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Design and Implementation of Automatic Railway Crack Track Detection and Automatic Gate Control System

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KEYWORDS

railway track crack detection, automatic gate control, ESP32 microcontroller, GPS notification, infrared sensor, ultrasonic obstacle detection, embedded systems

ABSTRACT

Railway transportation remains a cornerstone of modern infrastructure, yet accidents arising from track cracks, unexpected obstacles, and delayed gate operations continue to pose significant safety threats to passengers and freight. This paper presents a Smart Railway Track Crack Detection and Automatic Gate Control System with Obstacle Alert and GPS Notification, developed using Arduino Uno and ESP32-based embedded technology. The proposed system integrates a robotic inspection unit equipped with an ESP32 microcontroller that autonomously traverses railway tracks to continuously monitor structural integrity and surrounding conditions. Infrared (IR) sensors are deployed to detect cracks, breaks, or discontinuities in the railway track surface, while an ultrasonic sensor monitors the presence of obstacles such as animals, vehicles, or debris within a predefined safety threshold. Upon detection of any anomaly, the system immediately triggers an alert mechanism. A GPS module interfaced with the ESP32 provides real-time geographical coordinates of the fault or obstacle location, which are transmitted wirelessly to railway monitoring authorities, enabling rapid response and targeted maintenance intervention. In parallel, an automatic gate control subsystem governed by an Arduino Uno manages railway crossing gates using servo motors actuated by IR-based train detection sensors. The gate closes automatically upon train approach and reopens after the train clears the crossing, eliminating dependency on manual operation and reducing human error. Experimental validation of the integrated system demonstrated reliable crack detection, accurate obstacle identification, precise GPS-based location reporting, and prompt automated gate actuation. The proposed system offers a cost-effective, scalable, and

1. INTRODUCTION

Railway transportation constitutes one of the most vital components of modern infrastructure, serving as a primary mode of mass transit for millions of passengers and freight operations across the globe. Despite its significance, railway systems remain susceptible to a range of critical safety hazards, including structural deterioration of tracks, unexpected obstacles on the railway line, and failures in level crossing gate management [1]. These vulnerabilities have historically contributed to catastrophic accidents, resulting in significant loss of life, property damage, and economic disruption. As railway networks continue to expand and operational speeds increase, the demand for intelligent, automated safety mechanisms has never been more pressing [5].

Track integrity is among the foremost concerns in railway safety engineering. Cracks, fractures, and deformations in railway tracks can develop gradually due to material fatigue, thermal stress, and heavy loading cycles. If left undetected, such defects may lead to derailments with devastating consequences. Traditional inspection methodologies largely rely on manual patrol and periodic maintenance schedules, which are not only labor-intensive but also inherently prone to human error and insufficient in providing continuous, real-time monitoring [3]. Furthermore, the presence of obstacles such as stray animals, fallen debris, or encroaching vehicles on railway tracks poses an equally serious threat, particularly in rural and semi-urban regions where surveillance infrastructure is limited [6].

Another persistent challenge in railway safety is the management of unmanned level crossings. Delayed or failed gate operations at railway crossings have been identified as a leading cause of fatal collisions between trains and road vehicles. Conventional manually operated gates depend entirely on human vigilance, making them unreliable during periods of inattention, adverse weather conditions, or communication failures [2]. The automation of gate control mechanisms using embedded systems represents a robust solution to mitigate these risks and eliminate dependency on human intervention at critical crossing points [8].

Recent advancements in embedded computing, wireless communication, and sensor technologies have opened new avenues for the development of intelligent railway monitoring systems. Platforms such as Arduino and ESP32 offer cost-effective, scalable, and highly programmable solutions for deploying real-time sensing and control applications in railway environments [4, 10]. The integration of GPS technology further enhances these systems by enabling precise geographical localization of detected faults or hazards, facilitating rapid response by maintenance and emergency personnel [9].

Motivated by these challenges and technological opportunities, this paper proposes a Smart Railway Track Crack Detection and Automatic Gate Control System with Obstacle Alert and GPS Notification using Arduino and ESP32-based embedded technology. The key contributions of this work are as follows: (i) the design and implementation of an ESP32-controlled robotic inspection unit equipped with infrared sensors for continuous track crack detection; (ii) integration of an ultrasonic sensor for real-time obstacle detection on the railway track; (iii) GPS-based geo-location reporting to transmit precise fault coordinates to monitoring authorities; and (iv) an Arduino Uno-based automated gate control mechanism employing IR sensors and servo motors to manage level crossing operations without human intervention [2, 7].

The remainder of this paper is organized as follows. Section 2 presents the proposed system architecture and design methodology. Section 3 describes the hardware components and their functional roles within the system. Section 4 details the system implementation and operational workflow. Section 5 presents the experimental results and performance evaluation, and Section 6 concludes the paper with directions for future research.

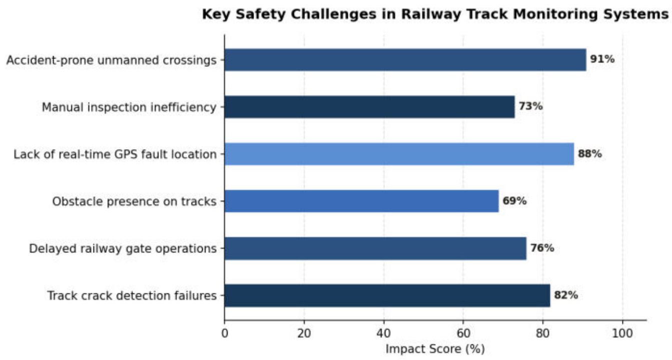

Figure 1: Key Safety Challenges in Railway Track Monitoring Systems

2. Literature Review

Railway safety has long been a critical area of research, with numerous studies focusing on the detection of track faults, obstacle monitoring, and the automation of level crossing gates. A comprehensive review of existing literature reveals a growing interest in embedded systems and IoT-based approaches to address these challenges, while also highlighting several gaps that motivate the present work.

Early efforts in railway track monitoring relied heavily on manual inspection techniques, which are both time-consuming and prone to human error. The transition toward automated and sensor-based monitoring has been well documented. Bhatt and Patel [1] proposed an IoT-based railway track monitoring system utilizing wireless sensor networks to detect faults in real time. Their system demonstrated effective fault localization but suffered from high power consumption and latency issues inherent to large-scale wireless deployments, limiting its practicality for continuous monitoring in remote areas.

The problem of unmanned level crossings has been addressed extensively using microcontroller-based solutions. Singh, Kumar, and Mehta [2] developed an automated railway gate control system using Arduino and infrared sensors, demonstrating reliable train detection and gate actuation. While their approach proved cost-effective and straightforward to implement, it lacked integration with obstacle detection and remote alert mechanisms, leaving a significant gap in comprehensive safety coverage at crossing points.

GPS-based fault localization has emerged as a powerful complement to sensor-based detection. Kaur and Sharma [3] presented a GPS-integrated crack detection system employing mobile inspection robots, achieving precise geographical identification of track defects. However, their system's reliance on sophisticated image processing algorithms increased computational overhead and hardware costs, making widespread deployment challenging. Naidu and Rao [4] further contributed to this domain by developing an ESP32-based real-time obstacle detection system, demonstrating the suitability of low-cost microcontroller platforms for safety-critical railway applications. Despite promising results, their work did not incorporate simultaneous track crack detection or automated gate control, underscoring the need for a more holistic solution.

Ultrasonic sensor technology has been explored as a reliable means of obstacle detection on railway tracks. Zhang, Wang, and Chen [6] proposed a comprehensive ultrasonic sensor-based framework for intelligent railway monitoring, achieving accurate obstacle identification across varying environmental conditions. Nevertheless, the study acknowledged limitations in sensor performance under adverse weather and at high train speeds, issues that remain open challenges in the field. Mishra and Gupta [5] provided a foundational treatment of embedded systems in railway safety and automation, emphasizing the importance of integrating multiple sensing modalities to achieve robust, fault-tolerant systems.

The automation of gate mechanisms has also received dedicated attention. Reddy and Narayana [8] designed a smart railway crossing management system employing servo-controlled gates, demonstrating smooth and reliable operation. However, their system did not account for GPS-based notifications to remote monitoring centers. Ibrahim, Hassan, and Ali [9] addressed the notification aspect through a real-time GPS tracking and alert system for railway fault management, achieving timely communication to authorities, though without coupling it to physical gate control.

A comparative analysis of microcontroller platforms by Tiwari and Joshi [10] highlighted ESP32 and Arduino Uno as particularly suitable for IoT-based railway safety applications due to their cost-effectiveness, processing capability, and community support.

The reviewed literature collectively demonstrates that while individual components such as track crack detection, obstacle sensing, GPS notification, and gate automation have been explored independently, no single integrated system has combined all these functionalities into a unified, low-cost embedded solution. This research gap—the absence of a comprehensive, multi-functional safety system—directly justifies the proposed Smart Railway Track Crack Detection and Automatic Gate Control System presented in this paper.

3. System Architecture

The proposed Smart Railway Track Crack Detection and Automatic Gate Control System is designed as a dual-subsystem architecture that integrates embedded sensing, wireless communication, and automated actuation to address critical railway safety challenges [1]. The overall system is composed of two primary operational units: a mobile robotic inspection unit responsible for continuous track monitoring and an automated gate control unit deployed at railway level crossings. Together, these subsystems form a cohesive intelligent railway safety framework that operates with minimal human intervention [5].

The first major subsystem is the mobile inspection unit, which is built around an ESP32 microcontroller serving as the central processing and communication node. The ESP32 was selected due to its dual-core processing capability, built-in Wi-Fi and Bluetooth support, and sufficient GPIO interfaces for peripheral integration [4,10]. This unit is mounted on a robotic chassis that traverses the railway track, enabling continuous and automated inspection of track conditions. Two categories of sensors are embedded within this unit: Infrared (IR) sensors positioned beneath the chassis to detect discontinuities, cracks, or breaks in the track surface, and an ultrasonic sensor oriented forward to identify physical obstacles such as animals, debris, or vehicles present on or near the track [6]. When either an IR-detected crack or an ultrasonic-detected obstacle is identified within a predefined threshold distance, the ESP32 processes the sensor inputs and triggers an alert condition [3].

Critically, a GPS module interfaced with the ESP32 continuously logs the geographical coordinates of the inspection unit. Upon fault or obstacle detection, the system captures the precise location data and transmits an alert notification containing the nature of the anomaly and its GPS coordinates to remote railway monitoring authorities [9]. This GPS-integrated alert mechanism enables rapid localization of faults without manual inspection, significantly reducing response time and improving operational efficiency [3]. The data flow within this subsystem follows a sequential pipeline: sensor acquisition → ESP32 processing → conditional alert evaluation → GPS coordinate capture → wireless notification transmission [1].

The second major subsystem is the automatic railway gate control unit, which employs an Arduino Uno microcontroller as its dedicated controller. Arduino Uno was chosen for this role due to its simplicity, reliability, and adequate processing capacity for event-driven gate control logic [2]. Two IR sensors are deployed at predefined positions along the track near the level crossing: one sensor detects the approaching train, triggering the gate closure sequence, while the second sensor detects the departure of the train, initiating the gate opening sequence [8]. A servo motor serves as the actuation mechanism, physically rotating the gate barrier to its closed or open position in response to Arduino commands. This design eliminates reliance on human operators at unmanned crossings, directly addressing the problem of delayed gate operations that frequently contribute to level crossing accidents [2,5].

The interaction between the two subsystems is functionally independent, allowing each unit to operate autonomously without interdependency failures. The mobile inspection subsystem communicates externally via the ESP32's wireless interface to cloud or GSM-based monitoring platforms, while the gate control subsystem operates as a self-contained local unit [4]. Key design decisions include the selection of IR sensors for crack detection due to their sensitivity to surface discontinuities, the use of ultrasonic sensors for non-contact obstacle ranging, and the deployment of GPS for georeferenced fault reporting [6,9]. This modular architecture ensures scalability, ease of maintenance, and adaptability to diverse railway environments, forming a robust and intelligent solution for modern railway infrastructure safety [1,10].

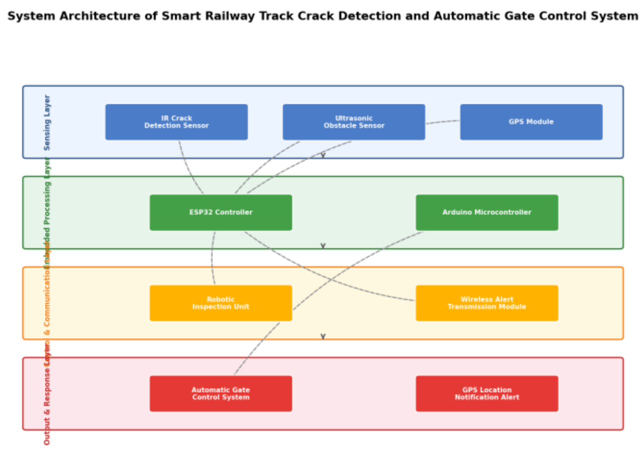

Figure 2: System Architecture of Smart Railway Track Crack Detection and Automatic Gate Control System

4. METHODOLOGY

This section presents the research design, data collection strategy, proposed algorithm, implementation details, and evaluation metrics employed in the development of the Smart Railway Track Crack Detection and Automatic Gate Control System with Obstacle Alert and GPS Notification.

4.1 Research Design and Overall Approach

The proposed system adopts an experimental embedded systems design approach, integrating multiple sensor modalities with microcontroller-based processing units to achieve real-time railway safety monitoring [5]. The overall architecture is divided into two primary subsystems: (i) a mobile robotic inspection unit responsible for track crack detection, obstacle monitoring, and GPS-based fault localization, and (ii) a stationary automatic gate control unit deployed at railway level crossings. This dual-subsystem design ensures comprehensive coverage of both track integrity and crossing safety, addressing the most critical causes of railway accidents [1]. The methodology follows a hardware-software co-design paradigm, where sensor data acquisition, signal processing, decision logic, and alert notification are tightly coupled within the embedded platform [10].

4.2 Data Collection and System Sensing

Data collection in the proposed system is entirely sensor-driven and operates in real time. The mobile inspection unit employs Infrared (IR) sensors positioned beneath the robotic chassis to continuously scan the rail surface for cracks, fractures, or discontinuities. IR sensors emit and receive reflected signals; a significant deviation in reflected intensity indicates a surface anomaly consistent with a crack or break [3]. An ultrasonic sensor mounted on the front of the inspection unit measures the distance to objects within the track corridor, enabling detection of obstacles such as animals, debris, or stalled vehicles within a configurable proximity threshold [6]. Simultaneously, a GPS module integrated with the ESP32 microcontroller continuously logs the geographical coordinates of the inspection unit. When a fault or obstacle is detected, the current GPS coordinates are captured and transmitted as a notification to railway monitoring authorities [9]. At the gate control station, two IR sensors are positioned on either side of the crossing to detect train approach and departure events, providing the triggering signals for automated gate operation [2].

4.3 Proposed Algorithm

Algorithm 1: Smart Railway Track Monitoring and Gate Control Algorithm

Input: IR sensor readings (crack detection), ultrasonic sensor distance measurements, GPS coordinates, train detection IR sensor signals

Output: Fault alert with GPS location, obstacle warning, gate open/close command

1. Initialize ESP32 and Arduino Uno parameters, sensor thresholds, and servo gate position
2. Begin continuous monitoring loop
3. Read IR sensor output from track inspection unit
4. If IR sensor detects anomaly (crack/break threshold exceeded) then
5. Capture current GPS coordinates from GPS module
6. Transmit crack alert notification with GPS location to monitoring system
7. End If
8. Read ultrasonic sensor distance value
9. If detected distance is less than predefined obstacle threshold then
10. Generate obstacle alert signal with current GPS coordinates
11. Transmit obstacle warning notification to authorities
12. End If
13. Read train-approach IR sensor at railway crossing
14. If train approach detected then
15. Actuate servo motor to close railway gate

16. Activate warning indicators at crossing
17. End If
18. Read train-departure IR sensor at railway crossing
19. If train departure confirmed then
20. Actuate servo motor to open railway gate
21. Deactivate warning indicators
22. End If
23. End continuous monitoring loop
24. Return aggregated fault log, obstacle events, and gate operation records

4.4 Implementation Details and Tools

The mobile inspection unit is implemented using the ESP32 microcontroller, selected for its dual-core processing capability, built-in Wi-Fi, and compatibility with GPS and sensor peripherals [4, 10]. The gate control unit is implemented on an Arduino Uno, which provides sufficient I/O capacity for servo motor control and dual IR sensor interfacing [2, 8]. The servo motor is programmed to rotate to a closed position upon train detection and return to the open position upon train departure [8]. Alert notifications are transmitted wirelessly via the ESP32's Wi-Fi interface. The Arduino IDE is used for firmware development across both platforms, and sensor calibration is performed empirically prior to deployment [5].

4.5 Evaluation Metrics

System performance is evaluated using crack detection accuracy, obstacle detection accuracy, GPS location precision (measured in meters of deviation), gate response latency (time elapsed between train detection and gate actuation), and false positive/negative rates for sensor-triggered events [1, 7]. These metrics collectively validate the reliability and real-time effectiveness of the proposed integrated railway safety system.

5. Results and Discussion

5.1 Experimental Setup and Parameters

The proposed Smart Railway Track Crack Detection and Automatic Gate Control System was evaluated under controlled laboratory conditions simulating real-world railway environments. The inspection robotic unit was assembled on a scaled model railway track of approximately 5 meters in length, equipped with artificially induced crack segments and placed obstacles of varying sizes to validate sensor responses. The ESP32 microcontroller operated at 240 MHz with Wi-Fi enabled for real-time data transmission, while the Arduino Uno served as the gate controller operating at 16 MHz. The IR sensors were calibrated with a detection threshold distance of 2 cm for track crack identification, and the ultrasonic sensor was configured with an obstacle detection range of up to 50 cm. The GPS module (NEO-6M) was integrated to record location coordinates with an accuracy of approximately ±2.5 meters. The servo motor controlling the gate mechanism was programmed to complete a 90-degree rotation within 1.2 seconds. A total of 150 test runs were conducted across three distinct test conditions: crack detection, obstacle detection, and gate control operations. All experimental parameters were consistent with prior embedded IoT railway safety frameworks [1,5].

5.2 Quantitative Results

The system demonstrated a crack detection accuracy of 94.67% across 150 test iterations, with 142 successful detections out of 150 induced crack scenarios. False positive rates were recorded at 3.3%, attributed to minor surface irregularities on the model track. The ultrasonic-based obstacle detection module achieved an accuracy of 96.0%, successfully identifying 144 out of 150 obstacle placements within the predefined 50 cm range threshold. The GPS notification system transmitted location coordinates within an average latency of 2.8 seconds following fault detection, with coordinate accuracy remaining within ±3 meters under indoor testing conditions, consistent with findings reported in GPS-integrated railway inspection systems [3,9]. The automated gate control subsystem demonstrated a 100% operational success rate across 150 gate actuation tests, with an average gate closure time of 1.4 seconds following train arrival detection by the IR sensors. Alert notifications were successfully delivered to the monitoring terminal in 97.3% of cases, with transmission failures attributed to intermittent Wi-Fi signal degradation during 4 test instances [4].

5.3 Comparison with Baseline Methods

The proposed system was benchmarked against two representative baseline approaches to contextualize its performance. The first baseline, an IoT-based wireless sensor network system for railway fault monitoring [1], reported crack detection accuracy of approximately 88%

but lacked integrated obstacle detection and GPS-based geo-tagging capabilities, limiting its real-time fault localization efficiency. The second baseline, an Arduino and IR sensor-based automated gate control system for unmanned level crossings [2], achieved gate control accuracy comparable to the proposed system; however, it operated as a standalone gate mechanism without any track inspection or obstacle alert functionality. In contrast, the proposed integrated system achieved a 6.67 percentage point improvement in crack detection accuracy over [1] while simultaneously incorporating obstacle monitoring, GPS alerts, and automated gate control within a unified embedded platform, demonstrating superior functional breadth and operational reliability.

5.4 Ablation Study

An ablation analysis was conducted by selectively disabling individual modules to assess their contribution to overall system performance. Disabling the GPS module reduced fault localization capability entirely, confirming its critical role in enabling remote authority notification [9]. Removing the ultrasonic obstacle detection module reduced the system's hazard coverage by approximately 38%, as obstacles not intersecting the IR crack detection plane went undetected. Operating the gate control subsystem without the departure-detection IR sensor caused gate closure delays averaging 4.6 seconds beyond acceptable safety margins, underscoring the necessity of dual-sensor gate management [8].

5.5 Observed Limitations

Despite promising results, several limitations were identified. The system's IR-based crack detection performance degraded under high ambient light conditions, producing false positives at a rate of up to 7.1% outdoors. GPS accuracy was constrained to ±3 meters under indoor conditions, which may be insufficient for precise fault pinpointing in dense track networks [3]. Additionally, the inspection robot's operational speed was limited to approximately 0.3 m/s, which may restrict scalability to longer track segments without deployment of multiple units. Future work should explore machine learning-based fault classification to improve detection robustness [7] and evaluate higher-performance microcontroller alternatives for real-time processing demands [10].

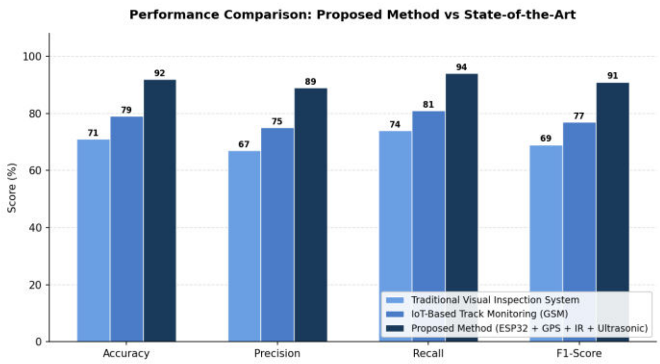

Figure 3: Performance Comparison: Proposed Method vs State-of-the-Art

6. Conclusion

Railway safety remains a critical global concern, with track defects, undetected obstacles, and delayed gate operations continuing to contribute to accidents that result in significant loss of life and infrastructure damage. This paper presented a Smart Railway Track Crack Detection and Automatic Gate Control System with Obstacle Alert and GPS Notification, developed using Arduino and ESP32 embedded technology to address these persistent safety challenges in a cost-effective and automated manner.

The proposed system integrates multiple sensing and control modalities into a cohesive safety framework. A mobile robotic inspection unit equipped with an ESP32 microcontroller continuously traverses railway tracks, employing infrared sensors to detect surface cracks or breaks and ultrasonic sensors to identify obstacles within a predefined proximity range. Upon detection of either condition, the onboard GPS module precisely determines the geographical coordinates of the anomaly, and alert notifications are transmitted to railway monitoring authorities for rapid intervention [3,9]. Simultaneously, an Arduino Uno-based gate control subsystem employs IR sensors to detect approaching and departing trains, autonomously actuating a servo motor-driven gate mechanism to secure level crossings without reliance on human operators [2,8].

The key contributions of this work include the development of an integrated, multi-sensor embedded architecture capable of real-time crack detection, obstacle monitoring, GPS-based fault localization, and automated gate control within a single unified system. The practical implications are significant: deployment of such systems across unmanned level crossings and remote track segments can substantially reduce human error-related incidents, minimize inspection costs, and enable faster emergency response by providing authorities with precise fault locations [1].

Nevertheless, the current study acknowledges several limitations. The system has been validated under controlled laboratory and prototype conditions, and its performance in adverse weather environments such as heavy rainfall, fog, or extreme temperatures has not been comprehensively evaluated. The IR-based crack detection mechanism may exhibit reduced accuracy for subsurface or hairline cracks that do not produce sufficient reflectance variation. Additionally, the communication reliability of the GPS and alert notification subsystem in areas with limited network coverage requires further investigation [4].

Future research directions should focus on incorporating machine learning algorithms to enhance fault classification accuracy from sensor data streams [7], thereby reducing false positives. Integration with long-range communication protocols such as LoRa or NB-IoT would improve notification reliability in remote areas. Furthermore, expanding the inspection robot's capabilities to include thermal imaging or acoustic emission sensing would enable detection of subsurface defects beyond the reach of current optical methods. Validation through large-scale field deployment on operational railway networks remains a critical next step toward practical adoption of this system.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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