Development of a contactless sensor system to support rail track geometry on-board monitoring

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Abstract

This paper is focused on the ongoing research, within a work package of the Shift2Rail project Assets4Rail, related to the development of an on-board contactless sensor system able to measure the wheel's transversal position in relation to the rail in order to support track geometry measurements.

In particular, this research work focuses on developing a sensor system to support track geometry monitoring performed by the master system under development in other Shift2Rail projects. The aim is to develop a sensor system to detect the relative transversal position between the wheelset and the rail, suitable for the use on commercial (in-service) vehicles. In fact, a possible track geometry monitoring system alternative to the sophisticated and expensive optical/inertial systems and suitable for use on commercial vehicles, could be based on the measurement of accelerations. However, some parameters of the track geometry, such as lateral alignment, are extremely difficult to determine through the measurement of accelerations. In this case, it is necessary to find an innovative sensor system able to determine the wheel's transversal position in relation to the rail.

For this reason, this project intends to focus on innovative systems that allow the detection of the wheel-track position by avoiding the optical/inertial systems already used on diagnostic trains. After a state-of-the-art overview on the potentially applicable technologies for the sensor system to be developed, a corresponding analytical tool for comparison of contactless sensors to choose the most suitable technology has been developed and two candidate technologies (stereo and thermal cameras) have been selected and assessed by means of a test platform in the facilities laboratory of VGTU (Vilnius Tech). This work will be the basis for developing a concept design of the sensor system together with a montage solution, which will be finally tested on a vehicle in real operation conditions.

Keywords: track geometry, monitoring, sensors, transversal displacement, commercial trains

1 Introduction

Assets4Rail project, founded within Shift2Rail Joint Undertaking [1], begun in December 2018 and will last 30 months if not longer. The project's main objective is to achieve cost-efficient and reliable infrastructure, developing a set of cutting-edge asset-specific measuring and monitoring devices. To achieve that, Assets4Rail follows a twofold approach, including infrastructure (tunnel, bridges, track geometry, and safety systems) and vehicles. The project is structured into two Work Streams (WS): the WS1 related to monitoring and upgrading solutions addressed to bridges and tunnels, the WS2 regarding monitoring solutions for three railway assets: trains, track geometry and data collection from fail-safe systems [2].

This paper reveals some preliminary results achieved in the EU Shift2Rail project Assets4Rail, which aims to contribute to the modal shift towards rail by exploring, adapting and testing cutting-edge technologies for railway asset monitoring and maintenance, in order to ensure proactive and cost-effective maintenance.

2 Background

This paper focuses on track geometry monitoring, which is an essential activity to ensure the safety of railways operation, nowadays performed by Infrastructure Managers by diagnostic vehicles capable to analyse track conditions and detect potential problems at an early stage. The research in the field of these diagnostic activities is mainly aimed at the improvement of maintenance strategies, in combination with the reduction of infrastructure management costs..

The focus is on track geometry monitoring systems based on contactless optical/inertial technologies (Fig. 1). Optical sensors are used for the rail profile measurements and the rail location, while the inertial unit makes available the linear and angular accelerations. The combination of optical and inertial data allows the determination of the track geometry quality through the measurement of track geometric parameters, the main five of which are: gauge, cross level/cant, longitudinal level, alignment and twist. The definitions for the principal track geometry parameters, their measurement requirements and the analysis methods are given by European Standard EN 13848-1:2019 [3].

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

Infrastructure Managers (IM) commonly deploy a dedicated Track Recording Vehicle (TRV) or hauled Track Recording Coach (TRC) running along with the network gathering track geometry data for inspection and general measurement purposes [4]. The measurement by TRV and TRC is a mature technology, standardised in the EN 13848-2:2006 [5], which covers several aspects concerning the characterisation of track geometry and measurement devices and methods. Track geometry parameters can be measured by using either an inertial or a versine system, which is also the measurement principle of TRV and TRC.

Monitoring of track geometry with in-service trains is more and more of interest for the IMs and RUs. In recent years, IMs attempted to deploy Unattended Geometry Measurement Systems (UGMS) on in-service vehicles without interrupting the regular traffic [4].

To avoid the sophisticated and expensive optical/inertial systems, acceleration measurement and advanced data processing techniques are the most popular option due to the robustness of accelerometers [6]. In comparison, optical sensors, such as laser based, camera based, etc., must be cleaned regularly to keep them working and thus need special treatment to avoid getting dirt when applied on commercial vehicles. Robustness is an essential factor for the applications on in-service vehicles, as the monitoring system should not require additional maintenance, affecting the reliability and the availability of the vehicles themselves.

Longitudinal level and vertical rail profile can be obtained by double integration of vertical accelerations. In terms of feasibility on commercial vehicles and accuracy, the best measurement is probably by the acceleration on the bogie over the axle-box and the vertical displacement from the accelerometer to the axle-box, despite displacement transducers are more vulnerable and expensive than accelerometers [4]. To avoid involving displacement transducers, axle-box mounted accelerometers, in conjunction with dedicated signal processing techniques, can also be used. Monitoring of the track's longitudinal levelling is a straightforward method thanks to the strong relationship between the vehicle reaction (e.g. vertical acceleration of axle boxes) and the vertical track defects. Therefore, monitoring track geometry with accelerometers is mainly done for this track geometry parameter only, like in the ICE2 for several years [4].

Other parameters of the track geometry, such as twist or lateral alignment measured by inspection cars and are also essential for maintenance and safety issues, are much more complicated to be monitored with commercial trains using accelerometers. Besides this, an accurate position of the measurements is important to verify the reproducibility, provide sufficient information for trend analysis, predict the degeneration, and identify the root causes.

3 Measurement of the transversal wheel/rail relative position

3.1 Drivers, benchmarks and emerging solutions

The initial results of Assets4Rail research in the field of track geometry monitoring allowed to identify some candidate technologies for the development of the on-board sensor system able to measure the transversal position of the wheel in relation to the rail.

They have been identified in the fields of:

- direct measurement systems, such as lasers, high speed cameras, stereo cameras and thermographic cameras;
- indirect measurements, such as accelerations and ultrasonic reflection.

In this large set of systems, for the specific target of wheel-rail relative position measurements, the most promising technologies to be taken into consideration for next developments seem to be stereo cameras and thermographic cameras.

In particular, thermographic cameras have already been tested with good results in two experiments [7], [8], even if for a restricted speed range and without facing most atmospheric conditions that may occur during normal operation of a commercial train.

3.2 Specifications of requirements

The next step for developing the envisaged robust and cheap sensor system to determine the wheel-rail relative position was the definition of a System Breakdown Structure (SBS) by considering the candidate technologies identified in state-of-the-art recognition described above.

In general, the system for wheel-rail relative position detection is articulated into the following modules:

1. Hardware technology (the image monitoring system should be composed of a camera, protection case, illumination device, on bogie montage solution, image processing unit and data storage);
2. Communication interfaces (data acquired by the sensor system should be synchronised with the whole monitoring system);
3. Software post-processing (algorithms should determine the transversal position of wheelset in relation to the rail by determining the wheel-rail contact points and the angle of attack);
4. Energy supply system (should be constituted by dedicated batteries powered both by sustainable and permanent technologies - e.g. harvesting systems using the vibration of bogies - and/or low voltage power supply system of the wagon).

For the whole system and each module, requirements have been identified and classified into Functional, Operational, Performance and Safety.

In general, the system for determining wheel-rail contact position should determine the transversal position of the wheel in relation to the rail continuously, must be integrated and synchronised with the primary on-board system for detecting the track geometry to be developed by Shift2Rail and should be able to be installed on different typologies of bogies. Moreover, the system should be able to work on in-service trains at 60÷200 km/h under a large set of weather and environmental conditions (dust, rain, snow, etc.). It must withstand the stresses due to vibrations in the entire operating speed range. Finally, the system should be easily maintained and should be powered by the low-voltage power supply system of the wagons or by dedicated batteries powered both by sustainable and permanent technologies (e.g. harvesting systems using the vibration of bogies).

4 Identification of the most suitable technology for sensors

4.1 Specific measurement issues due to the wheelset movement on the track

For developing devices to measure the transversal displacement of the wheelset, it is necessary to evaluate the features of the wheelset movement on the track. In fact, due to the wheelset oscillation phenomenon, the wheelset not only moves linearly along track longitudinal axis X, but also rotates about axis X and vertical axis Z as well even on tangent track, resulting in a sinusoidal motion, known as Klingel motion. The wheelset movement trajectory becomes even more complex and difficult to describe when the rolling stock is running on track curves and/or along track superelevation (inclined track).

Hence, the wheelset's multifaceted movement on the track, the distance from the sensor to the point to be measured on the wheelset (circular line of the rolling profile) is constantly changing both vertically and horizontally. This can lead to measurement inaccuracies, hard-to-reach repeatability and reproducibility, which needs to be considered.

4.2 Developing analytical tools for comparison of sensors to choose the most suitable technology

The most suitable sensor technology for transversal position estimation of the wheel to rail was defined through multi-criteria decision making (MCDM) analysis, considering the outcomes of track geometry measurement state-of-the-art study provided in previous sections.

Proposed MCDM method allows evaluating indicators that cannot be compared using classical mathematical-statistical methods. This significantly increases the practical value and novelty of the work.

Questionnaires were provided for the partners of Assets4rail project, and they made proposals about factors that are important for wheel-rail transversal position monitoring technologies. Eight categories of criteria were formulated.

It was found that the most important factors of the technology used for measuring the transversal wheel position are: 1. Dimensions and Weight; 2. Energy Consumption; 3. Life Cycle Cost (LCC); 4. System Robustness; 5. Measurement Accuracy includes sampling rate, system dependency on train speed; 6. Technical Compatibility (Interoperability); 7. Output Data; 8. Measurement Repeatability includes the reliability of results.

To decide the most important criteria, a questionnaire was established, the rankings were made by twelve experts and driver weights were defined. These procedures allowed the weights to be identified in two distinct ways: using AHP (Analytical Hierarchical Process) method and using direct evaluation. In conclusion, it was found that the most four important criteria are:

1. System Robustness;
2. Measurement Accuracy;
3. Life Cycle Cost;

4. Technical Compatibility.

4.3 Evaluation of candidate technologies

The results obtained in this study were evaluated using TOPSIS (The Technique for Order of Preference by Similarity to Ideal Solution). It defines alternatives by the distances between the indicators' best and worst values. If the result equals one, it is the best solution, if the result equals zero, it is the worst solution.

Using the estimated values of the criteria and their weights, applying the AHP (Analytic Hierarchy Process) and Direct evaluation methods, and evaluating the selected technologies was performed. The TOPSIS method was applied and the results are presented in Tab. 1. The technologies' ranking is similar using the two different calculations methods; only the ranks 7 and 8 were identified differently. It has no considerable significance since only the best one is needed.

Table 1. Measurement Technology Ranking

	Technologies							
	Reference technology Plasser Optical Gage Measuring System	Laser profile measurements	Distance sensor laser, time of flight	Time of flight camera	Digital Image Correlation (DIC) of high-speed filming	Laser based systems, displacement	Thermal vision	Stereo vision
TOPSIS DE	0,816	0,761	0,830	0,730	0,789	0,661	**0,847**	**0,879**
Ranking	4	6	3	7	5	8	**2**	**1**
TOPSIS AHS	0,886	0,808	0,888	0,655	0,863	0,801	**0,910**	**0,920**
AHP	4	6	3	8	5	7	**2**	**1**

It was found out that technology based on stereo vision is the best for this specific task. The technology-based on thermal vision came in second place. Therefore, it was decided to conduct the experimentation by investigating two sensors representative of these two technologies through laboratory and on-track testing.

4.4 Test platform for real-time testing of sensor solutions

During the experimental investigation, two technologies were under review:

a) Based on stereo camera (the Zed stereo camera developed by STEREOLABS);
b) Based on the thermal imaging camera (the T420 thermal imaging camera developed by FLIR).

Figure 2. Sensors under investigation: Stereo camera ZED by STEREOLABS (left image) and Thermal camera T420 by FLIR (right image)

Algorithms for required geometrical data evaluation from the image were created. The developed algorithms are suitable for both selected technologies. Methodology for measurement accuracy calculation was developed, and measurement accuracy for the devices under investigation was calculated, for the stereo camera it is ±0.7 mm and ±1.4 mm for thermal imaging camera. Using the developed algorithm measurement accuracy can be calculated for different devices that system developers may use in the future.

Test platform for real-time testing of sensing solutions initially in the facilities laboratory of VGTU was developed. It included cameras connected with power-efficient embedded AI computing device Nvidia Jetson TX2 and test rig. Data processing algorithm was validated using wild experimental data measured in Lithuanian Railways. Maximal power consumptions of measurement equipment with the camera is less than 20W for both technologies. Data can be transmitted to the data warehouse via Wi-Fi and Ethernet or stored in hard disk installed in Nvidia Jetson TX2. The algorithms were developed during the task implementation so output data format can be freely chosen.

5 Conclusion

This paper focuses on developing a sensor system to support track geometry monitoring that was carried out within the EU Shift2Rail project Assets4Rail. The initial results of Assets4Rail research for track geometry monitoring by systems suitable for installation on commercial trains, allowed to identify the System Breakdown Structure (SBS) and the requirements of an on-board sensor system for wheel-rail relative position detection. The most appropriate and promising candidate technologies to realise was found stereo cameras and thermographic cameras.

Algorithms for required geometrical data evaluation from the image were created. The developed algorithms are suitable for both selected technologies.

A methodology for theoretical measurement accuracy estimation was developed and measurement accuracy for the devices under investigation was calculated: a value of ±0.7 mm was calculated for the stereo camera and ±1.4 mm for thermal imaging camera (e.g. for track gauge measurement, the EN 13848-1:2019 standard requires an accuracy of ±1.0 mm). Using the developed algorithm measurement accuracy can be calculated for different devices that system developers may use in the future.

Test platform for real-time testing of sensing solutions initially in the facilities laboratory of VGTU was developed. It included cameras connected with power-efficient embedded AI computing device Nvidia Jetson TX2 and test rig. Data processing algorithm was validated using wild experimental data measured in Lithuanian Railways (LTG).

Finally, the main findings of the first step of experimentation described above are shown below. These results will be the basis for subsequent development of the sensor system design and a second experimental phase foreseen on a diagnostic train made available by the Italian Railways (Ferrovie dello Stato Italiane).

Both stereo vision and thermal imaging cameras used in the investigation can provide sampling frequency up to 60 Hz. Hardware used in the investigation allows processing at up to 120 frames per second and is suitable for real-time work. Selected technologies can be applied in trains performing at high velocity ranges, selecting devices with higher sampling frequencies. About mounting the sensors on the bogie frame, it was found that additional housings are required to prevent cameras from ambient conditions. Housings should be placed on bogies via dampers, which will protect the equipment from overloads up to 20*g*. Additional airflow should be provided to the housings; such a system requires about 3W and can prevent the system from dust, rain, snow, and ensure system performance at low temperatures.

Algorithm for wheel-rail transversal position monitoring requires precise positioning of thermal imaging camera during installation. Technology users and developers should consider if there is no way to guarantee the desired distance to the measuring object correction in the algorithm should be provided. In a stereo vision, this is not required, as the camera automatically calculates the distance to the object. However, the stereo camera should be calibrated before the installation. They are using technology based on a stereo vision; an additional light source is needed for wheel-rail contact.

Acknowledgements

The research is funded by the EU Shift2Rail project Assets4Rail (Grand number: 826250) under Horizon 2020/ Shift2Rail Framework Programme.

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