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ON-BOARD RAILWAY TRACK IRREGULARITY DETECTION WITH MACHINE LEARNING

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Summary: Railway track geometry maintenance is crucial for passenger comfort and the safety and efficiency of railway operations. Traditional inspection systems rely on inspection vehicles that are instrumented with high-precision measuring devices, such as accelerometers, laser scanners, among others. However, these vehicles are usually owned in limited numbers by infrastructure managers and typically involve high maintenance and operational costs, thus limiting the frequency of the track inspection activities. This work proposes addressing these limitations through the development of an onboard sensor system designed for installation on any rail vehicle, enabling the real-time monitoring of track quality. This research is built on two key components: a multibody (MB) model of the EM120 inspection vehicle; and machine learning (ML) techniques.

An MB formulation is used to simulate realistic vehicle-track interaction at specified operating conditions, supporting the analysis of the correlations between the vehicle dynamics and the track irregularities: alignment level, AL; longitudinal level, LL; cross level, CL; gauge, G. This work uses the MB software MUBODyn to simulate the vehicle-track interaction, enabling the assessment of the vehicle dynamics as a function of the track conditions. In particular, the motion of the bogie frame is acquired by a virtual representation of the sensor module that measures the six degrees of freedom: three accelerations and three angular velocities, and the standard deviation (SD) of these variables are calculated to serve as input for the ML models. The datasets used to develop the ML models are constructed using data from 1,014 km of synthetic track models, generated by combining all types of track irregularities at various levels. This approach covers a wide range of realistic scenarios, providing a comprehensive representation of real-world conditions. During the model training phase, the SD of track irregularities is used to classify 200-meter track sections into two classes: Class 1 for small irregularities (no maintenance required); and Class 2 for larger irregularities (maintenance required). Different Support Vector Machine (SVM) models are trained for both general and specialized track irregularity classification tasks, and evaluated with performance metrics such as accuracy, precision, sensitivity, specificity, F1 score, and Cohen's Kappa. This methodology enables a model to classify track sections as "regular" or "irregular" based on bogie frame dynamics. The results demonstrate a strong correlation between track irregularities and bogie frame dynamics, providing valuable insights into the relationship between the features used to train and test the ML models. Among the evaluated approaches, the Gaussian SVM achieved the highest performance metrics across all case studies, underscoring its reliability and robustness. While the models excelled in classifying LL, CL, and G irregularities, improvements are needed for AL irregularities, highlighting future refinement opportunities.

This research demonstrates the feasibility of continuous track monitoring using a sensor module mounted on the bogie frame to measure its dynamic behaviour, enabling the development of scalable, data-driven maintenance strategies. By combining MB dynamics, sensor data processing, and ML, this methodology offers a scalable and efficient alternative to traditional inspection methods, through the deployment of the proposed sensor module in non-inspection vehicles.