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Assessing Regulatory Readiness for Autonomous Railway Inspection and Maintenance Systems

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Abstract

Robotics and Autonomous Systems (RAS) are being deployed across multiple sectors, yet regulatory and product acceptance frameworks remain fragmented and often provide only partial coverage. This creates uncertainty and can hinder the adoption of autonomous technologies. This paper presents a structured roadmap methodology for assessing regulatory coverage and identifying gaps in existing RAS frameworks. Developed through a review of cross-sector literature and stakeholder engagement, the methodology combines system definition, regulatory mapping, gap analysis and framework prioritisation. A railway inspection and maintenance vehicle use-case is used to demonstrate its application. The results show that existing standards provide substantial coverage for conventional engineering domains, including communications, power systems and sensing technologies, but reveal notable gaps relating to artificial intelligence, adaptive systems, autonomous decision-making and safety-critical assurance. The proposed approach provides a repeatable method for evaluating regulatory readiness, prioritising framework development activities and supporting greater cross-sector harmonisation of RAS assurance practices.

Keywords: robotics and autonomous systems, product acceptance, regulation, policy, railways, autonomous inspection, safety assurance, artificial intelligence.

1 Introduction

Robotics and Autonomous Systems (RAS) are increasingly being adopted across transport, manufacturing, construction, agriculture, defence and critical infrastructure sectors to deliver economic growth, social progress, and to improve national security and resilience [1]. Advances in sensing technologies, communications, artificial intelligence (AI), machine learning (ML) and autonomous control have enabled RAS to perform tasks that traditionally required human intervention, creating further opportunities to improve safety, productivity and operational efficiency. However, the pace of technological development has exceeded that of the regulatory landscape, resulting in an uncertain path to deployment.

Recent policy and industry reports identify regulation and product acceptance as major barriers to RAS adoption. Existing frameworks provide limited support for autonomous decision-making, adaptive behaviour and AI-enabled safety-critical systems, leading to bespoke assurance processes, inconsistent regulatory practices and increased deployment costs [2,3].

Although numerous standards, regulations and codes of practice exist, they typically address individual technologies or sectors rather than RAS as integrated systems. While the diversity of applications makes a single universal framework difficult to achieve, many RAS deployments share common requirements, including communications, cybersecurity, perception, autonomous control, human-robot interaction and safety assurance. This creates opportunities for greater cross-sector harmonisation of regulatory and product acceptance frameworks.

The railway sector provides a representative example of these challenges. Autonomous systems are increasingly being considered for inspection, monitoring and maintenance activities to improve safety, operational efficiency and asset management [4,5,6]. However, deployment within the highly regulated railway environment introduces assurance challenges relating to autonomy, reliability, cybersecurity, human oversight and liability. While existing railway standards provide strong coverage of conventional engineering systems, their applicability to AI-enabled and adaptive autonomous systems remains uncertain.

To address this issue, a roadmap methodology is proposed for assessing regulatory coverage and identifying regulatory gaps in RAS deployments. Developed through a review of cross-sector literature, stakeholder engagement and analysis of existing standards, the methodology combines system definition, regulatory mapping, gap analysis and framework prioritisation within a structured assessment process. A Rail Inspection and Maintenance Vehicle (RIMV) use case is used to demonstrate the methodology and evaluate its effectiveness. The objectives of this study are:

1. Develop a methodology for assessing RAS regulatory and product acceptance coverage.
2. Quantify and prioritise regulatory gaps.
3. Demonstrate the methodology using a railway inspection and maintenance vehicle use-case.
4. Identify opportunities for cross-sector harmonisation of RAS assurance and regulatory practices.

2 Methods

2.1 Research Approach

The objective of this research was to develop a structured methodology capable of assessing the appropriateness of existing regulatory and product acceptance frameworks for Robotics and Autonomous Systems (RAS). The research adopted a mixed-methods approach that combined a review of published literature with stakeholder engagement and practical application through a railway use-case. The methodology was designed to identify regulatory coverage, quantify regulatory gaps, and prioritise future framework development activities using a repeatable and systematic process. The research was undertaken in four stages:

- Review of academic, policy and regulatory literature relating to RAS governance and assurance.
- Collection of stakeholder perspectives through surveys and semi-structured interviews.
- Development of a regulatory gap assessment roadmap.
- Demonstration of the methodology using a railway inspection and maintenance vehicle (RIMV) use case.

2.2 Literature Review and Stakeholder Engagement

A mixed-methods approach was used to develop and validate the proposed regulatory gap assessment methodology. The research combined a review of government, industry and academic literature with stakeholder engagement to identify common RAS regulatory challenges and define the constituent elements of a cross-sector assessment framework. More than forty key sources were reviewed, including governmental reports, policy papers, academic studies, industry white papers and regulatory publications (Table 1).

Research Activity	Quantity
Governmental reports, policy papers and regulatory publications reviewed	16
Academic papers and technical reports reviewed	16
Industry white papers and strategy documents reviewed	5
Total principal literature sources reviewed	43
Survey respondents	19
Interview participants	9
Industrial sectors represented	8
Standards, regulations, specifications and codes of practice reviewed during regulatory mapping	>150

Table 1: Research sources used in the development of the roadmap methodology.

The review identified recurring challenges, including the absence of dedicated RAS regulatory frameworks, uncertainty around liability and accountability, assurance of autonomous decision-making, trustworthy AI, and the need for interoperability and common standards. It also highlighted support for principles-based, technology-neutral regulation.

These findings were confirmed through surveys and semi-structured interviews involving 19 stakeholders from the rail, defence, aerospace, automotive and consultancy sectors. Participants represented developers, deployers and users of RAS, providing perspectives on adoption barriers, regulatory challenges, product acceptance practices and key system constituents.

Following the survey, nine stakeholder interviews were conducted to validate the findings and obtain further insight into regulatory challenges across sectors. Participants collectively possessed experience spanning rail, defence, construction, automotive, highways, mining, aerospace and manufacturing environments. Stakeholders consistently highlighted concerns regarding regulatory uncertainty, the pace of technological development, accountability for autonomous decision-making, and the adequacy of existing frameworks for artificial intelligence-enabled systems.

The findings from the literature review and stakeholder engagement informed the development of the roadmap methodology and the identification of thirteen core RAS constituent groups used throughout the subsequent regulatory assessment process.

2.3 Development of the Regulatory Gap Assessment Roadmap

The proposed methodology was developed as a structured sequence of analytical stages designed to assess the level of regulatory coverage associated with a particular RAS application. The roadmap consists of six principal stages, shown in Figure 1. The methodology was intentionally developed to be technology-neutral and capable of being applied across different industry sectors and operational contexts.

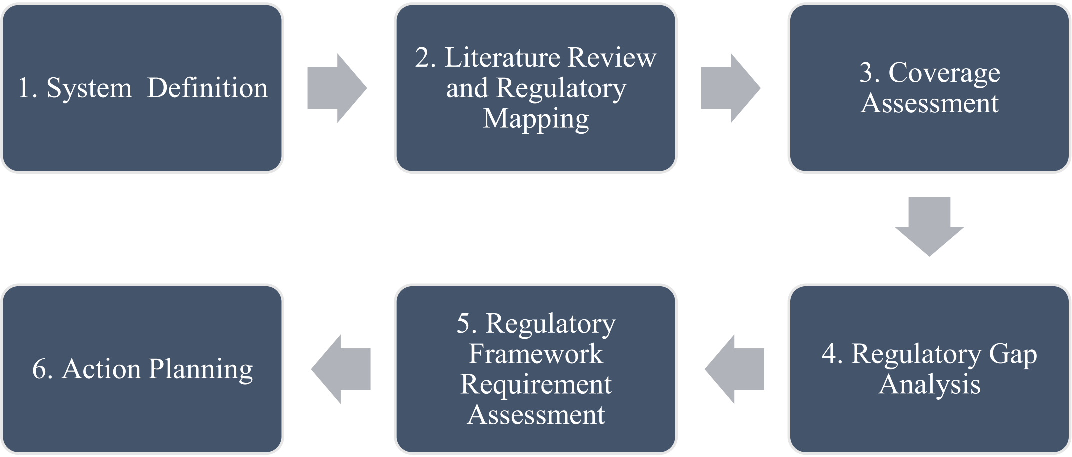

Figure 1: Roadmap methodology developed to identify, quantify and prioritise regulatory gaps associated with Robotics and Autonomous Systems.

2.4 System Definition

The first stage of the methodology involves defining the system under assessment. An initial high-level review is undertaken to identify the principal functions and technologies comprising the RAS. Where adequate regulatory coverage can be readily demonstrated, further analysis may be unnecessary. However, where uncertainty exists, a detailed system definition is undertaken. The detailed system definition decomposes the RAS into constituent functional areas. Based on stakeholder consultation and literature review, the following constituent groups were identified:

- Communication & networking
- Cybersecurity
- Navigation and positioning.
- Power systems.
- Learning and adaptation modules
- Electromagnetic compatibility
- Environmental management
- Interoperability

- Perception systems
- Control systems and actuation
- Safety, reliability and ethical governance
- Motion
- Human–robot interfaces

2.5 Literature Categorisation and Regulatory Mapping

The next stage involves identifying relevant legislation, standards, specifications and industry guidance that apply to the system being assessed. Documents are classified according to whether they provide a) Universal coverage, applicable across multiple sectors and b) Sector-specific coverage, applicable only within a particular industry.

Regulatory coverage is then mapped against each requirement identified during system definition. The assessment considers both direct coverage, where specific requirements are explicitly addressed, and indirect coverage, where standards provide broader principles or guidance relevant to the requirement under consideration. This process enables the creation of a comprehensive regulatory coverage matrix linking system requirements with existing regulatory instruments.

2.6 Regulatory Gap Analysis

Following completion of the regulatory mapping exercise, gap analysis is performed to identify areas where no relevant regulatory coverage could be found. The regulatory gap is calculated as (equation 1):

$$\text{Regulatory Gap (\%)} = \frac{\text{Number of uncovered requirements}}{\text{Total number of identified requirements}} \times 100 \qquad (1)$$

This approach enables a quantitative assessment of the adequacy of existing frameworks and facilitates comparison between different constituent groups. Constituents exhibiting higher proportions of uncovered requirements are deemed to require greater regulatory attention. In addition to calculating overall regulatory coverage, separate assessments can be undertaken for universal and sector-specific regulations, providing a clearer understanding of where deficiencies originate.

2.7 Regulatory Framework Requirement Assessment

To support prioritisation of framework development activities, the methodology incorporates a Regulatory Framework Requirement (RFR) assessment. The RFR assessment combines two indicators:

- Assurance Challenge Level (ACL)

The ACL assesses the challenge associated with assuring a system based on level of autonomy and safety criticality. Higher autonomy and greater safety criticality result in higher assurance challenge levels.

- Regulatory Gap Impact (RGI)

The RGI evaluates the impact of identified regulatory gaps based on the magnitude of regulatory deficiency and degree of deployment under current frameworks.

Systems exhibiting significant regulatory deficiencies and limited deployment receive higher RGI ratings. The ACL and RGI are combined to determine an overall Regulatory Framework Requirement level. This provides a prioritisation mechanism that identifies whether existing standards require clarification, modification or complete redevelopment.

2.8 Railway Use Case Demonstration

To demonstrate the practical application of the methodology, a Rail Inspection and Maintenance Vehicle (RIMV) was selected as a representative RAS deployment [7], (Figure 2). The use case was based on an autonomous track-mounted vehicle for railway inspection and maintenance. The RIMV was assessed using each stage of the proposed roadmap, including system definition, regulatory mapping and coverage analysis. The results were used to evaluate the methodology and identify areas where existing regulatory frameworks provide limited support for autonomous railway systems.

Figure 2: RIMV autonomous vehicle conducting a demonstration inspection at a heritage test railway.

3. Results

3.1 Application of the Methodology to the Railway Use-Case

The proposed roadmap methodology was applied to a Rail Inspection and Maintenance Vehicle (RIMV) use case to evaluate regulatory coverage and identify framework gaps. The RIMV comprises sensing, communications, autonomous navigation, control, actuation and AI-enabled functions representative of modern autonomous railway systems [8]. The assessment involved decomposing the system into thirteen constituent groups and mapping them against more than 150 standards, regulations and guidance documents from both universal and railway-specific sources. This enabled a quantitative assessment of regulatory coverage and the identification of areas where existing frameworks provide limited support for autonomous railway applications.

3.2 Regulatory Coverage Assessment

The literature mapping process demonstrated that substantial levels of regulatory coverage already exist for many constituent elements of the RIMV. Strong coverage was identified for traditional engineering disciplines including power systems, communications, networking, environmental management, electromagnetic compatibility, perception systems and interoperability. These domains are supported by mature international standards and well-established railway-specific requirements. The overall results indicated:

- Universal regulatory coverage: 88.68%
- Railway sector-specific coverage: 81.13%
- Overall regulatory gap: 7.02%

These findings suggest that most technological components required for deployment of autonomous railway inspection systems are already addressed by existing standards and assurance frameworks. The high level of universal coverage demonstrates considerable commonality between railway systems and RAS applications deployed in other industries. The results therefore support the proposition that future RAS framework development should focus on areas where current regulations provide limited coverage rather than attempting to replace existing engineering standards.

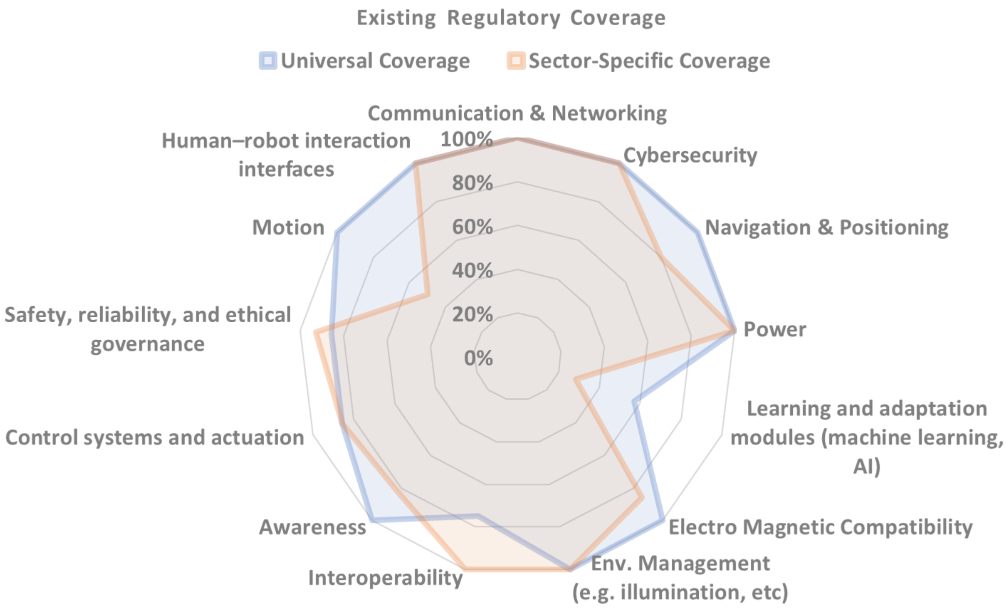

Figure 3: RIMV existing regulatory coverage

3.3 Analysis of Regulatory Gaps

Although existing standards provide substantial coverage, important gaps remain in areas related to autonomous and adaptive behaviour (Figure 3). The most significant gaps were associated with learning and adaptation systems, particularly AI-enabled decision-making, adaptive algorithms, explainability and assurance of self-evolving systems. Additional gaps were found in adaptive control and software assurance, as well as the governance of AI in safety-critical applications. These findings indicate that the primary challenge for future RAS assurance lies in regulating intelligent autonomy rather than conventional hardware technologies.

3.4 Regulatory Framework Requirement Assessment

Following the gap analysis, a Regulatory Framework Requirement (RFR) assessment was conducted using the Assurance Challenge Level (ACL) and Regulatory Gap Impact (RGI) framework. For the RIMV, both the level of autonomy and safety criticality were assessed as medium, resulting in ACL = 3. The identified regulatory gaps, particularly those relating to autonomous decision-making and safety assurance, were considered to have a significant impact on deployment, resulting in RGI = 3.

Combining these scores produced an overall classification of RFR = 3. An RFR3 classification indicates that existing frameworks provide substantial but incomplete coverage and require significant enhancement rather than minor revisions. Addressing these gaps will require coordinated action involving regulators, standards bodies, industry stakeholders and subject-matter experts. This finding is consistent with survey and interview feedback, which highlighted AI assurance, liability and autonomous decision-making as key regulatory challenges across multiple sectors.

3.5 Cross-Sector Implications

The regulatory challenges identified for the railway use case were also evident in other sectors, particularly defence, construction, aerospace and nuclear applications. Common concerns included accountability, explainability, predictability and assurance of autonomous decision-making. The high level of universal regulatory coverage suggests considerable scope for cross-sector harmonisation. Existing standards provide a strong foundation for communications, cybersecurity, perception systems and interoperability, allowing future efforts to focus on gaps associated with AI-enabled autonomy and adaptive behaviour. These findings support the adoption of a common cross-sector assessment methodology complemented by sector-specific requirements where necessary. Such an approach could improve consistency, reduce duplication and support the safe deployment of RAS across multiple industries.

4. Conclusions and Contributions

This study developed and demonstrated a structured roadmap methodology for assessing regulatory coverage and identifying regulatory gaps in RAS. The methodology combines system definition, regulatory mapping, gap analysis and prioritisation within a repeatable, cross-sector assessment process.

Application of the methodology to a Rail Inspection and Maintenance Vehicle (RIMV) demonstrated high levels of existing coverage (88.68% universal and 81.13% railway-specific), while identifying a 7.02% regulatory gap primarily associated with artificial intelligence, adaptive systems, autonomous decision-making and safety-critical assurance. These findings suggest that the principal challenge for future RAS deployment lies in assuring intelligent and adaptive behaviours rather than conventional hardware technologies. The RIMV was classified as an RFR3 system, indicating the need for significant enhancements to existing frameworks and greater collaboration between regulators, standards bodies and industry stakeholders.

Collectively, these contributions provide a practical framework for assessing regulatory readiness and prioritising future assurance activities for autonomous systems across multiple sectors.

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