A Backup System Based on a Decentralized Positioning System for Managing the Railway Traffic in Emergency Situations

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***Abstract*—Railway traffic management is performed in an automatic way using centralized systems based on wired sensors and electronic elements fixed on the tracks. In spite of these systems, called Centralized Traffic Control systems (CTC), are robust and highly available, when they fail the traffic management must be done manually, increasing the probability of accidents due to the occurrence of human errors. We present a backup system for managing the railway traffic in emergency situations in which primary CTC systems do not work properly. The most innovative issue is that it is based on a decentralized positioning system in which each train is responsible of calculating its own position using an on board system based on wireless positioning technologies (GPS) and other on board devices and information sources (such as MEMS gyroscope, maps, ATP, odometer, etc.). Moreover, it combines train-side systems and terrestrial applications that exchange information via a hybrid mobile and radio wireless communications architecture. The system developed, a decentralized backup traffic management system, is the result of the work made during the last four years in collaboration with a railway company of Spain. This system is currently on real deployment phase.**

I. Introduction

Security in railway industry is a critical issue. Intelligent Transportation Systems are becoming a very valuable way to fulfill these critical security requirements. In fact, today, rail traffic management is performed automatically using Centralized Traffic Control systems (CTC) [1]. These systems are based on sensors and different elements fixed on the tracks. They allow real-time traffic management: (a) location of trains, (b) states of the signals, (c) status of level crossings and (d) orientation of the needles. Most of the infrastructure management entities have a CTC that handles centralized all these issues. The applications and systems that handle these tasks are very robust and have a performance index near 100%. Problems occur when these systems fail. In those situations, traffic management has to be performed manually and through voice communications between traffic operators and railway drivers [2].

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The work presented in this paper is the result of the work made during the last four years alongside a regional railway company of Spain. It defines a support system to assist traffic operators in emergency situations in which CTC systems fail. The main objective of the new system is to reduce human error caused by the situations in which priority systems do not work properly.

The paper is organized into the following sections: the second section includes a brief description of the main functionality requirements of the new system developed. The third section details the architectural and design issues of the work done. The fourth section presents the results of the validation tests made. To close, the fifth section of the paper establishes the main conclusions of this work, as well as, the following steps to deploy the new system in a real scenario.

II. Functional Requirements

CTC traditional systems are centralized and rely on wired communications. When CTC system or communications fail, no one knows the location of trains, thus increasing the chances of an accident. In these situations, the railway companies put into operation its security procedures that transfer the responsibility of traffic management to traffic operators, who are people that monitor traffic in the terrestrial control centers. These people should manage the traffic manually communicating through analog radio systems to the drivers of the trains. As people get nervous in emergency situations and that leads to mistakes, the new system aims to reduce these errors by creating a new tool to help traffic operators in emergency situations. This new tool must be based on different technologies to those used by traditional CTC systems so that failure in the former does not cause failure in the latter.

Taking into account these motivations and requirements, we have developed a *Backup Traffic Management System* (henceforth BTMS). This system will assist traffic operators when the primary system fails. The main functions of this new system are:

- *Traffic situation representation for the track stretches where the main system do not provide information.* The new application represents the affected line stretches situation (train locations, track section occupation states, etc.) from information received from train-side systems through real-time wireless ‘train-to-earth’ communications (see Fig. 1).

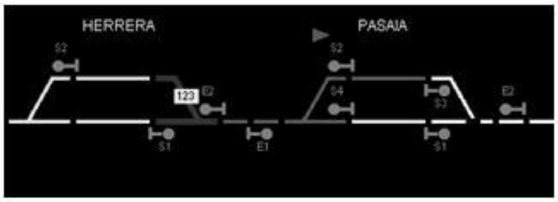

Fig. 1. Traffic situation representation.

- *Traffic management environment.* The objective is to provide a traffic assistance application in order to assist operators in tasks related to traffic control when the main system fails partial or totally.
- *Statistical analysis.* About aspects related to the system performance and reliability.
- *Control message sending from control centre to trains.* This functionality will allow traffic operators to send messages to the train drivers in order to manage and control the traffic.

The BTMS provides a traffic assistance application that works independently of the main CTC System. Thus, the new system is based on an application that informs about the position of the trains on track and permits to make tasks related to traffic management and control in an easier way. Moreover, this system permits a new way of communication between the traffic operators and trains drivers: exchanging control messages.

It is important to point out that even if the main system is working without failure, our backup system stores train position information received from the boarded system, and analyzes the coherence between the information provided by this new system and the information provided by the primary system. This analysis is important to guarantee the reliability of the BTMS. Furthermore, all the stored information could be used for other external applications.

III. Architectural and Design Issues

In this section, we describe the most important technical considerations about the developed system. The main aspects are related to (1) trains positioning, (2) wireless 'train-to-earth' communications and (3) added value services. These three issues are described below.

A. *Train Positioning System*

The BTMS permits a new way of train positioning which works independently of the main system operation. This system receives and stores positioning information generated by the hardware (accelerometers, gyroscope, odometer, etc.) and GPS modules boarded on the trains. Besides, the BTMS communicates with an external positioning information system which permits the reception of train positioning information generated by the main CTC system.

Therefore, in order to calculate new on boarded positioning information and check its reliability, the BTMS is based on a mixed train positioning architecture:

- *Centralized architecture.* In this case, BTMS receives raw data from all the trains (generated by the primary CTC system) and calculates itself the position of each train. In this architecture on board systems don't know what their position is.
- *Distributed architecture.* In this modality, each train is responsible of calculating its position using on boarded positioning system. It makes possible to develop new on board applications based on position.

It is known that on board systems have some performance limitations due to temperature and vibration conditions inside of the train. Moving the positioning algorithms into a centralized system avoids this problem. But at the same time some important capacities are lost. For example to exchange control message related with position or the development of other on board application based on positioning. Hence, it is interesting to publish as well position information from the on board systems. Consequently it is very appropriate the adoption of a mixed architecture as the one proposed in Fig. 2, where a distributed positioning is considered.

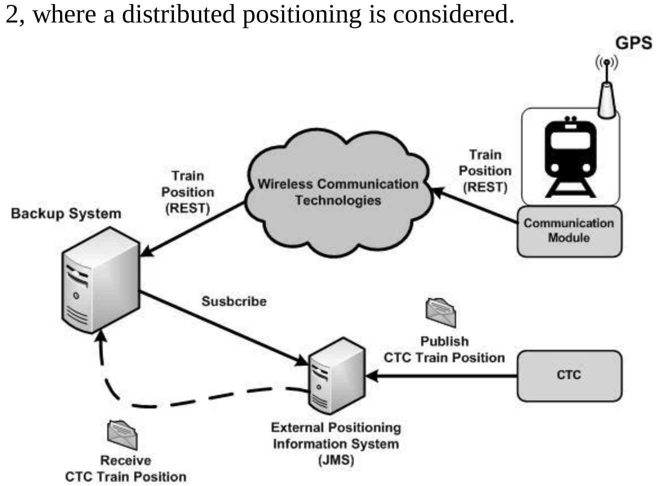

Fig. 2. Train positioning data reception in the BTMS, using a mixed distributed and centralized architecture.

1) *On Board Positioning System*

In order to enable a new way of train positioning generation and management, the presented system aims to board a new hardware/software module on each train (see Fig. 3). This system is based on GPS data and it is able to generate train positioning information applying a logical approximation algorithm for matching railway lines and GPS coordinates [3]. Then this positioning information is sent to the control center in real-time, so that the backup application can represent the train location in a synoptic.

To generate the most accurate positioning information, this system parts from a railway lines different tabulation ways. In this case, the tabulation is related to lines lengths (in kilometers) and the traffic signals positions. Based on this information, and the data extracted from the hardware and software modules boarded on trains (including GPS), this system translates this information to kilometric points. A *kilometric point* is a metric used by the railway company to tabulate the lines where its trains circulate. So, it can be said that this system is capable of translating GPS positions to kilometric points tabulated by the railway company.

Fig. 3. On board hardware used to generate train positioning information by combining different on board positioning information sources (such as MEMS gyroscope, maps, ATP, odometer) and applying a logical approximation algorithm for matching railway lines and GPS coordinates.

For this purpose, it is necessary to implement a correct positioning algorithm to make the whole system reliable, and as it will be shown, this is not a trivial task. Nowadays, GPS is a good and low cost solution because of its reliability in railway environments [4]. But due to GPS inherent error (multipath, ionospheric propagation…), GPS only based systems have not enough accuracy. The reason is that besides the position of trains, it is also necessary to know the exact track each train takes. This is especially complex because the GPS positioning accuracy is around three meters, and the tracks are separated by less than 2 meters. Thus, in railway lines with more than one track it is not possible to determine which the circulation track is. Therefore, more sources are needed in order to allow the detection of track changes.

Inertial Navigation Systems (INS) with three orthogonal lineal accelerometers and gyroscopes could work [5]. Integrating GPS and INS based on Kalman Filtering [6] or Artificial Neuronal Networks [7] it is possible to obtain centimetrical accuracy like in other environments as for example Unmanned Aircrafts [8], Naval [9] or Military [10]. However, the use of an INS in this system makes the solution become very expensive even using Microelectromechanical Sensors [11].

It is important to achieve a compromise between accuracy and low cost. The problematic of track selection could be solved using a simple MEMS gyroscope. To improve GPS and MEMS based map matching algorithms [12] [13] it is very useful to use train information systems. Using different position information sources it is possible to add a quality parameter to the position information. This is very useful to know how reliable the calculated position is. The different position information sources used in our system are:

- *GPS coordinates.* It provides absolute position data. The GPS chip is in the on board hardware.
- *MEMS gyroscope.* It provides angular speed. It is also integrated in the on board hardware.
- *Maps.* They are organized as in [12] [13] and [3] with coordinates information. Into the rail special data switchyard information is included. This makes train's track selection based on gyroscope data possible. All the map data is stored on the on boarded equipment (HMI) to make a distributed positioning.
- *Automatic Train Protection (ATP) data*. They are an additional part of signaling systems. There are different kinds of ATPs, but all of them need beacons located in the infrastructure. These beacons provide a unique id and are used to correct possible gyroscope based track detection mistakes. Relation between track and beacon id is also stored into the rail special data.
- *Odometer.* It provides relative position data. It is a covered distance register. It has an accumulative error due to wheels wearing away and wheels slide. But it is very useful when there is no GPS coverage. In fact, for tracks without GPS coverage, distance and speed data are used to determine the exact position of the trains.

However, if this positioning generation is compared with signaling systems, it is important to include communication delays in positioning error evaluation. The reason is that the transmission of train positions to the terrestrial control centre depends on the communication availability. On the one hand, position transmission from train to base station is based on expert system's rules. This means that not all position calculations are sent to the system. On the other hand, there could be coverage problems along the railway line. To solve this problem, all positions generated by the boarded system are stored locally on the trains in log files. These log files will work as a registry that permits to know what positions were not sent due to communication and coverage problems. Furthermore, the information contained by these logs can be integrated offline with the BTMS in order to guarantee system reliability.

As it can be guessed, the positioning module has been the most complex to develop because we have had to perform multiple tests outside the laboratory to refine the different types of positioning and to combine them appropriately.

It is important to remark that this positioning system has been developed based on standards; therefore, it is possible to migrate to another navigation satellite system like Galileo, or to combine GPS and Galileo in the future, creating an even more accurate global navigation satellite system.

2) *External Positioning Information System*

Our BTMS is continuously receiving and storing positioning information produced by the train-side systems. Furthermore, the BTMS can receive positioning information used by the primary traffic management system thanks to the existence of an External Positioning Information System that publishes the information generated by the primary positioning system (CTC). This positioning information is provided via a JMS based Message System using a publish/subscribe schema. So, the positioning messages published by the CTC system can be received by other subscribed external systems.

In order to receive positioning information generated by the CTC, the BTMS subscribes to the External Positioning Information System (Fig. 4). Consequently, the BTMS stores the information that receives from the distributed (on board) positioning system as well as from the centralized (CTC) one. This storage tasks are performed even when the primary CTC system is properly working, because the information collected will be used later for statistical purposes in order to analysis the reliability of the secondary system with respect to the primary one.

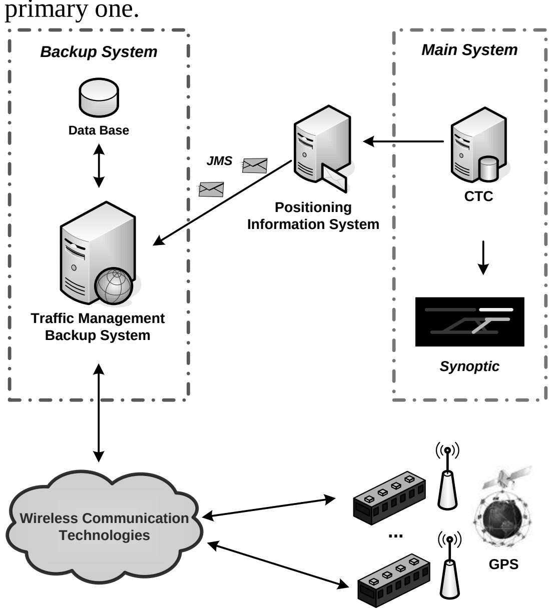

Fig. 4. Communication between the BTMS and the External Positioning Information System using Java Message Service (JMS).

These statistics will be used for the improvement of the system. Furthermore, this information may be exploited and used by future applications and systems.

B. *'Train-to-Earth' Communications*

The system presented on this paper permits a real-time train traffic management, so it is necessary to enable a wireless communication channel between the BTMS installed on the control centre and the trains. For this reason, the system that we propose in this paper uses a 'train-to-earth' wireless communications architecture based on mobile and radio technologies [14]. Fig. 5 shows the basic protocols and technologies applied in the communications architecture.

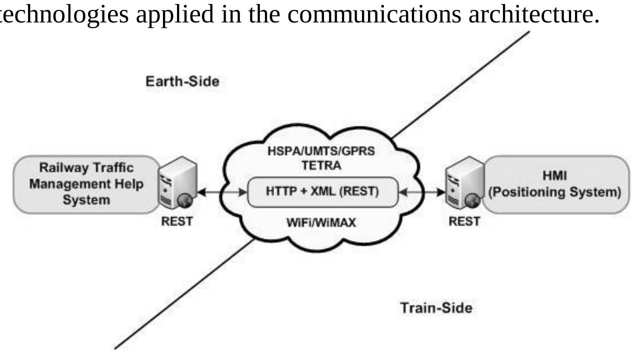

Fig. 5. 'Train-to-Earth' communications architecture.

1) *Communication Protocols*

The communication between the terrestrial and the on-board system is based on REST (Representational State Transfer) technology. This communication technology uses the HTTP (HyperText Transfer Protocol) protocol and XML formatted messages. This solution is similar to traditional XML Web Services but with the benefit of a low overload and computational resources consumption [15]. Although the information interchanged between the Terrestrial and the On-Board Communication Managers is encrypted, using the HTTP protocol allows the easy migration to HTTPS (HyperText Transfer Protocol Secure) that offers encryption and secure identification.

It is important to point out that REST is not a standard; it is an architecture style that is based on standards (HTTP, URL, XML/HTML/GIF/JPEG/.. resource representations, MIME types, etc.).

In addition, it can be said that the selected technologies are well known and broadly used in different application areas or contexts, but they are novel in the railway train-to-earth communication field.

2) *Communication Technologies*

In order to establish 'train-to-earth' communications, the system presented in this paper combines mobile (GSM/GPRS) and radio technologies (WiFi). In this case, according to the transmission characteristics (information volume, real-time communications needs, coverage and communications costs), the system combines these technologies selecting the best way of communication in each moment, taking into account train locations, and its connectivity state [16].

To make this communications possible, the trains have been equipped with the necessary connectivity hardware and software system. Furthermore, taking into account mobile communications coverage aspects, to enhance trains GPRS connectivity, the communication system boarded on trains allow GPRS communications within two different telephony providers, working one of them as main provider, and the second one as the secondary when the first one is not operative.

So, in this system mobile technologies such as GPRS/UMTS/HSPA are used for real time communications. These technologies do not offer either a great bandwidth or 100% coverage, and they have a cost associated to the information transmission. Despite this, these technologies are a good choice for the delivery of high-priority and small sized information. The selection of the specific technology (GPRS/UMST/HSPA) depends on whether the service is provided or not, (by a telecommunications service provider), and the coverage in a specific area.

On the other hand, this system use WiFi radio technology to realize communications between the trains and the railway infrastructure points equipped with WiFi connectivity (a private net of access points is needed). What is more, this technology allows the transmission of large volumes of information and does not have any costs associate to the transmission (for example log information stored on trains, or train services information that is uploaded on train periodically).

For a correct and optimized use of the communication architecture, we have defined two types of transmission. These two types take into account characteristics of both information and communication technologies, such us: the volume and the priority of the information, the existence of coverage, and the cost of the communication. Considering these aspects, we have defined [17]:

- *Slight Communications.* This type of communication is for the transmission of small volumes of information (in the order of KB) and with high priority. In general, information that has low latency (milliseconds or a pair of seconds) and needs to be transmitted exactly when it is generated or acquired (for instance, the GNSS location of a train, or a driving order to the train driver).
- *Heavy Communications.* This type of communication is tied to the transmission of large volumes of information (in the order of MB) and with low priority. The importance of this information is not affected by the passage of time, so it doesn't need to be transmitted at the exact time it is generated. The management of this type of transmission is described in [18].

It is important to point out that although each separate technology can't achieve 100% coverage of the train route, the combination of both comes very close to complete coverage. As the application layer protocols are standard, other radio technologies such as TETRA or WiMAX can easily substitute the ones selected now. These technologies can achieve a 100% coverage and neither one has a transmission cost. However, there are certain limitations such as the cost of deploying a private TETRA network, and the cost and the stage of maturity of the WiMAX technology [19].

C. Additional Services

Using the "Train-to-Earth" communication architecture and the information provided by the on board positioning system positioning, two services have been developed related with the functionality of the BTMS. They are described below.

1) Statistical Analysis Service

Using the information stored by the positioning system on a data base, the BTMS can make statistical analysis related to the system's reliability level, GPS and GPRS coverage, and other system functionality aspects.

Thus, one of the main goals of this service is to compare the received information, determining if the positioning provided by the train-side systems is according to the information generated by the primary CTC system.

2) Control Message Exchanged Service

This service allows the procedural alarms transmission to the train-side systems. These kinds of alarms indicate anomalous situations to the train drivers: primary system failure, signal exceeds authorization to a certain point as a consequence of a failure of any electro-mechanical track component, etc.

Moreover, taking into account the different circumstances that can occur, and notifications given to engine drivers, there are two types of messages:

- *Messages generated by the traffic operator*. The traffic operator in the terrestrial control centre can select and send messages manually to a train driver. These messages must be confirmed immediately by the driver when they read them on the on boarded equipment.
- *Temporal speed limitations.* These messages are predefined by a circulation inspector and they have greater priority than the others. Once the message is created, it is sent to all the trains immediately.

IV. Experimental Validation

The work that has been presented on this paper is the result of almost four years of joined efforts with a railway transportation company of Spain.

Currently the BTMS is on real deployment phase. Thus, the system has been deployed in a passenger train and in two freight transportation locomotives, allowing the sending of GPS based positioning information from trains to terrestrial control center.

We have performed test on laboratory and also in real scenarios. Laboratory tests have been satisfactory. Test on real settings have also been successful except for mountainous landscapes with numerous tunnels where wireless mobile communications were affected by the insufficient coverage related to these kind of technology. However, this difficulty can be easily overcome using a communication technology with a greater coverage. Furthermore, in order to ensure security on traffic management, coverage in all stations is guaranteed. So that, the BTMS is able to recognize when a train enters or leaves a station, helping to prevent conflicting movements (interlocking).

It is important to point out that during the system real tests, there has been improvements on the GPS based position generation and management. This work has been focused on what it is the best way to relate the position provided for CTC (track sections) and the position generated by GPS based boarded system (*kilometric points*). So, the CTC provide positions as a track sections where the train is. This track section is a range of kilometric points. Therefore, when the backup system receives train boarded system's position, it calculates what track section corresponds to the kilometer point provided by this position. However, while CTC generates track section based positions when the train enters or leaves this track sections, the boarded system provides the kilometric point calculated by the GPS module on the main coach where the engine driver is. Thus, it is possible that the backup system interprets that there is no correspondence between both positions when really there is.

Accordingly, these aspects have been considered to make improvements to achieve a better fit between the positions provided by both systems.

V. Conclusion and Future Work

In this paper we have presented the work made during the last four years in collaboration with a railway transportation company of Spain. The result is a backup system for managing the railway traffic in emergency situations in which primary CTC systems fail. The most innovative issue of this system is that it is based on a decentralized positioning system in which each train is responsible of calculating its position using an on board hardware/software positioning system. This system is based on wireless positioning technologies (GPS) and it is able to generate train positioning information by combining different on board positioning information sources (such as MEMS gyroscope, maps, ATP, odometer) and applying a logical approximation algorithm for matching railway lines and GPS coordinates. Moreover, it combines train-side systems and terrestrial applications that exchange information via a hybrid mobile and radio wireless communications architecture.

The main objective of the new system is to reduce human error caused by the situations in which priority systems do not work properly. As well, we have developed a new technology to resolve the detection of train track changes, knowing in railway lines with more than one track which is the exact track each train takes. The result is a solution which enables on board systems to know what their position is without the assistance of the primary centralized systems of positioning. It makes possible the development of other on board application based on positioning. Currently the Backup Traffic Management System (BTMS) is on real deployment phase.

In the future our efforts will be focused on (a) the improvement of GPS based positioning system enabling a more accurate position calculation; (b) improvement of communication capabilities; and (c) system deployment and integration with the new train series that are being manufactured by our partner railway company, as well as their adaptation to other railway lines topology in order to offer the solution to other railway companies.

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