Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 6.9
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.6.9

Real-Time IoT-Driven Predictive Maintenance: An Integrated Monitoring System for Railway Turnouts and Infrastructure

J.-Y. Shih[1,2], C.-M. Kuo[1], L.-W. Chen[3], K.-Y. Liu[4], C.-K. Chen[4] and M. Wang[4]

[1] National Cheng Kung University, Taiwan
[2]Zynamic Engineering AB, Stockholm, Sweden
[3]Grand Wisdom Technology Ltd., Taiwan
[4]China Engineering Consultants, Inc., Taiwan

Abstract

Railway turnouts are critical infrastructure requiring precise maintenance. This paper introduces an integrated Internet of Things (IoT) system utilizing wireless vibration nodes and solar-powered gateways. To optimize network efficiency and minimize power consumption, the nodes perform initial edge processing, including low-pass filtering and downsampling, to transmit only peak acceleration and processed datasets. The gateway then process the second analysis, applying a time-window during the train passage to calculate acceleration RMS values, train speed via harmonic frequencies, and sleeper displacement through double integration.
These metrics enable the real-time derivation of track geometry parameters, specifically level, twist, lateral, and vertical irregularities. Field results conducted in Kaohsiung Taiwan has validate the system's performance. It successfully identified a loss of lateral resistance in sleepers during heavy rain and quantified vibration mitigation following bolt and joint maintenance. Furthermore, the system captured a significant reduction in both vertical and lateral irregularities immediately following tamping operations. The proposed system facilitates a transition toward predictive maintenance, enhancing operational safety while significantly reducing lifecycle costs for railway infrastructure.

Keywords: turnouts, wireless, IoT, track geometry, predictive maintenance, condition monitoring

1 Introduction

The global railway sector is undergoing a profound digital transformation. The digital railway market, valued at USD 77.3 billion in 2023, is projected to reach USD 131.2 billion by 2030 with a compound annual growth rate (CAGR) of 7.8%. This surge underscores a global commitment to enhancing operational efficiency, safety, and cost-effectiveness through intelligent systems. In alignment with this trend, Taiwan has formalized its dedication to smart rail through the "National Smart Railway System Development Plan" and the 2024 issuance of the "ICT Specifications for Smart Railway Systems" by the Ministry of Transportation and Communications.

Among track assets, Switches and Crossings (S&C)—commonly known as turnouts—are the most critical and maintenance-intensive components. While representing only a small fraction of total track mileage, S&C maintenance accounts for approximately 25% of total infrastructure budgets and causes 25% to 30% of all traffic delays due to mechanical complexity and high dynamic impact loads.

1.1 The Challenge of Traditional Maintenance

Traditional maintenance still relies heavily on manual visual inspections, which are labour-intensive, prone to human error, and incapable of providing real-time data. A primary concern is ballast voiding beneath the sleepers. This phenomenon occurs when the ballast degradation, creating gaps between the sleeper and ballast layer that are invisible to the human eye and only can be detect when the train is passing. Furthermore, excessive or imprecise tamping operations intended to fix these issues can inadvertently accelerate ballast degradation, shortening the turnout's service life.

1.2 Critical Failure Modes in Turnout Components

The core components of a turnout—the crossing (frog) and the switch rail—are particularly vulnerable:

- Crossing Area: As wheels transition from the wing rail to the nose rail, they generate severe impact loads. Over time, this leads to foundational voiding, resulting in cracked crossing bases, sleeper damage, and fastener failure.
- Switch Rail Area: Foundational settlement in this transition zone directly threatens structural stability and derailment prevention.

Given that these defects often remain hidden until a catastrophic failure occurs, there is an urgent need for an automated, real-time monitoring solution. This paper proposes an Internet of Things (IoT) driven system designed to detect these sub-surface irregularities and transition railway maintenance from a reactive to a high-precision predictive strategy.

1.3 Existing Condition Monitoring Methods

Current monitoring strategies for Switches and Crossings (S&C) generally fall into two categories: vehicle-based monitoring and track-based monitoring. Each presents specific challenges that necessitate the development of more integrated, autonomous IoT solutions.

1.3.1 Vehicle-Based Monitoring

Vehicle-based methods—utilizing accelerometers or inertial systems mounted on bogies or axle boxes—are widely researched for their ability to cover large-scale networks [1]. However, their efficacy for S&C assessment is limited by two major factors. First, these sensors primarily capture long-wavelength track irregularities [2], whereas high-frequency, short-wavelength signals essential for identifying local turnout defects are often attenuated by the vehicle's suspension system [3]. Consequently, critical vibrations from S&C geometry faults are frequently discarded as outliers rather than being utilized for monitoring. Furthermore, distinguishing between vibrations from joints and turnouts remains a significant identification challenge [4]. Second, these systems rely on GNSS/GPS for fault positioning, which typically carries a horizontal error of 3 to 15 meters. This inaccuracy prevents the precise identification of specific S&C units [5], thereby limiting the practical value of the results for targeted maintenance [6].

1.3.2 Track-Based Monitoring

Track-based systems provide the advantage of direct proximity to the infrastructure, allowing for the capture of high-frequency dynamic responses and forces. This makes them superior for precise fault localization and condition-based maintenance. Accelerometers are frequently deployed on sleepers and rails to monitor wheel-rail impact forces at the frog [7][8] and to assess ballast support conditions and track stiffness [9]. Recent studies have reconstruct displacement from acceleration data [10][11] and predict ballast degradation [12].

While these track-based systems provide high-fidelity data, traditional installations demand extensive cabling and frequent field maintenance. This creates a clear demand for the proposed system: an autonomous, solar-powered IoT framework that combines the precision of track-based sensing with wireless scalability and multi-stage edge processing.

2 Real-Time Condition Monitoring System

A robust real-time condition monitoring system must harmonize physical insight with scalable digital infrastructure. The proposed system is built upon three pillars: an in-depth understanding of track physics to avoid "black-box" data fallacies, high-quality hardware calibrated for harsh environments, and deployable edge algorithms that balance analytical precision with computational efficiency.

2.1 Edge-Cloud Collaborative Framework

The system utilizes a scalable Edge-to-Cloud IoT architecture designed to optimize data throughput while ensuring low-latency response. As illustrated in Fig. 1, the architecture is organized into four functional layers: the Physical Sensing Layer, Edge Gateway Layer, Middleware Message Broker, and the Cloud Analysis Layer.

To balance the need for immediate visualization with the requirements for long-term big data analysis, the system implements a dual-path data flow:

- Real-Time Stream: Edge-processed metrics are transmitted via MQTT through an EMQX broker to an InfluxDB time-series database, enabling instantaneous visualization on a Grafana dashboard.
- Data Persistence: High-frequency datasets are uploaded via API directly to AWS S3 buckets, providing a foundational data lake for future deep learning modelling and structural health trending.

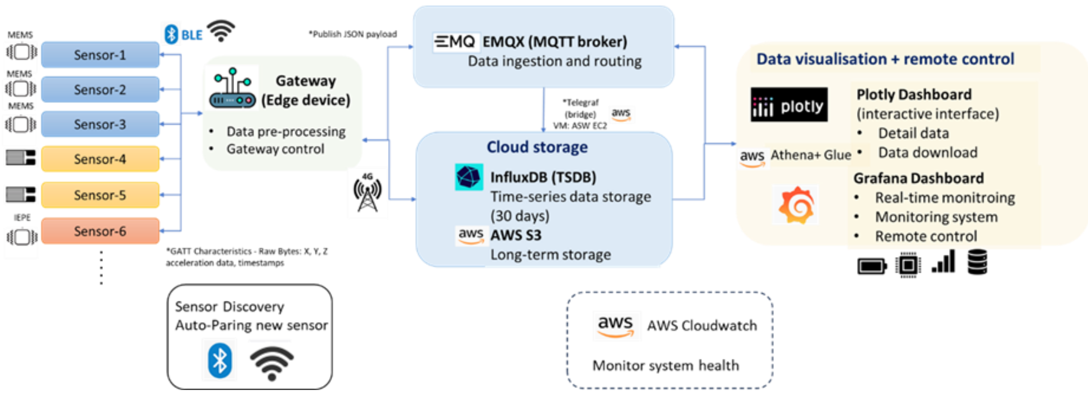


Figure 1: Real-time condition monitoring system

2.2 Local Sensing and Edge Processing

The local network comprises a series of vibration nodes linked to a central solar-powered gateway. Each node is equipped with a dedicated microcontroller and accelerometers. To optimize power consumption and network bandwidth, the nodes perform initial edge processing, including temperature compensation, low-pass filtering, and downsampling. While the current phase utilizes vibration data, the modular architecture allows for the seamless integration of strain gauges and other transducer types. The central gateway act as a high-performance data aggregator, it collects data from all vibration nodes and executes secondary analysis to obtain the critical metrics such as RMS values, harmonic-based train speed, and sleeper displacement.

Data is relayed from the vibration nodes to the gateway using an adaptive wireless protocol. Depending on the environmental interference and the specific payload size, the system toggles between Bluetooth Low Energy (BLE) and Wi-Fi to maintain a robust connection and maximize battery longevity.

3. Field Trial in Kaohsiung Taiwan

3.1 Measurement plan

To evaluate the feasibility and effectiveness of the proposed IoT monitoring system, a field trial was conducted on a problematic turnout section near the Xinzuoying Station under the jurisdiction of the Kaohsiung Engineering Department. The deployment was strategically designed to measure core track geometry parameters—

including level, twist, vertical, and lateral irregularities—to align with the maintenance standards of the Taiwan Railway Corporation (TRC), while also monitoring advanced health indicators such as voided sleepers, peak vertical displacement, and acceleration RMS trends. To accurately capture track displacement under dynamic wheel loads without interfering with routine tamping operations, sensors were mounted at the sleeper centres for internal positions and adjacent to the rail seats for calculating the track geometry, as shown in Fig. 2. The sensor layout utilizes a multi-point spatial configuration designed to capture full track geometry. Two wireless nodes were installed per sleeper: one at the sleeper centre and another near the rail seat to capture differential displacement. Longitudinally, three primary locations were instrumented: the wheel-rail transition zone at the crossing nose (Nodes S2 and S5), with additional monitoring points positioned 2.5 m ahead (Nodes S1 and S4) and 2.5 m behind (Nodes S3 and S6). This symmetric 5-meter array enables the derivation of twist, lateral, and vertical irregularities based on a standard 5-meter chord-length calculation. Notably, Sensor Node 5 was positioned near the wheel-rail transition point to facilitate future correlation analysis between vibration signatures and rail wear. Furthermore, the central gateway was installed 5 meters from the sensor nodes to ensure high-throughput, low-latency communication while maintaining operational safety clearances. The actual field deployment and hardware configuration of the system are illustrated in Fig. 3.

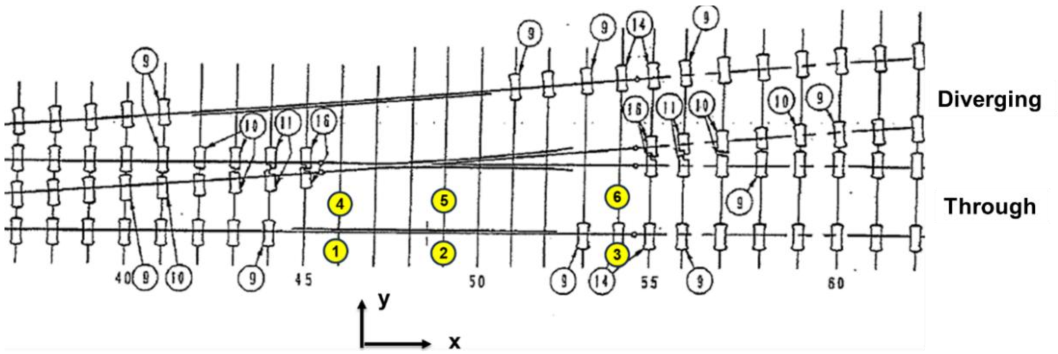


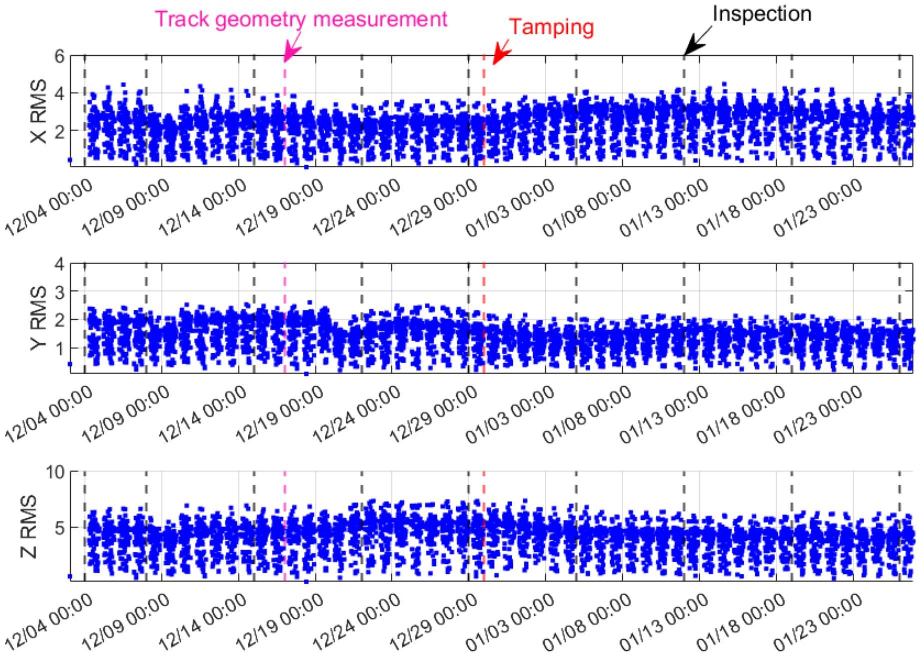
Figure 2: Measurement plan

(a) (b)

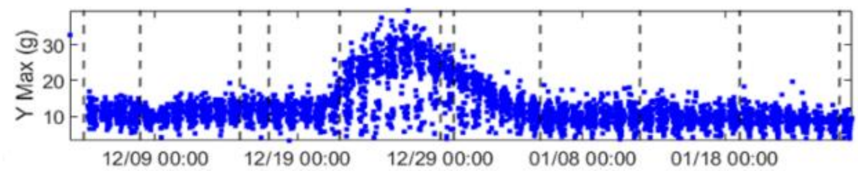
Figure 3: Monitoring system; (a) Vibration node; (b) Gateway

3.2 Data Post-Processing and Result Analysis

Field measurements demonstrate the system's monitoring capabilities, with Fig. 4 highlighting the dynamic response captured at Sensor 6 near the rail joint. During the trial period, several maintenance actions were recorded, including routine inspections, fastener tightening, and manual tamping. A notable reduction in vibration was observed on December 8, 2025, following a routine inspection where the fastener system was reinforced. This demonstrates the system's high sensitivity to the structural integrity of localized components, such as bolts and rail clips.



(a)



(b)

Figure 4: Sensor 6 results during trial period; (a) RMS in 4 axis (b) Max

A significant drop in the Y-direction (lateral) RMS was recorded during a period of heavy, continuous rainfall from December 19 to 21, 2025. This phenomenon suggests that water accumulating in the gaps beneath the sleepers acted as a "fluid damper," temporarily suppressing vibration levels during train passage. However, once the rain ceased, the maximum Y-acceleration increased rapidly starting December 22, indicating that the heavy rain likely accelerated ballast degradation and results in voided sleeper which cause high impact and eventually cause loss of lateral resistance. This degradation triggered an inspection on December 29, followed by a manual tamping operation on December 30.

These findings are further confirmed by the calculated track geometry shown in Fig. 5. Following the storm, a significant escalation in lateral irregularity was detected on December 22. This deviation subsequently diminished following the tamping operation, while vertical irregularity transitioned back within allowable safety thresholds. These findings validate the system's ability to accurately reflect turnout health and diagnose structural anomalies, demonstrating significant potential for a predictive maintenance framework.

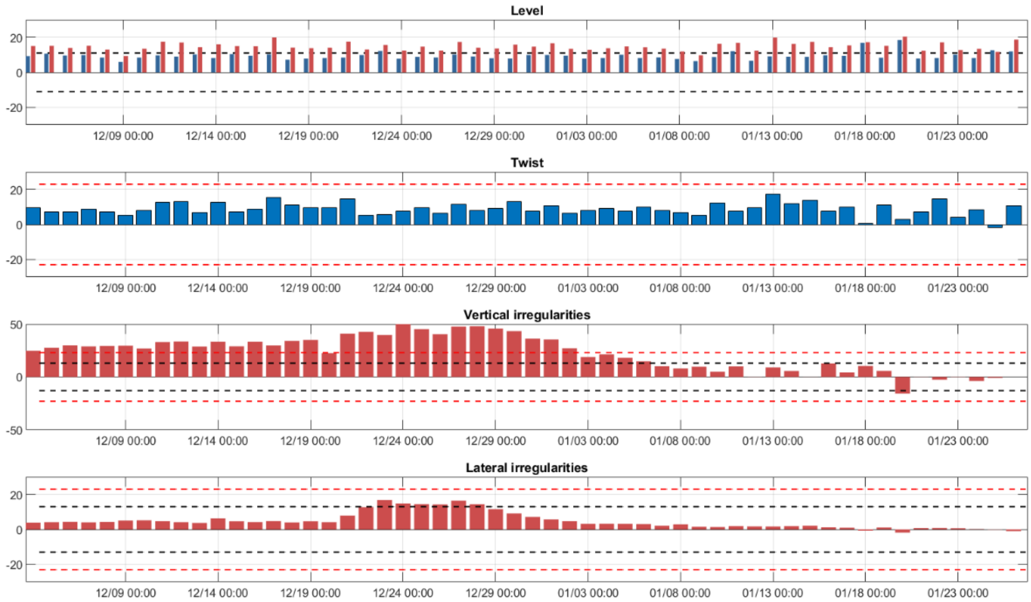


Figure 5: Track geometry results during trial period

4. Conclusion

The integrated IoT system presented in this study has shown potential transitions railway maintenance from reactive to predictive strategies. By utilizing wireless vibration nodes and a solar-powered edge-cloud architecture, the system achieves real-time derivation of track geometry parameters, specifically level, twist, lateral, and vertical irregularities. Field results from Kaohsiung, Taiwan, validate the system's performance in identifying critical structural changes, such as the loss of lateral resistance in sleepers during heavy rain and the quantification of vibration mitigation following fastener and joint maintenance. Furthermore, the system successfully captured significant reductions in both vertical and lateral irregularities immediately following tamping operations. By delivering actionable insights through multi-stage edge processing, the proposed framework enhances operational safety while significantly reducing lifecycle costs for railway infrastructure.

Acknowledgements

This work was funded by China Engineering Consultants, Inc. under Project No. 14925, as part of the "Real-time condition monitoring system for railway S&C" initiative. The authors would like to express their gratitude to the Taiwan Railway Corporation, Ltd. for providing the test field facilities and for their invaluable collaboration during the inspection and field trial phases.

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