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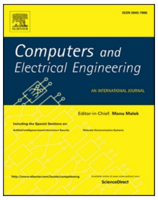

An autonomous rail-road amphibious robotic system for railway maintenance using sensor fusion and mobile manipulator

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ABSTRACT

The current maintenance of railway infrastructure replies heavily on human involvement, requiring possession of the track section during maintenance, resulting in high costs and inefficient execution. This paper proposes an autonomous rail-road amphibious robotic system for railway inspection and maintenance tasks. By virtue of its road and rail-autonomous mobility, it is able to execute the complete maintenance execution flow in multiple phases. The system provides flexible track job location access, low-cost maintenance execution, and reduced track network possession. The payload mobile manipulator and sensor fusion enhance the system's capabilities for multiple types of inspection and repair. The design of a command and control system was guided by a rule-based expert system strategy to enable remote operation of the whole system. The developed demonstrator of a track wheel accompanied unmanned ground vehicle was integrated and demonstrated in both operational and realistic track environments with multiple testing activities of remote operation, navigation, accurate job detection, inspection, and repair, confirming effective job completion and logical human interaction. The proposed method produces an outstanding hardware-software integrated robotic inspection and repair system with a high level of technological readiness for autonomous railway maintenance and intelligent railway asset management.

1. Introduction

1.1. Railway maintenance necessity and trends

Railway infrastructure networks have played a pivotal role in facilitating the growth of industries and enabling the efficient functioning of societies worldwide for centuries. They have served as a fundamental component of public transportation systems and have significantly contributed to economic development and well-being. The requirements of sustainable railway management from consumers and owners are intended to be met by the implementation of asset management within a railway infrastructure environment, which has grown from numerous sources, including the concept of Total System Support. Since 2012, more than 15–25 billion

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EUR have been spent annually on the maintenance and renewal of railway infrastructure assets, which is estimated at 70,000 EUR/km on 300,000 km of track [1]. The British railway network's management system encompasses over 20,000 miles of track, 30,000 bridges, and 2500 stations, some of which are nearly 200 years old, as well as an array of geographically dispersed signaling, electrification, and crossing systems [2]. The primary focus of a railway infrastructure asset management system pertains to the strategic planning, operational control, and ongoing maintenance of all hardware and rolling stock assets, encompassing various activities and their interconnections. The maintenance of railway tracks is essential in order to uphold the safety requirements of transportation, enhance the reliability and efficiency of the network, and promote the sustainable advancement of railway technologies. For decades, track maintenance in Great Britain required the involvement of humans; even today, more than 15,000 people are working on associated activities, including fixing signaling problems, rail crossings, broken rails, rolling stock, etc. [3].

Multiple life cycles, fault types, and degradation levels are intrinsic to the railway track due to the wide variety of servicing intervals, operational loads, and operating environment conditions [4]. Simultaneously, these defects are dispersed across the vast distances of the track network, causing the maintenance team to incur a substantial amount of periodic surveillance work. To ensure the safety of the entire network, periodic inspection, a dependable condition monitoring system, and corresponding remedial action are required [5]. In addition, the various inspection and repair interventions are mandatory but expensive and disruptive to traffic operations. This increases the need for timely, high-quality, adaptable, and repeated maintenance planning, behavior, technologies, devices, and tools [6].

Increasing maintenance tasks and scheduling conflicts with transportation traffic [7] drive systems and technologies toward comprehensive maintenance service, e.g., inspection, repair, and remote operation simultaneously. This phenomenon has the potential to enhance maintenance efficiency and minimize track possession and human intervention [8]. For example, defect re-localization and risk assessment maintenance are consistently cited as challenges and significant issues by the repair fleet [9], which necessitate periodic low-cost services in conjunction with component deterioration. Hence, there is a significant demand for automation maintenance and autonomous robotic systems technologies in order to accomplish tasks with efficiency and cost-effectiveness.

1.2. Towards complex autonomous systems

The "Intelligent Innovative Smart Maintenance of Assets by Integrated Technologies 2" (IN2SMART2) project is part of the Shift2Rail Horizon2020 funded European program [10]. The objective of the work is to substantially improve the management of railway assets through the use of innovative technologies, new economic possibilities, and enhanced legislative standards. The overall objective of the project is to enable the development of intelligent asset management systems in the railway sector by creating new and optimized strategies, frameworks, processes, methodologies, tools, and products in order to contribute to the achievement of the European Union's and Shift2Rail's objectives in the railway sector. Toward intelligent digitalization and management in railway maintenance, one of the objectives is to implement an AI-based robotic strategy to enhance the manner of task execution, task planning, and even the future maintenance rulebook. It will significantly decrease track occupancy, time required, human engagement, and maintenance activity costs.

To accomplish this, it is required that the autonomous robotic system be equipped with a complex remote Command and Control (C&C) system with autonomous perception, communication, travel, risk avoidance, and automatic task execution capabilities. Multiple subsystems, including sensor fusion, a signaling system, a propelling actuator, data processing, and an implementation effector, must be integrated to achieve these autonomous behaviors. System engineering approaches are essential for this type of complex system, as they are used in the specification of operating principles, architecture design, assessment of the Technology Readiness Level (TRL), creation of features, demonstration, and Verification and Validation (V&V) [11]. It serves as guidance and quality control for key stages of development, such as the following: Analysis of requirements and use cases; architecture design; hardware selection and integration; algorithm development; software development; use case implementation; testing and evaluation.

1.3. Current technologies for railway track maintenance

1.3.1. Automatic maintenance machines

Increasing demands and intelligent techniques are driving the rapid expansion of the autonomous system. Maintenance systems for railway assets differ in size, from carriages to handheld devices. The advantages and disadvantages of several devices for railway track maintenance are presented in Table 1. With the development of more integrated hardware and advanced data processing, off-the-shelf devices with the necessary modifications are used to accomplish specific duties.

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

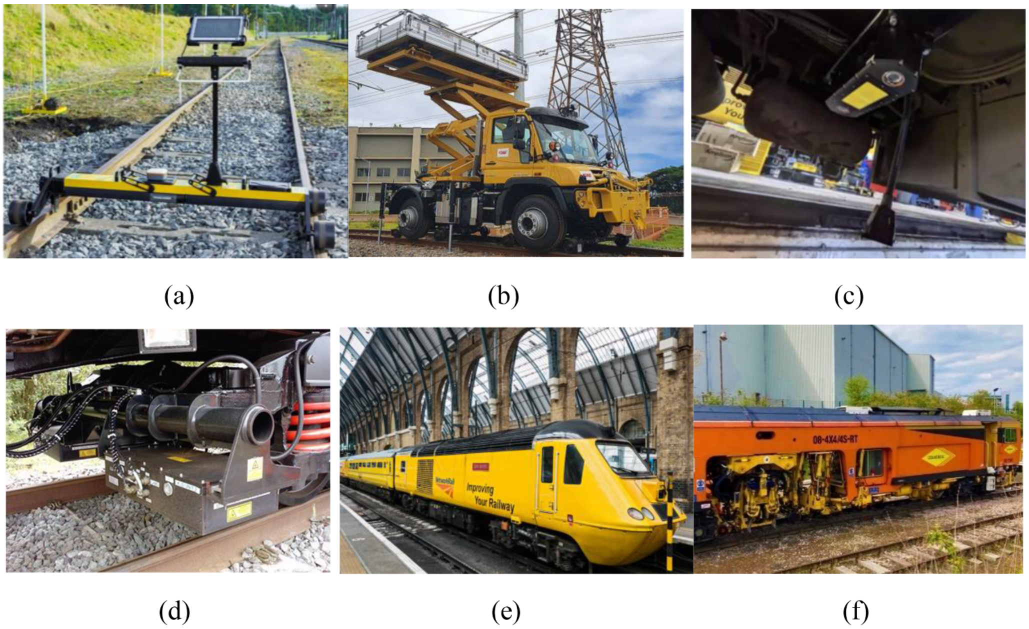
Type	Main tasks	Advantages	disadvantages
Push trolley	Track inspection, carry material	Smaller in size, easy to transport, low cost	slow speed, human-operated
Rail-road Vehicle (RRV)	Repair, transport material, inspection	Moderate speed, flexible track accessibility	costly, human-operated
Train-borne system	Track inspection, track repair	Moderate cost, high speed, demand-focused	Low task flexibility, no repair capability.
Specialist trains	Repair and inspection of track	High speed and payload, multiple measurements	Very costly, possession to the track network.

In railway maintenance, push-on-track trolleys were typically used for track inspection, as depicted in Fig. 1(a), carrying maintenance equipment, and transporting maintainers over short distances. Typically, inspection trolleys are trimmed to reduce superfluous mass and increase sensor payload capacity. They are capable of performing detailed damage inspection (ultrasonic or alternating current field measurement) and track surveying. However, due to its slow pace and significant human involvement, this type of technology is restricted to short-range and low-intensity workloads.

Rail-road Vehicles (RRV), as depicted in Fig. 1(b), are a unique type of maintenance equipment with both pneumatic and retractable rail wheels that can travel on both railways and roads, switching between on-track and off-track at specific locations (level crossings). The Hi-rail and Unimog rail-road vehicles are modified with specialized equipment and sensors to serve as mobile platforms for overhead electrical line maintenance and track surveying. These systems have flexible access and can travel quickly to the track, allowing for flexible inspection and repair execution. However, in order to carry out activities like driving a vehicle and doing detailed maintenance, a human operator is still required.

The train-borne systems depicted in Fig. 1(c) and (d) are intended to be deployed on the regular trains in order to conduct inspection and monitoring in accordance with the network's schedule. Train-borne systems offer a convenient means of evaluating the geometric and structural characteristics of railway infrastructure as well as facilitating remote condition monitoring. Balfour Beatty's Omnivision and Omnicapture3D systems [12] provide automated inspection and modeling functionalities for rail track components, as well as trackside mapping through the utilization of a 3D laser-scan modeling module that is installed on trains. Machines with Vision has successfully designed and implemented a train-borne track condition monitoring system that utilizes computer vision and high-precision condition monitoring sensors to facilitate proactive maintenance measures. The proposed system has the capability to conduct inspections with high efficiency while minimizing disruptions to transportation and possession networks. Nevertheless, these systems were designed with predetermined structures and sensors to cater to specific inspection requirements, thereby limiting their adaptability for modifications. As a result of its train-borne configuration, the system lacks the ability to deploy any form of repair capability.

Specialist trains are one of the largest types of equipment for achieving large network scope and intensive workload maintenance. These trains are designed to provide numerous sensors and repair tools for the entire hardware and software solution. The New Measurement Train (NMT) (illustrated in Fig. 1(e)) and Mobile Maintenance Train (MMT) are two state-of-the-art trains used in the United Kingdom for track inspection and maintenance. The automation filling and tamping systems [13], depicted in Fig. 1(f), offer an automated solution for track raising, lining, and ballast correction along the track, reducing the machine operator's burden and enhancing the quality of track ballast and sleepers. It focuses on large-scale track repair issues such as incorrect track settling, rail section twisting, and ballast faults. However, the acquisition and maintenance of these specialized trains incur significant expenses, encompassing both the initial investment in large-scale hardware systems and the ongoing costs associated with regular maintenance. Repair jobs including track cutting, grinding, milling, and foreign object cleaning using this automated equipment are not cost-effective due to the prevalence of several sorts of small-scale track faults and breakdowns that are dispersed throughout enormous networks. Currently, these tasks rely heavily on specialized equipment, such as track milling and cutting machinery, which must be operated by on-site laborers.



(a) (b) (c)

(d) (e) (f)

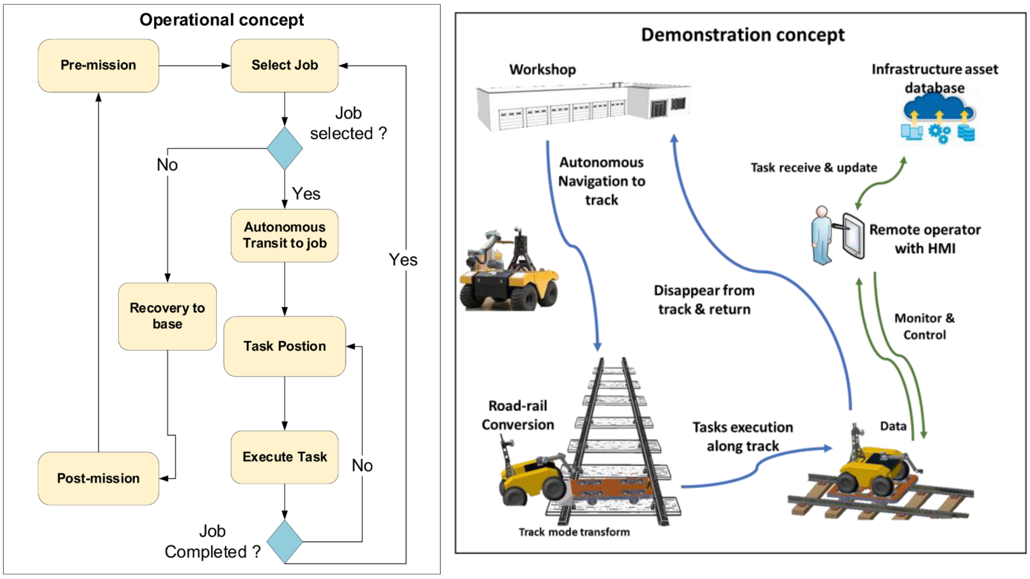
Fig. 1. Current railway maintenance systems and technology.

1.3.2. Robotic maintenance systems

Artificial intelligence (AI) has been used in hardware robots and autonomous actuation algorithms to move maintenance applications closer to becoming completely unmanned. On the software side, advanced computer vision and machine learning provide robots with multiple recognition capabilities, decision-making intelligence, and cybernetic security. Deep learning models aid the robot's camera vision in recognizing road signs, ensuring secure driving in a variety of road conditions [14]. Secure Internet of Things (IoT) communication and attack defense are made possible by AI-enhanced networks, which also help shift complicated processing to edge services for use in autonomous transportation systems [15]. These studies construct robust intelligence structures for the subsystems of perception, localization, and communication, ensuring hardware integration and demonstration under a variety of challenging circumstances and heavy workloads.

On the hardware side, due to their rail compatibility and light weight, track-based systems are a suitable substrate for a robot used for track inspection and maintenance. The Felix, invented by Loccioni [16], is a self-propelled inspection kart for the autonomous inspection of railroad crossings and switches. Switch and crossing zone geometries can be collected at speeds up to 5 km/h by the system. It can generate real-time evaluation reports and predictive analyses. Using LiDAR and cameras, the JDT track inspection robot is also a track inspection trolley that focuses on rail wear, track geometry, track clearances, the condition of sleepers and fasteners, welded junctions, and track bed profiles. The proposed accuracy for image-based recognition is 99%. The maximum speed is 10 km/h, and the accuracy of the mileage alignment is 99.9%. The track geometry detection accuracy is 0.1 mm. These track trolley robots are built for mobile inspection, but lack repair intervention payload capabilities, and their C&C architecture prevents them from doing autonomous intervention tasks. Even though some track robots are designed for autonomous surveillance [17], the vast majority of them are incapable of performing any sort of maintenance. In addition, the track trolley systems will be required to possess the track when traveling to and returning from a destination, resulting in inefficient track maintenance. Robots capable of mobile manipulation have been deployed to assist people in performing tasks that are hazardous, laborious, dirty, or dull. The ANYmal developed by Anionics, for instance, has been utilized for rolling stock inspection because it can easily navigate under trains and into cabins. To inspect defects under bridges, an unmanned aerial vehicle (UAV) was devised, expanding the inspection coverage area and method of the robot system for infrastructure inspection [18]. The AutoTrans [19] was designed as an Unmanned Ground Vehicle (UGV) to remove debris from outdoor roadways. It was created to solve the problem of taking up, transporting, and releasing novel objects with navigation, planning, and grasping abilities. Utilizing the benefits of both manipulator dexterity and mobile platform mobility, mobile manipulators can be utilized in industries for a variety of difficult tasks to reduce the risk to human workers, increase productivity, and maximize financial benefits.

Considering the current state of railway maintenance systems, a rail-road amphibious autonomous system with mobile manipulation for railway maintenance is both desirable and necessary in order to complete the entire maintenance job flow with less track possession, flexible navigation to the job, robotic inspection and repair, manipulation, and remote operation. The capabilities of the Command and Control (C&C) system used to manage this novel technology are currently constrained. The specification of the architecture and details for remote operator interface and local system autonomy, which transport robotic autonomy from an academic indoor system to a railway demonstrator, is thus highly valuable in order to fill this void. Moreover, the C&C concept for a robotic system with both on-track and off-track capability is essential for a higher-level autonomous maintenance system, which can perform



(a) (b)

Fig. 2. The operational concept diagram of RIRS. (a) The C&C phases flowchart; (b) The demonstration illustration for RIRS C&C.

maintenance with less track occupancy and transportation disruption by autonomously possessing and releasing the track according to the traffic plan. This paper presents a novel command and control (C&C) system designed for the autonomous Robotic Inspection and Repair System (RIRS) in the context of railway maintenance tasks. The primary contributions of the proposed system are as follows:

1. A proposed architecture is presented for an autonomous rail-road amphibious robotic railway maintenance system that incorporates a Command and Control framework. This architecture facilitates the complete execution workflow phase and enables unmanned remote operation.
2. The development of hardware and software integration on both the remote operator and local platform sides aims to achieve autonomous capabilities. These capabilities encompass localization, navigation, inspection, repair, and human-machine interfacing, effectively fulfilling the requirements of the proposed maintenance workflow.
3. The Validation and Verification (V&V) process was successfully carried out on both realistic and operational railway tracks, demonstrating satisfactory performance through the execution of multiple typical maintenance tasks.

This paper is structured as follows: Section 2 provides an overview of the system's design and architecture. In Section 3, a description is provided of the hardware prototype demonstrator that has been developed. The outcomes and effectiveness of the V&V demonstration are elaborated in Section 4. Finally, the conclusion is summarized in Section 5.

2. System design and architecture

2.1. Operational concept & use case

The C&C system has been specifically developed to facilitate the operation of an autonomous Robotic Inspection and Repair System (RIRS) for the purpose of carrying out maintenance tasks on railway tracks. These tasks are determined based on the information provided by the infrastructure asset management database. Fig. 2(a) outlines the various stages involved in the operational concept of command and control for RIRS. The process encompasses a series of operational phases, commencing with pre-mission preparations, progressing through mission execution, and concluding with post-mission activities. During the key stage of the mission, the system is instructed to receive and identify a specific task (as defined in the database of the stakeholders involved in infrastructure asset management) and independently navigate towards it. Subsequently, with help from the fault-detecting module, the robot can pinpoint the precise location of the problem. After successfully identifying the fault location, the RIRS utilizes its on-board payload device to carry out the designated task, which involves conducting inspection and repair activities according to the decision made by the fault detection module. After finishing the current task, the robot can move on to the next one, but only with the approval of the human

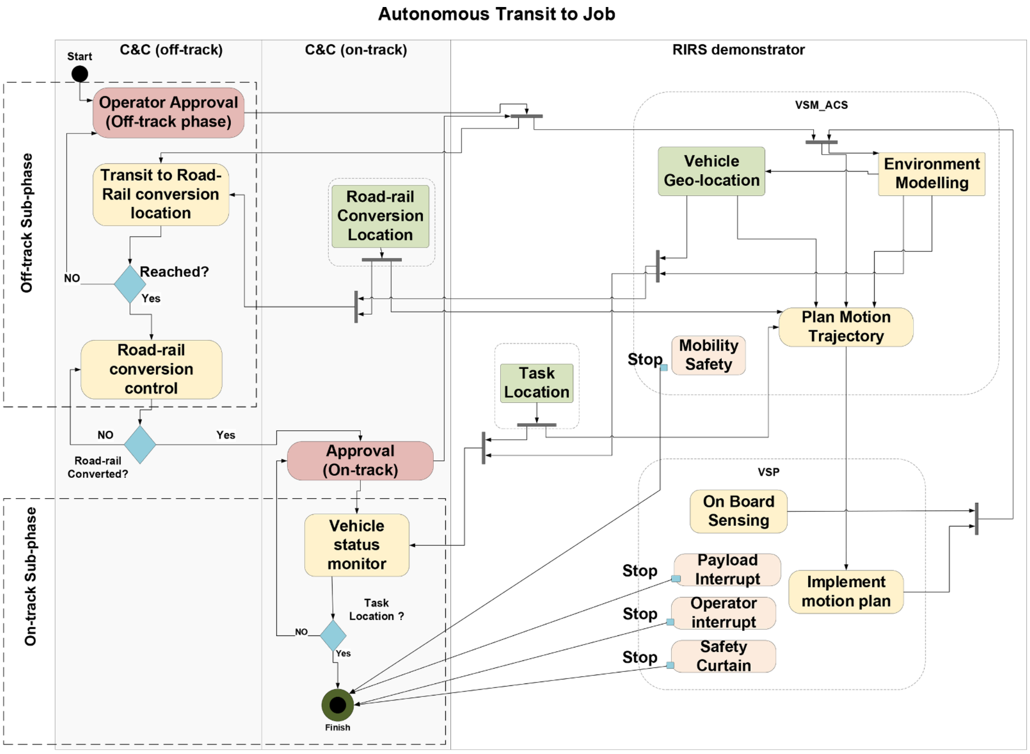


Fig. 3. Operational model of transit to job.

operator. When all tasks have been completed, the RIRS will return to base without further intervention.

In order to enhance maintenance efficiency and minimize disruptions to transportation, the RIRS system has been developed to incorporate both off-track and on-track dual modes. The RIRS C&C departs from its storage facility and travels by road to the section of track that will be maintained for the task. Then, by converting into on-track mode, it is able to perform maintenance along the track. Throughout the entire process, it is instructed to transmit surveillance data to a remote operator via a customized human-machine interface (HMI). The incorporation of rail-road dual modes in the design enhances the RIRS's capability to adhere to track signals while also providing increased flexibility in job completion and reducing disruption to rail traffic. When tasks are finished, they are capable of rapidly leaving the track and releasing the maintenance's possession. Fig. 2(b) illustrates the conceptual demonstration of C&C for the RIRS. In this demonstration, a road vehicle and a track trolley are utilized to showcase the C&C capabilities for the off-track travel process, rail-road conversion transformation, and the execution of tasks along the track. It is important to acknowledge that the demonstration involves the utilization of a road vehicle that has been converted into a track trolley in order to showcase the capabilities of the C&C system.

The operational model for every C&C phase is delineated in Fig. 3. The process of transitioning to a job involves three distinct stages: off-track navigation, rail-road conversion, and on-track navigation. These stages are facilitated by the implementation of sensing and actuation systems. The first stage involves directing the RIRS towards a predetermined location for trackside conversion, as specified in the assigned task. During the second stage, the road vehicle undergoes a controlled transformation to transition into track mode via a rail-road conversion procedure. During the final stage, the RIRS independently navigates to the designated location where the subsequent phases of the task are to be carried out.

The operational models for the task positioning and task execution phases are depicted in Fig. 4. In the left figure, the RIRS is instructed to creep back and forth once the transit-to-job phase has begun, allowing the vehicle to be precisely positioned and the payload maintenance tool (e.g., inspection, repair tool) to be activated at the fault area confirmed by the Non-destructive Testing (NDT) inspection. Once the RIRS is precisely positioned on the defect, the payload devices will proceed with additional inspection and repair activities based on the analyzed fault information. It is essential for the operator to provide initial approval and subsequently recheck the process.

2.2. System architecture

In order to execute the RIRS operational concept, a comprehensive system architecture for C&C was developed, as depicted in Fig. 5. The system is comprised of several subsystems that facilitate autonomous behaviors, such as (i) autonomous control, (ii) localization, (iii) data management, (iv) vehicle and platform actuation, (v) communication, and (vi) remote operation of the HMI. Each subsystem within the system possesses a communication connection and is associated with specific input and output data types. These subsystems work together to accomplish autonomous navigation, job execution, remote control, and operator interaction. The job list or plan is connected to and consistently synchronized with an external maintenance database.

The RIRS, an acronym for Remote Autonomous Robotic System, is a meticulously designed system architecture that prioritizes operationality, real-time communication, and data processing efficiency. In order to facilitate the operation of the RIRS across

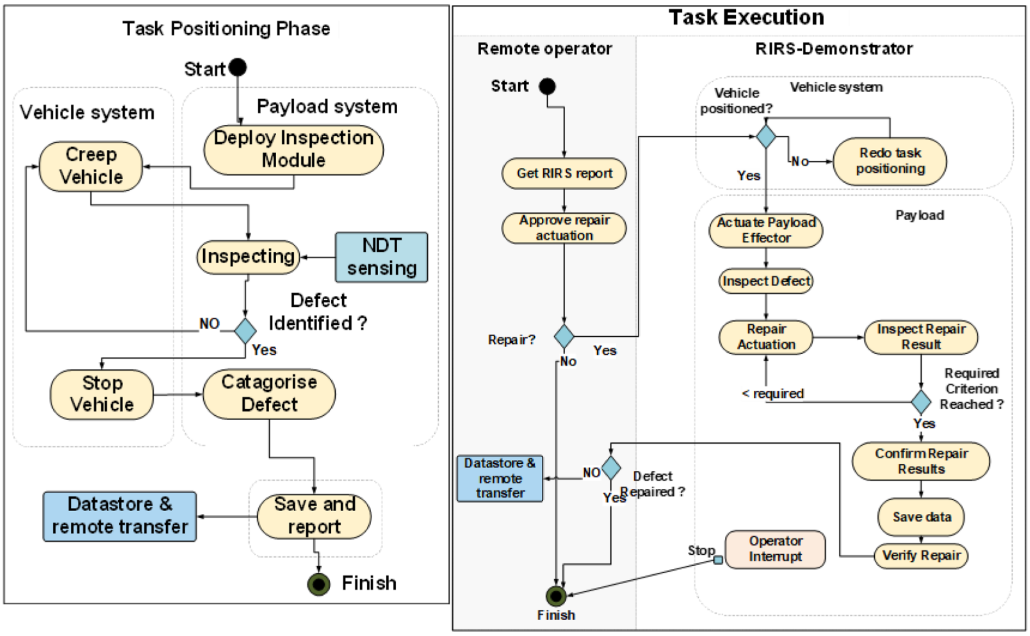


Fig. 4. Operational model of task positioning and execution phases.

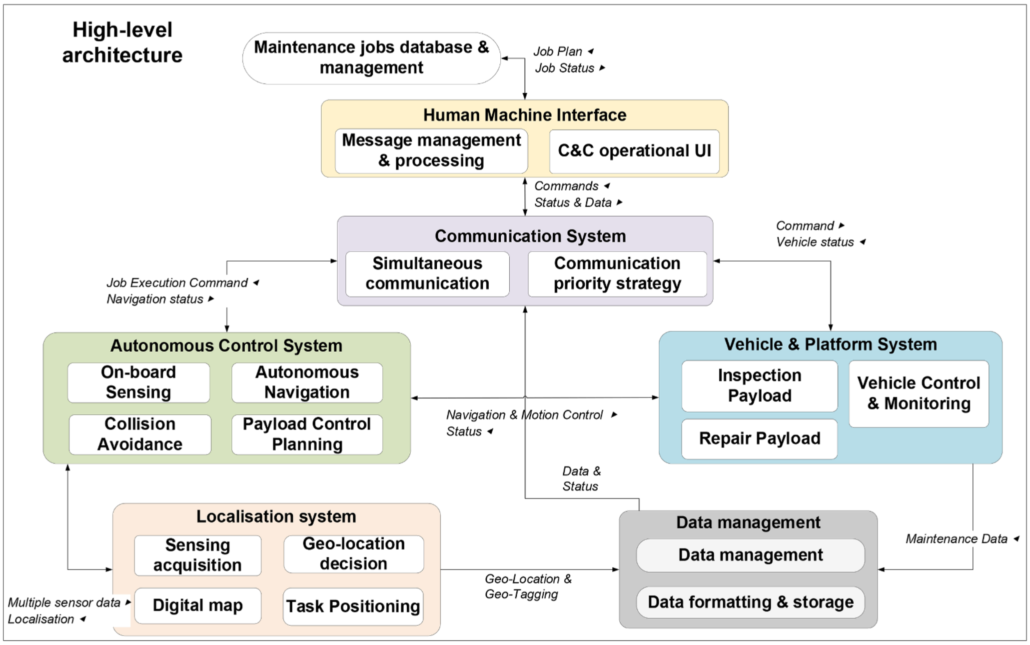


Fig. 5. The high-level architecture design of C&C.

extensive mileage tracks, the design approach entails the partitioning of hardware and software modules between the remote operator and the local vehicle ends. The Robotic Operation System (ROS) is a widely utilized platform and middleware suite that offers a standardized framework, formats, protocols, interfaces, and other components for the development of intricate robotic systems [20]. The ROS is utilized for the development of the C&C systems, encompassing both hardware interfacing and software compatibility aspects.

At the remote operator end, as depicted in Fig. 6a C&C Personal Computer (PC) is utilized for the purpose of command processing, HMI base, and communication exchange. Similarly, the HMI software and ROS clients are also assigned to the remote end in order to alleviate the communication load. In Fig. 7, the RIRS local on-board system is depicted, which consists of three PCs that are strategically distributed. These PCs serve the purpose of conducting various tasks such as data processing, control actuation, and sensing. This distribution of PCs facilitates the implementation of the edge computing design principle within the RIRS local on-board system. This approach effectively distributes the computational workload, thereby facilitating the identification and resolution of faults as well

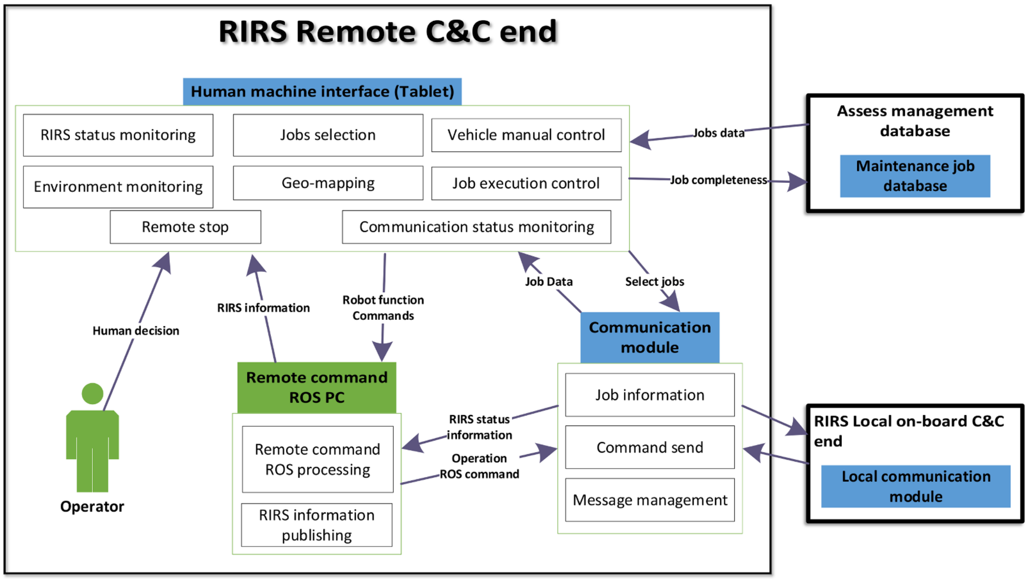


Fig. 6. Detailed system architecture design on the remote operator end.

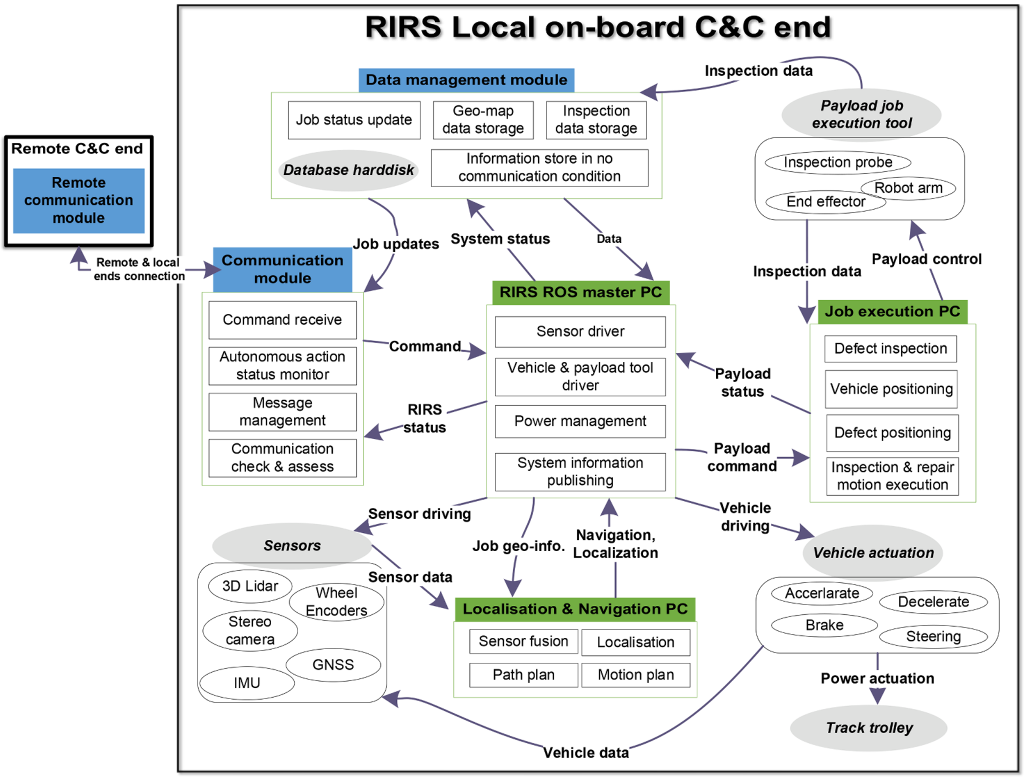


Fig. 7. Detailed system design on RIRS local on-board end.

as reducing the risk of system failures. Each of the key subsystems, namely navigation, localization, and payload device control, is equipped with an individual processor dedicated to data processing. The allocation of the vehicle driving task is assigned to the main ROS master PC. The sensor processing software, localization determination software, and payload control software are all situated in their own on-board spaces, which helps to lessen the data processing load and mitigate the domino effect of a failure.

The architecture of the localization and navigation system of the RIRS is depicted in Fig. 8. The process of localization utilizes the Global Navigation Satellite System (GNSS) signal as a universal point of reference for determining location. Moreover, following sensor fusion by the Simultaneous Localization and Mapping (SLAM) technique [21], the local mapping odometry and fault position feature are used as the local location reference. By integrating multiple sensors, such as an RGB camera, 3D Lidar, depth camera, IMU, and wheel odometer, a localization system generates a map and establishes the relationship between the vehicle or robot and its surrounding environment. This directs the path planning system to generate the motion trajectory and obstacle avoidance capability. It is noteworthy to mention that the off-track motion planner is capable of providing guidance to the RIRS in terms of steering, whereas the

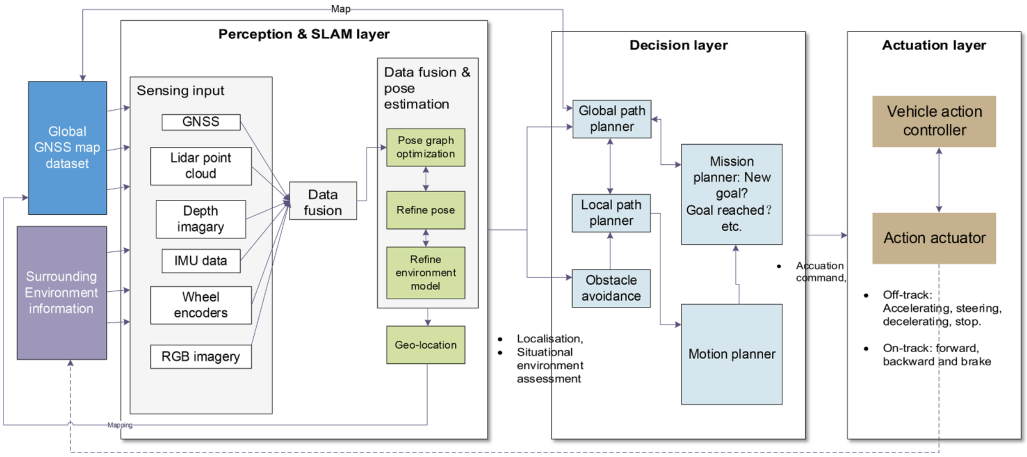


Fig. 8. Navigation system architecture.

on-track path planner restricts the motion to straight actions in order to mitigate the potential risk of derailment.

The architectural design of the safety system, which is essential to railway rolling vehicles, is depicted in Fig. 9. The on-board sensors are utilized as an autonomous platform to specifically identify obstacles within the rail range in order to avoid any potential hindrances to the vehicle's motion. The RIRS will respond to the detection decision to halt by alerting the remote operator and illuminating the third-party obstacle on-site with a light. The system will persist in performing its function in the absence of collision avoidance. The safety system will also issue a rescue request to the remote team if the RIRS becomes blocked, stops working, or experiences an error. The payload task actuator is equipped with the payload robot joint sensor and an external camera to enable collision detection. This functionality allows the system to detect potential collisions with both itself and other track components.

3. Hardware demonstrator

3.1. Unmanned ground vehicle (UGV) demonstrator

The vehicle employed for demonstration of the C&C is an Unmanned Ground Vehicle (UGV) from Clearpath, named as Warthog. It is a four-wheel drive unmanned ground electrical vehicle with payload devices shown in Fig. 10(a). It is a rugged, all-terrain unmanned ground vehicle with off-road tyres and can travel on land and in water. The Warthog fully supports the Robot Operating System (ROS) and can be equipped with a variety of payloads, including on-board sensors and a mobile robot manipulator, to accommodate a wide range of robotics applications in mining, agriculture, and environmental monitoring. It is equipped with on-board & remote emergency stops button to ensure safety and is mounted with a light indicator to present basic movability status. The on-board payload device for maintenance is a 6-joint robot manipulator as shown in Fig. 10(b). There are two main on-board PCs for driving the vehicle and robot arm, providing either programmable or manual control. The hardware architecture of the RIRS Warthog is illustrated in Fig. 11, which shows multiple connection approaches and interfaces including ethernet, CANBUS, USB/serials and wireless.

3.2. Sensors & payloads

To enable the RIRS with autonomy, multiple types of sensors are equipped to provide real-time perception including localization, motion pose, surrounding detection, and inspection and repair actuation. Table 2 presents the specifications of the sensors and payload robot manipulator. For the localization, the GNSS module provides a geo-location with an accuracy of around 5 m (differential-GNSS level status) or in 0.2 m (RTK-GNSS level status). The 3D Lidar and cameras provide surrounding detection from close range to middle range of 1–100 m. For the motion pose, the Inertial Measurement Unit (IMU) detect the inertia, and acceleration in 6 axes. A Universal Robot (UR) robot arm, an arm-tip camera, and a two-finger effector are deployed that can provide real-time joint angles, arm-tip view, and pick-up capability, respectively.

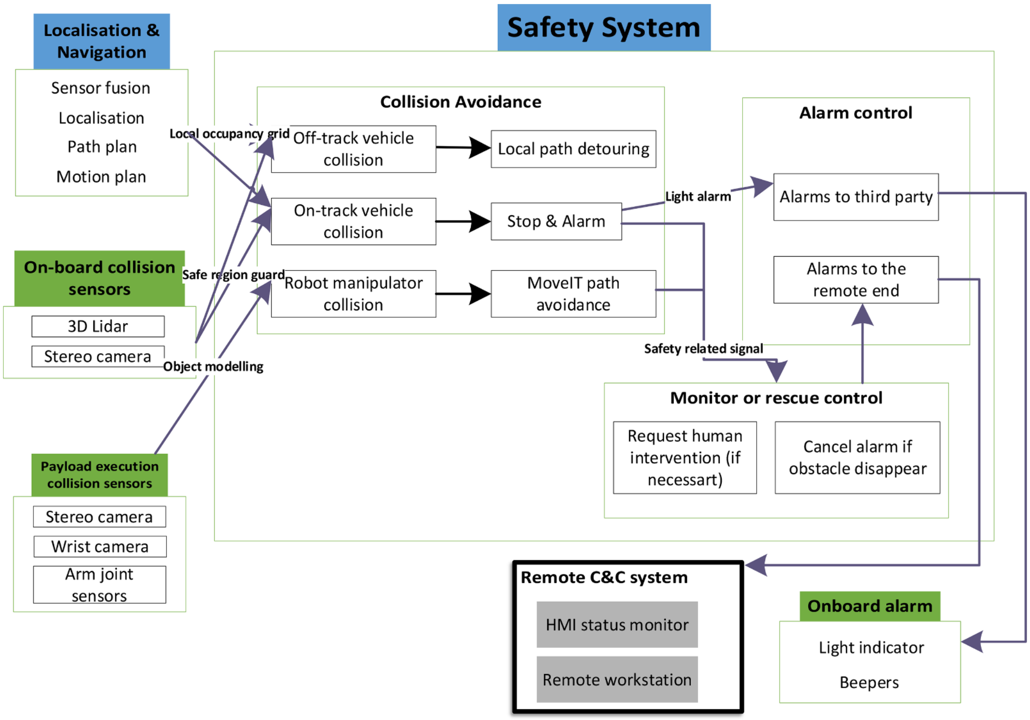


Fig. 9. Safety system architecture.

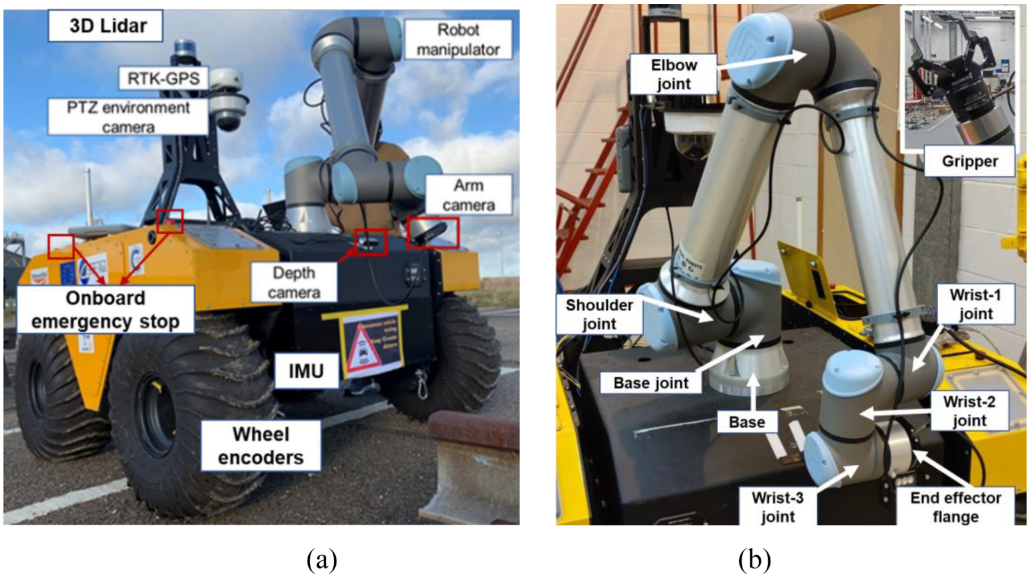


Fig. 10. The snapshot RIRS vehicle. (a) Warthog vehicle and its on-board sensors; (b) Payload robot manipulator.

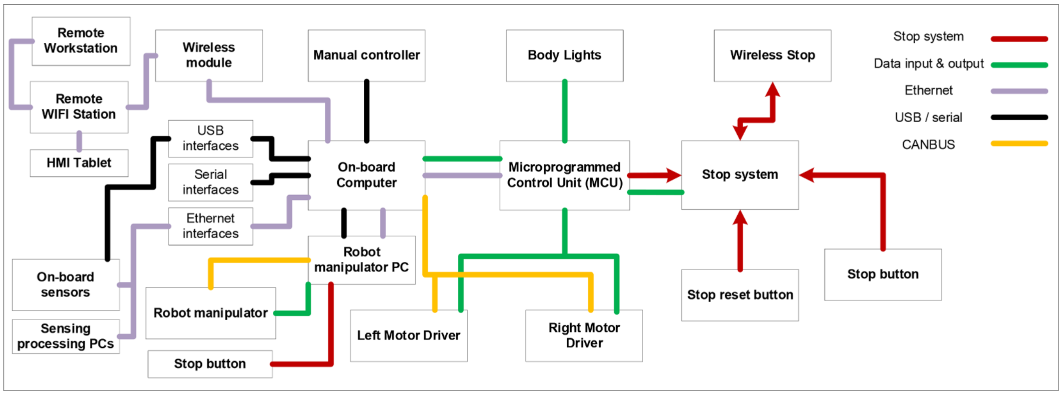


Fig. 11. Hardware architecture of RIRS platform and on-board payloads.

The nature of the input received from sensors and actuators is that they serve the essential routines of the tasks requested by the users. These routines run on separate threads and are created upon request from the main supervisory orders, which allows the job execution agents of C&C can control and load them selectively and simultaneously to improve the calculation performance and communication burden. For example, sensors like 3D Lidar, IMU, and GNSS serve for the real-time routines of the localization and collision avoidance etc. For the necessity of safety and localization, these sensor inputs are collected and calculated all the time when the RIRS is executing the maintenance jobs. In another case of the robot arm execution, the robot arm and NDT sensors and actuators should be responsive to the fault detection and platform positioning signals and wait until the operator's confirmation for next job. The robot arm sensors and moves are automatically selected based on the inspection data and need to be confirmed by the operator. At this time, the arm sensor input will be collected and used until the "repair execution agent" calls to do.

3.3. *On-track RIRS*

A track trolley was designed and manufactured (as demonstrated in Fig. 12) to guarantee the RIRS can run stably on track with compatible track wheels and traction power transmission mechanism. The track trolley is also stalled with a manual switch brake system for safety insurance. As shown in the right side of Fig. 12, after the Warthog is placed on its trolley position, each vehicle tyre will sit into the power transmission seats. And the vehicle chassis is mounted with the trolley by four fixing points.

It should also be noted that the track trolley approach is a temporary solution compatible with Warthog tyres to demonstrate the on-track C&C at this early stage. The track trolley will be placed on the track by the maintainer before job execution. This cannot achieve a full disappearance and non-possession of the track when the maintenance is finished. Even though it is a compromise option in the

Table 2
Specifications of RIRS sensors and payloads.

Devices	Brand & models	Mount position	Key specification	Signal type
3D Lidar	Velodyne Puck Lidar (VLP-16)	Tower peak	16 lasers (Channels); 360° horizontal field and a 30° vertical field of view; Maximum up to 100 m;	Point cloud;
Environmental camera	AXIS M5525-E PTZ Network Camera	Tower middle	1080p and 10x optical zoom; Continuous 360° pan	RGB video
Robot arm	UR10e	Base front cap	1300 mm / 51.2 inch 10kg payload; 6 joints;	Joints angles
RTK-GNSS	Novatel SMART6-L	Tower middle	All GNSS system support; 120 channels;	GNSS Mercator Decimal signal
Wrist camera	UR10 wrist camera	Robot head	70 mm to infinity; Maximum field of view (cm): 100*75; Minimum field of view (cm):10*7.5;	Video & images
IMU	Lord 3DM-GX5-25	Base body inside	Pitch-roll static/dynamic accuracy $\pm 0.25^\circ/0.4^\circ$ 25 $\mu g/\sqrt{Hz}$ (8 g option) IMU sampling rate up to 1000Hz	Acceleration, Gyro, Pitch and roll, etc.
Depth camera	Intel Realsense D435i	Front bulk head mount	Outdoor compatible; Depth resolution: 1280 by 720; Depth framerate: Up to 90 Hz; FOV: 91.2° × 65.5° × 100.6°	RGB & Depth image & point cloud
Two-finger gripper	UR10 finger gripper	Arm head	20 to 235 N; Payload: 5Kg; Position accuracy: 0.4mm	Binary trigger signal;

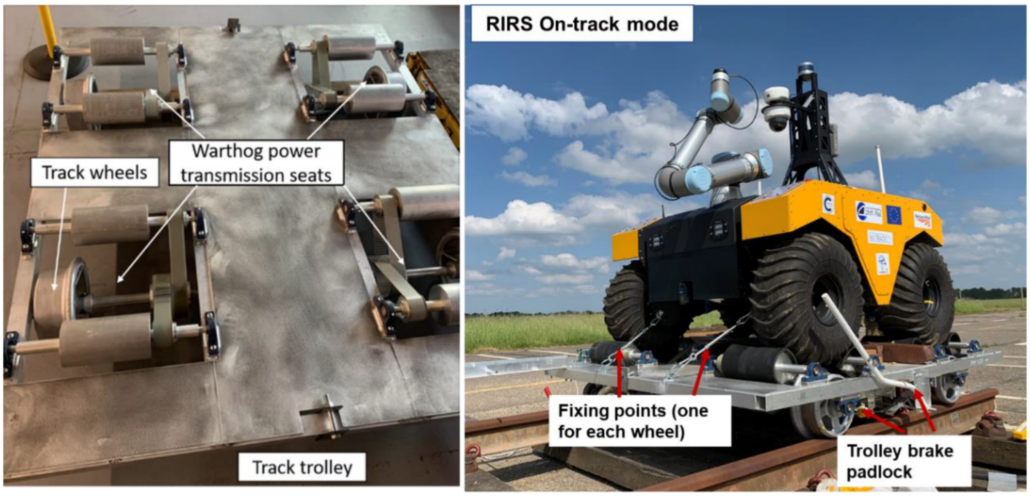


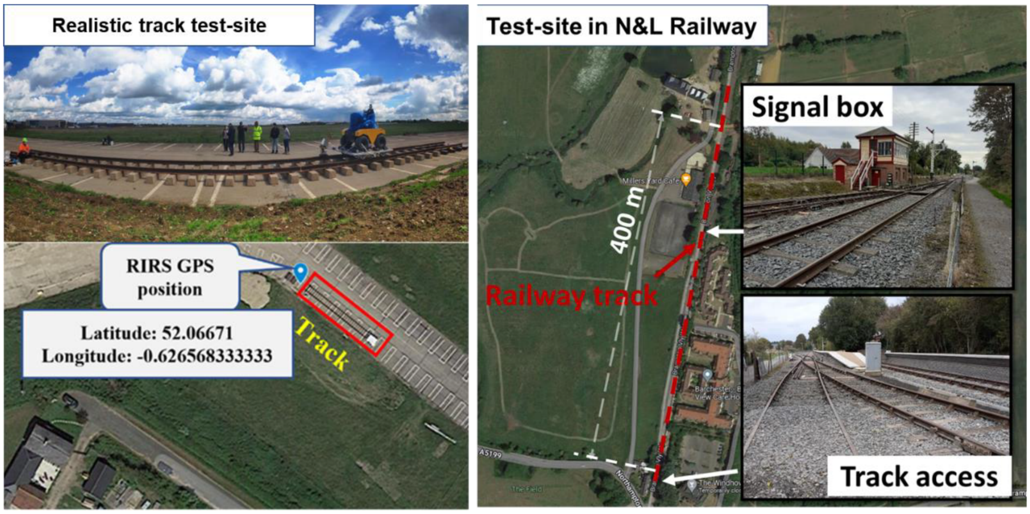
Fig. 12. The designed RIRS track trolley and the On-track mode.

early stage, it still can demonstrate the concept. This initial prototype does not represent the final hardware system. The final hardware platform will modify the UGV integrated with track wheels on the sides of road wheels. When the Rail-road conversion is required, the vehicle will automatically transform to a track mode travelling with track wheels. And the C&C will be improved to implement the transformation automatically.

4. Results and discussion

4.1. Demonstration test plan

The C&C was implemented, deployed, and successfully demonstrated in both a realistic and an operational track environment (see Fig. 13). The realistic track is a 20 m track section deployed at Cranfield University. The operational track test site is selected at Northampton & Lamport Railway (NLR), which is a heritage railway that still runs with tourist trains. Fig. 13 shows the snapshots and geo-map of the test environment. To ensure the safety, the demonstration has been implemented on the track possessed status, which means neither unauthorized train nor person is allowed to enter the test track. The realistic test area provides an off-track navigation environment, and the NLR tests its on-track performance. The demonstration at off-track part was demonstrated at the realistic track



(a) (b)

Fig. 13. Snapshots and geo-maps of the demonstration test sites; (a) Realistic track test area; (b) Operational test site of NLR.

test-site shown as Fig. 13(a). And the rest were demonstrated at an operational test site of NLR as Fig. 13(b).

The demonstration activities plan structure for C&C design is illustrated in Table 3. The test activities were designed and distributed following the C&C operation phases presented in Fig. 2. The demonstration success evaluation was also listed in Table 3, and these activities were tested with multiple repetitions, and the full job loop was demonstrated 5 times. The demonstration was implemented with the witness of industrial railway engineers and academic experts from companies of Network Rail, Trafikverket Rail and etc. During the demonstration, the remote operators demonstrate all test activities at a fixed location where the site and all RIRS behaviors can be monitored for safety.

It should be noted that the activities during the demonstration were focused on finishing the full loop of the RIRS job concept C&C. Several maintenance tasks, including fault inspection and repair execution, were simulated with artificial defects and pre-defined repair routines. Therefore, the simulated defect inspection employed a QR code to demonstrate the detection decision and positioning. Meanwhile, the repair process was demonstrated by pre-defined automatic control of the payload arm motion. The demonstration results of each operation phase of RIRS are presented in Section 4.2. And the performance evaluation related to job reach accuracy, action response, remote communication, safety collision avoidance and mobile manipulation inspection accuracy are discussed at Section 4.3.

4.2. Demonstration results

This sub-section describes the results of the C&C demonstration for the operation phases. The demonstration results of job key phases shown in the left column are presented below from the initiating from the base to the end of job execution and return.

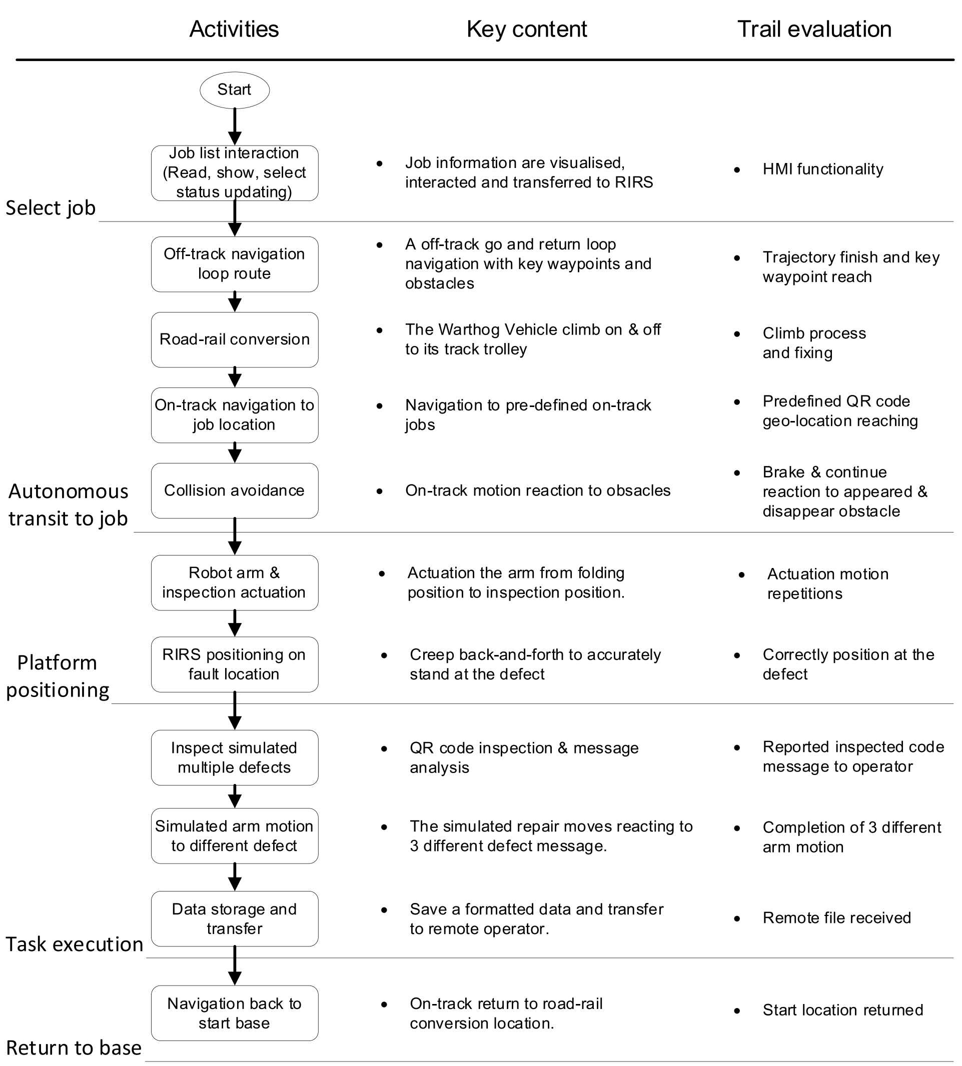
4.2.1. Job management and HMI

The operator HMI is essential to each execution process, including (a) job information management, (b) instructions transfer and (c) status monitoring visualization. Fig. 14 illustrates the connection structure of the remote operation subsystem and how it communicates to RIRS. The HMI was built based on the ROS bridge multiple client structure. The remote client was developed on the remote PC as the main operator that can be distributed to multiple tablet HMI clients for outdoor operators. To avoid command collision and disorder, the ROS client on the RIRS vehicle end was set to receive motion control messages (e.g. vehicle motion, arm motion, sensor control) only from the one specified remote HMI client. On the reverse, all the RIRS monitoring messages (camera, location, sensing data) can be subscribed to by all remote HMI clients.

The HMI is designed to support the trained operators for key operations, including job database interaction, system control, monitoring, vehicle and job state awareness and results management. After booting and self-checking, the HMI is the main tool for the whole job execution. Fig. 15(a) and (c) shows the HMI maintenance dataset management and control pages, respectively. In the "select-job" phase, the operator is required to download and read the job list from the dataset (shown as the top button in Fig. 15(a)). The job management system can interact with multiple statuses (undo, doing, finished) according to a combined decision of RIRS status and operator confirmation.

On the control page in Fig. 15(c), the HMI renders real-time vehicle geo-location and updates the speed, connection status, surrounding environment and etc. Fig. 15(b) and (d) shows the visualization of the environmental sensing from 3D Lidar and front-facing depth camera, and the payload arm-tip visual inspection, respectively. These updating perception monitors provide full awareness of

Table 3
Demonstration activities and evaluation.



	Activities	Key content	Trail evaluation
	Start		
Select job	Job list interaction (Read, show, select status updating)	Job information are visualised, interacted and transferred to RIRS	HMI functionality
Autonomous transit to job	Off-track navigation loop route	A off-track go and return loop navigation with key waypoints and obstacles	Trajectory finish and key waypoint reach
	Road-rail conversion	The Warthog Vehicle climb on & off to its track trolley	Climb process and fixing
	On-track navigation to job location	Navigation to pre-defined on-track jobs	Predefined QR code geo-location reaching
	Collision avoidance	On-track motion reaction to obsacles	Brake & continue reaction to appeared & disappear obstacle
Platform positioning	Robot arm & inspection actuation	Actuation the arm from folding position to inspection position.	Actuation motion repetitions
	RIRS positioning on fault location	Creep back-and-forth to accurately stand at the defect	Correctly position at the defect
Task execution	Inspect simulated multiple defects	QR code inspection & message analysis	Reported inspected code message to operator
	Simulated arm motion to different defect	The simulated repair moves reacting to 3 different defect message.	Completion of 3 different arm motion
	Data storage and transfer	Save a formatted data and transfer to remote operator.	Remote file received
Return to base	Navigation back to start base	On-track return to road-rail conversion location.	Start location returned

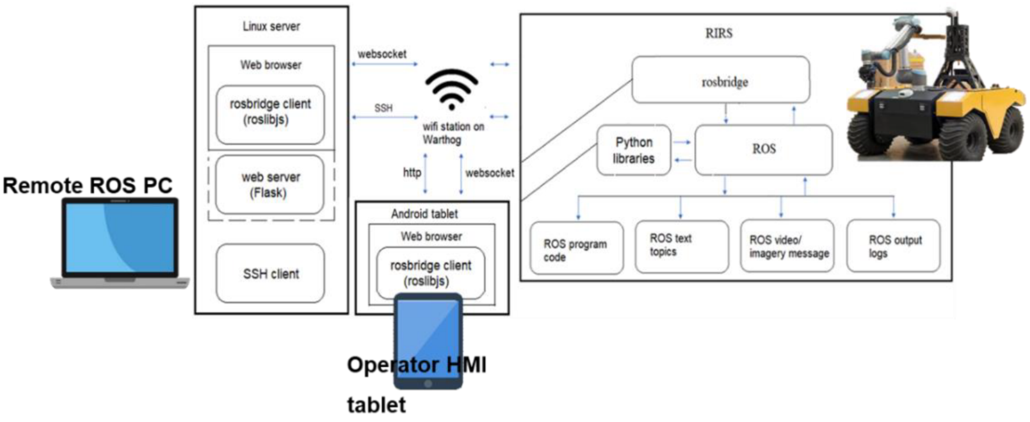
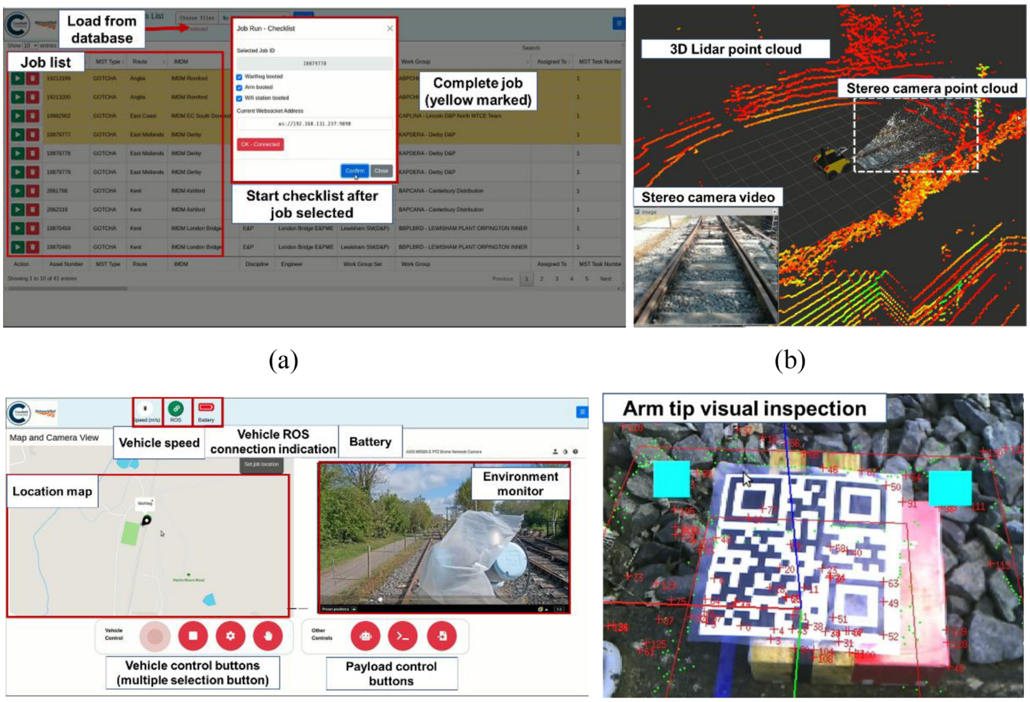


Fig. 14. Remote C&C subsystem structure.



(a) (b)

(c) (d)

Fig. 15. The remote HMI and C&C interface; (a) Maintenance job management; (b) Environment monitoring of sensors; (c) HMI command & monitoring page; (d) Payload arm-tip visual inspection image.

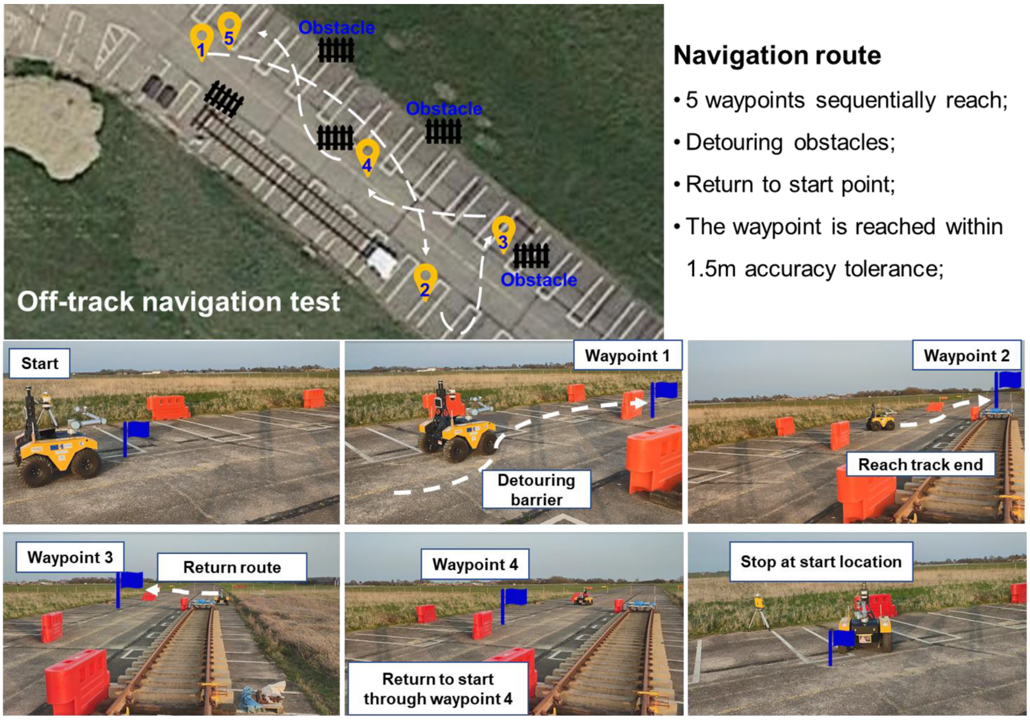


Fig. 16. Off-track navigation to several waypoints in a loop route.

the robot status from large (geo-map), middle (3D laser, round 100 m), close (vision cameras), scale and maintenance details (inspection camera). The control buttons for RIRS vehicle and payload robot, laid at the bottom, were arranged at the bottom of the page. The operator can manually and programmable control the vehicle travelling. In contrast, the payload arm action was programmed with several specific motion trajectories, which provide few selective button commands. Except for control and monitoring, the HMI was developed to equip with alert messages as pop-out windows. The complete message of each key steps like job reached, fault detected, arm motion executed, collision detected and system blocked and etc., will remind the operator as an alert for check and confirmation.

4.2.2. Transit-to-job and platform positioning

Once the "select job" phase is done, the RIRS is ready to travel to the job track location. The next "transit-to-job" is completed by 3 steps of off-track navigation, rail-road conversion, and on-track navigation to location.

The first step of off-track navigation was demonstrated at Cranfield University test area, shown the RIRS was commanded to finish several waypoints to finish a loop route starting from a base point to a rail-road conversion and ending by returning to the base. The key waypoints were pre-set to make the vehicle tackle with obstacle detouring, pause at the rail-road conversion at the track endpoint, turn around, and return to base. Fig. 16 shows a completed trail of the off-track navigation, which demonstrates the RIRS can autonomously implement basic tasks with the support of sensor localization, path planning, off-track path tracking, and detouring obstacles. The RIRS vehicle reached each waypoint within 1.5 m accuracy tolerance for safety considerations. It should be noted that this demo indicates that RIRS has an off-track travel capability in relatively open off-road space. The capability to manoeuvre in complex road traffic environments needs to be improved in future investigations.

After reaching the rail-road conversion trackside location, Fig. 17 demonstrates the capability of RIRS to climb on its rail trolley and to transform to track-mode through ramps. During this process, the trolley was engaged with its own brake to stop sliding and was supported with a jack stand to prevent tilting. Both the climbing on and off processes were smooth with slow speed control. It should also be noted that the track trolley approach is a temporary solution compatible with Warthog tyres to demonstrate the on-track C&C at this stage. The final hardware platform will modify the UGV integrated with track wheels on the sides of road wheels, achieving automatic travel mode transformation.

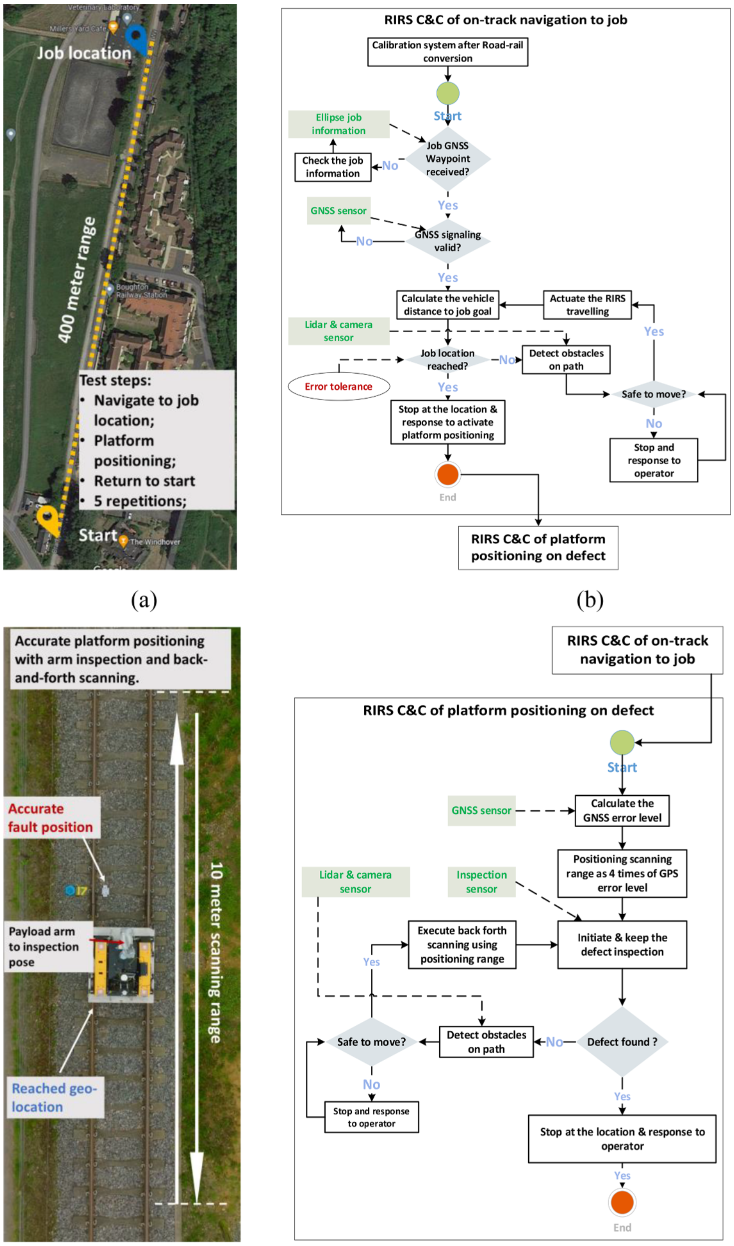
The 3rd steps of "on-track navigation to job" was demonstrated at the half-kilometre NLR operation railway test site. After the operator sending the travel command, the RIRS is autonomously controlled by following the automatic navigation logic as illustrated in the flowcharts in Fig. 18.

Fig. 18(a) and (b) presents the testing site and steps, and the autonomous rules of navigating to job geo-location. The RIRS was commanded to travel a half kilometre to a pre-defined job geo-location extracted from the database. And by guiding trajectory calculated by GNSS signal difference, the RIRS decelerated when it was close to the geo-location and stopped at the pre-defined 4 m accuracy tolerance. This accuracy tolerance strategy ensures that the first routine navigation will stop with a rough tolerance in accuracy and has a resistance to the various environments with different quality of GNSS signalling. The navigation to job geo-location were successfully reached with different vehicle speeds of 1, 2 and 4 m/s and 5 repetitions. All speed tests can be successfully executed with a stable location recognition and stopping at satisfied tolerance distance.

After the RIRS reach the job location based on the geo-location decision, it will then automatically perform platform positioning. The payload arm was unfolded to the inspection pose, and the arm tip inspection camera was activated and vertically facing towards the track to detect the exact fault and automatically stop the RIRS. Fig. 18(c) and (d) shows the platform positioning routine with a 10 m back-and-forth scanning range and 0.5 m/s slow speed creeping arm inspection. The top images in Fig. 19 present the arm inspection pose and positioning process. This step ensures the RIRS to accurately find defects and guarantees the whole defect area in the repair range of the payload manipulator for the next steps. All 5 repetitions demonstrated the feasibility and stability of platform positioning with the detected QR in the visual inspection frame.

During the travel, different obstacles were randomly placed within the track. The demonstrator robustly caught the obstacles and stopped at a safe distance to it and showed a light indicator flashing as an alert. When the obstacles were moved away, the RIRS continued its motion without any operator intervention, shown as in Fig. 19. The collision avoidance is achieved by both top 3D Lidar and front facing depth camera, and both collision sensing was developed within the track width horizontally. The 3D Lidar detects the obstacles within 30 m range and the depth camera detects on-track low-height obstacles within 5 m. The performance of the detected height and blind range of both sensors were measured and discussed in Section 4.3.

Fig. 17. Rail-road conversion at the footpath crossing at the NLR test-site.



(a) (b)

(c) (d)

Fig. 18. On-track autonomous navigation to job and platform. (a) The testing site and steps illustration; (b) Autonomous structure of navigation to job geo-location; (c) Platform positioning illustration; (d) Autonomous command rules of platform positioning.

4.2.3. Inspection and repair task execution

At the final phase of inspection and repair execution, the payload robot manipulator was commanded to perform simulated inspection actuation according to the QR code message shown in Fig. 20(a). At this stage, 3 typical behaviours of multi-view imaging, simulated grinding moves and folding arm, were defined according to 3 different QR code. Fig. 20(b) presents the arm poses and multi-view images when the "Type A code" is recognized. The ViSP (Visual Servoing Platform) [22] was employed to detect and analyze the QR detection, message, and its relative 3D distance to the inspection camera. The RIRS successfully executed the corresponding actuation motions (shown in Fig. 20(a)) for 3 different QR codes. After the multi-view images were taken, the message was sent to the remote operator for selection between data-saving, transferring or redoing the imaging.

To furtherly demonstrate its repair capability, another simulated repair job was designed, which is to select and deliver repair tools based on the inspected fault by using RIRS and payload arm. In this test, instead of acting simulated repair moves, the payload manipulator will select and drop off one toolbox from the board to the fault location based on the inspected QR code information,

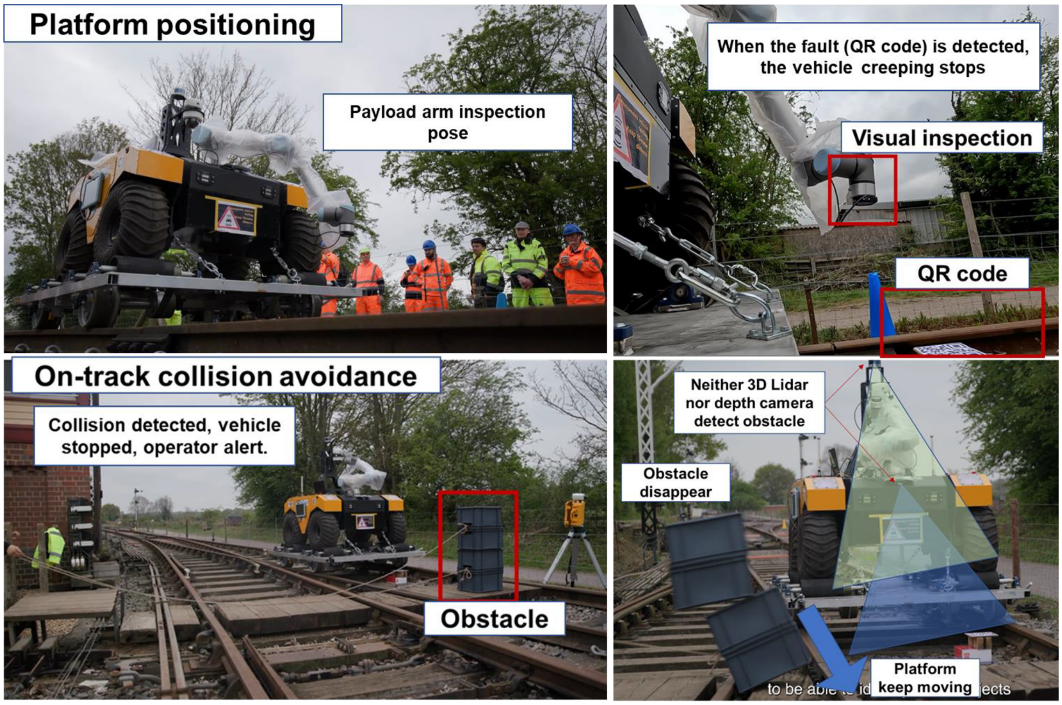


Fig. 19. RIRS on-track navigation to defect job and positioning itself.

which supports for the repair assistance task. Fig. 21 shows the demonstration results of the toolbox delivery. The Platform was prepared with three different colored toolbox. When the fault (e.g. Orange QR code) was detected, the arm manipulator automatically folded back and dropped off the orange toolbox to the location. The simulated inspection & repair execution tests demonstrate that the vehicle platform & payload device can collaborate to support multiple fault maintenance and ad-hoc application extension. The results demonstrated in Figs. 20 and 21 prove that the C&C system can remotely control the RIRS to finish each phase in the operational concept. The autonomous behavior, safety detection and status monitoring were successfully demonstrated.

It should be noted that the C&C for simulated inspection and repair tasks still need improvement to reach real NDT and required requirements. The automation control and interaction with NDT inspection sensors, such as Ultrasonic Testing (UT) and Alternative Current Field Measurement (ACFM), still need to be investigated and improved. For instance, to achieve full coverage accurate and reliable rolling contact fatigue crack inspection with ACFM, the development for inspection parameters of the vehicle speed, sensor angle and lift-off and should be carefully improved [24]. These studies will definitely support the future development of RIRS towards high technology readiness level.

4.3. Performance evaluation

In this sub-section, the key performance related to job reaching, action response, communication and motion safety reaction, listed in Table 4, in the whole maintenance job flow process are tested and analyzed with repetition tests.

4.3.1. Job reach & detect accuracy

The localization accuracy of the actual defect positions is essential and determines the job execution quality and efficiency. When the RIRS finishes its navigation and platform positioning at the defect locations, the distance from the robot arm tip to the defect is employed to describe the accuracy of job reaching. In the demonstration, the accuracy was assessed by measuring the distance between the QR code center point to the arm tip camera, which could be analyzed by an image processing technique using a calibrated QR code marking [23]. In this repetition of the fault-reaching tests, one QR code was fixed, and the RIRS platform was commanded to start from a start location at the track end (see Fig. 13(b)) and travelled 400 m to the QR code. The RIRS was controlled at a speed of 1m/s.

Fig. 22(b) shows the scatter plot of 30 repetition data, which shows the analyzed local coordinates on the QR code in the left image. The right one shows the X-Y scatter plot and the boxplot of each axis. The X coordinate denotes the direction along the track, while the Y coordinate denotes the direction across the track. The error along the track is with 0 cm of mean, maximum of 25 cm, and 10 cm between the 25th and 75th percentiles. It indicates the time difference uncertainty in the detection decision and its cooperation with brake control. The error cross track is with 5 cm of mean, maximum of 9 cm, and 5 cm between the 25th and 75th percentiles. This proves that the RIRS platform was drifting from left to right while rolling on-track. This fault-reaching performance of the RIRS demonstrates a satisfied vehicle control and this error range is covered by the payload arm movability for its repair actuation moves.

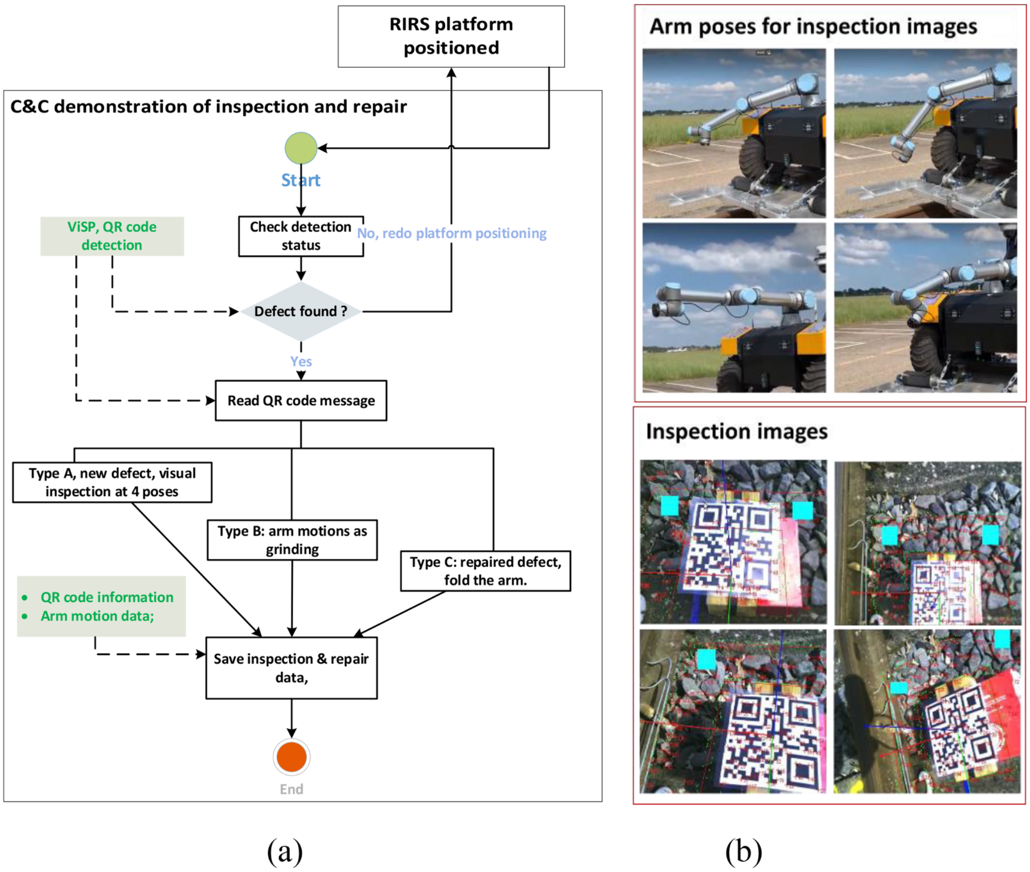


Fig. 20. Demonstration inspection & repair flowchart and results; (a) Flowchart; (b) Robot arm poses for image capturing of the type A defect.

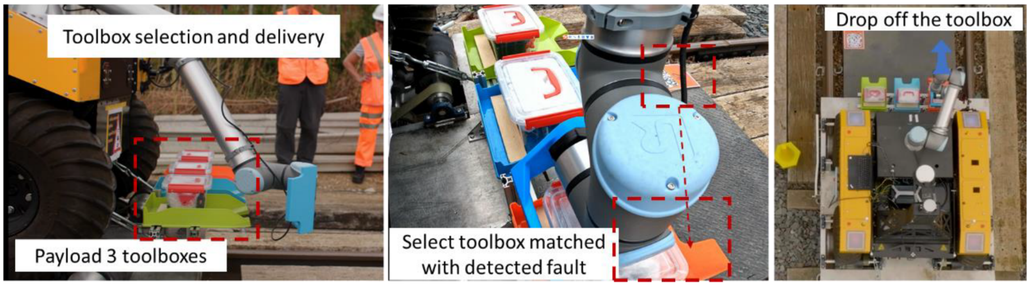
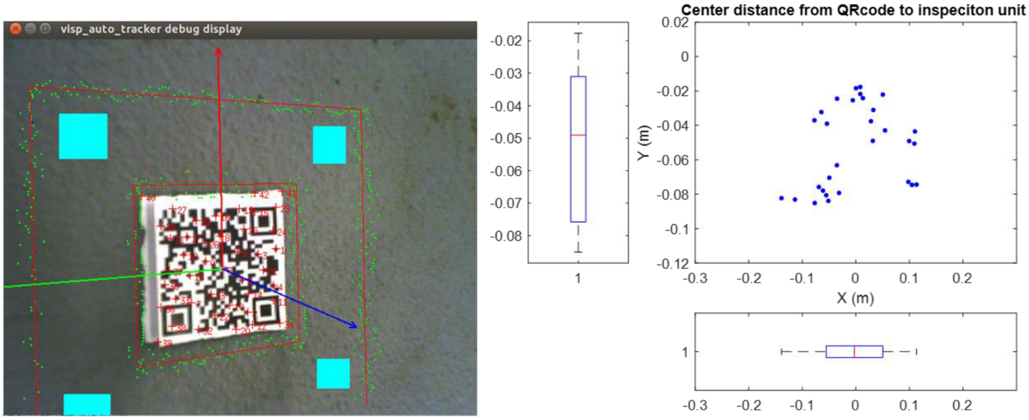


Fig. 21. The demonstration of Toolbox delivery testing.

Table 4
The key performance evaluation activities and method.

Key items	Measure activities	Evaluation
Job reach & detect performance	Repetition of reaching a fixed fault by executing the whole "Transit to job" process. The platform will arrive it and the inspection arm can accurately find it.	The payload arm will detect the fault with its camera. Analyzing the relative distance between it and camera with computer vision.
Action response efficiency	Several job-related key control and monitoring actions are tested to find out action response efficiency.	The time difference between vehicle end and operator end for several actions at 100m remote status are analyzed.
Remote C&C latency	A series of vehicle motion commands keeps sending at different remote distances. The command message at local vehicle end is measured and analyzed.	The latency, frequency, and data transfer bandwidth at the vehicle end are measured and analyzed.
Motion safety reaction	The vehicle platform collision avoidance range and blind spot is tested using different size obstacles.	The minimum distance and height of the recognized and avoided obstacles are tested.



(a) (b)

Fig. 22. The defect reaching accuracy; (a) The analyzed QR code centre position corresponding to image. (b) The repetition tests accuracy of distance from inspection camera to QR code centre.

For the payload control accuracy for inspection and repair execution, the investigation of the C&C on the robot arm precision has been conducted by previous work [23]. The previous work has proved that the payload manipulator can execute the repetitive maintenance motion (with different tool weights) of accuracy within 2 mm in 3D cartesian coordinates.

4.3.2. Action responses efficiency & remote communication

For the communication, the latency between the remote operator and the local vehicle on multiple commands and data feeding was tested. It was conducted by separating the RIRS vehicle and the operator at different distances. The same command was recorded on both ends to compare the time difference between sending and receiving. Fig. 23 presents the latency plot of the different communication distances of the same period of vehicle motion command. It indicates that the communication range limit is between 400 and 500 m based on the current hardware. Table 5 summarizes the communication performance in latency and message frequency variation at both ends. The maximum latency is almost 0.7 s at 400 m. At the 3rd & 4th columns, the average message frequency at both ends was compared. It indicates that there is a slight message loss at the remote end, which might affect the command performance. Fig. 24 shows the latency of multiple types of command messages and data. Based on the current 4G-LTE network communication, the video transfer and inspection data (visual inspection) are quite heavy for real-time operation with a latency of around 4s. These tests provide a basic operational performance analysis for the current system.

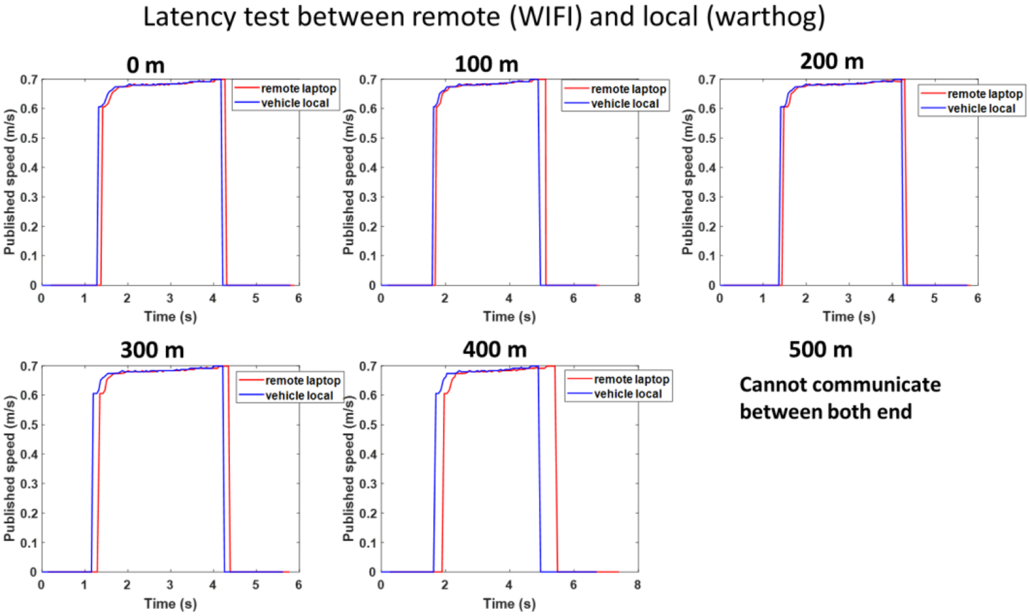
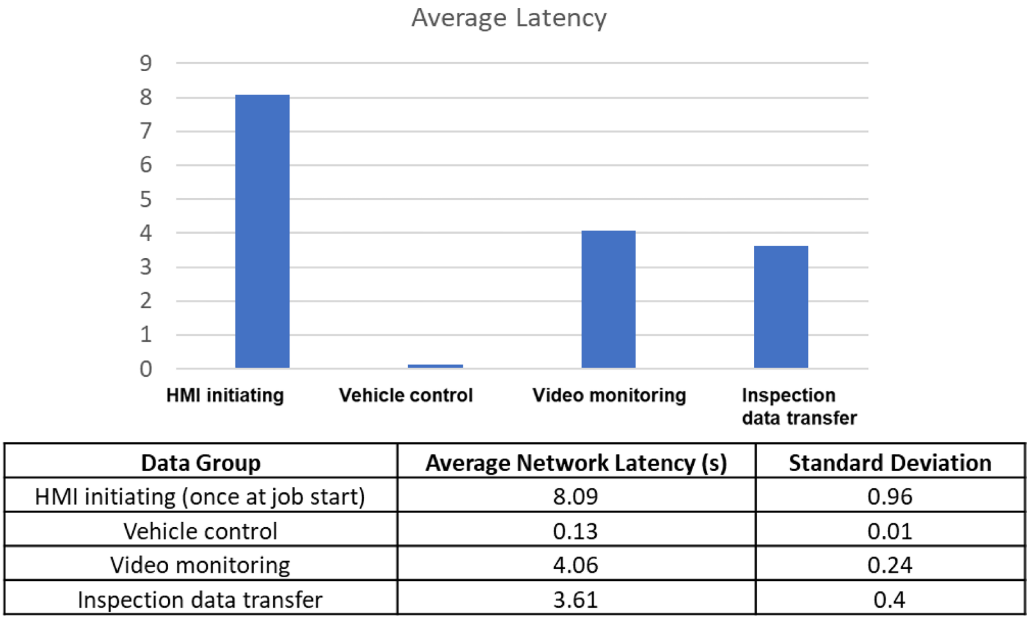


Fig. 23. Latency plot of same vehicle motion command on both ends.

Table 5
The latency and the message frequency difference.

	Max latency (s)	Average latency (s)	Average frequency (local)	Average frequency (remote)	Bandwidth
0 m	0.204	0.098	17.79	17.79	1.2MB / s
100 m	0.232	0.097	16.48	16.46	
200 m	0.338	0.088	17.56	17.46	140 -160 KB / s
300 m	0.407	0.139	17.01	16.67	
400 m	0.687s	0.399s	15.32	14.01	45–50 KB / s
500 m	Cannot build connection				

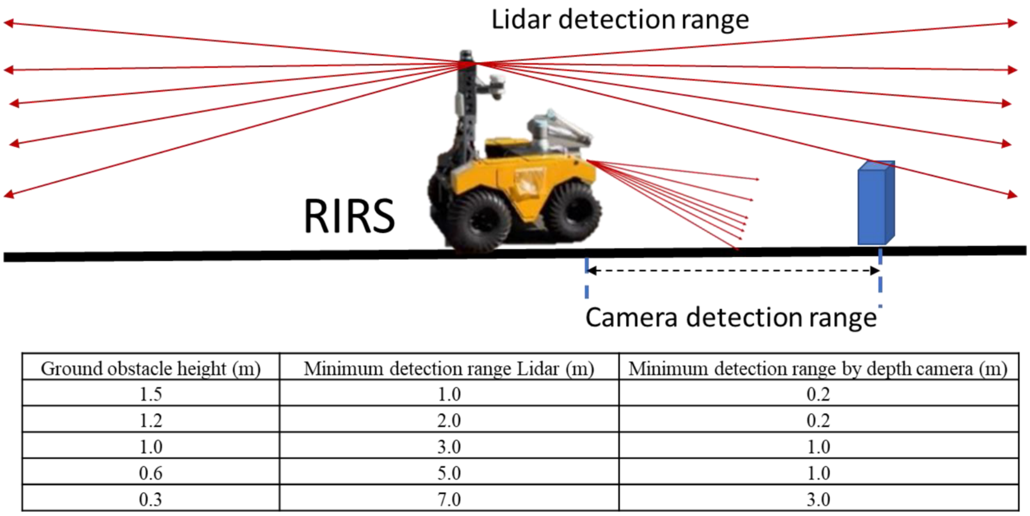


Data Group	Average Network Latency (s)	Standard Deviation
HMI initiating (once at job start)	8.09	0.96
Vehicle control	0.13	0.01
Video monitoring	4.06	0.24
Inspection data transfer	3.61	0.4

Fig. 24. The latency of different types of commands & data.

4.3.3. *Motion collision avoidance*

For the collision avoidance performance, the test to calibrate the robust minimum detection range of the Lidar and depth camera was also conducted in demonstration repetition tests. The 3D Lidar and stereo camera consists of combined range of sets for obstacle detection in the front and back. As the detection view of both sensors is fan angle range vertically due to its mount height as shown in



Ground obstacle height (m)	Minimum detection range Lidar (m)	Minimum detection range by depth camera (m)
1.5	1.0	0.2
1.2	2.0	0.2
1.0	3.0	1.0
0.6	5.0	1.0
0.3	7.0	3.0

Fig. 25. Collision avoidance detection range calibration.

Fig. 25, both sensors will have a blind range when it is too close to the vehicle body (illustrated by red lines in Fig. 25). The table in Fig. 25 shown below describes the robust minimum detection range corresponding to the obstacle height. It shows that the current system can robustly detect small objects with 0.3 m height. It should be noted that the avoidance detection was able to detect the object with a lower height using a more restrictive range setting. But it was found that this would cause unwanted false positive detection on the embedded track components like path crossing or track electrical box. To ensure a complete job execution without false positive detection, the current collision avoidance range is set as shown in the table of Fig. 25. In the future, the performance can be improved by introducing low trolley mounted sensors like sonar radars.

4.3.4. *Mobile manipulation inspection accuracy*

To furtherly evaluate and mobile manipulation accuracy develop the maintenance capability, a railway track 3D reconstruction method using robotic vision on a mobile manipulator was developed. The proposed method utilizes the RIRS sensing and payload system capabilities. Fig. 26 illustrates the workflow of this reconstruction use case. By following a scheduled maintenance job, the RIRS first autonomously navigates to the job location. RIRS stops navigation once the RGB-D camera detects the target object. Then by starting the modelling process, the RGB-D camera scans and evaluates the pose of maintenance targets to the robot. The measured target pose will then be used as a concentration centre to generate a reconstruction trajectory for the payload robot arm. Afterwards, the RIRS guides the manipulator to model the track component target by performing automated arm manipulation with a 3D scene reconstruction scheme. With the help of the arm-tip RGB camera, images with visible information (dimension, volume, color, surface condition) of the target will be acquired for 3D reconstruction. Then, to acquire an accurate model size, a scaling process is performed by referencing a site-measured dimension of the track gauge and sleeper. Finally, the 3D reconstruction is fused with target-surrounding sensing of the vehicle depth camera, 3D Lidar, and geo-location to acquire more digital twin information and compatibility to fuse with the current infrastructure database.

Fig. 27(a) presents the reconstruction work scenario using arm manipulation and vision camera. In the test, a track rail section was firstly 3D reconstructed by automatic arm orbiting control and vision sensing, as Fig. 27(b). The reconstructed rail section was compared with the its ground truth dimension to evaluate the reconstruction accuracy, shown as Table 6. This proves the system can achieve high accurate 3D reconstruction with error less than 3%. In another longer-range reconstruction, one side of track with total 6 m length was fully reconstructed with zig-zag arm manipulation marked as Fig. 27(c). The reconstructed 3D model was verified with real track objects with satisfied accuracy and efficiency, which can be used utilized as an autonomous digital twin model generator for the railway maintenance target to support inspection, condition monitoring, and track geometry survey. The detailed study can be found in the published paper [25]. This case proves the RIRS and C&C system has wide extension capability to deal with sophisticated maintenance execution.

5. Conclusion

A novel autonomous rail-road amphibious robotic system for railway inspection and repair using sensor fusion and mobile manipulation is designed and demonstrated in this paper. A comprehensive command and control system and high-level architecture were created to achieve the multifaceted workflow of railway maintenance tasks. The autonomous robotic inspection and repair system possesses various functionalities such as remote operation, sensor fusion, simultaneous localization, autonomous navigation, collision avoidance, payload actuator control, and human machine interface visualization. A demonstrator platform system consisting of a self-propelled unmanned ground vehicle and a track trolley was built to test the autonomy concept. At realistic and operational

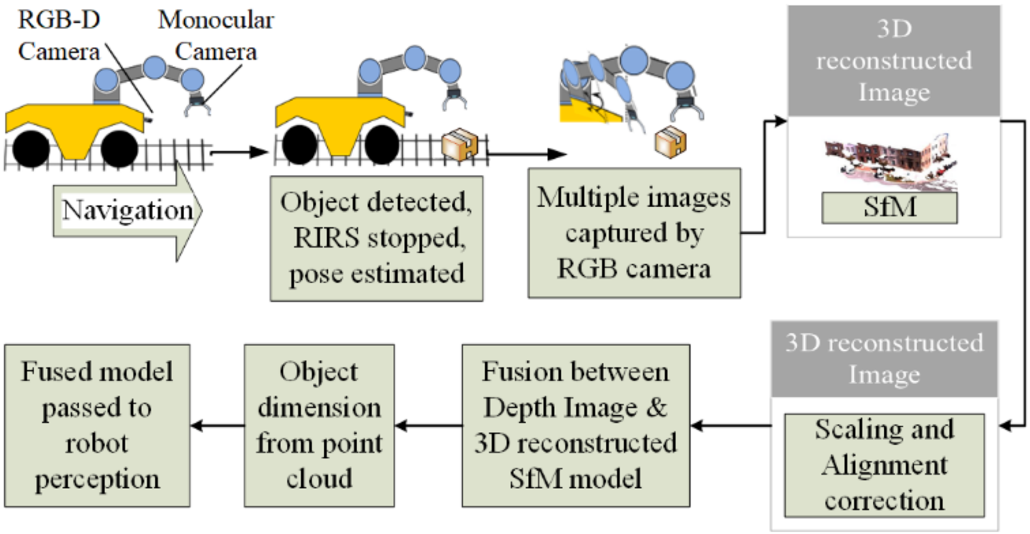


Fig. 26. The work flow of the proposed track component reconstruction method.

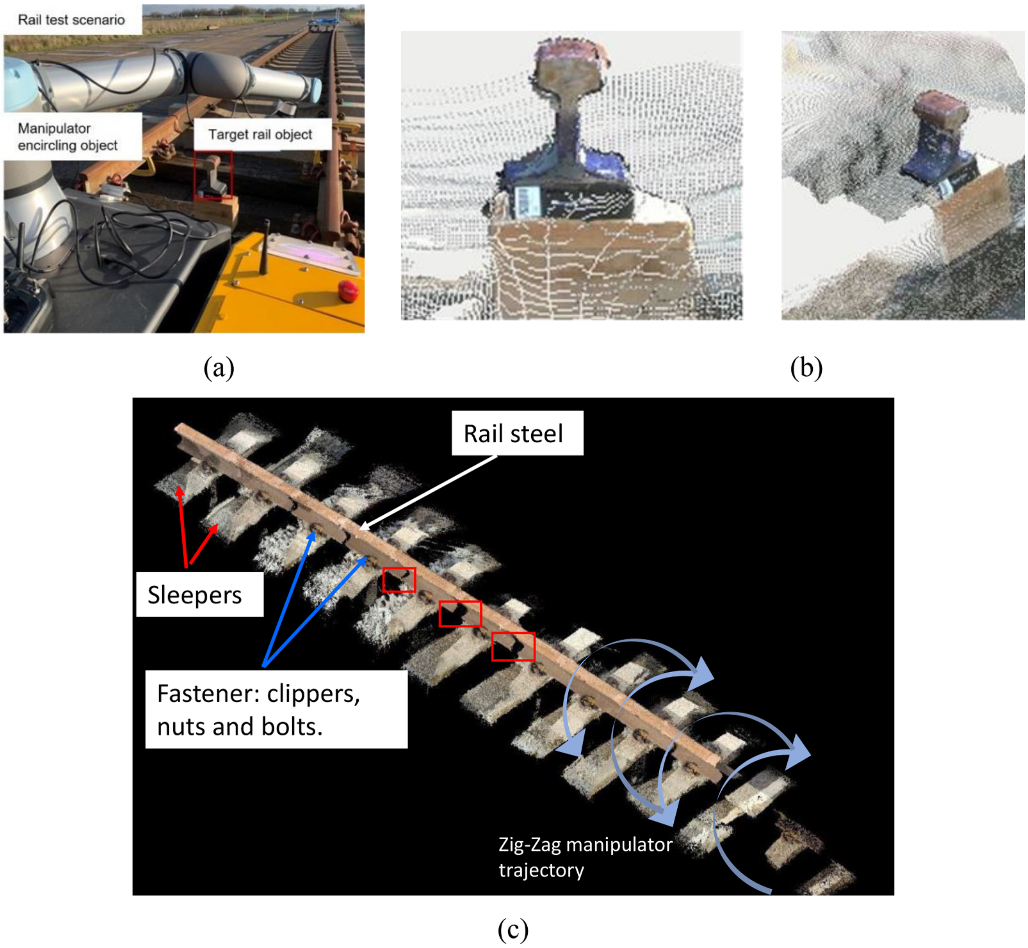


Fig. 27. The results of track component reconstruction; (a) The test scenario; (b) The reconstructed model of rail section; (c) The reconstructed model of one side of track [25].

Table 6
3D reconstructed accuracy compared with ground truth.

	Length (cm)	Width (cm)	Height (cm)
Ground truth	13.80	9.80	15.90
Reconstructed	14.16	9.97	15.95
Error	2.6%	1.7%	0.31%

railway test sites, the developed system was carefully tested validated. The successful demonstration included various maintenance execution-related behaviors, such as navigation, platform positioning, robot manipulator actuation, simulated defect inspection and repair, and obstacle avoidance. The findings clearly indicate that the command and control system effectively manages system to successfully execute each phase of the job while also enabling real-time monitoring of its status. The study examined and analyzed the performance of several critical command and control behaviors, including job-reaching, communication latency, collision avoidance, and robotic 3D reconstruction. The novel system introduces autonomous robotic operation in railway maintenance. This innovation is expected to significantly impact the execution methods of track maintenance tasks and potentially influence the rulebook through the integration of highly intelligent systems and AI technology.

The inspection performance compatibility with inspection non-destructive testing methods like ultrasonic testing or alternative current field measurement will be explored in future research and development. This research will also include practical *in-situ* repair tools like rail cutters and grinders.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

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