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Concept of Bio-Inspired Cyber-Physical Railway Infrastructure Towards Predictive Maintenance: Distributed Piezoelectric Sensing and Physics-Informed Digital Twins

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Abstract

This paper presents a conceptual framework for bio-inspired cyber-physical railway infrastructure based on distributed piezoelectric sensing, low-power edge computing, and physics-informed digital twins. Piezoelectric elements integrated into rails, switches, and structural components generate diagnostic signals directly from train-induced dynamic excitation. Analog front-end preprocessing and edge AI enable low-power extraction of physically interpretable indicators related to stiffness changes, modal behavior, damping evolution, and infrastructure degradation. Processed state markers are transmitted to continuously evolving digital twins supporting predictive maintenance and infrastructure management. The proposed architecture aims to reduce maintenance costs, improve degradation detection, and support scalable deployment of intelligent railway infrastructure systems.

Keywords: railway infrastructure, IoT, sensing, cyber-physical system, digital twin, predictive maintenance.

1 Introduction

Railway infrastructure maintenance is increasingly shifting from periodic inspection to predictive, condition-based maintenance strategies. Aging infrastructure, increasing traffic density, and rising maintenance costs create strong pressure for more efficient, intelligent infrastructure monitoring systems.

Current railway diagnostics are still predominantly based on periodic inspections performed by dedicated diagnostic vehicles or local monitoring systems installed at selected critical locations. Although these approaches provide high-quality measurements, they do not enable continuous, distributed assessment of infrastructure degradation processes. At the same time, railway infrastructure is a highly dynamic mechanical system whose structural properties continuously evolve due to ballast degradation, changes in stiffness, fatigue accumulation, wear, and environmental effects. Critical regions such as switches and crossings, bridge transitions, stiffness discontinuities, or local support degradations exhibit complex transient dynamic responses that contain valuable information about the infrastructure condition.

Recent advances in digital twin (DT) technologies, IoT sensing, and predictive maintenance demonstrate the growing importance of cyber-physical railway systems. Existing reviews highlight the increasing role of AI, IoT, and DT technologies in railway monitoring and maintenance optimization [1]. However, current implementations remain fragmented and are often focused on cloud-centric architectures and high-volume data acquisition rather than distributed low-power physically interpretable sensing.

This paper presents a conceptual framework for bio-inspired cyber-physical railway infrastructure based on distributed piezoelectric sensing, low-power edge computing, and continuously evolving physics-informed digital twins.

Current railway monitoring systems include diagnostic vehicles, fiber-optic sensing systems, weigh-in-motion systems, switch monitoring systems, and localized structural health monitoring installations. Fiber-optic sensing technologies provide highly distributed measurements and excellent sensitivity; however, they require extensive installation effort and infrastructure integration. Diagnostic vehicles provide detailed information about track geometry and dynamic behavior, but measurements are only available periodically.

Recent developments increasingly focus on Digital Twin architectures and AI-driven predictive maintenance systems. Several review papers demonstrate the growing interest in DT-enabled railway maintenance and cyber-physical railway systems [1,2]. Vibration-based railway condition monitoring has also emerged as a promising direction. Shen et al. proposed a physics-based digital twin approach capable of combining measurement data and vehicle-track interaction models for track condition assessment [3].

Nevertheless, several important limitations remain [4,5]:

- excessive dependence on centralized cloud processing,
- extensive installation effort,
- high communication and energy requirements,
- limited scalability,

- insufficient physical interpretability,
- lack of continuously evolving dynamic digital twins.

2 Methods

The proposed concept is inspired by biological nervous systems, similar to distributed sensory neurons in living organisms. Distributed piezoelectric sensing elements embedded into railway infrastructure, mainly on rail on Figure 1, continuously detect local dynamic excitations and structural responses (e.g., ballast stiffness, fastening conditions, local defects, wheel-rail interaction, etc.). The used piezoelectric macro-fibre composite (MFC) provides a very sensitive voltage signal for load excitation. The output voltage is proportional to the rate of rail strain and provides useful information about the deformation of railway infrastructure proposed on Figure 2.

Figure 1: A piezoelectric MFC sensing element embedded on rail and output signal

Instead of continuously transmitting large volumes of big data, local IoT edge processing performs low-power feature extraction and event-driven analysis. Only physically meaningful state indicators are transmitted to higher-level digital infrastructure models. This approach enables scalable and energy-efficient distributed monitoring while preserving physically interpretable diagnostic information.

Figure 2: A railway infrastructure can be interpreted as a distributed dynamic system and dynamic properties are continuously monitored over time

The proposed concept of a cyber-physical railway infrastructure consists of:

- Distributed and integrated piezoelectric sensing,
- Analog Front-End electronics and event-driven edge processing,
- Physics-informed Artificial Intelligence [6],
- IoT communication module,
- Continuously evolving digital twin.

The proposed concept of a cyber-physical railway infrastructure architecture is shown in Figure 3. It is based on a hierarchical processing chain that transforms distributed active piezoelectric measurements of railway dynamic behaviour into actionable maintenance information. The system starts at the physical infrastructure layer, which includes dynamically critical components such as switches and crossings [7], bridge transitions, stiffness discontinuities, and locally degraded support regions. Mechanical excitation generated by train passage induces characteristic transient and modal responses within the railway structure.

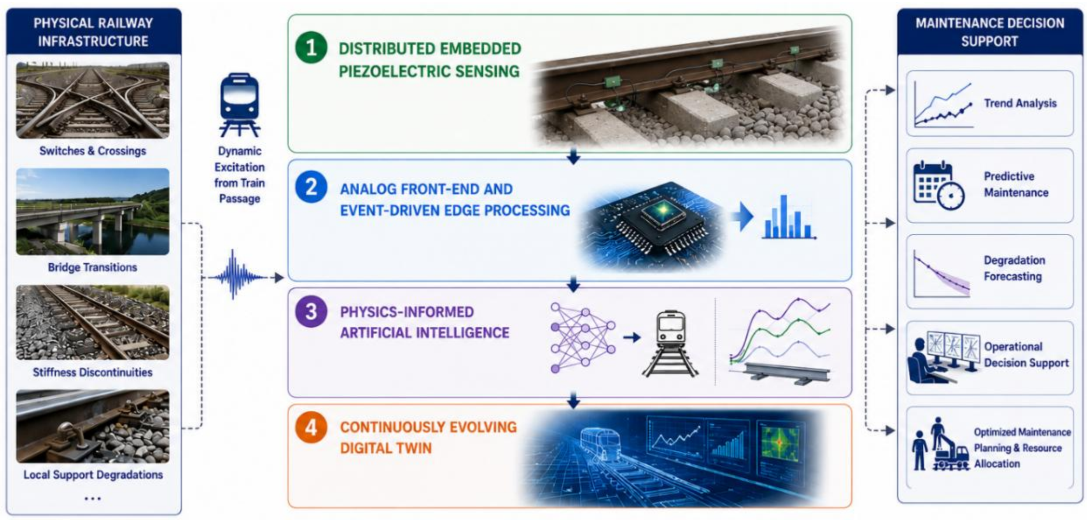

Figure 3: Proposed architecture of the cyber-physical railway infrastructure under consideration

These mechanical responses generate voltage signals of piezoelectric sensing elements embedded in the infrastructure which are captured by a distributed IoT network. Unlike conventional monitoring systems this approach is based on continuous active sensing, the proposed approach utilizes the dynamic excitation itself as a source of diagnostic information. The measured signals contain information related to local stiffness variations, damping evolution, wheel–rail interaction, and other degradation-sensitive dynamic phenomena. The acquired signals are processed by an ultra-low-power analog front-end and an event-driven edge-processing layer. Basic signal conditioning, filtering, envelope extraction, resonance tracking, and feature extraction are performed locally, significantly reducing computational requirements and communication demands. Instead of transmitting raw measurement data (BIG DATA), the edge node could generate compact health indicators describing the dynamic state of the monitored infrastructure.

These indicators are subsequently evaluated by physics-informed artificial intelligence models combining advanced machine learning techniques with physically interpretable railway dynamics. By integrating modal characteristics, transient response features, stiffness-sensitive indicators, and degradation evolution models, the system provides robust condition assessment while maintaining physical interpretability of the obtained results.

The extracted information is continuously integrated into a dynamic digital twin representing the current state of the railway infrastructure. In contrast to conventional static digital twins, the proposed model continuously updates effective stiffness, damping characteristics, modal parameters, degradation states, and dynamic response signatures. This enables long-term trend monitoring and provides a consistent representation of infrastructure condition over its operational lifetime. At the highest level, the digital twin serves as a decision-support platform for infrastructure managers. The continuously updated state information enables trend analysis, degradation forecasting, predictive maintenance planning, and optimization of maintenance resources. Therefore, the proposed architecture concept establishes a direct link between distributed sensing, edge intelligence, digital infrastructure models, and maintenance decision-making, creating a scalable framework for future data-driven railway asset management.

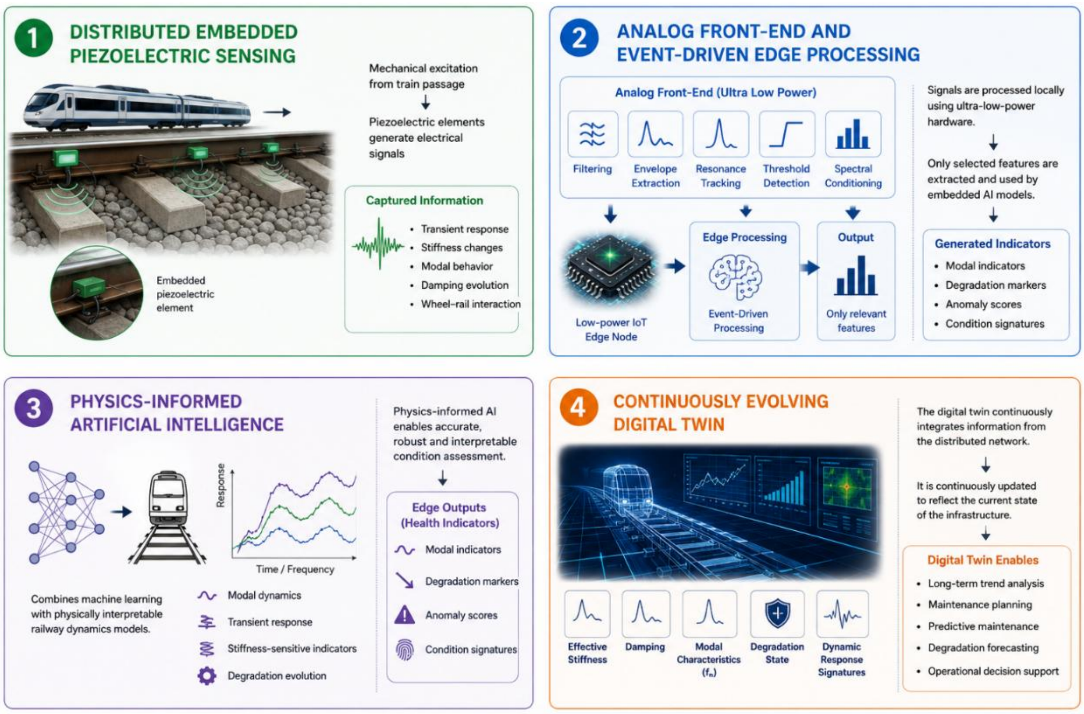

Figure 4: Operational principle of the proposed and tested IoT edge device

3 Results

To validate the feasibility of the proposed cyber-physical railway infrastructure concept, Figure 4 shows the operational principle of a piezoelectric MFC sensing and communication platform prototype that has been developed and tested under real railway operating conditions. The IoT system in Figure 5 combines an embedded piezoelectric MFC patch, analog front-end, low-power edge electronics, wireless communication, and cloud-based data management into a single monitoring architecture.

The sensing subsystem utilizes piezoelectric elements integrated into railway infrastructure components. Mechanical excitation generated by train passages is directly converted into electrical signals carrying information about the dynamic behaviour of the track structure. Long-term field measurements conducted on several operational railway lines near Brno (Czechia) have yielded a database containing more than 15,000 recorded train passages, providing valuable data for subsequent signal processing and model development.

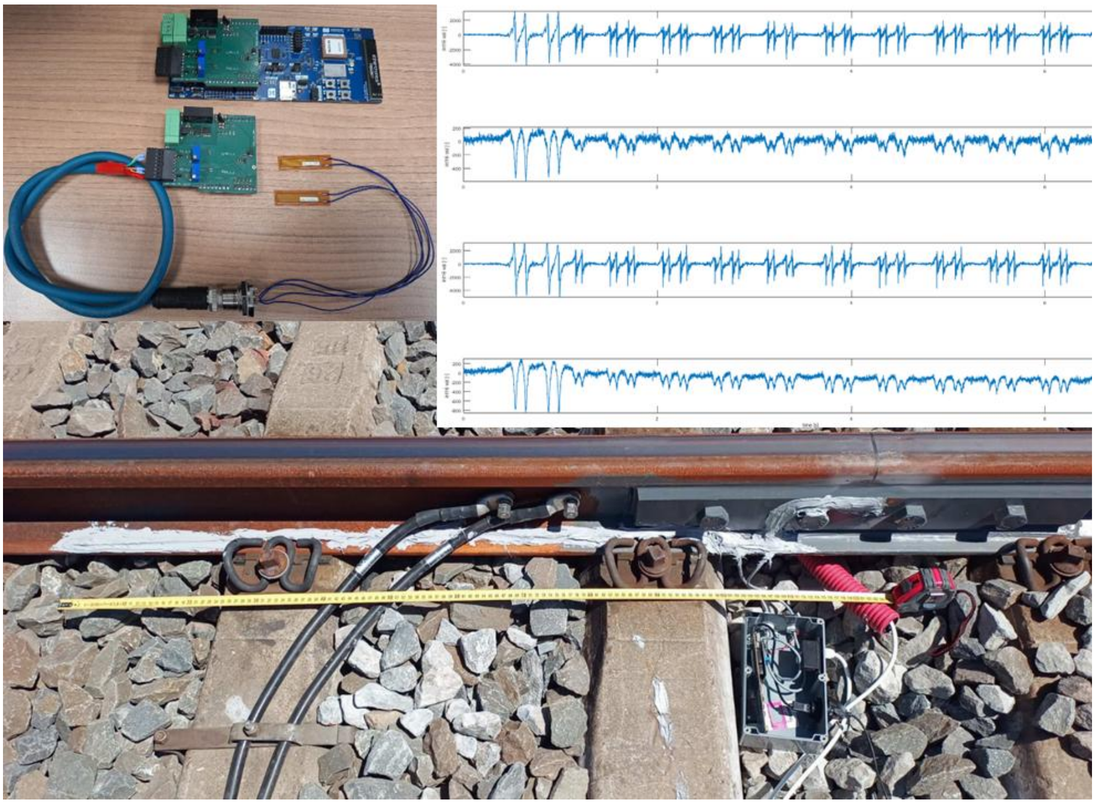

Figure 5: The sensing subsystem utilizes piezoelectric elements, output and processed signal and system integrated into railway infrastructure - straight rail and glued insulated joint

A dedicated analog front-end was designed to address the specific characteristics of piezoelectric sensing elements, which exhibit high output impedance and operate in an electromagnetically demanding railway environment. The analog circuitry performs charge-to-voltage conversion, signal conditioning, sensitivity adjustment, and analog integration before digitization. This approach significantly reduces computational requirements at the microcontroller level while preserving diagnostically relevant information. Particular attention was devoted to electromagnetic compatibility through galvanic isolation, optimized grounding, and protection against traction-related interference.

The embedded sensing node is based on the Nordic Semiconductor nRF9161 platform, combining low-power processing capabilities with cellular IoT connectivity [8]. Signal acquisition is implemented using an event-driven strategy, where measurements are triggered either by train detection or scheduled timing events. This approach minimizes energy consumption and enables long-term autonomous operation [9]. The firmware architecture is built on the Zephyr real-time operating system and separates sensing, communication, and firmware management functions into dedicated tasks. Remote firmware updates are supported through Firmware Over-The-Air mechanisms, enabling continuous improvement of deployed devices.

Communication between field devices and the backend infrastructure is implemented via MQTT-based telemetry. The current cloud architecture already supports data ingestion, database storage, device management, and user access control. A web-based interface could provide visualization of measured signals, diagnostic indicators, and long-term infrastructure trends. This infrastructure provides the technological foundation for the future implementation of digital twins, predictive maintenance models, and intelligent decision-support systems for railway asset management, as shown in Figure 6.

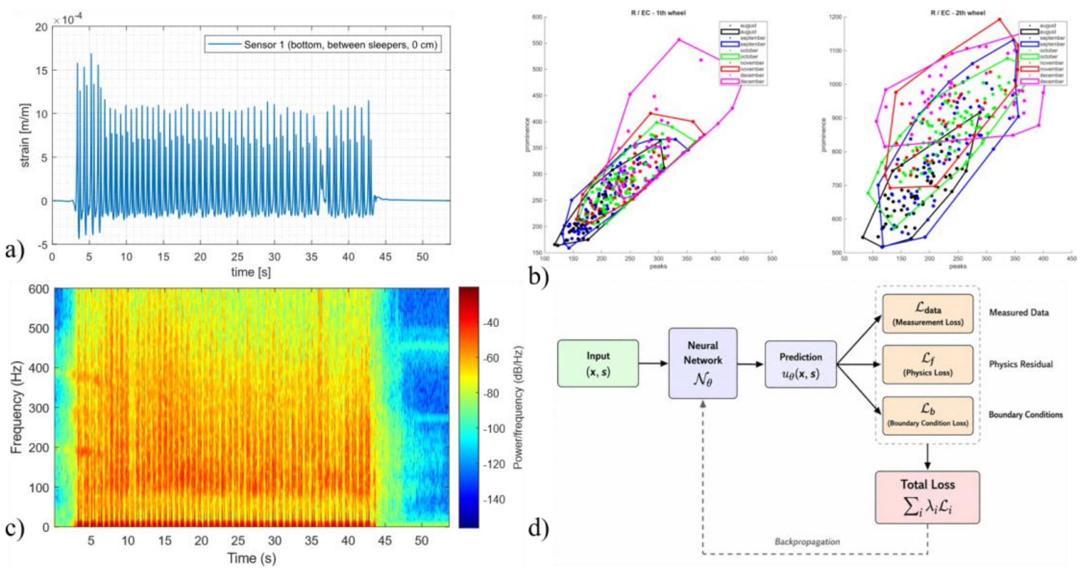

Figure 6: Examples of signal outputs: a) analog signal processing of a voltage signal proportional to strain; b) Machine Learning - clustering of the signal response based on the weather; c) spectral analysis of the voltage signal; d) schematic diagram of PI Neural Network for the prediction of infrastructure lifetime

The developed sensing concept, as shown in Figure 6, demonstrates that distributed embedded monitoring of railway infrastructure can be implemented using commercially available low-power technologies while maintaining robustness, scalability, and compatibility with future cyber-physical railway systems.

4 Conclusions and Contributions

This paper presented a conceptual framework for bio-inspired cyber-physical railway infrastructure based on distributed piezoelectric sensing, event-driven edge computing, and continuously evolving physics-informed digital twins. The paper opens several scientific and technological challenges that remain under research for future development:

- long-term robustness of embedded piezoelectric sensing,
- environmental variability,
- distributed synchronization,
- low-power edge AI implementation,
- uncertainty quantification,
- adaptive and scalable digital twin updating,
- integration of physics-informed neural networks,
- development and implementation of machine learning methods,
- interpretation of degradation-sensitive dynamic indicators.

The proposed concept interprets railway infrastructure as a distributed dynamic mechanical system equipped with low-power sensory nodes analogous to biological nervous systems. Piezoelectric sensing elements combined with analog front-end processing and edge intelligence enable scalable and physically interpretable monitoring of infrastructure dynamic behavior. The presented framework provides a potential pathway toward future predictive railway maintenance systems and it may provide several important benefits:

- continuous distributed infrastructure monitoring,
- reduction of raw data transmission requirements,
- low-power scalable sensing architecture,
- improved predictive maintenance capabilities,
- earlier degradation detection,
- reduction of maintenance costs,
- extension of infrastructure lifetime,
- improved operational safety,
- improved maintenance prioritization.

The proposed architecture also supports gradual deployment without requiring extensive modifications to existing railway infrastructure, and it continues to enable distributed assessment of infrastructure condition while reducing maintenance costs and improving infrastructure reliability.

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