolley platform can provide the final positioning solutions accurately by using the multi-sources information fusion and coordinate transformation model. In this section, the main point of the data processing algorithm is introduced along with the concept and workflow, including the positioning process by the GNSS/INS/odometer and the coordinate transformation. Figure 3 illustrates the flowchart of the post-processing algorithm based on the GNSS/INS/odometer integrated system.

A. POSITIONING PROCESS BY THE LOOSELY-COUPLED ALGORITHM

GNSS can provide long-term high-accuracy positioning results in any weather condition globally, but this system cannot continuously provide location information due to signal blocking and jamming during the surveying process on the track. The INS is autonomous and immune to jamming, and this system can provide high-accuracy positioning, velocity and attitude results for short-term periods, which are subject to drift due to IMU sensor output errors. The integration of GNSS and INS can avoid most of the drawbacks and achieve most of the advantages of both two systems.

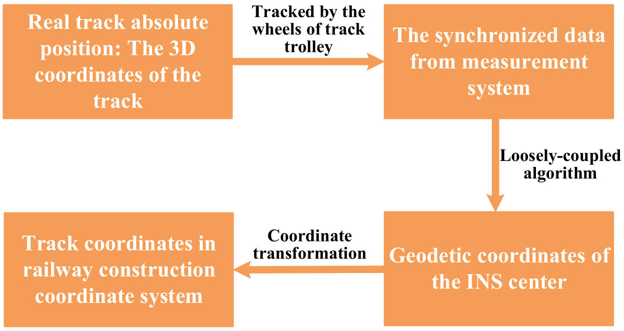

FIGURE 3. The flowchart of data processing algorithm.

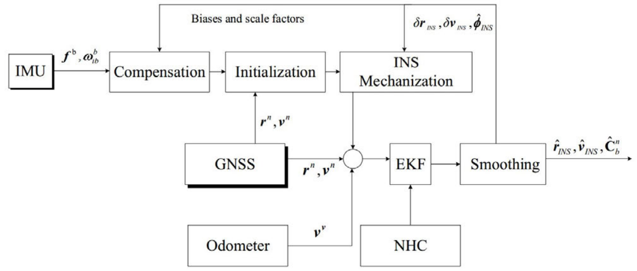

FIGURE 4. The design of the loosely-coupled algorithm based on GNSS/INS/odometer.

Moreover, the trolley velocity observation information from odometer and NHC is applied in the loosely-coupled filter to achieve high accuracy solutions when GNSS measurement is unavailable [18]–[20]. The design of the loosely-coupled algorithm process is shown in Figure 4. Therefore, the integration system mounted on the trolley platform can provide continuous, high-efficiency and reliable positioning solutions for the mobile measurement of existing line.

1) KALMAN FILTER DESIGN

As an important optimal estimation theory, the Kalman filter has been widely used in the GNSS/INS integrated system to obtain high-precision positioning solutions. The Kalman filter designs 21-dimensional error states estimating the position, velocity, attitude and IMU output errors in this paper. These position, velocity and attitude errors are expressed in the navigation frame (n-frame). The details of INS mechanization process can be referred to in the literature [19].

During the GNSS/INS integration calculation process, the residual error from the IMU is an important error source affecting the measurement accuracy and needs to be estimated and compensated in a timely manner. Since the IMU error changes slowly with time, this above error is modeled as a first order Gauss-Markov process and extended to the state vector to perform the online estimation in Kalman filter. The error state vector can be written as:

$$\boldsymbol{x}(t) = \begin{bmatrix} (\delta \boldsymbol{r}^n)^T & (\delta \boldsymbol{v}^n)^T & \phi^T & \boldsymbol{b}_g^T & \boldsymbol{b}_a^T & \boldsymbol{s}_g^T & \boldsymbol{s}_a^T \end{bmatrix}^T \tag{1}$$

where, $\delta \boldsymbol{r}^n$ denotes the position error in the local navigation frame (n-frame); $\delta \boldsymbol{v}^n$ expresses the velocity error in the n-frame; ϕ represents the attitude error, including roll, pitch and heading angles by using the Phi-Angle error model; $\boldsymbol{b}, \boldsymbol{s}$ denote the biases and scale factors, respectively, from the IMU accelerometers and gyros.

The position, velocity and attitude error differential equations in Kalman filter can be expressed as:

$$\begin{aligned} \delta \dot{r}^n &= F_{rr}\delta r^n + F_{rv}\delta v^n \\ \delta \dot{v}^n &= C_b^n \delta f^b + f^n \times \phi - \left(2\omega_{ie}^n + \omega_{en}^n\right) \times \delta v^n \\ &\quad + v^n \times \left(2\delta\omega_{ie}^n + \delta\omega_{en}^n\right) + \delta g_l^n \\ \dot{\phi} &= F_{fr}\delta r^n + F_{fv}\delta v^n - \omega_{in}^n \times \phi - C_b^n \delta\omega_{ib}^b \end{aligned} \tag{2}$$

In the above equations, ω_e expresses the magnitude of the rotation rate of the earth, δf^b and $\delta\omega_{ib}^b$ are the measurement errors of the accelerometers and gyros, respectively. C_b^n shows the body frame (b-frame) to n-frame transformation matrix, ω_{ie}^n represents the angular rate of the earth frame (e-frame) relative to inertial frame in n-frame. ω_{en}^n refers to the angular rate of the n-frame with respect to the e-frame resolved in the n-frame. δg_l^n is the local gravity error in the n-frame. The details of the error differential equations can be referred to in the literature [19].

The system model of the Kalman filter in continuous time can be expressed as:

$$\dot{x}(t) = F(t)\,x(t) + G(t)\,w(t) \tag{3}$$

where, F is the dynamic matrix, G is the design matrix of the system noise, $\boldsymbol{x}$ is the system state and w is white noise.

The measurement model uses the differences between the GNSS position solutions and INS positions derived from INS mechanization process. The observation equations can be shown as follows:

$$z = (r_{INS} - r_{GNSS}) \tag{4}$$

Since the IMU and GNSS antenna cannot be installed at the same place in the track trolley, the real position of the GNSS is different from that of the IMU, which is defined as the lever arm in the literature [19] and needs to be compensated before the measurement update process.

2) THREE DIMENSIONAL VELOCITY CONSTRAINT

For the railway track surveying application, the velocity of the integrated system can be regarded as the effective update information in the Kalman filter. When the GNSS is interrupted, the velocity information is used to replace the GNSS position update to estimate and compensate the inertial sensor residual error. During the existing line surveying process, the 3D velocity constraint from odometer auxiliary and non-holonomic constraints (NHC) determines the trolley velocities in the along-track and two cross-track directions, which can be well valid when the railway track is smooth and continuous [19].

The NHC generally refers to the conditions that the vehicle never jumps off or sideslips during vehicle running process and the velocities of the vehicle in the lateral and vertical directions are zero in the vehicle frame (v-frame) [19]. Since the wheels of the trolley can rigidly be in continuous contact with the track and the trolley does not jump off the rails in mobile surveying mode, the motion of the track trolley is governed by NHC and has only the along-track speed, which can be derived from the odometer signal. In this case, the trolley has only the along-track speed, and the velocities in both cross-track directions are zero in the v-frame. The 3D velocity information from odometer and NHC is an important measurement update in the loosely-coupled process and can effectively improve the accuracy of the integrated navigation solutions when GNSS signals definitely suffer from multipath and blocking effects. The velocity in the v-frame can be expressed as:

$$\tilde{v}^v_{wheel} = v^v_{wheel} - n_{vW} \tag{5}$$

$$\tilde{v}^v_{wheel} = \begin{bmatrix} v_{odo} & 0 & 0 \end{bmatrix}^T \tag{6}$$

where, $\tilde{v}^v_{wheel}$ is the velocity in the v-frame, v_{odo} shows the velocity along the track derived from the odometer signal, and n_{vW} is the velocity noise. It should be noted that the velocity constraint is suitable in the track trolley frame (v-frame), not in the body frame and the attitude misalignment of b-frame with respect to v-frame need to be calibrated precisely.

The velocity error measurement equation can be shown as:

$$\begin{aligned} z_{vW} &= \hat{v}^v_{wheel} - \tilde{v}^v_{wheel} \\ &= C^v_b C^b_n \delta v^n - C^v_b C^b_n \left(v^n \times\right) \phi \\ &\quad - C^v_b \left(l^b_{wheel} \times\right) \delta\omega^b_{ib} + n_{vW} \end{aligned} \tag{7}$$

where, C^v_b is calculated by the attitude misalignment of b-frame with respect to v-frame

3) SMOOTHING ALGORITHM

The smoothing algorithm is applied to obtain an optimal estimation of the GNSS/INS/odometer integrated system by using all the past, current and future navigation solutions and this algorithm can effectively improve the smoothness of positioning solutions when GNSS signals are interfered or blocked. In this paper, the Rauch-Tung-Striebel (RTS) algorithm is applied to the data fusion algorithm as follows [21], [22]:

$$\begin{aligned} \hat{x}_{k/N} &= \hat{x}_{k/k} + A_k(\hat{x}_{k+1/N} - \hat{x}^-_{k+1}) \\ P_{k/N} &= P_k + A_k(P_{k+1/N} - P^-_{k+1})A^T_k \\ A_k &= P_k \Phi^T_k (P^-_{k+1})^{-1} \end{aligned} \tag{8}$$

where, A_k refers to the RTS smoothing gain, Φ expresses the state transition matrix, P shows the state error covariance matrix and N denotes the total number of epochs.

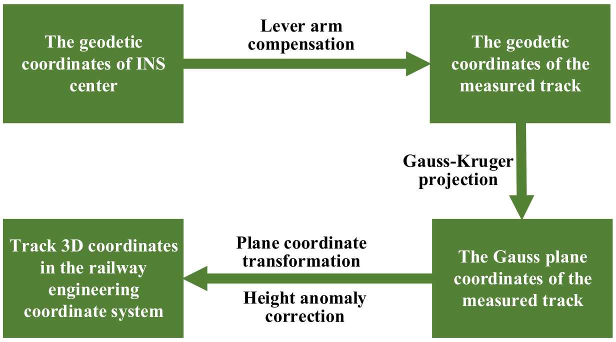

FIGURE 5. The process of the coordinate transformation.

B. COORDINATE TRANSFORMATION

Actually, the GNSS/INS/odometer integration positioning solutions are the geodetic coordinates based on the loosely-coupled processing, including the latitude, longitude and ellipsoid height in the Earth-centered frame (e-frame). However, the absolute position of the track centerline in 3D space is defined in the specific independent mapping projection coordinate frame [23]–[25]. In this section, four steps are applied for the coordinate transformation as shown in Figure 5. The first step is lever arm compensation for projecting the geodetic coordinates from the INS phase center to the measured railway track. The second step is the coordinate projection process. The projection coordinates can be calculated in the Gauss plane by using the Gauss-Kruger projection. After the projection process, the plane coordinates in the Gauss plane need to be transformed to the specific local mapping coordinate frame through a similarity transformation, which requires at least two control points with known coordinates in both coordinate frames. The last step is the correction of the height anomaly using for eliminating the difference of ellipsoid height between e-frame and the railway engineering coordinate frame.

1) LEVER ARM COMPENSATION

The GNSS/INS/odometer positioning results based on the integrated navigation process are the 3D coordinates of the IMU measuring center mounted on the track trolley, but these coordinates cannot express the actual position of the railway track. Therefore, it is essential to convert the IMU coordinates to obtain the positioning results of the measured track axis using lever arm compensation.

The lever arm is a three dimensional vector defining the distance between the IMU phase center and the rail top surface of the railway track in the b-frame, which is determined by track trolley calibration and the gauge surveying results. For railway track mobile measurements, precise lever arm compensation is essential for absolute positioning accuracy. After lever arm compensation, the absolute geocentric coordinates of the measured track centerline and both sides of the rail can be calculated in the e-frame.

$$r^e_{rail} = r^e_{IMU} + D^{-1}_R C^n_b l^b_{trolley} \tag{9}$$

In the above formula:

$$D^{-1}_R = diag\left(\begin{bmatrix} \frac{1}{R_M + h} & \frac{1}{(R_N + h)\cos\varphi} & -1 \end{bmatrix}^T\right) \tag{10}$$

where, r^e_{IMU} and r^e_{rail} are the positions of the IMU measuring center and the coordinates of the measured rail top surface in the e-frame, respectively; $l^b_{trolley}$ refers to the lever arm from the IMU measuring center to the track top surface in the b-frame, D_R^{-1} represents the Cartesian-to-curvilinear position change transformation matrix, R_M and R_N refer to the radiuses of the meridian and prime vertical in the measured location, respectively; h and φ are the geodetic height and latitude of the IMU measuring center, respectively.

2) GAUSS-KRUGER PROJECTION

In practice, the GNSS/INS/odometer surveying positioning solutions are the geodetic coordinates in the WGS-84 coordinate system, including the latitude, longitude and height, while the railway track is defined in the local level system. Therefore, the latitude and longitude calculated by GNSS/INS/odometer need to be converted to the plane coordinates for the railway engineering survey, including north and east coordinates.

The Gauss-Kruger projection is a kind of equiangular transverse elliptic cylindrical projection. Due to the high projection precision, easy calculation and small deformation of the Gauss projection, it has been adopted and popularized in many projects and countries. This projection is useful to project latitude and longitude in the geocentric coordinate system to the projection plane. The region on both sides of the central meridian can be projected onto an ellipsoidal surface and the cylinder surface is expanded as the projection surface during the Gauss-Kruger projection process. The details of the conventional Gauss-Kruger projection equations can be referred to in the literature [26].

To reduce the projection deformation of the length and area, ellipsoid expansion and Gauss projection plane rising are needed for the conversion between the geodetic coordinates and the projected independent coordinates. In addition to the ellipsoid expansion model, the arbitrary central meridian is applied to the Gauss projection. The arbitrary central meridian method uses the longitude of the surveying area center as the central meridian for the Gauss projection. The Gauss projection based on the arbitrary central meridian and ellipsoid expansion is a suitable method in engineering survey applications and the measured track coordinates will be calculated with high precision and small deformation by using this method.

On the projection plane, the central meridian is the longitude at the center of the surveying area, and the main content of the projection is to transform the geodetic coordinates (B, L) to the Gauss plane coordinates (x, y). Compared with the normal ellipsoid parameters, only the major radius of the ellipsoid changes in the expanding ellipsoid [27].

$$da = H_0\sqrt{1 - e^2 \sin^2 B_0} \tag{11}$$

$$\begin{bmatrix} dB \\ dL \end{bmatrix} = \begin{bmatrix} \dfrac{N}{M + H_0}\dfrac{e^2}{a}\sin B \cos B \\ 0 \end{bmatrix} da \tag{12}$$

where, B and L are the latitude and longitude of the converted coordinates, respectively; N and M express the curvature radiuses of the prime vertical and meridian in the measured location, respectively; e is the first eccentricity of the reference ellipsoid; a is the major radius of the reference ellipsoid; H_0 is the height of the projection plane; B_0 is the reference latitude for the Gauss projection; da, dB and dL are the differences between the normal ellipsoid and expanding ellipsoid.

3) PLANE COORDINATE TRANSFORMATION

In the process of the existing line survey, the projected coordinates of the measured track in Gauss- Kruger plane need to be transformed to the specific local mapping coordinate frame for railway track construction and maintenance. This transformation can be carried out by using the common points both in the two frames to establish a link between these two coordinate systems and solve the transformation parameters.

In this part, the Helmert transformation is applied to the plane coordinate transformation with the translation, rotation and scale factor estimation. The plane transformation algorithm needs at least two control points with known coordinates in both two frames along the existing line, and this algorithm is suitable for the coordinate conversion of the scope of railway track construction [28].

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} \Delta x_0 \\ \Delta y_0 \end{bmatrix} + mR(\theta)\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} \tag{13}$$

where, x_1 and y_1 are the plane coordinates before the transformation, x_2 and y_2 are the plane coordinates after the transformation, Δx_0 and Δy_0 are the translation parameters, m is the scaling parameter, θ is the rotation parameter and $R_{(\theta)}$ is the rotation matrix expressed as:

$$R(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \tag{14}$$

The error equation can be shown as follows:

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} x_2 - x_1 \\ y_2 - y_1 \end{bmatrix} - \begin{bmatrix} 1 & 0 & x_1 & -y_1 \\ 0 & 1 & y_1 & x_1 \end{bmatrix}\begin{bmatrix} \Delta x_0 \\ \Delta y_0 \\ a_1 \\ a_2 \end{bmatrix} \tag{15}$$

The coefficients of this equation can be expressed as:

$$\begin{cases} a_1 = m\cos a - 1 \\ a_2 = m\sin a \end{cases} \tag{16}$$

If the control points with known coordinates in both two frames along the existing line are more than the minimum requirement, the least square method can be used for the more precise conversion parameters, expressed as:

$$X_0 = \left(B^T PB\right)^{-1} B^T PL \tag{17}$$

The coefficients can be shown as:

$$X_0 = \begin{bmatrix} \Delta x_0 \\ \Delta y_0 \\ a_1 \\ a_2 \end{bmatrix} \quad B = -\begin{bmatrix} 1 & 0 & x_1 & -y_1 \\ 0 & 1 & y_1 & x_1 \end{bmatrix}$$

$$L = \begin{bmatrix} x_2 - x_1 \\ y_2 - y_1 \end{bmatrix} \quad P = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{18}$$

4) HEIGHT ANOMALY CORRECTION

In the railway track absolute measurement, the height from the GNSS/INS/odometer surveying position is the geodetic height, while the normal height is needed in railway construction determined from the leveling elevation, so the height anomaly between the geodetic height and the normal height needs to be corrected based on the common height control points with height values in these two height system. This practice has proven that the suitable conversion method for GNSS elevation fitting based on the actual situation can be widely used for engineering surveying and deformation monitoring. In this paper, GNSS elevation fitting combined with least-squares collocation is used to calculate the normal height of the surveyed railway track based on common control points.

The elevation fitting takes advantage of mathematical methods to estimate the height anomaly value based on the geometric relativity of the height anomaly. According to the control points with both GNSS height and leveling data, the regional quasigeoid is fitted by using the models of linear fitting, plane correlation fitting or quadratic surface fitting under the condition of least-squares collocation [26], [29], [30]. The polynomial of the height anomaly can be expressed as:

Linear fitting:

$$\zeta = a_0 + a_1 dB + a_2 dL \tag{19}$$

Plane correlation fitting:

$$\zeta = a_0 + a_1 dB + a_2 dL + a_3 dBdL \tag{20}$$

Quadratic surface fitting:

$$\zeta = a_0 + a_1 dB + a_2 dL + a_3 dB^2 + a_4 dL^2 + a_5 dBdL \tag{21}$$

The coefficients of these equations can be expressed as:

$$\begin{cases} dB = B - B_0 \\ dL = L - L_0 \\ \zeta = H - h \end{cases} \tag{22}$$

where, B and L are the geodetic coordinates of the control points; H and h are the geodetic height and normal height of the control points, respectively; B_0 and L_0 are the mean geodetic coordinates of the control points and ζ represents the height anomaly.

The principle of these three elevation fitting polynomials is to approach the real geoid by using mathematical methods and the accuracy depends on the distribution and density of the common control points. Since the measurement work in this paper is on railway track and the control network is built along the railway, the linear fitting under the condition of least squares collocation is applied for the height anomaly correction.

TABLE 1. The performance specifications of POS830.

IMU		
Parameter	Gyroscope	Accelerometers
Range	±300 deg/s	±10 g
Bias	0.01 deg/h	25 mGal
Scale factor	10 ppm	10 ppm
Sampling rate	200 Hz	
Shock	40 g	
GNSS		
Sampling rate	1 Hz	
Position accuracy	2 cm + 1 ppm (RMS) in RT-2 LITE mode	

IV. FIELD TEST AND ACCURACY ANALYSIS

A. EXPERIMENT DESCRIPTION

In order to access the performance of the proposed GNSS/INS/odometer measuring system, a field test on the newly built Zhengzhou-Xuzhou high speed line had been conducted and a data set consisting of GNSS, INS, odometer and gauge outputs was collected in March 2016. During the field test experiment, the track segment had just completed construction and precise adjustment, and the surveyed line had not yet started operations, whose absolute coordinates strictly complied with the design document and construction errors were less than 2 mm in horizontal and vertical directions, respectively.

In this experiment, a navigation grade INS/GNSS integrated system, POS830, integrating an IMU with a NovAtel OEMV-2 GNSS card was fixed on the trolley platform, whose performance specifications were listed in Table 1. A Trimble NetR9 receiver as a base GNSS station was located at one control point of the railway construction control network for carrier-phase differential GNSS processing, whose true coordinate can be gained from railway design document. The NovAtel OEMV-2 GNSS card as a rover GNSS station sampled simultaneously with the Trimble NetR9 receiver at a 1 Hz sampling rate to provide accurate positioning updates to the INS based on the PPK technology. An odometer was mounted on the wheel of trolley, whose cumulative error versus the travel distance was smaller than 0.2 %. To avoid other adverse effects on the proposed approach, this field test was carried out in an open-sky environment, where both the base and rover GNSS stations were under favorable observation conditions during the whole span of the existing line survey operation. The track segment was measured using GNSS/INS/odometer integrated system in mobile surveying mode over 4 km at a speed of 1.5 m/s, as shown in Figure 6.

B. ACCURACY ANALYSIS

The performance of the proposed system is assessed through evaluating its measurement consistency with the reference system. As mentioned above, the construction and the precise adjustment of track had just been completed and the railway

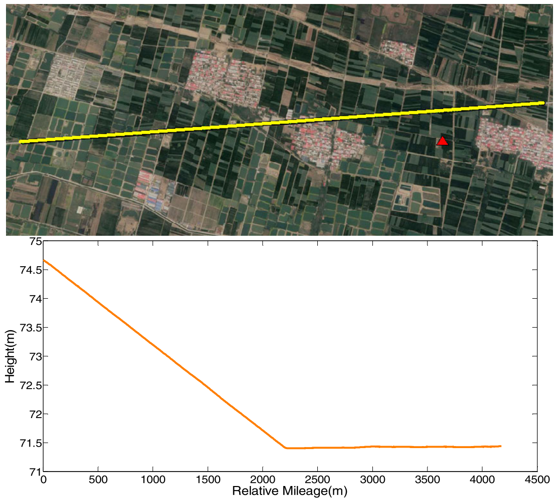

FIGURE 6. Horizontal trajectory (top) and ellipsoid height (bottom) of the measured track in Zhengzhou-Xuzhou high-speed railway. The red triangle in the top subplot refers to the location of GNSS base station.

had not been opened to traffic when the experiment was conducted. Therefore, there were no factors making the railway drift away from the design value due to the frequent passage of heavy trains, and the real coordinates of surveyed track strictly complied with the design document during the field test experiment. Since the design accuracy of the Zhengzhou-Xuzhou high-speed line is 2 mm, which is much less than the surveying requirement of 5 cm for absolute position accuracy, the design 3D coordinates of the surveyed line axis can be used as the reference system to access the performance of the proposed measuring system. During the accuracy analysis process, the real track construction errors of 2 mm can be ignored and the 3D coordinate differences between design document coordinates and measuring positioning results can be regarded as the surveying errors in both horizontal and vertical directions.

1) ABSOLUTE MEASURING ACCURACY ANALYSIS

Absolute measuring accuracy is the crucial index to assess the performance of proposed measuring system. Figure 7 depicts the coordinate differences between the measurement positioning results and the reference system. The horizontal error is the distance from the plane coordinates obtained by measuring system to the surveying line axis calculated from design document. The vertical error is the height difference between measuring system and reference system at the same mileage. In the following part, the GNSS/INS results only uses the GNSS and INS outputs for data post-processing and the GNSS/INS/odometer adds the 3D velocity constraint containing odometer auxiliary and NHC as presented in positioning process part.

Shown in Figure 7, the measurement errors based on the proposed surveying system in the horizontal and vertical directions are mostly smaller than 2 cm, both GNSS/INS and GNSS/INS/odometer integrated system. The solution errors based on GNSS/INS demonstrate a similar trend and are in a good agreement with the results of GNSS/INS/odometer system, both in horizontal and vertical directions, respectively, which illustrates continuous high-precision GNSS positioning results can compensate the inertial sensor drift effectively and the 3D velocity constraint has little influence on the proposed method under GNSS favorable observation condition. It is interesting to note that there seems to be a constant offset for measuring errors between GNSS/INS and GNSS/INS/odometer system results with the value of 2.5 mm and 0.4 mm in horizontal and vertical directions, respectively. Compared with GNSS/INS positioning process, 3D velocity update information from odometer and NHC is added in the loosely-coupled algorithm based on GNSS/INS/odometer, thus the GNSS position, velocity update and mounting angle errors make the proposed surveying performances different slightly. According to what is presented in the loosely-coupled algorithm part, smoothing algorithm is applied to obtain a smoother estimation by using all the past, current and future navigation solutions, which leads the position difference to be almost a constant offset during the whole date processing. As shown in the smaller panels of Figure 6, the difference of positioning result errors between GNSS/INS and GNSS/INS/odometer in the horizontal direction are larger than those in the vertical direction, which means the 3D velocity constraint has a greater impact on the correction of plane coordinate than height coordinate during the loosely-coupled processing when GNSS update is uninterrupted.

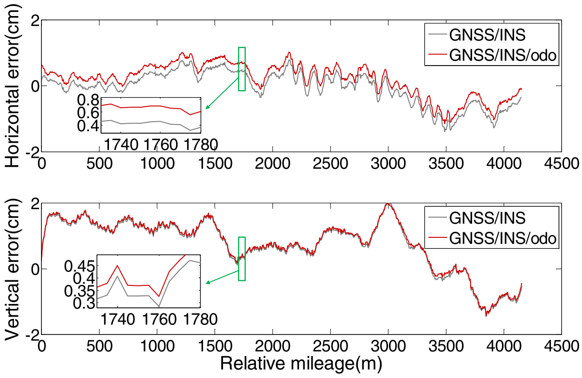

FIGURE 7. The absolute errors in horizontal (top) and vertical (bottom) directions utilizing the GNSS/INS system and GNSS/INS/odometer system, respectively.

Figure 8 shows the cumulative distribution function (CDF) of the measuring errors in two directions, both GNSS/INS and GNSS/INS/odometer, respectively. The positioning results of the two integrated systems by employing the proposed method maintain a high degree of consistency. Besides, the CDF image is illustrated that horizontal error is no more than 1 cm under a confidence probability of 90 percent for the proposed method, both GNSS/INS and GNSS/INS/odometer system, much smaller than that of vertical error. Table 2 shows the statistical data from Figure 6, inclusive of mean, maximum and standard deviation (STD) values of the measuring errors in horizontal and vertical directions, respectively. It is

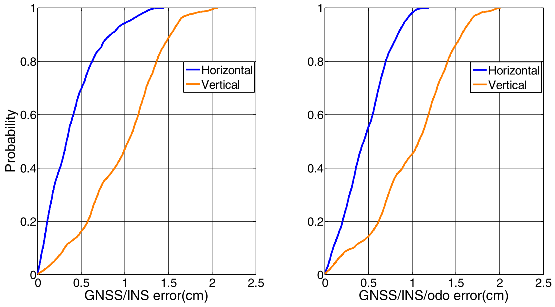

FIGURE 8. CDF of the absolute errors in the horizontal and vertical directions utilizing the GNSS/INS system (left) and GNSS/INS/odometer system (right).

TABLE 2. Statistical summary of the measurement errors.

	Absolute errors	Mean(cm)	Max(cm)	STD(cm)
GNSS/INS	Horizontal	-0.0496	1.3990	0.4997
	Vertical	0.7308	2.0680	1.0719
GNSS/INS/odometer	Horizontal	0.1912	1.1550	0.5327
	Vertical	0.7771	2.0130	1.0992

illustrated that the STD of position errors by GNSS/INS in horizontal and vertical directions are 0.45 cm and 1.07 cm, and the maximum values of GNSS/INS measuring errors are 1.40 cm and 2.10 cm, while the mean values are −0.05 cm and 0.73 cm. The statistical errors of GNSS/INS/odometer have a similar solution result as GNSS/INS. For the plane and height coordinate errors, the STD, maximum and mean values are 0.53, 1.16, 0.19 cm and 1.10, 2.01, 0.78 cm, respectively. Shown in Figure 8 and Table 2, the vertical precision turns out to be worse than horizontal precision, both GNSS/INS and GNSS/INS/odometer system, which is a result of that GNSS receivers attains worse positioning precision in vertical direction than horizontal direction due to satellite geometry. In addition, the elevation fitting method is applied for the height anomaly correction as presented in positioning process part. Although the linear fitting under the condition of least squares collocation can provide accurate height anomaly correction for railway track height coordinate conversion, there is a minor difference between the design height and the corrected height.

According to the China Specifications for Survey Engineering of High-speed Railway, the absolute measuring errors of railway track axis should be within 5 cm, both in horizontal and vertical directions, respectively. Figure 7 and 8 illustrate the absolute track position measurement errors based on the proposed surveying system in the horizontal and vertical directions are mostly smaller than 2 cm, and Table 2 shows the STD values of two direction errors are smaller than 1.1 cm, both GNSS/INS and GNSS/INS/odometer integrated system, which achieves the absolute accuracy of existing line axis measurement obviously and is surely able to be used in the track axis measuring application in mobile surveying mode under an open-sky environment.

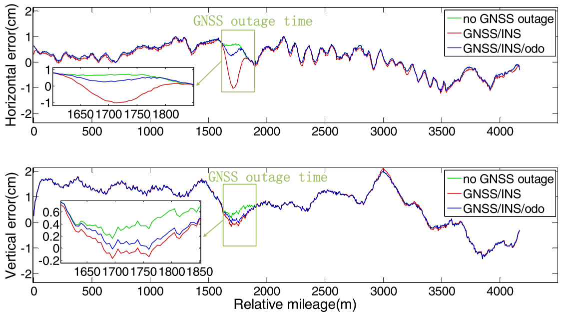

FIGURE 9. Horizontal (top) and vertical (bottom) measuring errors of the GNSS/INS and GNSS/INS/odometer, respectively, when GNSS signals are unavailable for a continuous time period lasting for 120 s.

2) ERROR ANALYSIS DURING GNSS OUTAGE

The GNSS signals are inevitably weakened and even blocked when the measuring system passes through those segments with shelters such as tunnels and viaducts, which causes the great loss of accuracy, reliability and continuity of the GNSS positioning results [31]. The aim of this subsection is to preliminarily explore the performance of the proposed GNSS/INS/odometer measuring system and the impact of odometer during data processing when GNSS signals are totally unavailable for a certain time period.

The consecutive GNSS signal outages lasting for different lengths are simulated by interrupting the corresponding GNSS positioning measurement epochs during data processing. The location starts from the mileage of 1600 m when GNSS is blocked. During the GNSS outage time, no GNSS position results are provided to the Kalman filter for GNSS/INS integrated navigation calculation as the update information, and the velocity derived from the odometer signal can be regarded as the velocity update along the forward direction. The odometer and NHC mentioned in positioning process compose a complete 3D velocity update in the v-frame and take the place of the position update from GNSS to maintain the precision of the positioning solution in the integrated system during the GNSS outage time. It should be noted that the attitude misalignment of the IMU with respect to the track trolley, also called mounting angles, will degrade the benefit of the velocity update, which need to be calibrated precisely before using the 3D velocity constraint in the Kalman filter [32].

Figure 9 depicts the horizontal and vertical measuring errors based on GNSS/INS and GNSS/INS/odometer, respectively, when GNSS signal outage occurs lasting for 120 s. Shown in Figure 9, the absolute measurement errors of the proposed surveying system in the horizontal and vertical directions are mostly smaller than 2 cm when GNSS is interrupted based on the GNSS/INS and integrated system, which illustrates INS can maintain high accuracy measurement without compensation from external observation information during the 120 s GNSS outage period. It is interesting to note that the vertical position drift error turns out to be smaller than horizontal position drift based on

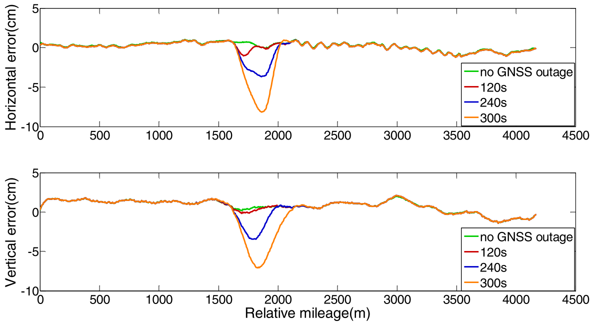

FIGURE 10. Horizontal (top) and vertical (bottom) measuring errors of the GNSS/INS, when GNSS signals are unavailable starting from the mileage of 1600 m for a continuous time period lasting for 120 s, 240 s and 300 s, respectively.

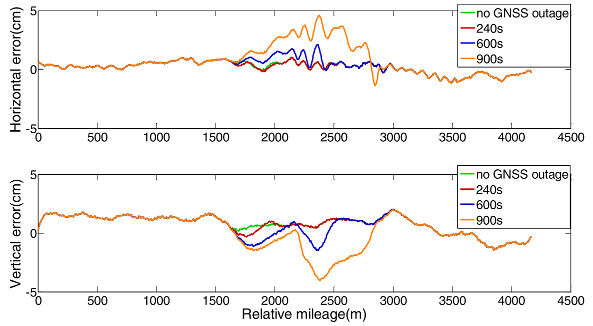

FIGURE 11. Horizontal (top) and vertical (bottom) measuring errors of the GNSS/INS/odometer, when GNSS signals are unavailable starting from the mileage of 1600 m for a continuous time period lasting for 240 s, 600 s and 900 s, respectively.

GNSS/INS. During GNSS signal outage, the position precision of GNSS/INS depends uniquely on the mechanization of INS, upon which the accuracy of attitude has an immense influence. It is widely recognized that heading angle and pitch angle of INS affect horizontal and vertical positioning precision, respectively, when GNSS signals are interrupted. During the loosely-coupled processing, heading angle has a slower convergence speed and is difficult to achieve an accurate estimation, which leads to a lower precision of heading than that of pitch. And heading angle has a faster divergence rate than pitch angle for INS calculation without assistance from other external sensors, which causes the horizontal position error diverges faster than that in vertical direction during GNSS outage time. Due to the constraint from 3D velocity updates, the GNSS/INS/odometer result errors are smaller than GNSS/INS in both directions and the 120 s GNSS outage tends to have little influence on the measuring precision by using the proposed method based on GNSS/INS/odometer as shown in Figure 9.

According to the China Specifications for Survey Engineering of High-speed Railway, the absolute measuring errors of railway track axis should be within 5 cm, both in horizontal and vertical directions, respectively. In order to find the longest GNSS outage which can satisfy the requirement of measuring accuracy, Figure 10 and 11 express the position drift errors in both directions based on GNSS/INS and GNSS/INS/odometer, with consecutive GNSS signal outages lasting for different lengths, and the length of GNSS outages are 120s, 240s, 300s and 240s, 600s, 900s for two system, respectively. Since the smoothing algorithm is applied to obtain a smoother estimation by using all the past, current and future navigation solutions, the coordinate correction results are smoother during the GNSS outage period in two figures. As shown in Figure 10, the measuring errors of GNSS/INS are smaller than 5 cm when the length of interruption time of GNSS signals is less than 240s. Figure 11 expresses that GNSS/INS/odometer system meets the requirement of absolute measuring accuracy even though GNSS signal are unavailable for a continuous time period lasting for 900s, which can satisfy the actual railway track axis measurement task under harsh GNSS environments. The 3D velocity constraint containing NHC and odometer auxiliary significantly improves the positioning accuracy and enhances the performance of the INS in GNSS-challenged urban environments by comparing the above two figures. Due to the compensate of the inertial sensor drift from 3D velocity updates, the GNSS/INS/odometer position drift errors are much smaller than GNSS/INS in both directions when GNSS signals are interrupted, and the proposed system can maintain the measuring accuracy of 5 cm during the 900 s GNSS outage.

In addition to the length of GNSS signal interruption and the sensor output errors, the position drift errors of GNSS/INS/odometer system in both directions are influenced by a variety of sources including the motion state and velocity of the track trolley during GNSS outage period. Therefore, the position drift errors have a certain randomness when GNSS signals are interrupted, and the maximum excursion error may be not exactly the same when GNSS outages start at different time with the same length. This part is to evaluate the performance of the proposed GNSS/INS/odometer measuring system when GNSS signals are totally unavailable by using the statistic value of ten different GNSS outages with the same length. During the data processing, these ten GNSS outages are added starting at different time, respectively, and these ten maximum excursion of measuring errors versus each GNSS outage in both directions are recorded for error statistic process. This part collects these ten different results and selects the maximum one as the statistic value of the ten different GNSS outages with the same length. Notably, this is a stricter measure than the common statistical methods to determine the maximum excursion errors based on GNSS/INS/odometer integration during GNSS outage period.

Figure 12 and 13 express the maximum position drift errors versus the GNSS outage lasting for different lengths in both directions based on GNSS/INS and GNSS/INS/odometer, respectively. The maximum position drift errors are the statistic maximum value of the ten GNSS outages starting at different time with the same length. Figure 12 depicts that the maximum position drift errors increase rapidly with time during GNSS outage, both in horizontal and vertical

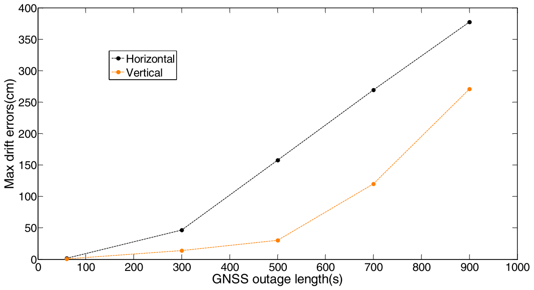

FIGURE 12. The statistic value of maximum position drift errors versus the GNSS outage length based on GNSS/INS in horizontal and vertical directions, respectively.

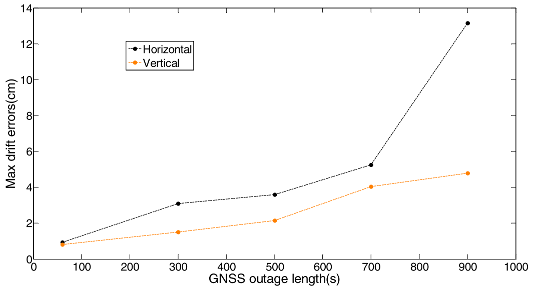

FIGURE 13. The statistic value of maximum position drift errors versus the GNSS outage length based on GNSS/INS/odometer in horizontal and vertical directions, respectively.

directions based on GNSS/INS. When continuous high-precision GNSS positioning results are interrupted, GNSS/INS system only uses the INS outputs for data post-processing and the INS navigation error accumulates quickly without the correction from the GNSS absolute position update information, which causes the navigation results deviate from the true values obviously. When GNSS signals are totally unavailable, there is no absolute position correction for INS, meanwhile, heading and pitch angles of the integrated system are highly correlated with the position processing mentioned above. The heading accuracy affects horizontal positioning precision, while pitch accuracy impacts the precision in the vertical direction. Compared with pitch angles, heading angle has a lower precision and causes the horizontal drift error is large than vertical error during GNSS outage period, as shown in Figure 12 and 13. Compared with GNSS/INS positioning process, 3D velocity update information from odometer and NHC is added in the loosely-coupled algorithm based on GNSS/INS/odometer, which has been proven to significantly improve the positioning accuracy and enhance the performance of the INS when no GNSS position results can compensate the inertial sensor drift effectively. GNSS/INS/odometer uses the velocity update in the Kalman filter to maintaining the navigation precision to obtain continuous, reliable and high-precision measurements of the track position effectively when the GNSS signals are interrupted. As shown in Figure 13, the maximum position drift errors of statistic values can keep the accuracy of 5 cm approximately in both directions when GNSS signals are interrupted for 700 s, which can meet the accuracy requirement of railway track centerline absolute surveying under harsh GNSS environments.

V. CONCLUSION

This paper has presented a railway track absolute measurement system based on the GNSS/INS/odometer. This kinematic measurement system for existing line axis survey does not depend on a dense and high-precision track control network and uses a rapid mobile surveying model, which can significantly improve the speed from 0.15 km/h to 5 km/h compared to the conventional methods based on total station. In addition, this solution for the existing line axis survey can obtain continuous and high-precision results in the absence of satellite signals. Firstly, the surveying foundation and data processing algorithm based on GNSS/INS/odometer are shown in great detail. Secondly, a field test on a segment of the real railway track (Zhengzhou-Xuzhou high-speed railway line, China) was conducted to assess the performance of the measurement system. Besides, in order to explore the performance of the proposed GNSS/INS/odometer measuring system under harsh GNSS environment, the consecutive GNSS signal outages lasting for different lengths are added to simulate the situation when the GNSS signals are inevitably blocked during measuring operation process. The results show that the measurement errors are less than 0.6 cm and 1.1 cm in the horizontal and vertical directions, respectively, when GNSS update is uninterrupted. GNSS/INS/odometer measuring system can keep the accuracy of 5 cm approximately in both directions when GNSS signals are interrupted for 700 s, which can satisfy the demand of the measured line with shelters. According to the China Specifications for Survey Engineering of High-speed Railway, the absolute measuring accuracy of 5 cm in horizontal and vertical directions can meet the tolerance required for the existing line centerline survey. Therefore, the proposed measuring system using GNSS/INS/odometer integration is applicable for railway track axis measuring, which is much more efficient than the conventional method based on the total station and can continuously complete the existing line surveying task with high efficiency, continuous and reliable solutions under harsh GNSS environments.

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