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Precise and reliable localization as a core of railway automation (Rail 4.0)

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Abstract:

High Speed Railway services have shown that Railways are a competitive and, at the same time, an environmentally friendly transport system. The next level of improvement will be a higher degree of automation, with partial or complete automatic train operation up to fully automatic unattended driverless operation to reduce energy consumption and noise, as well as improving punctuality and comfort. Based on extensive experience in separated railway systems such as Metros, VAL (Véhicule automatique léger) and subways, today's discussion focuses on the fully automatic train operation on regular railway lines. This introduces some questions that are more complex than in today's systems: the performance, length and weight of the trains spreads in a wider range; there are other and more complex operations; components such as level crossings in different equipment variants are added; requirements are higher and the technological equipment point is more heterogeneous. Many evolutionary or innovative approaches for railway automation rely on precise and reliable localization. Especially for higher levels of automation it is essential. Starting from existing technologies such as the European Train Control System (ETCS), moving on to advanced driver assistance systems for local automatic operation up to full automatic train operation (ATO), all of these solutions depend on knowledge of the position of the train on the network. Improved concepts for railway operation e.g. using moving block, on-board integrity supervision or virtual train sets will result in even higher requirements for accuracy and reliability of the localization. The contribution shows an approach based on Global Navigation Satellite Systems (GNSS) as a priority source of information used in combination with sensor data fusion. Elements such as trackside augmentation as well as the use of digital maps will be discussed. Different approaches are considered, e.g. those currently under development by projects in the innovation program in the joint undertaking Shift2Rail.

Keywords: localisation, odometry, GALILEO, train control, digital route map

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1. Introduction

The precise as well as reliable detection of the position and their safe communication play a key role for the train operation control system. In recent years, the tendency to shift more and more positioning equipment functionality for safety-critical applications from the track side to the vehicle on-board-side could be observed. Train-borne positioning systems enable a costeffective operation technology for railway lines with a low traffic density and a more flexible operation than track-side positioning systems can offer for lines with a high traffic density. For on-board positioning systems, such as satellite-based train positioning systems, the mapmatching process is of particular importance, since then the data provided by different positioning sensors, such as GALILEO receivers, Doppler radars, odometers and inertial sensors are related to a digital map of the respective railway network. This implies that the digital map is a key element in a positioning system for safety-critical applications.

2. State of the art

Train location is of main use in signalling applications. In Europe, the train position is traditionally processed with the help of equipment on tracks. The typical equipment is a track circuit, i.e. a simple electrical device used to detect the presence of a train on rail tracks. This equipment is thus not devoted to locating the train specifically but to locating it indirectly on a track portion. The location can also be determined with the help of detectors placed along the track, on which the train protection relies. These sensors can be transponders (Balises), which communicate with the train on-board equipment when the train runs over them. In order to harmonize European solutions, Europe has developed the European Train Control System (ETCS) for the signalling, control and train protection. In levels 1 and 2 of ETCS, a Balise or a group of Balises is installed on tracks to give a passing train a position reference. The Balise initializes the odometer, and the train position is computed by the odometer as a distance run since the last relevant Balise group. The system composed of a Balise and odometer computes the position of the train interfaced with the EVC (European Vital Computer) train-borne subsystem (cf. figure 1). In level 3 of ETCS, the train location shall be sent by the train itself to the ground [UNISIG SUB026]. No line side signals will be required for delivering movement authorities. All information will be exchanged between the ETCS on-board system and the Radio Block Center (RBC) trackside system through mobile networks. Two main pieces of information are communicated by the train to the RBC: its location and the confirmation that the train did not lose any wagon (train integrity). Fig. 1 shows the generic structure of the onboard train control system.

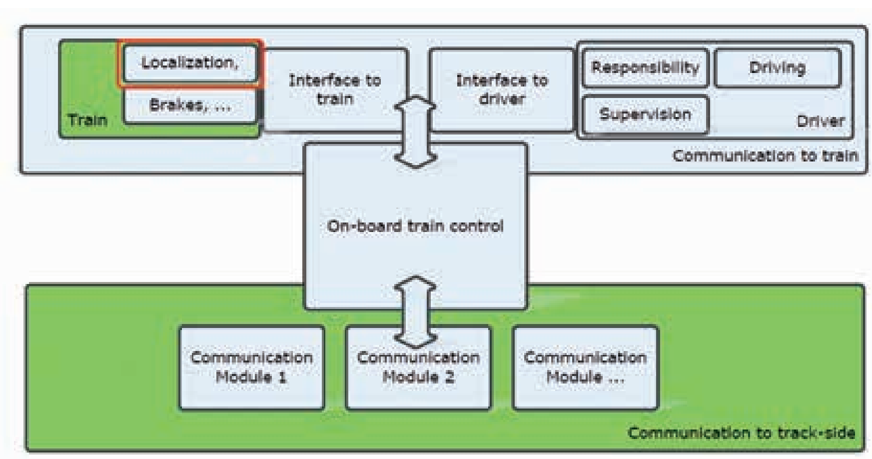

Figure 1. Overview of current setup of the localisation in the on-board train control

The last level of ETCS shall also improve line capacity by making it possible to manage circulations with moving blocks. ERTMS Level 3 will allow reducing the number of trackside equipment on the one hand, and the implementation of moving block in order to reduce the train spacing and then enhance capacity on the other hand.

Mainly driven by economic reasons and thus, acceleration of ERTMS penetration into the networks, the use of GNSS-based systems and, in particular, their introduction in signalling systems is seriously investigated today as a positioning opportunity included in ETCS and tested all around the world. In this context, GNSS is investigated to be the basis for a new embedded train locator.

The use of GNSS for low cost signalling solution and, in particular, in the highest level of ETCS (level 3) and the ERTMS Regional operation context, is an issue that has been investigated since the beginning of the 2000's [Raymond, 2004]. The concept of "virtual Balises" emerged to allow this new technology to penetrate the railway operational modes. The virtual Balises are dematerialized points, recorded in an embedded geographic database as illustrated in figure 2. These points are basically coordinates of the real (removed) physical Balises. The goal of the virtual Balise concept is to detect the position of the train when passing over the identified points by comparing the GNSS-based location of the train with the database. The train delivers then the same telegram that would have been sent with the use of the physical Balise. As such, the process could be as transparent as possible for the global system. The virtual Balise has been investigated in lots of projects since the beginning of the studies such as in RUNE [Albanese, 2004] or recently in 3InSat [Rispoli, 2013] or ERSAT [Facchinetti, 2015].

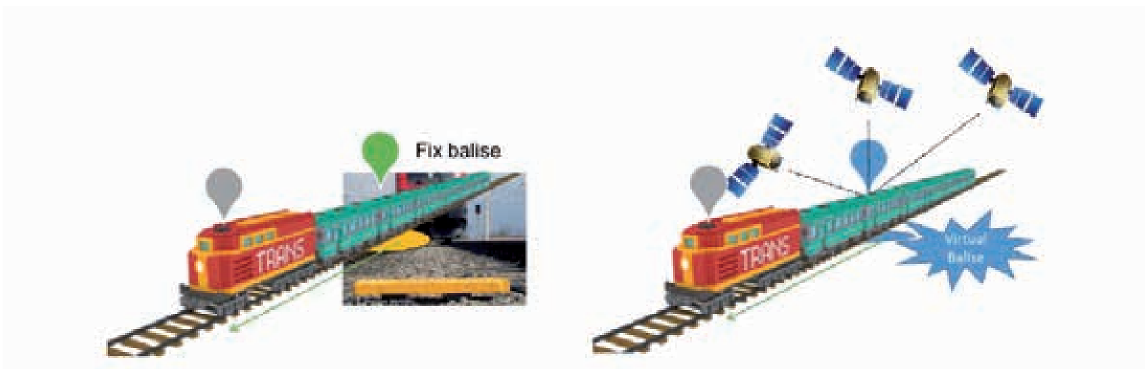

Figure 2. Virtual Balise use instead of physical trackside Balise

With several projects, the European Commission, through the successive Framework Programs, funded research in order to explore and promote the use of global navigation satellite systems for low cost signalling solutions and, in particular, in the highest level of ETCS (level 3) and the ERTMS Regional. First projects were APOLO [Filip, 2001], GADEROS [Urech 2002] and LOCOPROL [Mertens, 2003] but one can mention tens of others in the past decade until the recent Satloc [Gradinariu, 2017], GaLoROI [Manz, 2014] or 3inSat [Rispoli, 2014] projects. The concept of "virtual Balises" has been investigated in lots of projects since the beginning of the studies such as in RUNE [Albanese, 2004] or recently in 3InSat [Rispoli, 2013] or ERSAT [Facchinetti, 2015]. On-going projects are STARS [Gurnik, 2016] and Rhinos [Neri, 2016] focusing respectively on GNSS signal reception in railway environments and integrity concepts for railways. A complementary national project was DemoOrt in Germany [Meyer zu Hörste, 2009]

One European operated line embeds a light GNSS solution today. It is a single track line of 150 km length with a system developed by the University of Applied Sciences Upper Austria (FH OO) and operated by Stern & Hafferl, respective Salzburg AG. An on-board unit communicates the GNSS-based train position to the trackside train controller which is responsible for the movement authority of the train [Stadlmann; 2006]. The system is implemented in SIL2.

In April 2012, a big recognition step has occurred when the European Commission, the European Railway Agency and the European Rail Sector Associations signed together an ERTMS Memorandum of Understanding concerning the strengthening of cooperation for the management of ERTMS. It mentions in particular that GNSS can play a major role in the rail sector [ERTMS, 2012].

In the same period, new initiatives have been launched such as the NGTC project (Next Generation Train Control) that aims to study how the new developments for ERTMS/ETCS (for interoperable networks) and those for CBTC (Communication-Based Train Control) systems (for urban networks) can be mutualized. Satellite positioning is one of the NGTC focuses.

GNSS provides a means of absolute positioning with achievable accuracies at the order of metres using basic consumer-level devices to the order of centimetres based on more sophisticated solutions. It is today used in an extremely wide range of applications from smartphone navigation to network timing synchronisation in critical infrastructure to safetycritical aircraft operations. In the railways, GNSS is today widely used for applications where its use is not critical such as basic tracking and synchronisation of onboard systems. The industry is also starting to recognise the potential for using GNSS for more advanced applications, from those that are regulated and include an element of liability to train control and operations. For example, GNSS is currently used for Selective Door Opening systems which have an associated safety-criticality. Many of the more advanced applications have demanding requirements which are not straightforward to meet with GNSS due to the challenges presented by the railway environment in terms of GNSS signal availability and quality. Features such as tunnels, cuttings, trackside buildings and vegetation can block signals as well as reflect them, inducing multipath effects in GNSS receivers. There is a general consensus that GNSS must be integrated with other sensors and sources of information in order to meet the very demanding safety requirements of train control applications, which can be more demanding than in civil aviation applications. GNSS is also vulnerable to interference and spoofing threats and solutions must be identified to mitigate this.

In recent years there has been significant research and development undertaken into the Virtual Balise application. This uses an onboard GNSS-based positioning system to detect when a train passes well-defined ERTMS 'Balise' locations stored in a database onboard, enabling the odometer calibration to be performed. This allows physical Balises to be removed from the track, making savings in terms of CAPEX and OPEX (maintenance). The current focus for this application is on local and regional lines, largely since it represents an economically justifiable way of introducing ERTMS onto such lines which will improve safety and/or capacity. Other advanced developments include the mandated Positive Train Control concept in the USA, for which GNSS is an optional source of positioning, and the research into the use of GNSS for Degraded Mode Working in the UK.

3. The Role of On-Board Localisation in Future Train Control Systems

3.1 The SmartRaCon approach in Shift2Rail

The European research for Railways will be done for the next coming years mainly in the Shift2Rail Joint Undertaking. The European Union, two railways and six industry members founded the Joint Undertaking.

The Joint Undertaking Shift2Rail comprises five Innovation Programs (IP) and five Cross Cutting Activities (CCA) of railway research and development for the near future. More than 40 Technical Demonstrators will be developed in the field of rolling stock, traffic management and control systems, infrastructure, IT solutions and rail freight.

Four Partners with a strong expertise in research and development in the area of train control, communication and localisation formed the consortium “Smart Rail Control - SmartRaCon”:

- German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt – DLR), Germany
- Centro de Estudios e Investigaciones Técnicas (CEIT), San Sebastián (Gipuzkoa), Spain
- Fondation de Cooperation scientific RAILENIUM, Famars, France
- Nottingham Scientific Ltd. (NSL), Nottingham, England

The vision of SmartRaCon is to realise a fail-safe, multi-sensor onboard positioning system at minimal cost which not only provides train positioning to the ETCS kernel but also acts as an enabler for multiple areas within the area of signalling, potentially including Traffic Management, Train Integrity and Virtual Coupling. The objective of the consortium is to develop the constituents of the on-board positioning system based on multi-constellation GNSS, complemented by other positioning technologies. The activities will also include the definition of the expected performance thanks to field-testing, certification process definition and testing tools.

3.2 Concept and Approach

The overall concept is based on the need to ensure that the safety levels provided by existing signalling and control systems are not compromised in the movement towards an on-board positioning system. SmartRaCon will provide various contributions to ensure that this is achieved. This includes setting up and undertaking test campaigns, analysing the data from such campaigns, improving specifications, providing various inputs to the development of a safety case, as well as other more specific contributions which build on the positioning technology expertise within the consortium such as simulation based KPI evaluation, multiconstellation or sensor integration, etc.

Testing processes and the route to acceptance of GNSS and associated technology will be enhanced such that standardised methods are put in place in terms of the equipment used, measurements made, and analysis tools and results delivery. This includes a Route Clearance service, simulation tools for railway KPIs evaluation, Digital Route Maps (DRM) as an input to on-board positioning systems, in terms of their utilisation, distribution and management. Contributions will be made to the formation of a consolidated set of specifications, critically including methodology for testing the capabilities of common-off-the-shelf equipment against these specifications. There will be a focus on DRM technology and the Virtual Balise concept. The need for lab simulations will be identified here and it is proposed to develop a Local Environment Model as a specific task. Based on the outcomes of initial testing, solutions for performance optimisation will be proposed through in-depth knowledge in the hybridisation of GNSS with inertial sensors, odometry, dead reckoning, DRM and Wireless Communications Technology (WCT). Further specific tasks proposed are the development of a GNSS Railway Integrity Concept, input to the design of a Safety-Critical Railway GNSS Receiver, a Failure Modes and Effects Analysis (FMEA), formation of a GNSS Railway Threat Model, and demonstration of a Route Clearance service.

3.3 Expected Impact

In terms of impacts there is a target for the work to generate future business in various ways. Work will lead to an established core of safety expertise within the consortium concerning the use of on-board positioning technology for railway applications and this will be important as the technology grows and improves. There is an ambition to develop a Route Clearance service model for use in safely introducing the technology to specific new lines and for new applications. The partners will also gain a holding in the supply chain(s) involved in developing and certifying dedicated hardware, algorithms and the infrastructure required to deliver the services e.g. local integrity monitoring stations.

1. Improved services and customer quality: the use of enhanced communication technologies will derive in the following outcomes: trains will be managed more efficiently providing improved reliability, enhanced capacity of the lines and providing communication capabilities for real-time data transmission for improved passenger information, offering a better customer experience.
2. Reduced system costs: the design and implementation of the on-board gateway will be based on mass-market technologies and open interfaces, which will enable flexible architectures and application of engineering standards, allowing a correct system design adapted to the requirements of different market segments.
3. Enhanced interoperability: remaining technical “open points” related to electromagnetic compatibility will be closed.
4. Simplified business processes as modular architectures are introduced to divide the validation effort and improve standardization. The interface from the core system to the new technologies to be incorporated to the gateway will be defined as a seamless continuous upgrade possibility.

3.4 Implementation

Regarding the on-board positioning, the priority tasks are:

- to contribute to the test set-up, data collection and analysis according to specifications,
- to assist with further development of those specifications, • to provide input to the safety case,
- to build a DRM prototype.

SmartRaCon expect the contribution to data collection/test campaigns to be part of a wider effort including founder members to analyse and validate positioning system performance, throughout the various stages of the testing outlined in the Scoping Paper. The same may be said regarding progression of the specifications output from the NGTC project. The specific tasks proposed to contribute to the safety case will be led by SmartRaCon but will in certain aspects require input and cooperation with founder members. Other proposed tasks are seen as generally internal to the consortium requiring a low level of interaction with the founder members in order to set requirements and gain feedback on results. This is the case for example with the proposed Route Clearance service. In all cases a close level of cooperation with the founder members is important in order to take into account the specific characteristics of the proposed positioning system solution.

3.5 Integrated Assessment

A technology and impact evaluation is an essential element within the Shift2Rail Joint Undertaking in order to show the effect that this initiative will have on its key target KPIs: to double the capacity and availability and to reduce the costs of the railway system by 50%. The Shift2Rail Project “IMPACT-1” is producing a comprehensive bottom-up KPI model with the aim to show the interdependencies between the technological or procedural developments and the high level KPIs of the railway system. The overall objective is to prove the achievement of the objectives of Shift2Rail by determining to which extend the aims of reducing costs and improving availability and capacity will be reached. In a first step, these interdependencies will be analysed as cause-and-effect chains in order to obtain a qualitative model. Subsequently, the qualitative relations will be replaced by mathematical and logical descriptions. This is necessary in order to apply the model to data of the different market segments like high speed, regional, urban / suburban and freight rail. The analysis of the interdependencies as well as the application of the model is done in close collaboration between industry, infrastructure managers, railway operators and scientific institutions. Thus a KPI model will be generated which covers all aspects of the entire railway system. The presentation will cover the approach that has been chosen to develop the qualitative and quantitative model, share the experience made during this process and show the first results of the impact assessment of the Joint Undertaking Shift2Rail.

4. Impact on the Competitiveness of the European railway systems

The introduction of GNSS in the rail domain is now recognized as a powerful tool for ERTMS deployment, old system renewal. A study performed by Bocconi University for the ERSAT EAV projects shows that GNSS-based ERTMS proves to be especially convenient because of relevant savings in operating expenses: -67% each year compared to the traditional ERTMS [Galileo Services, 2016]. Moreover, the cost/benefit ratio will be maximized if satcoms are integrated in the global system.

This introduction is supported both by the GNSS domain through the GSA that identified rail as a real future market (figure 7), and by the railway sector in order to facilitate ERTMS diffusion, reduce costs and enhance safety on local and regional lines. As shown on figures 7 and 8, if asset management applications are currently driving shipments of GNSS devices, safetyrelevant applications (signalling and train control) based on GNSS will be increasingly developed in the next 15 years.

First application is through the Virtual Balise Concept in ERTMS L2 or 3 but next steps to be prepared are also Moving block operation and automatic train operation.

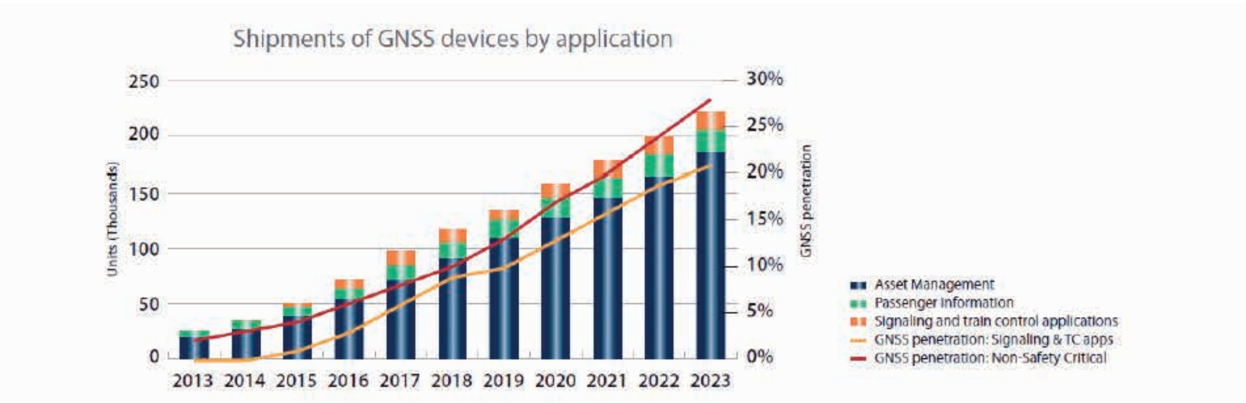

Figure 3. Future market evolution in rail applications

The NGTC project, that gathered together the main industries involved in ETCS and CBTC, consolidated the use of GNSS in the Virtual Balise concept and has developed and validated Generic Moving Block principles applicable to different railway types. Designed as a lighthouse project for Shift2Rail IP2, the outputs of NGTC regarding the analyses of the Satellite Positioning Signal Receiver Parameters that are relevant for the signalling applications and the process of their qualification and validation and, Initial Safety Analyses in regards to use of satellite positioning in ERTMS, will be major inputs for several Shift2Rail projects.

5. Conclusions and Perspective

Safe on-Board localisation is – besides reliable and safe communication – one of the key elements of future train control systems. Four partners from the science and innovation sector have founded the consortium SmartRaCon to perform research and innovation activities in the context of the European Joint Undertaking Shift2Rail. The aim is to develop and demonstrate technologies for safety-critical positioning applications in the railway sector where it is mandatory to guarantee a high safety and reliability the positioning result.

Several Shift2Rail projects will start in the next years to develop the technologies which will be demonstrated to show the results of the innovation. The aim of these projects is to demonstrate innovative onboard localisation technologies for future train control systems.

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