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Computer Simulation for Calculation of Expected Train Position at GNSS Signal Failure within a Railway Network Model

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Abstract

The article describes the use of computer simulation for assessment of a rail vehicle in the GNSS signal failure situation in a railway network model. Attention is paid to a brief overview of the existing solutions in the field of rail vehicles localization on regional lines, and to the description of a multi-layer rail network model. The article further deals with identification of rail vehicles position within a railway infrastructure model with the use of the GNSS system focusing on regional lines. The last part introduces the experiments of assessment of future position of a rail vehicle in the GNSS signal failure.

Keywords: Railway infrastructure models, railway infrastructure models, train positioning, railway traffic simulation

1. Introduction

With regard to the railway infrastructure identification of the rolling stock (train vehicle) position is one of the areas of rail transport. The current knowledge of the position enables processing of a whole range of procedures ranging from safety to providing operational information to the passengers. To successfully carry out the localization, it is necessary to design:

- relevant model of the railway network infrastructure
- appropriate technical solution of pairing the information on current location of the rolling stock with the infrastructure model.

Based on the importance and utilization rate of the lines various localization systems can then be applied with variable reliability and accuracy. Regional lines are not as important subject of interest as the main or international corridors, nevertheless in each country regional lines form a substantial part of the railway network. These lines have their specifics, including a. o. the fact that they often consist of single-track railways, have lower utilization rate, lower speed limits, but also lower requirements for control and localization systems. In 2011 the European Commission issued a white paper (Kom, 2011) defining goals and operations for the transport sector with the outlook until 2050. This white paper a. o. determines a plan of a single European transport area – Creating a competitive and resource efficient transport system. From the rail transport perspective, it concerns especially reinforcement of the rail transport on the main as well as regional lines and introducing intelligent systems using e.g. ERTMS (European Rail Traffic Management System) or GNSS (Global Navigation Satellite System). Also, with regard to this perspective, appropriate attention should be paid to regional lines.

2. State of Art

2.1. ERTMS Regional – Sweden

This system was developed in cooperation with the International Union of Railways (UIC), Swedish Transport Administration (Trafikverket) and the Bombardier company (Giuninho, 2014). ERTMS Regional is a simpler and cheaper variant of the ERTMS/ETCS L1 to L2, presenting an appropriate variant for the lines with lower traffic density. The proposed system is operated on a single-track line with the total length of 143 km with five stations and transportation density of 16 trains per day, whereas further extension to lines with the total length of 565 km is planned. The main principle consists in periodical (every 6 seconds) transmission of information on location to the radio block center (Train Control Centre) TCC, which issues running permits. The information on the rolling stock location is obtained from odometer, and more precise localization is realized by means of balises installed in stations and on tracks with fixed spacing of 5 km. The GSM-R and GSM mobile networks are used for the information transmission.

2.2. LOCOPROL – France

Another system, used in France, is the LOCOPROL technological solution (Libbrecht and Sturesson, 2005), with the abbreviation derived from the full name Low Cost Satellite based train location system for signaling and train Protection for Low density traffic railway lines. The system was developed under the direction of the ALSTOM company and other partners from Belgium, Germany, and France within a research project focused on the utilization of satellite navigation for lines with low traffic density. The LOCOPOROL system is used on a single-track regional line in the length of 35 km. The main principal again uses the Radio Block Centre (RBC), to which information on rolling stock location on the line is transmitted, and running permits are also issued by the RBC. Information on the rolling stock position is determined by means of satellite navigation (GPS, Glonass, in the future also Galileo) and odometer. More precise localization in critical spots (usually in stations and deviated tracks, or in places with radio shadow) is realized by means of the balises installed. The positioning locator is integrated directly into the on-board ECTS device and the mobile network of a public operator is used for the information transmission. The integrity of the train is controlled by the driver.

2.3. 3InSat – Italy

A system called 3InSat (Train Integrated Safety Satellite System) was developed in Italy under the auspices of the Ansaldo STS company in cooperation with other partners from abroad. The project was finalized in 2014 and the resulting system is used on a single-track regional line in Sardinia with the total length of 50 km. RCB is used here again to collect location data and issue running permits. The information on the rolling stock location is obtained from the satellite navigation (GPS EGNOS, Galielo) and odometer. The mobile network GSM, TETRA (Trans-European Trunked Radio) and satellite communication is used to transmit the information. The architecture of the solution is based on ETCS L2 (Mouna, 2013)

2.4. SATLOC – Romania

The SATLOC system was established under the auspices of UIC in cooperation with eleven organizations from six countries around the world with the support of the European Space Agency (ESA). The project focuses on the development and innovative use of GNSS to support rail traffic management within regional lines. Furthermore, the objectives of the project are focused on the design of new operational standards, software and hardware solutions and services.

Currently, the SATLOC system is operated in test mode on a single-track line in the length of 27 km. The designed and tested system meets the ETCS L2 standards (Redding, 2014).

2.5. Current situation in the Czech Republic

The infrastructure of the Czech railway network currently disposes of over nine and a half thousand kilometers of lines, which are divided into four categories (see Figure 1):

- corridor lines registered in the European railway system with the total length of 1,402 km – pink colour,
- national lines registered in the European railway system with the total length of 1,189 km – green colour,
- national lines not registered in the European railway system with the total length of 3,748 km – red colour,
- regional lines not registered in the European railway system with the total length of 3,232 km – blue colour.

Single-track lines account for approximately 7,607 km, which corresponds with approximately 80% of the total length of all lines. The regional lines as such account for over 33% of all lines (Dorazil, 2014; Kolář,2014).

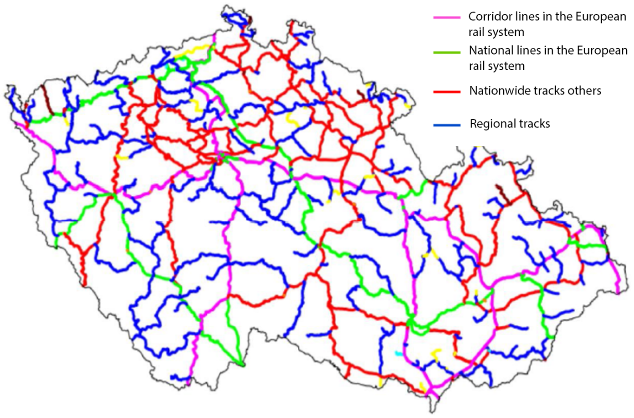

Figure 1. Line structure in the Czech Republic.

With regard to lower utilization rate, single-track lines and, especially, regional lines are perceived as less important, and this is connected with a lower level of control. On these lines it is often only possible to register that the train left the station or arrived at the station. Despite of that, hundreds of emergency situations have occurred over the last decade.

3. Localization

Generally, localisation is prone to a wide range of approaches on how to identify the position of trains on a track. Put simply, localisation may be divided into the following three groups:

- localization without the use of GNSS,
- GNSS using localization,
- GNSS-based, involving further support systems.

Our approach of trains localisation access to tracks is based on the correct pairing up of GPS information on position, provided by communication terminals, with the nearest vertex or edge of the graph (Fikejz and Kavička, 2011; Fikejz and Řezanina 2014.). The discovered vertex/hectometre post disposes not only of a multi-dimensional key in the form of a GPS coordinate, it is also linked, through definition sections, to further information concerning the railway network infrastructure.

View of the situation that the model of railway infrastructure is stored in the database Oracle we can use the native database functions and operators (Kothuri et al. 2007). The SDO_NN (nearest neighbor) operator was selected in view of realising this unique trains localisation approach. The aforementioned operator searches for a geometric object that is closest to the object entered (like a point, for example). In other words, it is possible to find the nearest vertex, or more precisely edge in a model, from the current position trains, Figure 2.

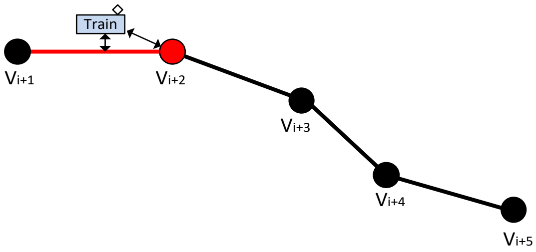

Figure 2. Main concept of localization

The actual detection of the current position of the trains can be divided into the following steps:

1. Finding the nearest vertex and edge of the graph – from the current position of the trains given the three-layer railway network model
2. Assessment of the relevancy of incoming GPS information from the communication terminal – verification whether the current position is not burdened by a disproportionate error (like, for example, that the distance of the trains from the nearest vertex/edge is a mere few meters or tens of metres, or that the trains is still assigned to the same super-edge, provided that it should still be located on it)
3. Calculation of the exact position of the trains on the edge of the model – using perpendicular projection of the point (current trains position) onto the line

The trains position data are collected from the communication terminals. These communication terminals sent position information to the central from 10 to 60 second (depends on configuration), Figure 3

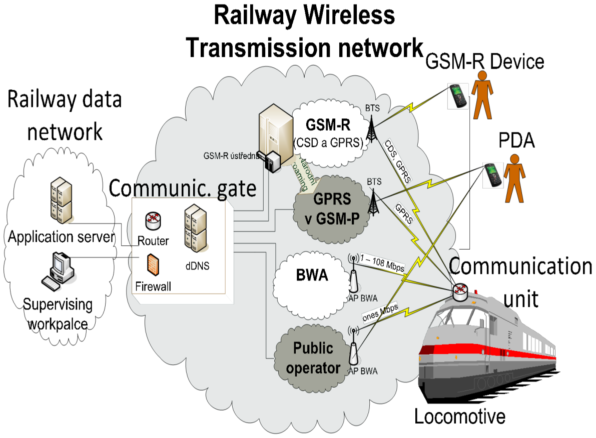

Figure 3. Communication between the rail vehicle and dispatching centre

4. Railway network model

Undirected graph, as defined graph theory, is a natural candidate for a railway network model. Based on an analysis of data provided by the company SŽDC-TUDC (consisting of service regulations, passports, and codebooks), sets of algorithms were subsequently created, with which it was possible to generate a three-layer model of the rail network (Fikejz and Kavička, 2011). Roughly speaking, the track can be divided into individual so called supertracks, which consist of definition supra-sections (TDNU), where each supra-section contains track definition sections (TUDU) with mileposts (in hectometres). Basic aspects of the description of the rail network are collectively shown in Figure 4.

Mileposts (in hectometres) are shown in Figure with the distance in kilometres and are graphically represented using gray points. TUDU is recorded using a six-digit code (163105, 163106, 16307, 173202) and are graphically represented using solid lines (red, black, orange, brown). Individual supra-sections (CLS 007, CLS008, REG023) are shown in light blue and supertracks (B421021 1 and B421021 1A) are shown in dashed lines. A place significant in terms of transportation (branch line) is symbolized by a green square.

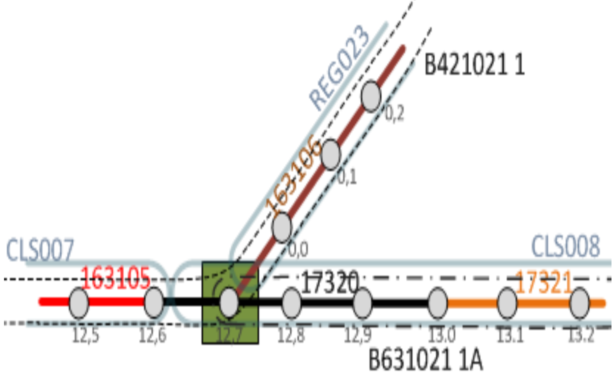

Figure 4. Basic aspects of the description of the rail network

The algorithm of railway network model (Fikejz and Kavička, 2011; Fikejz and Řezanina 2014.) was implemented directly on the database level using PL/SQL language. However, the algorithm had to be adjusted and generalized several times since there are various nonstandard conditions in the data, such as jumps in the mileposts (nonlinear growth of the kilometre succession between the mileposts) or change of an increasing kilometre sequence into a decreasing one and vice versa. The final model includes three data layers:

- **Data-Micro**, consisting of vertices and edges,
- **Data-Mezo**, include mezo-vertices and mezo-edges
- **Data-Macro**, containing super-vertices and super-edges.

Figure 5 presents the overall concept of a complete three-layer railway network model.

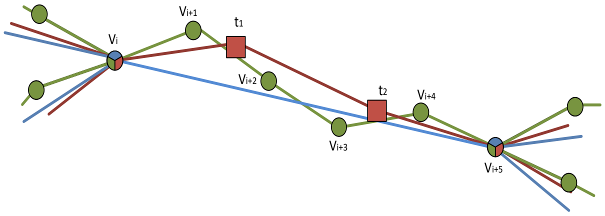

Figure 5. Illustration overall concept of a three-layer module

The data structure non-oriented graph was finally implemented directly in the ORCLE database using the ORACLE Spatial Network Data Model (Kothuri et al. 2007) technology. This technology enables the user to build a various network representation, involving also the object scheme and the communication interface API.

The objects scheme includes metadata and network tables. The interface contains on the server-side PL/SQL API (an SDO_NET packet) for the creation, control and analysis of the database network, and a middle layer Java API (on client´s side) for the network analysis. The actual network is then defined by means of two compulsory tables:

- Node table,
- Link table.

For the work with spatial data, ORACLE with Spatial technology defines a special object data type SDO_GEOMETRY, which enables its user to store a number of spatial information and geometric types, such as various points, arcs, linear chains or polygons.

5. Calculation of the expected position

When information about the current position of a rail vehicle fail or if the current position is declared invalid (see above), the new current position is extrapolated by a calculation on he basis of the historical data of the latest positions. The following factors are used for calculation of the extrapolated position:

- Vehicle speed,
- Vehicle azimuth,
- Rail azimuth.

These data are used to calculate the expected position of a rail vehicle, which can, for a limited period of time, substitute for the real vehicle position and use the localisation system in short-time or in exceptional failures of the supplied information about the current position. Computer simulation at different line sections then induced the GNSS system signal failures for the period of 60-450 seconds, while two different attitudes have been compared:

- Calculation of the new expected position without correction, Figure 7
- Calculation of the new expected position with correction, i.e. projection of the calculated position on the rail network model edge, Figure 8.

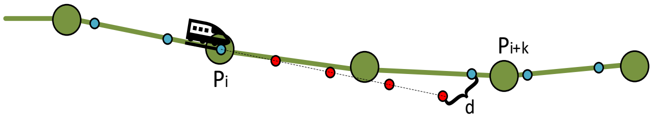

Figure 6. Calculation of expected position in the GNSS signal failure

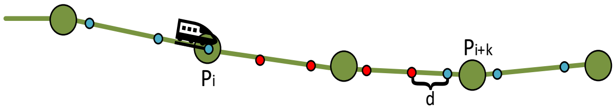

Figure 7. Calculation of expected position in the GNSS signal failure with projection of the position on the model edge

Calculation of the expected rail vehicle position is based on equation 1, 2 and 3, where distance s is calculated by means of template 1 upon the latest known speed

$$s = vt \quad (1)$$

The new expected coordinates in radians $latR_{cal}$ *and* $lonR_{cal}$ are calculated from the latest known position lat_{last} , lon_{last}) and the vehicle azimuth.

$$latR_{cal} = asin * (sin(latR_{last}) * cos(dR) + \left(sin(dR) * cos(latR_{last})\right) * \ cos(bR)) \quad (2)$$

$$lonR_{cal} = lonR_{last} + arctg \frac{sin(bR) * sin(dR) * cos(latR_{last})}{\cos(dR) - \sin(latR_{last}) * sin(latR_{fik})} \quad (3)$$

Where:

- $latR_{last} = \frac{PI}{180} * lat_{last}$
- $lonR_{last} = \frac{PI}{180} * lon_{last}$
- $dR = \frac{s}{R}$
- R = 6372.795
- $bR = \frac{PI}{180} * azimuth$

and finally, the expected coordinates can be expressed in grades by means of re-calculation $lat_{cal} = \frac{180}{PI} * latR_{cal}$ and $lon_{cal} = \frac{180}{PI} * lonR_{cal}$

After the GNSS signal is refreshed, we can calculate difference *d* of the last calculated expected rail vehicle position with the real vehicle position after the signal refreshing, for which we use equation 4.

$$= \text{acos}\ (sin(latR_{new}) * sin(latR_{cal}) + (cos(latR_{new}) * cos(latR_{cal}) * \cos\ (aR))) * R \quad (4)$$

Where:

- $latR_{new} = \frac{PI}{180} * lat_{new}$
- $lonR_{new} = \frac{PI}{180} * lon_{new}$
- $aR = \frac{PI}{180} * (lon_{cal} - lon_{new})$
- R = 6372.795

6. Experiments

Computer simulations were used, and several failure scenarios were verified for calculations of the expected rail vehicles position in a short-time GNSS signal failure. The experiments focused on the following failure periods:

- 60 seconds,
- 150 seconds,
- 300 seconds,
- 450 seconds.

Communication terminals send information about the position from the GNSS system at 30 s intervals; that is 2, 5, 10 and 15 information failures about positions at different line sections are in question.

Table 1. Distance after GNSS signal refreshing

	60 second Distance [m]	150 second Distance [m]	300 second Distance [m]	450 second Distance [m]
Min	24.71	127.48	189.66	111.15
Max	1145.55	2778.62	9110.60	12849.87
Standard deviation	300.37	655.84	2141.34	3118.50
Median	394.75	1257.04	2486.69	4506.52
Average	387.19	1108.43	2920.78	4714.93

Table 2. Distance after the GNSS signal refreshing with position projection on the model edge

	60 second Distance [m]	150 second Distance [m]	300 second Distance [m]	450 second Distance [m]
Min	14.08	51.03	103.13	233.31
Max	580.85	1687.72	7651.61	7429.06

Standard deviation	161.13	499.22	1592.21	2091.07
Median	216.96	564.95	1758.65	4188.65
Average	249.48	715.04	1989.88	3842.72

The measured data demonstrate that in the event of the calculated position with correction (i.e. with projection of the position on the model edge), the measurement results are more precise in all the monitored parameters. Especially the 60 and 150 s failures show an improvement for 45% median, or 55% median.

If we focus on the frequency of a rail vehicle distance of up to 500 m after signal refreshing, then for 60s failure it is 85% of the events and for 150 s failures it is 75% of the events. Regarding the focus of the localisation system on regional and single tracks, it seems that calculation of the expected rail vehicle position in the GNSS signal failure for tens of seconds is acceptable. The described method of the expected position substitution in rare signal failures can provide at least an approximate position of the monitored rail vehicle.

7. Conclusions

The article describes the use of computer simulation for assessment of a rail vehicle in the GNSS signal failure situation in a railway network model. Attention is paid to a brief overview of the existing solutions in the field of rail vehicles localisation on regional lines, and to the description of a multi-layer railway network model. The article further deals with identification of rail vehicles position within a railway infrastructure model with the use of the GNSS system focusing on regional lines. The last part introduces the experiments of assessment of future position of a rail vehicle in the GNSS signal failure. The experiments show that calculation of the expected rail vehicle position in the GNSS signal failure for tens of seconds is acceptable. The described method of the expected position substitution can provide, in rare events, at least an approximate position of the monitored rail vehicle.

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