Digital Twin Concept of the ETCS application

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Abstract. This paper presents the concept of a digital twin for the ETCS application. The ERTMS system is a technical solution aimed at ensuring the railway system's interoperability in signaling within the European Union. It is also an essential factor in the digitization and automation of railways. Its complexity needs solutions to support its activities in all phases of the life cycle, particularly design, implementation, maintenance, and operation. A digital twin is a virtual representation of a real system. According to many definitions, this mapping should be as close to identical as possible. Such mapping should, by definition, accompany the real system throughout its lifetime, providing a consistent description of the current state and history of its operation. This mapping should be the primary source of information about the real system for all stakeholders interested in its operation. This paper presents the basic assumptions of the Digital Twin of the ETCS application in terms of its structure and its application to verify its correctness.

Keywords: ETCS application, digital twin, digital railway, modeling, simulation

1. Introduction

The European Rail Traffic Management System (ERTMS) is a system supported by the European Union, aiming to unify the traffic management and control system on the Community rail network. The main objective of its introduction is to ensure the interoperability of rail transport. The ERTMS system consists of the European Train Control System ETCS and GSM-R – a digital railway radio communication system based on the GSM standard. The investments being made to develop the railway infrastructure contribute to the emergence of further ERTMS/ETCS applications (ETCS applications). Such application should be understood as ERTMS/ETCS system implemented on a specified railway network area, e.g., railway line. The ERTMS/ETCS system fulfills the tasks of the Automatic Train Protection System ATP [6], which include:
− determination of the movement authority,
− determining the dynamic speed profile permitted in the permit area,
− supervising the respect of the dynamic speed profile,
− automatically braking the train in the event of danger.

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The correct implementation of these functions shall guarantee the safety of railway traffic on the network under the ETCS application’s control. The proper implementation of the functions is a key requirement for the ERTMS/ETCS system. Its achievement is subject to many activities (testing, certification, verification of the persons involved, standardization of the processes) that have to be coherent and based on the same assessment subject. Simultaneously, it has to be borne in mind that the ERTMS/ETCS application forms a complex system, i.e., one built out of identifiable parts, i.e., objects and subsystems. For such systems, the difficulties in meeting the requirement indicated should not be sought in technical solutions that are already sufficient and are developing all the time. The barrier often turns out to be the enormous amount of knowledge and intellectual effort needed to design and software a given application and prove its correctness [22]. It is therefore essential to look for solutions to support these processes.

The ETCS application forms a geographically broad infrastructure consisting of many physical elements embedded in specific locations. Also, because of its crucial role, its operation cannot be disrupted. These facts significantly limit the ability to conduct research directly on the system. One solution that can be applied in this situation is to create a digital mapping of the ETCS application – Digital Twin of the ETCS application.

This paper aims to present the author’s concept, which will fill the gap in digital mapping of railway infrastructure in terms of the ERTMS system. This is particularly important due to the widespread use of this system on the European Community network soon connected with the implementation of the European Parliament’s Directive and the Council on Interoperability. This paper presents the whole concept at an appropriate level of generality. It is intended to serve as a reference for future detailed publications of selected topics.

2. Digital twin

Issues related to the digital representation of real-world structures and organizations are a topic addressed by many researchers concerned with the combination of scientific research and its practical applications. Over the past few years, a concept that ties together this work has gained popularity, referred to as the digital twin (DT) [2].

![Fig. 1. Structure of a digital twin (source: [2])](image)

The concept focuses on the digital replication of a product/system, covering both static and dynamic aspects. Designed to improve manufacturing efficiency, DT technology is the
digital replication of products/systems, enabling real-time bi-directional communication between cyber and physical space [7]. A review of current scientific papers shows that a definitive definition of the digital twin has not yet been formed. Still, they are all close to the definition given by its creator Professor Michael Grieves, together with Vickers 2017 in [3] "Digital Twin (DT) […] is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. […] That describes […] Operational States captured from actual sensor data, current, past actual, and future predicted. […] for a variety of purposes". From this definition, the level of detail of the mapping depends only on the advancement of development of a given Digital Twin.

Most of the described application examples come from the area of manufacturing processes. DT technology is used to integrate design and production processes. This approach is supposed to ensure better product quality and efficient production. In this respect, J. Guo [4] used a modular approach to help designers build a flexible DT to develop the design in the production line infrastructure. Authors [18] presented a digital twin-based product design method to redesign an existing product iteratively. Authors [16] combined DT with systems engineering based on modeling and simulation in experimental DT, introducing an agile enterprise environmental process covering the entire product life cycle.

Applications of the digital twin for rail transport systems are not apparent in the literature. An application for logistics systems is noticeable. In [5], the authors present such a solution considering different issues of sharing a digital twin by various stakeholders.

Gartner, leading global research and advisory firm, identified DT as one of the top ten strategic technology trends for 2019 [1]. At the same time, Grand View Research forecasted that the DT market would grow to $27.06 billion by 2025, an approximately tenfold increase from $2.26 billion in 2017 [15].

Based on a review of the current state of knowledge on the concept of [11], [19], the digital twin should be understood as an exact digital representation of the real system. Its purpose is to provide services that coherently support all of the issues that occur throughout a real system's full life cycle. The digital twin is a mapping of the system and its environment to map the interfaces between them.

The digital twin is first and foremost a repository in which all the data related to the real system are collected. The collection of this data necessitates the definition of a database structure for their storage. The DT is also a collection of models of selected elements of the real system and algorithms describing processes occurring in them. Thanks to the connection of models and algorithms, the DT provides a simulation environment that makes it possible to map the system's processes.

Considering the characteristics of the repository and the simulation environment, DT provides the service of the research environment, development environment, test environment, diagnostic environment.

 Appropriately selected repository records constitute a design documentation service in the field of design documentation, documentation of the operating process, organizational documentation for processes in the real system.

In operational terms, the DT provides an information service on the current status of the system and historical status records.

To provide services, the DT provides interfaces. These are input interfaces and output interfaces. These interfaces exist between the real system and the mapping and between the mapping and its operator (DT operator).
CB technology fulfills the requirements necessary for studying railway transport systems, where static mapping covers the railway infrastructure. In contrast, dynamic mapping covers the railway traffic and the movements of individual trains. CB is a holistic approach accompanying a real system through its entire life cycle from conception to decommissioning. This is a new approach, the benefits of which can be seen very well in the system design and operation documentation. Tools to support the construction and operation of this class’s rail transport systems are not evident in the state of the art review that has been carried out, and therefore represent an exciting area of research. The digital twin of the railway system is a very broad issue. To develop appropriate solutions, the author focuses on one of the subsystems in the current research phase.

3. The digital twin of the ETCS application

3.1. ETCS application

As already mentioned, an ETCS application is an implemented ERTMS/ETCS system in a defined area of the railway network (e.g., a section of the railway line). Such an area (an ETCS area) is defined by the boundaries through which an ETCS train (a train equipped with ETCS onboard equipment) transits to or from the ETCS area. An ETCS train is in an ETCS area when it is under the supervision of ERTMS/ETCS. The extent of that supervision at a given time and location depends on the level of ETCS application active in the area and the active mode of the onboard equipment. ERTMS/ETCS consists of a trackside part and an onboard part. The trackside part of an ETCS application is static, i.e., its configuration does not change. In other words, a change means a change (re-)engineering of the application. The onboard part is the dynamic part of the application related to the fact that trains enter and leave the area according to a timetable. Their number is variable. Additionally, individual trains can have different operating parameters.

The trackside part consists of equipment that has generic characteristics that are the same for all applications. A given application is defined and shaped by different types of configuration data, hereinafter referred to as ETCS data. ETCS data contain the following types of information:

− ETCS identifiers,
− values of national variables,
− list of groups of balises and balises with their location,
− messages assigned to individual balises,
− list of LEU encoders and their assignment to balises,
− conditions for associating LEU encoder to base layer equipment,
− list of RBCs (Radio Block Center),
− conditions for the association of RBCs to dependencies,
− the configuration of the messages to be transmitted to the train.

The conditions for linking the LEU and RBC with the environment create a description of one more boundary (the first one mentioned is the geographical boundary points - places of transit). This is a constructional boundary between the ERTMS/ETCS system and classic signaling equipment forming the base layer. This description is specific to the description of the interface [8], [9], which include:
a description of the physical medium,
− a list of signals or a data model together with the substantive meaning,
− the logic for exchanging signals or data in the form of combinations thereof or synchronous automata.

An ETCS train running within the ETCS application area is characterized by:
− construction parameters,
− composition configuration parameters,
− braking parameters,
− running parameters.

The creation of an ETCS application consists of an analysis of the organizational and operational requirements defined by the parameters of the expected transport process. Then, on the basis of the results of the analysis, a concept for the deployment of the equipment and the rules for the preparation of configuration data for the identified signaling and traffic control tasks are developed. The concept constitutes the basis for the construction and detailed design and the development of sets of parameter values for all components of the ETCS application. The resulting configuration is verified and validated according to the process described in the PN EN 50128:2011 [13].

The features of the ERTMS/ETCS system application show compatibility with the rationale for the use of the Digital Twin as a tool to support various activities related to the ETCS application throughout its life cycle. This is supported by:
− computer-based, information technology implementation,
− the existing specification in the form of TSIs and their subset,
− the practical need for digital representation related to ongoing implementations on the Polish and European railway network in order to test the installation of the system on individual lines in a consistent manner,
− the significant contribution of computer simulation in the system design methodology.

3.2. Concept of Digital Twin of the ETCS application

The Digital Twin of the ETCS Application (DT-EA) is a refinement and adaptation of the overall concept, and its structure is shown in Figure 2.

Fig. 2. Structure of the Digital Twin of the ETCS application (source: own elaboration).

The real part is the ETCS application and its environment. The virtual part is the digital representation of the ETCS application. Both parts are connected by communication
channels. For better identification, the link from real to virtual space is called the RV channel, and the link from virtual to real space is called the VR channel. These are logical channels and should not be identified with any specific technical solution. The virtual space provides an operator interface through which stakeholders use DT-EA resources.

The Digital Twin of an ETCS application is its digital representation that serves as a repository and universal simulation environment. The repository should be understood as the collection of all data and algorithms describing the application at any moment of its existence. The DT-EA provides a consistent approach in all phases of the life cycle to:

- digital description of the application (project),
- prototyping new solutions for the application,
- monitoring the real state of the system,
- application diagnostics,
- simulation replay of sequences of events that took place in the history of the application,
- simulating various operational scenarios impossible to carry out in reality, conducting experiments;
- testing using algorithms with proven/proven characteristics,
- analysis of real historical data in order to gain new knowledge about the application,
- prediction of undesired situations, failures, or other defined phenomena.

The Digital Twin of an ETCS application has a structure and provides specific functionality. The structure is described by models and the functionality by algorithms. The DT-EA has a modular structure, i.e., the individual models and algorithms are individual entities with defined interfaces to other elements. Interfaces are used to define the relationships between models and algorithms. For describing the DT-EA architecture, an object-oriented methodology is a suitable approach.

DT-EA is structured in models. The models representing the ETCS application environment focus on the trackside infrastructure and on classical base layer signaling equipment. They include:

- a model of ETCS area,
- a model of trackside infrastructure,
- a model of non-ETCS base layer signaling equipment,
- a model of the traffic situation,
- a model of train,
- a model of timetable,
- a model of organizational and operational rules,
- a model of rules for adjusting runs,
- a model of train stabling at stations and passenger stops.

The models representing the ETCS application are:

- a model of balis,
- a model of RBC,
- a model of the arrangement of the trackside ETCS components,
- a model of the balises and RBCs message,
- a model operational scenarios,
- the movement authority model,
- the DMI (Driver Machine Interface) model,
- permissible train speed profile model.
A detailed characterization of all models is beyond the scope of this article.

The behavioral model focuses on the representation of the modeled processes are implemented in the form of algorithms operating on structural models. These include:

- train running simulation algorithm,
- train traffic simulation algorithm,
- railway traffic control algorithm,
- algorithm for verifying the distribution of elements of the control-command basic layer,
- algorithm for verifying the distribution of balises,
- algorithm to verify the correct application of ETCS language,
- algorithm for verifying relationships between balises,
- algorithm to verify time dependencies between ETCS events,
- algorithm to verify braking paths,
- algorithm to verify the realization of operational scenarios.

Also, part of the DT-EA architecture is its interfaces to the real system. The RV channel interface allows loading data into the DT-EA. It allows loading the following data:

- description of track infrastructure,
- messages sent by balises,
- messages sent by RBC,
- messages sent by the train,
- train legal recorder recordings,
- instructions from the DT-EA operator.

Key to the effective use of DT-EA are interfaces to the real system as well as to the operator. The VR channel interface allows data to be transmitted from the DT-EA to the real system. These include:

- result of the verification of the track infrastructure model and the base layer of the signaling system,
- result of verification of the timetable model,
- result of the verification of operational scenarios,
- messages describing railway traffic simulation events,
- description of the identified model element.

The digital twin of the ETCS application has an operator console that allows actions to be performed in the following areas:

- managing access rights to DT-EA resources,
- managing databases and other data storage structures,
- managing the IT infrastructure of the DT-EA,
- view the current status of the ETCS application,
- view the historical state of the ETCS application for a selected period,
- to observe the currently mapped operating processes,
- observation of historical representations of movement processes,
- export data in agreed formats.

Both interfaces belong to the DT-EA architecture and are described by their respective models.
4. Object-oriented methodology

DT-EA is a technical solution in the form of software. An object-oriented methodology is used for its development, which is based on the concepts of object-oriented programming [20], [21]. The basic concept is the object, which encapsulates the properties of the object and the operations that can be performed on the object. It makes available to the environment only selected properties and operations that constitute its interface. The description of the architecture is implemented using languages derived from UML (Unified Modelling Language), namely SysML (Systems Modeling Language) [17] and BPMN (Business Process Modelling Notation). SysML is used for system description, while BPMN is used to describe the processes involved in its application. SysML is a technology that supports Model-Based Systems Engineering (MBSE). Its definition is contained in a non-commercial specification maintained by the Object Management Group [12]. The current version of the specification is 1.6, and it has been used to model DT-EA. The model is described by sysML in four aspects: structure, behavior, requirements, parameters.

DT-EA is characterized by the large amount of data exchanged with the environment. It uses a notation derived from XML, which also follows the object-oriented paradigm. The most important standard from the railway infrastructure point of view is RailML. It is a specialized language for this purpose. Its standardization and development are supported by various railway bodies, which guarantees the universality of the data format. The simulation experiments in this solution are realized in the ERSA Traffic Simulator environment (TS) [10]. This software is a tool for modeling and simulating train movements in the environment of railway infrastructure equipped with ERTMS/ETCS. The simulation in this environment reflects the interaction between trackside and onboard ERTMS/ETCS equipment occurring while the train is running. The tool allows detailed modeling of the actual equipment configuration and application data for ERTMS/ETCS and testing of the models created. The tool allows the exchange of data in RailML format [14].

4.1. Example of application

The experience gained from the EC verification processes of the Control-Command Subsystem, in which the author participated, shows that there is a need to automate the procedures carried out there. One of the initial activities is the verification of the correctness of the draft ETCS applications. Even if not all aspects of this process can be automated due to the lack of formalized rules, such activity contributes significantly to reducing costs and increasing the correctness of the ETCS application. The activities in the later stages of the verification process (certification during the build and final test phases) where DT-EA will be applied are the laboratory tests of the application. The tests shall verify the conformity of the ETCS application with the scope of:

− organizational and operational requirements,
− system requirements specification,
− design principles,
− regulations governing railway operations,
− interfaces with the control-command basic layer system,
− requirements for the EC verification process of the Control-Command Subsystem.
The test suite is divided into static tests and dynamic tests. Static tests check the correctness of parameter values and their mutual relations. They are a continuation of the correctness of application design verification. Dynamic tests check the implementation of specific functions in terms of interoperability of the adopted solutions.

The validation of the ETCS application design is an example of a static test. It consists of a preparatory phase and a real phase. The preparatory phase consists of the collection of data describing the application and presenting them in the form of a model built from the components:

- a model of the ETCS area model,
- a model of the track infrastructure,
- a model of non-ETCS base layer signaling equipment,
- a model of the arrangement of the trackside ETCS components,
- a balise and RBC message model.

Algorithms that process data describing the ETCS application and that check the relevant properties are then executed on the model. Tests are carried out:

- the correctness of ETCS area borders,
- the correctness of transitions,
- completeness of the assignment of LEUs to beacons,
- the correctness of the allocation of balises to LEUs,
- the correctness of rules for the interpretation of light signals by the LEU,
- the correctness of the configuration of groups of balises,
- the correctness of the location of the balises,
- the correctness of the applied ETCS component identifiers,
- the correctness of the links between balises,
- the correctness of the values of ETCS language variables
- the correctness of the use of packages,
- the correctness of message composition.

The execution of each test ends with the preparation of a report. If the result is negative, the report contains a description of the elements causing the non-compliance and a description of the non-compliance.

After testing with negative results, corrections are made to the relevant model, and the next version of the model is approved. After approval, the tests are repeated. This cycle is repeated until positive results are achieved.

An example of a dynamic test is the simulation of an ETCS train running in the ETCS application domain. For its realization, models describing the design of the ETCS application and models:

- a movement authority model,
- a traffic situation model,
- a model of train,
- a model of timetable,
- organizational and operational rules model,
- a model of rules for adjusting runs,
- a model of train stabling at passenger stations and stops,
- the dynamic profile of train running.
The model in the presented form is a virtual infrastructure on which virtual train runs are realized in the form of simulation. The simulation run is realized according to the algorithm of railway traffic simulation and consists of a sequence of steps for specified moments of time, for which the system state is determined in the form of a traffic situation, including:
- state of trackside signaling equipment,
- condition of trains,
- state of trackside - train communication.

The train traffic simulation algorithm includes control-command and train control processes. Depending on the purpose of a given dynamic test, operational scenarios describing relevant sequences of the interaction of the different elements of the ETCS application are taken into account in the preparation of the timetable. Obviously, the final confirmation of the correctness of the ETCS application should be a simulation of all possible journeys using all runs in all operating stations covered by the application. However, it should be kept in mind that the complexity of such a test, which translates into time-consumption, may be an obstacle to the realization of many tests. Therefore, simulations should be carried out gradually.

The use of the Digital Twin of an ETCS application for its full verification consists of the following steps:
- definition of the ETCS application,
- the definition of the ETCS application environment,
- static verification of the ETCS application,
- dynamic verification of the ETCS application.

In the target version, when all tests constituting the EC verification process will be implemented, the Digital Twin of the ETCS application will be a digital representation ensuring the full verification of the ETCS application. The implemented tests will also apply to the other phases of the ETCS application life cycle.

**Conclusion**

The digital twin as a virtual representation of the ETCS applications is a consistent modeling and simulation environment. Independently, as a repository, it provides a universal knowledge base for ETCS applications. Its application to the system is ERTMS/ETCS is a scientific challenge and a practical need arising from the ongoing implementation processes throughout Europe. This paper presents the concept of the Digital Twin, defines the ETCS application and its components, and presents an outline of the architecture for the ETCS Application Digital Twin (DT-EA). As an example application, the procedure for the design verification and the elements for the EC verification of the interoperability of the Control-Command Subsystem in relation to the provisions of the Interoperability Directive is indicated. This example shows how the advanced technology of the ETCS Digital Twin can be applied effectively to railway transport. DT-EA enables automatic checking of selected principles of correct design, i.e., the arrangement of railway signals, the arrangement of balises as well as simulation of train movements according to designed operational scenarios. Both services significantly reduce the duration and costs of the validation of ETCS applications.
The application of the DT concept to ETCS applications is a novel approach and represents the author’s contribution to the development of the concept of the digital twin of the transport process. It is an area of research, which should be the subject of intensive work. The European Community, having an extensive and diverse railway infrastructure and currently implementing solutions based on ERTMS/ETCS, needs solutions, which will ensure effective and flexible use of this technical solution for the development of an ecological and economical mode of transport – the railway.

References
Koncepcja cyfrowego bliźniaka aplikacji ETCS

Streszczenie. W artykule przedstawiono koncepcję cyfrowego bliźniaka aplikacji ETCS. System ERTMS/ETCS jest rozwiązaniem technicznym mającym na celu zapewnienie interoperacyjności systemu kolei w zakresie sterowania ruchem kolejowym na obszarze Unii Europejskiej. Jest również istotnym czynnikiem w procesie cyfryzacji i automatyzacji kolei. Ze względu na swoją złożoność potrzebuje rozwiązań, które będą wspomagać działania z nim związane na wszystkich etapach cyklu życia, a szczególności projektowaniu, wdrażaniu, utrzymaniu i eksploatacji. Cyfrowy bliźniak jest wirtualnym odwzorowaniem rzeczywistego systemu. Zgodnie z wieloma definicjami to odwzorowanie powinno być jak najbardziej zbliżone do identyczności. Takie odwzorowanie z założenia powinno towarzyszyć rzeczywistemu systemowi przez cały okres istnienia zapewniając spójny opis aktualnego stanu i historii jego działania. To odwzorowanie powinien stanowić podstawowe źródło informacji o rzeczywistym systemie dla wszystkich interesariuszy zainteresowanych jego działaniem.

Artykuł przedstawia podstawowe założenia Cyfrowego Bliźniaka aplikacji ETCS w zakresie jego struktury i zastosowania do weryfikacji jego poprawności.

Słowa kluczowe: aplikacja ETCS, cyfrowy bliźniak, cyfrowa kolej, modelowanie, symulacja