Field Experience with GPS based Train Control System

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Abstract

This paper presents the field experience with a new kind of GPS based train control system for branch lines which are operated by radio-based operational train control. Most branch lines with such operating limitation cannot afford the cost investment for modern signalling systems. The train control system presented herein is a low cost solution which improves safety, makes operation easier, and introduces an interesting level of automation without costly line-side installations. It is based on autonomous determination of train location using differential GPS and an odometer with data radio communication between the central computer and the on-board computer in the train. In Austria, this system has been in full operation since 2006 on several single-track lines with a total length of approx. 90km. This paper will therefore present the experience with this GPS based train control system and its safety aspects.

Keywords: Train control system; GPS based train location; safety of GPS location; regional branch line

1 Introduction

This paper presents a GPS based train control system which has been developed at the Upper Austrian University of Applied Sciences in Wels. The main goals are to improve safety and to simplify operation, moreover providing a low cost solution using common sensors like differential GPS. The paper states the motivation for the development, and presents the system with its components, its safety aspects, the operational experiences as well as the experience with GPS based location. Furthermore several possibilities to improve system safety are discussed.

2 The GPS based train control system and its functionality

2.1 Background of the train control system

Regional branch lines are very often operated by radio-based operational train control. The single-track line traffic controller gives the movement authority to the train driver via radio phone (e.g.: Train x has a movement authority until A-stop where it will cross paths with train y). The movement authority will be marked in a graph of train running.

Using this kind of operating principle the standard of safety is poor. An error on the part of one single person could result in a severe accident. Numerous accidents in the past have shown this risk. In Austria four accidents happened between 2002 and 2006.

It is obvious that safety must be improved, but many regional branch lines can not afford the investment costs for electronic switching and standard signalling systems.

2.2 Basic idea of the train control system

The basic idea of the train control system (TCS) is to leave the operational principle as it is, but the entire operation gets computer aided support by adding a radio data system for communication between trains and central train controller.

An overview of the presented TCS is given in Figure 1. The system consists of a central computer and an on-board-computer in each train.

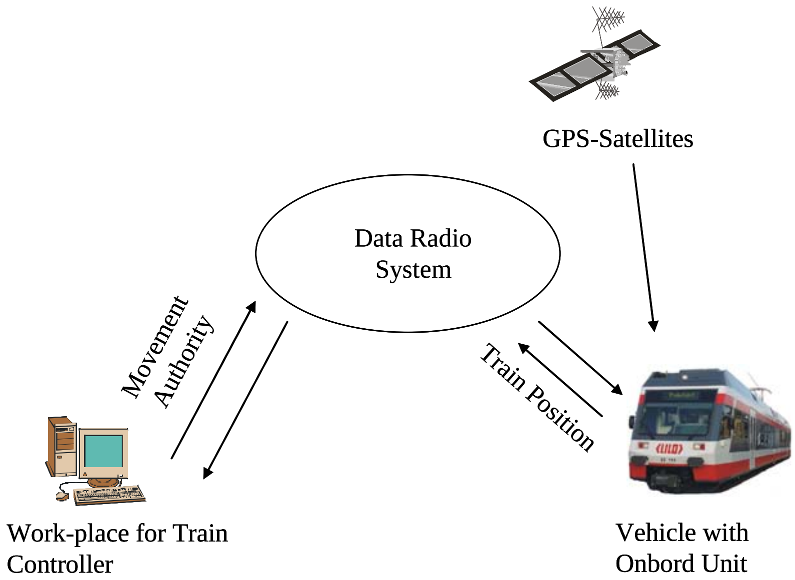

Figure 1 Schematic overview of the TCS.

(a) The on-board-computer is responsible for determining the train location, based on GPS position data and odometer. The odometer is used for measuring the trains speed and relative position during normal operation while the GPS data provides a point of reference and acts as a supervision and backup system. The result is matched with a digital line atlas to retrieve a position using line-based coordinates, hence an accuracy of the train position better than +/- 10 meters is achieved.

(b) The on-board-computer receives the movement authorities from the central train controller and displays them to the train driver (cab signaling). It also supervises their correct execution by the train driver. Furthermore it monitors the movement of the train and will automatically activate the emergency brake if the train driver tries to pass beyond the limitations of the given movement authority.

(c) The communication between the central device and the trains relies on a line-specific data radio system, thus no further line-side equipment has to be installed.

(d) The central computer is located where the train controller is situated and consists of two main parts. The first part is the safety relevant kernel, implemented as an ADA-application and manages the movement authorities and the collision avoidance algorithm. Furthermore it maintains the communication to the trains via the data radio system and transmits the received RTCM correction data from a stationary GPS-receiver to the trains. The second part is the GUI which presents a real-time view of the full operation on the line. It gives the train controller a schematic view of the line on the one hand and on the other hand a scaled electronic time table that includes both the planned and the actual train movements.

More details of the system can be found in [1].

3 Safety and reliability of the system and its GPS based location

The design of the system has been focused on low investment cost but safe operation. Low cost has been achieved by using standard industrial computer hardware within the trains and by omitting any line-side installations like signals. Safety of the train control system is based on a combination of technical safety and human supervision.

3.1 Technical safety

Technical safety of the on-board-unit and the central computer is achieved by the means of:

(a) Software redundancies and numerous plausibility checks, but in general without explicit hardware redundancy. The software development process has been structured in compliance with most of the requirements of the EN 50128 for SIL1 and SIL2. All safety relevant software components have been designed using UML and have been implemented in ADA. Due to the usage of a well-structured software specification and development process according to the V-modell, safe software function has been achieved.

(b) The movement authority is only valid if it has been acknowledged by the train driver and the on-board-computer.

(c) The determination of the train's location is based on a redundancy of location sensors and in addition to plausibility checks within the location algorithm.

(d) Plausibility checks are performed on the transferred differential RTCM corrections

(e) The on-board-computer automatically activates the emergency brake if the train driver tries to pass beyond the limitation of the given movement authority.

(f) Implementation of a highly independent collision-avoidance algorithm which automatically sends an emergency brake command to trains in danger of colliding. This occurs when the distance between two trains is smaller than the double braking distance and there is no station between them.

3.2 Human supervision

(a) All safety relevant actions need an explicit input by the train driver and/or by the central train controller.

(b) Checking the train location if the automatic algorithm determines an unreliable train location e.g. due to GPS-errors or long-term poor visibility of the satellites.

3.3 Safety and Security of data transmission

Given that the radio-transmission between the central computer and the board-side components is error prone to random errors and potential malicious attacks, a safety layer is installed to comply with the requirements of the EN-50159 [4]. The main features to ensure the safety are:

(a) Using message authentication codes to encrypt the transmitted telegrams to ensure their integrity and authenticity.

(b) The telegram encryption algorithm is comparable to the EuroRadio ETCS counterpart with a simplified key management structure due to the reduced system architecture complexity.
(c) Since the transmission hardware is untrusted, the safety layer ensures that unauthorized telegrams are detected.
(d) Besides ensuring the authenticity, the integrity is ensured due to timestamps and acknowledgements for critical telegrams.

These safety principles have recently been improved to fully comply with the EN-50159.

4 Experience with the TCS and its GPS based location

4.1 Safety of the calculation of the train location

Technical safety of train location is a very important part of the safety of the train control system. But system safety does not only depend on this technical safety. Safety of train location is assured by a combination of technical safety and human supervision (see chapter 3.2). The sequence of the alarm is:

(a) Calculation of a reliable train location including plausibility checks of the raw data and comparison between GPS receiver and odometer
(b) If unreliability is detected an automatic alarm to the engine driver and to the train controller will be generated
(c) Human supervision assures safety – wrong train location must be corrected and / or ignored.

4.2 Field experience with GPS location

Since 2006 the on-board units on the equipped trains have calculated nearly 700 million single train positions. According to the reported errors there were a very small amount of wrong train locations. Depending on the classification of the errors the rate of erroneous position is around 10^{-5}. The reasons for these errors are

(a) Shadowing by trees and buildings
(b) Missing RTCM correction data due to problems of the data radio channel
(c) Unclear reasons (e.g. no plausible position output of the receiver)

There was only one major location error at the beginning: The reason for this error was faulty RTCM data caused by a firmware bug of the reference station in combination with a strange behavior of the GPS receiver of the on-board unit. This error caused no safety relevant disturbance due to the alarm messages but it had bad operational consequences like train delays and angry passengers. It was fixed by a firmware update and an additional software for plausibility check of the RTCM data as mentioned in chapter 5.2.

The following figures show the static measurements (2 days) of the used GPS receivers. The left figure depicts the on-board GPS receiver with a 5m radius and the right figure depicts the reference station for the RTCM data with a 2 m radius.

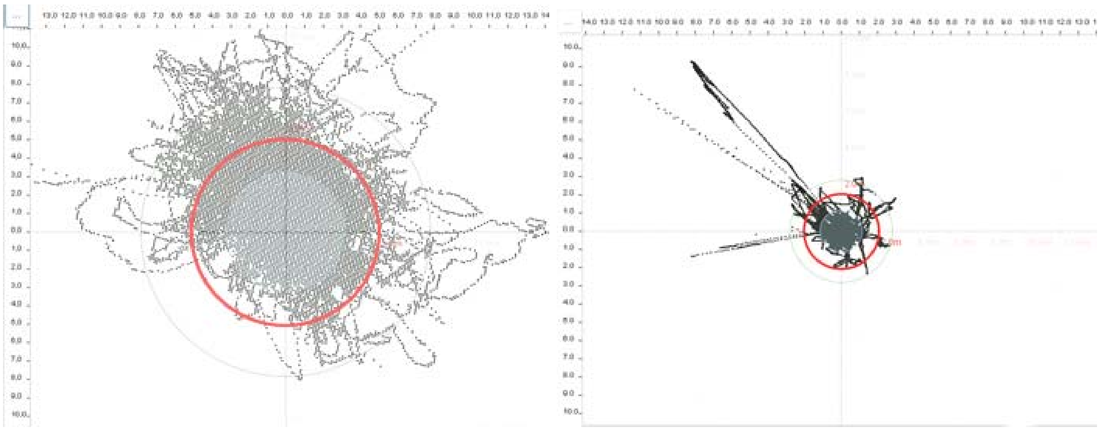

Figure 2 Comparision of static on-board receiver (left) and reference station GPS measurements (right).

4.3 Safety Integrity Level (SIL)

As defined in [2] and [3] the European standards have different safety integrity levels (SIL). Theoretical considerations in combination with the presented practical experiences show that this type of train location may not assure a technical safety necessary for a higher SIL level. At the present time a residual risk of higher than 10^{-5}/h is calculated based on operational experiences, which is near SIL 1.

The remaining risk for SIL 2 is less than 10^{-6}. This figure leads to the requirement of additional sensors to improve the algorithm of train location which are covered in the following chapters.

4.4 Operational experience

The TCS has received a final approval by the Austrian Federal Ministry of Transportation based on a long period of testing and two expert reviews, one of these dealing with the technical safety and the other one with the operational reliability. The final approval is based on the combination of the technical system and the operational sequences.

Since 2006 the TCS has been in full operation on several single-track lines in Austria with a total length of approximately 90 km. Under the responsibility of this TCS 1.1 million train km per year are executed. The technical availability of the system is appr. 99.9 %.

5 Possible improvements on navigation quality

5.1 Track detection with GNSS and low-cost sensors

As already mentioned the presented TCS strongly depends on safe and reliable train location mechanisms in combination with low overall costs for installations and trackside infrastructures. The use of differential GPS and wheel sensors on the trains for safe location purposes has the potential to avoid the installation of expensive line-side signaling equipment on regional branch lines. The steady increasing accuracy and integrity of modern differential GPS (and GNSS) receivers are the main drivers for many high-precision applications on railways. A major drawback of GPS-only based location principles is the lack of parallel track detection. Since many regional branch lines are single track lines with predefined crossing possibilities (often with spring switches), the track selective location is inherently provided. Nonetheless, for safety reasons in terms of track clearance detection and to enable a track selective navigation in complex shunting situations, it is necessary to distinguish between parallel tracks (which are approximately 4-5 meters apart).

An investigation of various GPS L1 receivers with combinations of RTCM and EGNOS enabled corrections showed a high probability of detecting the right parallel track course. However, due to environmental influences (i. e. high buildings and obstacles in stations with parallel tracks) and the accompanying effect of shadowing and multipath, the navigation accuracy is severely impaired. Supplementary sensors are therefore necessary to increase the reliability of the navigation results. The integration of an additional single-axis angular rate sensor offers additional information when passing track switches [5].

A major challenge is the design and implementation of a digital line atlas which represents the topology and geometry of the tracks. In the current operational TCS, station areas are approximated through polygonal planes without the possibility to distinguish parallel tracks. To represent the track course, a linear, monotonically increasing coordinate sequence is stored in the atlas.

To meet the requirement of a GPS based track-selective navigation, graph data structures are considered to be suitable means of creating consistent topologies and support the implementation of efficient map-matching algorithms. The nodes of the graph represent switches, while the edges are regarded as track segments. The graph adjacency lists are stored in the digital line atlas. Each switch, either a curved or a double turnout, can be represented and simplified as one or more single switches. Furthermore, each track segment is stored as linear coordinate sequence in WGS84 format. By traversing the graph structure and by taking into account the navigation history, the subsequent map-matching is able to determine the most-likely path a train is covering.

Detecting switch passing is crucial to determine the occupied track, since a change of a track segment is only possible at those junction points. To increase the reliability of switch detection, a single-axis low-cost gyroscope was taken into account in the map-matching process. By measuring the switch angle and by cross-correlating the measured angle curve with a predefined template curve for each type of switch, it is possible to detect which branch of a switch has been taken. Due to large gyroscope drifts of the deployed MEMS sensor, continuous calibrations have to be performed. Furthermore, the size of the switch location detection window has to be reduced according to the drift and bias effects.

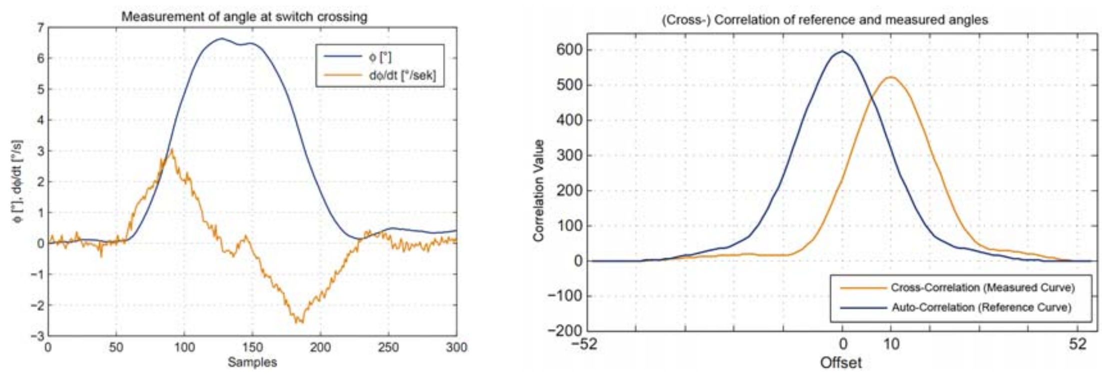

Figure 3 Detecting switches via gyroscope measurements and subsequent correlation.

5.2 Differential correction optimization

The central components of the TCS are able to generate RTCM Message Type 1 pseudo-range correction telegrams, which are transmitted to the trains via a proprietary radio communication system. Before sending the RTCM messages, the TCS software is able to decode and perform plausibility checks on the corrections. Corrupted RTCM messages are therefore prevented to be used on the train-side equipment.

To reduce RTCM outages in the system, an approach to self-generate RTCM messages from EGNOS was investigated. The ESA SISNeT service provides a convenient and satellite independent way to obtain the EGNOS signal-in-space over the internet. The SBAS message is decoded into fast, slow and atmospheric components, which are subsequently converted into corresponding RTCM messages.

By using this approach, SISNeT provides a solid backup strategy in order to maintain the differential correction transmission whenever a RTCM outage in the main reference station is detected or a plausibility check fails.

5.3 Balises

In regional branch lines, changes in track-side installation components are not preferred and often impossible. Track clearance signals or line-side devices for navigation support are cost-intensive and increase the amount of maintenance necessary.

Nonetheless, to meet higher safety requirements, balise systems may be used to support train navigation algorithms. Passive balise tags, which are mounted on track sleepers at crucial points like end of movement authorities, can be detected by a train-side balise reader. To improve the safety level of the TCS and its train location, balises are an additional way to verify the positioning results of the differential GPS approach. The on-board digital line atlas is used to store a list of balises in combination with their expected GPS position. This approach enables the navigational algorithms of the TCS to calibrate the GPS and Odometer based position at the time of passing a balise.

Additionally, a track-selective navigation is possible by incorporating balises at track beginnings and signaling locations.

These additional Balises will be used in additional lines of the TCS.

6 Outlook

Due to the successful experience up to now two more lines in Austria will be equipped with a length of appr. 70 km. The two lines will go into operation 2011 and 2012 respectively. The main focus of the improved implementation will be a SIL2 certification according EN 50126. This reduced remaining risk target implies two major improvements: (1) Additional balises for the location will be installed in addition to the dGPS system and (2) supplementary verification and validation processes will be established in collaboration with the safety assessors.

Further research will be done on the use of the EGNOS integrity information.

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