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User Needs for the Development of New Methodologies and R&D Tools for Building a Railway Digital Map and for the Experimental Performance Evaluation of On-Board Subsystems

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Abstract

Novel signalling systems are expected to use Digital Maps to implement Automatic Train Operation (ATO) functions or to augment technologies such as European Global Navigation Satellite Systems (EGNSS), inertial sensors or optical sensors for localization purposes. However, the construction of a Digital Map requires with current technologies expensive railway surveying campaigns. Additionally, the cost for their maintenance and update is a major challenge that prevents its adoption. With regard to the evolution of Control-Command and Signalling (CCS) systems, a new verification infrastructure is also needed to characterize new on-board solutions in terms of train position, speed and acceleration errors, as well as to assess their expected performance.

Our research, on one side, aims to develop a methodology and related toolset for executing railway surveying, building and maintaining Digital Maps based on the post-processing of data recorded by trains in commercial service, equipped with Commercial Off The Shelf (COTS) sensors like GNSS receivers, cameras, Inertial Measurement Units (IMUs), and LIDARs. On the other side, a similar approach and development can be used to provide “high precision and high accuracy ground truth reference data” as true values for carrying out error and performance analysis. This Ground Truth methodology does not require installation of trackside equipment or modifications to existing trackside signalling systems and a-priori knowledge of track databases. This paper summarizes the main user needs of (1) the use of Digital Maps for signalling subsystems purposes, (2) the availability of innovative Ground Truth sources for performance assessments. These user needs are essential for the future design of such methodologies and toolsets.

Keywords: Digital Map, Ground Truth, ERTMS, Railway Survey

1. Introduction

In the last decade, many R&D projects have investigated the use of EGNSS navigation and sensors' technologies such as IMU, LIDAR and Camera in Automatic Train Protection (ATP) systems with the objective of improving the performance of the on-board train position and odometry functions and, possibly, reducing the costs of the whole signalling system. The use of Digital Maps in ATPs or ATOs is also assumed to play a crucial role in the evolution of CCS systems. The performance analysis of signalling systems is in most of previous work analysed with project dependent mechanisms and procedures that identify key points along each train trajectory as one dimensional trustable reference locations to compute the position errors. Furthermore, other types of on-board subsystems (e.g. braking or tilting subsystem¹) require the use of “reference ground truth data” to perform verification activities.

¹ A train capable of tilting the bodies inwards in curves are called tilting trains

Unfortunately, there is no agreed methodology for building “reference ground truth data” in railway applications; each project used their own mechanisms and procedures. In 2018, in the context of a R&D GSA project, UNISIG suppliers defined and developed a first Ground Truth methodology [1]. It required the use of the track database and the availability of absolute and relative reference measurement systems associated with the lines for which the Ground Truth had to be built and, therefore, representing a huge investment. Indeed, the need of a track database is a very demanding requirement and the survey procedures for building and maintaining such databases are very expensive and time consuming.

In general, the methodologies for building a Ground Truth investigated up to now also suffers of other two limitations, i.e. it provides (a) “reference ground truth data” for the **train position only** and (b) **no information about the accuracy** of the provided “reference ground truth data”. On the other hand, with regard to the design of Digital Maps and trackside signalling subsystems, they are based on the knowledge of two types of data: (a) the longitudinal positions of Points Of Interests (POIs) (e.g. light signals, ETCS markers) with respect to the track centreline and (b) the grades or slopes of the track segments adjacent to them. Therefore, as a first step, such designs require the acquisition or the verification of the data related to POIs (i.e. nominal values of locations and gradients along with their related accuracies) and this causes extra costs and time-consuming surveying activities leading to delays in the commissioning of the lines.

The R&D RAILGAP project has three main objectives. The first one is the development of an innovative Ground Truth methodology and related toolset that overcome the above described constraints and limitations; they are based on the post-processing of recorded measurement data and provide reference ground truth data and related accuracies for different types of physical entities such as **position, velocity, acceleration, and attitude**. This Ground Truth does not require (a) installation of trackside equipment or modifications to existing trackside signalling subsystems and (b) a-priori knowledge of track databases. The second objective is to perform field surveys by using measured physical entities collected with trains during commercial services for building and maintaining Digital Maps. The third one is the use of Artificial Intelligence (AI) techniques to off-line process big amount of collected data to allow the extraction of the information required for building and maintaining Digital Maps. The RAILGAP measurement system used for both methodologies is composed of COTS sensors like GNSS antenna and receivers, cameras, IMUs, and LIDARs.

This paper presents the user needs related to both methodologies and the expected benefits coming from the R&D RAILGAP project.

2. Ground Truth User Needs

Ground truth provides information on the knowledge of the truth of a measured or observed entity related to a specific application. In a measurement process or during a research activity, the knowledge of the truth value to be measured or of the truth about the hypothesis to be verified plays a key role. This truth knowledge is named “Ground Truth”. This Ground Truth is obtained or computed by gathering the proper objective (provable) data, named “reference ground truth data” or simply “reference data”. In the context of the R&D RAILGAP project, the Ground Truth concept has been defined as:

“Set of georeferenced data with known accuracy, precision, availability and reliability, built by means of a well described process, to be considered (a) a stable and true reference, suitable for the purpose of relative comparison and validation of other data sources in the railway domain according to established requirements and (b) the basis for developing other railway components such a high accurate Digital Map”.

During the first year of the project, we examined different R&D initiatives related to (a) train positioning and

odometry functions, (b) surveys of railway areas aimed at getting the geographical data for designing trackside signalling subsystems, and (c) digital maps for ATP and ATO systems. This analysis has allowed the identification of the types of “reference ground truth data” that might be required for performing the quantitative performance assessment of new products (e.g. kinematic sensors, GNSS receivers), subsystems (e.g. Odometry, Train Positioning, Braking, Doors Management), systems (e.g. ERTMS/ETCS, ATO) or survey processes (e.g. those used for designing signalling systems or building Digital Maps). The following examples are used for describing some results of the analysis of the RAILGAP Ground Truth user cases. Let us suppose that a train position function has to be characterized for correctly sizing the **safe confidence interval** under any possible environmental and operational conditions. This characterization has to consider the different sources of noise, biases and environmental conditions that can impact the performance or safety. Consequently, this activity cannot be only done by laboratory verification tests since experimental field data are essential to evaluate the effects of external influences such as, radio frequency interferences, vibrations, multipath, NLOS, adhesion factors between wheels and rail, and styles of guidance of the train drivers.

To reach this objective, the test facilities have to allow the collection of the measurement data and the execution of a comparative analysis w.r.t. related ground truth data. Thus, there are a Unit Under Test (UUT) which includes the Train Position function and the set of sensors required (e.g. wheel sensors, accelerometers – usually supplier dependent) for estimating the train position and Ground Truth facilities with their own sensors, i.e. IMU, LIDAR, Camera and GNSS Receiver. The UUT directly or indirectly via an external data record unit records the Estimated train Position $EP(t)$ values, timestamped with GPS time, to allow offline post processing. Each $EP(t_i)$ value represents the front end position of the train Active Cabin at the time instant t_i . On the other hand, the Ground Truth facilities are made up of both on-board and trackside components; the former is the measurement environment responsible for (a) collecting measured data timestamped with GPS time during each train ride and (b) sending them to trackside component; the latter contains tools for building the ground truth, i.e. sequence of reference data $GT(t_k)$. Each $GT(t_k)$ represents the truth front end position of the Active Cabin that the train had during the train movement at time instant k , projected at the track centreline on the rail plane. The Ground Truth facilities also produce the truth travelled distance values starting from the sequence of $GT(t_k)$ reference data. Therefore, the comparative analysis of $EP(t_s)$ values stored during a train ride “i” can be done by using the ground truth reference data related to the same train ride “i”. Let us suppose that two different field test train rides have been executed, one at day “i” and the second one at day “k”; both started from the same location towards the same final location, and characterized by two different speed profiles. Figure 1 outlines the position errors occurred during the two train rides at the same relative time instants t_1 , t_2 and t_3 from the starting time. Table 1 summarizes such position errors for the simple case of two train rides and three time instants only. The analysis of errors in time can allow the detection of correlations between the position errors and the related occurrence time instants; for example, GNSS technology can present unacceptable performance in some daily time windows due to the occurrence of low DOP values or time-dependent local multipath phenomena. On the other hand, the train position function has to constantly and safely compute the train confidence interval; therefore, the analysis of the position errors at any location has to confirm that the true train position always lie² within the interval [minimum safe front end position, maximum safe front end position]. Table 2 reports the position errors occurred during the train rides only at the two locations S1 (e.g. Danger Point location) and S2 (e.g. Imperative Signal location). It is evident that an accurate characterization of the train position function requires a statistical inference analysis based on many train rides, large numbers of time instants and locations so as to define and dimension the Error Models of Train Position and Odometry functions. The Ground Truth facilities have to provide support for these analysis and the Ground Truth methodology has to be defined to automatically recognize the route followed by the train during the field measurement campaigns (i.e. has to

² According to the required confidence level.

discriminate the track) and has to guarantee a robust behaviour with respect to events that influence the train position performance.

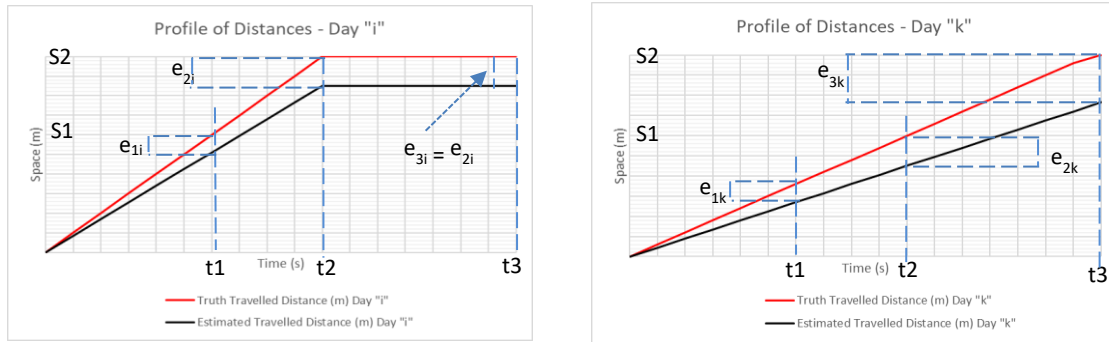


Figure 1: Truth and Estimated Travelled Distances and Related Position Errors

Relative Time Instant (s)	Position Error –Day “i”	Position Error –Day “k”
t1	e_{1i}	e_{1k}
t2	e_{2i}	e_{2k}
t3	e_{3i}	e_{3k}

Table 1: Position Errors vs. Time Instants

Truth Travelled Distance (m)	Position Error –Day “i”	Position Error –Day “k”
S1	e_{1i}	e_{2k}
S2	e_{2i}	$e_{3k} = e_{2i}$

Table 2: Position Errors vs. Ground Truth Locations

In addition to the train position function, there are other signaling functions for which the Ground Truth plays an important role. For example, Ground Truth has to allow the characterization of the Standstill function, i.e. verification of: (a) minimum speed for notifying the standstill condition during the decreasing speed process, (b) maximum speed for exiting from the standstill indication, and (c) travelled distance for exiting from the standstill indication during low speed movements.

The RAILGAP Ground Truth methodology and related toolset [2] provides ground truth data for different types of physical entities such as position, velocity, acceleration, and attitude (i.e. pitch, roll and yaw) and facilities for efficiently supports error and performance analysis on signalling functions or on-board equipment.

3. Digital Map User Needs

The ERTMS principles for monitoring and controlling the safe movements of trains use two types of location based data [3], *location* and *profile* data, which are referred on the track with respect to LRBGs. The design of any ERTMS/ETCS trackside signalling system requires [3] the **correct installations of reference points** (in terms of balise locations in the track), and the setup of ERTMS/ETCS **trackside configurations to dimension the trackside data** to be sent to on-board, e.g. **distances of fixed signalling targets³ from LRBGs**.

To this end, the trackside design documents would contain geographical data of fixed existing Points of Interests (POIs) with respect to the centrelines of tracks, e.g. signals, joints, toe of points. The geographical data are set

³ A signalling target is defined as the couple {target location and target speed} to which a train must decelerate before reaching the target location [3].

out as the results of trackside surveys (eventually carried out during the construction of the line if still valid) and are composed of two known components, i.e. POI Location and POI Gradient. The former is the POI longitudinal position along the track centreline; whereas, the POI Gradient is the grade or slope of the track segment adjacent to it, and defines the input data for the profile used by an on-board equipment for performing the ERTMS speed and distance monitoring [3]. In consequence, all the POIs have a defined position along the track, according to the trackside surveys while the data regarding the type and location of the signalling targets is transmitted to the on-board constituents via balises located along the track or an RBC. Therefore, the final accuracy of the target location in the ERTMS/ETCS system depends on several factors that goes from the track survey precision, passing through the longitudinal accuracy of each balise location, up to the accuracy of the relative (rolling) distance between a fixed target and the last balise group (i.e. LRBG).

With regard to the evolution of ERTMS/ETCS, the use of an ATO subsystem leads a Digital Maps to be a mandatory component. Furthermore, in the context of innovative train localizations that use technologies such as, for example, GNSS receivers eventually aided with an IMU or a combination of IMU and LIDAR, the use of a Digital Map can enable the exploitation of the track geometry for (a) computing a track constrained position solution with better location accuracy [4],[5], (b) determine on which track the train is operating when the line consists of parallel tracks, (c) detecting the train passage over known trackside locations usable for reducing the train confidence interval, and (d) providing continuous input to update the trackside inventory. In consequence, the Digital Map could lead to define new POIs that provide additional information to increase or optimize the system performance. The RAILGAP Digital Map focuses on the description of the railway network infrastructure and addresses topics related to the following information:

- Railway infrastructure elements: in the RAILGAP Project, these elements consider the Commission Regulation (EU) No 1299/2014 [7] recommendations such as track geometry, gradient, curvatures, height of the check rail, cant, gauges;
- Trackside signaling elements: for example, signals, Eurobalises, marker boards, points, buffer stops, level crossings, fouling points;
- Track elements: for example, tunnels, bridges, viaducts, platforms, pole of overhead power line.

The main user needs behind the design and generation of the RAILGAP Digital Map are based on (see Figure 2):

- The post processing of imaging and ranging sensors' records (done by using cameras and LIDAR) aimed at detecting the railway infrastructure elements and estimating their relative positions w.r.t. the train position;
- The combination of the train location derived from sensors' data with the object's relative position and the absolute (geographic) object's location based on previous runs stored in the Digital Map to set/update the absolute position of each infrastructure element. The process of building the Digital Map is an incremental process that improves the accuracies of the Rail Net Elements by increasing the number of runs;
- The post processing of the GNSS records aimed at detecting the presence of local phenomena (multipath, EMI) [8] and estimating their temporal occurrence during a run;
- The combination of the train location derived from sensors measurements with the temporal occurrence of the events associated with the presence of immaterial objects to set/update the absolute (geographic) position of each of them as a function of the train mileage, based on the post processing of the GNSS records.

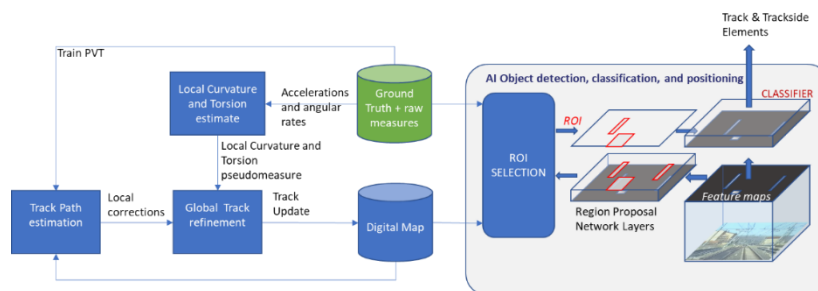


Figure 2: Methodology for digital map generation, verification and validation

5. Conclusion

Even though different R&D projects used LIDAR, IMU and EGNSS, only some of them have done an accurate technology characterization in railway environments. In addition, the Ground Truth facilities developed up to now satisfied specific projects' needs only and required significant investments. Furthermore, no public information is available on methodologies for executing accurate and precise railway surveys and building Digital Maps, by using measured data collected with commercial trains.

The RAILGAP project aims at providing the characterizations of the LIDAR, IMU and EGNSS technologies in railway environment and the definitions of both methodologies (i.e. Ground Truth and Digital Map) to the R&D communities as project public deliverables. In particular, the RAILGAP Ground Truth provides "reference data along with their accuracy" for different types of quantities to be monitored (i.e. position, speed and acceleration) and does not require installation of trackside equipment and the a priori knowledge of the database of the lines.

The RAILGAP project objectives have been conceived from the analysis of the real needs of the project beneficiaries RFI and ADIF in the role of Infrastructure Managers, and Trenitalia in the role of the Railway Undertaking. The project started on Jan 2021; the first year has been focused on the user requirement phase related to Ground Truth and Digital Map and the identification and characterization of the measurement sensors to be installed. The installations of the sensors and the field test campaigns for recording measurements will start on 2022 both in Italy and Spain along with the technologies' characterizations. The last year (2023) will complete the tools' development and their verification.

RFI and Trenitalia have already planned the use of our research outputs during the deployment of the satellite-based Italian ERTMS solution; whereas, ADIF will use the project results for supporting the system requirements phase for Spanish ERTMS applications. In addition, from 2022, Hitachi Rail STS will apply the results of our research to the Hitachi Innovative Train Position under development.

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