Analysing Construction Robotics Safety Standards for Safety Modelling and Simulation

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Abstract -

Construction robotics operates within a fragmented landscape of safety standards. While many national and international organisations have been proposing guidelines on boundaries, sensing, emergency response and risk management, these documents vary widely in how safety is articulated. However, many guidelines rely on qualitative or procedural descriptions rooted in local practices, making them difficult to align, compare or formalise. To the authors' knowledge, there is no shared abstraction layer through which regulatory safety logic can be consistently expressed or tested in simulation environments. This study addresses this gap through a cross regional analysis of twelve safety standards from Japan, the United Kingdom and the International Organization for Standardization (ISO). We identify six recurring safety principles and map them to simulation relevant parameters: *human-machine separation*, *mode-aware behaviour*, *sensor monitoring*, *fail-safe response*, *progressive risk mitigation* and *context dependent validation*. To operationalise these principles, we propose a formal safety envelope model that defines a bounded region of admissible system states, structured around four core runtime variables: separation distance, motion intensity, sensing confidence, and operational mode. The remaining parameters govern rule enforcement and environmental adaptation. This abstraction enables simulations to function as a shared reasoning layer across diverse regulatory contexts, supporting interpretable and interoperable safety design for autonomous construction systems. This study contributes to advancing safety modelling for construction robotics.

Keywords -

Construction Robots, Safety Standards, Simulation-based Evaluation, Regulatory Analysis, Human Robot Interaction

1 Introduction

Safety has always been a key concern in the construction industry. Despite improvements in equipment and site management, construction consistently ranks among the most hazardous sectors worldwide, with high rates of injuries and fatalities [1, 2]. To address this, many governments and industry groups are turning to intelligent construction technologies, such as automated excavators, remote controlled bulldozers and AI powered mobile robots, to reduce human exposure to risk and improve productivity [3, 4].

As automation enters these complex, human inhabited environments, it introduces new challenges: How should robots behave when people are nearby? What happens if a safety sensor fails or loses its signal? Who is responsible when safety devices malfunction? These questions are no longer merely technical; they are increasingly shaped by evolving safety standards and regulatory frameworks. Existing safety guidelines vary in how they define and operationalise safety, often relying on qualitative or procedural descriptions rooted in local practices. This limits their comparability and hinders formalisation in simulation and system design [5, 6]. As a result, there is no shared abstraction layer through which regulatory safety logic can be consistently expressed, tested, or interpreted in system design, simulation environments, or runtime monitoring.

This paper analyses twelve safety standards and guidance documents relevant to construction robotics from Japan, the United Kingdom and ISO. Japan and the UK are selected as contrasting regulatory contexts: Japan provides relatively detailed and prescriptive guidance for automated and remote construction systems, whereas the UK adopts a more procedural and risk-based approach centred on site management and supervision. This contrast enables a meaningful comparison of how safety principles are defined and implemented across different regulatory settings. ISO standards are included as an international reference framework due to their broad applicability to machinery and robotics safety.

From these documents, we derive six recurring safety principles and translate them into a simulation-oriented model that links regulatory concerns to measurable parameters and system behaviour. The study addresses the following research questions:

- **RQ1:** What core safety principles underpin construction robotics standards across Japan, the UK and ISO, and how are they structured and emphasised in different regulatory contexts?
- **RQ2:** How can these principles be abstracted into simulation oriented representations to support system

design and cross standard reasoning?

2 Related Work

Robotics safety has long been structured by international standards, but recent scholarship has begun to examine how these frameworks embed assumptions about autonomy, control, and acceptable risk. Chemweno et al. [7] review how collaborative safety logic is encoded in ISO 15066, noting tensions between static force thresholds and dynamic real world interaction. Arents et al. [8] and Berx [9] further argue that safety readiness in human–robot collaboration requires system level modelling beyond narrow physical constraints. Construction robotics introduces new challenges. Unlike industrial environments, construction sites are unstructured, open and often shared with human workers. This makes zoning, proximity detection and fallback response more complex. Recent studies highlight the need to adapt industrial safety models to mobile and perception driven systems [10]. While prior work focuses on system implementation, it rarely addresses how safety requirements are defined or formalised at the regulatory level.

Prior work has also examined construction robotics safety through the lens of compliance or system integration. For instance, Chinniah et al. [11] compare ISO and national level safety standards for mobile equipment, noting gaps in guidance on sensing degradation and uncertainty. Several technical papers explore safety control architectures [12], risk assessment workflows, or digital twin validation [13], but rarely engage with how safety is formally represented or compared across standards. In industrial robotics, formal verification and analysis techniques have been explored to augment traditional safety assurance and control logic. For instance, Murray et al. [14] apply formal verification methods to an industrial robot control system to identify potential safety-critical flaws beyond standard compliance. In autonomous driving, simulation oriented frameworks [15] have been proposed to translate regulatory logic into testable scenarios. However, few studies address how safety logic in construction robotics can be abstracted into simulation compatible representations.

This study addresses these gaps by examining how construction robotics safety is framed across national and international standards and identifying the principles that underlie these frameworks. It further proposes a parameterised abstraction that enables simulation based analysis and cross standard comparison of safety logic.

3 Methodology

This study adopts a structured semi-systematic review methodology to identify, collect and analyse national and international safety standards and guidelines relevant to construction robots. In this study, we combine (1) Scope and Document Selection (2) Qualitative Coding Methodology as explained in the following subsections.

3.1 Scope and Document Selection

We selected twelve standards and guidance documents based on three criteria: (i) They are issued or endorsed by officially recognised regulatory authorities or organisations for standardisation; (ii) They are relevant to autonomous or semi autonomous construction machinery, including aspects such as safety critical human-machine interaction or operational safety. Documents were excluded if they were unrelated to operational safety or if they focused exclusively on factory based industrial robots with no applicability to dynamic or outdoor construction environments. (iii) They represent Japanese and British national standards alongside internationally adopted ISO standards. As a result, we selected twelve documents as shown in Table 1.

	Ref.	Standards Document Title
Japan	[16]	Safety Guidelines for Automated and Remote Construction from MLIT
	[17]	ICT equipped Construction Machinery
	[18]	i-Construction 2.0
	[19]	Implementation Policy for Onsite Verification of Automation and Remote Control Technology for Construction Machinery Operation
UK	[20]	RR1214: Review of Key Machinery Safety Standards
	[21]	HSE HSG144: Vehicles on Construction Sites
	[22]	RR906: Collision and Injury Criteria for Collaborative Robots
	[23]	UK Government Drone Safety Guidance
ISO	[24]	ISO 12100: Risk Assessment Framework
	[25]	ISO 10218-1/-2: Industrial Robots
	[26]	ISO/TS 15066: Collaborative Robots
	[27]	ISO 21873-2: Building Construction Machinery – Mobile Crushers Safety Requirements

Table 1. Twelve selected documents from Japan, the UK and ISO respectively for the study presented in this article.

3.2 Qualitative Coding Methodology

To address **RQ1** examining how safety is articulated across construction robotics standards, we conducted a qualitative content analysis using an inductive, multi-stage coding process. At the first stage, we performed open coding at the rule level. Each document was reviewed with provisions describing safety relevant requirements, such as spatial restrictions, sensing conditions, emergency responses or operational procedures, were extracted into a structured dataset. Each extracted entry was recorded together with its source standard and contextual conditions.

At the second stage, these rule level codes were iteratively clustered into a set of recurring *themes* (see Table 2). Theme development followed an inductive process: codes were merged, refined and re-labelled through repeated comparison across standards and jurisdictions. In the final stage of analysis, we synthesised these themes

into six higher order analytical groupings, which we refer to as *safety principles*.

To ensure coding consistency, the first author conducted the primary extraction and open coding, while a second reviewed all coded entries and resolved ambiguous or overlapping cases through collaborative discussion. In keeping with a consensus based interpretivist approach [28], we did not calculate interrater reliability (IRR); instead, we prioritised analytic transparency and alignment with the research objectives. The finalised codebook served two purposes as follows: (1) it supported cross regional comparison and principle synthesis (Section 4), enabling us to address **RQ1**; and (2) it informed the construction of a simulation oriented abstraction (Section 5), thereby guiding our response to **RQ2**.

4 Standards Analysis Findings

This section answers **RQ1** and presents the results of a comparative qualitative analysis of twelve selected national and international safety standards relevant to construction robotics, addressing **RQ1**. Through inductive coding, we identified a set of recurring nine *safety themes*, which are introduced explicitly in the subsections below summarised in Table 2. The themes were subsequently synthesised into six higher-level *safety principles*. Some principles correspond primarily to a single dominant theme, while others integrate multiple related themes. This synthesis preserves traceability to specific regulatory provisions while enabling cross-standard comparison at the level of regulatory logic. The six principles are discussed below.

4.1 Principle 1: Human Machine Separation

Spatial zoning and boundary management. Human machine separation is most explicitly formalised in Japanese standards. The *Safety Guidelines for Automated and Remote Construction* issued by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) defines a layered spatial structure consisting of unmanned construction areas, management buffers and broader automation management zones, with clearly specified boundary conditions and fallback rules [16]. These zones function as preconditions for autonomous operation rather than informal safety recommendations.

The guidances from the UK, such as *HSG144: The Safe Use of Vehicles on Construction Sites*, approach separation primarily through site planning measures, including segregated routes, signage and physical barriers, with limited specification of how machines should respond autonomously to human intrusion [21]. The ISO standards, including ISO 12100 and ISO/TS 15066, introduce concepts such as restricted or collaborative workspaces but deliberately avoid prescribing zoning architectures, instead of delegating implementation to application-specific risk assessment [24, 26].

Several Japanese documents go further by specifying enforcement behaviour when separation is breached. The *Management Requirements for ICT-equipped Construction Machinery* require robots to define a work envelope and to reduce speed or stop when human entry cannot be avoided [17]. By contrast, the UK guidances tend to assume human-led supervision; while the ISO standards leave enforcement logic to system integrators. Overall, separation is treated as a system enforced constraint in Japan, a procedural objective in the UK and a design consideration within the ISO frameworks.

4.2 Principle 2: Mode Aware Behaviour

Modes and behavioural states. Mode-aware behaviour captures how standards constrain robot actions under different operational conditions. ISO/TS 15066 explicitly defines multiple safety-related modes, including safety-rated monitored stop, hand guiding, speed and separation monitoring, as well as power and force limiting, each associated with specific control and sensing requirements [26]. However, the standard intentionally leaves mode selection and transition logic to system designers. Japanese standards express similar distinctions through lifecycle-oriented operational states. The *Management Requirements for ICT-equipped Construction Machinery*, for example, differentiate between initial setup, supervised test operation and fully unmanned operation, with formal verification required before transitions [17]. Unlike ISO, these transitions are treated as auditable organisational events rather than purely technical configurations. UK guidance, including *HSG144* and *RR1214*, does not formalise operational modes in technical terms, instead assuming continuous human supervision and operator responsibility [20]. This reflects a regulatory model in which accountability is tied to human oversight rather than explicit autonomous state management.

4.3 Principle 3: Sensor Monitoring

Sensor-based monitoring and localisation. Sensor monitoring is treated most explicitly in Japanese standards. Documents such as the *Implementation Policy for On-site Verification of Automation and Remote Control Technology* specify detailed requirements for localisation accuracy, continuous sensor integrity monitoring, and automated responses to perception degradation [19]. Sensor systems are framed as first-order safety components embedded directly in control logic. ISO standards take a more abstract approach. ISO/TS 15066 requires safety rated sensing for functions such as speed and separation monitoring but avoids prescribing sensor types, fusion

Table 2. Coverage of Safety Themes Across National and International Standards

	Ref.	Standards Document	**Principle 1** Zoning & Boundary	**Principle 2** Mode Behaviour	**Principle 3** Sensor Monitoring	**Principle 4** Emergency Stop	**Principle 4** Hazard Identification	**Principle 5** Risk Assessment	**Principle 5** Speed Control	**Principle 5** Safety Logic	**Principle 6** Environmental Validation
Japan	[16]	Safety for Robots	✓	✓	×	✓	✓	×	×	×	×
	[17]	ICT-equipped Machinery	×	×	×	×	✓	✓	×	✓	×
	[18]	i-Construction 2.0	×	×	×	×	×	×	×	✓	×
	[19]	On-site Verification	×	×	×	×	×	×	×	×	✓
UK	[20]	RR1214	×	×	×	×	×	✓	×	×	×
	[21]	HSG144	✓	×	×	✓	×	×	✓	×	×
	[22]	RR906	×	×	✓	×	✓	×	×	×	×
	[23]	Drone Safety	✓	×	×	×	×	×	×	×	✓
ISO	[24]	ISO 12100	✓	×	×	×	✓	✓	×	✓	×
	[25]	ISO 10218-1/-2	×	✓	✓	✓	✓	×	✓	×	×
	[26]	ISO/TS 15066	✓	✓	✓	✓	✓	×	✓	×	×
	[25]	ISO 21873-2	×	×	×	✓	✓	×	×	✓	×

Note: ✓ indicates the theme is addressed in the standard; × means not mentioned. The nine theme categorised in six principles refer to Section 4.

strategies, or confidence thresholds [26]. ISO 12100 further positions perception primarily as an input to risk assessment rather than a runtime safety mechanism [24]. The UK guidances, including *HSG144* and *RR906*, focus largely on visibility aids that support human operators, such as mirrors and cameras, rather than autonomous perception systems [21, 22]. As a result, hazard detection is implicitly assumed to remain human-led.

4.4 Principle 4: Fail safe Response

Emergency stop and protective stop functions. All analysed standards require emergency stop functionality, but differ in how fail-safe behaviour is operationalised. Japanese guidelines, including *i-Construction 2.0*, distinguish between manual emergency stops and automated protective stops triggered by sensor-detected anomalies such as human intrusion or signal loss [18]. These responses are embedded directly into system control logic. ISO/TS 15066 similarly distinguishes emergency stop and safety-rated monitored stop but leaves detection logic, redundancy strategies, and response timing to system integrators [26]. The UK standards acknowledge emergency stop requirements but rarely specify autonomous trigger conditions, placing responsibility primarily on operators or site managers.

Fail-safe and hazard detection. Japanese standards adopt a more system integrated view of fail safe behaviour. The *Weather, Visibility, and Environmental Constraints* guidance document identifies four key categories of safety technologies: (i) positioning and state monitoring, (ii) anomaly detection and alerts, (iii) environmental sensing, and (iv) communication links for stop transmission [16]. The expectation is that machines will self monitor sensor status and system state and autonomously trigger mitigation responses when anomalies occur. For example, if GNSS signal degradation or interference is detected, the machine must reduce speed or enter a safe mode. Similarly, if hazard detection sensors (e.g. LiDAR, cameras) are obstructed, a protective stop must be initiated automatically. These conditions are embedded within the control logic, not merely procedural checklists. The ISO standards provide an intermediate position. ISO 15066 supports 'safety rated monitored stop' modes and requires that systems detect violations of safety conditions in real time. However, the specifics of detection logic, redundancy strategies or confidence thresholds are not fully prescribed and left to system integrators [26].

4.5 Principle 5: Progressive risk mitigation

Risk assessment methodology. Risk identification and mitigation responsibilities are handled very differently across jurisdictions. UK guidance documents, particularly *RR1214: Review of Key Machinery Safety Standards*, highlight the lack of formal risk identification procedures for emerging technologies like AI assisted machinery. They critique existing machinery safety practices for assuming static workspaces and foreseeable risks [20]. This suggests a regulatory expectation that risk assessment must be updated for dynamic, adaptive systems. ISO 12100, by contrast, presents a generalised risk assessment framework applicable to a wide range of machinery. It outlines stages such as hazard identification, risk estimation, and risk reduction, but leaves much of the procedural responsibility to system integrators. It is intended to be flexible across applications, including mobile or intelligent systems [24]. Japanese documents take a more prescriptive approach. MLIT and related standards often define when and how safety verification should occur, which actor (e.g. site supervisor, remote operator) is accountable for specific system states, and how transitions must be documented [18]. This embeds responsibility in both system logic and organisational workflow.

Speed control as progressive mitigation. Several standards recognise that machine speed should adapt dynamically based on human proximity or sensing confidence. For example, the MLIT manual specifies that automated machines must reduce operational velocity when a human is detected within a defined buffer zone surrounding the

unmanned construction area [16]. This creates a graded safety envelope that tightens in response to risk, rather than a binary stop condition. The UK guidance document in HSG144 also references speed management for large vehicles operating near pedestrian routes, although the enforcement mechanisms are typically procedural through supervision and signage rather than sensor driven or automated [21]. ISO 15066 formalises this logic through its speed and separation monitoring provision, where allowed robot speed is linked to real time separation distance and the relative vulnerability of human body regions. It mandates that these parameters be continuously updated during operation, especially in shared or dynamic environments [26].

System integration and general safety logic. ISO 12100 positions itself as the foundational safety logic for all machinery, including construction robotics. It sets out conceptual models for integrating safety functions into system design but does not specify architectures for specific application domains [24]. It assumes that control authority will be distributed across components (e.g. controller, actuator, operator), and requires that safety be designed into the system from the outset, via functional safety principles and lifecycle integration. Japanese standards reinforce this principle but with stronger top down governance. For example, MLIT guidelines treat integration not just as a design task but as a regulated process requiring traceability of roles, mode transition events and override decisions [16]. The UK documents often lack this level of structural integration, reflecting a looser coupling between system logic and safety accountability.

4.6 Principle 6: Context Dependent Validation

Verification and field testing conditions. Context dependent validation is most explicit in Japanese standards. The *Weather, Visibility and Environmental Constraints* guidance document mandates scenario based testing under site relevant conditions such as fog, illumination and signal degradation, explicitly linking operational limits to sensing reliability [16]. ISO standards incorporate environmental variability into risk assessment without prescribing validation procedures [24, 26]. The UK guidance documents address environmental risk primarily at the site management level. Differences in environmental assumptions are further illustrated by domain specific guidance document such as the *UK Drone Safety Guidance*, which imposes operational constraints unique to airborne systems [23].

5 Safety Representation Framework

This section addresses **RQ2** by introducing a simulation-oriented abstraction that translates regulatory safety principles into a computational form suitable for analysis, comparison, and scenario-based evaluation. While Section 4 identified six core safety principles shared across Japanese, UK and ISO standards, these principles are articulated using heterogeneous regulatory languages, ranging from procedural guidance documents to context dependent technical rules. As discussed in Section 1, this diversity results in the absence of a shared abstraction layer through which safety logic can be consistently expressed or reasoned about in simulation environments.

To bridge this gap, we propose a two level representation. First, each safety principle is mapped to a corresponding simulation relevant parameter that captures its regulatory concern in operational terms. Second, a subset of these parameters is structured into a safety envelope that defines admissible system states at runtime, while the remaining parameters govern rule activation, thresholds and validation conditions.

5.1 Computational Representation

To clarify the mapping process, this study adopts a structured approach to translate qualitative safety principles into simulation parameters. First, the principles are analysed to identify their underlying operational intent (e.g. separation, motion control, stability). Second, these intents are expressed as measurable variables. Third, each variable is operationalised as a parameter that can be implemented within the simulation model. This mapping does not imply a strict one to one relationship, but rather captures the most relevant and measurable aspect of each principle. In cases where a principle includes multiple aspects, the selected parameter represents the most relevant or directly measurable aspect for simulation, rather than all dimensions of the principle. Each of the six principles implies constraints on system behaviour and is abstracted into a measurable or configurable parameter, as summarised in Table 3. These parameters are not directly extracted from standards, but derived from how regulatory requirements constrain operational behaviour. For example, a principle concerning safe human robot separation can be represented by a distance variable, which is then defined as a minimum separation parameter in the simulation."

5.2 Safety Envelope

We define a *safety envelope* as a bounded region of system states that are considered acceptable under given operational and environmental conditions. The envelope serves as the core runtime abstraction through which safety is evaluated during simulation. Formally, it is defined as:

Table 3. Mapping of Safety Principles to Simulation Parameters

Principle	Simulation Parameter
Human machine separation	d (separation distance)
Mode aware behaviour	m (operational mode)
Sensor monitoring	c (sensing confidence)
Fail safe response	r (response latency)
Progressive risk mitigation	v (motion velocity)
Context dependent validation	θ (parameter thresholds)

$$E = f(d, v, c, m) \in \mathbb{S} \tag{1}$$

where $\mathbb{S}$ denotes the space of permissible system configurations. The envelope is parameterised by four core state variables separation distance (d), motion speed (v), sensing confidence (c), and operational mode (m) which directly describe the instantaneous interaction between the robot, humans, and the environment. The remaining parameters, response latency (r) and context dependent thresholds (θ), do not define the envelope itself, but govern how envelope violations are detected and enforced. Time is not explicitly defined as a standalone parameter in the equation, but is treated as an implicit or scenario dependent variable that influences the evaluation of system behaviour within the simulation. Unlike rule based checklists, the envelope model supports dynamic interaction between parameters. For instance, reduced sensing confidence and decreasing separation distance may jointly constrain allowable motion, triggering mitigation before hard limits are exceeded.

To illustrate in practice, we present a simplified scenario involving an autonomous earthmoving machine operating on a construction site with intermittent human presence. The machine runs in autonomous mode (m = autonomous) and navigates based on internal maps and sensor feedback. A human worker enters the vicinity, causing the separation distance d to decrease while partial visual occlusion degrades sensing confidence c. The system continuously evaluates its safety envelope $E = f(d, v, c, m)$ as both d and c evolve. When proximity and sensor confidence jointly approach envelope thresholds, rule based logic initiates a graded mitigation response: the machine reduces velocity v rather than stopping immediately. If envelope violations persist or worsen, a fail safe transition is triggered after a response latency r, bringing the machine to a controlled stop. Throughout this scenario, safety behaviour is conditioned on the operational mode m: for example, in manual or override mode, human control would take precedence. Although the scenario is evaluated within a unified simulation framework, the same conditions may lead to different responses under different standards. For instance, a reduction in separation distance combined with lower sensing confidence may trigger earlier motion constraints in more prescriptive frameworks that emphasise predefined safety zones and verification procedures. In contrast, frameworks that rely more on risk assessment and site-level judgement may allow more context-dependent responses before intervention. International standards, such as ISO, typically define general safety requirements but leave the specific implementation of these responses open.

6 Discussion

Building on our cross regional analysis of safety standards (Section 4), we find that construction robotics regulations converge on high level safety principles such as human machine separation, fail safe response and sensor monitoring yet diverge significantly in how these principles are articulated, operationalised and enforced. This divergence reveals not just technical variation but deeper differences in regulatory philosophy: who is expected to ensure safety, how autonomy is bounded, and what forms of uncertainty are tolerable. While all standards recognise the importance of human machine separation, their implementation logics vary. The Japanese standards frame automation zones as privileged spaces requiring layered access control, authenticated gatekeeping and geofenced planning. On the other hand, the UK standards rely on site managers to supervise segregation, while ISO offers modular guidance documents, assuming integration into broader risk frameworks. These differences illustrate how the same principle can reflect different governance assumptions: safety through spatial design, procedural oversight, or system modularity.

Mode aware behaviour further reveals contrasting views of autonomy. In Japanese standards, autonomy is conditional permissible only under documented configurations, with explicit transition protocols and traceable operator accountability. ISO emphasises functional modes such as monitored stop and hand guiding, without prescribing when or how they should be used. The UK guidance documents largely treat autonomy as a supervised state, offering few constraints on mode transitions. These distinctions influence how systems handle uncertainty, respond to failure, and delineate control boundaries. Sensor requirements expose another axis of divergence. The Japanese documents mandate redundancy and confidence triggered fallback, suggesting that perception systems are first order safety agents. In contrast, UK documents treat sensors as supplementary aids for human operators. The ISO standards acknowledge safety rated sensing but delegate thresholds and fallback logic to integrators. This reflects varying expectations about how actively machines must reason about environmental risk.

Our findings suggest that these divergences are not mere semantic variations but encode structurally different assumptions about risk, accountability and the role of autonomy. Current standards are not easily interoperable: even where similar language is used, the underlying governance logic often differs. This complicates efforts to develop unified testing regimes, transferable safety envelopes or international simulation based evaluation protocols. We argue that simulation can serve as an intermediary layer between these regulatory traditions. By abstracting safety principles into parametrized behaviours, such as istance thresholds, sensor confidence bounds and control state transitions, simulation environments can instantiate and test multiple interpretations of 'safe' operation. However, this requires explicit translation layers: from procedural language to computational logic, from qualitative obligation to operational constraint.

From a comparative perspective, each regulatory framework exhibits distinct strengths and limitations. Japanese standards provide strong prescriptive guidance that supports consistent implementation, but may reduce flexibility in dynamic site conditions. The British guidance documents offer adaptability through risk based and management oriented approaches, yet relies heavily on practitioner judgement, potentially leading to variability in application. ISO standards contribute a generalisable and widely adopted framework, but often lack construction specific detail required for direct implementation. Across all standards, several blind spots remain. In particular, the integration of dynamic human robot interaction, real time uncertainty in sensing and adaptive system behaviour is not comprehensively addressed.

Limitations and Future Work This study focused on twelve standards from Japan, the UK and ISO. While this gives us a strong basis for comparison, it does not yet capture the full global picture. Future work could include other countries and sectors like mining or disaster robotics to broaden the scope. Our analysis also looks at what the documents say, not how they are applied in the real world. Fieldwork, system audits, and simulation in the loop testing could reveal how these standards are actually interpreted on site. Finally, while we have introduced the envelope model as a conceptual tool, there is still work to do in building software, test scenarios and simulation toolkits that make this approach usable in practice.

7 Conclusion

This paper investigates how safety standards for autonomous construction systems articulate regulatory intent across jurisdictions and how such intent can be translated into simulation oriented representations. Through qualitative coding of twelve national and international documents, we identified six safety principles that underpin construction robotics regulation: human machine separation, mode aware behaviour, sensor monitoring, fail safe response, progressive risk mitigation and context dependent validation. To address **RQ1**, we show that while these principles are widely acknowledged, they are enacted through divergent assumptions about control, autonomy and human oversight. To address **RQ2**, we introduce a simulation oriented abstraction in the form of a *safety envelope*, a parametrized structure that enables regulatory safety logic to be instantiated, tested and compared in virtual environments. Our work bridges regulatory analysis and computational modelling, offering a framework through which heterogeneous safety standards can be systematically reasoned about during early stage design and scenario testing. As robotics systems grow more complex and globally distributed, simulation based abstraction offers a promising path toward regulatory interoperability and principled safety evaluation.

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