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Track geometry monitoring by an on-board computer-vision-based sensor system

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Abstract

This paper illustrates some outcomes of the EU project Assets4Rail, funded by the Shift2Rail Joint Undertaking, as well as on-going research developments.

Nowadays, many Track Recording Vehicles (TRV) are equipped with contactless optical/inertial systems to monitor Track Geometry (TG). The dedicated trains and sophisticated measurement equipment are costly to acquire and maintain. Therefore, the interval between two TRV recordings of the TG on the same line section cannot be too short (twice per month to twice per year).

Recently, railway operators are showing increasing interest in the use of commercial trains to monitor track condition in a cost-effective manner.

TRVs' expensive and constantly maintained optical systems make them unsuitable for commercial fleets. On-board sensor systems based on indirect measurements such as accelerations have been developed in various studies. While detection of the vertical irregularity is relatively straightforward through double-integration of the recorded acceleration, it is yet an unsolved issue for lateral irregularities due to the complicated relative wheel-rail motion.

The investigated system conceptually combines on-board measurements of wheel-rail lateral relative position and lateral axlebox acceleration to detect rail alignment variations. It includes a functional prototype of an on-board Computer Vision (CV) sensor capable of monitoring the Lateral Displacement of the Wheel with respect to the Rail (LDWR). Further progress is aiming at the reduction of the measurement errors due to wheelset lateral displacements relative to the track, which is essential for calculating rail alignment.

The sensor system prototype was tested in Italy at 100 km/h on the Aldebaran 2.0 TRV of RFI (Rete Ferroviaria Italiana), the main Italian Infrastructure Manager. It was found that the estimated lateral displacement correlates to the lateral alignment acquired by the Aldebaran 2.0 commercial TG inspection equipment.

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Moreover, a Simpack® simulation of a multi-body model of Aldebaran 2.0 provides the axlebox acceleration values not measurable during the test runs, to evaluate the relationship between them, LDWR and track alignment.
Keywords: Track Geometry, monitoring, Sensors, Commercial Trains, Lateral Displacement, Simpack®

Introduction

The idea of this work started from the Assets4Rail project, funded by the Shift2Rail Joint Undertaking [1]. The project was developed from December 2018 to December 2021 with the major goal of developing a set of cutting-edge asset-specific measurement and monitoring devices towards cost-effective and reliable infrastructure. The project was divided into two Work Streams (WS). The first WS dealt with monitoring and upgrading solutions for bridges and tunnels, and the second addressed monitoring solutions for three railway assets: trains, track geometry, and data collection from fail-safe systems [2].

This article includes some Assets4Rail findings related to the development of an on-board contactless sensor system to support track geometry measurements, as well as the outcomes of a subsequent and ongoing research activity conducted by railway group of SAPIENZA University of Rome, whose aim is to accomplish the research by developing the sensor system hardware, performing validation tests as well as implementing a simulation to overcome the challenges of the validation tests in a real environment. The results support the design of a robust and cheap TG monitoring system capable of detection of rail lateral irregularities and suitable for mounting on commercial trains.

Background

This research concentrates on track geometry monitoring, which is an important activity for ensuring the safety of railway operations. It is presently carried out by Infrastructure Managers using Track Recording Vehicles (TRV) or hauled Track Recording Coaches (TRC) that can analyze track conditions and detect potential problems early [3]. The study in the field of these diagnostic activities is primarily focused on improving maintenance strategies while also lowering infrastructure management expenses.

The focus is on track geometry monitoring systems based on contactless optical/inertial technologies (Fig. 1). The rail profile and rail location are measured with optical sensors, while the linear and angular accelerations are provided by an inertial unit. The measurement of track geometry characteristics- including gauge, cross level/cant, longitudinal level, alignment, and twist - by using a combination of the optical and inertial data allows for the determination of track geometry quality. European Standard EN 13848-1:2019 provides specifications for the major track geometry characteristics, as well as measurement criteria and analysis procedures [4].

Figure 1. Track geometry monitoring system composed of an inertial unit and two optical sensors (source MERMEC)

TRV and TRC measurement is based on mature technology that is standardised in EN 13848-2:2006 [5]. The standard includes multiple aspects of track geometry characterisation as well as measurement devices and procedures. However, the vehicles are expensive, require frequent maintenance, and occupy train paths, which could be exploited for commercial services. Therefore, it is not viable to monitor a line section with a frequency greater than twice a month.

To monitor the infrastructure more frequently, the IMs are becoming increasingly interested in track geometry monitoring with in-service trains. Recently, IMs have attempted to put Unattended Geometry Measurement Systems (UGMS) on in-service cars without disrupting normal traffic [3].

TRV and TRC both use an inertial - or alternatively a versine - system as a basis for the measurement of track geometry characteristics, but these devices are quite sophisticated and expensive and, therefore, not suitable for being mounted on commercial trains.

Due to the stability of accelerometers, acceleration measurement and modern data processing techniques are the most common solution for avoiding costly and expensive optical/inertial systems [6]. On the other hand, optical sensors, such as laser-based, camera-based, and other types, must be cleaned on a regular basis to maintain them in working order, and hence require specific treatment to avoid contamination when used on commercial vehicles. The monitoring system should not require additional maintenance, harming the vehicles' reliability and availability. Robustness is an important factor for use on in-service vehicles.

Due to the strong relationship between vehicle reaction (e.g., vertical axlebox acceleration) and vertical track defects, monitoring the track's longitudinal level is relatively straightforward. As a result, accelerometers are primarily used to monitor track geometry for this track geometry parameter. Other track geometry characteristics, such as twist or lateral rail alignment, which are essential for maintenance and safety issues and are assessed by TRV / TRC, are much more difficult to monitor with commercial trains simply using accelerometers. Aside from that, precise measurement positioning is critical for ensuring reproducibility, providing sufficient data for trend analysis, degradation prediction, and root-cause identification.

A possible solution is to develop a sensor system capable of detecting the lateral position of the wheel in relation to the rail. The main purpose of this measurement is to allow the track geometry measurement system to avoid the possible measurement error due to the lateral displacements of the wheelset with respect to the track. In particular, this measurement is essential to correctly measure alignment [7-8].

A prototype of such a sensor system for measuring the wheels' lateral displacement on the rail (LDWR), developed in the Assets4Rail Project, is described in the following section.

1. Sensor System Prototype

The technology that has been selected for the development of the sensor system is based on stereo-cameras, i.e. cameras with binocular vision allowing the assessment of depth in the acquired images. The prototype of the sensor system consists of an off-the-shelf stereo-camera (the ZED stereo-camera developed by STEREOLABS, see Fig. 2), an air cleaning system, a processing unit, a lighting system, and a mounting system with vibration dampers. The air cleaning system cleans the camera lens by blowing compressed air regularly. For optical sensing, the camera is configured to output videos with a resolution of 1920×1080 pixels at a sample rate of 30 frames per second (fps). The processing unit, an NVIDIA Jetson Tx2, has a 256 core NVIDIA Pascal architecture and ARMv8.6 core multi-processor CPU complex, enabling real-time execution of Deep Learning (DL) models.

Figure 2. The Sensor under investigation: stereo camera ZED by STEREOLABS

The prototype is designed to be installed in the lower part of the bogie frame of the vehicle, facing the wheel, as shown in Fig. 3. Two systems would be required to monitor the wheel-rail pair on the left and right sides simultaneously. The mounting solution on the bogie frame consists of vibration dampers, a crossbar and a clamp, which allows the prototype to be easily installed on different bogie types. The camera housing is equipped with an external lighting system, which consists of a series of LEDs. The processing unit is inside the vehicle cabin, connecting to and powering the camera.

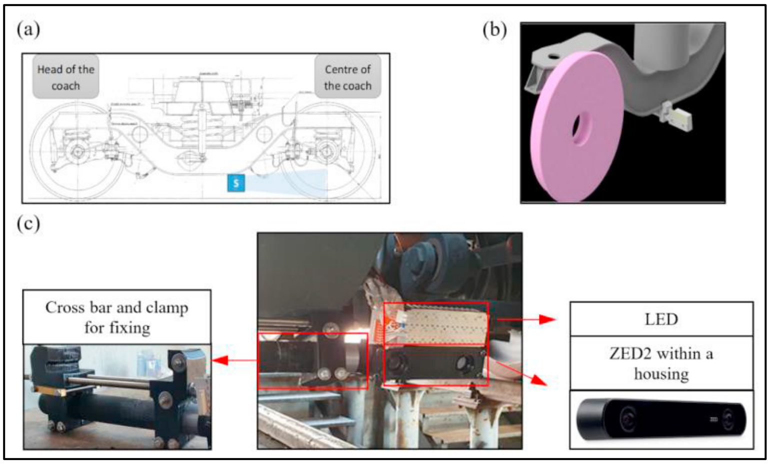

Figure 3. Camera position on the bogie frame

The algorithm to track the wheel and rail relies on virtual point tracking, consisting of four steps, as shown in Fig. 4. The first step is calibration, executed for the first-time installation. This calibration process detects a Region of Interest (RoI), which corresponds to the wheel-rail contact area. The outputs are the coordinates of the centre point of the RoI. The next two steps are executed to detect and track virtual wheel and rail reference points in real-time. The fourth step of the algorithm consists of the measurement of the LDWR itself, performed utilising the reference points on wheel and rail previously identified. More details can be found in a previous paper [9].

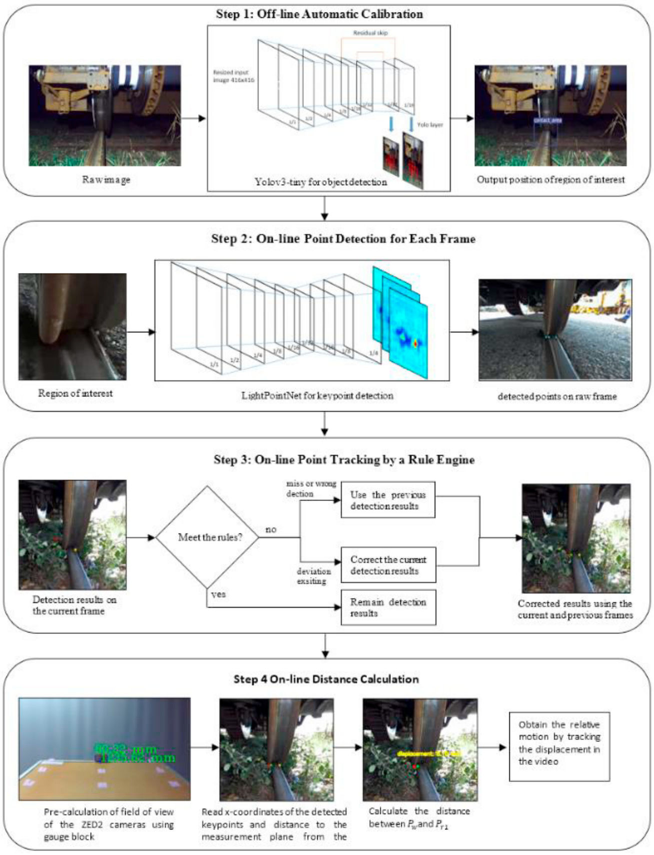

Figure 4. Description of the algorithm developed to track virtual points on the wheel and rail and to measure the LDWR

4. Validation Test

A test was carried out in Italy, on the conventional railway line from Rome (Roma Tuscolana station) to Pisa (Pisa Centrale station) for a total of approximately 330 km travelled. The prototype was installed on the bogie frame of the Aldebaran 2.0 coach, which is the newest track recording car of RFI. This coach was chosen in order to compare the data acquired by our sensor system with that acquired by its commercial high-value track geometry measurement system (TGMS) provided by MERMEC, thus allowing a benchmarking exercise.

Although the maximum speed of some line sections was 180 km/h, the speed of the train was limited to 100 km/h, both because the Aldebaran 2.0 car was still in the pre-operation phase and because of the low braked weight percentage of the train consisting of only three vehicles (two locomotives and the Aldebaran 2.0 coach itself, see Fig. 5).

The stereo-camera was connected via a USB cable to a PC, positioned in the coach, for image acquisition and processing. The lighting system was powered with a cabled connection to an Uninterruptible Power Supply (UPS) system positioned in the coach.

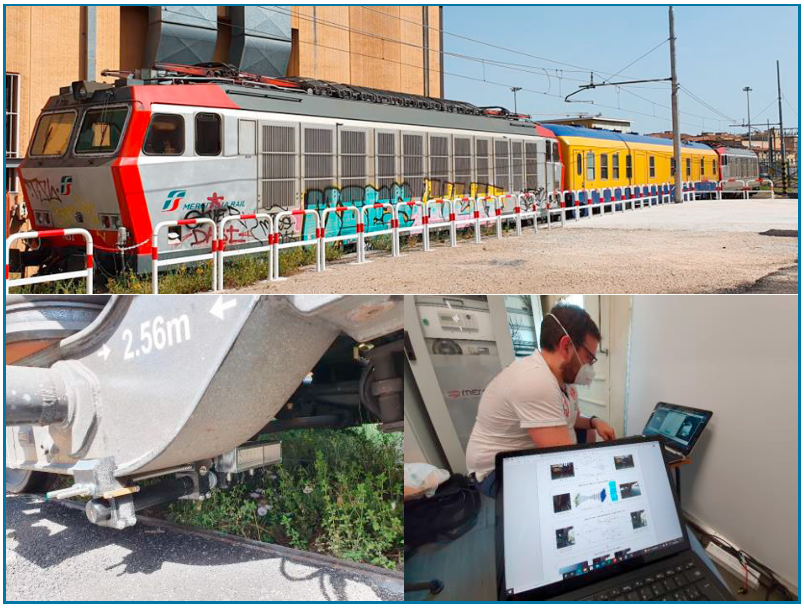

Figure 5. Top image: train used for the validation test, consisting of two E652 locomotives (leading and trailing) and the Aldebaran 2.0 track recording coach; bottom left image: sensor system mounted on the bogie frame; bottom right image: PC for image acquisition and processing, positioned in the coach

During the test, both the stereo-camera and the MERMEC Inertial Platform system were monitoring the track simultaneously. The output of the stereo-camera was the LDWR and the MERMEC system provided the TG deviations including track gauge, cross-level, twist, longitudinal level, alignment. Among the MERMEC data, for the comparison of the two systems, our focus is on the alignment of the right rail which is in the different wavelength ranges. This parameter is equal to the deviation y_p in the y-direction of consecutive positions of point P (refer to EN 13848-1:2003+A1:2008, section 4.2.1) on the right rail, expressed as an excursion from the mean horizontal position (reference line) and is calculated from successive measurements (refer to EN 13848-1:2003+A1:2008, Figure 5).

The MERMEC system outputs the final processed results, that is the track geometry parameters and the parameters indicating rail profile wear. These parameters do not contain the data of LDWR and thus are not directly comparable with the outputs of our system. However, a comparison is still possible as described in the following sub-section. Our computer-vision-based sensor system aims to measure LDWR in a real-time manner. It has to be combined with the accelerometers and relies on a sensor fusion algorithm to reconstruct the lateral alignment.

4.1. Comparison of sensor system measurements

A synchronisation between the LDWR calculated by our sensor system and the alignment outputted by the MERMEC system was performed in order to investigate the relationship between the two measured quantities. It was seen that although the wheels do not follow the lateral alignment as exactly as the vertical level – as expected – the larger lateral alignment generally induces a larger wheel movement in the lateral direction.

Although this observation is not a rigorous comparative validation, it indicates that the LDWR calculated by the proposed CV sensor system does relate to the measured alignment (Fig. 6). The LDWR alone cannot be used to derive the alignment. It should be combined with the lateral acceleration of the wheels.

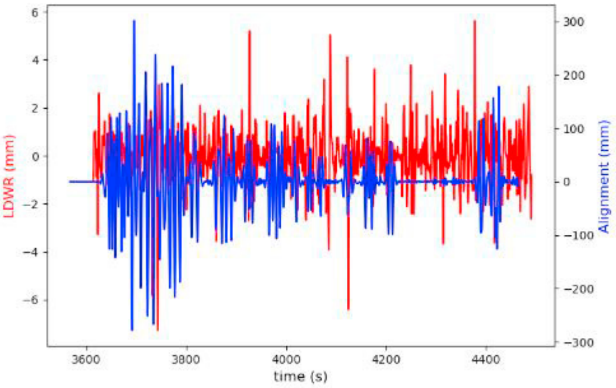

Figure 6. Comparison between LDWR calculated by our CV system and Alignment D3 measured by MERMEC TGMS

4.2. Simpack Simulation

As mentioned above, it was not possible to work with axlebox accelerometer data acquired during the validation test. Therefore, we decided to use the Simpack multibody simulation software to reproduce 26 km of the ride made by Aldebaran 2.0 during the test including this time the virtual measurements of the axlebox accelerations.

The virtual axlebox accelerations were firstly filtered with a high-pass and low-pass filter. The filter band was calculated as a function of the train speed and the selected defect wavelength band D1 (between 3 and 25 meters, so the low-pass frequency is $V_{max}/3$ and the high-pass frequency is $V_{min}/25$). The virtual lateral accelerations were double-integrated and compared with the virtual lateral displacement of the wheel to understand the challenges in using accelerometers for the assessment of absolute wheel displacement, a crucial step in deriving rail alignment by combining accelerometer and stereo-camera data. A Kalman filter was used to improve the match during curve negotiation, where the quasi-static component of the lateral acceleration has an influence. The results are shown in Fig. 7, in which it is possible to notice that the values of the absolute lateral wheelset displacement obtained through double-integration and Kalman-filtering ("calculated LD"– magenta line) closely approximate the benchmark (called "real" LD – blue line). This occurs particularly on straight track (the curvature of the track is shown with an orange line), but also in curves.

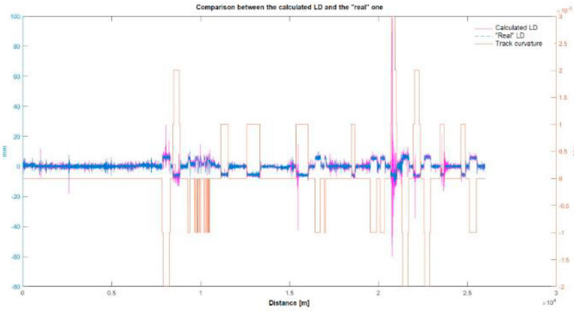

Figure 7. Comparison between the double-integrated virtual accelerometer signal ("calculated") and the "real" benchmark LD

It is interesting to compare the values of the "calculated LD" with the sum of left and right "L+R" alignment (i.e., the measured TG values used as input for the simulation), see Fig. 8.

Visually, there is a reasonably good correlation between them (the blue line is the LD and the orange one the L+R alignment).

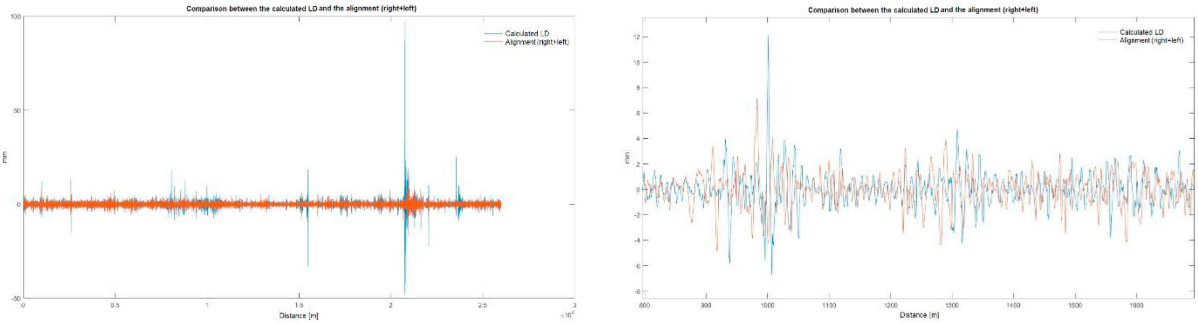

Figure 8. Comparison between the "calculated LD" (double-integrated, Kalman-filtered) and the track alignment (sum of the right and left rail alignment) along all 26 km of the simulation (left image) and zoom on a section of 1 km (right image)

As expected, between the peaks of the LD and of the L+R alignment, a phase shift can be noticed. This depends not only on the lateral inertia of the vehicle, but also on the equivalent conicity of the wheels and the characteristics of the suspension. It is interesting to examine whether this phase shift affects the standard deviations over sections of 200 meters, which correspond to key maintenance indicators when applied to right and left alignment, as well as other TG quantities. The standard deviations over 200 m-sections of the "calculated LD" and the measured L+R alignment were compared along all 26 km of the simulation (Fig. 9).

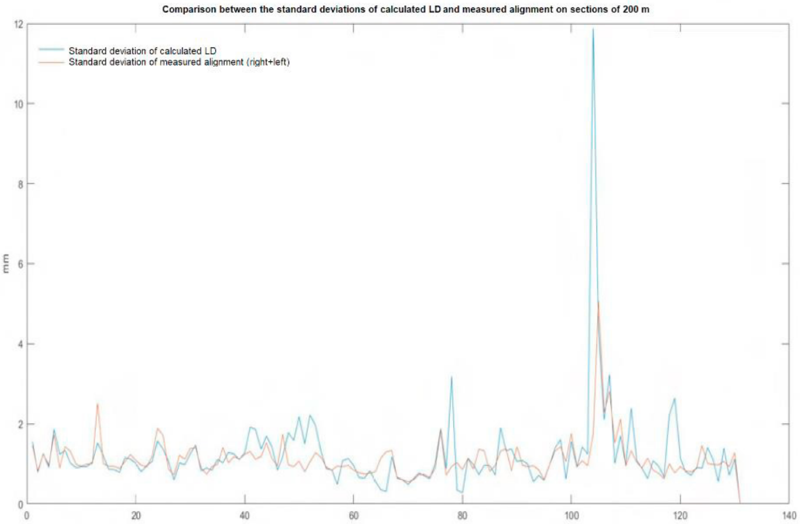

Figure 9. Comparison of the standard deviations on sections of 200 meters of the calculated LDWR and the measured alignment along all 26 km of the simulation (130 points)

This comparison also shows a reasonably good visual correlation between the LD and the L+R alignment. As mentioned above, the curves could undergo further improvement in the match with further work. The 12 mm peak at approximately the abscissa 104 also shows a less satisfactory match. It corresponds to a line section in which there are numerous switches leading to higher lateral displacement values. The R^2 representing the correlation between the two standard deviation curves turns out as 0.5 if the entire section is considered. Exclusion of the data associated with the 12 mm value peak causes it to rise to 0.7. A further rise to 0.8 occurs if only the first straight section is considered.

5. Findings and Conclusions

In conclusion, the developed prototype of the computer-vision-based sensor system was tested in regular train operating conditions (i.e. Technology Readiness Level TRL 5). The hardware system worked well for data acquisition up to the maximum test speed of 100 km/h. The acquired images were not affected by shock and vibrations. The lighting system guaranteed correct lighting both outdoors, in different environmental conditions, and in tunnels, thanks to the fact that the LEDs used can create a light with a colour spectrum very similar to the solar spectrum. The main problem encountered in the validation tests was a loss, however insignificant, of frames of the acquired images. This was caused by the excessive length of the USB cable used to connect the stereo-camera to the processing unit, which in the case of the validation test was a laptop on board the vehicle. Therefore, in the final prototype of the sensor system the processing unit should be placed in the underbody. We also found that the measurement uncertainty of the current computer system could be up to 2 mm, which is not sufficient to derive the track geometry parameters. Replacing the current camera with one having a narrower field of view and closer focusing distance will help decrease the measurement uncertainty.

The Deep Learning algorithm (Convolutional Neural Network) to track the lateral displacement of the wheels on the rails (LDWR) was improved and validated through numerical experiments. The calculated LDWR was compared with the alignment measured by a commercial track geometry inspection system. The comparison indicates that LDWR indeed relates to lateral alignment, however LDWR must be used together with the wheel acceleration to derive lateral alignment. Neither LDWR nor the wheel acceleration alone are sufficient.

Multi-body simulation of the running dynamics of a virtual replica of the Track Recording Coach used for the tests showed, particularly on straight track, a good correlation between the lateral wheelset displacement values obtained by integrating the axle-box accelerations with the ones obtained directly from Simpack and with the sum of the measured left and right alignment.

Having verified the existence of the correlation between these quantities, the next step of the research will be to find the algorithm that allows the calculation of the alignment of the two rails starting from the right and left LDWR measured with two stereo-cameras and the values of the lateral displacement obtained by integrating twice the axlebox accelerations.

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References

[1] https://shift2rail.org/

[2] http://www.assets4rail.eu/about/

[3] Weston P., Roberts C., Yeo G., Stewart E.: Perspectives on railway track geometry condition monitoring from in-service railway vehicles, Vehicle System Dynamics, 53:7, 2015, 1063-1091, DOI: 10.1080/00423114.2015.1034730.

[4] EN 13848-1:2019: Railway applications - Track - Track geometry quality - Part 1: Characterisation of track geometry.

[5] EN 13848-2:2006: "Railway applications - Track - Track geometry quality - Part 2: Measuring systems - Track recording vehicles".

[6] De Rosa A., Alfi S., Bruni S.: Estimation of lateral and cross alignment in a railway track based on vehicle dynamics measurements, Mechanical Systems and Signal Processing, Volume 116, 2019, pp. 606-623, ISSN 0888-3270, https://doi.org/10.1016/j.ymssp.2018.06.041.

[7] Weston PF, Ling CS, Goodman CJ, Roberts C, Li P, Goodall RM. Monitoring lateral track irregularity from in-service railway vehicles. IMechE Pt F: J Rail Rapid Transit. 2007;221(1):89–100

[8] Corazza G.R., Licciardello R., Malavasi G., Marcone M., "La ruota come sensore di interazione ruota-rotaia", Ingegneria Ferroviaria, Marzo 1999; 119-131

[9] Shi D., Šabanovič E., Rizzetto L., Skrickij V., Oliverio R., Kaviani N., Ye Y., Bureika G., Ricci S., Hecht M. (2021). "Deep learning based virtual point tracking for real-time target-less dynamic displacement measurement in railway applications" - Mechanical Systems and Signal Processing, Open Access, Volume 166, 1 March 2022, Article number 108482, ISSN 08883270, DOI 10.1016/j.ymssp.2021.108482