PUBLICATION ANALYSIS OF CONCEPTS FOR TRAIN INTEGRITY MONITORING SYSTEMS

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ABSTRACT

Experts anticipate a significant increase in the globally transported rail freight volumes for years to come. A promising solution approach to this challenge is to implement the European Train Control System (ETCS) at level 3. In this way, the distances between trains would no longer depend on infrastructural fixed block sections and thus trains could follow at shorter intervals one after the other. For this approach to increasing the capacity of tracks, a demanding challenge is to realise a continuous train integrity monitoring system (TIMS) especially for freight trains, as there is no continuous electrical line in many of those trains. Within this challenge, the purpose of our publication is to present the methodical approach and the results of a publication analysis of approaches and concepts for TIMSs. For this goal, we researched and analysed intellectual property right documents (patents, utility models, patent application documents, etc.), scientific and business publications, etc. During our project work as part of smartrail 4.0 for Swiss Federal Railways SBB in 2018 and 2019, we contributed results first to the report Zwischenbericht Technologie PoC Lokalisierung as a part on safe train length and train integrity based on the research of in total 609 publications. Building on this, we have classified and enhanced the results. The solution concepts found cover fields like axle counters and track circuits as well as the main brake pipe, a continuous electrical line and coupling concepts. Furthermore, we researched concepts based on global navigation satellite systems, distributed acoustic sensing (DAS), optical systems or wireless data transmission. In conclusion, we have identified three promising solution classes for the future: digital automatic coupling, DAS and end-of-train device. Since we could not find a comparable publication, we contribute with this publication an up-to-date overview of concepts for TIMSs and in particular a corresponding classification.
Keywords: train integrity monitoring systems, TIMS, European Train Control System, ETCS level 3, CTCS level 4, moving block, virtual block, localization, digitalisation of freight trains, DAC.

1 INTRODUCTION

In the rail sector, a number of railway infrastructure companies around the world may need to increase the capacity of their tracks in the next years (see [1], [2]). Specialists expect that the entire global freight and logistics market will grow by 5% p.a. in the years to come [3]. In its "Sustainable and Smart Mobility Strategy" [4], the European Commission calls for rail freight transport to grow by 50% by 2030 compared to 2015 and to double by 2050 [4].

In order to achieve these goals, increasing the density of trains on tracks is a promising basic approach. By contrast, in many cases an extension of train lengths or an increase of train heights is not possible or only possible to a limited extent [1], [2].

A promising approach to increase train density on tracks is the introduction of the European Control System (ETCS) at level 3 or the similar Chinese Train Control System (CTCS) at the corresponding level 4. The highest level 3 of the ETCS differs from all other levels in the side where train completeness monitoring, which is also referred to as train integrity monitoring, is performed. In the lower levels of the ETCS, two consecutive trains are protected from each other by having fixed block sections on the track side. Only one train may be in a block section at a time [5], [6]. On the one hand, these fixed block sections result

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in a limitation of the track capacity and, on the other hand, high infrastructure costs for the installation and maintenance of track-sided monitoring technology [7]. The ETCS level 3 is associated with the significant advantage that the train integrity monitoring is no longer performed on the track side, but on the train side [5], [6]. As a consequence, track-sided technology becomes superfluous and two trains can follow one after the other in the braking distance of the succeeding train, which is also referred to as *moving block* and can lead to an increase in track capacity [5], [6].

The introduction of the ETCS at level 3 is not yet feasible on the main routes of European rail traffic, as there is no sufficiently practicable, reliable and safe solution for train-sided train integrity monitoring, especially for freight trains [5], since these trains often lack a continuous electrical line [7]. As a result, there is still the challenging research area of developing a train-sided train integrity monitoring system (TIMS) that meets the requirements of European mainline rail traffic (see [1], [2]).

In this research area, the purpose of our publication is to outline the methodical approach and the results of a publication analysis of approaches and concepts for TIMSs. For this objective, we researched and analysed intellectual property right documents (patents, utility models, patent application documents, etc.) as well as scientific and business publications, etc. During our project work as part of smartrail 4.0 for Swiss Federal Railways SBB in 2018 and 2019, we contributed our results first to the report Zwischenbericht Technologie PoC Lokalisierung [8] as a part on safe train length and train integrity based on the research of in total 609 publications. In 2022, we updated our work by expanding the results and classifying them. As a result, we give a brief overview of the main concept classes for TIMSs with this publication.

In continuation of our previous work (see [1], [2], [8], [9]), this publication is structured as follows: After this introduction in Section 1, we present in Section 2 our methodical research approach. In Section 3, we provide an overview of the results of our in total broad publication analysis. Finally, in Section 4, we draw a conclusion and give an outlook on future work.

2 METHODICAL APPROACH

In this section, we expound our methodical research approach to search concepts for train integrity monitoring. For this purpose, we first explain the document types considered in Section 2.1. Based on this, we elucidate our search strategy in Section 2.2.

2.1 Document types

In this section, we present the two classes of researched documents: intellectual property documents in Section 2.1.1 and further publications in Section 2.1.2.

2.1.1 Intellectual property documents

In the case of intellectual property documents, we considered the following three document types as part of our research:

- Patent applications;
- Patents;
- Utility models.

Patent applications are usually published by default a certain time after filing, unless the patent has already been granted before the end of this period. In the case of utility models, there is usually no distinction between the application and the published utility model.

2.1.2 Further publications

Apart from intellectual property documents, we considered all other documents that were publicly available, especially online. These include e.g. scientific publications, popular scientific articles, documents published by companies, associations, etc.

2.2 Search strategy

In this section, we describe the two search strategies applied depending on the document type. We explain the one for intellectual property documents in Section 2.2.1 and the one for further publications in Section 2.2.2.

2.2.1 Intellectual property documents

In the case of intellectual property documents, we used the DEPATISnet database of the German Patent and Trade Mark Office, which is regularly updated internationally. Within the DEPATISnet database, we applied the expert mode with wildcards. Generally speaking, due to the patent examination procedure, patent applications can be more extensive than patents. Accordingly, if we had the choice between a patent application and a patent in the results, we used the patent application.

In the years 2018 and 2019, we conducted a total of three research passes, each building backwards on the results of the preceding one. During the three research passes, we found a total of 414 documents of relevance. In the year 2022, we perform an update.

2.2.2 Further publications

In the case of further publications, we used the search engines Google and Google Scholar in particular. In addition, we applied further databases such as SpringerLink, ScienceDirect, Eurailpress, etc. Moreover, we also searched in the local literature collections of the university and the institute.

In the years 2018 and 2019, we found a total of 195 further publications of relevance in this way. In the year 2022, we also perform an update.

3 RESULTS OVERVIEW

In this section, we give a structured overview of the results of our publication analysis. For this, we perform a top-level classification of the results in Section 3.1. In the following Sections 3.2 to 3.7, we explain each of the six main classes defined in Section 3.1.

3.1 Top-level classification

In this section, we introduce a top-level classification for the researched solution concepts. Since a train-sided TIMS is required for using the ETCS at level 3 [5], we differentiate fundamentally between track-sided and train-sided solution concepts in our classification. In practice, we have found numerous concepts that are not, or not only, applicable on one side. As a result, there are various combinations, so that we have defined six main classes as shown in Fig. 1.

For the six main classes according to Fig. 1, there are various examples. A track-sided TIMS can be e.g. an axle counter, whereas a train-sided concept can be based on the use of the main brake pipe, for example. There are also concepts with system parts that can be applied only on the track side or only on the train side, such as some optical systems. In addition, there are two-sided concepts that require system parts on both the track side and the train side, such as a system comprising a balise in a track and a transponder on a train.

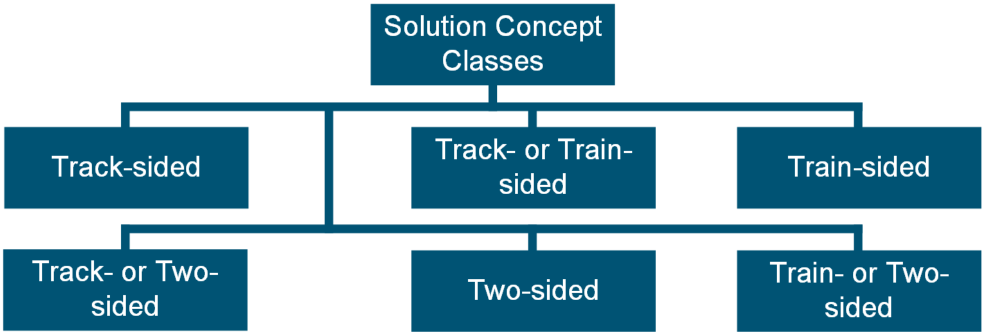

Figure 1: Top-level classification of solution concepts.

Moreover, there are also concepts for implementation either on the track side or on both sides, as well as concepts for implementation either on the train side or on both sides.

Overall, the researched concepts are very heterogeneous in terms of their kind. Some concepts represent an approach to a complete TIMS, while others can be, for example, a technique for measuring, especially for localization. As a result, the subclasses of the six main classes are correspondingly heterogeneous. They are considered in more detail in the following Sections 3.2 to 3.7.

3.2 Track-sided solution concept classes

In this section, we present three only track-sided solution concept classes. These classes are axle counter in Section 3.2.1, track circuit in Section 3.2.2 and distributed acoustic sensing (DAS), which is also referred to as fibre-optic sensing (FOS), in Section 3.2.3.

3.2.1 Axle counter

This section comprises the solution concept class of axle counters. After a general explanation of the class, we present researched options and enhancements.

Generally speaking, an axle counter is a track-sided track vacancy detection system based on the counting of entering and leaving wheelsets at both ends of a track section. By calculating the difference of those two numbers, the axle counter can determine the vacancy of that track section. An axle counter includes rail contacts usually realised as inductive sensors and implemented twice at each end of a track section in order to detect the direction of travel. In Germany, railway infrastructure companies prefer axle counters for new installations since the mid-1990s [5].

During our work, we have found a patent application for the use of diversity in axle counting systems. In this patent application, the author explains the usage of different variants of diversity, such as spatial diversity, time diversity, wheel diversity by detecting both wheels of a wheelset, and processing diversity [10].

In addition, we have found publications on the enlargement of axle counters by measuring distances between axles or differences in weights [11], [12]. One patent application comprises a procedure for gaining the number of axles, the number of vehicles, the axle distances, the vehicle lengths, and the lengths of coupled vehicle groups with only two track means and an evaluation unit [11]. In another patent, the writers expound an invention to identify engines or locomotives in a moving train by counting and weighing axles at different points along a track [12].

From our point of view, axle counters have the advantages of their many years of proven experience and the possibility of any block section length. In contrast, the disadvantages are the high costs and in particular the necessity to implement track-sided fixed block sections. As a consequence, axle counters are not suitable as an essential concept for a TIMS when using the ETCS at level 3.

3.2.2 Track circuit

This section covers the solution concept class track circuit. Based on a general introduction to track circuits, we give the researched results.

The solution concept class track circuit together with the solution concept class axle counter presented in Section 3.2.1 form the two conventional solution concept classes for train integrity monitoring (see [13]) and have high costs in common [7].

For a track circuit, an electrical voltage is applied to both rails of a track. If a rail vehicle is on such a track, there will be a short circuit via the wheelsets. Therefore, the rail vehicle becomes detectable. Traditionally, this method requires that sections of a track are electrically isolated from each other. Due to the electrical resistance of tracks, the length of the sections is currently mostly limited to about 2 km (see [13]).

A significant disadvantage of track circuits compared to axle counters is the limited length of block sections of about 2 km when using track circuits. As a consequence, there are different concepts to increase the length of track circuits. For example, to extend the transmission length of the signal of a track circuit in the track and thus the length of track circuits, the authors of a patent application propose the use of capacitors connected in parallel between the rails [14].

The authors of other publications propose concepts to determine the length of trains using e.g. track circuits. For example, one patent application covers an approach for calculating roughly the length of a train by using more than two consecutive track vacancy detection sections. This approach is based on detecting the chronological sequence of the occupancy of the individual track vacancy detection sections and on the section lengths [15].

In our opinion, the advantages and disadvantages of track circuits are largely comparable to those of axle counters. The long-term probation in use is advantageous. By contrast, the high costs and in particular the need for track-sided fixed block section lengths are significant disadvantages. Consequently, track circuits are not suitable as a basic TIMS for the implementation of ETCS at level 3. In addition, there is the disadvantage of limited block section lengths.

3.2.3 Distributed acoustic sensing

DAS is also referred to as FOS sometimes. Specifically, DAS is the application of special FOS methods e.g. relevant to rail systems. For this reason, the designation DAS is used in the following [16].

In general, DAS is a relatively new technology that has not yet been approved for European mainline traffic and is currently still under development (see [17]). In order to use DAS, the main requirement is a fibre-optic cable running alongside a track. Laser light is pulsed into that cable from one end and reflected at natural impurities. If a train drives on the track, the train will cause vibrations in the track bed and the surrounding area. The vibrations perpendicular to the cable also influence the reflection behaviour of the laser light in the cable. As a consequence, the backscatter pattern of the laser light changes at the end of the cable. By evaluating these changes, the train can be localized [18].

From our perspective, DAS is linked to several advantages, such as the ability to use existing fibre-optic cables [17], the possibility to detect unequipped people and vehicles [8], the ability to continuously monitor, and the non-necessity of a vehicle migration strategy. Nevertheless, DAS suffers from disadvantages such as difficulties in detecting slow-moving vehicles and the inability to detect stationary vehicles [8], difficulties in distinguishing between axles of a train and parallel tracks [8], [18], and the susceptibility to vibrations from e.g. road traffic in the vicinity [8].

3.3 Train-sided solution concept classes

In this section, we consider the eight only train-sided useable solution concept classes in Sections 3.3.1 to 3.3.8. These solution concept classes are based on the techniques main brake pipe, continuous electrical line, coupling, force evaluation, wireless sensor network (WSN), eddy current sensor, inertial sensor and gyroscope, and end-of-train device (EOT).

3.3.1 Main brake pipe

There are quite a number of approaches dealing with train integrity monitoring via the main brake pipe. Various concepts are based, for example, on monitoring the air pressure and/or volume flow on the traction vehicle or using an EOT at the end of a train [19], [20]. In addition, there is the approach for determining train length e.g. by measuring and evaluating air pressure, air-mass flow and temperature of the main brake pipe [20]. In our opinion, the evaluation duration in the literature sources available to us is very long with a target value of e.g. 30s [19], so that we cannot currently see any breakthrough with concepts based on the main brake pipe.

3.3.2 Continuous electrical line

With regard to a continuous electrical line in trains, there is e.g. a method to monitor the breakage of such a line [21]. Another concept proposes how the existing electrical wiring in passenger trains can be used for integrity monitoring [22]. Due to the great effort involved, we expect that a continuous electrical line in freight trains can only be implemented in practice on the basis of the digital automatic coupling (DAC).

3.3.3 Coupling

In the area of couplings, the DAC is currently the main topic as a replacement for the screw coupling in freight trains. With the introduction of a DAC, a continuous electrical line and, depending on the DAC type, possibly also a continuous data line would become reality in freight trains and form the basis for a TIMS in those trains. Additionally, the DAC would offer various logistical advantages, such as automatic coupling, better traceability of freight wagons, etc. The expected costs of EUR 6.6 to 8 billion presently represent a significant risk for a Europe-wide implementation. Moreover, a demanding migration strategy would become necessary [23]. Currently, as the goal of the DAC4EU project, experts are researching how a DAC can be designed for Europe [24]. Independent of the DAC, there is e.g. also a concept for the monitoring of couplings by detecting the inclination angle of screw couplings [25].

3.3.4 Force evaluation

In the field of force evaluation, there are concepts on the basis of measuring e.g. tensile and compressive forces between the locomotive and the first wagon. During a journey, a device compares the force curve with previously recorded force curves and evaluates the data with regard to the integrity of the train [26].

3.3.5 Wireless sensor network

There is also the approach of wireless train integrity monitoring based on a WSN. For example, a concept deals with a train-specific protocol for communication between a locomotive as the master unit and wagons as slave units [27].

3.3.6 Eddy current sensor

An eddy current sensors allows for precise relative train location from a known starting point [28]. In our opinion, this sensor technique seems to be very useful for traction vehicles, while we do not expect equipment costs to be realisable for freight wagons.

3.3.7 Inertial sensor and gyroscope

In the area of inertial sensors and gyroscopes, there are publications to use an inertial sensor as part of an EOT [8], [19]. The authors of a further publication propose to utilize gyroscopes track-sided to detect the path of a train in a switch [29].

3.3.8 End-of-train device

An EOT can be a module of a TIMS. After completing assembling of a train, railway workers can attach an EOT to the end of the last wagon of that train. An EOT includes different submodules, e.g. a telematics submodule for communication with the traction vehicle and a sensor module for self-localization. A sensor module can, for example, comprise a global navigation satellite system (GNSS) sensor and an inertial sensor [7], [8], [30]. Moreover, there is the approach of supplying energy to an EOT via the main brake pipe [31].

From our point of view, EOTs offer various advantages such as the ability to be relatively inexpensive to implement without expensive changes to infrastructure or vehicles, the feasibility without a migration strategy, and the possibility of simply replacing devices in the event of a defect. In contrast, there are disadvantages such as the possibly technically difficult communication with the traction vehicle, the potentially challenging energy supply, reliable attachment at the end of the last wagon and reliable pairing with the right traction vehicle, and limitations in the choice of sensors compared to a locomotive.

3.4 Track- or train-sided solution concept classes

In this section, we describe the track- or two-sided solution concept classes in the three Sections 3.4.1 to 3.4.3: optical sensor, acoustic sensor, and vibration sensor.

3.4.1 Optical sensor

In the area of optical systems, there are both train-sided systems for recording the track side [7], [8] and vice versa [32]. In our opinion, optical systems have potential for the future.

3.4.2 Acoustic sensor

In the field of acoustic systems, there are concepts for detecting trains on the track side [33] as well as for monitoring the own train or the track side on the train side [34].

3.4.3 Vibration sensor

In order to detect trains on the track side, there is e.g. an approach on the basis of vibration detection to initiate safety measures such as closing a gate [35].

3.5 Two-sided solution concept classes

In this section, we present two-sided solution concept classes in Sections 3.5.1 to 3.5.4: balise, radio-frequency identification (RFID), GNSS, and mobile communications.

3.5.1 Balise

A balise is a device installed in the track and working in accordance with the transponder principle. Correspondingly, a balise does not require its own energy supply [5], [13]. There is also the approach to use this punctiform information transmission for train integrity monitoring, e.g. by equipping trains with a transmitter at the front and at the end [36].

3.5.2 Radio-frequency identification

According to a researched concept, the installation of RFID transponders on freight wagons, for example, allows for identifying the freight wagons when driving past a track-sided detection device [37].

3.5.3 Global navigation satellite system

In the area of GNSS, there are e.g. different concepts to utilize a GNSS sensor as part of an EOT [7], [8], [19]. GNSS can also be combined with mobile communications [38].

3.5.4 Mobile communications

Regarding mobile communications, there are concepts with telematics modules for various e.g. also logistical applications [38], [39]. The concepts also pertain to the combination with GNSS in an EOT to monitor the integrity of a train [40].

3.6 Track- or two-sided solution concept classes

In this section, we consider the two track- or two-sided solution concept classes in the Sections 3.6.1 and 3.6.2: magnetic field sensor and waveguide.

3.6.1 Magnetic field sensor

In the area of magnetic field sensors, there are e.g. concepts for trackside detection of rail vehicles using anisotropic magnetoresistive (AMR) sensors, which allow also for measuring speed [41].

3.6.2 Waveguide

For an electrical waveguide along a track, there is a concept according to which a train sends a signal into the waveguide. A track-sided receiving device processes the signal to locate the train [42].

3.7 Train- or two-sided solution concept classes

In this section, we describe the three train- or two-sided solution concept classes in the Sections 3.7.1 to 3.7.3: ultrasound, radio detection and ranging (radar), and radio.

3.7.1 Ultrasound

With regard to ultrasound, there is a concept on the basis of track-sided devices to detect train-sided ultrasound transmitters at EOTs [43]. In addition, there are train-sided concepts such as sending ultrasound signals from an EOT through the main brake pipe to the traction vehicle or sending ultrasound signals from the traction vehicle into the main brake pipe and measuring the reflection patterns both on the traction vehicle and with an EOT [44].

3.7.2 Radio detection and ranging

In terms of radar, there is a concept for identifying track-sided reflectors from a train and thus improving the self-localization of the train [45]. Conversely, there is also a concept for monitoring train integrity with track-sided radar devices, e.g. at train stations [46].

3.7.3 Radio

In the field of radio, there is e.g. a concept that includes a transmitting and receiving module on the traction vehicle and in an EOT. Based on this, for train integrity monitoring, one module sends an electromagnetic wave to the other one at a defined point in time and the receiving module measures the transmission duration and signal strength [47]. Additionally, there are further concepts that deal, for example, with communication between trains and track-sided devices, e.g. with regard to the positioning of transmitter and receiver units [48].

4 CONCLUDING PART

In this section, we draw a conclusion of our publication analysis and give an outlook on future research work.

In general, we conclude that we have developed a classification for TIMSs with this publication. The classification is based on the idea to distinguish between track-sided and train-sided solution concept classes. Since in reality there are many mixed forms, the classification comprises a total of six main classes and 23 subclasses.

On the basis of the developed classification, we have identified two particularly proven and three especially promising solution concept classes. These classes are the proven subclasses axle counter and track circuit on the one hand and the promising subclasses DAC, DAS and EOT on the other hand.

With regard to the two proven solution concept classes axle counter and track circuit, we consider in particular that they require track-sided fixed block section lengths. Consequently, they are not suitable for the ETCS at level 3 or only suitable as a supporting system in train stations, at level crossings, etc.

Regarding the three promising solution concept classes, there are different advantages and disadvantages. From our point of view, the best long-term solution for European rail freight transport is certainly the implementation of the DAC, but the financing of the high investment costs and the need for a migration strategy still seem to be associated with considerable risks. DAS is a promising technique, although the inability to detect stationary vehicles will require a supporting solution. From our perspective, the further development of DAS and the answers to the current questions will be important. The concept class on the basis of an EOT presently seems to be the best solution for short- to medium-term implementation. In particular, the relatively low implementation costs and the fact that there is no need for a migration strategy allow us to regard the class of EOT as a promising bridge technique to the DAC.

In addition, various further solution concept classes, such as eddy current sensor and optical system, appear promising to support the implementation of the ETCS at level 3.

In the future, in order to be able to evaluate the presented concepts in more depth, we intend to continue researching the requirements for future TIMSs. In this process, we will focus in particular on the reliability, availability and safety of possible future solutions.

With our structured analysis of publications on concepts for TIMSs, we contribute a new classification of concepts for TIMSs and a current overview of corresponding concepts. During our literature research in the last years, we could not find a comparable publication comprising a similar scientific overview. As we attribute great importance to this research field, we close this gap with our present publication.

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