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AI-Based Development on Laser Based QR Code Marking on Track Fitting on Indian Railways

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Abstract: The Indian Railways, one of the world's largest transportation networks, relies on millions of track fittings and related components to ensure safe and uninterrupted rail operations. Effective identification and traceability of these components have become increasingly critical as the network expands and maintenance demands grow. Currently, track fittings are marked using conventional practices such as paint-based labels, stamping, or manual tagging.These methods are often prone to fading, corrosion, mislabeling, and tampering over time. Such inconsistencies lead to difficulties in asset tracking, inaccurate maintenance records, and inefficient replacement planning.To overcome these limitations, this project proposes the development of an integrated AI-driven laser□based QR code marking system for railway track fittings. In this solution, precision laser engraving technology is used to mark durable and permanent QR codes on metallic fittings. These QR codes store essential information such as unique component identification numbers, manufacturing data, installation timelines, inspection logs, and maintenance histories. Laser-based marking ensures high resistance to environmental conditions including heat, moisture, and abrasion.The system leverages artificial intelligence for automated QR code recognition and classification through mobile scanning devices and automated inspection tools. AI algorithms enable fast and accurate data retrieval, integrity verification, and predictive analytics to identify wear patterns or potential structural failures.This digital ecosystem enables more efficient planning of maintenance activities, reduces manual labor, and minimizes the risk of human error. By establishing secure traceability and real-time monitoring of track components, the proposed system is expected to significantly enhance operational reliability, maintenance efficiency, and overall safety in the Indian Railways infrastructure. It also promotes data-driven decision-making, reduces cost overheads, and supports future expansion through seamless integration with asset management platforms.Therefore, this AI-based laser QR code marking framework represents a transformative step toward smart and sustainable railway maintenance systems in India.

INTRODUCTION:

Indian Railways, the fourth-largest railway network in the world, plays a critical role in national connectivity, economic growth, and public transportation. Its extensive infrastructure is supported by millions of track fittings such as fishplates, fasteners, clips, bolts, and baseplates, each essential to ensuring track stability, operational safety, and structural integrity. Effective identification, monitoring, and maintenance of these components are therefore crucial to preventing failures and enhancing system reliability. However, traditional component marking and maintenance practices rely largely on manual tagging, paint-based labeling, or stamping. These approaches are susceptible to fading, corrosion, misidentification, environmental wear, and data loss over time.

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Consequently, the absence of a standardized and durable identification system limits traceability, complicates inspection tasks, and increases maintenance costs. Recent technological advancements have prompted a shift toward digital asset tracking and predictive maintenance in transportation infrastructures. Among these, laser-based marking systems have emerged as a highly precise and permanent solution for industrial identification. When combined with Quick Response (QR) code technology, they offer compact and data-rich encoding capabilities. QR codes can store component-specific information such as manufacturing details, installation dates, material specifications, service history, and performance logs. Yet, the ability to extract and analyze this data efficiently in real time depends heavily on intelligent processing and analytics. Artificial Intelligence (AI), particularly in computer vision and pattern recognition, provides powerful tools to automate QR code detection, surface-condition assessment, and asset verification. Integrating AI with laser-generated QR codes enables the development of a smart asset-management ecosystem that supports accurate scanning, automatic data interpretation, and predictive maintenance decision-making. Such a system can address key challenges faced by Indian Railways—such as labor-intensive manual checks, inconsistent documentation, and limited lifecycle visibility of track components. The proposed AI-based laser QR code marking system is designed to deliver robust traceability, efficient inspection workflows, and enhanced maintenance planning. It enables real-time access to asset data through handheld or automated scanning systems, reducing human dependency and ensuring reliable tracking throughout the component lifecycle. This digitization approach not only strengthens safety standards but also improves operational throughput and long-term sustainability. Thus, this research aims to explore and establish a comprehensive framework for implementing AI-driven laser QR code marking on railway track fittings, paving the way for intelligent infrastructure and data-centric maintenance practices within Indian Railways.

CONTRIBUTION:

- Development of a Laser-Based QR Code Marking Framework:
  A robust framework is proposed for laser engraving QR codes on metallic track fittings, ensuring permanence, corrosion resistance, and high readability even under harsh railway environmental conditions.
- Integration of AI-Driven Recognition and Data Processing:
  The work introduces an AI-enabled recognition system capable of accurately detecting, scanning, and interpreting engraved QR codes from handheld or automated inspection devices, even when subject to dirt, wear, or partial damage.
- Standardized Digital Traceability Architecture:
  A digital architecture is designed to store and link QR-encoded information—such as manufacturing details, installation history, inspection logs, and maintenance records—to a centralized database, enhancing lifecycle traceability.
- Automation of Track Component Monitoring:
  The proposed system reduces manual dependency in inspection activities by enabling automated identity verification and component state reporting, contributing to faster and more reliable maintenance procedures.
- Predictive Maintenance Support Using AI Analytics:
  Integrated data models support condition assessment and predictive decision-making, helping maintenance teams identify high-risk components and schedule timely replacements, thereby minimizing failure risks.
- Cost- and Time-Efficient Maintenance Workflow:
  By reducing misidentification, redundant inspections, and paperwork, the system optimizes maintenance operations, lowering overall operational time and cost for Indian Railways.
- Scalable and Adaptable Solution for Railway Infrastructure:
  The system is designed to scale across diverse track fittings and geographical zones, with potential integration into existing asset-management platforms used by Indian Railways.

RELATED WORK:

- Laser engraving for permanent part identification is well-established in industry studies and vendor guides describe process parameters, material effects, and on-line marking for metals to ensure long-lasting, machine-readable codes. QR codes are widely used for low-cost asset tagging in transportation, linking physical parts to maintenance and inventory systems
- Recent work in AI/vision focuses on robust QR detection and decoding under rotation, occlusion, low contrast and physical damage; techniques include learned denoising, geometric rectification, and damage-tolerant decoding pipelines tailored for field images. Industry pilots also demonstrate integrated mark→inspect workflows where laser marking is immediately verified by machine vision to avoid dispatching unreadable parts.
- For railways specifically, standards and asset-management practices (GS1 profiles, railway technical manuals) set identification and lifecycle-traceability requirements but there is limited published research that (a) evaluates long-term readability of laser-engraved QR codes after real railway exposure (abrasion, oil, corrosion), and (b) combines AI models tuned to engraved-on-metal QR imagery with an implementation roadmap for Indian Railways. This paper addresses those gaps by evaluating marking parameters on typical track-fitting materials and developing AI-based recovery and verification methods suited to in-service railway conditions.

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PROBLEM DESCRIPTION:

Indian Railways manages an extensive network of track infrastructure where thousands of track fittings such as fishplates, bolts, clips, and base plates are deployed and frequently replaced during maintenance activities. Currently, most of these components lack a standardized, permanent, and digitally trackable identification mechanism. Existing manual or paint-based marking methods are prone to wear, corrosion, environmental degradation, and human error. This makes it difficult to establish accurate traceability of fittings across their lifecycle, resulting in inefficiencies in inventory management, difficulty in linking components to manufacturing/maintenance history, and challenges in failure analysis. Laser-based QR code engraving offers a durable solution for embedding unique identifiers directly onto metallic track fittings. However, field conditions such as dust, rust formation, abrasion, geometric irregularities, and orientation complicate reliable scanning. Conventional decoding approaches fail when QR codes are partially damaged or poorly contrasted. Therefore, there is a need for an AI-driven recognition system capable of accurately detecting, restoring, and decoding engraved QR codes under operational railway conditions. Additionally, the integration of these identification and recognition mechanisms with centralized digital asset-management platforms remains limited. This research addresses these issues by developing an AI-based system to enhance the readability of laser-engraved QR codes on track fittings and enabling real-time lifecycle traceability within the Indian Railways ecosystem.

PROPOSED SOLUTION:

Our solution introduces an integrated framework that combines laser-based QR code marking with AI-enabled decoding and digital asset management to achieve reliable, permanent identification and lifecycle traceability of track fittings within Indian Railways. The system begins with the laser-engraving process, wherein each track fitting such as fishplates, rail clips, and bolts is permanently marked with a unique QR code. Key laser parameters, including wavelength, pulse duration, marking depth, and focal characteristics, are optimized to achieve high-contrast, wear-resistant impressions on diverse steel grades commonly used in railway hardware. Surface preparation techniques, suchas cleaning and finishing, are incorporated to enhance engraving uniformity and long-term legibility. This ensures that QR markings can withstand extreme outdoor exposure, including mechanical abrasion, water ingress, corrosion, ballast impact, and temperature variations. The second component of the solution focuses on AI-driven QR code recognition. A computer-vision pipeline is developed to detect and decode engraved QR patterns even under degraded conditions. The system incorporates tailored pre-processing techniques contrast enhancement, edge sharpening, denoising, glare suppression, and segmentation to improve signal clarity. Machine-learning modules are trained using datasets of real and simulated railway conditions (dust, rust, scratches, partial occlusion, uneven lighting), enabling the model to reconstruct missing or distorted modules and interpret codes that traditional scanners fail to read. This enhances reliability in field environments where tracks accumulate dirt, grease, and corrosion.

A mobile/handheld scanning application acts as the user interface, allowing track maintenance staff to conveniently scan QR-marked fittings in situ using smartphones or portable devices. Upon successful decoding, the application retrieves component-specific metadata such as manufacturer, batch number, installation date, maintenance records, and condition history from a centralized digital asset-management platform. The backend maintains a unified database with role-based access, enabling seamless tracking of components from production to end-of-life. Finally, the framework enables advanced functionalities including predictive maintenance using historical data, automated reporting of component failures, and analytics-driven planning of replacement cycles. By eliminating manual recordkeeping, the system reduces data errors, facilitates rapid field audits, and enables evidence-based infrastructure decisions. Overall, the solution establishes a standardized, intelligent, and scalable approach to track-fitting identification aligned with the technological modernization objectives of Indian Railways.

SYSTEM ARCHITECTURE:

The proposed system architecture integrates laser-engraved QR code identification, AI-driven recognition, and centralized digital asset management to achieve end-to-end traceability of track fittings deployed in Indian Railways. The architecture is organized into five functional layers:
(1) QR Code Generation & Laser Marking,
(2) Field Image Acquisition,
(3) AI-Based QR Decoding,
(4) Data Management & Cloud Storage, and
(5) User Application Interface.

1. QR Code Generation & Laser Marking Unit

In the manufacturing or maintenance depot, a unique identification number is assigned to each track fitting (e.g., fishplates, clips, bolts). This identifier is encoded into a QR code and permanently engraved on the surface of the component using a laser-marking device. Laser parameters—such as power, pulse width, focal depth, and engraving speed—are optimized to produce high-contrast, durable markings capable of withstanding harsh railway environments, including mechanical abrasion, corrosion, moisture, and temperature variations. After engraving, the components are deployed for field use.

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2. Field Image Acquisition Layer

During routine inspection or maintenance, field personnel capture images of the engraved QR code using handheld devices such as smartphones, rugged tablets, or portable industrial scanners. These images are transmitted to the processing system either locally or via network connectivity. To support remote zones with limited connectivity, the acquisition layer may buffer images for later processing.

3. AI-Based Recognition & Processing Layer

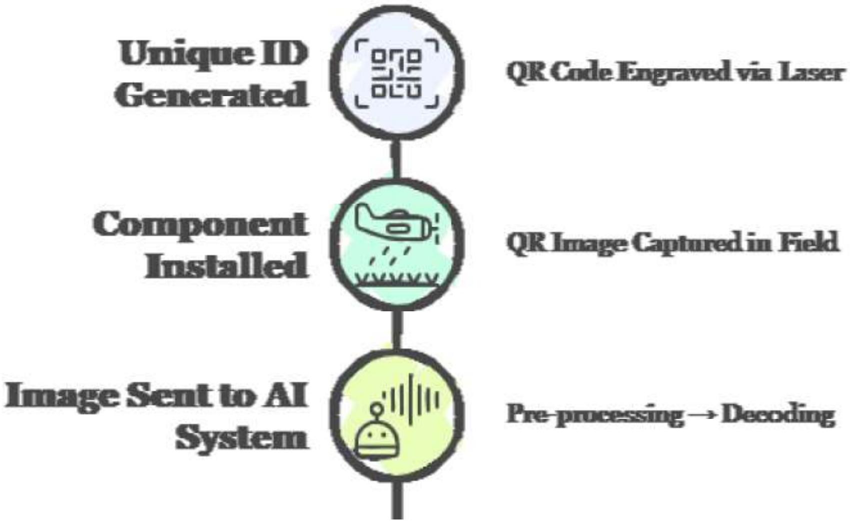
Captured images undergo processing through an AI-enhanced computer-vision pipeline designed to decode engraved QR patterns under degraded real-world conditions. Pre-processing techniques including noise removal, contrast enhancement, glare suppression, and segmentation are applied to improve QR visibility. The AI model identifies the QR region and reconstructs incomplete or distorted modules using patterns learned from datasets reflecting actual railway conditions (e.g., dust, rust, scratches, partial occlusion, uneven lighting). Once processed, the QR code is decoded to extract the component ID and embedded metadata.

4. Data Management & Cloud Backend

The decoded identifier is cross-referenced with records stored in a centralized asset-management database. This repository maintains the complete lifecycle history of each component, including manufacturing details, installation location, service history, inspection notes, and failure records. The backend supports secure data exchange, remote synchronization, and integration with existing Indian Railways inventory and maintenance systems.

5. User Application Interface

A mobile or web-based application provides authorized personnel with real-time access to component information. The interface enables technicians to view fitting details, log maintenance activities, update condition status, and upload inspection images. Additional tools for visualization, alerts, and analytics support decision-making and predictive maintenance planning.



IMPLEMENTATION DETAILS:

The proposed solution is implemented through coordinated development of laser-based QR marking, computer-vision–assisted decoding, and backend asset-management integration. The implementation framework consists of hardware configuration, data acquisition, AI processing pipeline, and information retrieval components.

1. Laser-Based QR Code Marking

The system employs an industrial fiber laser engraver to permanently mark QR codes on railway track fittings such as fishplates, bolts, and clips

→QR Code Assignment:

Each component is assigned a globally unique identifier, which is encoded into a standard QR format.

→Laser Parameter Optimization:

Parameters including power (20–60 W), pulse duration, marking depth, focal distance, and scan speed are calibrated according to the metallurgical composition and surface finish of the component.

→Surface Preparation:

Mechanical cleaning or solvent wiping is used to minimize contaminants and ensure uniform etching.

→Engraving & Validation:

The QR is engraved at a depth ensuring long-term corrosion and abrasion resistance. Post-marking imaging validates code visibility and contrast.

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2. Dataset Development

To train the recognition model, a dataset of QR-marked components is created,Images collected under varying field conditions dust, rust, partial occlusion, grease, scratches, temperature variation, and low illumination,Synthetic augmentations, including Gaussian noise, glare simulation, blur, and distortion, are applied to increase robustness,Dataset images are labeled with ground-truth text to support supervised learning.

3. AI-Driven Vision Pipeline

A hybrid computer-vision and machine-learning pipeline is implemented to decode engraved QR codes even under adverse conditions.

→Pre-Processing:

Denoising, histogram equalization, contrast improvement, glare suppression, sharpening, and adaptive thresholding are applied to improve scan clarity.

→QR Localization:

A CNN-based detection algorithm identifies and isolates the QR region from the background.

→Module Reconstruction:

AI models trained on degraded patterns reconstruct partially worn or occluded QR modules when code elements are missing or distorted.

→Decoding:

Standard QR decoding libraries extract the encoded ID, aided by machine-learning-based error correction.

4. Mobile Scanning Interface

A mobile application is developed for field deployment, allows personnel to capture images of QR engravingsperforms on-device enhancement and basic decoding; forwards images to backend when needed.offline capability stores data temporarily when network connectivity is limited.

5. Database & Backend Integration

A cloud-based asset-management platform stores and manages metadata for each track fitting,records include manufacturing batch, installation location, service dates, maintenance history, and status,the platform supports authentication, encryption, and synchronization,the backend communicates with existing Indian Railways asset-tracking workflows.

6. Maintenance Analytics & Reporting

Decoded information is presented to field engineers throughdashboards,displays location, installation history, failure logs,allows updating inspection status and maintenance activity logssupports predictive maintenance through trend analysis.

CHALLENGES AND LIMITATIONS

The implementation of an AI-based laser-engraved QR code marking system for Indian Railways track fittings introduces several technical, environmental, and operational challenges. Key limitations are summarized below.

1. Environmental Degradation

Track fittings are continuously exposed to harsh outdoor conditions such as dust, rust, grease, humidity, rainfall, UV radiation, and temperature variations. These factors may degrade QR visibility over time, making consistent decoding difficult.

2. Due to high vibration, ballast impact, and handling during maintenance, engraved QR surfaces may experience abrasion or deformation, leading to partial or complete loss of QR structure.

3.Variability in Material Properties

Track fittings come from multiple manufacturers with varying steel grades, surface roughness, coating presence, and finishing. This inconsistency makes it challenging to standardize laser engraving parameters and maintain uniform readability.

4. Limited Scan Quality in Field Conditions

Field images captured through handheld devices may suffer from poor focus, glare, motion blur, improper angle, insufficient lighting, or occlusion.These variations reduce the accuracy of AI-based decoding.

5. Data Scarcity for Model Training

Properly annotated datasets of QR codes under railway field conditions are limited. Collecting sufficient real-world degraded samples for training and validation is time-consuming and labor-intensive.

6. Partial or Severe Damage to QR Mark

In cases of extreme wear, corrosion, or structural cracks, QR modules may become unreadable beyond the capacity of AI reconstruction, leading to failure in identification.

7. Integration With Existing Railway Systems

Seamlessly linking the QR identification platform with existing Indian Railways asset-management workflows and IT infrastructure may require significant customization, standardization, andsecurity validation.

8. Requirement for Skilled Operation

Laser marking equipment requires trained operators. Improper calibration or handling may result in low-quality engraving and shortened code lifespan.

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9. Connectivity Limitations

Remote track locations may lack stable cellular or network connectivity, restricting real-time data transfer and database access. Offline storage and delayed synchronization may be necessary.

10. Cost and Deployment Scale

Large-scale deployment across thousands of kilometers of track and numerous components may involve high initial cost, adoption time, and logistical challenges.

CONCLUSION:

This work presents an integrated framework for applying AI-based recognition to laser-engraved QR codes on Indian Railways track fittings, enabling a reliable and digitized component-tracking ecosystem. The proposed approach ensures permanent identification through optimized laser marking, while an AI-driven decoding pipeline enables robust QR recognition under challenging field conditions, including dust, rust, abrasion, and variable lighting. The introduction of a centralized asset-management backend provides lifecycle traceability, improves maintenance efficiency, minimizes manual data entry, and supports quicker failure analysis.By combining durable marking technology with intelligent visual interpretation and digital record-keeping, the system significantly enhances operational transparency and supports data-driven maintenance strategies. Overall, the solution demonstrates promising potential to modernize component traceability across India's extensive railway network.

FUTURE WORK

1. Advanced AI Algorithms:
   Incorporation of deep learning–based super-resolution and generative reconstruction models to further improve QR decoding when severe damage or occlusion is present
2. Alternative Marking Techniques:
   Investigation of hybrid marking strategies—such as dot-peen, RFID embedding, or micro-engraving—to complement QR marking for redundancy in extreme wear conditions.
3. Automated Data Collection:
   Integration of mounted scanning units on track-recording vehicles or drones to automate large-scale data acquisition without manual effort.
4. On-Device Inference:
   Deployment of lightweight AI models for real-time decoding on edge devices to reduce dependency on cloud connectivity.
5. Predictive Analytics:
   Development of predictive maintenance models based on historical component-failure trends to forecast service needs and replacement cycles
6. Standardization Framework:
   Establishment of QR placement guidelines, marking depth standards, and database integration protocols to enable seamless nationwide adoption.
7. Scalability & Deployment Trials:
   Large-scale field trials across diverse terrains and climatic conditions to evaluate performance and refine system robustness before full deployment.

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