Cost-effective Localization of Railway Track Faults using GNSS Antenna under Train's Roof

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SUMMARY

Since 2023, the Institute of Engineering Geodesy (IIGS) and the Institute of Railway and Transportation Engineering (IEV) at the University of Stuttgart have been working together on the German Research Foundation (DFG) project ConMoRAIL (Efficient Sensor-Based Condition Monitoring Methodology for the Detection and Localization of Faults on the Railway Track). The first results of IIGS's contribution to the localization of railway track faults are the main topic of this paper.

After the project ConMoRAIL is introduced, the system requirements and setup will be introduced. Challenges regarding the GNSS (Global Navigation Satellite Systems) positioning technology will be explained. Extra permission is necessary if the GNSS antenna is placed on the top of the train. Aiming to develop a permit-free system, the GNSS antenna is placed under the train's roof.

One cover plate using the same material as the train's roof was constructed to investigate the effect of the train's roof on the GNSS measurements. In the first step, static measurements were conducted, and the results were presented and analyzed. Then, kinematic measurements were realized directly on the train. The cost-effective Inertial Measurement Unit (IMU) was also integrated into the system, and an error state Kalman Filter (ESKF) was implemented to integrate GNSS and IMU data. The results with and without integrating the IMU will be illustrated and analyzed. Finally, future work will be discussed.

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1. INTRODUCTION AND MOTIVATION

Railway systems have always played a critical role in modern society and economy. It is essential to guarantee railway transport's safety and reliability. To reduce the number of track faults and increase the railway system's performance in a modern context, the industry requires a more advanced maintenance strategy than the one currently in place (Bahamon-Blanco et al. 2019). Therefore, the early detection and precise localization of track faults, especially overlapping ones, is an important current research topic in the construction and maintenance of railways.

Nowadays, supervision of the track quality can be performed, e.g., by dedicated Track Recording Vehicles (TRV) and, to a small extent, with regularly operating vehicles equipped with specialized, high-cost sensor sets (Obrien et al. 2018). However, the number of TRVs is limited, and planned inspections are often canceled or must be postponed, which leads to the nonfulfillment of the required inspection intervals in accordance, for instance, with DB Netz AG guideline 821 in Germany (DB Netz AG, 2013).

A solution to this problem is track quality monitoring via vehicles with low-cost and compact sensor sets during regular service, making continuous measurement of large-scale railway networks possible (Weston et al. 2015). In addition to its affordability, this solution is acceptable for normal railway operations. It leads to a lower occupation of the infrastructure in comparison to TRV monitoring because the monitoring devices are mounted on regular trains (Obrien et al. 2018).

Therefore, since 2023, the Institute of Engineering Geodesy (IIGS) and the Institute of Railway and Transportation Engineering (IEV) at the University of Stuttgart have been working together on the German Research Foundation (DFG) project ConMoRAIL (Efficient Sensor-Based Condition Monitoring Methodology for the Detection and Localization of Faults on the Railway Track).

This project aims to develop a methodology for efficient detection and localization of track faults to support intelligent, condition-based maintenance planning to prevent infrastructure damage while increasing safety and reducing maintenance costs. The monitoring system should be cost-effective, board-autonomous, and permit-free (it should not require special authorization from railway regulatory authorities). It can be installed on vehicles during regular service so that continuous recording of the track condition is possible. The continuous measurements will allow for the development of methods that will be used to define the quality of the track and detect and classify railway track faults by using Machine Learning algorithms. The same measurement system will synergistically be used to localize and spatially and temporally separate the identified defects efficiently. IEV is responsible for the detection and classification of track faults, while IIGS is responsible for the localization of track faults.

Within this project, the IIGS focuses on implementing a sensor fusion algorithm using filter algorithms such as error state Kalman Filter (ESKF) and Unscented Kalman Filter (UKF). The sensor fusion is based on multi-band GNSS (Global Navigation Satellite Systems) and Inertial Measurement Unit (IMU) measurements. Another step is implementing a data model and a relational database based on available map data. This will serve as a digital track map integrated into the algorithm. This track map will be refined and updated with time schedules and maximum and average speeds. This is necessary for the reliable and accurate localization of a specific fault and for the spatial separation of overlapping faults.

The first localization steps were realized at IIGS and will be introduced in this paper. The first challenge is that the GNSS antenna, which delivers the absolute positions, should be installed under the train's roof instead of the top. If the GNSS antenna is installed on the top of the train's roof, special examination and permission are necessary for safety reasons. This means that every train equipped with this system in the future will need this special examination and permission, which is not cost-effective or practical. Therefore, after a discussion with the cooperation partner Württembergische Eisenbahn Gesellschaft (WEG), IIGS has decided to test the performance of the GNSS under the train's roof, which is very challenging for GNSS due to the obstructions and reduction of the signals.

2. SYSTEM REQUIREMENTS AND SYSTEM SETUP

2.1 System Requirement

Different types of faults can occur in railway tracks for various reasons, and they have different wavelength ranges (see Table 1, Haigermoser et al. 2015, Podwórna 2015). If the train is driving with a velocity over the tracks, a frequency will be initiated, which can be measured by the accelerometer.

Table 1: Type of defects and wavelength ranges (Haigermoser et al. 2015, Podwórna 2015)

Type of Defect	Specific Defect	Wavelength Range λ [m]
Superficial Rail Defects	Short Wavelength Corrugation	0.03 - 0.10
	Long Wavelength Corrugation	0.10 - 1.00
	Long Waves and rolling defects	1.00 - 3.00
Track Defects	Structural Defects, Track Irregularities	3.00 - 25.00
	Track Irregularities	25.00 - 70.00
Design Geometry	Track Layout	>70.00

The system must detect and identify the middle-length (wavelength is between 3 m and 70 m) track faults. These track faults are due to changes in the track substrate's physical parameters, e.g., alignment, rail joints, breakages, and local instabilities. The maximum train velocity is assumed to be 350 km/h, and the middle-length track faults can induce frequencies between 0 and 30 Hz.

Because the track faults could also overlap within one section of the track, the precise location of the track fault is critical. Therefore, localization accuracy aims to be as accurate as possible and at least under a meter. Besides, the measurement system should be cost-effective and permit-free.

2.2 System Setup

One cost-effective measurement system was set up in 2021 (before the project started) to test its feasibility (see Lerke et al. 2021). In spring 2024, a new measurement system was installed on one train (Stadler Reginal Shuttle) of WEG (see Figure 1).

Figure 1: Stadler Reginal Shuttle of WEG

The current measurement system consists of one cost-effective GNSS u-blox C102-F9R application board (C102-F9R, 2024) and two ASC7 LN IMUs (ASC IMU 7 LN, 2024), one real-time computer NI cRIO-9042 (NI cRIO-9042, 2024), and a computer for recording and the visualization of the measurement data. The self-developed LabVIEW realizes the data acquisition. The real-time computer could provide precise and reliable synchronization of the sensors, which is very important for the localization of detected track faults.

The cost-effective GNSS u-blox application board C102-F9R was used. The C102-F9R consists not only of GNSS but also of the IMU module. Additionally, it could deliver the integrated solution or the GNSS alone solution. The essential part of this application board is the ZED-F9R GNSS receiver. This multi-band GNSS receiver receives the GPS/QZSS, GLONASS, Galileo, and Beidou signals and outputs the raw data. It can receive not only RTK corrections but also PPP-RTK corrections from the PointPerfect service (C102-F9R, 2024).

Figure 2 (a) shows a GNSS antenna with a ground plate (GP) under the train's roof. GP reduces part of multipath signals from the antenna vicinity. The performance of the choke ring GP is even better (Zhang and Schwieger 2017). However, it cannot be used due to its weight and limited space under the train's roof. Figure 2 (b) shows the antenna vicinity. There is not only the roof directly above the antenna but also many metal objects, e.g., pipes and electric cables, which may be critical for the GNSS measurement. So, it is generally a very challenging antenna vicinity for GNSS measurement.

(a) (b)

Figure 2: (a) ublox ANN-MS GNSS antenna under the train's roof and (b) antenna vicinity in the train

(a) (b)

Figure 3: IMU (a) on the bogie and (b) inside the train

Two IMUs are installed on the train. Both IMUs are analog and have a 3-axis accelerometer and 3-axis gyroscope. Ideally, one IMU should be installed on the axle so that there is no signal attenuation and the acceleration can be measured directly. Because there are mechanical components between the axle and bogie as well as between the bogie and the train body to attenuate the massive acceleration, only attenuated acceleration can be measured by the IMUs on the bogie and inside the train body. The task of IEV is to model the train dynamically and primarily to determine the influence of the dynamic models on vertical acceleration (Fernández-Bobadilla and Martin 2023, Fernández-Bobadilla and Martin 2024).

However, the installation on the axle needs special permission. For the test, one IMU was installed on the bogie (see Figure 3a), and the other was installed inside the train (see Figure 3b). The main difference between the two IMUs is their measurement range (see

Table 2). The IMU on the bogie (7.025 LN.300) has a more extensive measurement range than the IMU inside the train (ASC IMU 7.002 LN.150). Due to track faults or irregularities, there could be huge accelerations, especially in the vertical direction, which could be measured on the axle very well.

Table 2: Measurement ranges of IMU

IMU	Measurement Range Acceleration	Measurement Range Rational Rate
7.025LN.300 (bogie)	± 25 [g]	± 300 [°/s]
7.002LN.150 (train)	± 2 [g]	± 150 [°/s]

Both IMUs are analog, and the sampling rate of 300 Hz is chosen. Because the maximum velocity of the WEG train is 70 km/h. The minimum resolution is about 6 cm, sufficient for detecting the middle-length track faults in this case. For a train with a maximum velocity of 350 km/h, the resolution is about 30 cm, which would be sufficient, too. The resolution is about 1/10 of the minimum wavelength (3 m). In this way, aliasing effects are avoided.

3. STATIC TEST

Because the GNSS antenna is not allowed to be installed on the train's roof, it is impossible to compare the GNSS performance directly on and under the train’s roof. To investigate the effect of the train’s roof, one cover plate using fiberglass-reinforced plastic (the same material as the train’s roof) was constructed at IIGS. Figure 4 shows this self-constructed cover plate and one GNSS antenna with GP below it.

Figure 4: Self-constructed cover plate and GNSS antenna with ground plate (GP)

The antenna plays an essential role in the performance of GNSS measurements (Takasu and Yasuda (2008)). In Zhang and Schwieger (2013), the patch antenna from the u-blox EVK-6 evaluation kits didn't show very reliable results. The u-blox ANN-MB patch antenna, which the C102-F9R application board includes, was investigated. For comparison, one Tallysman TW3972 antenna was taken. One Tallysman TW3972 antenna costs about 350 euros, which is still cost-effective. Figure 5 shows the Tallysman TW3972 antenna and the u-blox ANN-MS antenna, which were tested. Both antennas are equipped with self-constructed GP.

(a) (b)

Figure 5: (a) Tallysman TW3972 antenna and (b) u-blox ANN-MS antenna and with GP

In the first step, GNSS measurements were conducted for static objects to investigate the influence of the train's roof and the performance of the two antennas. On the University of Stuttgart campus, there are many control points. Their coordinates were precisely measured and estimated. On 8th November 2023, one point (point 4400) was occupied for the tests. One SAPOS station is only about 300 meters away from point 4400 (see Figure 6).

Figure 6: Test on static objects in Campus University of Stuttgart

Four sessions (see Table 3) were conducted on point 4400. The two antennas were measured with and without the cover plate (see Figure 4). Each session lasted about 30 minutes. The GNSS receiver received the RTK correction data from SAPOS (Germany satellite positioning service), and the U-center calculated and recorded real-time results (U-Center 2024). The RTK correction service provided by SAPOS is free and used for the test. The receiver could get RTK correction from SAPOS for each second. The integration of internal IMU solutions within the application board was turned off to investigate only the GNSS performance.

Table 3: Test Scenario

Session No. (Time)	**Antenna Type**	**Cover Plate**
1 (08:18-08:49)	Tallysman TW3920 +GP	without
2 (08:51-09:19)	Tallysman TW3920 +GP	with
3 (09:22-09:52)	u-blox ANN-MS+GP	without
4 (09:53-10:22)	u-blox ANN-MS+GP	with

Quality characteristics (e.g., accuracy, correctness, reliability) can be defined to evaluate GNSS performance (see Zhang and Schwieger 2013, Zhang and Schwieger 2017). Quality parameters can be specified to confirm the quality characteristics. The standard deviations of the baselines in the UTM coordinate system were estimated and regarded as a parameter of accuracy. The differences between the estimated and reference coordinates of point 4400 were regarded as a parameter of correctness. However, for correctness, only the east and north components were considered, because there are no antenna calibration files available for both low-cost GNSS antennas, the antenna phase centers are unknown. Antenna correction in height may be several centimeters.

Table 4 shows the accuracy and correctness of the RTK results from the U-center, and Table 5 shows the number of satellites and the PDOP of the four sessions.

Table 4: Accuracy and correctness of RTK results from u-center

Quality parameter	**Accuracy (Standard Deviation [mm])**	**Correctness (Mean of Difference [mm])**

Session No.	s∆dN	s∆dE	s∆dh	s∆d3D	m∆dN	m∆dE	m∆d2D
1	5.1	2.1	7.7	9.5	3.6	3.3	4.9
2	5.0	3.9	9.9	11.7	-5.2	5.0	7.2
3	3.7	3.6	5.4	7.5	-1.3	3.2	3.5
4	4.5	3.2	6.5	8.4	2.2	3.4	4.1

Table 5: Number of Satellites and PDOP (maximum, mean, and minimum)

Session No.	Number of Satellites			PDOP		
	min	mean	max	min	Mean	max
1	21	22.5	24	0.8	0.9	1.0
2	20	22.1	24	0.9	1.0	1.3
3	18	21.0	23	0.9	0.9	1.1
4	18	20.7	23	0.8	0.9	1.0

Generally, the accuracy is realistic. The standard deviations in the north component are slightly higher than in the east component, and the standard deviation in the height component is about a factor of 2-3 higher than in the horizontal components. In this short test (ca. 30 minutes for each session), standard deviations in 3D positions are about 1 cm, almost comparable with the geodetic GNSS receiver systems.

The 3D position standard deviation (accuracy) for the same antenna is about 1.2 factors higher if the antenna is with the cover plate than without it. The differences compared to the given coordinates of the reference point (correctness) are also greater (about 1.2-1.5 factor) if a cover plate is above the antenna. The cover plate has slightly reduced the number of available satellites and increased the PDOP. The results show that, in this test, the cover plate reduced the quality of GNSS measurement; however, not dramatically. This means that the train's roof should not reduce the quality of the GNSS measurement that much. However, it should be kept in mind that there are a lot of "reflectors" inside the train in the vicinity of the antenna (as shown in Figure 2 b).

By comparison of the accuracy of the two antennas, the accuracy of the u-blox ANN-MS antenna (sessions 3 and 4) is even better than the Tallysman TW3920 (sessions 1 and 2) in this test. Of course, the time of measurement is different. Therefore, the satellite constellations are also different. Sessions 3 and 4 have the same PDOP as sessions 1 and 2, and sessions 3 and 4 have even more satellites than sessions 1 and 2. Besides, the u-blox ANN-MS antenna is also small and lightweight. Therefore, it is taken for the measurement on the train later on.

4. FIRST RESULTS OF KINEMATIC POSITIONING OF TRAIN

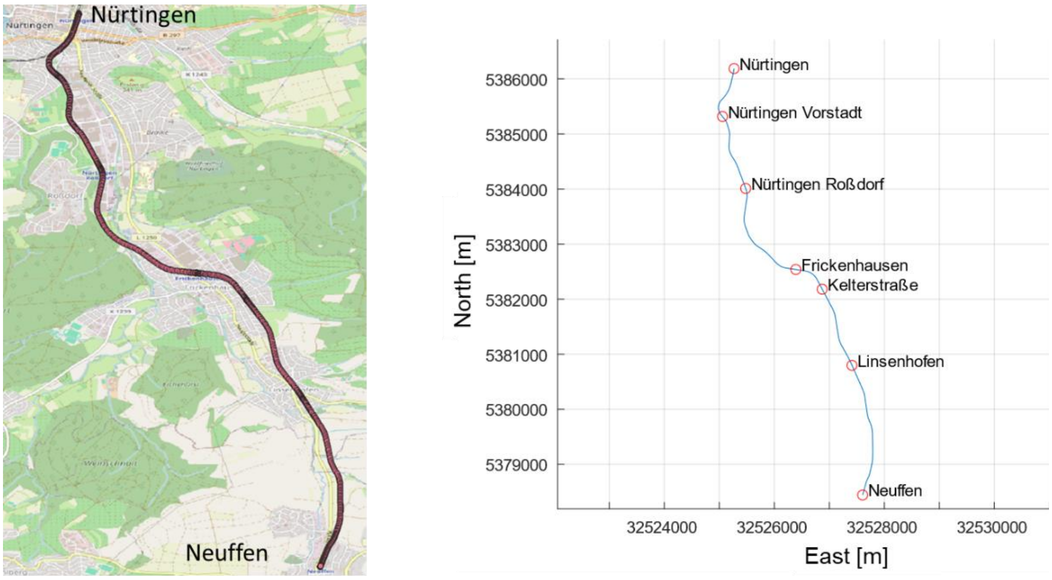

Figure 7: Overview of total trajectory between Nürtingen und Neuffen

The kinematic measurement was conducted on the WEG train Stadler Regional Shuttle (see Figure 1). This WEG train shuttles between the “Nürtingen” and "Neuffen." There are five railway stations in between (see Figure 7). The total distance is about 8.9 km, and it takes about 12 minutes for one direction. The maximum velocity of the WEG train is 70 km/h. In the vicinity of the tracks are buildings (most are not very high and have about three floors) and trees.

An ESKF was implemented to fuse the GNSS and IMU data. ESKF has been shown to estimate the bias of IMU satisfactorily (see Solà, 2017; Wachsmuth et al., 2020). The GNSS positions are the input of the ESKF along with the accumulated IMU data (from the IMU inside the train) to calculate the position and orientation of the train. This provides a significantly denser position estimation than a GNSS-only solution. The details of the ESKF will not be given in this paper.

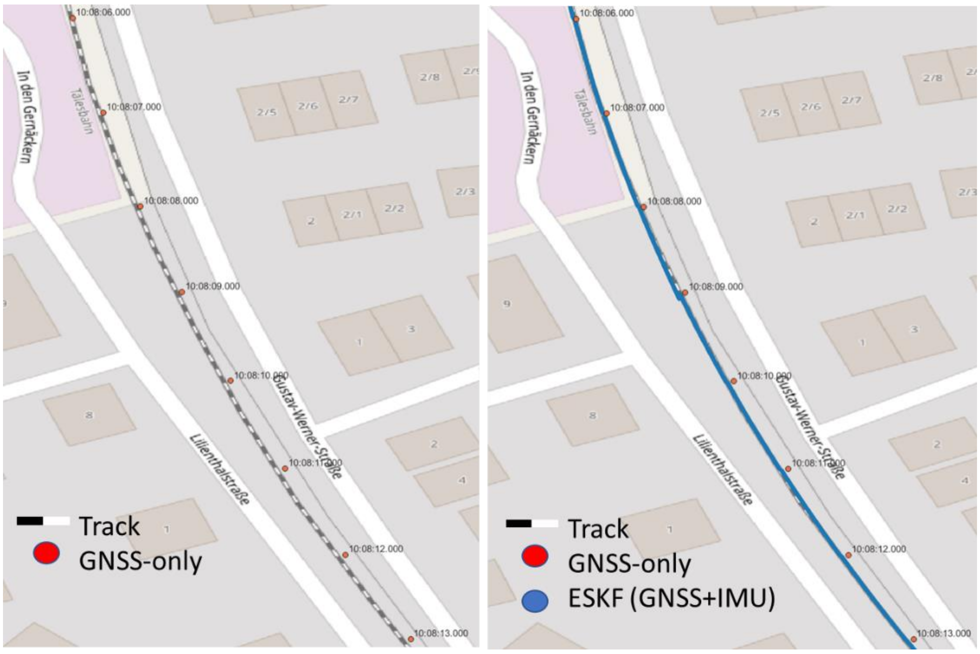

Figure 8: GNSS-only (float solutions) vs. ESKF (GNSS+ IMU) results for one track section

Even though the antenna is under the train's roof, the GNSS-only trajectory matches generally surprisingly well with the available map, which is the Open Street Map (OSM). Several times during the test, GNSS gave only float solutions, usually when SAPOS correction data was not received or due to multipath effect. Figure 8 shows several GNSS-only positions with a float solution (red dots) along one track section. The blue dots are the results from ESKF. The ESKF results (blue dots) match the underlying track in the map (black-white lines) much better. For numerical comparison, the perpendicular distances between the positions (from GNSS-only or ESKF) and the nearest segment of the map data were calculated. In this example, the GNSS has float solutions for 7 seconds, with 7 GNSS-only positions and 2100 (7 seconds·300 Hz) ESKF positions. The standard deviations of the perpendicular distances for the shown track section are calculated and presented (see Table 6). The standard deviation of the GNSS position is 0.98 m, while the standard deviation of the ESKF position is 0.17 m compared to the OSM.

Table 6: RMS of GNSS and ESKF solution

Dataset	**Standard Deviation ([m])**
GNSS-only	0.98
ESKF (GNSS+IMU)	0.17

For the other positions where the GNSS has fixed solutions, the deviations to the maps vary from several centimeters to several decimeters. The average of the deviations is about 3 to 4 decimeters. One reason is that the positioning accuracy is worse for kinematic objects than static objects. It can happen that the ambiguities were fixed to the wrong values. The other reason is that the map data is not error-free. There were many quality assessments of digital road maps at IIGS. For example, Wang et al. (2017) showed that HERE, TomTom map, and OSM have an absolute accuracy of about 2 meters and a relative accuracy of about 1 meter. The commercial map NDS (Navigation Data Standard) showed about 1.5 meters absolute accuracy and 0.6 meters relative accuracy in Zhang et al. (2019). All the assessments were regarding the digital road maps. The maps were updated, and their quality may change. Future work will investigate the quality of OSM in the test area for the tracks.

5. CONCLUSION AND OUTLOOK

In this paper, the project ConMoRAIL is introduced. This project aims to develop one cost-effective and permit-free measurement system for the detection and localization of railway track faults. For this reason, the GNSS antenna could not be installed on the top of the train and needed to be placed under the train's roof.

Comprehensive tests were conducted on the static case to investigate the influence of the train's roof on the GNSS positioning. The results show that the train's roof reduces the quality of GNSS positioning but not dramatically. The ambiguities could still be fixed.

Then, the GNSS antenna was installed under the train's roof to test the performance in a kinematic case. The GNSS-only and the ESKF (GNSS+IMU) solutions are shown. ESKF could improve the results if GNSS has a float solution. The standard deviation of lateral deviations to the available map (OSM) for the tested area is several decimeters. In the future, the quality of the map needs to be evaluated so that the accuracy of the positioning can be evaluated by using a more accurate map. The unscented Kalman Filter (UKF) will also be developed and compared with the ESKF.

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