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IOT-DRIVEN TRACK HEALTH MONITORING FOR SUSTAINABLE RAILWAY OPERATIONS

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Abstract

The modernization of railway infrastructure maintenance practices demands innovative approaches to ensure safety, optimal performance, and optimized operational costs through the integration of novel technologies. The Internet of Things (IoT) delivers for this domain the innovative cloud- and edge-powered data collection, aggregation and processing which enables the cost effective and performant data-driven maintenance strategy. The traditional approach to track maintenance relies on periodic inspections done with Track Recording Vehicles (TRV). Data collected by TRV measurements offers the most reliable information regarding the track geometry simply because the measurement is done under dynamic load. However, most of the rail network maintenance organizations are facing issues with the limited availability of the TRV. This impacts the condition monitoring schedule and proper maintenance of the track, often effecting speed restrictions to be applied. This paper presents a comprehensive study on the continuous monitoring of railway track conditions using an IoT measurement device that assures non-invasive track monitoring with the possibility to be installed on passenger trains which are transiting the railway network much more frequently than a TRV. Our IoT measurement device captures and transmits critical information related to track geometry (alignment, longitudinal level, cross level, and twist of the track) by analysing the specific motions of the bogies of passenger trains. The collected data is saved and processed in cloud and can be accessed through a centralized monitoring dashboard, providing railway operators with valuable insights to the health of their track infrastructure. Furthermore, this paper explores the possibility of defining degradation models of the track by analysing historical data patterns and predicting potential maintenance needs. The implementation of such predictive maintenance strategies not only improves safety but also optimizes operational costs by reducing the likelihood of unexpected track failures.

Keywords: track monitoring, track geometry, retrofitting, Internet of things

1 Introduction

Railway transportation is still one of the most efficient and sustainable option for both public and commercial transportation. Safety and comfort of the rail transport can be achieved by an efficient track maintenance process. The fundamental task in railway track maintenance is the measurement of track geometry irregularities. For this purpose, the most important challenge in track maintenance should be a correct assessment of the railway track geometry [1].

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There are several types of equipment and technologies available to fulfill this job, but the most reliable information regarding the track geometry condition is given by the Track Recording Vehicle (TRV), simply because the measurement is done under dynamic load.

Although many track geometry measurement solutions exist, some rail administrations are facing issues with the limited availability of the TRV, more than that, some cannot afford it. This impacts the rail monitoring schedule and proper maintenance of the track, often affecting speed restrictions to be applied. In this regard, a new need has risen in the railway industry to develop alternative solutions that monitor track geometry. The underlying assumption is that the measuring system can be mounted on any rail vehicle (regular train, wagons, or dedicated measurement train) which continuously monitor the track.

In this paper we are proposing a non-invasive retrofitting methodology, powered by IoT, for a cost-efficient track monitoring, which can pave the way towards to an efficient predictive inspection scheduling, i.e., predictive maintenance.

2 Related work

The acceleration measurements on the bogie can indicate track quality and can detect local variations in track geometry. However, the measurements are sensitive to vehicle dynamic behaviour as well as other factors such as climatic conditions and wheel-rail interaction. Also, the position where these measuring systems are mounted must be assessed [1]: on the bogie and/or on the vehicle box. Several authors [2] have shown that notable results can be achieved by using Inertial Measurement Systems (IMU) for track geometry measurements. The IMU device mounted on the bogie is the optimal track monitoring solution, provided that the primary suspension is rigid. It should be noted that this solution does not offer the possibility of measuring the gauge. Adding an axle-mounted accelerometer allows collecting data on short-wavelength defects. Thus, vertical acceleration measured on the bogie together with axle displacements ensures a qualitatively good measurement of the longitudinal track level.

In [3] an IMU, cameras and an encoder were utilized in an experimental setting to test the possibility of measuring the geometric parameters of the track and identifying all defects. Also, 3D kinematics for measuring geometric parameters was studied wit3h detailed description of kinematic approximations and simplifying hypotheses were used. Results showed a good correlation between the two calculation methods. Using gyroscope sensors can be effective if mounted on bogies and less efficient if mounted on axles. Gyroscopes can provide valuable data at low vehicle speeds compared to conventionally used accelerometers [4].

3 Proposed solution

The proposed solution is relying on the principle that the quality of the track can be measured by recording the motions of the wheels and the axels while the train is travelling on the track. To accomplish this, we applied a motion recorder mounted on one of the bogies that continuously monitors the behavior of the bogie during movement.

Furthermore, the track geometry can be estimated using the recorded motions, by performing mathematical transformations. One of the main advantages of this approach is that it permits non-invasive retrofitting for all the railway equipment, i.e., it can be mounted on the bogies of all the railway vehicles, essentially turning them into monitoring units. Thus, the track monitoring can reach a very high frequency, which opens the way for a more sophisticated quality analysis and prediction, e.g., predictive maintenance.

Furthermore, this approach provides highly cost-efficient track monitoring solution because i.) the rail operators can decrease the effort and investment of running dedicated equipment and personnel for track monitoring; ii.) since the monitoring system is independent, i.e., not part of the rail vehicle, this simplifies the authorization costs; iii.) profiting from the modern IoT sensors, the motion recorder can be built using components available in large-scale; and iv.) all the data processing components can be centralized in the cloud, therefore these are not replicated per motion recorder unit, which simplifies the maintenance, increases the performance, and as a result, decreases the costs.

Figure 1 presents the system's 3 layers. The *Measurement Layer* represents the totality of the Motion Recorder Devices (MRD) placed on the different rail vehicles. Each MRD contains a system on chip for managing the sensors, the battery-based power supply, and the communication interfaces. As sensors, classical IMUs are used, which encapsulate accelerometers, gyroscopes, and magnetometers measuring on 3 axes. In addition, internal MRD case temperature is measured. The measurements are continuously streamed via Bluetooth to the *Edge Layer*. The MRD is designed to be able to operate on battery up to 24 hours and it includes a battery management unit which permits the permanent power supply, too. In this respect, the MRD can be used as on-demand measurement device, but also as a persistent accessory of the rail vehicle.

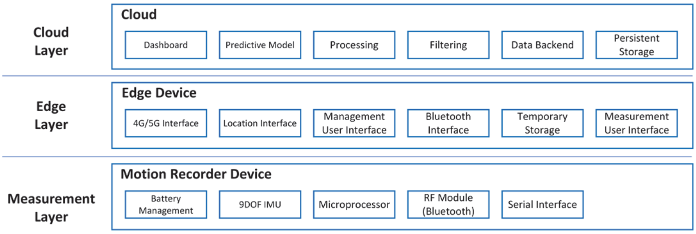

Figure 1 System architecture

The Edge Device is responsible for receiving, temporarily storing, enriching, and synchronizing with the cloud the measurement data. Based on the proposed architecture each rail vehicle is mounted with one and only one Edge Device and one or more MRD devices. While MRDs are fixed on the bottom side of the rail vehicles, the Edge Device should be placed to an exposed location, where good 4G/5G and GPS signal is expected, e.g., in cabin. Furthermore, the Edge Device extends all measurements with the GPS coordinates. It is also responsible for measurement data synchronization with the cloud through the Internet. Besides the data manipulation tasks, the Edge Device provides user interfaces (UI) for management and diagnostics purpose.

The track monitoring data from all Edge Devices ends up in the cloud where it is stored and processed with all the benefits of cloud computing (e.g., storages optimized for time-series-like data which provide scalability and performance in saving and withdrawing data). The flexibility and the scalability provided by cloud computing makes the proposed system compatible from private or regional railroads up to national or international networks. The next step is data filtering and processing during which raw measurements are contextualized, i.e., are turned into usable rail maintenance information. For this transformation, the data is submitted to a series of mathematical calculations, which based on the quantity of the data may require increased computational power. Cloud computing provides again a solution for this challenge by running the algorithms on scalable resources. The resulting rail information is represented in dashboards of cloud-based web dashboard. The system also contains a database with historical track data. This database in combination with modern data science (including cloud-based machine learning and AI) enables predictive maintenance.

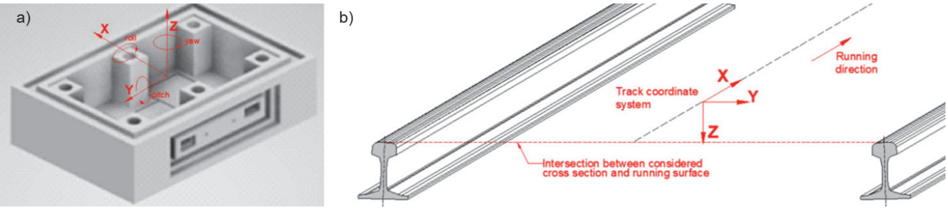

Figure 2 Cartesian coordinate systems of the IMU and the track: a) IMU coordinate system; b) Railway coordinate system [1]

Mounting MRDs in various positions on the bogies of rolling stock, can also provide information about other geometric parameters of the track such as: longitudinal level and direction. MRD data is transformed into superelevation from which torsion can be deduced, both affect the quality of track geometry [2]. The MRD measures acceleration and angular velocity. All these are measured according to X, Y, Z axes (Figure. 2/a) like the one defined by the EN 13848-1 European standard track coordinate system (Figure. 2/b). Table 1 presents the angular velocity notations:

Table 1 Mapping of the angular velocities

Axis of rotation	Euler angle	Symbol	Meaning
X	Roll	γ	Superelevation
Y	Pitch	β	Slope
Z	Yaw	α	Heading

Superelevation is the difference in height of the adjacent running tables calculated from the angle between the running surface and the horizontal reference plane, in this case the roll angle *g*. To eliminate the disturbance due to additional accelerations and dynamic effects, the superelevation calculation can be solved by fusing the rotation angle measured by the gyroscope with the accelerometer data.
If the MRD is mounted on the rolling stock, it will always follow the trajectory of the carrying vehicle. To determine the angle of inclination of the vehicle on which the MRD is mounted relative to a particular plane, the angular velocity around X axis (g) must be integrated with respect to time [5]:

$$\gamma = \int_{0}^{t} \Gamma \, dt \tag{1}$$

where Γ is the angular velocity relative to X axis [rad/s].

The disadvantage of gyroscopic measurements is that the result is dependent on the previous MRD position because the rotation angle is compared to the earlier position of the gyroscope itself. For this reason, the MRD IMU must be calibrated before measurement. Another disadvantage is that a systematic measurement error appears involving the accumulation of a certain offset or bias over time [6-7]. Knowing the roll angle of the vehicle when moving on track (Figure 3/a), superelevation can be determined by the following formula:

$$C = E \cdot \sin\gamma \tag{2}$$

where C is the superelevation [mm] and E [mm] is the centerline spacing of the rails. For a nominal gauge of 1435 mm this is equal to 1500 mm [1].
The vehicle's roll angle around X axis can also be determined from accelerations. When the vehicle is stationary or moving in tangent track, the roll angle generated by a level difference between the rail running faces in a certain cross-section may be determined from the components of the accelerations on the Y and Z axes with the following relationship:

$$\gamma = arctg\left(\frac{a_y}{a_z}\right)a \tag{3}$$

where a_y is the transverse acceleration on Y axis [m/s^2], and a_z is the acceleration on Z axis [m/s^2].

Traveling in a circular curve, with or without transition curves, an additional transverse acceleration will occur, namely the centrifugal acceleration (Figure 3/b). If the vehicle is considered a material point moving at speed *v* in a railway curve of radius *R*, the relationship between centrifugal acceleration, vehicle speed and curve radius is as follows:

$$a_c = \frac{v^2}{R} \tag{4}$$

where speed can be determined by integrating acceleration in the X:

$$v = \int_0^t a_x \, dt \tag{5}$$

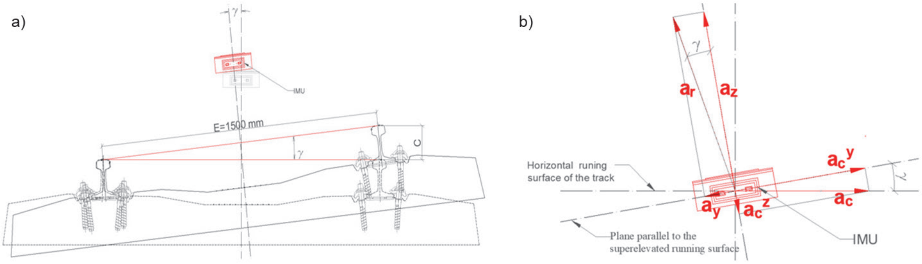

Figure 3 Physical system model: a) Superelevation calculation; b) Acceleration in curved track

Both the accelerations in the Y-axis and Z-axis direction given by the IMU are already containing the centrifugal components on Y axis respectively Z axis (a_c^y and a_c^z), thus the roll angle can be assessed by:

$$\tan\gamma = \frac{a_y - a_c^y}{a_z - a_c^z} = \frac{a_y - a_c \cdot \cos\gamma}{a_z - a_c \cdot \sin\gamma} \tag{6}$$

To simplify calculations for small angles, the following approximations can be made: cosγ = 1 respectively tanγ = sinγ, then substituting (4) into (6), to find the roll angle of the IMU, a second-degree equation must be solved:

$$-\frac{v^2}{R} \cdot \sin^2\gamma + a_z \cdot \sin\gamma + \frac{v^2}{R} - a_y = 0 \tag{7}$$

The curve's radius can be determined from evaluating the direction. By measuring and analyzing the arrows, considering the length of measuring chord *l,* one can calculate the radius R of the circular curve [8].

4 Prototype description

To validate in practice the proposed architecture and methodology a prototype has been designed and realized covering all 3 described layers in Figure 1. Using this prototype, a series of laboratory-scale experiments have been conducted.

In the design phase of the MRD prototype the main principles were: i.) suitability; ii.) reproducibility; and iii.) cost effectiveness. From a suitability perspective the aim was to create an easy to mount case resistant to the conditions (shocks, humidity, temperature), independent from power supply, and able to perform accurate measurements. Reproducibility consists of creating modular structure, and easy to access components. Finally, to maintain the cost effectiveness the goal was to work from existing modules and components and use readily available technologies. As a result, the case has been mechanically designed in CAD using simple shapes which can be easily 3D printed or CNC milled. For the electronics ready to use development boards and modules have been paired to fulfil all the requirements. The SparkFun 9DoF IMU Breakout was selected as the sensing unit, and the SparkFun Thing Plus ESP32 WROOM board encapsulates the processing unit, the RF module (including Bluetooth), the battery management, and the serial interface. The components are supplied by Li-Ion batteries and the battery capacity can be scaled up to 10000 mAh.

An Android tablet is used as an Edge Device prototype because it matches all the requirements: 1) Bluetooth interface for MRD communication; 2) persistent storage for temporary storing the measurements; 3) GPS receiver and an extended location service; 4) 4G/5G connectivity for data-to-cloud synchronization; 5) touchscreen for the UIs; 6) enables easy development; 7) cost effective, widely accessible and replaceable. A dedicated application was developed which contains the business logic to orchestrate the tasks assigned to the Edge Device.

As cloud provider Microsoft Azure was selected. For receiving the data from the Edge Device an Event Hub resource is used which saves the measurements into an Azure Data Explorer resource. The data filtering and transformation is implemented using Python in Azure Durable Functions.

5 Experimental evaluation

The evaluation at this phase is limited to laboratory-scale experiments. The main goal was to define a test environment which enables precisely reproducible test scenarios. In this respect, for simulating the different movements of the MRD a Franka Emika robotic arm was used. This approach makes possible to program a series of test movements and precisely repeat them. Using a 3D printed holder, the MRD has been mounted to the gripper of the robotic arm (Figure 4). The robotic arm has been programmed to simulate railway specific movements.

During the experiment (Figure 4/a), the robotic arm was simulating superelevation on both rail pairs by performing rotations around the X axis of the MRD (Figure 4/b). This experiment compares two calculation approaches, as explained in Section 3: 1) calculating roll angle based on the measured acceleration on Y and Z axis; and 2) through sensor fusion combining acceleration with angular velocity.

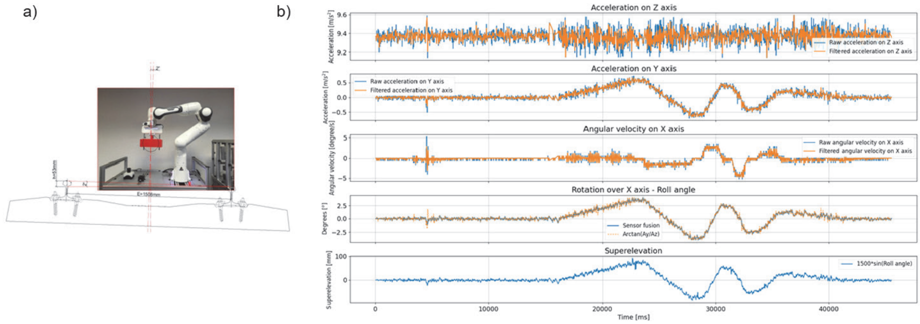

Figure 4 Laboratory-scale experiments: a) Simulating superelevation; b) Superelevation calculation

During the measurement, the robot was programmed to perform a series of rotations around axes X as follows: 1) 3°; 2) -3°; 3) -3°; 4) 2°; 5) -2°; 6) -2°; and 7) 1°. It can be seen on Figure 4/b that the calculated roll angles exactly match this pattern using both calculation methodologies. As a last step, the overlifting is calculated based on the previously calculated angle. This proves that the proposed methodology using the prototype is suitable for rail track geometry measurements.

6 Conclusions

In this paper a novel solution is presented to perform rail track monitoring and geometry measurement using an IoT-powered non-invasive retrofitting approach. The main advantage of the proposed system is that it can extend a regular rail vehicle with measuring capabilities, therefore the track geometry monitoring becomes a daily basis activity in comparison with the regular schedule-based approaches. The paper describes the architecture of the measurement and the data acquisition system, and briefly presents a prototype realized for validating the proposed methodology. The experiments prove that the measurements collected by the prototype system can be used for rail track geometry evaluation.

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