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Review

A Review on the Prospects of Mobile Manipulators for Smart Maintenance of Railway Track

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Abstract: Inspection and repair interventions play vital roles in the asset management of railways. Autonomous mobile manipulators possess considerable potential to replace humans in many hazardous railway track maintenance tasks with high efficiency. This paper investigates the prospects of the use of mobile manipulators in track maintenance tasks. The current state of railway track inspection and repair technologies is initially reviewed, revealing that very few mobile manipulators are in the railways. Of note, the technologies are analytically scrutinized to ascertain advantages, unique capabilities, and potential use in the deployment of mobile manipulators for inspection and repair tasks across various industries. Most mobile manipulators in maintenance use ground robots, while other applications use aerial, underwater, or space robots. Power transmission lines, the nuclear industry, and space are the most extensive application areas. Clearly, the railways infrastructure managers can benefit from the adaptation of best practices from these diversified designs and their broad deployment, leading to enhanced human safety and optimized asset digitalization. A case study is presented to show the potential use of mobile manipulators in railway track maintenance tasks. Moreover, the benefits of the mobile manipulator are discussed based on previous research. Finally, challenges and requirements are reviewed to provide insights into future research.

Keywords: mobile manipulator; railway track maintenance; robotic maintenance technology; autonomous systems

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1. Introduction

Railway infrastructure networks are among the most important transportation assets and have served the worldwide growth of industry and civilization for hundreds of years. The notion of asset management within a railway infrastructure context is developing to fulfill the needs of both users and owners for sustainable railway management. The railway infrastructure network can include vast numbers of tracks, bridges, tunnels, stations, trackside markers, overhead electric lines, etc. For example, the British railway network has approximately 20,000 miles of track, 30,000 bridges, and 2500 stations, some of which are almost 200 years old, as well as a plethora of signaling, electrification, and crossing systems that are geographically spread out [1]. Railway infrastructure operators are responsible for planning, controlling, and maintaining all asset-related hardware operations and maintenance. Railway track inspection and repair are fundamental requirements for ensuring safe transit and long-term growth [2]. The quality of the railway track also impacts both the reliability of pantograph–catenary interactions [3] and ride comforts [4]. Railways maintenance or repair tasks have primarily relied on human interventions for decades. Although many modern tools and machines have been introduced recently, human involvement is still essential. Currently, over 40,000 people are working in Britain to maintain the appropriate operation of infrastructures (e.g., signals and power supplies) and assets (e.g., tracks and bridges) [5].

Train services are considered among the safer, greener, and most reliable public transport systems. Construction of new railway infrastructure is time-consuming and costly. For example, the construction cost of the High Speed 2 (HS2) railway line of 330 miles may rise to more than GBP 100 billion [6]. Moreover, the construction cost per km of railway track is 12.5 to 30 times higher than per km per lane road [7]. Modern asset management systems ensure the life cycle of well-maintained railway assets, producing environmental and financial benefits by balancing maintenance, renewal, and enhancement activities [8]. Thus, governments and stakeholders strive to maximize the availability of railway networks by introducing enhanced asset management systems, including AI-based robotics [2]. As a result, there is avid demand for flexible and autonomous robots that can perform maintenance tasks effectively and which possess remote, reliable communication and sensing technology. Maintaining adequate track quality ensures a safe and comfortable journey for passengers and timely freight delivery. Railway maintenance tasks demand dexterity, quality, versatility, and speed. Some tasks can be repetitive and need to be performed out of hours or in adverse weather conditions.

Smart maintenance is a concept which could revolutionize the available maintenance systems across different industries. It uses IoT, faster computing, sensor technologies, etc., to digitalize the maintenance process. Moreover, with the advancement of robotic technologies, it will include different solutions with which to optimize the existing maintenance tasks in order to minimize the whole life cycle cost and ensure the optimum usage of the assets. When used in railway inspection and maintenance tasks, robotics technologies will enable smart maintenance. During the inspection process, robotic technologies should detect any defects if provided with enough information, such as defect type, size and location, for the actuation tasks. In the maintenance tasks, robots should perform the repair tasks with or without human involvement based on the information from the inspection.

A manipulator or robotic arm is a multipurpose mechanical device which is programmable for various tasks. Manipulators are articulated kinematic chains, linked with one another with flexible joints [9] and programmed to perform some motions in a designated workspace. Based on the requirements and design, manipulators have multiple joints known as "Degrees-of-Freedom" or DoFs. The use of industrial manipulators can be dated back to 1954 when General Motors began using Unimate, a hydraulic arm, to lift heavy loads [10].

A mobile manipulator combines an industrial or robotic arm with a mobile platform. In the literature, mobile manipulators can be dated back to 1992, when the mobile robot lab at LAAS developed "Hilare 2bis" [11], shown in Figure 1. A mobile manipulation system benefits from both the manipulator's dexterity and the mobile platform's mobility. Because of these advantages, mobile manipulators can be used across industries for various challenging tasks to reduce the risks to human workers, increase efficiency, and maximize financial benefits.

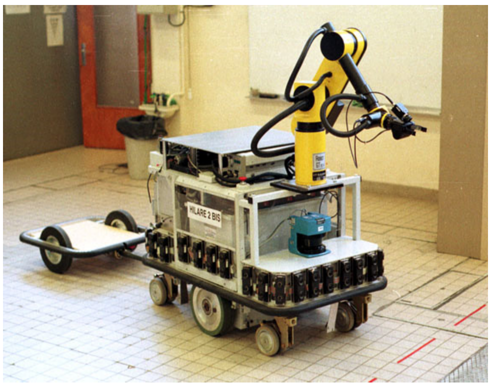


Figure 1. Upgraded Hilare 2bis from LAAS with 6-wheel robot and a manipulator [11].

Only 28% of track inspection and repairs involve robotic and autonomous system (RAS) techniques, even though railway track faults cause 17% of train delays and 33.1% of passenger train cancellations [5]. A mobile manipulator is a particular type of robot with a mobile base and a robotic arm. With the help of multiple sensors and computational algorithms, mobile manipulators can perform various tasks, such as cleaning a nuclear reactor [12] or inspecting a railway tunnel [13]. With the recent advancement in sensor and computation technologies, the mobile manipulator has revealed many promising use cases in maintenance technologies across various industries [14–17]. These promising results substantiated an increment in productivity, efficiency, and safety for the human operators [18,19]. This research aims to discuss the prospects of adopting mobile manipulators for railway track inspection and repair tasks, as observed in other industries.

This paper will begin by reviewing the current state of the art maintenance machines for railway track inspection and repair tasks. Afterward, robotic technologies for railway track inspection and repair tasks will be discussed in Section 3. Section 4 reviews the definition, classification, and usage of the mobile manipulators found across other industries during the last 20 years for inspection and repair. Next, a mobile manipulator made of a commercially available unmanned ground vehicle (UGV) and an industrial manipulator for railway track inspection and repair tasks will be introduced in Section 5. The benefits of adopting mobile manipulators for track inspection and repair will be presented in Section 6. Then, Section 7 will discuss the challenges and requirements of the use of a mobile manipulator for track maintenance. Finally, Section 8 will present our conclusions.

2. Current Technologies for Railway Track Maintenance

Railway asset maintenance systems range in size from carriages to hand-held devices. These can be stationary or movable. Fixed maintenance assets are usually positioned along the railway infrastructure network at crucial locations. They record information, such as passing train information, and monitor track components. On the other hand, movable devices are designed to run along the railway track in order to perform specific tasks at a certain speed. In some cases, the movable platform can be airborne, such as an unmanned aerial vehicle (UAV) or a helicopter. Table 1 shows the advantages and disadvantages of several devices for use in railway track maintenance. These devices are equipped with various types of sensors for navigation, monitoring, surveying, and inspection. Common inspection methods used so far include visual inspection, digital image correlation (DIC) [20] and thermal cameras [21] for rail component inspection, laser vision sensors [22] for rail wear and track geometry assessments, laser distance meters [23] for rail corrugation, ultrasonic sensors [24] for surface and internal defect determination, light detection and ranging (LiDAR) [25] for track clearance and vegetation detection, eddy currents [26] for internal rail defect inspection, electromagnetic acoustic transducers (EMAT) [27] for surface and internal defect analysis, ground-penetrating radar (GPR) [28] for ballast fouling and moisture assessment, interferometric synthetic aperture radar (InSAR) [29] for track settlement, etc.

Table 1. Type of track maintenance devices and systems used in railway.

Type	Main Tasks	Advantages	Disadvantages
Push trolley	Track inspection, carry material	Smaller in size, easy to transport	Slow speed, human-operated
Road-Rail Vehicle (RRV)	Repair, transport material, inspection	High speed, easy to transport	Costly, human-operated
Specialist trains	Repair and inspection of track	High speed and payload, multiple measurements	Very costly to operate
Train-borne system	Track inspection, track repair	Moderate cost, easy to install	Limited validation

2.1. Push-Trolley

Inspection trolleys used in railway maintenance are capable of on-track navigation because of their rail-shaped wheels. The size of the trolley used depends on the payload requirements. They can be used for different purposes, whether carrying materials for maintenance or carrying people. Depending on their size and design, these simple trolleys can carry up to 60 kg of material [30].

Inspection trolleys are typically trimmed to reduce mass and increase sensor payload capability. They are ideal for use in ultrasonic inspection systems because of their slower operating speed. Moreover, they are widely used for track geometry validation on short track lengths [31]. GPS capability provides the defect location [32]. However, as humans typically push these devices, their maximum speed is limited, and they are only suitable for use over short distances. Figure 2 is an example of a track geometry inspection trolley. The disadvantage of using a push-trolley for smart maintenance is that it can only carry a limited payload before it becomes cumbersome. Moreover, it lacks the capability for payload deployment.

(a) (b)

Figure 2. Track geometry inspection trolley: (**a**) track geometry validation trolley [31]; (**b**) track geometry inspection trolley with GPS [32].

2.2. Road–Rail Vehicle

Road–rail vehicles (RRV) are a unique type of maintenance equipment with both pneumatic and retractable rail wheels, as shown in Figure 3. These multipurpose maintenance machines can be used for transporting material or persons or as an inspection device with a proper sensor attachment. The Rail Industry Safety and Standards Board (RISSB) classifies RRVs into three main categories based on power transmission mechanism: self-powered, friction drive and direct drive RRVs [33]. Moreover, braking power, safety procedures during road–rail conversion and seating arrangements are also standardized by the Rail Safety and Standard Board (RSSB) to reduce accidents and maintain safety [34].

(a) (b)

Figure 3. Road–rail vehicles for track maintenance: (**a**) Unimog road rail vehicle for overhead line maintenance [35]; (**b**) mobile asset management RRV [34].

High-load-carrying RRVs are usually used for repair or construction tasks, while smaller RRVs are used for inspection. For example, Unimog, shown in Figure 3a, from Mercedes-Benz [35] can tow up to 1000 t, and has served the railway industry for a long time. A range of instruments can be installed in to the RRVs to convert them into a mobile asset management platform for surveying and inspecting the railway environment to assess the condition of road–rail access points, vegetation, and track infrastructure. Figure 3b shows a mobile asset management platform which can provide LiDAR point cloud and images at a maximum speed of 20 mph [36]. RRVs are much faster than manual inspection trolleys and can carry more weight, as demonstrated by Runner Wizard V2R [37]. The localization of defects and payload deployment are still challenging and control of RRVs remains in the hand of a human operator.

2.3. Train-Borne System

Train-borne systems are convenient for assessing the geometrical or structural properties of railways or for performing remote condition monitoring. These can be adapted to train vehicles and do not need separate power sources. They are economically viable and can be more efficient than the conventional track inspection method [38]. For example, machines with vision have been used to develop a train-borne track condition monitoring system based on computer vision and condition monitoring sensors for preventive maintenance [39]. With easy-to-fit hardware, this system is capable of millimeter-level accuracy and real-time data communications and processing software. Another example of a train-borne system is the RILA system from Furgo [40]. This is a remote train-mounted system combining laser scanners, computer vision, and GPS to perform unmanned remote track surveys. These systems provide significant advantages for inspection as they are easy to install on a running passenger or a freight train. However, the lack of actuation capability is the most significant disadvantage of these systems.

2.4. Specialist Train

The inspection and monitoring of vast railway networks require faster inspection methods and specialist trains. Equipped with a variety of sensors, these trains can finish inspection tasks quickly and carry repair crews and materials. The new measurement train (NMT) [41] and mobile maintenance train (MMT) [42] are two state-of-the-art specialist trains, used in the UK for track inspection and repair, as shown in Figure 4.

(a) (b)

Figure 4. Specially designed train in the UK for railway maintenance: (**a**) new measurement train (NMT) [41]; (**b**) mobile maintenance train (MMT) [42].

NMT, shown in Figure 4a, is fitted with multiple cameras, laser sensors, transducers, and accelerometers [41]. Plain line pattern recognition (PLPR) methods [43] can detect anomalies with the camera at a top speed of 125 mph, while the transducers and accelerometers can record the track geometry. This model generates and records almost 10 terabytes of data on an onboard computer for every 440 miles. On the other hand, MMT, shown in Figure 4b, is a specially designed and equipped train for track maintenance tasks and has been described as a “workshop on wheels,” providing a workplace which is from the sun, rain, and trains in operation [42]. Based on their design, attached sensors, and actuation systems, specialist trains can perform inspections at a higher speed or can perform some repair tasks. However, these specialist trains require human involvement, are costlier to run, and reduce track possession while in operation.

3. Robotic Technologies Used in Railway Track Inspection and Maintenance

Due to their efficiency and safety reasons, robotic technologies are being gradually adopted by the railway industry [13]. Though railway track is one of the most critical infrastructures in railway, most RASs are developed for rolling stock maintenance. This review will report on the state-of-the-art robotic inspection technologies for railway tracks, tunnels, and bridges to show the trend of past research and the future need for research into robotic maintenance technologies for railway tracks.

3.1. Robotic Inspection Technologies in Railway

3.1.1. Track Inspection

Railway track constantly degrades with use. It is subject to the enormous stresses of the lateral and longitudinal forces from trains [44]. Environmental conditions such as heavy rain, extreme cold, snow, scorching heat, etc., accelerate degradation. The first significant study on the use of robotic technology for track maintenance was carried out by Trivedi et al. The project, SysTem for Autonomous Railway TRACK operations (STAR-TRACK), aimed to studying 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 [45]. Other attempts have been made to address different tasks, such as railroad crossing inspection [46], faulty rail profile detection [47], crack detection [48], etc. Table 2 shows a summary of different track inspection robots.

Table 2. Track inspection robots.

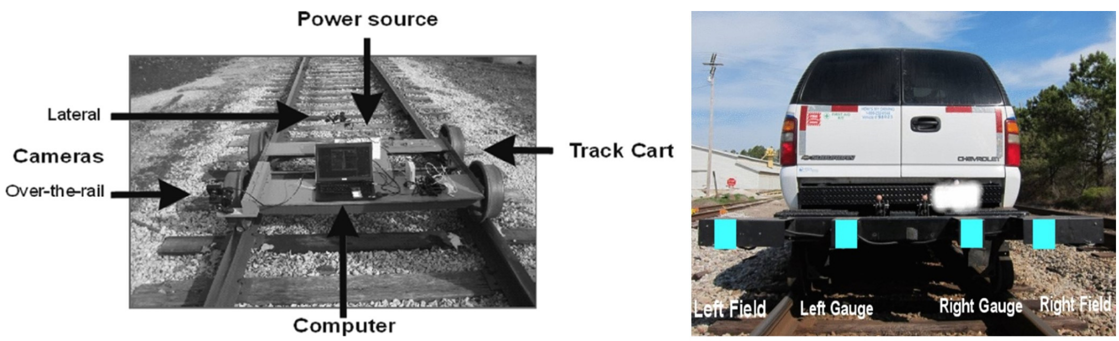
Type	Main Function	Sensing Method	Key Technology and Contribution
STAR-TRACK [45]	Fastener maintenance	Monocular camera	Multi-robot autonomous track maintenance
Train-borne system [49]	Fastener inspection	TV camera	Neural classifier for fastener detection
Train-borne system [50]	Fastener detection	Video camera	Artificial lighting source to reduce ambiance noise
Visual inspection system for railway (VISyR) [51]	Fastener detection	Camera	Computer vision and machine learning, a maximum speed of 200 km/h
Train-borne system [52]	Fastener detection	Camera	Machine learning, structured lighting condition
Manual trolley [53]	Turn out and tie detection	Multiple cameras	Slow speed, a machine learning algorithm
RRV [54]	Track inspection	Four cameras, GPS	Defect location based on GPS
Train-borne system [55]	Fastener detection	CCD camera, GPS	Machine learning for detection and GPS for location information
Comprehensive track inspection vehicle (CTIV) [56]	Fastener detection	Camera	Fastener quality based on image and machine learning algorithm
Modified truck with sensor [46]	Railroad crossing inspection	Camera, LiDAR	Pattern recognition, 3D point cloud using support vector machine (SVM)
Diagnostic analysis for railways and trams (DART) [57]	Track geometry	Track measurement	Computer-assisted diagnostic tool
Hand-pushed inspection device [47]	Faulty rail profile detection	Multiple laser camera	3D modeling, deep learning model for fault detection

Table 2. *Cont.*

Type	Main Function	Sensing Method	Key Technology and Contribution
Railpod [58]	Track inspection	Customizable based on requirements	Easy to transport, both rail and pneumatic wheel
Robot trolley with sensors [59]	Fatigue cracks on track	Alternating current field measurement (ACFM)	Automatic crack detection robot
AutoScan [48]	Crack detection on track	Electromagnetic acoustic transducer (EMAT)	Manipulator for inspection
RIIS1005 [22]	Multiple track defects	Camera, LiDAR	Easy-to-assemble and -disassemble, pattern recognition, deep learning
Felix [60]	Switches and crossings (S&C)	laser	Artificial vision system, wireless data transfer

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 [49] using a camera, which increased detection reliability than 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 [50]. Marino et al. presented a visual inspection system for railways (VISyR) to determine the presence of fasteners using computer vision and machine learning at a maximum speed of 200 km/h [51]. Another machine learning-based fastener inspection method was proposed by Zhang et al., who combined unstructured and structured lighting conditions to reduce the impact of light, vibration, and obstacles [52]. 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 detection and tie detection [53], as shown in Figure 5a. 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, as shown in Figure 5b [54]. Wang et al. also used machine learning and computer vision for missing fastener detection with a high-speed charge-coupled device (CCD) camera [55]. Gibert et al. proposed a machine learning approach based on histograms of oriented gradients (HOG) and trained the model using images collected from the comprehensive track inspection vehicle (CTIV), which could detect missing clips and classify existing clips into different categories [56].



(a) (b)

Figure 5. Track inspection with multiple cameras: (**a**) inspection trolley [53]; (**b**) modified RRV [54].

Track geometry parameters describe the quality of the track and issues that might need repair interventions. The diagnostic analysis of railways and trams (DART) was able to point out the weak location of railway tracks by calculating and measuring multiple geometrical components using a laser scanner [57]. Later, those degraded or deteriorated track locations for potential future defects were further inspected by a human. Using multiple laser cameras, Santur et al. created 3D modeling of the rail track in order to train it and thus identify defects [47].

In recent years, multiple state-of-the-art robotic solutions have been developed for track inspection, as shown in Figure 6, which are easy to transport and reduce human involvement. Railpod, shown in Figure 6a, is an inspection platform that can perform autonomous navigation along the track or can be controlled by remote operation. Because of having both the pneumatic and rail wheels, it can be easily transported along the road [58]. Rowshandel et al. proposed a system consisting of a commercially available alternating current field measurement (ACFM) sensor attached to a trolley and a robot for detecting rolling contact fatigue cracks in rails [59], as shown in Figure 6b.

(a) (b) (c) (d) (e)

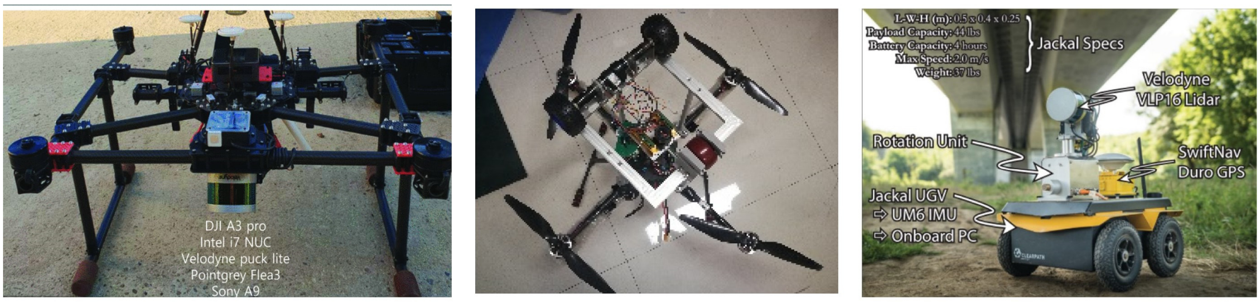
Figure 6. Autonomous track and S&C inspection robot: (**a**) Railpod [58]; (**b**) robot with ACFM sensor [59]; (**c**) AutoScan [48]; (**d**) RII1005 [22]; (**e**) Felix [60].

AutoScan, a project from Horizon 2020, is another example of an autonomous robotic inspection platform with a manipulator for close inspection, shown in Figure 6c. Initially, rolling contact fatigue (RCF) or electromagnetic acoustic transducer (EMAT) sensors are used to find the defect [48]. Then, the operator can use the manipulator to perform further inspection by standing on the side of the rail. RIIS1005 is another intelligent track inspection robot developed by Shenhao Technology, as shown in Figure 6d [22]. The combination of deep learning, pattern recognition, and feature-matching algorithms can detect multiple defects on rail surfaces, fasteners, ties, etc. Finally, Felix, shown in Figure 6e, an automated inspection kart developed by Loccioni, was designed to inspect the switches and crossings (S&C) and track with a maximum operational speed of 5 km/h [60].

3.1.2. Tunnel and Bridge Inspection

Tunnels and bridges are essential components of the infrastructure of the railway network. The inspection of bridges poses fatal risks for the operator from ergonomics and workplace perspectives. Tunnels are usually dark and enclosed, lacking a cellular signal or GPS. Apart from the track inspection in the bridge and tunnel, a particular inspection method is required to inspect structural integrity.

An unmanned aerial vehicle (UAV) can navigate in remote places both with and without the help of a human. Jung et al. proposed a framework for autonomous bridge inspection using a UAV equipped with LiDAR, GPS, IMU, and a camera [61], as shown in Figure 7a. Initially, a map of the test area was created with the help of a human operator, and then the UAV localized and navigated between different waypoints on a predefined map and acquired inspection data which were processed later. Wang et al. also demonstrated automatic data acquisition for bridge bottom inspection using a tethered UAV [62], which is shown in Figure 7b. Phillips et al. developed an autonomous bridge bottom inspection robot with an unmanned ground vehicle (UGV) [63], as shown in Figure 7c.

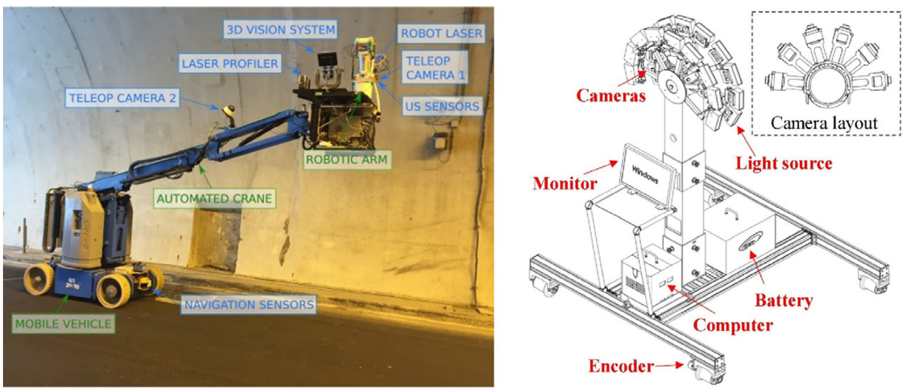


(a) (b) (c)

Figure 7. Bridge inspection robot: (**a**) UAV with multiple sensors [61]; (**b**) UAV for bridge bottom inspection [62]; (**c**) UGV for bridge bottom inspection [63].

Liu et al. designed a prototype of a steel bridge inspection robot, a combination of a rail kart and a manipulator, to discover research challenges [64]. Next, Rui Wang and Youhei Kawamura designed and experimented with a robot with a magnetic wheel for steel bridge inspection. Magnetic wheels provide two advantages: they can climb vertical steel structures and create magnetic fields for sensing [65]. A specially designed robotic system with a guide rail was proposed, which came with a user interface for controlling it from a long distance [66].

Cracks are common in tunnel walls. Zhang et al. presented tunnel wall surface crack detection and classification techniques based on a camera [67]. A semi-supervised computer vision-based robotic system, named ROBO-SPECT, with multiple degree-of-freedom was designed by Menendez et al. for use on a road tunnel [13]. As shown in Figure 8a, with the help of a robotic arm, the robot was able to inspect the crack on the surface wall with an ultrasonic sensor. Huang et al. used deep learning-based semantic segmentation of images to detect cracks on the surface [68]. Moving tunnel inspection (MTI-200a), shown in Figure 8b, was used to acquire data which were later analyzed using a deep learning algorithm.



(a) (b)

Figure 8. Tunnel inspection robot: (**a**) ROBO-SPECT [11]; (**b**) MTI-200a tunnel inspection robot [68].

3.2. Robotic Repair Technology in Railway

Inspections are important in railway asset management to verify the integrity of assets and to prevent catastrophic failures. For example, in the UK, once a defect is detected on the track, details of the defect are recorded in track geometry reports (TGR). Based on the standards of Network Rail Limited (NR-L2-TRK-001-MOD11), infrastructure maintenance engineers (IMEs) and track maintenance engineers (TME) categorize the defects as immediate action-level (IAL), intervention-level (IL), and alert-level (AL) faults [69]. Both IAL and IL defects require repair without delay, while AL defects can be scheduled. Repair tasks in railways vary, including bolt or clip removing or fastening, grinding rail surface, welding, removing obstacles, demolishing trackside vegetation, fixing overhead electric lines, cleaning snow or leaf from the track, cleaning rolling stock, repairing rolling stock, etc. Most repairs involve humans and specially designed tools and machines. Moreover, adverse weather conditions and out-of-hours work can create hazardous conditions. Some tasks are physically demanding, involving heavy loads that result in the fatiguing of railway workers, posing a risk to their health and safety. Although robots are used in many inspection tasks around the railway network, they are rarely used in any repair task. This section will summarize all the repair robot-related literature, despite focusing only on the track. Even after scrutinizing the literature rigorously, very few examples of repair robots have been found; those discovered are mostly used in cleaning tasks and are related to the repair task of rolling stock.

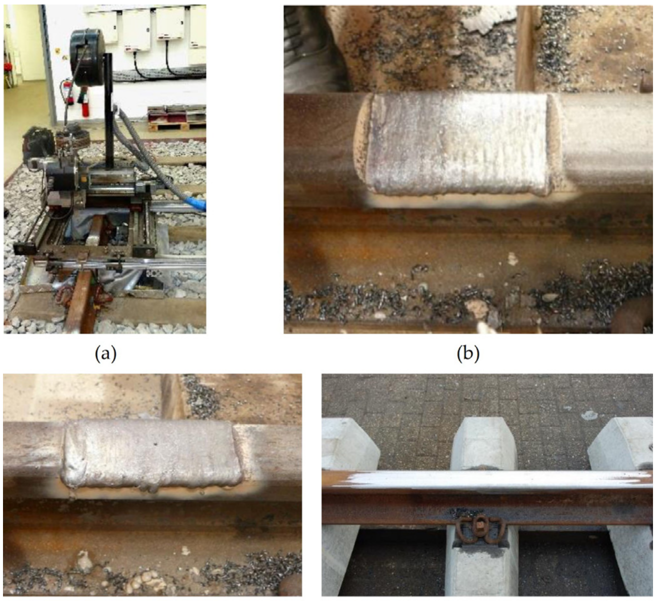
The first attempt to determine the usability of robots in repair tasks was carried out in 1987. After considering 24 technically viable processes in locomotive rebuilding, the researchers concluded that most of the processes were neither economically beneficial nor productive [70]. Just 2 years later, carrying out a separate study in Toronto Subway, Wiercienski and Leek assessed that robots are economically and technologically advantageous for cleaning rolling stock [71].

Four types of cleaning robots were introduced by the East Japan Railway to tackle the problem posed by the lack of cleaning staff. Among the 4 types of self-propelled cleaning robots, 2 types were for stations, and 2 types were for rolling stock, including dust-collector or sweeper types and floor cleaning or scrubber types [72]. Those robots were equipped with ultrasonic sensors and laser sensors for navigation and obstacle avoidance. Xu et al. designed and demonstrated a self-traction model for cleaning the vehicles used for urban mass transit in China. The robot was designed with a mobile platform and a manipulator to save energy and water. Apart from the path planning and control algorithm, the researchers also developed an efficient energy and water management algorithm [73]. Tomiyama et al. discussed the requirements and conceptual design of a rolling stock front cleaning robot [74], and a prototype was built to analyze the cleaning time and force applied at the cleaning head [75].

Apart from cleaning, robots are also used for cutting, welding, grinding, or material handling. Vale, a mining company in Brazil, developed a robot to repair the rail cars used for the mining operation. As shown in Figure 9, the system had multiple manipulators capable of cutting and welding carbon steel [76]. The wheelset of rolling stock, a combination of 2 wheels with a shaft, is very heavy and requires expertise for repair. NSH USA, formerly known as the SIMMONS Machine Tool Corporation, utilized a robot and overhead cranes to altogether remove the human involvement in transporting wheel sets in different workshop locations [77].

Figure 9. Robot used for repairing rail cars in mining operations [76].

A novel technology has been developed in Britain for in situ rail defect repair which is both cost-effective and semi-automated. The discrete defect repair (DDR) process removes the defective part of the rail head and then repairs the defective rail using semi-automatic arc welding [78]. Finally, a milling tool was used in grinding the rail profile, and quality has been ensured with an automatic inspection process. Figure 10a shows the railhead repair machine, while Figure 10b–d show the intermediate process of DDR technology, respectively.



(a) (b) (c) (d)

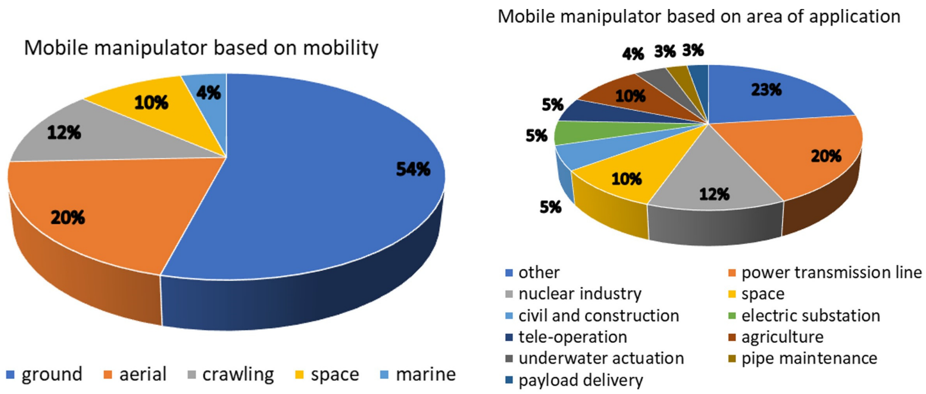
Figure 10. DDR technology [78]: (**a**) the machine; (**b**) cavity created after removing defected rail head; (**c**) the rail head after arc welding; (**d**) final repaired railhead.

4. Robotic Maintenance Technology in Other Industries

Mobile manipulators represent a remarkable area of research for robotics, control, and automation enthusiasts. A simple search in an indexing website will provide thousands of research articles in several research areas, such as control of strategy, design, simulation, safety, cost analysis, motion planning, navigation, perception capability, etc. To match the objectives of this specific research, the search criteria have been narrowed down to "mobile manipulator" and "maintenance". After scrutinizing the search results, 74 pieces of research have been selected which discuss the application of mobile manipulators, specifically for inspection and repair tasks, in various fields for the last 20 years, namely from 2002 to 2022. Furthermore, after reviewing the selected literature, mobile manipulators have been classified based on mobility features and application area.

4.1. Overview of Mobile Manipulator Based on Mobility and Applicability

Initially, the concept of a mobile manipulator started with attaching a manipulator with a wheeled robot. However, in many cases, the navigation capability of mobile ground manipulators is limited. Therefore, instead of using an unmanned ground vehicle (UGV), the use of an unmanned aerial vehicle (UAV) can extend the navigation capability of a mobile manipulator at any height and traverse terrain. Moreover, the mobile manipulator can operate underwater with proper design and fabrication. Apart from in the ground-, air-, or water-based applications, mobility features are required for mobile manipulators used in space or along overhead high-voltage power transmission lines. Based on the mobility features, the mobile manipulator can be divided into several categories: ground, aerial, marine, space and crawling. After analyzing all the selected mobile manipulator-related studies for this research, they have been divided into multiple categories based on their mobility features, as shown in Figure 11a. More than half of the mobile manipulators, 54%, were based on a ground vehicle. In comparison, 20% and 12% had aerial navigation and crawling navigation capability, respectively.



(a) (b)

Figure 11. Classification of the mobile manipulator: (**a**) based on mobility features; (**b**) based on the area of application.

As sensor and instrumentation technology continues to improve, mobile manipulators are becoming more capable of performing many monotonous and repetitive tasks, which might pose a risk to human health and financial penalties. For example, a mobile manipulator can routinely survey and inspect nuclear reactors or perform inspection or repair at an overhead high-voltage power transmission line. Moreover, with the correct configuration, mobile manipulators can perform inspection and repair tasks inside and outside a pipe or clean a window, wind turbine, cellular tower, etc. The selected publications were divided into several categories, as shown in Figure 11b, on the basis of their area of application.

Among the selected studies, the mobile manipulator's highest percentage (20%) was used for inspection and repair tasks in high-voltage power transmission lines. A notable percentage, 12% of the mobile manipulators, were used to find defects in nuclear reactor vessels or other nuclear power plant infrastructure. Other relevant application fields included space vehicles, surveillance, and repair of civil infrastructure and construction sites, electric substation maintenance, teleoperation, agriculture, etc.

4.2. Mobile Manipulators for Inspection and Repair Tasks

4.2.1. Maintenance in High-Voltage Transmission Line and Substation

High-voltage power transmission lines can be hazardous and unergonomic workspaces for a human operator because of heights and live electricity risks. Mobile manipulators require unique moving mechanisms to navigate along power transmission lines. A semi-autonomous teleoperated mobile manipulator was designed to inspect the aircraft warning spheres of the overhead power transmission lines [79]. A sensor arm was designed to be a mobile manipulator that can move along the transmission line via sliding mechanism and perform inspection using a high-quality camera [80]. A robotic system was designed to inspect and repair the switch in the underground power transmission line, as shown in Figure 12a. The designed models consisted of a vehicle with a five DoFs hydraulic arm holding a six DoFs manipulator, a tool rack and a pneumatic tool changer [81,82].

LineScout, a teleoperated robot with a programmable pan and tilt camera, was proposed for live transmission lines with a rolling wheel for obstacle avoidance [83]. Another live transmission line inspection robot was proposed in [84] with two locomotion strategies to provide obstacle-crossing capability. Obstacles in a power transmission line include compression slices, vibration dampers, spacers, suspension clamps, etc., and the capability of crossing these obstacles is a desirable feature [85]. Simulations of and experiments using a mobile manipulator to adjust the vibration damper in the transmission line were performed in [14]. This robot hung on the line with the arm and moved along the line with the rolling wheel, as shown in Figure 12b.

Apart from inspecting the power transmission line, mobile manipulators can perform various actuation and repair tasks. For example, an autonomous live-line maintenance robot (ALMR), shown in Figure 12c, stripped and clipped wire clips on a 10 kV transmission line [86]. Zhang et al. proposed a mobile manipulator with a creeping mechanism that moved along horizontal and suspended insulator strings via extra-high-voltage (EHV) lines [87].

Apart from the ground, creeping, or crawling, an aerial mobile manipulator can be a feasible option for overhead transmission line maintenance. Aerial robots could easily reach different heights and navigate in the air without a special kinetic or driving mechanism [88,89]. POSITRON, shown in Figure 12d, was a conceptual design and simulation for controlling the aerial mobile manipulator in a GPS-denied environment.

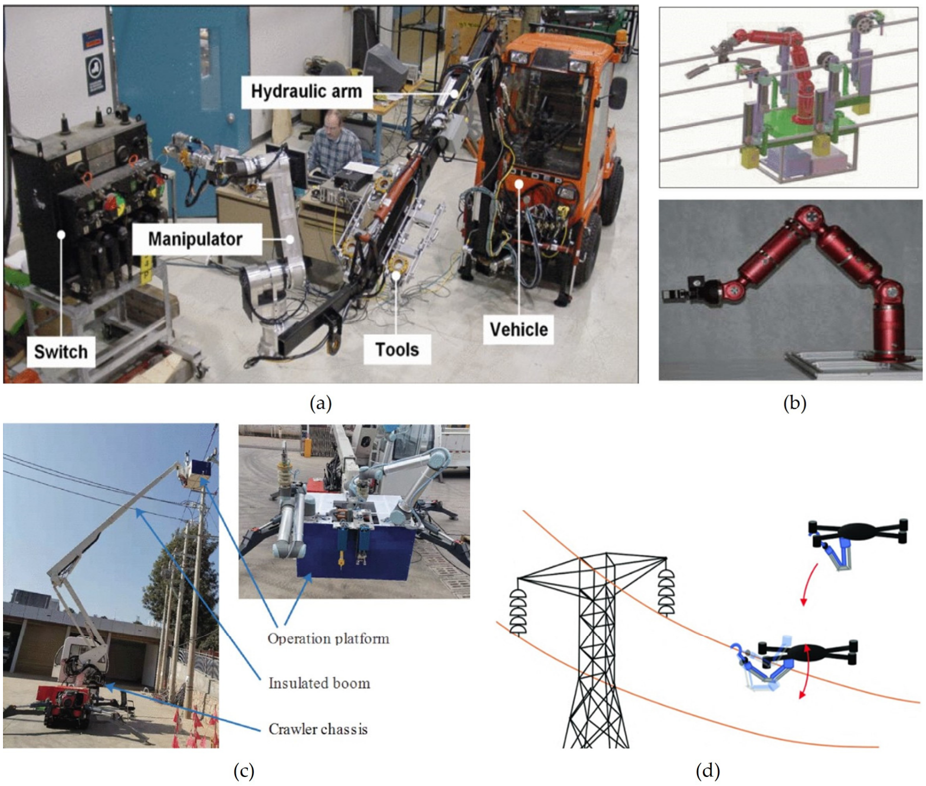


Figure 12. Mobile manipulator for maintenance of power transmission line: (**a**) specially designed mobile manipulator for underground transmission line [79,80]; (**b**) for vibration damper maintenance [12]; (**c**) autonomous live-line maintenance robot (ALMR) [84], (**d**) POSITRON [86,87].

A substation is an important part of electricity transmission. However, most of the equipment in the substation is installed outdoors, which is heavily affected by the environment and weather conditions. Research was carried out by Want et al. to find a suitable robotic technology for performing maintenance both in the indoor and outdoor environment [90]. Zhang et al. designed, fabricated, and experimented with a mobile manipulator to clean and remove ice from the insulator and repair broken wires [91,92].

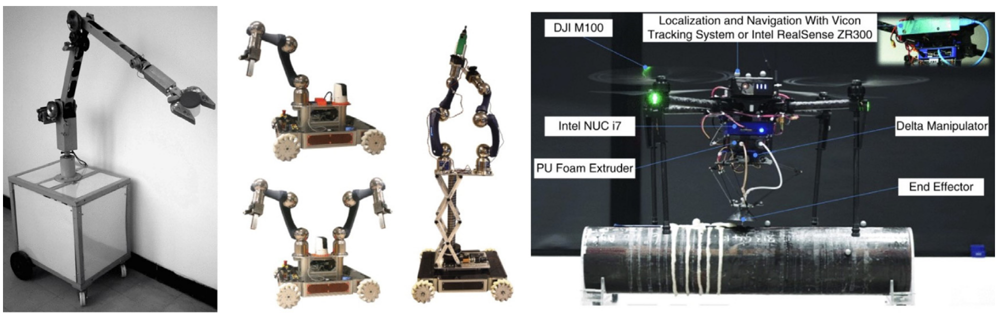
4.2.2. Maintenance in Nuclear Power Plants & Hazardous Places

Nuclear materials, the mining industry, or any container with radioactive material are incredibly hazardous to humans. Short exposure may create cancerous cells, while prolonged exposure will create severe health effects such as skin burns or radiation sickness, leading to death. Although many protective measures are in place to minimize exposure, a remote mobile manipulator is the ultimate form of protection.

A wheeled mobile manipulator, called radiation protection assistant robot (RPAR-I), was designed for surveillance and monitoring of radioactive material [15] with a camera for safe navigation and this was controlled remotely to protect the worker from exposing themselves to radiation. Figure 13a shows 4 DoF manipulators attached to a 2-wheel drive robot base. Instead of teleoperation, many researchers took a dual approach to design the control system, considering both autonomous and remote-controlled modes [93–95]. A semi-autonomous system, CERNbot [94], was designed with few predefined standard operating procedures, as shown in Figure 13b. CERNbot used an autonomous mode for inspection and navigation and an operator-friendly human–machine interface (HMI) for teleoperation. As all these robots had teleoperation capability, these robots were also equipped with computer vision systems and had data transfer capabilities.

The multifunctional inspection and rescue robot (MIRR) was engineered to execute inspection, maintenance, and rescue operations, such as the remote handling (RH) system in the tokamak fusion facility [96]. Equipped with two manipulators, operation robot arm (ORA) and inspection robot arm (IRA), on an omnidirectional mobile vehicle (OMV), MIRR navigated in a narrow space by avoiding multiple obstacles and performing different tasks. Another omnidirectional mobile manipulator was MIRA SPS, which detected and navigated through a narrow passage in a semi-structured environment by leveraging a computer vision strategy [97].

In many cases, manipulation was required underwater [98], in the air [99], or inside a steam generator [100]. For example, the underwater mobile manipulators designed in [98] detected and removed unwanted objects from the bottom of nuclear reactor vessels. In contrast, the lightweight aerial mobile manipulator proposed in [99] was experimented with for accessing hard-to-reach and hazardous locations. The aerial mobile manipulator was equipped with a manipulator and deposited material through a small-scale extruder to repair a crack, as shown in Figure 13c.



(a) (b) (c)

Figure 13. Mobile manipulator in the nuclear industry: (**a**) RPAR-I (radiation protection assistant robot) [13]; (**b**) CERNbot with single- and dual-arm configuration [92]; (**c**) aerial mobile manipulator extruding PU foam to block a crack in surface [97].

4.2.3. Maintenance in Aerospace

The aerospace industry deals with aircraft and spacecraft for space. Workspaces and environments are different in the aerospace industry, which requires motion and navigation capability in the air with or without gravitational force. For example, ground, aerial, or underwater navigation systems are not usable in space because of the lack of gravitational force. Hence, researchers developed free-flying or free-floating mobility features for mobile space manipulators [101,102]. The dual-arm free-flying space robotic system (DAFSAR), shown in Figure 14a, can estimate the target object's pose, self-dock onto the host, and perform robotic maintenance.

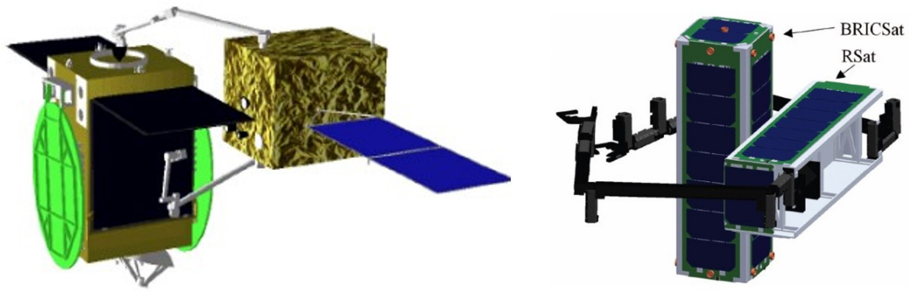


Figure 14. Mobile manipulator in space for maintenance application: (**a**) DAFSAR space mobile manipulator [99,100]; (**b**) AMODS [101].

To increase the repair capability and real-time on-orbit assessment, researchers from the United States Naval Academy designed a mobile manipulator called Autonomous Mobile On-orbit Diagnostic System (AMODS), which was a combination of multiple CubeSat (Cube shaped Satellite) with 7 DoFs manipulator [103]. This robotic system consisted of two satellite systems, one for repair (RSat) and one for navigation (BRICSat), as shown in Figure 14b.

The control system of a space mobile manipulator requires special attention as a free-floating mobile base, disturbance from the host spacecraft, and end-effector motion can affect the pose of the whole robot. A coordinated control system considering the attitude of the base robot and the motion of the dual arm manipulator system was investigated [104]. Alternatively, Dongming et al. discussed an impedance-based control system by designing the end-effector motion as a mass damper-spring system for target grabbing [105]. Another impedance-based control system was investigated for the docking of the robot onto the spacecraft [106]. Teleoperation or virtual reality (VR) controllers were used for control system for space mobile manipulators [107,108].

4.2.4. Maintenance in Civil and Construction Sites

Civil infrastructures such as buildings, roads, bridges, etc., require scheduled inspection and repair to ensure their asset life, safety, and user comfort. Inspection and repair technology for civil and construction infrastructure requires human involvement. Although robots have been used in civil infrastructure since the early 2000s [16,109,110], they have mostly been used for inspections, but not to perform any repair work. The earliest mobile manipulator with repair capability found in this review was published in 2013. In this work, Liu et al. demonstrated a mobile manipulator for dry friction-based drilling for bridge deck repair tasks [111].

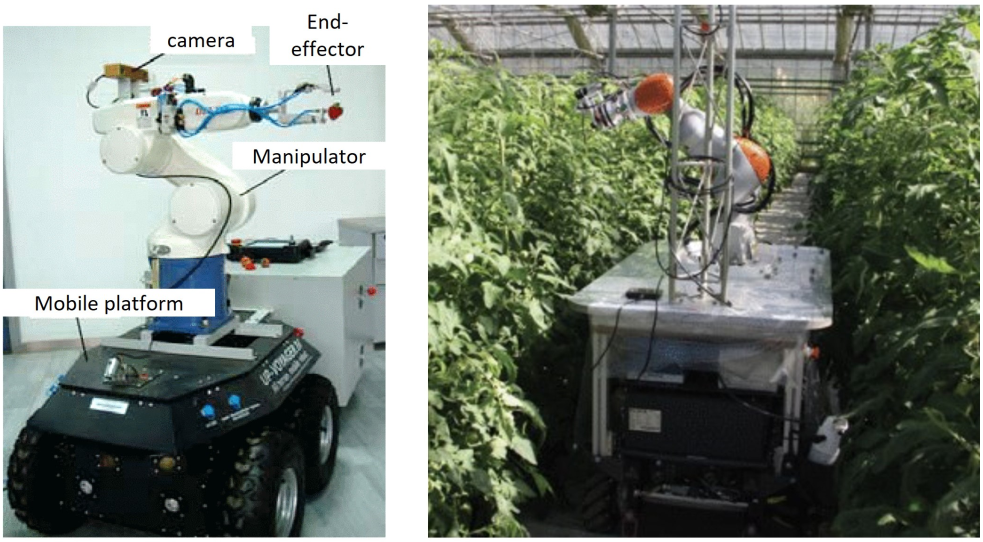
Nguyen et al. designed a civil infrastructure inspection and evaluation with a mobile manipulator with a combination of computer vision and thermal camera technologies for detection, shown in Figure 15 [112]. Apart from a ground-based system, an aerial mobile manipulator can be used for civil infrastructure inspection and repair, as many places are hard-to-reach with a wheeled robot. Therefore, collaborative aerial mobile manipulators were proposed, in which one can detect cracks using artificial intelligence, and the other can localize and repair cracks by depositing material [113]. Usually, commercially available drones and UAVs can only carry a light payload, typically one of less than 1 kg. However, repair work in civil infrastructure regularly requires a larger payload capacity. To solve this issue, research was carried out to design and fabricate an aerial manipulator with a coaxial tri-rotor arrangement capable of carrying a high payload [114].

Figure 15. Proposed mobile manipulator system with multiple sensors [110].

4.2.5. Application of Mobile Manipulator in Agriculture

The world population continues to increase, but cultivatable land and the workforce are decreasing [115]. Food production methods demand exact and efficient robotic solutions. Examples include a dredger robot that can perform maintenance tasks such as removing debris, weeds, and sediments [116].

Mobile manipulators can assist and even replace humans in labor-intensive fruit or vegetable picking. To succeed, they should be able to locate the plant, determine the ripeness of fruits, navigate autonomously, and pick the fruits or vegetables without damaging them [117–120]. As shown in Figure 16a, most of these mobile manipulators are made of ground-based mobile-base robots equipped with a vision system for fruit detection [119].



(a) (b)

Figure 16. Mobile manipulator for agricultural application: (**a**) strawberry picking robot [117]; (**b**) pest detection and spraying robot for a greenhouse [15].

Another complex task conducted by mobile manipulators is detecting weeds and spraying pesticides while navigating the traversal of terrain. Vineet et al. proposed a pesticide-spraying robot with a skid-steering mobile manipulator [121]. Tracked wheels with skid-steering mechanisms were used instead of pneumatic wheels, as tracked wheels improved the navigation capability on deformable terrain. Martin et al. demonstrated a mobile manipulator with a robot operating system (ROS), shown in Figure 16b, fitted with multiple sensors (RGB camera, RGB-D camera, GNSS, IMU, LiDAR, and laser scanner) on a Segway RMP Omni Flex mobile robot [122,123] with mecanum wheels for pest detection and spraying inside a greenhouse [17].

4.2.6. Other Applications of Mobile Manipulators

Mobile manipulation is an issue of particular importance. Industry 4.0 uses modern technologies such as automation, digitalization, cyber–physical systems, and artificial intelligence to increase efficiency and productivity, while Industry 5.0 is planning to push the limit of modern technologies to create a human-centric industrial model with increased human–robot collaboration to increase resilience and sustainability. With dexterity and mobility features, mobile manipulators can help industries to achieve future demands by introducing Industry 5.0. Conceptual designs of mobile manipulators to assist helping humans in the industry surfaced in the research community in early 2000 [124,125]. Various companies offer commercially available mobile manipulator platforms that can be reprogrammed for various use cases [126,127]. As their versatility, accuracy, and environment perception improve alongside collaboration capacity, the areas of application are also expanding. Table 3 illustrates some of the diverse applications of mobile manipulators.

Table 3. Different areas of application for mobile manipulators.

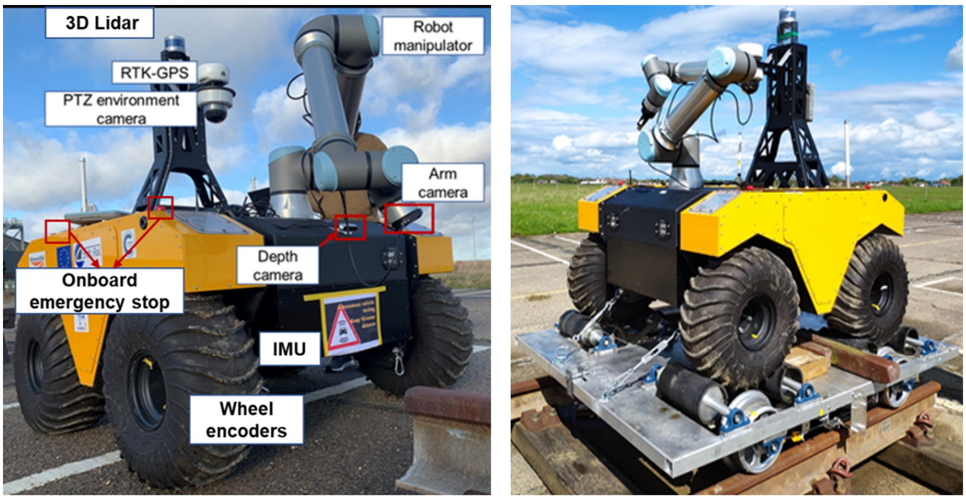
Application	Base Robot	Sensing Method	Key Technology and Contribution
5G tower maintenance [128]	Aerial	Camera	Tower inspection and repair, a study of manipulator stability with wind disturbance
Aerial drilling and screwing [129]	Aerial	Camera	An adaptive robust control system, real-time object detection
Outdoor maintenance in industry [130]	Aerial	LiDAR, stereo camera, GNSS	Multidirectional thrust controller
Cooperative payload delivery [131]	Aerial	RGB-D camera	Heavy load control, learning-based planning for aerial cooperation
Lifting bars for assembly [132]	Aerial	External motion capture system	Multidirectional thrust control flying
Window cleaning of building [133]	Magnetic climbing	Force sensors	Elastic actuators, passive obstacle avoidance
Archive room patrolling [134]	Ground	Infrared camera, laser	Storage basket, monitor abnormal temperature
Assembly task of space telescope [135]	Ground	Two cameras	Stretchable manipulator, assembly in space
Indoor sign inspection [136]	Ground	Camera	Scissor mechanism for manipulator
Dual robot payload delivery [137]	Ground	Multiple cameras	Extended payload carrying capability
Penstock inspection [138]	Ground	Camera, laser	Wall climbing capability
Water distribution pipe maintenance [139]	Ground	Four cameras	Navigation inside a pipe, contamination less rehabilitation (CLR) of pipe

Table 3. *Cont.*

Application	Base Robot	Sensing Method	Key Technology and Contribution
Garbage collection and sorting [140]	Ground	RGB-D camera	Deep learning for garbage type identification
Bomb disposal [141]	Ground	Two cameras	Teleoperation
Hydraulic manipulator for undersea environments [142]	Underwater	Multiple cameras	Deep underwater operation
Transformable autonomous underwater vehicle [143]	Underwater	Camera	Control system similar to spaceflight, user in the loop over low-data transmission
Seabed inspection, repair [144]	Underwater	Camera	Free-floating actuation, a convolutional neural network for object recognition

5. Case Study

To examine the feasibility of mobile manipulators for railway track maintenance tasks, a robotic inspection and repair system (RIRS) has been developed by Cranfield University in conjunction with Network Rail Limited, UK. RIRS combines rail trolley, warthog UGV, and UR10e. These can navigate both off-track and on-track, as shown in Figure 17. Although the conversion between off-track and on-track navigation is performed manually, this is a unique capability of RIRS, which changes the kinematics of the whole system [145]. Moreover, different navigation strategies are required for off-track and on-track navigation [146].



(a) (b)

Figure 17. Railway inspection and repair system (RIRS) in two different operational modes; (**a**) off-track navigation mode and (**b**) on-track navigation mode.

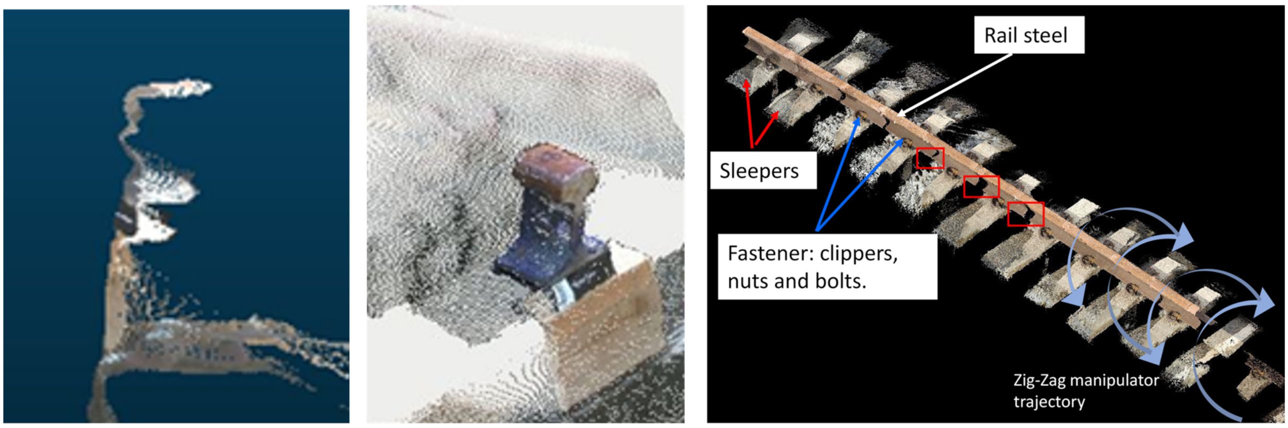
RIRS has multiple sensors such as IMU, wheel encoder, PTZ environment camera, monocular wrist camera, RGB-D camera, LiDAR, and RTK-GPS. Table 4 lists the sensors and functions of RIRS. The monocular camera, attached to the manipulator end, can detect a range of defects. The manipulator enables it to inspect from different perspectives, providing comprehensive defect information. Combining the features from ROS, a UR10e industrial manipulator, and a monocular camera, RIRS can repeatedly and precisely inspect for defects [147]. The manipulator has a payload capacity of up to 10 kg, but the Warthog UGV has a higher capacity of 250 kg. Because of this, a RIRS can be equipped with additional auxiliary devices, such as ultrasonic track inspection instruments [148] or repair tools.

Table 4. Purpose of different sensors in RIRS.

Sensor	Purpose in RIRS
IMU	Localization and navigation
Wheel encoder	Localization and navigation
PTZ environment camera	Environment awareness
GPS	Localization, navigation, referencing defect position
Monocular camera	Defect detection, close inspection of defect
RGB-D camera	Defect detection, obstacle avoidance
LiDAR	3D perception of surroundings, obstacle avoidance

Multiple experiments were conducted in the Northampton and Lamport Heritage Railway facilities to demonstrate the command-and-control system of RIRS and find the operational challenges for autonomous systems in the railway environment. Successful results showed the capability of RIRS in static and dynamic obstacle avoidance, short-range and long-range navigation, defect detection, and repair actuation. Furthermore, the testing facility provided standard gauge operational railway environments. Hence, a technology readiness level (TRL) of −7 [149] was achieved after successful experiments.

Moreover, as a mobile manipulator, RIRS can provide many flexibilities and cost–benefits in railway track maintenance. The attached RGB-D camera can provide 3D image of the target object, but it fails to capture information from the side and back of the object (Figure 18a). A 3D reconstruction method has been proposed and demonstrated with RIRS and sensor fusion technology to improve the track inspection technique as the reconstructed 3D model (Figure 18b) provides more dimensional and textural information than RGB-D camera output (Figure 18a) [150]. Additionally, the 3D reconstructed model can be fused with depth camera to provide better robot perception, with the LiDAR point cloud for environmental sensing and GPS data for geo-location.



(a) (b) (c)

Figure 18. Reconstructed 3D model of railway track components; (**a**) distorted side view of a rail section from RGB-D camera (**b**) reconstructed 3D model using proposed technique (**c**) reconstructed 3D model of a railway track section using mobile manipulator and SfM technique [148].

Though there are some industrial 3D imaging solutions such as Zivid 2 [151], they are more expensive than monocular cameras. The method proposed in [150] was a cost-effective solution as it created 3D model of the target object using a monocular camera and open source structure-from-motion (SfM) technique [152]. Moreover, because of the flexibility of the overall method, this technique can be used for creating digital model of the railway track without human involvement, as shown in Figure 18c, which can be beneficial for creating a digital twin of railway tracks, performing digital surveys or creating railway datasets for machine learning algorithms.

6. Benefits of Using a Mobile Manipulator for Railway Track Maintenance

(a) Environmentally friendly and sustainability

Current maintenance techniques in railways are heavily dependent on humans, a fact which poses severe health and life risks. This dependency on humans also reduces the efficiency of the rail network. Train services are greener means of public transportation compared to other public transportations system. For example, modern Eurostar rail only emits 6 g of CO_2 per passenger per kilometer (pppk), which is almost zero and insignificant compared to other transport systems such as small and medium petrol cars, which emit 96 g and 192 g CO_2 pppk, respectively [153]. Adopting train services for public transport will contribute towards the sustainable development goals (SDG) by reducing carbon footprint. However, delays and cancellations of trains impact customer satisfaction negatively and discourage users. In the UK, 3.3% of the train services were canceled, whereas 10.7% were delayed by at least 3 min during 2021–2022 Q4 [154]. Of these, almost 17% of delays could be attributed to track faults [155]. Therefore, timely track maintenance is essential to maximize the availability of railway networks. A flexible mobile manipulator system with inspection and repair capability, capable of working out of hours and in adverse weather conditions, could provide a considerable positive impact.

(b) Efficiency and productivity

Mobile manipulators are gaining more flexibility and productivity features. Robots are well known for their accuracy and repeatability in many industries. For decades, industrial manipulators have been performing many challenging and repetitive tasks, such as welding in the automotive industry. The same benefits could be available for railway track maintenance if using the correct designs and control strategy. As the manufacturing cost of robots has been reduced gradually [156], some hardware features, such as water and dust resistance, are becoming easy to achieve. Hence, the design and fabrication of outdoor mobile manipulators are becoming more feasible. Moreover, manipulators are now capable of carrying very high payloads. For example, ABB has multiple models of industrial manipulators which can carry more than 200 kg payload [157]. As many railway maintenance tasks require a high payload, these manipulators can perform railway track repair tasks.

(c) Financial impact

The financial benefits of robots and automation have already been demonstrated for other industries. A cable-driven construction robot can save more than EUR 1.2 million in 5 years after considering the cost–benefit analysis with the labor [18]. Furthermore, after considering 10 robots working in 12 different construction sites, researchers concluded that robots save 13% on cost while increasing quality by almost 50% [19]. A whole life-cycle cost model showed that an autonomous robotic tunnel inspection system can save 81% of labor costs and reduce 8700 h of inspection time annually [158]. Another study on tunnel inspection concluded that inspection based on photogrammetry could reduce the cost and data acquisition time to one-fifth, which will directly impact safety costs and conditions [159]. These examples show that railway infrastructure owners will benefit from using mobile manipulators for railway track inspection and repair tasks which will reduce human involvement. With adequately equipped inspection sensors, mobile manipulators can inspect the railway track autonomously. Moreover, they can perform some repair tasks autonomously, assist humans in repair tasks, and ensure information flow in different steps of digital asset management system.

(d) Asset utilization

Currently, many railway asset management companies use state-of-the-art railway track monitoring devices. New measurement train (NMT) is a track monitoring train deployed by Network Rail Limited. This is very costly to operate and needs many crews per shift to collect, analyze and verify recorded data [41]. Because of the size (Figure 4a), NMTs are unable to locate defects in a short range, which is essential for the planning of repair tasks. Besides, these track monitoring trains can only perform inspection. Moreover, other trains are not allowed to use the same track during the inspection, which increases track possession and reduces asset utilization. Human intervention is required for instant inspection, defect verification, and performing repair tasks. The forecasted increased demand for railway usage requires more frequent passenger and freight trains. More frequent track maintenance will be needed with this increased track usage. This is a dilemma and challenge for the railway track maintenance companies to ensure the optimum utilization of the assets. A fleet of mobile manipulators can assist humans in frequent and instant inspection and repair tasks, reducing track downtime and possession.

(e) Safety of workforce

Although many modern inspection technologies perform track inspection tasks in railways, confirmation, sizing, and criticality classification are often performed by human operators. Weather conditions, tiredness, monotony, etc., can negatively affect inspection results and the quality of repairs completed by a human operator. According to rail safety statistics, there were 3978 workforce physical injuries and 806 workforce shock and trauma incidents on the main line from March 2021 to April 2022 [155], accounting for 20 million pound cost for the companies [160]. A reduction in the number of injuries could be expected if robots could undertake those high-risk maintenance activities.

(f) Connectivity

As 5G and cellular technologies become more robust, a fleet of connected mobile manipulators is becoming feasible. These connected mobile manipulators could securely communicate with the central command and control center. Upon receipt of a task command, a mobile manipulator could autonomously navigate to the designated intervention or possession area.

7. Challenges and Requirements

7.1. Challenges for a Mobile Manipulator for Track Maintenance

The mobile manipulator has a lot of potential uses in railway track maintenance. However, it has to overcome some challenges before successful deployment. These challenges arise from the railway track structure and maintenance systems, communication and localization methods, power, and weather conditions.

(a) Track structure and access points—Railway track surface condition is different than road or industrial setup. The railway track is an uneven terrain. Moreover, the workspace for the robot is limited inside the tunnel or bridge. Additionally, as the mobile manipulator cannot stay on track after finishing the tasks, it will need access points to use the track. Railway infrastructure such as platform, trackside furniture, overhead line equipment (OLE), and leftover material may cause navigational problems for autonomous robots [161].

(b) Communication—Other challenges come from the communication perspective. Communication between the control or operation center and the mobile manipulator is required. With the advancement of teleoperation, human skills can be transferred to robots. However, stable communication between the human operator and the robot is a must in this scenario. Moreover, in the case of a fleet of robots, communication among mobile manipulators is required for safety and task collaboration. As railway track passes through mountains, forests, or remote locations, there is a lack of signal or weak signal along the track.

(c) Location awareness—Localization of the robot is essential for defect location referencing and for re-locating the defect for repair tasks. Due to the remoteness of the track, overhead line equipment (OLE), nearby buildings, or dense forest interfere with the

GPS signals. Additionally, tunnels are GPS-denied areas. Hence, in many places, the GPS positioning accuracy will be very low, or there will be no GPS signal.

(d) Power—Most of the mobile manipulators are battery-powered, which is convenient. The mobile manipulator will need powerful batteries to perform many repair tasks, such as welding, grinding, drilling, and lifting heavy payloads. However, powerful batteries will increase the weight of the mobile robot and reduce the usable space on the robot. Although internal combustion (IC) engines can provide power instead of batteries, this is not feasible from an environmental perspective. Thus, power capacity and management are still challenging for mobile manipulators.

(e) Data budget and management—The mobile manipulator will record sensor output for inspection. Depending on the control architecture, the mobile manipulator will analyze those data in real-time or save those for future usage. The data budget analyzes and estimates the requirements of data storage capacity and computational cost based on the sensor output. On the other hand, data management determines which data to store for future usage, the computation requirement for onboard data processing, and the data transfer process between the robot and the primary control system. As a portable machine, the mobile manipulator has limitations in processing large quantities of data, while the lack of internet connectivity in many places along the railway track will hinder the data transfer process.

7.2. Requirements of a Mobile Manipulator for Track Maintenance

As railway infrastructure is becoming smarter, robotic technologies are being gradually deployed. Mobile manipulators are particularly advantageous for use in inspection and repair. Based on the use case mentioned in Section 5 and the benefits mentioned in this section, mobile manipulators specifications for railway track maintenance include:

(a) Reduced track possession—Track possession is important to maintain the safety of the maintenance people. Usually, total possession time is the sum of 3 times: time from last train to start of work, work in progress time, and time from end of work to the first train. In the UK, the average time for the last train to start work was around 50 min and 20 min for AC-electrified and non-electrified routes, respectively [162]. Moreover, the end of work to the first train passing time was calculated as 25 min for AC-electrified routes and 100 min for non-electrified routes. Additionally, a minimum safety distance of 2 m is maintained between the staff and train in case of parallel tracks [162]. To ensure financial benefits and maximize asset utilization, mobile manipulators should have reduced track possession.

(b) Safety and security—With the advancement of Industry 5.0, the collaboration between robots and humans is increasing gradually. Safety aspects of a robotic system should integrate both the autonomous and collaboration modes. Robotic systems should be capable of identifying static objects, dynamic objects, humans, or animals visible inside the workspace. Robotic systems should avoid any collision with objects. Lack of safety measures in robotic systems can cause fatalities in the workplace [163]. Security in a robotic system ensures that the environment does not create any harm to the robot or robot operation. Cybersecurity measures such as the security layer and authenticity of data communication are required to minimize the risk of hijacking or cyberattacks. Identifying the hazard; assuring safe design, safe operation, hazardous failure management; and verifying action are important tasks for any autonomous system working in complex environments [164].

(c) Design for maintenance—Design for maintenance is a guideline to enhance the maintainability, reliability, and supportability of a product to ensure maintenance of the product at less expense, less time, and less effort [165]. The mobile manipulator used for track maintenance will require regular maintenance such as sensor calibration, battery condition monitoring, links, and joint integrity. Easy maintainability will keep the robot ready for the next repair job and extend the life of the robot. Design for maintenance is also important to achieve overall cost-effectiveness [165].

(d) Task verification capability—finally, the mobile manipulator should be equipped with a task verification system. This will certify that the successful task completion is compliant with the railway's standards. This verification system will also capture any repair faults and save trains from any catastrophic accidents.
(e) Using intelligence: Robots are becoming smarter gradually in terms of perception, object detection and control system with the usage of machine learning (ML), deep learning (DL) and artificial intelligence (AI). Although ML is used in many inspection tasks [46,51–56], more research is needed to ensure smart and intelligent robotic maintenance. Usage of ML, DL, AI can improve the efficiency of perception to differentiate between railway and foreign objects, detect humans, and identify faults. Moreover, robotic intelligence can improve the decision-making ability of control systems. Hence, the usage of robotic or machine intelligence is required in the future robots.
(f) Legal and regulatory requirements: Railway is a highly regulated industry. As railway carries more people and freight than other mass transportation systems, policy makers give maximum priority to safety. For example, RSSB [166] and Network Rail [167] develop, modify, and maintain standards in all aspects including the detail design of rolling stock, railway infrastructures, safety standards, driving and controlling methods, maintenance procedures, engineering acceptance, etc.

8. Conclusions

Railway is an environmentally friendly, safe, and reliable public transport system. The track is the most critical part of a railway asset management system, which requires rigorous maintenance to ensure a safe and comfortable travel experience. The railways are older than the automotive or aerospace industries yet do not use modern robotic technologies in a widespread fashion. As the demand for trains is increasing, more attention is required to upgrade current maintenance technologies using robotic and autonomous solutions. Although a small number of railways robots have been developed, the vast majority do not have manipulation capability and only focus on inspection tasks without repair capability.

The feasibility and benefits of using mobile manipulators for maintenance tasks across various industries have been found throughout extensive research in the past few decades. An extensive literature review has classified mobile manipulators into different categories based on the base robot type and application areas. Although most mobile manipulators are based on ground robots, researchers are looking into other types of base robots, such as aerial, underwater, etc. The high-voltage power transmission line is the most significant area of application for application of mobile manipulator. However, mobile manipulator usage is increasing across the nuclear reactor, aerospace, agriculture, and construction fields.

With adequate design, instrumentation, computational algorithms, and workflow frameworks, the usability and benefits of mobile manipulators can be successfully adopted in the railway track maintenance activities. Previous studies have proved the economic and safety benefits of modern robotic technologies in different applications in railway [48,71,158,159]. Hence, the usage of intelligent mobile manipulators for track maintenance will provide robust, reliable, and greener support for a mass transportation system which can increase human safety and asset digitalization.

Nonetheless, improved navigation methods in GPS-denied areas and local data storage capabilities are required to achieve deployment in remote areas. Additionally, safety and security measures are demanded for successful operation. Moreover, the design of maintenance is a desirable criterion for cost optimization. Finally, the hardware and software of robots should be capable of verifying the completed task by following the railway standard.

Most of the current mobile manipulators are not designed to consider railway applications. Hence, more research is required in the future to design and fabricate railway-compatible mobile manipulators. Furthermore, as many of the railway sites lack good signal for data transfer-, teleoperation-, and mixed reality (MR)-based mobile manipulation in railway track environment can be potential future research. Besides, railway track maintenance requires different types of tools. Thus, self-reconfigurable end-of-arm tools constitute another research prospect in the field of mobile manipulators.

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