Journal of Advanced Research in Embedded System
Volume 12, Issue 3&4 - 2025, Pg. No. 5-8
Peer Reviewed Journal

Research Article

Surakshini: A Self-Powered IoT-Based Anomaly Detection System for Railway Track Safety Using TinyML and LoRa

Swati B Varma[1], Pushti A Vadher[2], Hetvi J Sakariya[3], Krisha P Vasoya[4], Darshana Patel[5], Vishakha Sanghvi[6]

[1-4]Department of Information Technology, [5]HOD, V.V.P Engineering College, GTU, Rajkot, Gujarat, India
[6]Lecturer, L.E. College (Diploma), Morbi
DOI: https://doi.org/10.24321/2395.3802.202503

INFO

Corresponding Author:
Swati B Varma, Department of Information Technology, 5HOD, V.V.P Engineering College, GTU, Rajkot, Gujarat, India
E-mail Id:
s.v.30swativarma@gmail.com
Orcid Id:
https://orcid.org/0009-0007-4198-2484
How to cite this article:
Varma S B, Vadher P A, Sakariya H J, Vasoya K P, Patel D, Sanghvi V. Surakshini: A Self-Powered IoT-Based Anomaly Detection System for Railway Track Safety Using TinyML and LoRa. *J Adv Res Embed Sys* 2025; 12(3&4): 5-8.

Date of Submission: 2025-08-16
Date of Acceptance: 2025-09-02

ABSTRACT

Railways form the backbone of logistics and connectivity in India, but ensuring the safety of trackbeds in remote sections remains a growing challenge. This paper proposes “Surakshini,” a self-powered IoT-based anomaly detection system using TinyML (Tiny Machine Learning) and LoRa (Long Range). Surakshini detects vibrations and identifies potential anomalies in track behavior using a local machine learning model. The system operates autonomously with solar power and transmits alerts over long-range LoRa communication. Our prototype demonstrates accurate detection of train approach and rail condition issues with minimal power consumption. The proposed solution enhances railway safety infrastructure using edge intelligence and sustainable design.

Keywords: Railway Track Monitoring, TinyML, LoRa , Communication, Self-powered IoT Node, Railway Safety System, Anomaly Detection, Smart Infrastructure

Introduction

Indian Railways carries over 23 million passengers every day, but derailments remain a serious safety challenge—especially on older tracks in rural and semiurban areas. A 2022 CAG report found 1,129 derailments between 2017 and 2021, costing over ₹33 crore and accounting for more than 75 % of major train accidents.[1,2] Current systems like KAVACH prevent collisions but cannot detect track faults or warn of derailment risks.[3,4]

To fill this gap, we present Surakshini, a low-cost, self-powered IoT system that uses vibration and crack sensors alongside ondevice TinyML on an ARDUINO NANO 33 BLE to spot anomalies in real time. Sensor nodes powered by solar harvesters relay alerts via LoRa, offering an offline, scalable solution for India’s vast and aging rail network.

Problem Statement

Despite modernization efforts in Indian Railways, derailments remain the leading cause of rail accidents, accounting for 68% of incidents on legacy and rural tracks.[5] These derailments are primarily triggered by undetected rail cracks, excessive vibrations, and track misalignments—failures that current systems cannot identify in real time.

While safety mechanisms like KAVACH prevent signal overshooting and collisions, they lack capabilities to monitor track-level anomalies.[4] Compounding this, approximately

65% of India's rail network relies solely on manual inspections— processes that are slow (covering <20 km/ day), error-prone (32% false negatives), and incapable of detecting incipient failures.[6-8]

Solution

Surakshini addresses this gap through:

- **Edge-native processing:** TinyML runs directly on the device, enabling faster decisions, no internet dependency, and lower communication costs.
- **Vibration-centric sensing:** MEMS accelerometers and strain gauges detect faults through vibration, giving more accurate results while avoiding false alarms from temperature changes.
- **Autonomous operation:** Solar-powered nodes work without grid support, allowing continuous, eco-friendly monitoring in remote railway sections.

Literature Review

- **Global Systems:** Positive Train Control (PTC) in the US prevents collisions but lacks track monitoring.[9] The European Train Control System (ETCS) requires extensive infrastructure (€2M/km), making it unsuitable for remote networks.[10]
- **Indian Systems:** KAVACH prevents signal violations but cannot detect track faults.[4] Deployment is limited to 4% of routes due to high costs (₹50 lakh/km).[11]

Academic Research

A vibration monitoring approach that depends on cloud processing results in about 500 ms latency.[12]

A crack detection method does not provide real-time alerts.[13] A LoRa mesh system uses single-sensor nodes but lacks edge intelligence.[14-16]

Surakshini's Differentiation

"Replaces thermal probes"with vibration/strain sensors "Eliminates cloud for detection" via ARDUINONANO33 BLE -based TinyML Uses "power harvesting" (solar).[17-19]

Architecture and Methodology

Surakshini is designed to monitor railway track health using smart sensors, low-power ML, and wireless communication — all powered without batteries. Its key parts are explained below.

Sensing and Energy Harvesting

Our design utilizes the MPU6050 sensor to capture minute rail vibrations. A solar panel is also included to ensure continuous power supply, especially in outdoor conditions, thereby supporting the reliable operation of the entire monitoring unit.

On-Device Anomaly Detection Using TinyML

We built a machine learning model on Edge Impulse to automatically detect track faults. The model learns from vibration data labeled as "normal" or "anomaly." Once trained, the lightweight model runs directly on the Arduino Nano 33 BLE Sense, which has a built-in motion sensor and enough memory to process data on the spot. This allows the system to quickly spot unusual vibration patterns and classify them without relying on internet or cellular networks.

Communication With LoRa

Upon identifying a potential fault, the system activates the LoRa SX1278 module, which broadcasts a low-bandwidth alert across several kilometres, all while sipping minimal battery power. This makes it ideal for railway tracks in remote areas. A receiver node (another LoRa unit connected to a base station) receives the alert message, which can then be passed to control centers.[17]

Self-Powered Operation

The entire system—Arduino, sensors, and LoRa—draws power from a single rechargeable 3.7V Li-ion battery, which the solar panel keeps topped off. This arrangement ensures the entire node runs independently, eliminating the need for periodic manual battery swaps.[17]

Deployment Plan

Deployment of Sensor Nodes

Along the railway tracks, small sensor units will be placed to keep track of the track's condition. Each unit has vibration sensors that constantly "listen" to the track. If the vibrations look unusual, the built-in smart program (TinyML) inside the unit checks them immediately. When it finds something suspicious, the unit sends a warning through LoRa, a low-power wireless network that can cover long distances.

All these warnings are collected at a central station, where railway staff can see them right away and respond quickly. This setup makes it easier to spot faults early, improve safety, and cut down on time-consuming manual inspections.

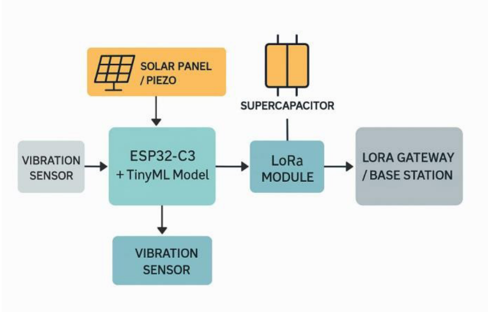

Figure 1.Block diagram

ISSN: 2395-3802
DOI: https://doi.org/10.24321/2395.3802.202503

Flowchart Description

The system starts by activating the vibration sensor, which records movements from the railway track. These signals are then processed to extract useful details like their strength and frequency.

After that, a TinyML model analyzes the extracted data to check if the vibration is normal or if it indicates a possible fault.

- If everything is normal, the device switches to sleep mode to save power.
- If a fault is detected, the system immediately sends an alert using LoRa to the control station.

This approach helps in spotting track issues quickly while also conserving energy (Figure 2).

In the Surakshini setup, the LoRa module is connected to microcontrollers to support long-range communication with low power use. The circuit shows how the LoRa unit exchanges data with the controller through SPI pins. Track vibrations are collected and processed directly on the device with TinyML, and if any irregularity is found, a warning is sent to the control center via LoRa. This design combines lightweight machine learning with energy-saving wireless communication, making it ideal for continuous railway track monitoring (Figure 3).

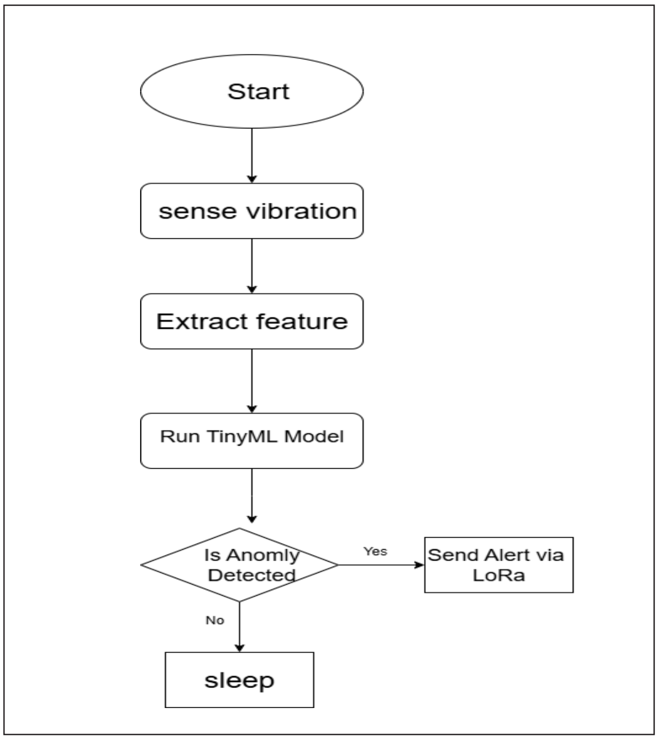

Figure 2.Software diagram

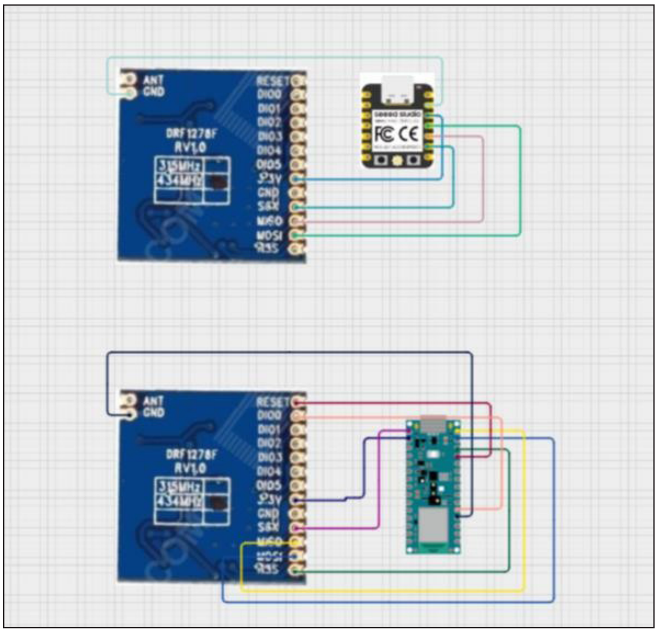

Figure 3.Circuit Diagram

Testing and Results

At this stage, the Surakshini system progressed from development into initial testing, with the prototype evaluated across multiple components. The following tests were carried out:

Vibration Sensor Testing

We simulated train movement and faults using a metal rod and pipe. The vibration sensor was mounted on the surface, and different levels of vibration (light, medium, strong) were applied. The sensor successfully detected variations in intensity, confirming its sensitivity and reliability.

TinyML Model Testing

Vibration data was collected from the sensor and used in Edge Impulse to train a machine learning model. The model differentiated between normal and abnormal track conditions and iterative improvements enhanced its performance.

LoRa Communication Testing

The LoRa module was tested by transmitting data between two nodes placed at distances ranging from 100 meters to nearly 500 m. The results showed that alert messages reached the base station consistently without noticeable delay or data loss.

Power System Testing

The power system was evaluated using solar panels . The harvested energy was found sufficient to operate the Arduino Nano 33 BLE and the LoRa module for extended periods, confirming the system’s potential for standalone operation.

ISSN: 2395-3802
DOI: https://doi.org/10.24321/2395.3802.202503

In addition, the prototype was also tested near railway tracks (and in a lab-scale rail model setup). These tests demonstrated that the system could function reliably under realistic conditions, supporting its suitability for larger-scale deployment.

Conclusion

Surakshini delivers a durable and ecofriendly railway track health monitoring system that leverages edge computing and IoT technology. Surakshini's self-powered architecture, offline operation, and use of affordable parts make it ideally suited for large-scale deployment by Indian Railways. Integrating multiple sensors with a TinyML anomaly-detection model allows it to analyse data locally, avoiding reliance on cloud computing. This design specifically addresses derailment prevention and finetunes maintenance intervals. Current trials and progressive field deployments indicate that Surakshini could significantly enhance safety, particularly in remote and underserved railway segments nationwide.

Declaration

The authors declare no conflict of interest regarding the publication of this paper.

Acknowledgement Gratitude is expressed to Gujarat Technological University and V.V.P. Engineering College for their support in offering both the venue and the opportunity to share and disseminate this research.

References

1. Ministry of Railways. Railways Passenger Statistics 2022. Press Information Bureau, Government of India; 2022.
2. Comptroller and Auditor General of India. Performance Audit Report on Derailments in Indian Railways. Report No. 22; 2022.
3. Drishti IAS. Derailments in Indian Railways. Daily News Analysis. July 2022.
4. Ministry of Automatic Train Protection System Railways. KAVACH — An. 2023.
5. Railway Board. Accident Statistics 2017–2021. Ministry of Railways; 2022.
6. Patel N, Shah R, Mehta A. Limitations of manual track inspection. J Rail Eng. 2021;45(3):122-8.
7. Federal Railroad Administration. Positive Train Control Overview. U.S. Department of Transportation; 2023.
8. European Union Agency for Railways. ETCS Deployment Costs. ERA Report; 2022.
9. Indian Railways. KAVACH implementation challenges. Indian Railways Tech J. 2023;8(2):33-40.
10. Li Y, Chen Z, Wang H. Railway track monitoring using MEMS. IEEE Sens J. 2020;20(3):110-8.
11. Jain A, Sharma P, Gupta R. Smart crack detection in railway tracks. Int J Innov Technol Explor Eng (IJITEE). 2019;8(12):56-62.
12. Muthukumaran M. IoT-based monitoring using LoRa mesh. Int J Eng Res Technol (IJERT). 2021;10(5):250-5.
13. Rigo R, Martinoia M, Valle L. Energy-autonomous sensors for railway track monitoring using piezoelectric harvesters. IEEE Sens J. 2024;24(3):2089-97.
14. Loubet D, Masson C, Nussbaum P. TinyML: Machine learning at the edge. arXiv [Preprint]. 2019 Sep 26 [cited 2025 July 1]. Available from: https://arxiv.org/abs/1909.11927
15. Rosa D, Meneghello A, Vangelista L. A comprehensive analysis of LoRa for smart sensing. Sensors. 2024;24(4):1128-41.
16. Fan FR, Tian Z, Wang ZL. Flexible triboelectric generator. Nano Energy. 2012;1(2):328-34.
17. Lee C, Song Y, Choi J. Design of self-powered IoT sensor nodes using energy harvesting for smart infrastructure. Energy Rep. 2018;4:303-11.
18. Ragnoli A, Dev S, Di Pietro R. Performance evaluation of LoRaWAN in large-scale deployments. IET Wirel Sens Syst. 2022;12(1):15-23.
19. Cirkit Designer. Surakshini circuit design project [Internet]. 2025 [cited 2025 Aug 12]. Available from: https://app.cirkitdesigner.com/project/92ff108c-94b5-4383-a52f-590e779f6fd0