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A Study of Innovations in Robotic Designs and Technologies for Application in Railway Transportation Systems

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Abstract: Railway transportation systems are complex networks designed to facilitate the movement of passengers and goods efficiently. Railway infrastructure consists of the track, trackside, furniture, stations, platforms, switches and crossings (S&C), tunnels, bridges, etc., but tracks are the most critical railway infrastructure. Many types of defects can appear in the tracks, incurring huge costs for maintenance and inspection tasks. This paper reviews robotic design basics, the development of robotic design technologies, that have increasingly transformed railway operations, and an overview of related past research with examples of robots designed for the purpose. Integration of these robots in railway systems enhances efficiency, safety, and cost-effectiveness, addressing the limitations of traditional manual methods. It also explored the recent innovations in developing robotic designs and technology for railway infrastructure maintenance and inspection applications. These innovations either facilitate comprehensive maintenance by allowing for flexible access and reduce track possession time; enable efficient inspection through sensor fusion and mobile manipulation to reduce human involvement and costs, or utilize advanced imaging systems to capture clear video footage of components for improving safety and reducing the reliance on human inspectors. These advances in robotics are promising but manual interventions affect their performance and accuracy. So, there is a need to create a completely autonomous process for railway systems in the future.

Keywords: Robotics, Innovations, Design, Technology, Applications, Railways.

I. INTRODUCTION

Transportation systems require various innovative designs and technologies to enhance efficiency, capacity, and environmental sustainability. It refers to transporting goods and passengers using railcars on fixed routes, characterized by economic efficiency, environmental friendliness, and governmental regulations. The infrastructure and rolling stock constitute Railway assets. Infrastructure the fixed assets used for the operation of the railway, includes tracks, tunnels, bridges, and catenary systems. Rolling stock refers to assets that can move on a railway network; The problems arising in these assets include failures that originate from the usage of infrastructure components (rail defects), the rolling stock (such as door opening failures), or due to exogenous factors like collisions with people at stations and non-authorized/ trespassing people on railway stations and different weather conditions (flooding). Railway infrastructure networks have played a pivotal role in facilitating industries' growth, significantly contributing to economic development and well-being [1,2].

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Due to the running of the trains, the quality of railway infrastructure gradually deteriorates over time leading to accidents. Thus, railway infrastructure should be kept in workable conditions despite different degradation mechanisms. Additionally, disruption might affect passenger and freight transport in highly-used networks. So, it needs to ensure the prevention of safety issues, and that rail users do not shift to other modes of transport [3]. Maintenance involves a task or series of tasks that protect or reinstate a system's anticipated condition, including technical, administrative, and managerial actions taken. Maintenance strategies can be reactive, preventive, or predictive. These strategies keep trains running and product quality within acceptable levels [4]. Reactive maintenance keeps response time low, equipment deterioration to minimal, and there are few maintenance personnel. Predictive maintenance was developed to reduce failure rates, and repair rates, detect equipment problems before failure, and minimize downtime and response time [5]. Preventive maintenance involves routine maintenance techniques [6] to ensure the safety, reliability, and availability of components. Inadequate maintenance leads to service disruptions, emphasizing the importance of preventive measures to reduce delays and enhance customer satisfaction.

II. ROBOTIC DESIGN AND TECHNOLOGY INNOVATIONS FOR APPLICATION IN RAILWAY SYSTEMS

2.1) Basics of Robot:

A robotic system is a complex system consisting of a mechanical system endowed, with a locomotion apparatus (wheels, crawlers, mechanical legs) and a manipulation apparatus (mechanical arms, end-effectors, artificial hands). An actuation system provides the capability to exert locomotion and manipulation. The concept of such a system refers to the context of motion control. The capability for perception is entrusted to a sensory system which can acquire data on the mechanical system's internal status and the environment's external status. The capability for connecting action to perception in an intelligent fashion is provided by a control system that can command the execution of the action concerning the goals set by a task planning technique, as well as the constraints imposed by the robot and the environment. Therefore, robotics is an interdisciplinary subject concerning the cultural areas of mechanics, and control. computers, and electronics.

A robot is a computer-programmable multifunctional manipulator designed to move materials, parts, tools, or specialized devices for various tasks. It has been classified into three classes based on the amount of human intervention necessary to control them. Teleoperated robots depend on human operators for planning, perception, and manipulation. Programmed robots perform tasks with preprogrammed instructions. Cognitive robots are capable of sensing, modeling, planning, and acting, independently of human operators. Power sources for robots include Hydraulic drive to give a robot great speed and strength; Electric drive to provide a robot with less speed and strength and is adopted for smaller robots; Pneumatic drive is used for smaller robots to carry out simple pick-and-place material handling operations.

Railway robots utilize a variety of advanced sensors to enhance safety and efficiency in track inspection and maintenance. These sensors are crucial in detecting defects, monitoring infrastructure integrity, and automating inspection processes. The key types of sensors employed in railway robots

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include Ultrasonic sensors, LiDAR sensors, and multi-sensing technologies to enhance inspection capabilities for internal defect detection, remote sensing, and obstacle monitoring respectively.

2.2) Robotic Technology:

Robotic technology encompasses a multidisciplinary field focused on the design, development, and application of robots, that integrate mechanics, electronics, control systems, and artificial intelligence. This technology finds applications across various sectors including the railway industry. Robotic technology in railways is revolutionizing maintenance and safety through innovative inspection and monitoring systems. These advancements enhance operational efficiency, reduce human error, and improve safety standards across railway networks.

2.3) Need for Robotic Technology in Railway Transportation Systems:

Properly maintaining infrastructure, rolling stock and other resources in the railway industry is vital in providing a safer, reliable, efficient, and resilient output. It has been revealed that accidents in railways occur due to rolling-stock faults or infrastructure failures [7]. Additionally, railway maintenance tasks are costly, and failure to conduct preventive maintenance would lead to expensive consequences leading to delays, train cancellations, and customer dissatisfaction [8]. The maintenance of railway tracks is essential for the safety requirements of transportation, enhancing the network's reliability and promoting the sustainable advancement of railway technologies.

Due to rapid expansion, railway companies are continuously improving processes. In addition, railway maintenance technicians risk their lives to assure passengers' safety and keep trains operating. On most occasions, railway technicians work in unfavorable weather conditions and encounter risks while working with live power transmission lines/rails near trains traveling at high speeds from adjacent tracks, working at heights, or in unergonomic postures for prolonged periods [9].

The transmission fluid changing process of rolling stock is another hazardous maintenance process, where technicians execute the work beneath rolling stock while exposed to slip risks on oil spills or working close to electrified third rails [10]. Besides, human errors in the railway are inevitable and can cause disastrous failures and, subsequently, the loss of lives. Therefore, introducing robotics to such dangerous maintenance tasks could potentially minimize the health risks to technicians and hence would be an ideal solution for achieving cost benefits and high accuracy.

Railway companies consider robotic systems to handle monotonous maintenance tasks and utilize railway technicians to do challenging and value-added tasks. Further, it has been revealed that maintenance of rolling stock assets could be clustered and distributed among local contractors. This would encourage them to be specialists in the field and apply techniques to achieve increased productivity through automation [11]. Additionally, increased automation is expected to eliminate or minimize human intervention in processes and to obtain operational cost benefits.

Robotic systems can optimize maintenance tasks in the railway sector by improving efficiency, and safety. Recent technological advances have made robotic systems more feasible and economical, with significant potential for cost savings in rolling stock maintenance. The introduction of robotics is seen

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as a solution to the challenges posed by increasing rail traffic and the need for continuous improvement in maintenance practices and technological advancements.

III. APPLICATIONS OF ROBOTS IN RAILWAY TRANSPORTATION SYSTEM

Railway asset maintenance systems record information, such as passing train information, and monitor track components or perform specific tasks at a certain speed. The movable platform. devices are equipped with various sensors for monitoring, inspection, surveying, and navigation.

3.1) Robotic Applications in Maintenance:

- ***In Rolling-Stock Maintenance:***

  Most robotic developments for rolling-stock maintenance focus on inspection and monitoring, while others are dedicated to cleaning tasks. Applications of robotic systems in rolling-stock maintenance include fluid servicing and rebuilding, showcasing the versatility of robotic systems in various maintenance functions. Integrating robotic systems in rolling-stock tasks aims to enhance safety and efficiency, reducing the physical burden on maintenance workers [12].

- ***In Rolling-Stock Cleaning:***

  Various robots have been developed for cleaning tasks, including a mobile robot for commuter rail car floors and an articulated robot for train bonnets. The cleaning robot can be operated in both automatic and manual modes. Sweeping the floor, collecting dirt, sprinkling water, mopping the floor, pulling dirty water, and polishing the floor are the capabilities of cleaning robots. These robots utilize advanced navigation and cleaning technologies, demonstrating the potential for automation in routine maintenance tasks.

  Xu et al proposed a self-traction model to clean transit vehicles [13]. Tomiyama et al. [14] suggested A systematic analysis of the train cab front cleaning task and generated subclasses that allowed researchers to efficiently and effectively solve each sub-task. Furthermore, a theoretical control and path-planning methodology for a train cab front-cleaning robot was suggested by Moura and Erden [15] by exploiting the operational space formulation and simultaneous force and position control introduced by Khatib [16].

- ***In Rolling-Stock Fluid Servicing:***

  Studies have shown the viability of robotic systems in servicing passenger train fluids, with proposed designs for Cartesian and articulated robots. Research emphasizes the importance of addressing the variability in fluid port sizes and positions across rolling stock. Advanced methodologies, including machine learning algorithms, are being explored to enhance the automation of fluid servicing tasks. However, few studies [11,17,18] have tried to introduce robotic systems in rolling-stock fluid-changing tasks.

  Automated systems for monitoring rolling-stock wheels and bearings have significantly reduced derailments, showcasing the effectiveness of robotic systems in enhancing safety. Various technologies, including acoustic emission and vibration analysis, are employed to detect defects in rolling-stock components. Therefore, several automated wayside detectors were designed and developed to overcome this issue. Hart et al. [19] proposed a multi-spectral rolling-stock

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undercarriage inspection technique that allowed for recording both physical and thermal conditions. The study included inspecting disc brake condition, and bearing performance, and detecting any anomalies in electrical systems. Edwards et al. [20] and Liu et al. [21] presented online visual inspection systems that are capable of inspecting rail car safety appliances and bogie block keys of freight trains respectively.

- ***In Rolling-Stock Rebuilding:***
  Robotic systems have been successfully implemented in rail car rebuilding processes, significantly reducing maintenance cycle times and improving safety. Automation in wheelset maintenance has minimized human contact with hazardous components, enhancing worker safety and operational efficiency. The use of reprogrammable robots in maintenance shops demonstrates the potential for increased productivity through automation.
- ***In Power Transmission Line Maintenance:***
  Human workers perform many maintenance operations on live power transmission lines. These tasks are hazardous for these workers, due to the risks of falling from high places and the risk of electric shock. Obtaining skilled workers to perform these tasks is quite difficult due to the job's high training and labor requirements. Innovative systems have been developed [22] for inspecting power transmission lines, utilizing laser technology and autonomous robots to enhance inspection efficiency. These systems can operate at high speeds without disrupting normal train services, showcasing the potential for integrating robotic systems into existing infrastructure. Autonomous robots have been designed in Japan [23], Spain [24], and China [25] for power line inspections capable of navigating obstacles and utilizing advanced image processing techniques for effective monitoring.
- ***In Bridge Maintenance:***
  Integration of advanced sensors and imaging technologies in bridge maintenance robots aims to improve the accuracy and efficiency of inspections. Railway bridge maintenance is labor-intensive and needs technicians to execute the tasks in dull, dirty, and dangerous environments. Therefore, to relieve human workers from such labor-intensive and dangerous tasks, a robotic system was designed by Liu et al. for stripping paint and rust from steel bridges [26]. Wang and Kawamura proposed a semi-autonomous magnetic climbing robot for steel bridge inspection [27]. Oh et al. [28] prototyped a bridge inspection robot capable of fully autonomous operation or teleoperation by distant users enhancing inspection capabilities without disrupting traffic.
- ***In Tunnel Maintenance:***
  The available tunnel inspection systems utilize ground-penetrating radar (GPR) to monitor tunnel conditions, providing valuable data for maintenance planning. Automated systems for monitoring tunnel deterioration are being developed to enhance the efficiency of maintenance scheduling and execution. Integrating sensors on regular trains for tunnel inspections demonstrates a novel approach to maintaining infrastructure.
  IRIS Hyrail a commercially available semi-autonomous tunnel inspection system consists of a GPR. The inspection module is mounted on a vehicle that can be driven on the rail tracks. Specialized software manages, collects, and displays GPR data [29]. An integrated robotic system was

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proposed by Rowshandel et al. [30] for the detection and characterization of rolling contact fatigue cracks in rails. A higher-technology robotic solution for rail track inspection developed by "Autoscan", uses electromagnetic acoustic transducers that are mounted on inspection carts with a robotic arm [31]. Another platform was introduced by "RailPod" composed of a vehicle that remotely controlled and contains ability to configure based on individual customer needs [32].

3.2) In Other Railway Maintenance Tasks:

Various robots have been designed for cleaning and monitoring tasks in railway stations, showcasing the versatility of robotic technology in maintenance applications. The development of automated systems for monitoring railway track circuits aims to improve safety and reduce human error in maintenance practices.

- ***In the Cleaning of Railway Tracks:***

  The railway track is the most critical infrastructure. Rails guide the trains along the designated path. The manual method of cleaning tracks and the railway platforms is tedious and the desired level of sanitation or cleanliness is not achieved. While on the job, many of the workers develop serious health problems over time. The health hazards include exposure to harmful gases such as methane and hydrogen sulfide, cardiovascular degeneration, musculoskeletal disorders, infections, respiratory system failure, etc. Four different designs of robots [33] have been proposed for track cleaning, which include the baseline design which uses the Leo Rover robot platform and the PhantomX Pincher robot arm; The Vacuum Arm Design utilizes a vacuum-powered grabbing arm to collect both coffee cups and newspapers; The Scoop Design closely mimics the manual cleaning process, designed to store and manage collected waste; The Conveyor Design- which utilizes a conveyor instead of a traditional manipulator to collect waste. The conveyor design is the most suitable automated cleaning system for collecting and disposing of waste from passenger trains.

  To overcome the problems posed by huge waste collection in the tracks, the fabrication of automated robotic machines was proposed [34] to save human labor costs and time with excellent precision machines which are eco-friendly as well. Another study [35] presented vacuum-based technology for cleaning the track. The investigation by Nathan et al [33] reported conveyor belt design as most appropriate for effectively cleaning the train carriage interior. The railway cleaning bot developed by Neil et al [36] consists of a scissor lift mechanism, retractable wheels, a chlorination unit, a train alarming unit, and a height-adjustable sweeping mechanism. The robot runs on the track via its retractable wheels and collects waste lying within it using a height-adjustable roller brush. At the same time, the chlorination unit pours disinfectant onto the swept path. A semi-automatic floor-cleaning machine has been developed using solar energy [37]. The Smart floor cleaning robot proposed [38] automatically cleaned the floor using the vacuum suction system and collected it in the dust collection chamber, emptying it when full.

- ***In Sanitization of Railway Stations:***

  The spread of COVID-19 has necessitated the sanitization of large and crowded public environments like railway stations. Riccardo et al [39] proposed a multi-robot approach to

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sanitize railway stations using a distributed Deep Q-Learning technique. The framework uses Wi-Fi networks to localize passengers inside the station and to develop a map of possible risky areas to be sanitized. Dezhao et al [40] implemented the improved algorithm on the self-designed robot platform to complete the automatic disinfectant dispersion of the train carriage and their results showed that the designed robot could flexibly realize the functions of localization, navigation, and obstacle avoidance in the carriage, and achieve the purpose of intelligent disinfection.

- ***In Railway Track Scavenging and Crack Detection:***
  Railway track scavenging and crack detection systems using LED and LDR sensors or optocoupler assembly were designed [41]. The cracks and other defects in the rails go unnoticed due to improper maintenance and the currently irregular and manual track line monitoring that is carried out to detect the cracks present in the track to avoid accidents and also the obstacles present in the track. An autonomous railway track monitoring system [42] using ultrasonic sensors was used to detect track faults more accurately and encryption techniques to prevent data tampering during transmission. A laser-based railway track inspection robot [43] utilized advanced technology to autonomously scan tracks for defects. Remote monitoring and control via ESP12E base and Microcontroller ensured prompt response to identified issues to reduce labor-intensive inspection efforts and enhance railway safety [44].
- ***In Rail Car Manufacturing Learning Factory (LF):***
  LF serves as a platform to disseminate research findings into industrial practice and to educate prospective engineers in hands-on courses [45]. The use of LF offers the potential to transfer digitally designed solutions to real systems for testing and demonstration, within the framework of digital manufacturing. The teaching-based conceptual framework accounts for the knowledge needed for factories in the future. The use of LF is used to prepare students and employees to understand Industry technologies where workplace-related scenarios could be mapped through practical learning of work in smart factories by using communication and information technology modules.
- ***In Package Stacking for Train Loading:***
  The stacking robots can carry out the stacking operation for the bagged material by specific types of train carriages. Intelligent control is applied to ensure the stacking process is reasonable and orderly. Several characteristics of the robotic package stacking of the train loading system exist. The working environment was greatly improved and the working region was made the best use of. The automation of the robotic package stacking train loading system was greatly improved, providing chances for bulk grain handling innovation. With the development of stacking robots, studies were carried out to improve the performance of robots [46].
- ***Design and Application of Robotic Package Stacking for Train Loading:***
  A robotic package stacking system for train loading was designed by the China Waterborne Transport Research Institute [46]. The package stacking train loading system consisted of three parts: the packing units, bagged material delivery lines, and the stacking robot. The packing unit combined functions such as weighing, quantitative filling, and bag sewing, the bagged material delivery line bag-inverting machines, parallel belt conveyors, turning belt conveyors, climbing belt

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conveyors, weighing machines, bag handling machines, material leakage conveyors, shunting belt conveyors, and shaping machines. Before the bags were bots handled the bags, the sealed bags had to be delivered, inverted, converged, tested, shaped, and shunted.

- ***In Railway Track Reconstruction:***

  The shape and appearance of an object can be recovered using a 3D reconstruction tool in Computer vision. It can be done by active and passive methods. Sensors like laser, ultrasound, or microwave interact with the object actively and create a 3D profile in the active method. The passive method is preferred for outdoor scenarios and uses a sensor to measure the light reflected or emitted from an object to infer its 3D structure. Structure from motion is a cost-effective and widely used method for 3D reconstruction that uses a single camera to calculate the photogrammetric properties of objects concerning the movement of the camera [47]. The autonomous system combines this technique with robotic sensing to achieve an unmanned 3D reconstruction for the track.

- ***Robot for Drilling Railway Structures:***

  A robot has been designed for drilling holes for anchor bolts that fasten rails to concrete slabs. Its special features are high precision and the relatively large diameter of the holes it can drill [48]. In developing a drilling robot to install railway tracks, the results indicated the robot's flexibility and dexterity to perform self-motions in cluttered spaces and to cross through narrow passages via sequences of movement.

- ***In Railway Track Monitoring with Obstacle Detection and Data Security:***

  The proposed robot runs along the tracks [42] to detect the presence of humans on the track. It starts a loud buzzer to warn them about the approaching train. If some anomalies are detected then the latitude and longitude of that location will be sent to the nearest railway station and the exact location of the fault can be retrieved by using an Android application. From this information, necessary action can be taken. The data sent by the robot should not be tampered with by any adversary and for that purpose, the data security is also provided.

- ***In the Inspection of the Railways Assets:***

  Inspection is the activity in which state information is monitored to allow prediction or early detection of disturbances. Railway inspection is crucial to know potential hazards in the network. Human inspectors conduct measurements manually while walking along the track. Railway inspection is required because the total railway mileage in the world has increased, especially in developing countries, the train speed and standards for passenger comfort and operation safety have increased, the labor expense has increased [1], and the degradation of railway infrastructures due to climatic deterioration.

  Visual inspection, digital image correlation and thermal cameras for rail component inspection, laser vision sensors for rail wear and track geometry assessments, laser distance meters for rail corrugation, ultrasonic sensors for surface and internal defect determination, light detection and ranging for track clearance and vegetation detection, eddy currents for internal rail defect inspection, electromagnetic acoustic transducers for surface and internal defect analysis, GPR for ballast fouling and moisture assessment, interferometric synthetic aperture radar for track

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settlement, are the commonly used methods for inspection. Improvement in inspection effectiveness is expected to reduce carbon dioxide emissions. In recent years, inspection robots have been developed to gradually replace human inspectors in railways. Using minimal time and energy consumption, a railway inspection robot perceives its environment through sensors, to reach its desired destination without human intervention and to collect all data needed [49].

- ***Design of Inspection System:***
  The rail track detection robot system showed the presence of two ultrasonic sensors, a Global System for Mobile (GSM) module, an Arduino microcontroller, two IR sensor arrays, and DC motors [50] in its architecture. The Arduino microcontroller board has digital input/output pins, a crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It connects a computer with a USB cable, supplying power through AC to DC adapter or battery to get it started. An external supply of up to 20 volts is required for the board operation. IR sensor array device has seven infrared sensors that detect black and white colors. After emitting sound, the array performs detection at proper distances. When pressed, the connector provides power, and the right button helps to initialize the array with set threshold values. For detecting the object, an ultrasonic sensor sends out a burst of ultrasound and listens for the echo when it bounces back from an object.
  GSM Communication modem accepts SIM cards to operate over a subscription to a mobile operator. A GSM modem and a computer together enable the GSM module to communicate over the mobile network. DC motors can drive in either direction with the help of a motor driver. It can control two DC motors simultaneously in any direction and can drive small and quite big motors as well. It works on the H-Bridge circuit concept, in which voltage flows in either direction. The proposed robotic system uses seven DC motors to work on the principle that when a current-carrying conductor is placed in a magnetic field it experiences a mechanical force, whose direction is given by Flemings' left-hand rule. For the operation of modules, which are present in the faulty rail track detection system architecture, two inputs namely, the IR sensor array and the ultrasonic sensor are used. The output includes the GSM module and motors.

IV. ADVANTAGES OF INSPECTION ROBOTS

- Inspection robots can significantly reduce the risks faced by human inspectors in hazardous environments.
- They provide more standardized and objective results compared to human inspections, which can be inconsistent.
- The use of robots can lower inspection costs, particularly important in light of an aging workforce in the industry.
- Automation and digitalization of asset management through robots can enhance the efficiency and precision of railway inspections.
- Detailed documentation of the train's condition for subsequent maintenance follow-ups.

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V. INNOVATIONS IN RAILWAY INSPECTION ROBOTIC TECHNOLOGY

- **Visual Inspection Technology:**
  Vision inspection technology in railways encompasses advanced methodologies that leverage computer vision and machine learning to enhance the safety and efficiency [51] of railway maintenance. This technology addresses the limitations of traditional manual inspections by providing automated, real-time analysis of railway components, significantly improving defect detection and monitoring processes. Vision inspection technology significantly enhances rail safety and reduces maintenance costs through automated, accurate defect detection and monitoring. By leveraging advanced computer vision and deep learning techniques, these systems can identify issues that traditional manual inspections often miss, leading to timely interventions and improved safety outcomes. Technologies enable continuous monitoring of rail conditions, allowing for immediate detection of defects and reducing the risk of accidents
- **Ultrasonic Inspection Technology:**
  Ultrasonic rail testing is a full-track inspection solution that uses high-frequency sound waves to inspect materials without damaging them. High-frequency sound waves are sent from the ultrasonic probe into the material being inspected. The sound waves pass through flawless material, but they bounce back in case of flaws. The time echoes return and their strength is recorded and analyzed. The signal from the sound waves creates a 3D visualization of the material. This will help monitor the condition of railway tracks and maintain them in good condition, thus preventing train accidents to a large extent.
- **Ultrasonic Phased-Array Inspection:**
  Phased array ultrasonic testing (PAUT) is a non-destructive testing method that uses ultrasonic imaging to detect material flaws [52]. It uses a probe with multiple ultrasonic transducers that emit and receive ultrasonic waves. By adjusting the timing of the waves, the ultrasonic beam can be focused and steered electronically without moving the probe. Various defects, including cracks, voids, pits, and corrosion can be detected and measured with the help of PAUT. It can also be used to measure the thickness of materials and coatings and to assess the quality of welds and rivets. This method offers real-time analysis and detailed imaging, which can improve inspection efficiency and reliability.
- **Ultrasonic Guided Wave Inspection:**
  Ultrasonic-guided wave inspection [53] is a nondestructive technique that uses sound waves to monitor and inspect railway tracks for defects and structural health. It can monitor large areas of a structure from a single location and can be used to inspect inaccessible parts. It helps to determine longitudinal stress in rails, detect internal defects in railheads, and monitor the structural health of railway tracks.
- ***Electromagnetic Acoustic Transducer (EMAT) Inspection*:**
  EMAT inspection is a non-destructive testing technique that uses ultrasonic waves to detect flaws, cracks, and residual stresses in electrically conducting metal structures [54]. EMATs are advantageous over conventional piezoelectric transducers because they produce ultrasonic waves in the thin surface of the rails steel, rather than transmitting them through a coupling

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medium like water/oil. This allows for contactless inspection without producing physical contact with the rail. This is accomplished by generating bias magnetic field and employing a set of pulsed wire coils. This technology revealed a high degree of detection and characterization of rail flaws.

- ***Laser ultrasound Technology (LUT)*:**
  LUT is a nondestructive, noncontact method for inspecting materials. In this method, a laser pulse is directed at a sample [55], causing an ultrasonic pulse to propagate through the material. The material acts as a transducer to generate and detect the ultrasonic waves. LUT can measure material properties like density, detect discontinuities like cracks and voids, and determine geometrical properties like thickness. LUT can be operated remotely and is well-suited to harsh environments. LUT has fast scan times and flat frequency response that can be tuned to detect different discontinuity sizes. LUT can generate and detect multiple vibration modes simultaneously.
- ***Eddy Current Inspection Technology*:**
  The eddy current method is an electromagnetic test process based on magnetic induction. An electrical coil system is driven by alternating current acting as a transmitter and detector for material defects [56]. The coil system generates an alternating magnetic field, which causes eddy currents in the metallic test object due to the induction principle. These eddy currents produce a secondary magnetic field that retroacts to the coil. With inhomogeneity in the metallic surface, the secondary magnetic field and the electromagnetic characteristics are changed and these changes can be detected.
- ***Eddy Current Pulsed Thermography (ECPT)*:**
  ECPT is a nondestructive evaluation (NDE) technique used to detect defects in railway tracks. ECPT uses a magnetic field to generate eddy currents in a conductor, which are then captured by a probe [57]. The probe measures the decay rate of the eddy currents and converts the electromagnetic signal into a thickness reading. ECPT can detect and characterize structural degradation, such as defects, fatigue, corrosion, and residual stress. It can also be used to quantify closed cracks in railway tracks. ECPT is well-suited for railway inspection because of the high electrical conductivity, thermal conductivity, and permeability of rails. The technique is applied to detect surface cracks in rails from a moving test car.
- ***Magnetic Flux Leakage (MFL) Inspection Technology*:**
  MFL is a non-destructive testing technique that uses a powerful magnet to detect defects in ferromagnetic materials, such as steel rails. MFL detection is mainly for the damage on the top surface and near the surface of the rail [58]. It first needs to magnetize the tested rail. The design principle of the magnetizer is to make the magnetic force line cut the defect's edge. In an MFL tool, a magnetic detector is placed between the magnet's poles to detect the leakage field. Circumferential MFL is a new implementation that has the potential to detect and quantify axially oriented defects such as cracks, seam weld defects, mechanical damage, and groove corrosion.
- ***Alternating Current Field Measurement (ACFM)*:**
  ACFM [59] is a technique for detecting and measuring surface-breaking metal cracks. ACFM sends an alternating current into the surface of a component, which induces electric currents in the

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sample. If there are no cracks, the electric currents remain undisturbed. If there is a crack, the current flows around the ends and down the face of the crack. ACFM produces fewer false signals than other nondestructive methods (NDT) and immediately sizes and records defects. These inspections are shorter because they require less cleaning.

- ***Magnetic Barkhausen Noise (MBN) Testing***:
  MBN inspection is a non-destructive method for evaluating the surface and subsurface of ferromagnetic materials by an applied magnetic field. It is used to inspect surface characteristics after heat treatments and detect cracks. It uses an alternating current to magnetize a core, which in turn magnetizes the test material, resulting in the domain wall movements [60].
- ***Acoustic Emission Inspection Technology***:
  The acoustic emission inspection method uses the release of ultrasonic stress waves to identify defects in materials. The principle of acoustic emission testing is that the elastic waves sent from the acoustic emission source are transmitted to the material surface via a transmission media. Sensors produce electric signals before they are processed and recorded [61]. This technique can detect a range of damage mechanisms, including fiber breakages, friction, impacts, cracking, delamination, and corrosion, in their early stages before they become significant issues.

VI. RECENT DEVELOPMENTS OF RAILWAY INSPECTION ROBOTS

Several railway inspection robots have been developed, showcasing their potential as alternatives to traditional methods. The Geo-MMS UAV and other self-propelled inspection karts are highlighted for their efficiency in inspecting railway tracks and switches. The JDT track inspection robot accurately detects various track conditions, tested on high-speed railways. These robots are designed for bridge, tunnel, and catenary inspections, indicating a growing trend towards automation in these areas.

6.1) Examples of Robots Developed by Companies:

- **BogieBot** A Climbing Robot in a Cluttered Confined Space of Bogies with Ferrous Metal Surfaces, that can be deployed inside the undercarriage areas of trains and other large vehicles for inspection and maintenance purposes, for the first time. A manipulator or visual sensor is carried on BogieBot's main body. The novel compact design utilizes six identical couple joints and two mechanically switchable magnetic grippers that together, empower multi-modal climbing and manipulation [62].
- **A humanoid robot** was introduced by West Japan Railway Company to handle maintenance tasks on its rail network to address labor shortages and enhance worker safety. The large arms of the 12-meter-high robot are fitted with various tools such as blades and paintbrushes. It operates through a truck-mounted platform that drives on rails, and from the cockpit, the operator controls the robot using cameras and motion-tracking technology [63].
- **Felix** is a mobile robot for the automatic inspection of railway S&C. which was developed by Loccioni Research for Innovation and Rete Ferroviaria Italiana (RFI) to increase railway switches' reliability, guaranteeing railways safety, and solve maintenance planning problems [64].

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- **TrainMate** is an autonomous, safe, practical, modular, efficient, and cost-effective robotic system that delivers the independence and visibility that passengers with disability desire. The platform is also capable of providing side functionalities that are highly demanded by our transit agencies such as public announcement, security and surveillance, crime prevention, passenger escorting, and facility inspection for timely repairs while in idle mode and not providing lift services [65].
- **Boots Off Ballast** (BOB) is a safer and more cost-efficient digital process for railway asset inspection and interaction, based on a lightweight robot system that is capable of railway travel. The system will reduce the need for humans in the dangerous areas of railways and reduce the cost of inspection and light maintenance [66].
- **Distributed Acoustic Sensing** Condition Monitoring: Distributed acoustic sensing offers rapid sensing capabilities over long distances, enabling real-time analysis of large datasets for structural health monitoring [67].

VII. OVERVIEW OF PAST RESEARCH

Trivedi et al. aimed to study the feasibility of using robots in track maintenance and developing a multi-robot autonomous track maintenance system for the high-speed Shinkansen line to perform two specific tasks; loosening bolts after detection and assembling new fasteners automatically [68]. Other attempts were made to address different tasks, such as railroad crossing inspection [69], faulty rail profile detection [70], crack detection [31], etc. Fasteners fix the rails to the sleepers. If fasteners are missing, the stiffness of the track is reduced. A computer vision-based approach, based on wavelet transform (WT) and principal component analysis (PCA), was developed by Mazzeo et al. to detect the absence of fasteners [71] using a camera, which increased detection reliability in comparison to manual inspection. Another computer vision-based missing clip detection technique was developed by Singh et al. using a video camera and an artificial lighting source to eliminate the inconsistent illumination effect in image processing [72].

Marino et al. presented a visual inspection system for railways to determine the presence of fasteners using computer vision and machine learning at a maximum speed of 200 km/h [73]. Another machine learning-based fastener inspection method was proposed by Zhang et al., to reduce the impact of light, vibration, and obstacles [74]. This proposed method was more reliable in practical conditions as its training dataset was robust. A conceptual hand-pushed cart with computer vision and a machine-learning algorithm was developed for turnout and tie detection [75].

Li et al. proposed another vision-based track component inspection system that could detect multiple components using 4 cameras with geo-location from onboard GPS [30]. Wang et al. also used machine learning and computer vision for missing fastener detection with a high-speed charge-coupled device camera [76]. Gibert et al. proposed a machine-learning approach based on histograms of oriented gradients and trained the model using images collected from the comprehensive track inspection vehicle (CTIV). The model could detect missing clips and classify existing clips into categories [51].

MBN testing techniques can detect not only the magnitude of stresses but also the fatigue life of ferromagnetic materials and microstructures [77]. Acoustic emission techniques could detect dynamic rail cracks [78] and Eddy currents testing (ECT) is commonly used to inspect conductive materials for

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detecting surface and subsurface defects [56]. Wu et al. (2023) offered a comprehensive solution that covers both track components and adjacent areas through UAV imagery marking a further step towards enhancing inspection efficiency [79].

Song et al. (2023), developed a GAN-based framework for analyzing pedestrian behavior without the need of location-specific adjustments, enhancing its applicability across various settings [80]. Rail surface defect (RSD) is another major concern for railway safety, contributing to a significant portion of rough vehicle-track interaction and even derailments. To address RSD, Guo et al. (2021), quantified RSD areas automatically. This approach, along with other advancements such as the implementation of advanced models like RailFormer [81]. Guo et al. (2024) demonstrated a significant improvement in detecting RSDs at various scales [82]. The pioneering work by Jiang et al. (2022) introduced a deep-learning framework capable of detecting unusual pedestrian behaviors through video analysis and skeleton tracking [83]. While these advancements present promising solutions, challenges remain in their reliability and integration into existing systems, necessitating further research and development to realize their potential in railway safety and efficiency fully.

VIII. CONCLUSION

Robotic applications in railways are transforming maintenance practices, enhancing safety, and improving operational efficiency. Robots have good potential to improve railway track maintenance, inspection, and repair performances because of the improved sensor and computational capabilities. The integration of robotics is crucial for addressing the challenges of modern railway systems as evidenced by the development of diversified autonomous robots for maintenance and inspection tasks significantly reducing the time and cost associated with manual inspections. Robotic railway vehicles designed for multi-sensing and profiling can autonomously collect data on safety parameters, aiding in fault management and infrastructure resilience.

Successful deployment of robotics in railways requires addressing human factors, including trust and acceptance among workers, as well as adapting organizational structures to integrate robotic systems effectively. The growing interest in robotic systems is driven by the need for cost-effective and reliable maintenance solutions in a competitive environment. While the benefits of robotic applications in railways are substantial, challenges remain in terms of public acceptance and the need for a cultural shift within organizations to fully embrace these technologies.

This will help in the maintenance and monitoring of the condition of railway tracks without any errors and thereby maintaining the tracks in good condition, preventing train accidents to a very large extent Railway track crack detection autonomous vehicle is designed in such a way that it detects the cracks or deformities on the track which when rectified in time will reduce train accidents. The addition of solar panels is an added advantage, which also helps conserve the power resource. This will help in the maintenance and monitoring of the condition of railway tracks without any errors and thereby maintaining the tracks in good condition, preventing train accidents to a very large extent Railway track crack detection autonomous vehicle is designed in such a way that it detects the cracks or deformities on the track which when rectified in time will reduce train accidents.

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