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Intelligent in-service shunters in German harbor railways

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Abstract

The DLR Institute of Transportation Systems is an active member of several research projects funded by the German funding initiative IHATEC. These projects involve shunters in harbor railways that are equipped with intelligent sensor units, with different applications in focus. The paper gives a technical perspective on the multi-sensor systems to collect data on in-service vehicles, positioning algorithms that calculate the accurate geo-information which is key to intelligent applications, and advanced condition monitoring using axle-box-acceleration data.

Keywords:

Railway, industry 4.0, German harbors, multi-sensor systems, positioning, condition monitoring

Introduction

The railway sector has great potential to contribute towards more sustainable transportation in many ways. Harbor railways are of particular interest because of their central role in the transfer of goods between cargo terminals and the inland. From the fact that railway must always be understood as a complex system of vehicles (locomotives, wagons) and the infrastructure (rail networks, signals) follow demanding challenges. For instance, shunters (US: switchers) must be well-coordinated in order to minimize transit times and efficiently use the limited capacity of the harbor railway networks. The harbor railway infrastructure is subject to particularly intensive use and must be maintained accordingly. Defects in the infrastructure must be prevented and maintenance actions must be well-coordinated so that no further bottlenecks are introduced in the transportation process.

It must be noted that the railway sector is rather conservative regarding the implementation of novel solutions for the above and further challenges. Reasons for this include the long lifetimes of rail vehicles and infrastructure, strict safety regulations, but also long-established maintenance routines and their documentation. It follows that technical solutions must be able to work also on vehicles that have been in operation for decades. Novel condition monitoring and maintenance approaches must first complement the existing ways of working. With the often outdated and costly maintenance schemes in place, however, the potential of novel solutions quickly becomes apparent.

The present work describes how multi-sensor systems on in-service shunters and the acquisition and intelligent processing of data can contribute towards more competitive harbor railways. Details of three research projects are provided, all carried out within the IHATEC program [1] of the German

Federal Ministry of Transport and Digital Infrastructure (BMVI). The project titles (in German) and the DLR contributions relevant for this article are:

- *Ortung im Hafen* (12/2017 to 03/2019) – track-selective positioning of shunters in the Hamburg harbor railway using low-cost portable onboard sensor systems, applications to train operator management and charging of infrastructure usage;
- *HavenZuG* (12/2018 to 11/2021) – condition-based maintenance of the railway infrastructure using onboard sensor systems that collect and analyze geo-referenced axle-box-acceleration and camera data; operation and experiments in the Hamburg and Braunschweig harbor railways;
- *Rangierterminal 4.0 (*06/2020 to 05/2023) – contributions to positioning for autonomous shunting in a pilot project in the JadeWeserPort Wilhelmshaven.

Some similarities can be highlighted. The above projects should be understood in an industry 4.0 context, with sensors and intelligent data processing schemes that facilitate novel services and ultimately reduce costs. All employ autonomously operating multi-sensor systems using low-cost hardware. The estimation of accurate, track-selective vehicle positions and other quantities of motion is important, with real-time applications in the first and third and the benefit of post-processing in the second project. The first two provide novel services to infrastructure and railway operators, whereas the third touches safety-critical aspects and ultimately contributes to autonomous rail vehicles. It should be noted that research on non-safety-critical applications can yield valuable insights also for safety-critical positioning, and provide the much-needed flexibility for advancing novel technologies. The above IHATEC projects are good examples for the application-driven research that is the core interest of DLR.

The outline of the paper is as follows. The following sections highlight aspects of the DLR work on multi-sensor systems, positioning algorithms, and condition monitoring using axle-box acceleration data. Finally, some concluding remarks are provided.

Modular low-cost multi-sensor systems

Over the recent years, researchers at DLR have developed several variants of modular multi-sensor systems for use on in-service rail vehicles. The in-house development is motivated by a lack of commercial products that satisfy the specific needs of the respective research questions. The prototypic systems are used to show the feasibility of technological solutions and to collect the required data for our application-driven research. Figure 1 shows an example of the multi-sensor system that is used for HavenZuG and permanently installed on a shunter in the Braunschweig harbor.

Figure 1 - The main part of the multi-sensor unit that is installed on a shunter in the Braunschweig harbor railway. An industrial PC is visible on top, the remaining components including GNSS receiver and IMU are underneath. Not illustrated are the GNSS and communication antennas and the ABA sensors.

In order to serve for positioning and condition monitoring applications the multi-sensor systems are equipped with a number of central components. For onboard positioning, receivers for global navigation satellite systems (GNSS) such as GPS and Galileo are employed. GNSS [2] is a key technology that offers immediate access to global position and speed information. Because of large container stacks and other obstacles, as well as sub-optimal antenna placement on shunters, the GNSS signal reception is often compromised in harbor railways. Inertial measurement units (IMU) are used as complementary sensors that measure three-dimensional accelerations and turn rates, from which position and velocity information can be derived. Whereas IMU technology did cost a fortune and was mostly used on aircraft and rockets only decades ago, low-cost miniaturized MEMS IMU [3] can be found in every smartphone today. GNSS and IMU components make up the minimum sensor set-up for state-of-the-art positioning. With their ubiquitous availability, prices for GNSS and IMU hardware are as low as tens of Euros for typical components off-the-shelf (COTS) choices. Condition monitoring requires data that carries information about the health of, for instance, the tracks in a harbor railway network. Potential candidates include cameras (specialized or general purpose) and the axle-box acceleration (ABA) sensors highlighted here. Similar to IMU, three-dimensional accelerations are provided. Differences include the ABA sensor mounting positions in the vicinity of wheels and axles, which can be at a considerable distance from the remaining hardware. Furthermore, ABA data are sampled at much higher rates (up to several kHz) than IMU (depending on the application from 10 to 200 Hz). Analog ABA sensors require an analog-to-digital converter (ADC) as extra component. In the current market ABA/ADC-combinations are beyond low-cost, with prices of

1000 Euros upwards depending on the specific choice.

The multi-sensor systems are equipped with computing hardware to collect and process the sensor data, among further tasks. Depending on the application, budget, and requirements, the range of devices can vary from single-board computers (SBC, similar to the popular Raspberry Pi for tens of Euros) to industrial PC (1000 Euros upwards). The SBC option is especially suitable for low-cost sensor units and has been used in *Ortung im Hafen* for the positioning of shunters in the Hamburg harbor. The more expensive industrial PC typically come with the advantage of a rugged design, more interfaces (for example PCI-e slots), and other features. Further components include communication devices for the LTE or upcoming 5G mobile network and solid-state-drives (SSD) for the reliable storage of large data sets. From a hardware perspective it is important to discuss the power supply as sensitive component in the rail environment. Here, galvanically isolated rail-certified components must be chosen because the power supply is an unavoidable interface to the host vehicle power network in a permanent installation. In order to bridge short power outages and ensure controlled operation and shut-down, an uninterruptable power supply (UPS) is part of all multi-sensor units.

From the application on in-service rail vehicles follow strict hardware requirements. Obviously, the multi-sensor systems must not interfere with existing signaling and protection systems of the shunters and the infrastructure. Hence, interfaces to built-in vehicle sensors are typically not available. Rooftop antennas must be rail-certified. Alternatively, small and low-cost cabin antennas have been used, with effects on the GNSS reception that must be compensated by multi-sensor positioning algorithms. All hardware must provide a certain robustness. On the one hand, all components of the multi-sensor systems must be protected from dirt, moisture, and impact using appropriate housing, and reinforced cables and connectors. On the other hand, the system must not pose a hazard for the vehicle and, for example, needs to be equipped with a fire-proof housing. For a comprehensive summary of requirements, the reader is referred to the EN 50155 international standard [4]. The use on in-service vehicles often requires a permanent installation. Here, custom hardware mounting solutions have been designed at DLR. Examples include magnetic antenna and camera mounts as well as adapter plates to attach ABA sensors to vehicle bolts. The internal components are held in place by custom made 3D-printed device mounts.

The popular software framework ROS [5] is used for sensor data acquisition and processing. ROS provides a modular architecture with individual nodes for each sensor and processing block. The individual nodes exchange pre-programmed messages. One especially useful feature of ROS is the recording of ROS-bag files that contain a stream of messages and that can be conveniently re-played for experiment purposes in the back-office. The data gathered by the different multi-sensor units is further processed at DLR and stored in a data management system for later use.

Positioning Algorithms

The term positioning here refers to the estimation of the dynamically changing rail vehicle position and other quantities of motion using onboard sensor and map data. Position information is a crucial ingredient of future railway systems because it facilitates services such as advanced fleet and railway operator management, infrastructure usage assessment and documentation, data-driven condition monitoring via the analysis of geo-referenced monitoring data, and ultimately autonomous rail vehicle operation.

From a research perspective, positioning is a topic with many interesting challenges. There are recent technological improvements. For instance, GNSS receivers nowadays process not only GPS but also the signals of the European Galileo system, possibly in several frequency bands with advanced processing schemes that exploit the respective signal structures to obtain improved accuracy [2]. With GNSS as ubiquitous technology, receivers and antennas become better and more affordable. Conversely, the railway environment and especially harbors exhibit many challenging GNSS characteristics such as non-line-of-sight and multi-path errors. Intermediate GNSS outages must be compensated with complementary sensors. Here, IMU are the most obvious candidates. However, the typical bias errors that low-cost MEMS IMU exhibit must be estimated in addition to the position and velocity information. The actual combination of different sensor data with individual sampling rates and the characteristic errors is best addressed with algorithms from the field of statistical sensor fusion. Here, Kalman filters (KF) [6] are an established tool. Furthermore, map data must be incorporated in order to exploit the rail-constrained vehicle motion, which is a bit of a challenge in the KF world.

The introduction already distinguished between online and offline positioning algorithms. The former processes an incoming stream of measurements to estimate the current vehicle position. The latter operates on batches of previously collected sensor data. In the KF literature [6] the latter is called smoothing, as opposed to online filtering.

In order to incorporate context knowledge about the rail-constrained vehicle motion that must take place along paths in the railway network, the inclusion of map data is crucial. Here, the railway network geometries and topology are important. With geometry information the two-dimensional position estimation in the horizontal plane can be reduced to a scalar estimation problem of the along-track distance for a single track. Because the motion typically happens over several switches, the topology information becomes relevant. Only allowed transitions from track to track should be considered as valid solutions. The pre-processing of openly available map data for use in track-constrained positioning is a large topic in itself.

The offline positioning chain of [7] has been refined within the IHATEC projects, and works as follows. First, the available sensor data batches of entire measurement days or sessions are divided into journeys that comprise single sequences of vehicle motion without intermediate stops. Hence, each journey comprises either forward or backward motion. The on-track velocity does not change sign. The separation into journeys is carried out with the help of the GNSS speed information and the IMU data. The latter can be used to detect vehicle standstill phases robustly. Given a single journey the path taken in the railway network can be estimated using the entire GNSS data and the map. From potential start and end tracks of the journey that are estimated from standstill data, the network is queried for the possible paths that connect them. The GNSS data are then projected onto the path hypotheses. Wrong paths exhibit overall higher projection errors. Intermediate GNSS errors in underpasses or next to obstacles result in fewer larger projection errors. With considerate robust averaging, the correct path can be found in most cases. Given the path, a path-constrained KF is used with the along-track position and velocity in its state vector. Depending on the use case, further state components such as the IMU biases can be included. Furthermore, the offline extension of the KF, Rauch-Tung-Striebel smoothing, can be used. From the input data of ca. 1 Hz GNSS with intermediate outliers, ca. 100 Hz variable IMU data, 100 Hz constant on-track position and velocity data are obtained. Furthermore, uncertainty information is provided in the form of covariance matrices. With the above offline positioning used to create position stamps for monitoring data, it can be interpreted as geo-referencing of monitoring data.

The online case is more difficult because the path and journey estimation cannot be carried out separately. However, standstill and motion detection from the GNSS and IMU data can still be applied to devise different KF motion models and update steps. Path estimation can be used online by continuously considering a list of possible paths. That is, if a vehicle passes a switch, new path hypotheses are created. For each path hypothesis a separate KF is operated. The different KF or hypothesis are continuously evaluated using the GNSS data. Paths that perform badly (by showing large GNSS residuals in the KF) are discarded and likely ones are maintained. In addition to the KF tools a dedicated hypothesis management is required in the positioning algorithm, including routines for creating new and merging hypotheses.

Monitoring data analysis

The following paragraphs discuss the use of geo-referenced ABA data for condition monitoring purposes.

For monitoring the track condition, accelerations at the axle box are recorded continuously during regular operations. The measured vibrations consist of different components caused by various sources. In particular they comprise the dynamic vehicle-track interactions excited by the common surface of wheel and rail. The analysis of collected ABA data therefore has the potential to give information on the existence of wheel and track defects and their severity. Numerous research papers have shown that the use of acceleration sensors is in general suitable for monitoring the track quality [8]–[11]. The idea behind a data collection with embedded sensors on in-service vehicles during regular shunting operations is to quasi-continuously monitor the condition of the railway infrastructure in order to timely detect evolving defects and to reduce work load for infrastructure maintainers. Traditional inspection methods as the usage of measurement trolleys are on one hand expensive and can on the other hand only be performed when there is no traffic in the respective track area, limiting the availability of the infrastructure. They therefore are only applied rarely, often time-based after fixed intervals and hence are not suited for timely detection of e.g. suddenly appearing defects, or to continuously monitor the track condition. For the railway infrastructure in harbor areas with huge transport amount and many diverse infrastructure operators like the Hamburg harbor rail network, the minimization of infrastructure unavailability due to failure, maintenance or inspection is crucial. In smaller harbor areas as in Braunschweig the focus is more on reducing the work load for inspection and maintenance staff.

In order to obtain data describing the real condition of the infrastructure, reference measurements of track geometry parameters as track gauge or twist and of the rail longitudinal profile have been performed in two subsequent years (2019 and 2020) for the main part of the Braunschweig harbor railway network and several tracks of the network of Hamburg Port Authority. This data serves as ground truth for ABA data analysis. EN/DIN norms as well as standards and rules of e.g. Deutsche Bahn and requirements of the infrastructure operators provide a basis for assessing track segments based on the measured parameters. The reference data and relevant features obtained from ABA data can be illustrated in an interactive web-frontend. Figure 2 shows the measured track gauge in Braunschweig for two track segments as displayed on the frontend. Red bars correspond to locations of the track where gauge narrowing has been detected.

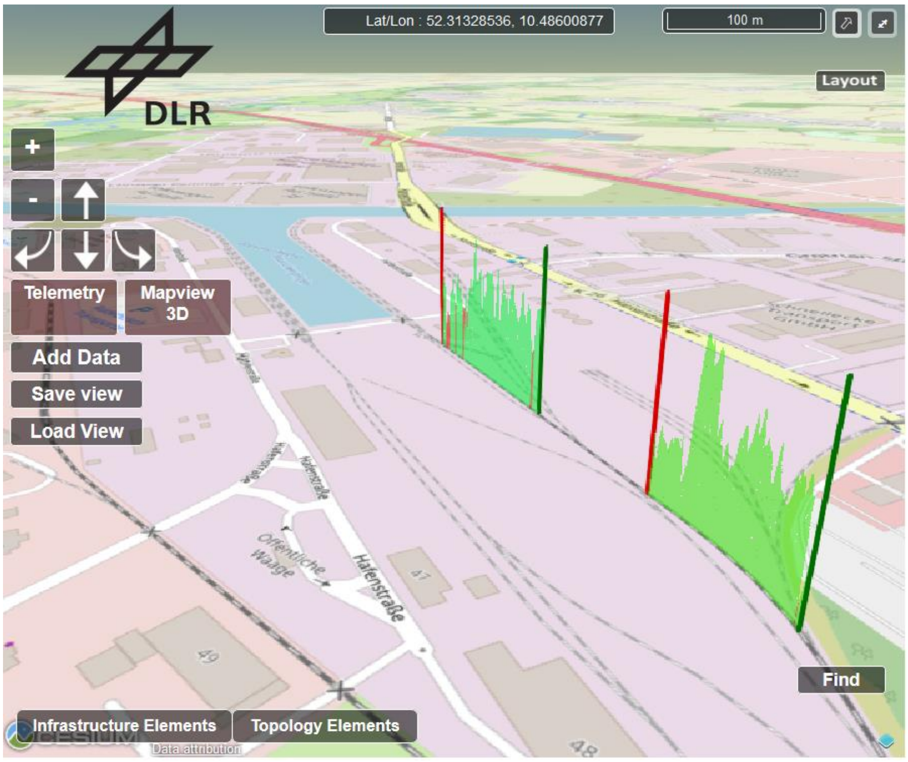

Figure 2 - Frontend visualization of reference data (track gauge).

Red bars show areas of narrow track gauge.

The aim of *HavenZuG* [12] is to detect defects as e.g. gauge narrowing from ABA data and to differentiate between different failure types, for example by deriving classifications of track segments concerning different aspects of the track condition from ABA data that coincide with the results from the assessments based on the reference data respective the considered parameter [13]. Challenges in the present research resulting from the harbor-specific setup are e.g. given by low vehicle speeds and a data collection during shunting operations which comes with disturbing vibrations and shocks.

ABA data analysis addresses identification and extraction of relevant features from ABA time series, clustering as well as identification and separation of relevant signal components, e.g. in the time-frequency domain [14]. Features can be extracted in the time domain (e.g., maximal amplitude, root mean square, crest factor, percentiles) of the broadband signal or bandpass filtered components, in the space domain or in the time-frequency domain.

Fine-tuning of the relative position of ABA data from different journeys measured at the same track segment can be done by comparing the ABA raw and processed signals. This process requires a high a priori position accuracy and should be done for smaller segments of up to several meters. Varying speed accuracy and speed differences between journeys for which the data is compared raise challenges in synchronizing the data in both the time as well as in the space domain. Approaches to find the final high-accuracy absolute position of aligned signals are to average shifts of different journeys (which does not require reference data information) or to align with respect to the position information given by the reference data using distinctive shapes in ABA and reference data (longitudinal profile), e.g. welds. Figure 3 shows multiple ABA signals of a specific track segment where the locomotive drives backwards, in all depicted journeys. The reaction at a weld at m 29 is suitable for synchronizing the different signals for that subpart of the track.

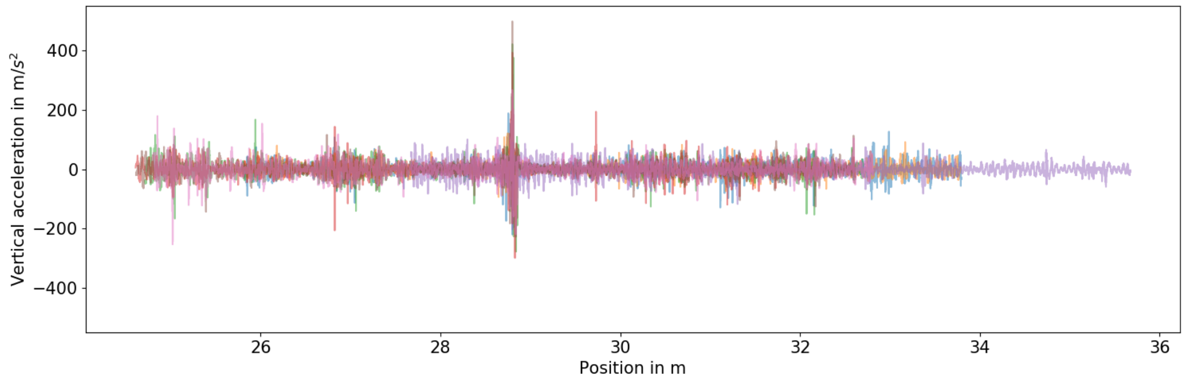

Figure 3 - Vertical acceleration measured at multiple runs over the same track segment.

One example for deriving information concerning the track quality from ABA data is a processing sequence where rail longitudinal profile parameters are extracted in order to detect periodic defects of the rail surface. The reference data which comprises the corresponding information is the rail longitudinal profile. The ABA data is processed via double integration, transition to the space domain and bandpass filtering to the wavenumber domain of interest. Figure 4 shows the bandpass filtered rail longitudinal profile (reference data) for wavelengths from 0.03 to 0.1 meters and the double integrated and bandpass filtered ABA data for one track of the harbor network in Braunschweig. The obtained components from reference and ABA data show different absolute values but a similar shape. By comparing the mean absolute values to thresholds, track segments of fixed length are classified based on reference and ABA data. Alternatively, other parameters than the absolute amplitude can be used (e.g., ratio of threshold exceedances per segment). Thresholds are wavelength-specific and differ from reference to ABA data.

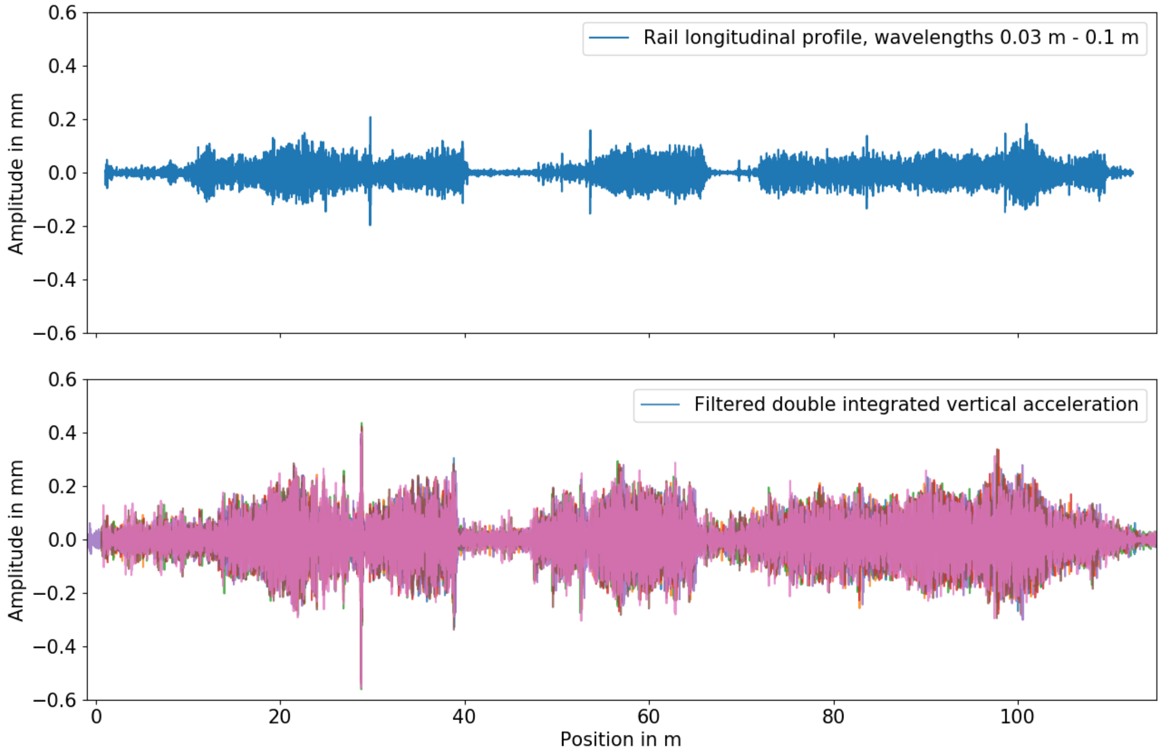

Figure 4 - Filtered rail longitudinal profile (reference data) and filtered double integrated vertical acceleration of multiple crossings of the same track (bottom).

The given track is for large parts affected by corrugation. Figure 5 illustrates the classification results obtained from reference and ABA data.

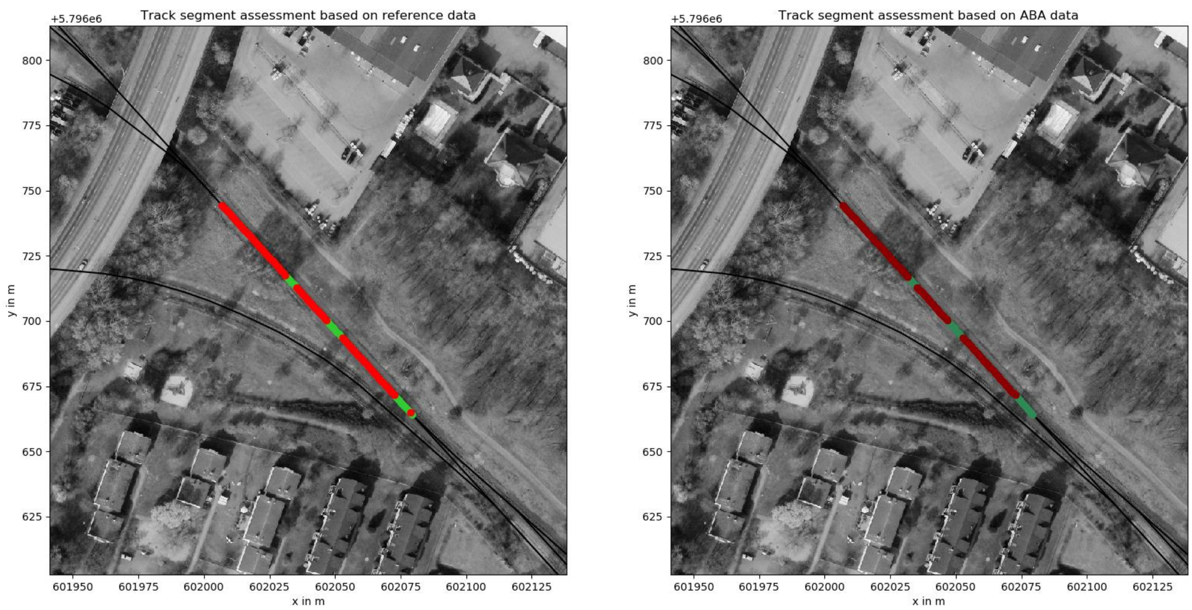

Figure 5 - Corrugation detection based on reference and ABA data.
Aerial image: Digital Orthophoto, 2014, Stadt Braunschweig.

On the left aerial image light red points display parts of the track where corrugation is detected from the reference data (measured rail length profile) and light green points mark the parts without corrugation. The length of the assessed segments is 1 meter, with 10 cm overlap. On the right side, dark red points illustrate the position of track subparts where corrugation is identified from analyzing the ABA data, and dark green points the ones where no corrugation is detected from ABA data.

Concluding remarks

This paper has presented the research work of several DLR research projects within the IHATEC program. Aspects of multi-sensor systems, positioning algorithms, and condition monitoring using ABA data have been discussed. Given the limited scope of the paper many relevant topics were only briefly mentioned. This includes algorithmic and hardware details, data management, and the preparation of map data. Future topics that will have an impact on multi-sensor systems and intelligent data processing for rail vehicles include the use of novel communication technologies and the machine learning algorithms based on deep neural networks.

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