

Implementation and Demonstration of Autonomous Ultrasonic Track Inspection Using Cloud-based AI Rail Flaw Analyzer

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Abstract

This research successfully demonstrated autonomous rail inspection feasibility up to Technology Readiness Level (TRL) 7. A prototype integrating an autonomous rail vehicle and Sperry's Ultrasound Testing (UT) system was developed at Cranfield University. It was first tested at Cranfield's Railways Innovation Test Area (RITA) at TRL 5 and tested at heritage operational railway, in Idridgehay, Derbyshire, UK achieving TRL 7. Experimental works included a 15-meter track test at RITA and nine rounds demonstration of a 250-meter track inspection at Idridgehay, showcasing inspection, localization, navigation accuracy, and defect location precision. The prototype successfully detected artificial rail defect during the demonstration and promptly communicated to command centre via email. We characterised the vehicle performance by measuring the positional error and detection rate. The positional accuracy measurements, verified through GPS and odometry, revealed an odometry-based error of 0.27-3.2 metres and an 8-metre GPS-associated error. The absence of differential GPS and a data fusion approach contributing to these errors. In addition, Weak 4G signal coverage in the fields impacted operator-vehicle communication and data uploading. Future iterations should address these limitations, exploring alternatives for enhanced accuracy and advancing defect-sizing technology.

Keywords: Autonomous vehicle, railway inspection, ultrasonic inspection

1. Introduction

Railway traffic is an important part of the transport system. The increased rail transport demands have put considerable pressure on the existing infrastructure including tracks. As a result, the rail industry faces a significant challenge in inspection, maintenance, and improving track reliability.

Nowadays, track inspections can be undertaken through a combination of specialist track inspection vehicles, on-foot inspections and service train inspections. Nevertheless, they all require some level of intervention by a human worker. Labour-intensive operations significantly raise safety risk concerns and inspection costs. UK's Rail staff suffered 83 specified injuries on all rail networks from 2022 to 2023 based on the Rail Safety report from the Office of Rail and Road, UK [2]. Therefore, safety concerns were the primary change drivers in developing new inspection techniques. No rail workers will be injured if we introduce an autonomous rail inspection system. In the case of ultrasonic inspections, a specialist ultrasonic testing unit typically performs an initial survey, identifying fault suspects. These require manual operator location and scanning confirmation before a repair is enacted. Furthermore, the economic benefit motivates the development of the autonomous rail inspection system as another driver. Annual Efficiency and Financial Assessment (AEFA) from Network Rail (NR) has reported that they spent £2,089 million maintaining the condition and capability of the existing infrastructure to the previously assessed standard of performance from April 2022 to March 2023, underperforming by £214 million [3]. This underperformance can be

attributed to dealing with staffing disruption and compliance with internal safety standards.

Therefore, the academia and industry are dedicating to developing the autonomous rail inspection system to reduce pedestrian inspections, which can mitigate the above issues. Liu et al. developed an autonomous rail-road amphibious robotic system for railway inspection and maintenance tasks through integrating a track wheel accompanied unmanned ground vehicle with a robotic manipulator [4]. Rahman et al. analysed the dynamic principles of the system [5] and proposed a health assessment based on 3D reconstruction technology for railway track maintenance by combining multiple sensing and taking advantage of the robotic manipulator [6]. The developed system was 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 [4]. Furthermore, Durazo-Cardenas et al. integrated a commercially available ultrasonic instruments to the system and demonstrated the autonomous ultrasonic rail inspection at the Technology Readiness Level 5 [7], [8].

Based on these studies, the presented research aims to prompt the existing autonomous ultrasonic inspection functionality to a higher TRL for eventual potential commercialisation possibilities. The works encompassed the development and demonstration of a new autonomous inspection prototype with the integration of a commercial ultrasonic kit in an operational environment. It is worth noting that the presented paper does not involve the development of new inspection technology. Instead, it applied the

available ultrasonic rail inspection solution with the recent autonomous rail vehicle research advancements.

2. Methods

2.1. Inspection prototype development

The research discarded the previous prototype developed by Liu. et al [4] due to its poor dynamic performance in the test and cybersecurity vulnerabilities introduced by its Robot Operation System (ROS) 1 framework. A new generation prototype was then developed with the integration of an autonomous rail flatbed vehicle and an ultrasound testing system from Sperry®.

2.1.1. Autonomous Rail vehicle

A manual-controlled motorised trolley from BANCE® was procured and upgraded to an autonomous robot platform which supports self-navigation and obstacle avoidance functions as shown in Figure 1. This vehicle is lightweight, battery-powered, and capable of carrying a payload of up to 830 kg while reaching speeds of up to 8 km/h. In order to implement autonomous driving function easily, seven speed levels were pre-defined covering the vehicle speed range.



Fig.1 Autonomous Rail Trolley, equipped with LiDAR, GPS, Encoder and Camera

2.1.2. Ultrasonic Inspection System

A commercial ultrasonic rail inspection system from Sperry® Rail Inc. was utilised and integrated with the autonomous rail vehicle. The inspection kit consists of a tablet as a data and control centre, batteries, a water tank, two Sperry Proprietary Ultrasonic 9 Probe Array (UX9) Roller Search Units (RSUs) and one walking stick to house RSUs. This inspection kit can record the echo signals with the corresponding GPS and odometry tags. Sperry's cloud AI rail flaw detection system, Elmer®, provides the software support to process the data collected by RSUs.

2.1.3. System integration

Given that the autonomous vehicle and UT system are two distinct systems that were not originally

intended for integration, the appropriate mechanical and electrical interfaces are necessary to facilitate their seamless integration.

The walking stick and trolley platform are joined using two aluminium angle components as the mechanical integration. The tablet, batteries and water tank are accommodated on the vehicle front platform and secured in place with a foam energy absorber to suppress vibrations. Since the UT system does not inherently possess an autonomous inspection function, the research establishes a serial port communication interface between the vehicle and UT system to facilitate the control of the inspection procedure start and stop functions. Three string commands are employed. Initially, UT system transmitted the 'CTR_RD' command to the vehicle to indicate that inspection kit is on standby. Subsequently, the vehicle sends the 'CTR_ST' command to the UT system to initiate the inspection process, while the 'CTR_SP' command is used to terminate data collection. The integrated prototype is shown in Figure 2.



Fig.2 Integrated autonomous ultrasonic rail inspection system prototype

2.2. Experimental works

2.2.1. Test Site and flawed track information

The demonstration was conducted on a heritage railway situated at Idridgehay, Derbyshire, UK, owing to the presence of pre-existing calibration and test tracks containing multiple defects. Pre-installed three rails, consisting of the flawed track section, spanned a total length of approximately 15 meters. Table 1 lists the information about the artificial defects present in the three rails. The inspection results can be analysed by making a comparison with this data.

2.2.2. Test setup

Approximately 250 metres of test track was used for the demonstration. The prototype departure position was established approximately 150 meters before the defective rails, while the end of the test was 250 meters from the starting point across a bridge. This location was selected due to better

signal coverage beyond the bridge, facilitating the UT system's data upload to the cloud analyser.

Table 1 Defects summary for the rails onsite

Rail No.	Defect location	Defect Type	No. of Defects	Specifications
1	Rail End	Inclined flat bottom hole	2	
1	Rail Head	Through Hole	4	Φ6, 500mm interval
2	Rail End	Inclined flat bottom hole	1	
2	Rail foot (Lower Surface)	Slot	2	Two slots of 5mm depths with 500mm interval
2	Rail End's head	Flat bottom hole	4	Φ5, 100mm depth

Several cones were positioned alongside the tracks to identify specific locations. The precise distances separating the cones are listed in Table 2.

Table 2 Specific locations and corresponding cones

Cone	Distance from the base (m)	Representation
Yellow	97.1	Approaching phase endpoint
Red	146.15	Starting point for inspection
Blue	172	Endpoint for flawed rails
White marker near the track	253.9	Endpoint for test

2.2.3. Test sequence

Figure 3 depicts a vehicle speed diagram during the demonstration with the communication commands between the vehicle and the UT system. It is divided into three stages: Approaching stage, Inspection and data transmission stage, and Return stage. The inspection speed was set higher than the approaching speed because the UT system requires a minimum data collection speed of 5 km/h. If the vehicle speed is not increased to meet this requirement, the UT system may incorrectly identify the fishplate joint as a defect.

Figure 4 show the corresponding sequence flow chart, the UT system issued a 'CTR_RD' command to the vehicle when the prototype was positioned at the base and remained in a standby state. The operator then initiated the sequence command to commence the procedures. During Stage 1, the approaching phase, the vehicle proceeded from the base to the yellow cone position at speed level 4 until it reached the yellow cone, where it stopped momentarily before resuming acceleration to reach speed level 6 prior to the red cone. At this point, the vehicle transmitted the "CTR_ST" command to the UT system to initiate data collection at the red cone location. The prototype then continued to propel the probes at speed level 6 until it reached the blue cone and issued the "CTR_SP" command to cease inspection work. Subsequently, the vehicle reduced its speed to level 4, arriving at the data uploading point, which marks the end of the test track. The prototype remained in this location for a duration of 2 minutes to enable the uploading of the recently collected data. Finally, the prototype returned to the

base at a speed level 4 and remained in standby mode, awaiting further instructions.

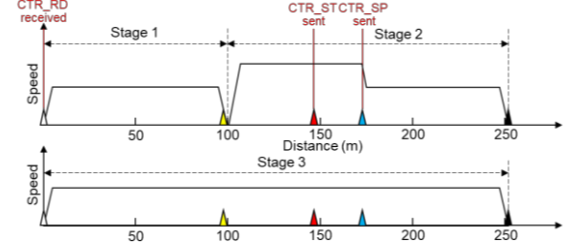


Fig.3 Speed diagram of the demonstration. The horizontal coordinate represents the distance of the prototype from the departure point.

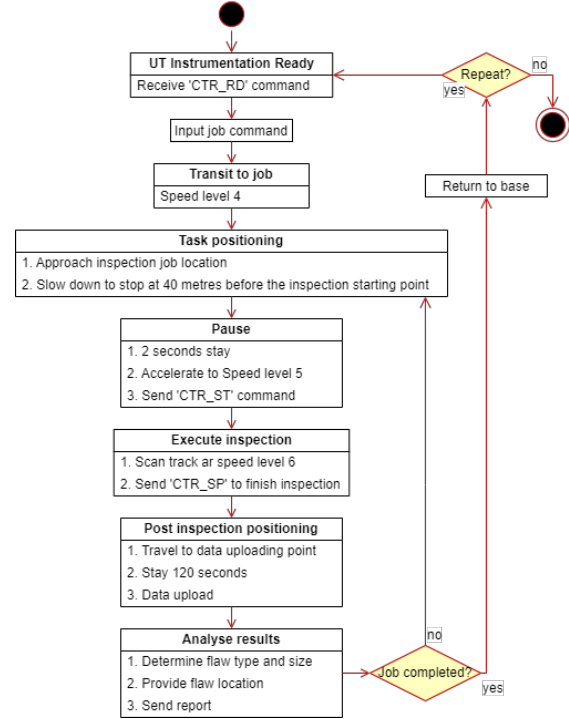


Fig.4 Flow chart of the sequence in the demonstration

3. Results and Discussion

Nine iterations of the tests were conducted in the demonstration, each executed accurately. The repetitive trials substantiated the practicality of the autonomous rail inspection system. Nonetheless, in the first seven rounds of testing, the data uploading phase failed because of the weak communication signals, preventing UT system from establishing a connection to the network. To address this issue, a mobile hotspot was employed to provide mobile network access to UT system in the final two

experiments. As a result, in the eighth trial, the data was uploaded manually to the cloud-based analyser, while in the last iteration, the data was uploaded automatically upon the prototype's arrival at the designated data uploading location.

3.1. Navigation accuracy investigation

3.1.1. GPS accuracy investigation

A measurement of vehicle GPS localisation accuracy was conducted while the prototype was stationary in RITA before the demonstration on the heritage railway. The GPS sensor detected a total of 20 satellites, of which 19 were used for localisation during this measurement. Table 3 showed the actual and measured latitude/longitude coordinates with the error.

	Actual GPS sensor location	Measured GPS sensor location	Error (m)
Latitude	52.066605	52.066610	1.91
Longitude	-0.626347	-0.626324	

The localisation error was found to be approximately 1.91 metres. Despite the use of 19 satellites for localisation, the performance of the single GPS sensor used in the prototype is insufficient for practical autonomous inspection applications. Unfortunately, the GPS accuracy got worse at heritage railway, Idridgehay, with initial coordinates offset by approximately 15 metres and gradually diminishing to roughly 8 metres before stabilising at this level. Therefore, it is recommended to implement a differential GPS combined with odometry to improve the localisation performance to an acceptable level.

3.1.2. Odometry accuracy investigation

Although the sequence was executed without issue, the positional deviation was an area of concern that necessitated further investigation. Notably, upon each return of the prototype to its base, it came to a stop at a slightly different position from its initial starting point. As shown in Table 4 and Figure 5, the corresponding error was collected and analysed quantitatively.

11 valid error data were collected from the rehearsals and tests. The positive and negative values indicated that the prototype either stopped before or surpassed the starting point, respectively. Notably, the error distribution appeared to be relatively arbitrary, spanning from -1.45 to 3.2 metres. The average error was approximately 0.29 metres. However, when accounting for the absolute value of the error, the mean value increased to 1.1 metres. The source of the observed odometry error was determined to be wheel slippage during the trolley operation.

Table 4 Error summary for 11 tests

	Test No.	Error (m)	Absolute error (m)
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Rehearsal	1	3.2	3.2
	2	1.7	1.7
Test	1	-0.85	0.85
	2	-0.5	0.5
	3	-1.45	1.45
	4	1	1
	5	-0.27	0.27
	6	-0.52	0.52
	7	-0.84	0.84
	8	1.05	1.05
	9	0.72	0.72
Mean		0.29	1.1

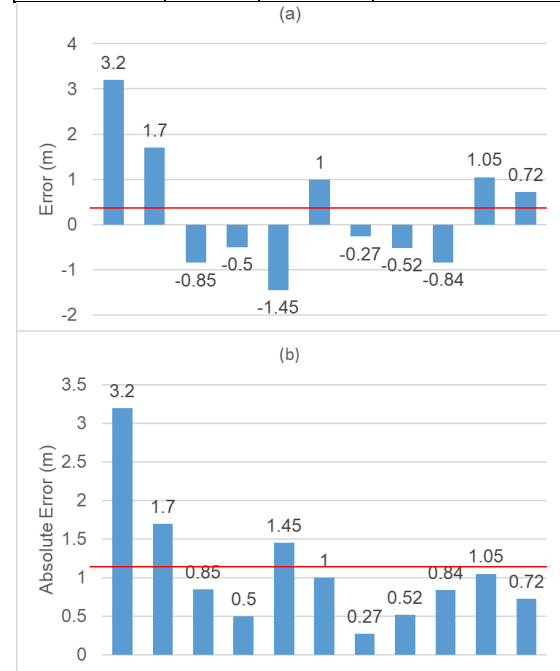


Figure 5 Measured Error of each test (Red line represents the mean value)

3.2. Inspection results investigation

In the demonstration, the data collected from the final test iteration was successfully uploaded to Elmer®. This dataset was subsequently employed to identify rail defects. The defect size was estimated, the defect type was classified, and a final defect list comprising the defect type, size, and location information was automatically generated. Following data processing, the suspect list was automatically forwarded to a designated email address (utreport@cranifled.ac.uk).

Upon completion of the sorting process, the defect information has been organized and part of them are presented in Table 5. The term 'measured intervals' refers to the distance between a given defect and the preceding defect that was detected.

Table 5 Detected defect list for the right rail

Detected Defect No.	Artificial defects	Suspect type	Odometry distance to the first suspect (m)	Measured intervals from Odometry (m)	GPS Distance to the first suspect (m)	Measured intervals from GPS (m)
1		70Cluster	0	0	0.00	0.00
2		Bolt Hole Crack (BHC)	0	0	0.09	0.09
3		Transverse Defect (TD)	0	0	0.20	0.11
4	Through hole	70Cluster	0.8	0.8	1.88	1.67
5	Through hole	70Cluster	1.28	0.48	1.88	0.00
6	Through hole	TdSmall	1.76	0.48	1.88	0.00
7		TD	1.76	0	1.88	0.00
8	Through hole	70Cluster	2.24	0.48	1.88	0.00
9		70Cluster	5.12	2.88	5.45	3.57
10		TdSmall	5.12	0	5.52	0.07
11		BHC	10.88	5.76	11.52	6.00
12		BHC	14.24	3.36	14.75	3.23
13		BHC	14.72	0.48	15.09	0.33

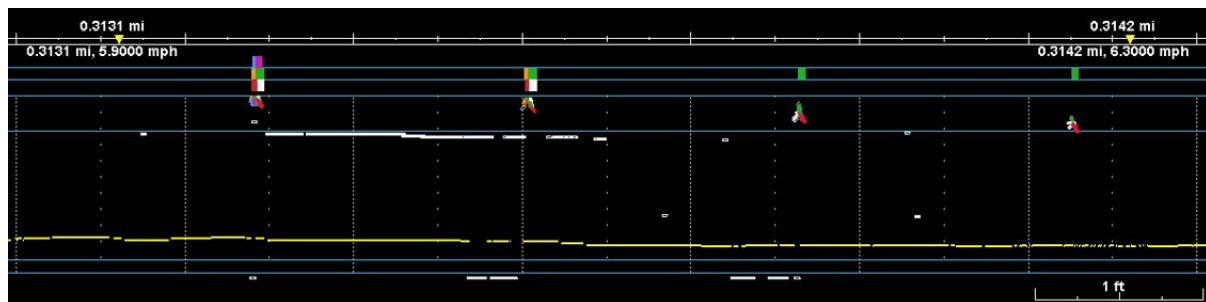


Fig.6 B-Scan images for the through-hole defects at the rail head of the right rail. Different colour marks represent the correct trigger of probes at different angles.

A total of 28 defects were detected on the track, with 13 presents on the right rail and the remaining 15 on the left rail. Comparing the detected and actual defects, we could find all through holes in both the left and right rails were detected successfully. For instance, Figure 6 presents a B-Scan image captured during the inspection, highlighting the UT system's successful detection of through-hole defects on the rail head of the right rail.

On occasions, the system may classify a single defect occurring as distinct categories, denoting them, for instance, as No. 6 and No. 7 defects in the right rail. Regrettably, due to the limited available data, the research was unable to establishing a correlation between the other potential suspects and the actual defects.

As for the defect localisation, it becomes apparent that there is a lack of consistency between

the odometry and GPS data with respect to the location of each individual defect. Our level of confidence in the odometry data exceeds that of the GPS data, primarily due to the fact that the GPS sensors of the UT system were placed on the vehicle, providing a relatively accurate approximation of its position rather than that of the probes. Moreover, it is important to note that the GPS data was derived from the nearest available latitude and longitude coordinates, thus introducing a certain degree of measurement imprecision.

With regards to the positioning derived from the odometry data, as illustrated in Table 5, it can be observed that the measured intervals between Defect No.4 and Defect No.8 remain consistent at 0.48m. This value is almost identical to the actual intervals of 0.5m. This outcome serves to confirm the

accuracy of the UT system's odometry-based positioning methodology.

4. Conclusions and Contributions

The presented research aimed to demonstrate the feasibility of autonomous rail inspection at TRL 7, which was successfully achieved. An autonomous ultrasonic rail inspection prototype was developed by integrating an autonomous rail vehicle and a commercial UT system. Mechanical, electrical and communications integrations between the vehicle and the UT system were achieved both physically and architecturally. The assembled prototype was tested its inspection capabilities at the calibration track at Idrighay heritage railway at operational environment, complying with TRL 7. The system's performance, including the vehicle's localization and navigation accuracy, inspection capacity, and defect location accuracy, was investigated during the demonstration. The following conclusions can be drawn:

- Autonomous rail inspection functionality has been demonstrated up to TRL 7.
- A novel autonomous rail inspection system was developed, utilizing a commercial UT system and an autonomous rail vehicle. The prototype was carefully calibrated and rigorously tested.
- During a demonstration on the heritage track, the prototype successfully detected artificial rail defects, generating a downloadable suspect list that was promptly communicated to the operator via email.
- The prototype's positioning accuracy was thoroughly investigated using GPS and odometry techniques. The odometry-based positional error was found to range between 0.27 and 3.2 metres in the Idrighay area, while the largest error, around 8 metres, was associated with GPS measurements.

The following rectifiable limitations were found:

- The prototype's localization accuracy was limited by the absence of differential GPS, which resulted in large errors in the GPS positioning. To improve positioning performance, a potential solution is to apply differential GPS, install encoders on trailing wheels, and fuse data from IMU, GPS, and odometry sensors. Alternative solutions include track-side object detection relative to LiDAR and ballast pattern recognition.
- The prototype demonstrated the capability to provide an initial estimation of the defect size, although it cannot provide an exact

measurement. The development of automatic defect sizing capability is still required with the utilisation of more advanced algorithms, more extensive datasets and test procedures to enhance accuracy and precision.

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- Communication signal strength was found to be extremely weak, thereby adversely affecting both the operator-vehicle communication and data-uploading procedure of the Sperry system.

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