Safety Relevant Positioning Applications in Rail Traffic using the European Satellite System "Galileo"

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Summary: Die Ortung im Eisenbahnverkehr hat eine hohe sicherheitstechnische Relevanz. Eine falsch detektierte Position eines Fahrzeugs kann zu einer erheblichen Gefährdung führen, da die ermittelte Ortsinformation für die Freigabe und das Wiederbesetzen von Gleisabschnitten genutzt wird. Daraus abgeleitet, müssen Ortungssysteme bei der Zulassung unter anderem die folgenden sicherheitskritischen Anforderungen erfüllen Genauigkeit, Zuverlässigkeit, Integrität und Verfügbarkeit der Ortungsinformation, die gemäß SIL 4 nachzuweisen sind.

1 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. DemoOrt [12], 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 avail-

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ability of the satellite signals and as a result from it the quality of the gained 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.

2 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.

2.1 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

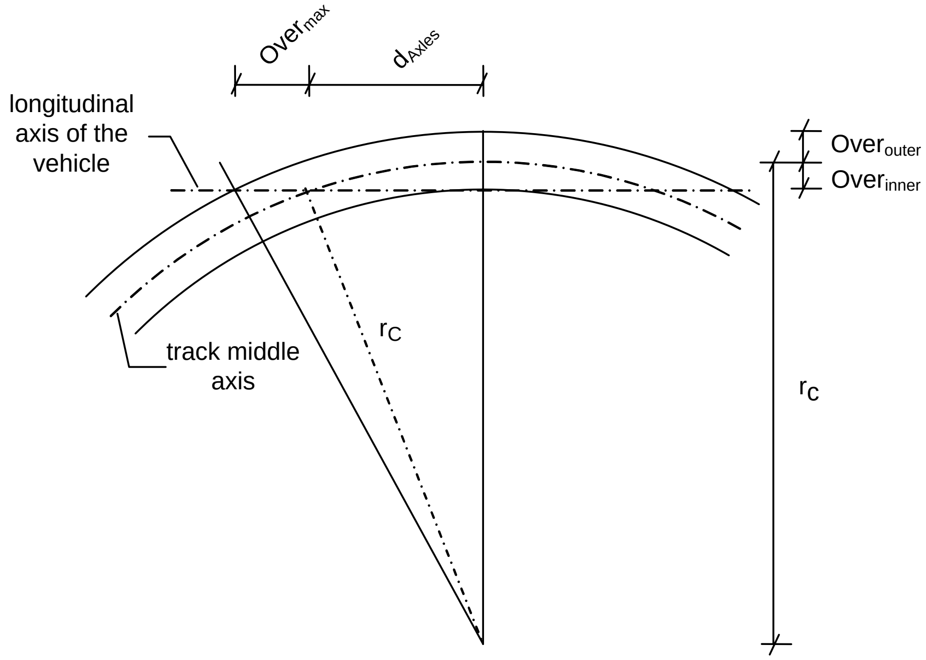

Figure 1: Calculation of the maximum overhang

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. [13]

2.2 *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.

2.3 *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.

2.4 *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.

3 Application Requirements

3.1 *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 these 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-publication 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.

3.2 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.

3.3 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.

3.4 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.

3.5 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]

3.6 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.

4 Possible solutions

In the last years some approaches are made for solving the problems by using GNSS based positioning performing safety relevant applications [3, 10]. All these approaches need to deal with the actual standards and regulations applicable for railway. 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 requirements coming from standards and rulebooks follows, that a GNSS based navigation for safety critical applications can only be performed in combination with other positioning solutions. Some approaches for the development of such a system with diversity have been investigated:

- odometer;
- transponder / balises (e.g. international 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 can be demonstrated that the required safety and availability for safe railway application can be reached with the apporach of diversity.

In a simplified version, these approaches 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 Control” can operate [11]. Such a system is comparable to the German system “Satellitengestützter Zugleitbetrieb - SatZB”.

4.1 Performance of different combinations of positioning systems

As mentioned above, a GNSS like the European system Galileo needs to be combined with other positioning systems to reach the safety level required.

The Institute of Transportation Systems will built up a GNSS based positioning platform, which can be combined with different other navigation system, to develop a platform that can be used for safety related applications.

Only a few of the systems that can be combined with the GNSS based platform will be discussed in this chapter.

4.1.1 Eddy-Current-Sensor

Eddy-Current-Sensors can perform a reliable and slip free distance measurement [5]. Based on the use of magnetic fields, inhomogeneities like rail clamps or switches can be detected.
The inhomogeneities will be shown in frequency signatures, which then must be compared with stored signatures of the line to get position information.

The eddy current sensor provides a continuous path measurement, comparable with other odometer technologies, but with a higher accuracy and without influences due to slip and slide. At irregular discrete points an absolute position can be provided by using switch detection. For this purpose databases with track signatures and a digital map are needed.

The advantage of the eddy current technology lies in the wheel independent measurement of path, velocity and special events like switches. In addition to this, the eddy current sensor is extremely robust against climatic influences. The quality of the navigation information does not decrease by snow, ice or other hard weather conditions.

The huge drawback of this system is the need of databases for the comparison of the measured electromagnetically signatures for receiving position information.

The combination of GNSS with an eddy current sensor was developed in the research project “DemoOrt”, funded by the German Ministry of Research and Education, and will be tested in 2007 on different tracks [12].

4.1.2 Inertial system

An inertial navigation system performs the measurement of orientation and position changes out of the acceleration of moved objects.

High-sensitive accelerometers in three axles register accelerations in these three directions in space. Over the time integrated they determine speed, and a further integration leads to the distance in these directions in space. Since the inertial navigation platform itself can turn, angular accelerations must be measured too.

In operation many errors influence the quality of the position information. The most important ones are gyroscope drift, scale error and balance error. They cause a square increase of the positioning error over the time. A drift of a few percentages is possible.

Inertial navigation systems combine proven and robust technology with insensitivity against weather conditions. But on the other side, inertial systems tend to high drift in the measurement of acceleration and need recalibration in short terms.

4.1.3 Radar

Microwave radars are contactless sensors for the measurement of the way and the speed above ground. For measurement two microwave lobes are radiated diagonally with a frequency by approximately 24 GHz on the ground. The waves reflecting from the underground are received, whereby the Doppler Effect is used.

Doppler Effect means that frequency shift between sent and received wave exists, which depends on the speed of the train and the angle, with which the electromagnetic field is sent relative to the ground.

The evaluation procedure determines the frequency in the intersection of the two Doppler spectra. In addition apart from the determination of the Doppler frequency the Doppler phase of an antenna is measured. From these measured values the sensor speed, the path and the sensor direction of motion can be calculated. [12]

On the one hand radar sensors take the advantage of no influences by slip and slide because of the contact less measurement. The measured signals can only be transformed in relative position information. Absolute position information cannot be performed by a radar sensor.
On the other hand a radar sensor is sensible towards rain and ice, which can deflect the signals.

Radar sensors are still in operation in railways, for example in locomotives of the 101-series of the German railway DB.

5 Conclusions

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 for safety related applications with the required availability, reliability and accuracy the combination of different positioning methods is needed. The combination of GNSS together with other train borne systems, e.g. eddy current sensors, inertial navigation system or radar, can bring a technological diversity, which is required for safety-related positioning.

Every train borne positioning approach 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 in the nearer future.

But also every positioning system has its own failures, like drift, sensitivity against climatic influences and other that have to be taken into account while developing a navigation platform.

A navigation platform for train borne positioning based on GNSS will be built up at the IFS to analyse the interaction between different positioning systems.

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