Performance Investigation and Accuracy Assessment of Using an Aided INS Trolley for Railway Track Surveying

BOUCHIBA Mohammed[1]
[1]Institut National de Cartographie et de Télédétection

ملخص: التطور السريع للسكك الحديدية الصينية العالية السرعة يظهر أن هناك حاجة ملحة إلى وسائل جديدة تتسم بالكفاءة والدقة للتغلب على مشكلة صيانة السكك الحديدية، وهي على وجه التحديد الصعوبة التي تواجه مرحلة قياس انحرافات مسار السكك الحديدية. أحد هذه الوسائل هي الطريقة القائمة على استخدام عربة مسح مسار السكك الحديدية التي تعتمد على نظام الملاحة بالقصور الذاتي المدعوم بقياسات المحطة الكاملة، والتي يمكن أن تقيس معاملات هندسة مسار السكك الحديدية بطريقة غير متصلة عن طريق دفع العربة على المسار.

تتمثل أهداف هذا البحث في التحقق من صحة الطريقة القائمة على استخدام عربة مسح المسار التي تعتمد على نظام الملاحة بالقصور الذاتي المدعوم بقياسات المحطة الكاملة بدلا من الطريقة التي تعتمد على نظام الملاحة بالقصور الذاتي المدعوم بقياسات النظم العالمية لسواتل الملاحة، من خلال استقصاء أداء استخدام العربة المتحركة المستشهد بها في اختبارات ميدانية على مسار السكة الحديدية، وتقييم الدقة الداخلية من خلال تحليل قابلية تكرار القياس، وتقييم الدقة الخارجية من خلال مقارنة النتائج مع تلك المتعلقة بالعربة المتعارف عليها Amberg GRP 1000.

تشير نتائج الاختبارات الميدانية إلى أن:

1). الطريقة المعتمدة التي تم التحقيق فيها و التي تستند على نظام الملاحة بالقصور الذاتي المدعوم بقياسات المحطة الكاملة هي طريقة موثوقة، وأن معدل تكرار قياس المسار، والارتفاع الفائق، والانحراف الأفقي والعمودي لمحور المسار أقل من 0,2 مم (1σ).

2). تفي كل من العربة القائمة على نظام الملاحة بالقصور الذاتي المدعوم بقياسات المحطة الكاملة والعربة Amberg GRP 1000 بمتطلبات الدقة الثابتة لقياس انحرافات مسار السكك الحديدية المحددة في المعايير الصينية.

3). يمكن استخدام الطريقة القائمة على نظام الملاحة بالقصور الذاتي المدعوم بقياسات المحطة الكاملة كبديل لعربة Amberg GRP 1000، بل ويمكن استبدالها بسبب دقة القياس العالية التي تحققت في وقت قياس أمثل (أسرع حوالي 16 إلى 20 مرة من العربة المتحركة المتعارف عليها).

4). من السهل الحصول على مكان انحرافات المسار لأن الانحرافات ترتبط مباشرة بقيمة المسافة المقطوعة بالميل، وبالتالي يمكننا تحديد موقعها على مسار السكك الحديدية.

الكلمات الأساسية: عربة مسح مسار السكك الحديدية، نظام الملاحة بالقصور الذاتي المدعوم، معاملات هندسة مسار السكك الحديدية، انحرافات مسار السكك الحديدية، الدقة النسبية والدقة المطلقة.

Abstract : The rapid development of China's high-speed railway shows that new efficient and accurate means are required to overcome the problem of rail track maintenance, precisely the difficulty in the stage of measuring the track irregularities. One such mean is the method that involves the use of track measuring trolley based on aided inertial navigation system (INS) with INS/Total station configuration, which can measure the track geometry parameters in a non-contact manner by running on the track.

The aims of this research were to validate the method that involves the use of the new track inspection trolley based on aided INS and total station measurements instead of global navigation satellite system (GNSS) measurements, by investigating the performance of using the cited trolley in real tests on the rail track, and assessing the inner accuracy through measurement repeatability analysis, and assessing the outer accuracy via comparison of the results with those related to the traditional trolley Amberg GRP 1000.

The field tests results indicated that :

1).The investigated method based on aided INS is reliable and itstrack irregularities measurement repeatability of track gauge, super-elevation, horizontal and vertical deviation of track axisis smaller than 0.2 mm (1σ).

2).Both the trolley based on aided INS and the Amberg GRP 1000 meet the static accuracy requirement for railway track irregularity measurement defined in Chinese standards.

3).The method based on aided INS can be used alternatively with the Amberg GRP 1000, and even can replace it due to the high measurement accuracy achieved in optimized measuring time (faster about 16-20 times than the traditional trolley).

4).It is easy to obtain where the track irregularities are because deviations are directly related to their mileage value, and therefore we can locate it on the railway track.

Keywords : Track measuring trolley, aided INS, track geometry parameters, railway track irregularity, relative and absolute accuracies.

1. Introduction

With the rapid development of the high-speed railway (shortened hereinafter as HSR) in China, on the one hand, a great challenge is brought to high-speed railway administrators with respect to the high traffic density, short skylight, high demand of track quality, and difficulties in rail track maintenance which plays a key role in the policies that promote railway transport in the country. On the other hand, the demands for track irregularities measurement methods and systems with high-accuracy and high-efficiency are increasing rapidly.The track irregularity can be assessed by track geometry parameters, the measurement of which plays a significant role in monitoring the track deformation and managing the railroad maintenance[1].

The railroad infrastructure administrators in China classify track irregularity detection methods into two categories, namely the static-detection methods and the dynamic-detection methods, where the latter use an automated track inspection vehicle with sensors to measure divers track geometric parameters while the vehicle is moving on the track. In contrast, static-detection methods used without load and measure the track geometric parameters[2]. It is in the context of the static-detection method for railway-track irregularity that the work carried out during this thesis is included. This thesis studied principally the measure of railway-track irregularity by the static- method based on track surveying trolleys. The most well-known products of the high-precision track surveying trolley in China are Amberg GRP1000 provided by Amberg Technologies and the Trimble GEDO system provided by Trimble Inc. These track trolleys equipped with motorized total station can provide relative accuracy and absolute accuracy of the track geometry parameters with millimeter and even sub-millimeter accuracy in the stop-and-go mode[3].

Although the conventional surveying trolleys based on the motorized total station can satisfy the precision requirement and have achieved the most extensive applications in railway track surveying, there are still some limitations. The high precisionmeasurement by total station requests the trolley to be operated in static measurement (stop-and-go) mode[4], [5]. The distance between two position measurement points is short (62.5 cm) which makes it not efficient enough for track surveying[5], [1].

With the evolution of inertial sensors, Inertial navigation systems (Shortened hereinafter as INS) are no longer pricey and voluminous. Therefore, track recording systems based on INS have been broadly implemented in railway surveying, however, the INS unfavorable error propagation is the limitation of a stand-alone INS. Consequently, INS error drifts should be diminished by the aid of other apparatus which provide relative or absolute measurement updates[6].

To address the limitations of conventional surveying trolleys based on motorized total station, and in order to surmount the drawback of INS error drifts, Chen & Niu [5],[7] at Global Navigation Sattelite System (Shortened hereinafter as GNSS) Research Center at Wuhan University have designed new track measuring trolley based on aided INS with GNSS measurements to ensure at the same time i) carry out measurements of track irregularities with high accuracy and ii) to survey with high speed in contrary to the traditionaltrolley. They have achieved in a validation trial high relative accuracy of 1 mm and absolute accuracy of several centimeters in the kinematic surveying mode. This track inspection trolley is marketed by the Chinese company Wuhan MAP Space Time Navigation Technology Co., Ltd. (Shortened hereinafter as MAP Inc.), and was the first version prototype of the track inspection trolley based on Aided INS with total station measurements investigated in this thesis.

Nevertheless, since the performance of a Position and Orientation System (POS) which is the core of this track measuring trolley based on aided INS, depends on both INS and GNSS, a crucial issue is that the GNSS signal may become obstructed by tunnels, bridges and other obstacles, mostly long-term GNSS outage which is a predominant problem that affects POS performance which results in divergence of navigation solution and error accumulation of INS and in consequence decrease of measurement accuracy. In the other hand, the absolute accuracy of this track measuring trolley is well-known to be of centimeter level when the GNSS measuremnts are used to aid INS which is lower than the requirements of some railway surveying tasks such as adjusting and laying the railway track.

2. Methodology

The work carried out within this thesisis included in the context of the development program of the measuring trolley based on INS/ GNSS integrated system by Wuhan University and the Chinese company MAP Inc.
This research performed in MAP Inc., in order to validate the method that involves the use of the new track inspection trolley based on INS/ Total station integrated system. To do so, in real tests weinvestigate the performance and assess the accuracy of using the track surveying trolley based on aiding INS by total station measurements instead of GNSS for measurement of the absolute position of track axis and other track geometry parameters.

2.1 Track Irregularity and Assessment

Track irregularities are indices that are characterized by deviations of 3D track positions from the designed positions.

Within the course of this study, track gauge (figure 01), super-elevation (figure 02), lateral and vertical deviations of track axis (figure 03) will be evaluated to investigate the measuring accuracy and the surveying performance of the proposed method with respect to the reference method according to the available data of the latter. Track gauge, super elevation and track axis coordinates are only the three geometric parameters taken in consideration within this study.

Track gauge is the smallest distance between lines perpendicular to the running surface intersecting each rail head profile at point P in a range from 0 to Z_p below the running surface. Super elevation : The difference in height of the adjacent running tables computed from the angle between the running surface and a horizontal reference plane. Track axis coordinates are derived from the coordinates of the higher and lower rails, and a half of the distance between the middle lines of the surface of the two rail-head **G/2**, then Track axis coordinates are substracted from track axis design coordinates to determine the horizontal and vertical deviation of the track axis.

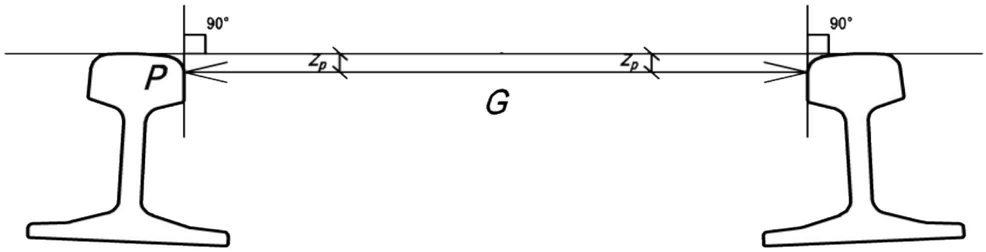

Fig. 1 Track gauge

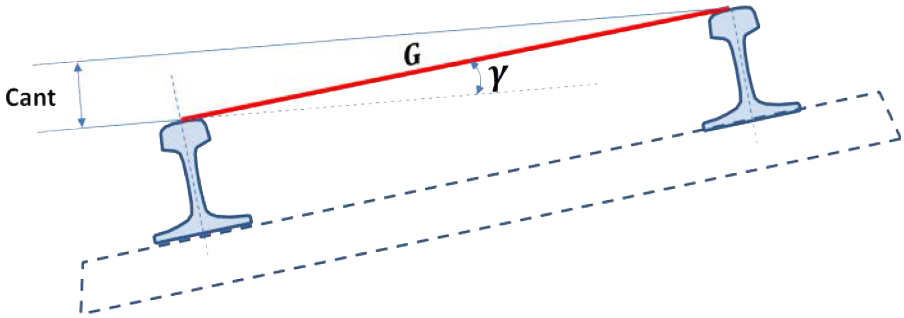

Fig. 2 Super elevation

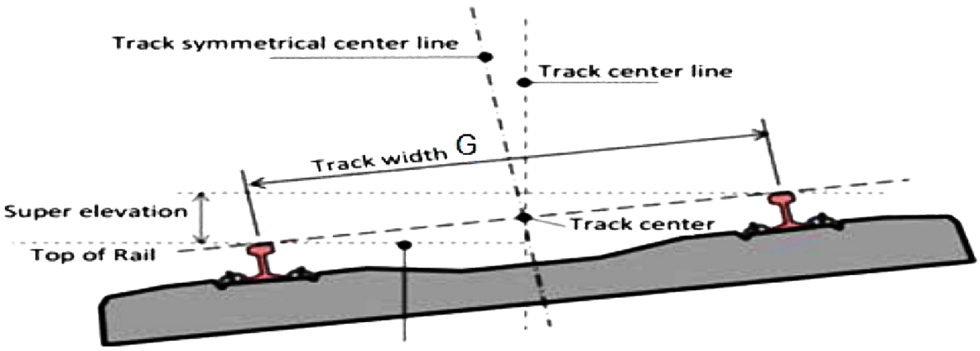

Fig. 3 Track axis

2.2 Measuring Principle of Track measuring trolley Based on AINS combined with total station

Unlike other Navigation and positioning technology, INS is an autonomous positioning system, its performance will not be corrupted in the challenging circumstances as GNSS-free environments, being independent of external signals. INS can additionally measure the attitude information. Unfortunately, INS provide position and attitude information with high relative accuracy in the shortest period. in other words, the primary drawback of the INS is the degradation of its measurement's performance over the time, consequently, a regular update are required from an externaldevice of positionningto resolve this problem.

Throughout the course of this study, we use position information provided by total station and vehicle frame velocity information provided by odometeras update information, to correct the error accumulation of the INS in order to : i) sustain its measurements performance with extremely high relative accuracy over a longerperiod, and in the other hand, ii) attach the measurements to an absolute geo-reference. (Figure 04) illustrates the measuring principle of the track measuring trolley based on AINS combined with total station.

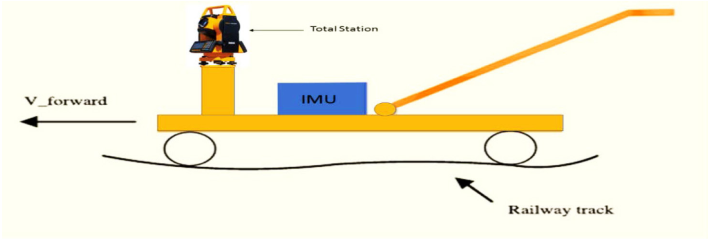

Fig. 4 Illustration of the track measuring trolley based on TS/INS system

2.3 System components (Hardware)

The Track Surveying Trolley (TST) based on aided INS used in this investigation is classified in the absolute TSTs category. The lightweight trolley conceived in a manner to i) measure both the track external geometry, namely track axis absolute position, and the track internal geometry, namely gauge, cross-level, twist, alignment, and longitudinal level, at the same time. ii) enable the track quality assessment. iii) provide the measured data with its precise localization information. The AINS trolley features a modular design for system's structure implementation as shown in (figure 05), the system incorporates several components namely track trolley platform, inertial measurement unit, absolute positioning module, gauge measuring system, odometer, sleeper recognizer and data recording system. The common basic configuration consists of the trolley platform which is the support that all sensors are mounted on, IMU, two odometers, and a gauge measuring system. The absolute positioning component ensures the absolute georeferenced for the multi-sensor data fusion. A total station is configured as absolute positioning module within this research. Event signals are recorded at the same time to label some important information, such as tagging the sleeper position. Data recording system enables the synchronization in time in a central manner, thus registration of all data provided by several sensors.

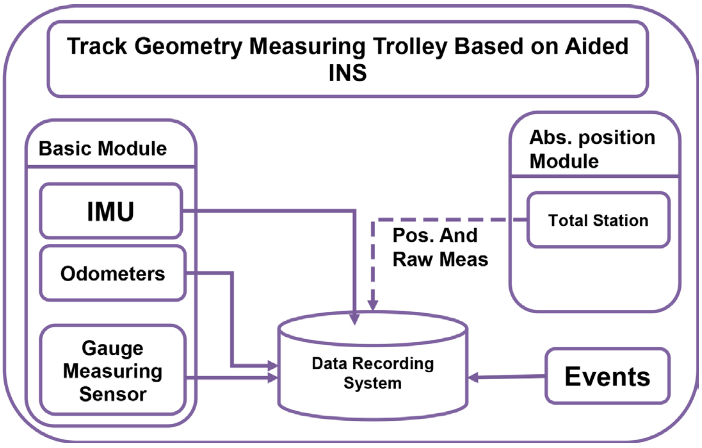

Fig. 5 Modular design of track surveying trolley based on AINS

2.4 Software environment and data workflow

In fact, there are two set of software associated with the AINS trolleynamely, InsRail and INSTrolley. InsRail is responsible for data processing, whereas INSTrolley is responsible for data collection and reporting. The relationship between INSTrolley and InsRail and the data workflow can be represented by (figure 06).

2.4.1 Data collection

Based on the measured data, INSTrolley generates a configuration file which contains all the information necessary for the data processing, such as design axis, control point, parameters and raw data path.

2.4.2 Data Processing

InsRail provides a command interface, by using a configuration file.When you clicked the data processing button on the basic menu interface of INSTrolley, the latter pass the configuration file to InsRail by a command using (CUI) Command Use Interface. So,InsRail can automatically complete the data processing, not step by step by using (GUI) Graphic Use Interface.

2.4.3 Reporting the results

When the data is fully processed, InsRail package the results in a specific file. INSTrolley knowsthe path and formats of this specific file. By reading thisspecific file, INSTrolley can reporte results to Excel.

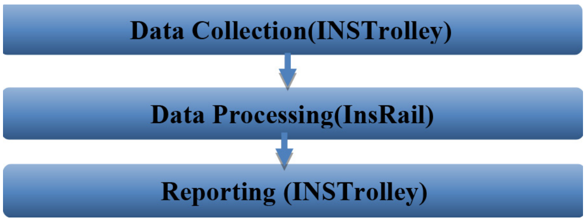

Fig. 6 Relationship between INSTrolley and InsRail and data workflow

3. Experiment and Results Analysis

3.1 Experiment description

To investigate the surveying performance and assess the accuracy of applying the track surveying trolley based on aided INS to measure the railway track geometry parameters, forward and backward measurements by the aided INS trolley had been carried out and compared with the result from an Amberg GRP1000 system. In this experiment, about 334-m-length (YDK148+486~YDK148+820) of ballastless slab trackincluding straight lines, curved and transitional segment, was surveyed by both the trolley based on aided INS and the Amberg GRP1000 trolley which is used to validate the investigated system. Field tests were conducted in October 2017 on the existing Beijing-Shanghai high-speed railway track.

The AINS trolley stopped every 120 m to free stationing to get the absolute 3D coordinates of the position in the CPIII control network, and surveyed in kinematic mode amongst every two stationing points with operating speed about 2,5 km/h. Whereas the conventional trolley Amberg GRP1000 survey in stop-and-go-mode with operating speed about 150 m/h, knowing that it stops at each sleeper about every 0.625 m to obtain the values of track gauge and cross-level, and the absolute 3D position coordinates of track axis in the control network frame CPIII. (figure 07) is a photo of the field test, which shows the entire setup.A navigation-grade IMU POS830, a Leica Nova TS50 optical tracking total station, gauge measuring sensors and 02 odometers are mounted on rigid track trolley platform.

Fig. 7 The experimental setup of the track measuring trolley based on Aided INS

3.2 Results

After treatment of the raw data in the post-processing software, InsRail, we obtain the final solution of the average between backward and forward measurements carried out by the AINS trolley is obtained in the following form as depicted in (table. 1).

Tab 1. Extract of the first five sleepers of the final solution for the average between the backward and the forward measurements by the trolley based on aided INS

N°	Mileage (m)	Track gauge (mm)	Super elevation (mm)	Hor. Dev of track axis (mm)	Ver. Dev of track axis (mm)
1	148486.515	-0.1	0.45	0.43	-3.45
2	148487.141	-0.1	0.2	1.33	-2.6
3	148487.777	-0.15	0.2	1.185	-2.555
4	148488.413	-0.15	0.25	1.515	-2.665
5	148489.048	-0.1	0.2	1.78	-2.75

The solution of the difference between backward and forward measurements carried out by the AINS trolley is obtained in the following form as depicted in (table. 2).

Tab 2. Extract of the first five sleepers of the final solution for the difference between the backward and the forward measurements by the trolley based on aided INS

N°	Mileage (m)	Track gauge (mm)	Super elevation (mm)	Hor. Dev of track axis (mm)	Ver. Dev of track axis (mm)
1	148486.515	0.2	-0.1	2.06	0.5
2	148487.141	0	0	-0.2	-0.3
3	148487.777	0.1	-0.2	-0.23	-0.15
4	148488.413	0.1	-0.1	-0.37	-0.17
5	148489.048	0.2	0	-0.3	-0.2

The solution of the measurements carried out by the Amberg GRP1000 trolley is obtained in the following form as depicted in (table. 3).

Tab 3. Extract of the first five sleepers of the final solution for the measurements by Amberg GRP1000 trolley

N°	Mileage (m)	Track gauge (mm)	Super elevation (mm)	Hor. Dev of track axis (mm)	Ver. Dev of track axis (mm)
1	148486.515	-0.1	0.3	1.6	-2.4
2	148487.141	-0.1	0.3	1.4	-2.3
3	148487.777	-0.1	0.1	1.4	-2
4	148488.413	0	0	1.4	-1.9
5	148489.048	0.1	0	1.6	-1.8

The solution of the difference of the average of backward and forward measurement by the AINS trolley and the Amberg GRP1000 measurements is obtained in the following form as depicted in (table. 4).

Tab 4. Extract of the first five sleepers of the final solution for the difference between the average of the backward and the forward measurements by the trolley based on aided INS and the Amberg GRP1000 measurements

N°	Mileage (m)	Track gauge (mm)	Super elevation (mm)	Hor. Dev of track axis (mm)	Ver. Dev of track axis (mm)
1	148486.515	0	0.15	-1.17	-1.05
2	148487.141	0	-0.1	-0.07	-0.3
3	148487.777	-0.05	0.1	-0.21	-0.56
4	148488.413	-0.15	0.25	0.11	-0.77
5	148489.048	-0.2	0.2	0.18	-0.95

3.3 Results Analysis and Discussion

In this phase, results are analyzed in two strategies to validate the proposed method and evaluate itssurveying performance. First, the results of forward and backward runs over the same railway track segment are compared to investigate their repeatability, which is an indication of reliability and the internal accuracy of the investigated method. Second, the track gauge, super-elevation, horizontal and vertical deviations of track axis identified by the proposed method based on AINS are compared with the reference result provided by the Amberg GRP1000 to investigate the external accuracy of the proposed method based on AINS.

3.3.1 Determination of inner accuracy

The railway track geometry parameters identified by the AINS trolley, i.e., track gauge, super-elevation, horizontal and vertical deviations of track axis, in forward and backward measurements should be in accord with each other if the proposed method is reliable. The minimum, maximum, mean and standard deviationsvalues related to the differences between forward and backward runs are illustrated in (table. 5) to determine the inner accuracy of the surveying system based on AINS.

Tab 5. Differences between forward and backward measurements by the trolley based on aided INS

Parameter	Min (mm)	Max (mm)	Mean (mm)	Std. Dev (mm)
Track gauge	-0.2	0.3	0.08	0.1
Super elevation	-0.2	0.2	-0.02	0.08
Hor. Dev of track axis	-0.7	2.06	-0.09	0.2
Ver. Dev of track axis	-0.53	0.5	-0.13	0.14

(Figure 08) depicts the track gauge and super elevation values identified in the forward and backward measurements over the same track section to indicate the measurement repeatability. (Figure 09) depicts the horizontal/lateral and vertical deviations of track axis identified in the forward and backward measurements over the same track section to indicate the measurement repeatability.

Both statistical comparison in (table. 5) and graphical comparisons in (figs 08 and 09) between forward and backward measurement carried out by the surveying system based on aided INS show that the measurement repeatability of track gauge and super-elevation by the trolley based on aided INS is smaller than 0.1 mm (1σ), whereas the measurement repeatability of the horizontal and vertical deviation of track axis by the AINS trolley is smaller than 0.2 mm (1σ). This indicates that the proposed method based on aided INS is reliable and its measurement repeatability meets the static accuracy requirement for railway track irregularity measurement defined in Chinese standards. Track irregularities measurement repeatability is an indicator ofthe inner accuracy of the system based on the proposed method, i.e., the inner accuracy of the surveying system based on aided INS had been achieved.

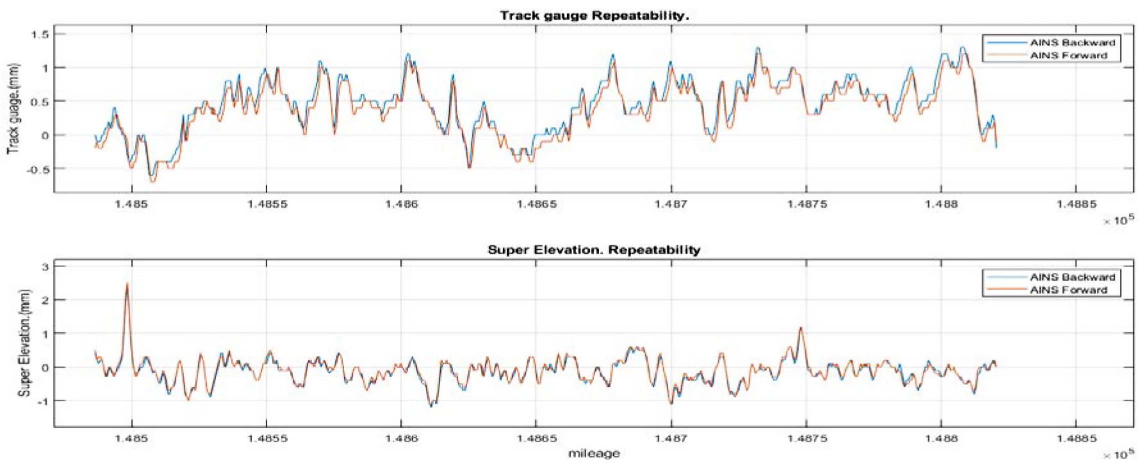

Fig. 8 Track gauge and super-elevation measurement repeatability of forward and backward measurement by the surveying system based on Aided INS

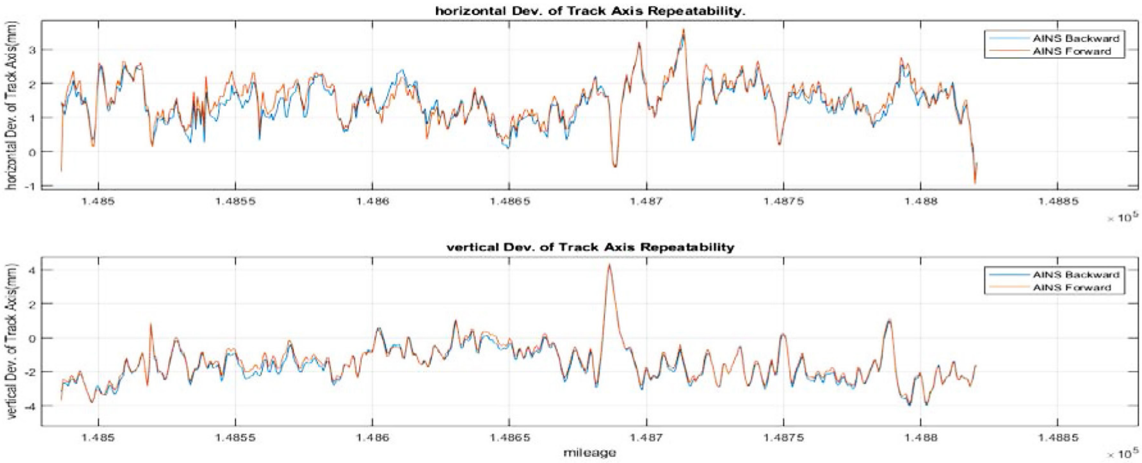

Fig. 9 Horizontal and vertical deviations of track axis measurement repeatability of forward and backward measurement of the aided INS trolley

3.3.2 Determination of outer accuracy

To determine the outer accuracy of the aided INS trolley, first, we need to calculate the average of backward and forward runs carried out by the aided INS trolley. Second, the difference between the average offorward and backward measurement carried out by surveying system based on aided INS and the Amberg GRP 1000 measurementswere calculated to determine the outer accuracy of the surveying system based on aided INS. The minimum, maximum, mean and standard deviationsvalues related to the above-indicated difference are illustrated in (table. 6).

Tab 6. Difference between the average of forward and backward measurement by surveying system based on aided INS and Amberg GRP 1000 measurement

Parameter	Min (mm)	Max (mm)	Mean (mm)	Std. Dev (mm)
Track gauge	-0.8	0.45	-0.2	0.22
Super elevation	-0.5	0.5	-0.01	0.18
Hor. Dev of track axis	-1.34	2.2	0.42	0.5
Ver. Dev of track axis	-1.85	1.52	0.005	0.69

(Figure 10) depicts the comparison of the track guage and super-elevation measurements, respectively, from the AINS trolley and the Amberg GRP 1000 trolley. (Figure 11) illustrates the comparison of the horizontal and vertical deviations of the track axis, respectively, from the AINS trolley and the Amberg GRP 1000 trolley.

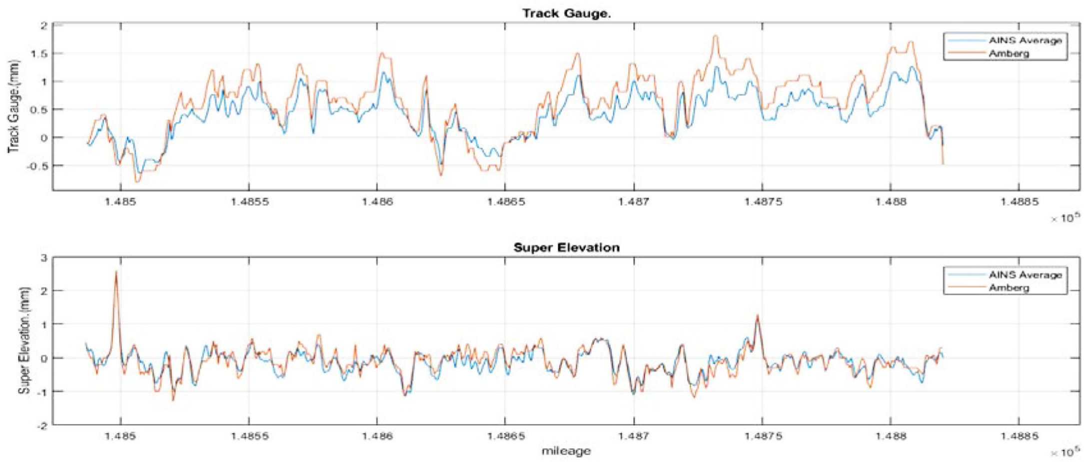

Fig. 10 Comparison of the track gauge and super-elevation measurements from the AINS trolley and the Amberg GRP 1000

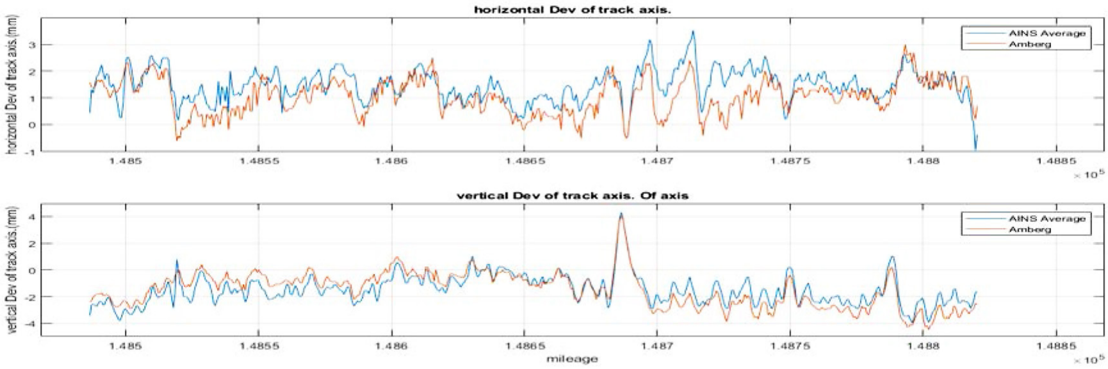

Fig. 11 Comparison of the horizontal and vertical deviations of the track axis measurements from the AINS trolley and the Amberg GRP 1000

Both Statistical Comparisons in (table. 6), and Graphical comparison in (figs 10 and 11) show that the difference between Average of Backward and Forward Measurements of AINS system and Amberg Measurements in determination of track gauge and super-elevation is smaller than 0.8 mm. Whereas the difference in determination of Horizontal and vertical deviations of track axis is smaller than 2.2 mm. In other words, it can be said that the differences are insignificant. Furthermore, the outer accuracy of the surveying system based on aided INS had been achieved. Thus, the proposed method based on aided INS is validated.

4. Conclusion

The objective of this work was to validate the method that involves the use of the new trolley based on aided INS and total station measurements instead of GNSS measurements by investigating its performance and assessing its accuracy for the railway track surveying in real tests. The investigated trolley uses the position information provided by total station and vehicle frame velocity information provided by the odometer as external auxiliary information to aid the INS and compensate their drifts.

Validation tests of railway track irregularities measurements were carried out, followed by method comparison study between the investigated trolley based on aided INS and the Amberg GRP1000 trolley, and the results obtained showed that :

1. The measurement repeatability of track gauge, super-elevation, horizontal and vertical deviation of track axis by the aided INS trolley is smaller than 0.2 mm (1σ). This indicates that the investigated method based on aided INS is reliable and its track irregularities measurement repeatability meets the static accuracy requirement for railway track irregularity measurement defined in Chinese standards, which means that the inner accuracy of the surveying system based on aided INS had been achieved.

2. The difference between the average of backward and forward measurements of the trolley based on aided INS and Amberg measurements in the determination of track gauge and super-elevation is smaller than 0.8 mm. Whereas the difference in the determination of horizontal and vertical deviations of track axis is smaller than 2.2 mm, which signify that the differences are insignificant. In other words, it can be said that the outer accuracy of the surveying system based on aided INS had been achieved.

From the two above outcomes, we can conclude that the investigated method based on aided INS trolley with total station measurements is validated.

3. The trolley based on aided INS in kinematic surveying mode can achieve sub-millimeter accuracy (0.4 mm (1σ)) in determination of track gauge and super-elevation, i.e., the relative accuracy; and millimeter accuracy (1.11 mm (1σ)) in determination of the horizontal and vertical deviation of track axis, i.e., the absolute accuracy, whereas Amberg GRP1000 in stop-and-go surveying mode can achieve sub-millimeter accuracy (0.57 mm (1σ)) in determination of track gauge and super-elevation ; and millimeter accuracy (1.32 mm (1σ)) in determination of the horizontal and vertical deviation of track axis. This indicates that both the trolley based on aided INS and the Amberg GRP 1000 meet the static accuracy requirement for railway track irregularity measurement defined in Chinese standards[8]. Furthermore, we can conclude that the trolley based on aided INS can achieve the same relative and absolute accuracies as the Amberg GRP1000, and even better in optimized surveying time (16-20 times faster).

References and Bibliography

[1] *E. Andreas, "Railway surveying-A* case study of the GRP 5000," Royal Institute of Technology (KTH), 2011.

[2] *Y. Lianbi, S. Haili, Z. Yueyin, L. N, and S. P*, "Detection of high speed railway track static regularity with laser trackers", Surv. Rev., vol. 47, no. 343, pp. 279–285, 2015.

[3] *J. Qingan, W. Wenqi, J. Mingming, and L. Yun*, "A New Filtering and smoothing algorithm for railway track surveying based on landmark and IMU/Odometer," Sensors, vol. 17, no. 6, p. 1438, 2017.

[4] *G. Ralph*, " Kinematic track surveying by means of a multi-sensor platform", ETH Zurich, 2006.

[5] *C. Qijin, N. Xiaoji, Z. Quan, and C. Yahao*, " Railway track irregularity measuring by GNSS/INS integration" ,Navigation, vol. 62, no. 1, pp. 83–93, 2015.

[6] *J. Qingan, W. Wenqi, L. Yun, and J. Mingming*, "Millimeter Scale Track Irregularity Surveying Based on ZUPT-Aided INS with Sub-Decimeter Scale Landmarks", Sensors, vol. 17, no. 9, p. 2083, 2017.

[7] *N. Xiaoji, C. Qijin, K. Jian, and L. Jingnan*, "Return of inertial surveying—Trend or illusion" ?, in Position, Location and Navigation Symposium (PLANS), 2016 IEEE/ION, 2016, pp. 165–169.

[8] *China Ministry of Railway*, "TB 10621-2009 Code for Design of High Speed Rail", China Railw. Publ. House, Beijing, China., 2009.