Hybridized GNSS and IMU Positioning for Train Infrastructure Asset Health Status Monitoring within the SIA-Project

Ramin Moradi[a] and Michael Hutchinson[a]

[a] Nottingham Scientific Ltd (NSL), Nottingham, UK

Abstract

Railway infrastructure and rail vehicle maintenance costs above 20,000M€ per year at the European level. With this background, the System for vehicle-infrastructure Interaction Assets health status monitoring (SIA) is being developed to provide prognostic information about the health status of the railway's most demanding assets in terms of maintenance costs. In SIA, infrastructure and railway related events (i.e. defects in the track and catenary) are captured by a network of sensors, time-stamped and accurately positioned, from which the localized health status of the track and vehicle can be extracted. In SIA, Global Navigation Satellite Systems (GNSS) with focus on European GNSS (EGNSS) is at the core of the positioning approach. In railway environments, positioning based on GNSS technology is very challenging due to events such as signal masking, multipath and interferences. Hence, in SIA it is essential to use complementary sensors such as Inertial Measurement Unit (IMU) in combination with GNSS to improve the availability as well as accuracy of the positioning. As part of SIA, a high accuracy GNSS-IMU hybridized positioning approach tailored for railway environments is being developed. Preliminary results show that the proposed approach can overcome GNSS measurement gaps up to 10s with several metre degradation in the horizontal position accuracy.

Keywords 1

SIA, GNSS, EGNSS, GALILEO, PPP, IMU, railway

1. Introduction

Railway infrastructure and vehicle maintenance costs above 20,000M€ per year in Europe. From the infrastructure point of view, depending on the country and organization, track maintenance cost varies between 40%-70% and electrification system cost varies between 8%-20%. From the vehicle part 30% to 50% of costs are due to wheelset and 5-10% is due to pantograph maintenances [1]. This highlights the need for an advance low-cost system for railway assets health status monitoring. System for vehicle-infrastructure Interaction Assets health status monitoring (SIA) is being developed by a consortium from five different European countries to provide prognostic information about the health status of the railway's most demanding assets in terms of maintenance costs.

One of the main limitations of the currently available railway assets maintenance techniques, is that they are mainly based on sporadic inspection. Such process may miss sudden events such as wheel flats or rail squats that evolve rapidly until generating an important component failure and causing service unavailability, which results in large extra maintenance expenses. SIA will instead provide real time monitoring of key assets such as wheel, pantograph, rail and catenary and predicts their health status. Most available Railway on-board devices or infrastructure monitoring systems are sold as equipment with maintenance. In the case of SIA, the services will be sold as web-based services.

The objective of SIA is to develop four ready-to-use new services named iWheelMon, iPantMon, iRailMon and iCatMon. These services will provide prognostic information about the health status of the railway's most demanding assets in terms of maintenance costs, at the points of the interaction

ICL-GNSS 2020 WiP Proceedings, June 02–04, 2020, Tampere, Finland
EMAIL: ramin.moradi@nsl.eu.com (A. 1)

between the vehicle and the infrastructure, which includes wheelset, pantograph, rail and catenary. These four services are defined briefly below:

- iWheelMon: This provides real time information about wheel status (e.g. presence of wheel flats) and prognostic health status information within a certain time frame, as well as maintenance recommendations for meeting ISO 1005-8 and train operating companies' specific requirements.
- iPantMon: This provides real time information about the pantograph status and prognostic health status information in a certain time frame, as well as maintenance recommendations for meeting EN 50405 and train operating companies' specific requirements.
- iRailMon: This provides real time information about the rail status (e.g. broken rail) and prognostic health status information in a certain time frame, as well as maintenance recommendations according to ISO 5003:2016 and infrastructure managers' specific maintenance requirements.
- iCatMon: This provides real time information about the catenary status and prognostic health status information in a certain time frame, as well as maintenance recommendations for meeting EN50119.

In SIA, railway infrastructure and vehicle events captured by a network of sensors need to be time-stamped and accurately positioned. These are done by the SIA_POS on-board module for real-time failure localization. The positioning will be further improved in post-processing mode in the back-office. The focus of this paper is SIA_POS on-board module. GNSS has been selected as the core positioning technique in SIA. Despite the high potential of GNSS in supporting a wide range of positioning-dependent applications in the railway environment such as safety-related train control, asset management and on-board passenger information, its application in the rail industry to date has generally been limited to ad hoc cases only, typically involving mass-market receivers integrated within larger on-train systems.

In this paper, following the current introduction, the on-board positioning approach adapted for the SIA project is presented, followed by a description of the experimental data used for the feasibility study. Then the preliminary results of the positioning approach are presented. Finally, the conclusions are made, and future work is discussed.

2. SIA positioning algorithm

In this section, SIA_POS on-board module will be discussed, and the data set used for the algorithm development and feasibility study will be presented. Some preliminary results will be shown at the end.

2.1. Algorithm

GNSS-based positioning in railway environments is very challenging due to events such as signal masking, multipath and interferences. Hence, in SIA it is essential to use complementary sensors such as odometer and IMU to improve the availability as well as accuracy of the positioning. In SIA on-board positioning module, 100% position availability and horizontal positioning accuracy of better than 20m at 95% confidence level are targeted. For the most demanding parts of the railway, such requirements can be challenging. The accuracy can be improved by utilizing multi-frequency multi-constellation GNSS signals and application of precise clock and orbit corrections based on Precise Point Positioning (PPP) approach [2] [4] [5]. In this work orbit and clock corrections are obtained from CNES Analysis center. CNES provides open source multi-constellation corrections in real time, which makes them ideal for SIA. To achieve the required availability, using a multi-constellation (at least GPS plus Galileo) solution is essential. In addition, to overcome complete GNSS signal blockages in locations such as tunnels and under bridges, it is essential to unitize additional complementary sensors such as odometer and/or IMU devices to update the position during the full gaps in GNSS observations. One appropriate option in railway environments with relatively simple train dynamics is using the odometer and a single gyroscope in a dead-reckoning approach. However, accessing an odometer in a train is not straightforward due to reasons such as safety regulations. Alternatively, GNSS integration with IMU sensors can be used during the GNSS outages. Previous studies showed that a GNSS-IMU coupled solution, if low-cost IMU is used, degrades the GNSS solution during the GNSS availability and it cannot provide results during GNSS outages that are comparable with the dead-reckoning approach. This is believed to be due to the increased complexity of the GNSS-IMU integration algorithm compared to a simple dead reckoning solution [4], and the unique dynamics of a train. As the objective of SIA is to provide low-cost services, it is essential to use a low cost IMU. Therefore, a simplified GNSS-IMU integration approach in which only one accelerometer and one gyroscope will be used has been adopted for SIA. In the proposed approach it is approximated that train accelerations in the cross-track and up directions are negligible. With such approximation, a dead reckoning methodology can be adopted using along-track accelerometer measurements instead of odometer measurements. Although this is an oversimplified approach, but it is expected to deliver the required accuracy level by SIA.

A PPP solution is used as the main solution during the GNSS signal availability. The horizontal speed and heading are initialized based on PPP solution and are updated using along-track acceleration and Z axis gyro measurements, respectively (Equation 1 and 2).

$$speed_H = speed_H^- + a * dt \tag{1}$$

where $speed_H$, $speed_H^-$, a and dt represent horizontal speed at current epoch, horizontal speed at previous epoch, along-track acceleration and time step respectively.

$$heading = heading^- + gyro_z \tag{2}$$

where $heading^-$ and $gyro_z$ represent previous heading and rotation angle around the z-axis.

In on-board SIA-POS, the horizontal speed and heading will be used to propagate the PPP solution during the GNSS outages.

2.2. Experimental Data

For feasibility study and development of SIA_POS, 13 sets of dual frequency GPS and IMU measurements which were collected in a passenger train as part of work undertaken for the UK Rail Safety and Standards Board (RSSB) [4] have been used.

The GNSS and IMU data were collected by a SPAN device which contains a high grade NovAtel GNSS receiver and a high grade IMU device. The train from which the data was collected was travelling regularly through Birmingham city centre in the UK (Figure 1). In the figure, the track has been divided into different sections according to GNSS availability. They are classified as open (green), intermediate (yellow) and obstructed (red) areas. The data set durations are shown by Table 1.

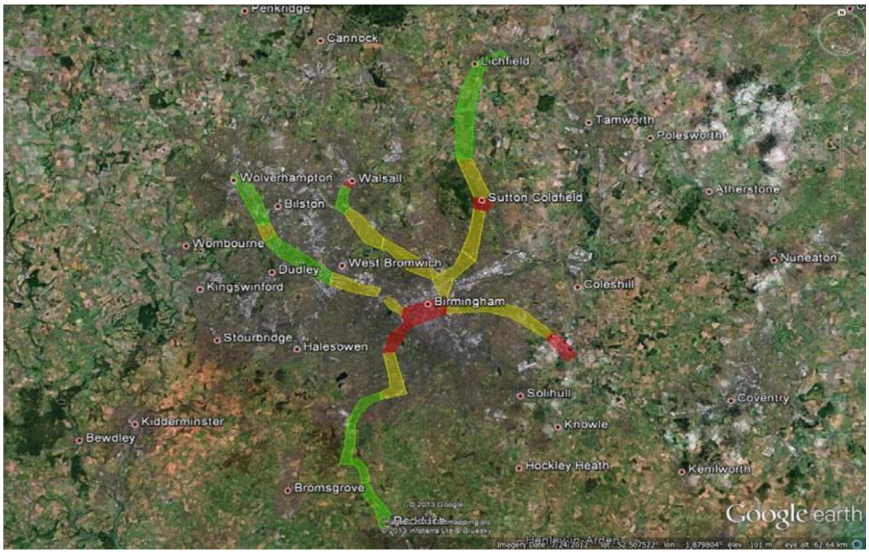

Figure 1: Track classification based on GNSS availability

Table 1
Data Set Duration

Data set	Duration [s]
1	315
2	1146
3	4195
4	1317
5	1952
6	2183
7	2068
8	1046
9	3719
10	1373
11	1254
12	4183

The main limitation of the RSSB data is a lack of Galileo measurements, due to the low availability of both Galileo-enabled equipment and the constellation itself at the time of data collection. However, it can be used for feasibility study and generation of preliminary results. A new data campaign has been planned for collection of Galileo (EGNSS) observations for further analysis and algorithm improvement.

2.3. Preliminary results

One of the main challenges of GNSS-based positioning in railway environments is signal masking and measurement discontinuities. Figure 2 shows PPP solution availability using the experimental train data. As it can be seen from the figure the solution availability can be as low as 80% in some sections of track.

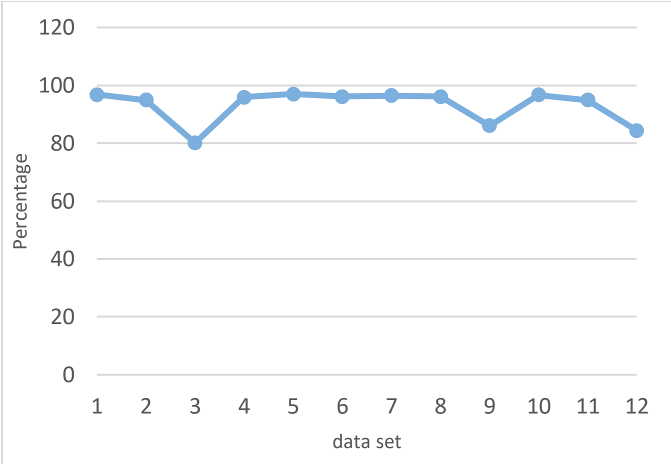

Figure 2: PPP solution availability for different data sets

To improve the availability, one can propagate PPP solutions using the PPP velocity over the measurement gaps. This approach may be good enough for short gaps in railway environments due to relatively simple train dynamics. However, with curved tracks or long measurement gaps (e.g. in tunnels) this approach may not generate the required accuracy. Alternatively, the SIA GNSS-IMU hybridized positioning approach (as discussed before) can be used. For evaluation purposes, synthetic GNSS gaps every 20s for a duration of 10s were generated in the experimental data (for each data set listed in TABLE I) and two types of solution were generated; a) PPP solution propagated over the gaps using PPP velocity, b) PPP solution propagated over the gaps using the proposed hybridized algorithm. Figure 3 compares 95% horizontal positioning errors of the two solution types.

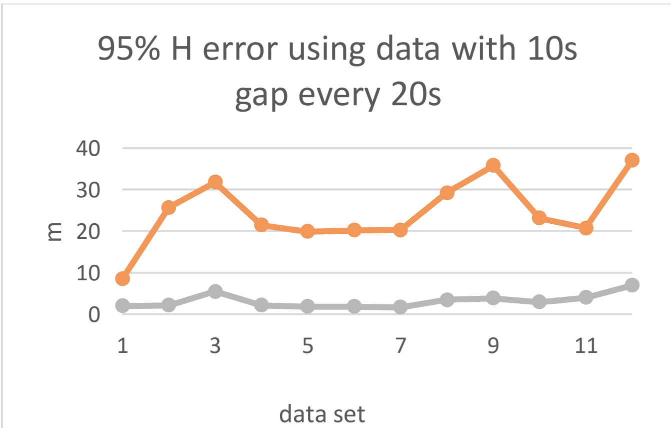

Figure 3: PPP (orange) and SIA_POS (grey) horizontal error comparison

From the figure, it is clear that the SIA_POS approach is superior over PPP solution for these data sets, even though only one accelerometer and gyroscope have been used instead of utilizing full IMU mechanization.

Figure 4 shows an example of positioning error time series for both solutions. From the figure, it can be seen that SIA_POS performs were worse than PPP solution for some cases (i.e around epoch 730). This could be either due to the bad quality of the reference solution or bad initial speed and heading calculation which are done based on PPP.

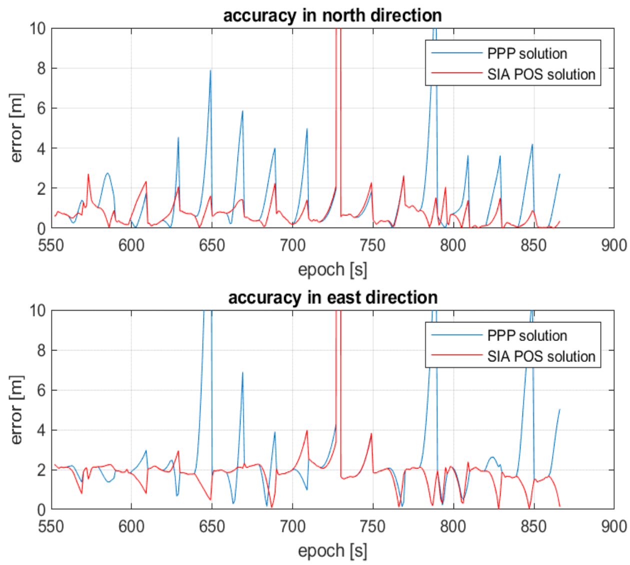

Figure 4: PPP and SIA_POS position errors for data set 1 with 10s gaps every 20s

To further analyse the performance of SIA_POS, the two solutions trajectories are compared for two curved parts of the track (Figure 5). In the figure, SIA_POS and PPP solutions are shown in purple and green colours respectively.

From the figure, it is clear that SIA_POS was able to estimate and propagate train heading relatively well even at complex track geometries with highly curved path.

Figure 5: PPP (green) and SIA_POS (SIA_POS) trajectories over two curved sections of the tracks having 10s measurement gaps every 20s.

3. Conclusion and Future Works

In this paper a new high accuracy positioning approach based on GNSS and IMU hybridization tailored for railway environments has been introduced. The technique has been tested using real GNSS and IMU data collected in a passenger train and preliminary results have been presented. The results show that the new technique, despite its simplified hybridization approach, can overcome regular GNSS observation gaps of up to 10s with minimum degradation of the accuracy during the gaps.

As part of ongoing and future work, it has been planned to collect new EGNSS and IMU data from a train in Spain. The data will be used to further improve and validate the SIA_POS module which eventually will be integrated into the SIA system.

4. Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program and from the European Global Navigation Satellite Systems Agency under grant agreement No 776402.

5. References

[1] Campos, Javier, and Gines De Rus. "Some stylized facts about high-speed rail: A review of HSR experiences around the world." Transport policy 16.1 (2009): 19-28.

[2] Cai C. "Precise Point Positioning using dual-frequency GPS and GLONASS measurements." In Masters Abstracts International 2009 Aug (Vol. 48, No. 03, p. 172).

[3] Héroux, Pierre, and Jan Kouba. "GPS precise point positioning using IGS orbit products." Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy 26.6-8 (2001): 573-578.

[4] RSSB "Data analysis for a cost effective Global Navigation Satellite System based locator with simple augmentations (T892)", October 2013.

[5] Kaplan E, Hegarty C., Understanding GPS: principles and applications, Artech house; 2005.