Requirements for Safety Relevant Positioning Applications in Rail Traffic – a demonstrator for a train borne navigation platform called "DemoOrt"

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Abstract

The positioning of vehicles in rail traffic plays a significant role in the system safety, since the positioning information is used for the train separation and train control. The basis for giving a route to a train is the safe track-vacancy proving. This again needs an integrity check and safe train end identification on board of the train. Therefore, the generation of positioning information is a safety relevant function. Safety critical requirements arising from the criticality of the information are accuracy, reliability, integrity and availability of the positioning information that are to be demonstrated according to the new CENELEC standards EN 50126 and 50129 with the safety integrity level 3 or 4, which are the highest levels used in the area of railways.

From the operation mode of the track result further requirements, e.g. precision of positioning information of 1 to 2 metres to receive a track selective train position, or the real-time position calculation for the detection of the safe train end in the Moving Block mode.

In order to make the railway transport competitive in comparison to other transport modes cost efficiency is a necessity, both in acquisition and maintenance, but also in operation. Therefore a future oriented positioning system should operate in a vehicle autonomous mode. There are several approaches to a vehicle autonomous safety relevant positioning system using GNSS, particularly the future European system Galileo with its integrity signal and diverse systems, which use different methods of measurement and determination of the position.

The effects of multi-path propagation or complete shadowing and their relevance to the development of a safety relevant satellite based positioning system haven't been taken into account in the systems investigated so far. A significant need for research has been identified in this area.
From the stated requirements of the rail system and the characteristics of GNSS emanates the conclusion, that the position of a train can't be calculated sufficiently on the basis of satellite based positioning systems alone. Hence, further data has to be included in the calculation of positioning information.

The DLR's Institute of Transportation Systems is working on the development of a demonstrator for the train borne, self-supporting navigation for safety relevant applications in the project "DemoOrt" in cooperation with the Technical University Braunschweig, the University Karlsruhe and Bombardier Transportation – Rail Control Solutions.

The objective of the project "DemoOrt" is the integration of different navigation systems into an innovative platform, to demonstrate a self-supporting navigation of the rail vehicle. The harmonized concept, consisting of a GNSS-Receiver – nowadays GPS, in future the European system GALILEO, an eddy-current sensor and a digital map, performs the calculation of the positioning information with high accuracy, reliability, integrity and availability.

The efficiency of the platform will be tested and demonstrated in the years 2006 and 2007 on a track near Karlsruhe in Germany and a narrow gauge line in the High Tatras in Slovakia.

Introduction

In the last years, several research projects developed systems for the navigation of railways by using Global Navigation Satellite Systems. Some results were demonstrated all over Europe, e.g. SATNAB [1], LOCOPROL [8] or APOLO [3].

The Institute of Transportation Systems (IFS) of the German Aerospace Center (DLR) in Braunschweig is intensively involved in processing basic research in the field of satellite-based navigation, especially in self-sustaining vehicle navigation for safety-related applications.

The detection of railway vehicles has a high safety-relevant meaning, since the positioning information is used for the track vacancy proving and represents the basis for the release of track sections for further trains. Among the safety relevant requirements derived from this application rank accuracy, reliability, integrity and availability of the positioning information, which are to be proven in accordance to the CENELEC standards with Safety Integrity Level 4.

From the mode of operation further requirements result in each case, e.g. to obtain an accuracy of the local information of about 1 to 2 meters for track-exact detection information, or real-time near computation of the position for driving in "moving block".

While looking at the characteristics of satellite-based navigation systems (GNSS - Global Navigation Satellite System), like the US-System GPS (Global Positioning System) or the future European system Galileo, however questions with substantial meaning are not yet solved concerning the availability of the satellite signals and as a result from it the quality of the won information. This is in particular in tunnels, roofed stations or forest areas the case, since the signals are shaded by the environment and thus no signal or only insufficient signal strength arrive at the receiver.

The same applies to railways, which operate in urban areas, e.g. in urban areas where the signals are shaded by buildings or the signal running times are extended by multi-path propagation. The positioning information, which is to be received from these signals, does not correspond then to the actual position of the receiver. The deviation can show extreme drift in those areas.
The effect of multi-path propagation and/or complete shading within urban areas and their impact on the development of detection systems with safety relevance using satellite navigation were not considered and/or were not pursued so far by the examined positioning systems. The need of further research can be recognized [2].

From the positioning requirements mentioned above and the characteristics of GNSS follows, that the position of a rail vehicle cannot be determined alone by means of satellite-based systems. Therefore further positioning sensors have to be used.

Today's Systems - Technical Requirements

For the introduction of new electronic systems for safety related functions, replacing established systems, the safety integrity level of the old system has to be proven (GAMAB principle – Globalement Au Moin Aussi Bon). This means for a positioning system, that the same accuracy and quality of the signal must be reached.
Further tasks that are solved by the existing system, e.g. track vacancy proving or signalling of speed restrictions, the new navigation system has to perform in the same quality or an additional system has to be implemented.

Track vacancy proving by rail contacts

Track vacancy proving systems are the main pillars in railway operation. In former times mostly axle counters or track circuits are used. A high requirement for safe track vacancy detection is the exact knowledge of the blocked track on lines with parallel tracks. Further the position of the train in longitudinal direction has to be known in a sufficient quality for the automatic blocking of track sections.

The required position accuracy in cross direction is given by the space between the middle axles of two parallel tracks. EBO, §10 (Eisenbahn-Bau- und Betriebsordnung – German law for railway construction and operation) defines this space with 4 metres – in special situations with 3.80 metres. To obtain track-exact positioning information a accuracy of less than 1.90 metres is needed.

In longitudinal direction the accuracy of the positioning information is given by the system used today. Systems like axle counters do not register the true train front or train end. They only can detect the first and the last axle of a vehicle or train. The accuracy of the positioning information is therefore according to the design of the vehicle.

The error in the positioning information by using axel counters can reach a maximum equal to the space between the vehicle front end and the first axle or last axle and the vehicle rear end.

The following assumptions for a simplified equation for the maximum error are made:

- the outline of the vehicle is a rectangle
- the first axle is not part of a bogie

Figure 1: Calculation of the maximum overhang

The maximum error can be calculated as followed:

$$r_C^2 - (r_C - over_{inner})^2 = (d_{Axles} / 2)^2 \quad (1)$$

$$(r_C + over_{outer})^2 - (r_C - over_{inner})^2 = (d_{Axles} / 2 + d_{max})^2 \quad (2)$$

with

r_C – radius of the curve

d_{Axles} – maximum distance between two axles

$over_{outer}$ – maximum overhang at the outer side of the curve

$over_{inner}$ – maximum overhang at the inner side of the curve

d_{max} – maximum distance between first axle and vehicle front end

The axles of a vehicle have to be designed in a way that curves with a radius of 150 m with a gauge of 1.435 metres can be driven without problems (EBO, §21).
By using r_C = 150 m, $over_{outer}$ = 195 mm and $over_{inner}$ = 165 mm (see EBO, Annex 2) the maximum overhang $over_{max}$ is given to 3359 mm. The following maximum error in the positioning of the vehicle by using axle counters can be calculated to 3.3 m.

Depending on the vehicle type the outline differs. Vehicles with a merely square outline shall not exceed the calculated value of 3.3 m for the maximum overhang. If the outline of the vehicle is rounded the maximum overhang can be exceeded without problems.
To take in account that it is not known in complete, which vehicle type is detected by the axle counter or track circuit, the proceeded error should be set to 3.3 m.

A new positioning system, which will replace the existing one, must detect vehicles at least with the same accuracy as the existing system. This means, new systems should detect vehicles with an accuracy of 3 metres or less. If the system is supposed to detect vehicles track-exact, the error must be lower than 1.5 metres.

From this it follows, that new positioning systems for railways should detect the vehicles on the track with an accuracy of less than 1.5 metres in cross direction.

Track vacancy proving by transponders

Transponders used for positioning applications contain modules in track- and vehicle-side. Examples for transponders are IR-systems or systems reacting on metal masses. All these systems use antennas to provide transmission of information.
Depending on the used vehicle and transponder type the antennas can be mounted on different places at the vehicle. Because of this it can be followed, that different distances between vehicle end and antenna is realized.
This will lead to errors in the detection of the vehicles as it is shown above for the vacancy proving by axle counters or track circuits. But by using transponders the error can be much greater, because the antennas for the transponders can be mounted in the middle of the vehicle, i.e. the distance between front-end and antenna can raise up to 10 metres – the ETCS-specifications allows distances up to 12 metres.
The radiation beam can cause additional errors.

If a positioning system based on transponders will replace the existing systems, an accuracy of 5 metres in longitudinal direction will be sufficient.

ETCS – European Train Control System

ETCS requires accuracy for positioning of vehicles using balises of not more than 5 metres for the absolute position, added with a deviation of 2% of the travelled way since the last absolute position.

The accepted error for the positioning of the vehicle is much higher than system operating today can provide.

Odometer

By using odometer, relative positioning information can be generated. The accuracy of the information depends on the one side on the used odometer type, and on the other side on the reference points and the information transmission type between reference points an vehicle.

A systematic failure can occur, based on the changing diameter of the vehicle, which needs a regular recalibration of the system to minimize the errors.
In addition to the systematic failures random failures must be taken into account. Because of slip and slide of the vehicle wheels, the measured distance deviated from the covered distance. The failure mainly depends on the actual weather conditions like rain or foliage on the track.

The failures cause by drift, and slip and slide can grow with 3% of the covered distance. The absolute error of the positioning information depends on the net of reference points used and their accuracy.

Application Requirements

Standards and Regulations

The usage of the positioning information entails the requirements towards availability and reliability of the system.

For all safety-related application, the positioning information needs to meet high requirements regarding to reliability and availability. The positioning systems for railways mentioned rank among the se highly safety-related applications.

The development of safety-related systems depends on several national and international standards and regulations. Some standards and regulations applicable in Germany are listed below:

- DIN EN IEC 61508
- CENELEC standards
    - DIN EN 50126
    - DIN EN 50128
    - DIN EN 50129
- VDV-paper 161
- DIN EN 50159
- EBO

During the development of positioning systems special attention needs to be drawn to the accuracy, reliability and availability of the positioning information.

Accuracy

As mentioned above, different accuracies of positioning information can be reached by using different positioning systems.

The required accuracy is depending on the application, which is using the positioning information. In case of track vacancy proving, an accuracy of about 3 metres is fully sufficient. The needed accuracy for automatic trains in comparison is in a range of a few centimetres.

Reliability

For safety-critical applications the knowledge of the position of a vehicle is of very high importance. But not only the position, also is the confidence interval of the positioning information relevant. Hidden errors in the positioning information can lead to fatal accidents.

The possibility to identify errors in the positioning information should be taken into account by choosing a navigation system. The best way, is the usage of a combination of different systems for performing positioning information as will be explained below.

Availability

The availability is determined by the navigation process, the geography of the railway line and the process of transmitting the information. Depending on the application

- a continuous availability of the information is needed or
- the positioning information needs to be available at a certain point, time or event.

The positioning information of an axle counter is available at a special point, i.e. when the train is passing the counter. The report of an accident in combination with the location is positioning information which is triggered by a certain event.

If the transmission medium is not available or the passing of last reference point is out of range, the whole positioning information is not available.

Especially by using GNSS this problem is given when the vehicle is passing for example tunnels or roofed station. These obstacles prevent the reception of satellite signals. As at least 4 satellites are necessary for the generation of positioning information, the shadowing may cause an unavailability of the satellite-based positioning system.
Are there enough satellites available, but with a high elevation, the accuracy of the horizontal positioning information descends, because the distance between the several satellites is to low. In this case, usable information is not available.

Conditions and characteristics of navigation by using GNSS

At the moment, two different satellite navigation systems exist. At first there is the GPS provided by the USA and second the Russian system GLONASS which only has an insufficient availability. In 2009 the European system Galileo will go in service. The Galileo system will then be the only civilian GNSS available.

There are some experiences from the usage of GNSS for dynamic traffic applications:

- For several years, systems based on GPS are operated in commercial aviation. But it has to be mentioned, that in the aviation the pilot can get back the control of the aircraft in most of the situations. [9]
- In road traffic, several non-safety critical applications are using common off-the-shelf GNSS based systems. The price of these systems decreases since the demand is increased. These applications show that GNSS in combination with other positioning solutions, such as dead-reckoning, is usable for different dynamic application.
- In case of GNSS based systems for railways, an external operation is responsible for providing the information used for safety critical applications. Looking at GPS or GLONASS, the ministries of defences of the two countries are the operator. Consequently in railways both systems can be used for non-safety critical applications only.

Unlike in aviation, where no obstacles influence the reception of the satellite signals in the aircraft, several impacts on the GNSS signal can be detected. Out of a long list only a few may be mentioned here:

- partly shading by bridges, forests, slopes, buildings, etc.;
- total shading by tunnels, roofed stations, etc.;
- electromagnetically influences by overhead cables or high voltage lines;
- mirroring by buildings, slopes, bridges, etc.;
- sabotage by jamming transmitters.

All these disturbances can lead to a reduction of the signal quality and further more to inaccurate or total failing positioning by GNSS.

A train is travelling most of the time between slopes, buildings or in forests where only a small part of the sky can be seen and the signals of only a few satellites are available. A reduces signal and positioning quality is the result of such a situation. Some of these impacts can be mitigated by means of technical procedures, e.g. by special orientation of the antennas. Other ones, like full shading of the signal can not be removed technically. [2]

Digital map

Some navigational functions, e.g. determination of travelled way or actual speed can be fulfilled without using a digital map. Other like the topological positioning can not be performed without such a digital map. The digital map is a central element for safety related positioning that must not failed. The map is a single point of failure, because typical failures are made during the production of the map. Even verification or proving of plausibility can only perform low security against failures in the map.

Possible solutions

In the last years some attempts are made for solving the problems by using GNSS based positioning performing safety relevant applications. [3, 10]
All these attempts need to deal with the actual standards and regulations apply for railways. Systems for safety-related applications must be designed as a system with two parallel channels in diversity. There are two reasons for this:

- technical safety and availability can be reached and
- systematically problems with measurement processes are reconcilable.

From these requirement s coming from standards and other rulebooks follows, that a GNSS based navigation for safety critical applications can only be performed in combination with other positioning solutions. Some attempts for the development of such a system with diversity have been investigated:

- odometer;
- transponder / balises (e.g. projects like Gaderos [4] or Locoprol [8]);
- GSM;
- eddy current sensor [5];
- radar [6];
- inertial systems [7].

Even if these merely are research projects it could be seen that the required safety and availability for safe railway application can be reached with the attempt of diversity.

In a simplified version, these attempts are known in the USA for systems as “Direct Train Control” or “Dark Territory Control”. In these situations a more or less simple system called “Positive Train Separation” can operate [11]. Such a system is comparable to the German system “SatZB”.

The navigation platform ‘DemoOrt’ as a possible solution

The requirements listed above led to the development of a train borne navigation platform called ‘DemoOrt’.

Since August 2004 the Institute of Transportation Systems of the German Aerospace Center in Braunschweig / Germany has developed a positioning system for safety related applications. The project was realized together with two partners from other research institutions and one industrial partner from Germany.

The platform will guarantee the positioning of a rail vehicle with the required high precision and availability. As mentioned, GNSS can not be used alone for safe positioning. Therefore the targets of ‘DemoOrt’ will be reached by combining different navigation systems:

- GNSS for the absolute positioning
- Eddy current sensor
- Highly detailed digital map

Figure 2 shows the system design.

Figure 2: System design of the navigation platform 'DemoOrt'

The DemoOrt platform operates with two different self-sufficient positioning modules in addition to a digital map:

- The satellite receiver mounted on the roof of the train determines the position of the train with data from a satellite system. The positioning is for a start tested with GPS. Later on the European system Galileo will be used.
- The eddy current sensor underneath the train creates a magnetic field which reacts on metal structures. These reactions are transferred into a graph, with a shape, characteristic to a certain route. Since the structure of bolts and switches differs from normal tracks the graph can be read like a map. After having driven the route with the eddy current sensor once and saved the signals in a database, the exact position of the train can be determined on every following journey.
- A highly detailed digital map provides a map matching. The acquired position from the GNSS receiver and the switches detected by the eddy current sensors are compared with the data of the digital map. The result of this map matching process is positioning information with the required accuracy.

During the design phase of the DemoOrt-platform the following requirements regarding accuracy and availability have been defined:

Requirement	Quality
Position in longitudinal direction	+/- 5m, plus 2% of the travelled distance since last reference point.
Position in cross direction	Track-exact positioning without tolerance.
Identification of driving direction	The actual driving direction must be identified by the DemoOrt modules
Identification of acceleration	The actual acceleration of the vehicle must be identified by the DemoOrt modules
Identification of stand still	The actual driving status (standstill / no standstill) of the vehicle must be identified by the DemoOrt modules
Identification of actual speed	The actual vehicle speed must be identified by the DemoOrt modules. The minimum accuracy of the speed is defined by the ETCS SRS. The tolerance is: +/- 2 km/h at a speed < 30 km/h; linear increasing up to +/- 12 km/h at a speed of 500 km/h
Data provision	The data provision must be able in minimum with a frequency of 10 Hz.
Actual time	The actual time (UTC time) must be transmitted to all DemoOrt modules. The maximum tolerance of time failures is 0.1%.
Vehicle ID	Every protocol must contain the actual vehicle ID.
Initialization of the system	The DemoOrt platform must be able to perform movement detection after switching on.
Digital map	The digital map must contain all track relevant data, which are necessary for positioning the vehicle. The accuracy of the map data must be better than 20 cm. The digital map must contain a time stamp for identification the data version. The digital map must contain an identification code of the valid map area.

Table 1: Requirements of the DemoOrt platform

There are two reasons for using two positioning principles. First, the determination of the absolute train position is possible by means of the combination of accurate positioning with GPS and track bound positioning with the eddy current sensor. Second, two systems based on different information guarantee a high safety level, because they complement each other on each other. Additionally, the obtained data are compared to a map before mutually determining the exact position of the train.

DemoOrt poses a special challenge for the researchers as they are developing a completely novel system. At this, the compliance with the safety requirements is of significant importance since DemoOrt must be absolutely reliable. The positioning must work so precisely that also with several parallel tracks it is possible to identify the exact position of the train on the right track. A huge advantage of the new technology is the contact-free operation of the two positioning modules. That way, hardly any attrition influences the accuracy, which considerably reduces maintenance charges. Especially on rarely driven routes these financial benefits will be noticeable.

With the future of the European Rail System in mind DemoOrt will be compatible with ETCS (European Train Control System). If the system proves itself, new operational concepts could result from it. Visions are convoy-driving of vehicles attached virtually together with short distance in -between or running of trains in Moving Block mode.

The DemoOrt platform will go into long-time tests on two tracks. One test will be established in Germany on a tramline track near Karlsruhe. The second long-time test will take place in the High Tatras in Slovakia on a narrow gauge track.
The tests will each take a whole year, so all functions of the platform can be tested under all weather condition in a year’s time.

Summary

There are some experiences in the field of navigation of rail vehicle with different measurement processes which are collected during several research projects in the last years. All these projects show, that positioning on vehicle side can be made in principle.

To perform a positioning with the required availability, reliability and accuracy the combination of different navigation method is needed. The combination of GNSS together with track-related systems, e.g. eddy current sensors can bring a technological diversity, which is required for safety-related positioning. This combination of navigation systems will be tested on two tracks during the research project ‘DemoOrt’.

Every train borne navigation attempt needs a safe and highly detailed digital map. This map is a single point of failure in the whole positioning system. Therefore a well described standard for carrying out a safety case for digital maps needs to be developed during the nearer future.

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- Technical University of Braunschweig, Institute for Transportation Safety and Automation
- University Karlsruhe, Institute for Measurement and Control Systems
- Bombardier Transportation - Rail Control Solutions, Ulm

Abbreviations

DIN	Deutsche Industrie Norm – German Industrial Standard
DLR	Deutsches Zentrum für Luft- und Raumfahrt – German Aerospace Center
EBO	Eisenbahn Bau- und Betriebsordnung - German law for railway construction and operation
EN	Europäische Norm – European Standard

ETCS	European Train Control System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GSM	Global Standard for Mobil Communication
IR	Infrared
VDV	Verband Deutscher Verkehrsunternehmer – Association of German Traffic Companies

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