AI Based Acoustic Wave Monitoring of Rail Defects Like Cracks, Fracture and Prediction for Rail Wear, Quality Along with Other Parameter

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Abstract

Railway safety relies heavily on the prompt identification of track defects such as cracks, fractures, and material degradation. Existing track inspection approachesare often constrained by manual involvement, absence of continuous monitoring, and limited capability to predict failures in advance. This study proposes an intelligent acoustic wave–based monitoring framework that combines acoustic emission sensing with machine learning and IoT technologies to enable real-time detection and forecasting of rail defects. The system acquires sound signals produced by structural irregularities and analyzes them using sophisticated signal processing procedures with AI-driven algorithms. Additionally, an extensive review of existing approaches—such as ultrasonic inspection, magneto-acoustic techniques, deep learning models, and IoT-enabled systems—is presented, highlighting their strengths and limitations. The proposed solution improves operational safety, lowers maintenance expenses, and supports predictive maintenance strategies in railway systems.

Keywords-Railway defect detection, Acoustic emission, AI, Machine learning, IoT, Predictive maintenance, Ultrasonic testing

1. Introduction

Railway transportation is a fundamental component of modern infrastructure, enabling efficient movement of passengers and goods while supporting economic development. The safety and reliability of railway systems are strongly dependent on the structural integrity of the tracks. However, railway tracks are subjected to continuous mechanical loads, environmental variations, and material degradation, which causes defects such as cracks, fractures, and surface wear. If such defects are not identified at an early stage, which results in severe consequences, including derailments, operational disruptions, and risks to human safety [4], [9].

Traditional inspection techniques, including manual inspection and non-destructive testing methods such as ultrasonic evaluation, have been widely employed for track monitoring. Although these techniques are effective to some extent, they are often time-consuming, expensive, and reliant on skilled personnel. Furthermore, they lack the ability to provide continuous monitoring and real-time insights into track conditions, making early fault detection and prediction difficult [1], [8].

Emerging innovations in AI, sensor systems, and IoT have enabled the development of highly efficient and sophisticated frameworks.automated monitoring systems. Acoustic emission (AE) approaches have become popular due to their capability to detect stress-induced signals generated by structural changes in materials. These signals offer valuable insights intothe initiation and propagation of defects, enabling early-stage detection [3], [10].

The unification of machine learning with acoustic sensing enhances the system's capability to examine complex data, extract patternsand predict potential failures. ML based algorithms can be trained to classify defect types, evaluate severity, and estimate the remaining useful life of railway components [3], [16]. Additionally, IoT-based communication systems facilitate real-time data transmission, remote monitoring, and immediate alert generation, allowing maintenance teams to respond promptly [11].

This research focuses on developing an integrated monitoring system that combines acoustic sensing, intelligent data analysis, and IoT-based communication. The proposed system aims to provide a reliable, efficient, and cost-effective solution for real-time defect detection and predictive maintenance, thereby improving railway safety and operational efficiency.

2.Related Work

Railway track monitoring frameworkvastly studied using various non-destructive testing (NDT), acoustic sensing, and artificial intelligence-based approaches. Ultrasonic guided wave (UGW) methodologies are predominantly utilized for detecting internal defectsin rail structures. Xie *et al.* [1] demonstrated that specific guided wave modes, particularly the S6 mode, are highly sensitive to transverse fissures, enabling accurate identification of subsurface defects. Similarly,ultrasonic surface wave approaches have been widely applied fordetecting surface cracks, where methods such as phased array focusing and spatial averaging improve signal clarity, although challenges remain due to interference from multiple wave modes [8].

Magneto-acoustic coupling combined approaches have also been suggestedfor rail defect detection by combining electromagnetic excitation with acoustic wave propagation. Huang *et al.* [2] developed a multi-physics model that captures the interaction between electric, magnetic, and acoustic fields to detect microcracks with high sensitivity. While effective for early-stage defect detection, the approach introduces complexity in modelling and implementation.

Acoustic emission (AE) techniques have garnered considerable attentionforreal-time monitoring of crack initiation and propagation. Barat *et al.* [4] showed that AE signals generated under operational loading conditions can effectively differentiate between defective and non-defective rails based on signal amplitude and hit rates. Similarly, Yilmazer [9] demonstrated that AE-based structure monitoring frameworks support continuous tracking ofcrack growth under both laboratory and simulated field conditions. However, AE methods are highly sensitive to environmental noise and rely on enhanced signal processing methodologies for precise analysis.

To improve AE signal analysis, advanced signal processing and machine learning approaches have been incorporated. Mahajan and Banerjee [5] utilized clustering algorithms along with PCA, FFT, and wavelet transforms to separate noise from meaningful signals, thereby enhancing classification accuracy. Furthermore, Kundu *et al.* [6] proposed an ANN-based approach for AE source localization, providing high accuracy with low localization error. Deep learning methods have additionallyimproved performance; Suwansin and Phasukkit [3] developed a deep learning-based AE system capable of automatic crack localization, while Barbosh*et al.* [15] applied wavelet-assisted convolutional neural network models for precise damage localization.

In addition to acoustic methods, surface defect detection usingComputer Visionand Deep Learning has beenexplored. Kou [7] presented a comprehensive review of modern technologies like Convolutional

Neural Networks (CNNs) for detecting defects such as spalling and rolling contact fatigue. Similarly, Wu *et al.* [16] enhanced traditional ultrasonic inspection by using Deep Learning algorithms along withultrasonic imaging, achieving improved detection accuracy for internal defects.

IoT-based railway monitoring systems have been engineered to enable real-time data acquisition and remote monitoring. Siddiqui *et al.* [11] proposed an IoT-based acoustic fault identification system using Machine Learningclassifiers, achievinggood performance in defect classification and localization. Swetha and Kayalvizhi [12] implemented a wireless sensor network with AE sensors with GSM communication to provide real-time fault identification andalerting mechanisms.

Surface acoustic wave (SAW) techniques have also been evaluated for their applicability indetecting gauge corner cracks. Gruber *et al.* [10] demonstrated that wave attenuation characteristics can effectively indicate the presence of defects. Additionally, hybrid techniques combining acoustic emission and digital image correlation (DIC) have been proposed to provide both detection and precise measurement of cracks subjected to dynamic forces [14].

Recent studies and research works have explored acoustic signal-based Machine Learningtechniques and algorithmic models for intelligent railway automationfault detection. Shafique *et al.* [20] utilized acoustic attributes such asMel-frequency cepstral coefficients (MFCCs) with machine learning models to classify multiple fault types. Onboard detection systems using AE sensors have also been consideredto eliminate the necessity oftrack-mounted sensors. Jia *et al.* [18] evaluated on-vehicle acoustic emission detection systems, highlighting their scalability despite limitations in signal strength under real conditions.

Furthermore, defect detection techniques have been extended to railway components such as axle bearings and wheels. Amini *et al.* [17] demonstrated the effectiveness of AE signal analysis for detecting bearing defects under operational conditions, while Bollas *et al.* [19] applied AE techniques for real-time wheel defect detection.

Although considerable advancements have been achieved, existing approaches continue to face challenges, including elevated implementation costs,sensitivity to noise, and lack of integrated real-time predictive capabilities. Many approaches focus on either detection or localization but do not provide a unified framework for continuous monitoring and prediction. Thus, it becomes necessary todevelopan integrated system that combines acoustic sensing, artificial intelligence, and IoT technologies to enable accurate, real-time, and predictive railway track monitoring.

3.Methodology

The introduced railway track monitoring system System is developed using an Internet of Things (IoT)-based autonomous robotic platform [11]. The methodology is structured into multiple stages, including system design, sensing, data processing, communication, and alert mechanisms. Each stage has a key role in ensuring accurate and real-time fault detection.

1. System Architecture

The overall system architecture consists of a robotic vehicle integrated with hardware components such as an Arduino Uno microcontroller, ultrasonic sensors, ESP8266 Wi-Fi module, GSM module, GPS module, motor driver (L293D), and DC motors [12]. The robotic system is designed to move autonomously along the railway track and continuously monitor its condition.

The Arduino Uno acts as the central control unit, coordinating all operations including sensor data acquisition, processing, and communication. The ultrasonic sensor is responsible for detecting track irregularities, while the communication modules (Wi-Fi and GSM) enable data transmission and alert generation. The GPS module provides real-time location tracking of detected faults [12].

2. Autonomous Robotic Movement

The system employs a robotic vehicle that travels along the railway track using DC motors controlled through an L293D motor driver. The robot is designed to move at a constant speed to ensure uniform inspection of the track.

The movement mechanism is programmed in a manner that therobot is capable of covering long distances withminimal human intervention. Continuous motion allows the system to perform real-time monitoring without interruptions, thereby increasing efficiency compared to manual inspection methods [8].

3. Fault Detection Using Ultrasonic Sensor

The primary sensing mechanism of the system is developed usingultrasonic technology. The ultrasonic sensor emits high-frequency sound waves toward the railway track and receives the reflected signals. The time taken for the echo to return is applied to computethe distance between the sensor and the track surface [1].

Any deviation in the expected distance indicates the presence of cracks, gaps, or misalignments. These variations are continuously monitored, and the sensor provides real-time data to the Arduino microcontroller for further analysis. This method ensures non-contact and accurate detection of faults.

4. Data Processing and Decision Making

The Arduino Uno processes the data received from the ultrasonic sensor. It compares the measured values with predefined threshold limits to determine whether the detected variation is normal or indicates a fault.

If the deviation exceeds the threshold value, the system classifies it as a fault condition. The decision-making process is implemented using embedded C programming within the Arduino environment. This ensures quick and efficient processing of sensor data, enabling real-time fault detection [5].

5. IoT-Based Data Transmission

Once a fault is detected, the system transmits the data to a cloud-based platform (ThingSpeak) using the ESP8266 Wi-Fi module. This enables real-time monitoring of railway track conditions from remote locations [11].

The cloud platform stores and visualizes the data, allowing railway authorities to analyze trends and track health over time. IoT integration enhances accessibility, scalability, and data-driven decision-making for maintenance operations.

6. GSM-Based Alert System

In addition to cloud communication, the system includes a GSM module for sending instant SMS alerts to railway authorities. When a fault is detected, a notification message is generated automatically [12].

This message provides relevant details about thedetected fault together with its preciselocation. The GSM-based alert system ensures immediate communication, even in regions where network connectivity may be constrained, thereby increasing system reliability.

7. GPS-Based Location Tracking

The GPS module is integrated into the system to provide precise geographic coordinates of the detected fault. This allows maintenance teams to quickly locate the affected section of the track [12].

The GPS data is included in both the cloud update and the SMS alert, ensuring accurate and efficient fault localization. This leads to a significant reduction in response timeand improves maintenance efficiency.

8. Continuous Monitoring and Operation

The system is designed for continuous operation, enabling uninterrupted monitoring of railway tracks. The robotic vehicle moves along the track while simultaneously performing sensing, processing, and communication tasks [9].

This continuous monitoring approach ensures early detection of faults and supports preventive maintenance strategies. It reduces dependency on periodic inspections and enhances overall system reliability.

9. Energy Efficiency and Power Management

The robotic system is powered by a regulated power supply and rechargeable batteries, ensuring stable and long-duration operation. Energy-efficient techniques are utilized tooptimize energy consumption of sensing components and data communication system modules.

This makes the system suitable for real-world deployment, where continuous operation and reliability are essential.

10. Overall Workflow

The complete workflow of the system can be outlined as follows:

The robotic vehicle moves along the railway track. The ultrasonic sensor continuously scans the track surface. Sensor data is processed by the Arduino microcontroller. If a fault is detected, the system identifies it based on threshold values. Data is transmitted to the cloud platform via Wi-Fi [11]. An SMS alert with GPS location is sent to authorities [12]. Maintenance teams take corrective action based on the received information.

4.Results and Discussion

The proposed IoT-based Railway Track Fault Detection Robo System was implemented and evaluated to analyse its effectiveness in detecting faults and improving railway safety [11]. The system's performance wasassessed based on parameters such as detection accuracy, response time, communication efficiency, and overall reliability.

1. Fault Detection Performance

The ultrasonic sensor-based detection mechanism demonstrated satisfactory performance in identifying track faults such as cracks, gaps, and misalignments [1]. The sensor was able to measure variations in distance accurately and detect abnormalities when the measured values exceeded predefined thresholds.

During testing, the system successfully identified faults placed at different positions along the track. The non-contact sensing capability of the ultrasonic sensor ensured consistent readings without physical wear or damage to the sensor. The system was particularly effective in detecting visible cracks and discontinuities in the track structure [1].

However, the detection capability may vary depending on the size and depth of the fault. Very small cracks or irregular surface textures may produce minimal variations, which can sometimes fall within the threshold limits. Despite this, the overall detection performance was found to be reliable for practical applications.

2. Real-Time Data Processing

The Arduino Uno microcontroller efficiently processed the sensor data and executed decision-making operations in real time. The processing speed was sufficient to handle continuous data input from the ultrasonic sensor without any noticeable delay [5].

The system demonstrated stable performance during continuous operation, ensuring that no data loss occurred while scanning long sections of the track. The use of embedded C programming enabled quick comparison of sensor values with threshold limits, resulting in accurate classification of faults.

This real-time processing capability is a significant improvement over traditional inspection methods, where delays in detection can lead to severe consequences [8].

3. IoT Communication and Cloud Monitoring

The integration of the ESP8266 Wi-Fi module enabled seamless data transmission to the Thing-Speak cloud platform. The system successfully uploaded real-time data, allowing remote monitoring of track conditions [11].

The cloud platform provided a user-friendly interface for visualizing sensor readings and analysing trends over time. This feature is particularly useful for predictive maintenance, as authorities can monitor changes in track conditions and take preventive measures before faults become critical [20].

The communication performance was stable under normal network conditions. However, in areas with poor internet connectivity, delays in data transmission may occur. Despite this limitation, the system ensures data availability whenever connectivity is restored.

4. Alert Mechanism Efficiency

The GSM-based alert system proved to be highly effective in providing instant notifications to railway authorities. Upon detection of a fault, the system generated and sent an SMS containing the fault information along with GPS coordinates [12].

The alert messages were delivered within a short time, ensuring quick response from maintenance teams. This feature significantly reduces the time required to identify and locate faults compared to manual reporting methods [7].

The inclusion of both IoT-based cloud monitoring and GSM alerts ensures redundancy in communication, making the system more reliable in real-world scenarios.

5. GPS Localization Accuracy

The GPS module provided accurate location data for detected faults, enabling precise identification of the affected track section [12]. The coordinates obtained were sufficient for maintenance teams to locate the fault without ambiguity.

Accurate localization assists in minimizing response time andimproving maintenance efficiency. The combination of GPS tracking and SMS alerts ensures that authorities receive complete information required for immediate action.

6. Comparison with Existing Methods

Compared to traditional manual inspection methods, the proposed system offers several advantages [7]:

- Reduced Human Effort: Eliminates the need for continuous manual inspection.
- Time Efficiency: Enables faster detection and reporting of faults.
- Improved Accuracy: Minimizes human errors through automated sensing.
- Real-Time Monitoring: Provides continuous updates through IoT integration [11].
- Cost Effectiveness: Reduces long-term maintenance and operational costs.

In contrast to advanced methods such as image processing or machine learning-based systems, the proposed solution is simpler, more cost-effective, and easier to implement, making it suitable for practical deployment in developing regions [16].

7. System Reliability and Limitations

The system demonstrated reliable performance during testing and continuous operation. The integration of multiple modules (sensor, microcontroller, Wi-Fi, GSM, GPS) ensured smooth functioning of the overall system.

However, certain limitations were observed:

- Ultrasonic sensor performance may be affected by influencingenvironmental factors including s temperature and humidity [1].
- Detection of very fine or internal cracks may not be highly accurate [13].

- Dependence on network connectivity for cloud data transmission [11].
- Power consumption may limit long-duration operation without proper battery management.

These limitations can be addressed in future work by incorporating advanced sensors, machine learning algorithms, and improved power management techniques [3], [16].

8. Overall System Evaluation

The overall evaluation of the system indicates that it is an effective and practical solution for railway track fault detection. The combination of real-time sensing, IoT communication, and alert mechanisms ensures timely detection and response to faults [11].

The system enhances railway safety by enabling proactive maintenance and reducing the risk of accidents caused by track failures [13]. Its cost-effective design and autonomous operation make it suitable for large-scale deployment in modern railway networks.

5. Conclusion

This paper presents an IoT-based Railway Track Fault Detection Robo System designed to improve railway safety through automation and real-time monitoring. The system effectively addresses the limitations of traditional manual inspection methods by integrating ultrasonic sensing, microcontroller-based processing, and wireless communication technologies.

The proposed system facilitates continuous track monitoring in railways and ensures early detection of faults such as cracks and misalignments. The integration of ESP8266 and ThingSpeak facilitates real-time data transmission and remote monitoring, while the GSM and GPS modules provide instant alerts with precise fault location.

The development of this system significantly reduces the risk of railway accidents, minimizes maintenance costs, and enhances operational efficiency. Its cost-effective design and autonomous operation make it suitable for large-scale deployment in modern railway infrastructure.

In conclusion, the proposed system offers a reliable, scalable, and efficient solution for railway track fault detection. Future enhancements, including the integration of AI, Machine Learning, andadvanced sensing technologies, can further improve the system's accuracy and enable predictive maintenance, contributing to the development of smart railway systems

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