Acoustic Sensor Based Rail Track Defect Detection

by

Sai Likhitha G
Roll No. 224G1A3278

Venkata Balaji Sai R
Roll No. 234G5A3213

Ganganna G
Roll No. 234G5A3205

Pranay Kumar Reddy V
Roll No. 214G1A3277

Under the guidance of

Dr. P.Chitralingappa M.Tech, Ph.D
Associate Professor & HOD

SRIT
Empowering Knowledge

Department of Computer Science and Engineering (Data Science)

Srinivasa Ramanujan Institute of Technology

Autonomous

Rotarypuram Village, B K Samudram Mandal, Ananthapuramu – 515701.

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Review – 0 Comments

- **Asked a minor modification in project title** to align with the selected research paper
- Asked to ensure the **proposed project matches the problem statement and methodology of the published paper**
- Suggested improving clarity in **problem definition and objectives**

Review – 1 Comments

- Asked about the **detection range of acoustic sensors**
- Asked explanation of **hardware components used in the system**
- Recommended refining system architecture explanation

Abstract

This project presents a non-contact and intelligent railway track defect tracking system based on acoustic signal analysis and deep learning. The system captures sound signals generated during wheel–rail interaction using microphone sensors and processes them through noise filtering, normalization, and time–frequency transformation. Mel-spectrogram and MFCC features are extracted to represent frequency variations caused by cracks, loose joints, and surface defects. A hybrid CNN–BiLSTM model with an attention mechanism is employed to learn both spatial and temporal acoustic patterns for accurate defect classification. The proposed approach enables early and reliable detection of track abnormalities, improves robustness under noisy and real-world conditions, and supports predictive maintenance. Overall, the system offers a cost-effective, scalable, and real-time solution for enhancing railway track safety and operational reliability.

Problem Statement

Existing railway track inspection systems rely mainly on manual inspection or contact-based sensing techniques, which are time-consuming, costly, and unable to provide continuous monitoring under real operating conditions. These methods often fail to detect early-stage defects such as cracks, loose joints, and surface irregularities, leading to increased risk of accidents and unplanned maintenance. There is a need for a reliable, non-contact, and intelligent tracking system that can automatically detect and classify railway track defects in real time. Therefore, the problem addressed in this project is to design and develop an acoustic-based deep learning system that analyzes sound frequency variations generated during wheel–rail interaction to accurately identify track defects and support timely maintenance and improved railway safety.

Objectives

- To develop a non-contact, acoustic-based deep learning system to automatically detect and classify railway track defects such as cracks, loose joints, and surface irregularities.

- To enable early and reliable identification of track abnormalities from sound frequency variations in order to support real-time monitoring and predictive maintenance for improved railway safety.

Literature survey

1. Rezaei *et al.* [1] proposed a real-time rail surface crack detection and quantification framework using **surface acoustic waves and piezoelectric patch transducers**, enabling precise identification of surface-level defects through active sensing.
2. Zhang *et al.* [2] introduced an **enhanced deep learning–based defect recognition model**, which improves the automatic identification of rail surface anomalies from inspection data by learning discriminative visual features.
3. Kumar and Singh [3] developed an **IoT-based railway track crack detection and alerting system**, where detected crack events are transmitted to monitoring authorities for immediate response.
4. Patel *et al.* [4] presented a **wireless sensor network–based monitoring architecture** that employs distributed sensing nodes to continuously assess track conditions and support real-time condition awareness.
5. Rao and Mehta [5] proposed a **low-power and long-range IoT communication architecture** specifically designed for railway track structural health monitoring, enabling scalable deployment with reduced energy consumption.

Contd…

From the study in **[1]**, it is evident that although real-time rail surface crack detection using surface acoustic waves and piezoelectric transducers enables accurate identification of surface-level defects, the approach relies on specialized sensing hardware and does not focus on learning rich frequency–time patterns from naturally generated rail sounds. This limitation motivates the first objective of this project, which is to design a **non-contact and low-cost acoustic deep learning framework** that can automatically detect railway track defects by analysing sound frequency variations generated during normal train movement.

Similarly, the work in **[3]** demonstrates that IoT-based crack detection and alerting systems can successfully transmit detected fault information to monitoring authorities in real time. However, the reported system mainly depends on discrete sensing and rule-based detection and does not provide intelligent classification of multiple defect types using advanced learning models. This observation leads to the second objective of the proposed work, which is to develop a **CNN–BiLSTM-based intelligent classification system** capable of accurately identifying and differentiating various railway track defects from acoustic signals, thereby enabling reliable real-time monitoring and supporting predictive maintenance.

Proposed Work

- Proposed a **non-contact intelligent railway track defect detection system** using acoustic signals and deep learning
- Acoustic sensors capture wheel–rail interaction sounds, which are processed using **time–frequency analysis**
- **Mel-spectrogram and MFCC features** are extracted and analyzed using a **CNN–BiLSTM with attention model**
- The system **classifies track conditions in real time** such as normal track, cracks, and surface defects
- Detected defects are **visualized and alerted** to maintenance authorities for timely action

Introduction

Railway track safety is a critical factor in ensuring reliable and accident-free transportation, as defects such as cracks, loose joints and surface irregularities can lead to serious failures if not detected at an early stage. Conventional inspection methods mainly rely on manual checks and contact-based testing, which are time-consuming, expensive and unsuitable for continuous large-scale monitoring. To overcome these limitations, this project introduces a non-contact and intelligent railway track defect detection system based on acoustic signal analysis and deep learning. The proposed approach captures sound signals generated during wheel–rail interaction and analyses frequency variations to identify abnormal track conditions. By combining low-cost acoustic sensing with a CNN–BiLSTM deep learning model and real-time monitoring, the system enables early defect detection, supports predictive maintenance and improves overall railway safety and operational reliability.

Existing System

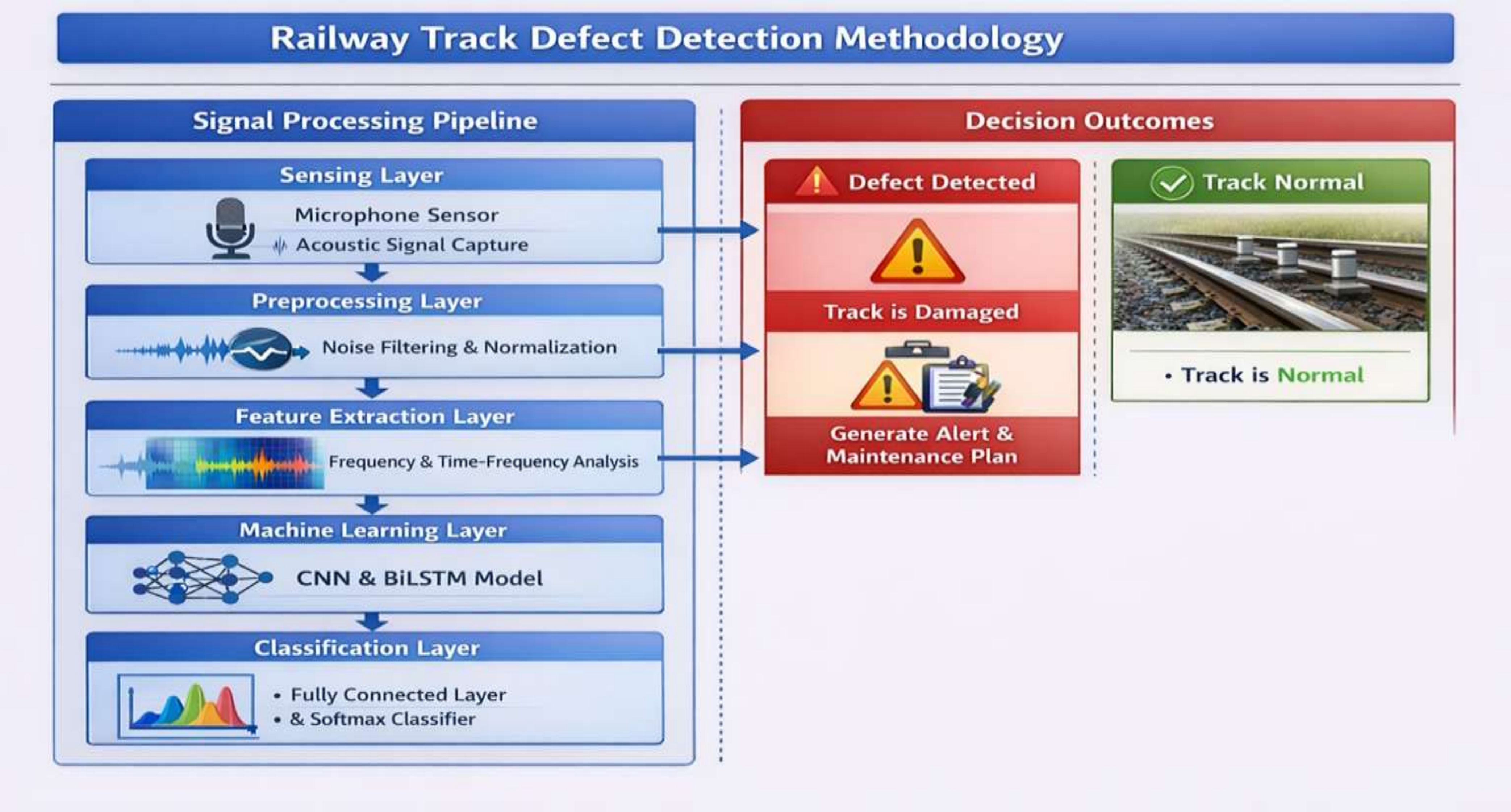
- Most existing systems rely on **manual inspection or periodic checks**, which are time-consuming and prone to human error.
- Contact-based inspection methods such as ultrasonic testing require **specialized equipment and track access**, making frequent monitoring difficult.
- Many conventional systems are **not suitable for continuous real-time monitoring** over long railway networks.
- Vision-based inspection systems are **highly affected by lighting, weather and surface conditions**.
- Traditional approaches mainly use **rule-based or handcrafted features**, resulting in lower accuracy for complex and early-stage defects.
- Existing solutions often provide **limited defect classification capability** and cannot reliably distinguish multiple defect types.

Proposed System

This project proposes an **Enhanced Acoustic-Based Smart Railway Track Defect Monitoring System** that builds upon conventional railway inspection frameworks by integrating **non-contact acoustic sensing, deep learning–based defect intelligence, real-time track condition monitoring, and automated alert generation** into a single, low-cost and scalable platform

Feature	Existing Solution (Conventional Systems)	Proposed Enhanced Solution
Track Condition Monitoring	Periodic or manual inspection	Continuous real-time acoustic monitoring
Sensing Method	Contact sensors / visual inspection	Non-contact microphone-based sensing ity
Defect Detection Technique	Rule-based or handcrafted features	CNN–BiLSTM with attention-based deep learning
Defect Classification	Limited or binary classification	Multi-class defect identification (crack, loose joint, surface defect, normal)
Noise Robustness	Sensitive to environment	Attention-based noise-robust learning
Maintenance Support	Reactive maintenance	Predictive maintenance and early warning alerts
Cost & Scalability	High installation and maintenance cost	Low-cost and easily scalable acoustic sensing system

Planning & Design



Requirements

Functional Requirements	Non-Functional Requirements
Acoustic data acquisition using microphone sensors	Scalability for large railway networks
Continuous wheel–rail sound signal capture	Reliability and fault tolerance
Noise filtering and signal normalization	Real-time processing performance
Segmentation of acoustic signals for analysis	Robustness to environmental noise
Generation of Mel-spectrogram and MFCC images	Security of data transmission and storage
Deep learning-based defect detection (CNN–BiLSTM with attention)	High system availability
Multi-class track condition identification (normal, crack, loose joint, surface defect)	Usability for maintenance staff
Real-time defect detection and alert generation	Maintainability and ease of model updates
Track condition visualization through monitoring dashboard	Cost effectiveness using low-cost sensors
Storage of acoustic data and detection results in server/cloud	Data consistency and interoperability

UML Diagrams

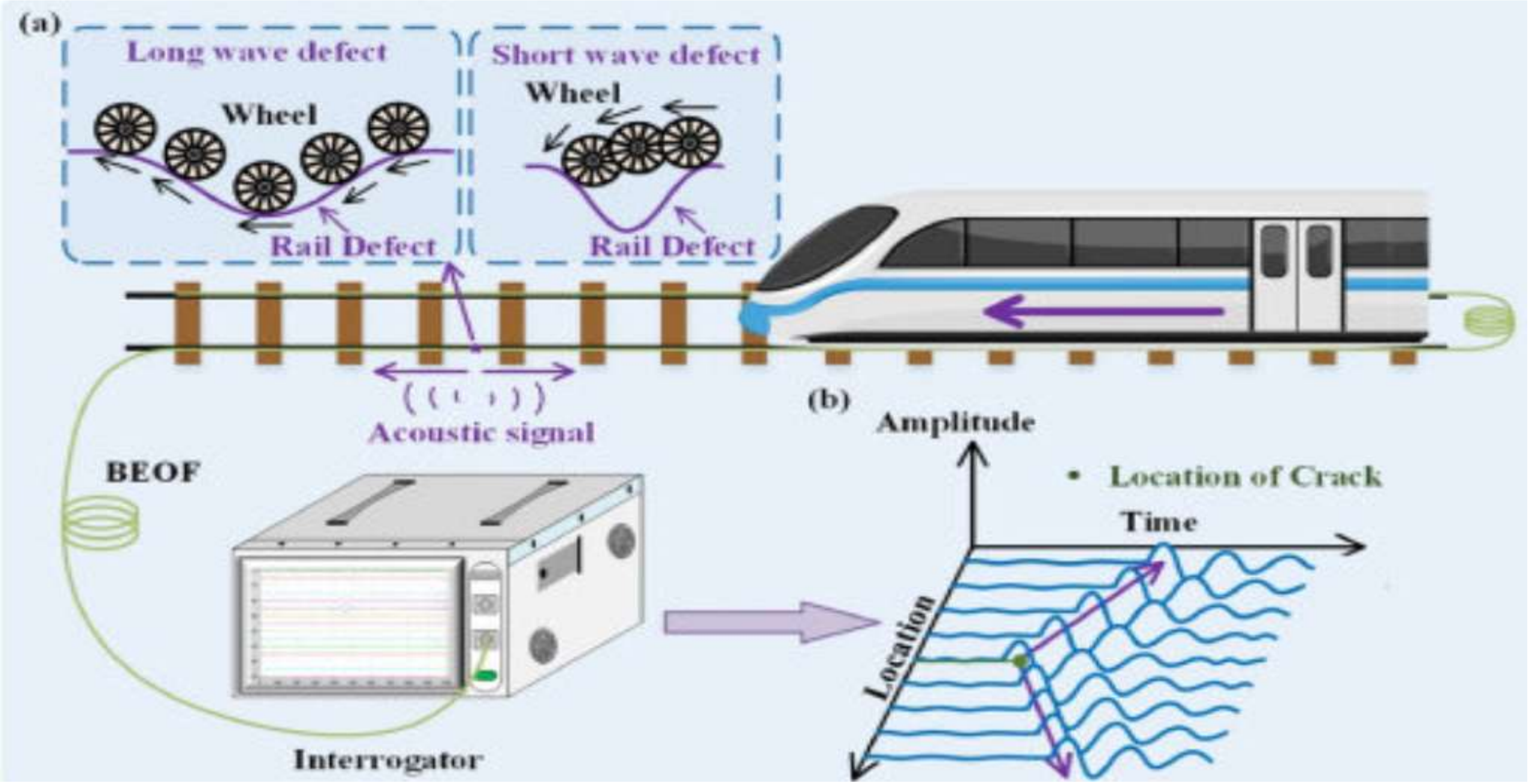
Use Case Diagram:

Microphone sensors continuously capture wheel–rail sound signals and submit them to the system, while maintenance engineers view track condition, defect type, and alert notifications through the monitoring dashboard.
The system administrator manages data storage, model updates, and overall system supervision.

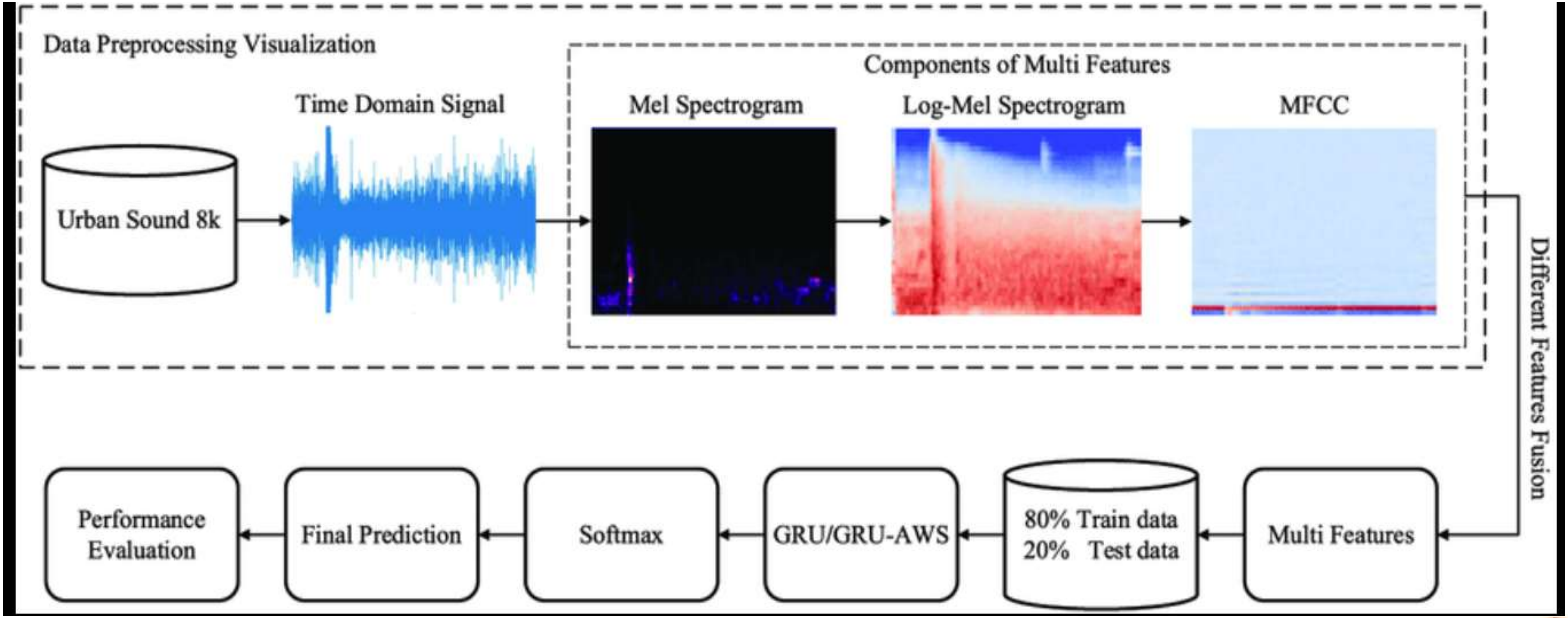
Sequence Diagram:

Captured sound signals are transmitted to the processing server, preprocessed, converted into time–frequency representations, and classified using the CNN–BiLSTM model with attention. The detected track condition and defect type are then displayed on the monitoring dashboard, and alert notifications are automatically generated for maintenance personnel when a defect is identified.

UML Diagram


(a)
Long wave defect
Wheel
Rail Defect
Short wave defect
Wheel
Rail Defect
Acoustic signal
BEOF
Interrogator
(b)
Amplitude
Location of Crack
Time
Location

UML Diagram


Data Preprocessing Visualization
Components of Multi Features
Time Domain Signal
Mel Spectrogram
Log-Mel Spectrogram
MFCC
Urban Sound 8k
Different Features Fusion
Performance Evaluation
Final Prediction
Softmax
GRU/GRU-AWS
80% Train data
20% Test data
Multi Features

Sample Code

esp32_acoustic_crack_detection.ino.cpp ● | gsm_alert.cpp | Untitled-1

C: > Users > admin > Downloads > esp32_acoustic_crack_detection.ino.cpp

```
#include <Arduino.h>
#define ACOUSTIC_PIN 34

float NORMAL_LIMIT = 0.6;
float CRACK_LIMIT  = 1.0;

String deviceID = "RAIL_ESP32_01";

void setup() {
  Serial.begin(115200);
  pinMode(ACOUSTIC_PIN, INPUT);

  Serial.println("Railway Track Crack Detection System");
  Serial.println("ESP32 Initialized");
}

void loop() {
  // Read acoustic sensor
  int rawValue = analogRead(ACOUSTIC_PIN);

  float signal = rawValue / 4095.0;

  Serial.print("Acoustic Signal: ");
  Serial.println(signal);
  if (signal > CRACK_LIMIT) {
    Serial.println("CRACK DETECTED");
    sendAlert("CRACK");
  } else {
    Serial.println("TRACK NORMAL");
    sendAlert("NORMAL");
  }

  delay(3000);
}
void sendAlert(String status) {
  Serial.print("Sending Alert: ");
  Serial.println(status);

}
```

esp32_acoustic_crack_detection.ino.cpp ● | gsm_alert.cpp | Untitled-1

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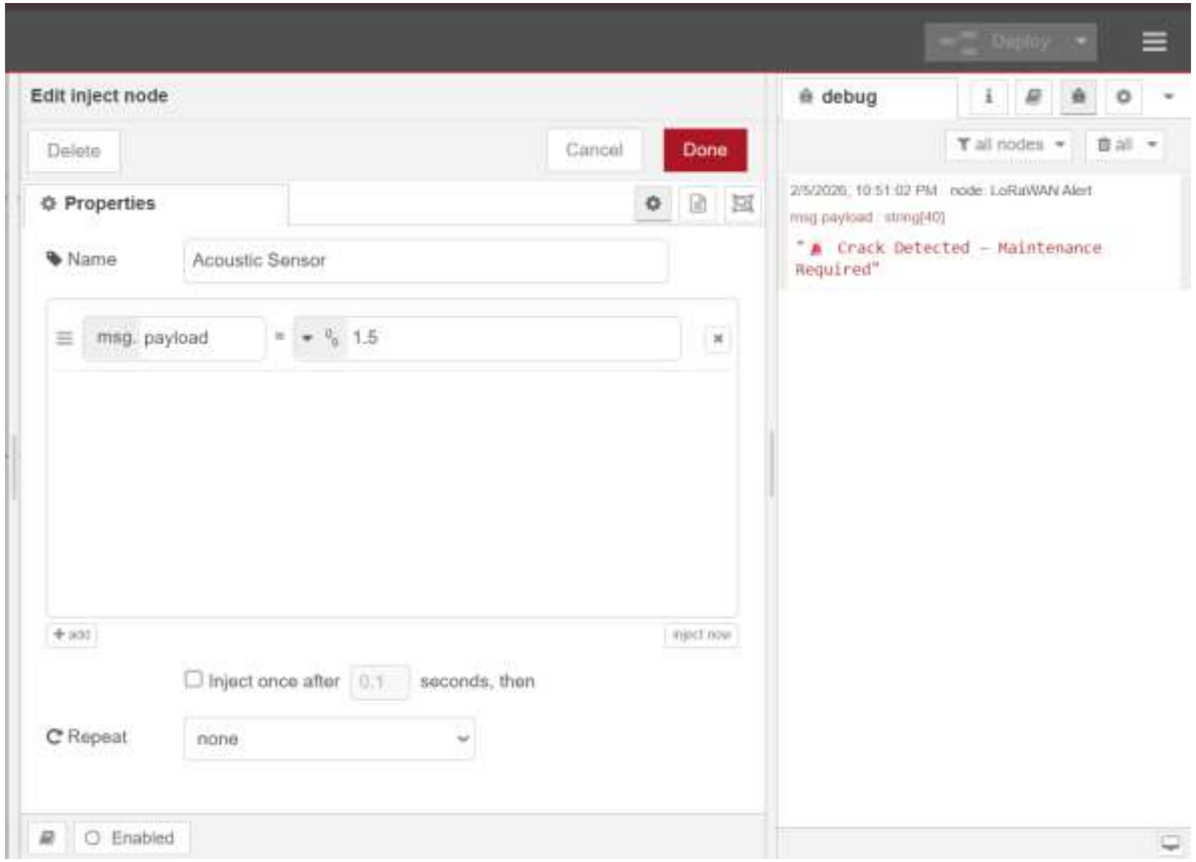
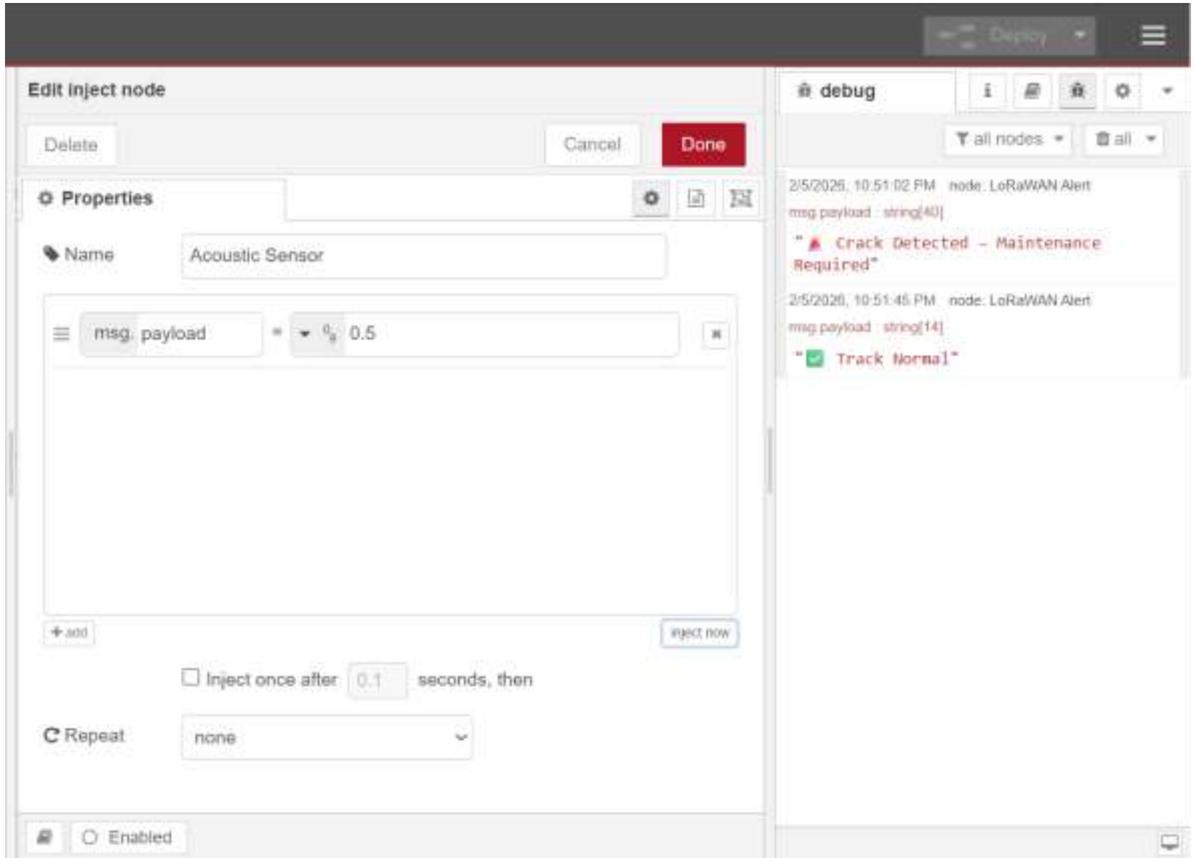
Output





Project Execution: http://127.0.0.1:1880/

References

[1] M. Rezaei et al., "Real-Time Detection and Quantification of Rail Surface Cracks Using Surface Acoustic Waves and Piezoelectric Patch Transducers," Sensors, vol. 25, no. 10, p. 3014, May 2025.

[2] Y. Zhang, L. Wang, and H. Chen, "Rail Surface Defect Detection Based on an Enhanced Deep Learning Model," Measurement, vol. 224, p. 113956, Jan. 2024.

[3] R. Kumar and P. Singh, "IoT-Based Railway Track Crack Detection and Alerting System," in Proc. ICICC, 2024.

[4] S. Patel, A. Mehta, and K. Shah, "Wireless Sensor Network-Based Railway Track Monitoring System for Real-Time Condition Assessment," International Journal of Smart Transportation Systems, 2024.

[5] A. Rao and N. Mehta, "Low-Power Long-Range IoT Communication Architecture for Railway Track Structural Health Monitoring," IEEE Internet of Things Journal, vol. 11, no. 3, pp. 2341–2350, Mar. 2024.

Thank You!!!