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Intelligent aerial surveillance for safer railways using machine learning

Nagarathna C R

Department of AI and ML, BNM Institute of Technology, Bengaluru, Karnataka, India.

(*Email: Nagarathna.binu@gmail.com*)

Abstract

The integrity and usability of the rail systems are seriously compromised by problems including broken welds, unseen blockages, and non-functioning rails. Since they are primarily manual and offer no real-time information about what is happening, the present inspection methods are extremely labor-intensive, especially when it comes to remote and inaccessible places. The suggested system is a drone-based railway track surveillance system that can identify anomalies like fractures, welding flaws, and obstacles in real time. High-resolution camera drones and artificial intelligence (AI) models such as YOLO gather and evaluate data in a variety of environmental settings, and the problems they identify are geotagged. Resilient data transmission is ensured via a hybrid 4G/5G and LoRa network. Actionable insights and abnormalities are visualized and shown on a real-time dashboard. By accurately, scalably, and robustly observing the railway, the system increases maintenance efficiency.

Keywords: Computer vision, Drone equipped with AI, Real-time defect detection, Train safety.

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1. Introduction

Indian Railway networks are vital for ensuring the smooth and efficient transportation of passengers and freight. They form the backbone of many global transportation systems. However, their safety and reliability largely depend on the structure of railway tracks. Cracks, welding issues, or unexpected obstacles on the tracks pose serious risks of derailment, operational delays, or even loss of life in some cases. Traditionally, Indian railway inspections have been predominantly manual operations: track-walking personnel observe the tracks and infrastructure with the naked eye to identify defects and obstructions. Maintenance personnel would examine cracks, loose fittings, and worn-out conditions using minimal instruments and limited instrumentation. This approach was cumbersome and time-consuming, with significant room for human error across the vast Indian railway network. Despite these challenges, current systems primarily utilize track-mounted cars equipped with ultrasonic UV sensors to inspect track conditions. These systems detect internal rail defects such as crack initiation, weld failures, and other structural damage by sending waves through the internal sound reflection inside the rail. In manual mode, they operate semi-automatically, providing valuable insights into track integrity. However, these systems have limitations, including slower inspection speeds, dependence on human intervention, and inadequate coverage of the extensive railway network. Additionally, adverse climatic conditions and the inability to monitor tracks continuously reduce their effectiveness, highlighting the need for advanced automated technologies.

This proposed system integrates the agility and flexibility of drones with the analytical strength of AI by processing captured data to derive high-accuracy identification and classification of anomalies using advanced object detection models. The system benefits from robust integration with reliable communication technologies that ensure real-time transmission regardless of network coverage areas. This has also optimized maintenance efforts, and operational costs will be reduced with less delay, thereby contributing to a safer and more reliable railway network.

2. Literature Review

Extensive research has been conducted on leveraging drones and artificial intelligence for railway track monitoring to enhance safety and operational efficiency. Numerous methodologies, algorithms, and architectures have been proposed, focusing on defect detection, anomaly classification, and real-time data processing. This review aims to analyze these approaches, synthesize key insights, and identify critical gaps to inform the development of robust and efficient drone-based railway monitoring solutions. Aela et al. [1] analyzed the application of UAVs in railway infrastructure monitoring by utilizing camera- and sensor-enabled drones for anomaly detection in real-time. The methodology was efficient in image processing but was limited by the range and battery life of drones, which affected long-term monitoring. Similarly, Gugan and Haque [2] studied path planning for autonomous drones, with an emphasis on the algorithms used to navigate dynamic environments. However, the study did not test the prototypes in actual complex environments.

El-Sayed et al. [3] presented a drone-based railway inspection system that adopted machine learning to classify defects with high accuracy, but was limited by range and workflow integration. Guan et al. [4] applied a saliency detection algorithm on UAV imagery to track intrusions, thereby providing new detection techniques but lacking real-time applicability and adverse weather handling. This implies the potential of UAVs for monitoring railways but raises issues related to scalability, operational constraints, and challenges in integration.

Equinox's Drones [5] proved UAV applications in railway track inspection: its capability to take highly detailed pictures that would help detect defects and allow maintenance planning. Although the study reported operational efficiency, it did not discuss in detail how to incorporate drone-collected data into current maintenance workflows and did not mention regulatory challenges. Banić et al. [6] designed an intelligent machine vision-based inspection system using drones and achieved significant advancements in image processing. However, for large railway networks, it still faced scalability issues since no robust fleet management techniques existed.

Lau Banh et al. [7] demonstrated the feasibility of inspecting remote BART rail systems using drone technologies, but they also pointed out the problem of comparing the safety and operating efficiency of drone-based inspection with classical methods. It does not discuss scalability or whether the long-term deployment would be cost-effective for large networks. Dubey [8] conducted a qualitative analysis of drone applications in industries such as infrastructure monitoring, focusing on the regulatory landscape and adoption trends in India. The study, however, lacked technical details and economic impact assessments, thereby limiting its practical value for railway applications. Falamarzi et al. [9] review sensors applied in devices for railway infrastructure inspection and evaluate available technologies such as ultrasonic and infrared sensors.

The research provided some insight into sensor performance but was limited in real-life applications and lacked an elaborate discussion about economic viability. Flammini et al. [10] discussed automated surveillance of rails by drones, integrating sensors such as LiDAR for improved efficiency. The primary focus was on automation opportunities, without addressing practical challenges related to implementation, such as regulatory constraints and data integration.

Ghassoun et al. [11] offered a UAV-photogrammetry-based system for rail track inspection, which resulted in highly accurate 3D models for defect identification. However, environmental factors such as weather and high costs made the system not scalable. Higgins and Liu [12] presented an overview of track geometry degradation models that were statistically and mechanistically based but lacked the actual integration of UAV data and comprehensive testing conditions under different operational conditions.

Karpowicz [13] examined the ROI of drone technologies for infrastructure inspection, transportation, and airport surveillance. It found cost savings and operational efficiency but did not provide any quantitative evidence and did not take into account regulatory issues. Lesiak [14] used UAVs for railway infrastructure inspection with a focus on defect detection using high-resolution imagery. It suffered from constraints such as dependence on favorable weather and skilled operators, which influenced the cost-effectiveness.

Manatunga et al. [15] applied CNNs for the analysis of visual data from drones used in railway track monitoring with promising accuracy. However, the approach required a large amount of labeled data for training, which was difficult to obtain due to diverse environmental conditions faced by the system. Manatunga et al. [15] published a method for mapping railroad lines and land use utilizing UAVs, which emphasizes aerial view images. The work encountered problems arising from GPS inaccuracies and the processing of large datasets, leading to issues with scalability.

Morgenthal and Hallermann [16] assessed UAV-based visual inspection for structures such as bridges and railway tracks, demonstrating promise with high-resolution imagery. However, the study highlighted challenges related to flight endurance and vulnerability to environmental factors such as wind. Nyberg et al. [17] used image processing to identify plant species on railway embankments, providing some insights into vegetation management. However, the study was limited by the inability to distinguish between similar plant types.

Rahman and Mammeri [18] used advanced machine learning techniques for vegetation detection in UAV imagery, achieving reliable classification in many cases. However, cluttered environments and similarities between vegetation and objects posed accuracy challenges. Schwab et al. [19] outlined the benefits of UAVs for railway operations, emphasizing use cases such as track defect detection and safety assessments. The study lacked quantitative data and faced challenges with regulatory and logistical constraints for large-scale implementation.

Table 1.
Literature Review Summary Table.

Paper Name	Summary	Limitations	Methods Used
UAV-Based Studies in Railway Infrastructure Monitoring Aela et al. [1]	Makes use of real-time track inspection based on image processing and anomaly detection using UAVs equipped with cameras and sensors.	Drones have limited range and short battery life, factors affecting the feasibility of long-term monitoring.	UAVs, real-time image processing, anomaly detection.
Path Planning for Autonomous Drones: Challenges and Future Directions Gugan and Haque [2]	Research into algorithms and applications in track monitoring in dynamic environments.	Poor testing and validation involving realistic scenarios of real-world railway.	Path planning algorithms, simulation frameworks.
Railway Track Monitoring Using El-Sayed et al. [3]	Utilize UAVs incorporating high-resolution cameras and sensor technologies for detecting and classifying track defects, utilizing machine learning for real-time inspection.	Problems include the battery life of drones, the impact of weather, and the integration of the system into the workflows of railway maintenance.	High-resolution cameras, sensors, and machine learning algorithms.
A Visual Saliency-Based Railway Intrusion Detection Method by UAV Remote Sensing Image Guan et al. [4]	Capture resolution remote sensing imagery using UAVs and apply saliency detection to identify obstructions or intrusions on railway tracks.	It fails to discuss the applicability of real-time monitoring and is limited in addressing adverse environmental conditions, for instance, low visibility.	UAVs, saliency detection algorithm, anomaly detection.
Railway Inspection & Monitoring Using	It illustrates real-time defect detection and maintenance.	Lacks discussion on integrating drone data with existing systems.	High-resolution cameras, UAV-based data analysis.
UAV/Drone Technology Equinox's Drones [5]	Planning for the railway infrastructure with a camera- and sensor-equipped UAV.	systems and does not address regulatory challenges or large-scale deployment hurdles.	
Intelligent Machine Vision-Based Railway Infrastructure Inspection Using UAV Banić et al. [6]	Explores image processing algorithms for inspecting railway infrastructure, focusing on drones capturing images of tracks and components.	The system does not scale well for large networks. There is no effective fleet management strategy in place.	UAVs, image processing algorithms.
Evaluation of the Feasibility of UAV Technologies for Remote Surveying BART Rail Systems Banh Lau Banh et al. [7]	Compares drone-based data collection with traditional methods of surveying rail systems in terms of feasibility, efficiency, and safety.	Limited focus on long-term scalability and integration challenges, such as operational costs and regulatory compliance.	Feasibility analysis, UAV-based data collection.
Usage of a Drone Technology in India: Changing Phases Dubey [8]	Provides a qualitative analysis of the application of drones in industries, highlighting possibilities in various sectors. infrastructure and surveillance.	Very insufficient discussion on technical matters, plus insufficient consideration of specific railway applications.	Case study analysis, qualitative review.

A Review on Existing Sensors and Devices for Inspecting Railway Infrastructure Falamarzi et al. [9]	Very insufficient discussion on technical matters, plus insufficient consideration of specific railway applications.	Has fewer real-world case studies, especially not considering economic or integration challenges for large-scale applications.	Sensor technology review (ultrasonic, laser, infrared).
Towards Automated	Highlights that cameras	Lacks discussion on	UAVs, LiDAR,
UAV/Drone Technology Equinox's Drones [5]	planning for the railway infrastructure with a camera- and sensor-equipped UAV.	systems and do not address regulatory challenges or large-scale deployment hurdles.	
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Towards Automated	Highlights that cameras	Lacks discussion on	UAVs, LiDAR,
Unmanned Aerial Vehicles Lesiak [14]	on cameras to detect and document infrastructure defects.	operation and skilled workforce are significant barriers.	
Development of a Methodology to Map Railway Lines and Surrounding Land Use Using UAVs U. Manatunga et al. [15]	This presents a method of collecting and analyzing UAV-based aerial imagery of railway lines and their environment with better planning for the infrastructure. .	GPS errors, big data handling difficulties, and the reliance on good weather.	UAVs, GIS-based analysis, and aerial imagery processing.
Vision-Based Railway Track Monitoring Using Deep Learning Manatunga et al. [15]	Employs convolutional neural networks (CNNs) to analyze visual data from UAVs or train-mounted cameras for the detection of railway defects.	Requires extensive labeled data and struggles with environmental diversity affecting model accuracy.	CNNs, deep learning, and visual data analysis.
Quality Assessment of UAV-Based Visual Inspection of Structures Morgenthal and Hallermann [16]	Explores UAV-based visual inspection methods for structural elements such as bridges and towers, emphasizing efficiency and accuracy.	Limited flight endurance, susceptibility to environmental conditions like wind, and the need for specialized expertise.	UAVs, visual inspection, structural monitoring.
Detecting plants on railway embankments Nyberg et al. [17]	This work proposes image processing techniques to analyze vegetation on the railway embankment to monitor growth and assess potential risks.	Poor differentiation of certain canopy categories with superficial image processing techniques.	Image processing, vegetation detection.
Unmanned Aerial	on cameras to detect and	operation and skilled	

Vehicles Lesiak [14]	document infrastructure defects.	workforce are significant barriers.	
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3. Proposed Methodology

The railway track monitoring system is modeled as an autonomous anomaly detection framework, with the drone as the primary agent. The goal of the system is to identify and report defects such as cracks, welding problems, slag inclusions, undercuts, and obstructions on railway tracks. Main assumptions include: drones equipped with high-resolution cameras and sensors that capture real-time data; tracks and their surroundings experiencing varying environmental conditions, such as lighting and weather; and reliance on a hybrid model of 4G/5G and LoRa when cellular networks are unstable. The operational environment is designed to simulate real-world railway conditions, and it includes:

- Track geometry data (e.g., alignments, joints).
- Dynamic environmental changes (e.g., low-light intensities, covered by vegetation).
- Network Conditions for Testing Communication Resiliency.

3.1. System Architecture

The proposed system architecture is shown in Figure 1.

3.1.1. Drone Configuration

- High-resolution camera for real-time image and video capture.
- GPS and IMU for navigation and location tagging.
- Solar Panels Auxiliary Power for Long-endurance Missions.

3.1.2. Data Capture and Transmission

The drone streams live video to the cloud [20] through a 4G/5G module or LoRa fallback in low-network areas.

3.1.3. Cloud Infrastructure

- It involves processing video streams through AI advanced models such as YOLO [21].
- Anomalies are assigned geolocation information and then inserted into a database for further action.

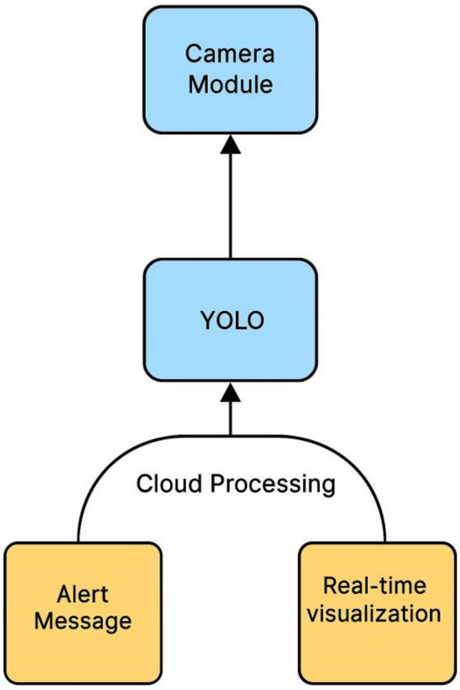

Figure 1.
System Architecture.

4. Conclusion

The proposed drone-based railway track monitoring system offers a transformative approach to addressing the challenges of track inspection and maintenance. By leveraging the speed and flexibility of drones, the system can survey extensive railway tracks in a fraction of the time required by traditional methods. Integrating cutting-edge AI algorithms ensures accurate and real-time detection of defects such as cracks, welding issues, and obstructions, enabling timely interventions. The incorporation of hybrid communication technologies ensures seamless data transmission even in areas with poor network connectivity. This framework not only enhances railway safety and operational efficiency but also optimizes resource utilization, reducing manual inspection efforts and associated costs. By processing data on the cloud and providing actionable insights via a real-time dashboard, the system empowers railway operators to make informed decisions, minimizing delays and preventing accidents. These contributions are particularly impactful in regions with vast railway networks, where timely maintenance is critical for uninterrupted service. Future directions for this work include incorporating predictive analytics to foresee potential track failures, integrating blockchain for secure data management, and scaling the system for nationwide deployment. This solution represents a significant step toward modernizing railway infrastructure, aligning with broader goals of safety, efficiency, and sustainability, and setting a foundation for smarter transportation systems.

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