CCC 2024

Proceedings of the Creative Construction Conference (2024)
Edited by: Miroslaw J. Skibniewski & Miklós Hajdu
https://doi.org/10.3311/CCC2024-039

A TAXONOMY OF EXTENDED REALITY FOR HUMAN-ROBOT INTERACTION IN CONSTRUCTION BASED ON A SYSTEMATIC LITERATURE REVIEW

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Abstract

Extended Reality (XR) applications for Human-Robot Interaction (HRI) in construction, while still in a developmental stage, are rapidly gaining much attention for their ability to enhance communication with robots. However, this area of research often consists of individual explorations, leading to a lack of uniformity in terminology and interaction design techniques. Our study addresses this issue by proposing a comprehensive taxonomy for XR-HRI in construction. We conducted an exhaustive literature review of 51 papers in the construction domain to synthesize the state of the field. Our findings led to the construction of a novel taxonomy comprising three primary design spaces: (1) interface, (2) interaction, and (3) context. Our work contributes significantly to the field by providing a foundational framework that supports researchers and practitioners in the systematic development, standardization, and evaluation of XR-HRI designs in construction.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2024.

Keywords: extended reality, human-robot interaction, taxonomy, construction robotics.

1. Introduction

The increasing adoption of robots in construction tasks underscores the need for effective Human-Robot Interaction (HRI) design for construction [1]. Currently, interaction between human workers and robots often relies on the direct control and command execution via traditional interaction devices such as teach pendants and handheld controllers. While these interfaces are effective for automating construction tasks through programming or teleoperation of various robots, they often lack the capabilities for bidirectional communication. The lack of feedback from robots to human workers hampers the workers' ability to comprehend the robots' current state, motion plans, and intent [2]. This gap in communication can potentially lead to poor work quality and, more critically, safety issues on construction sites [3,4].

Recent developments in Extended Reality (XR) technology offer a promising solution for information exchange between users and robots [2]. XR, an umbrella term used for Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) [4], enables users to view 3D virtual imagery either in a virtual space or integrated within their physical environment [5]. In construction, XR has been explored for advanced visualization, often integrated with Building Information Modeling (BIM) [5]. Although a nascent research field in construction, XR applications for HRI are rapidly gaining much attention due to their potential to facilitate free-hand and intuitive interactions with robots in a shared physical space or entirely virtual environments, especially implemented through Head-Mounted Displays (HMDs) [2]. Previous work has investigated how XR can be integrated into such interactions with construction robots, for various purposes, such as human safety training [6], robot learning from demonstration [7], intuitive on-line programming [8], or real-time data overlay to enhance safety while working with robots [9].

However, often these research projects are individual explorations, resulting in disconnected terminology and interaction design techniques.

Despite recent proliferation of this research field, little is known regarding the different approaches to design such interaction via XR within construction contexts and existing works on this topic are limited in terms of purpose (e.g., human training and safety enhancement) and interactivity (e.g., explicit interaction) of HRI. With the recent proliferation of this research field, we see a need for a common ground and understanding for construction robotics researchers, which both includes XR-enhanced HRI (XR-HRI) and robotic user interfaces research.

To this end, we present a taxonomy of XR for HRI in the construction domain. We conducted an exhaustive literature review of 51 papers in the construction domain to synthesize the state of the field. Our analysis focused on the terminology, interaction techniques, applications, and findings. This work expands the research landscape of XR-HRI in construction by offering three main contributions. First, we present an analysis of current work in the field of construction robotics using XR, focused on interface, interaction, and context design spaces. To best of our knowledge, this is the first attempt to systematically categorize existing works in this field. Second, we derive a comprehensive taxonomy for XR-HRI in construction research and practice. We propose that this taxonomy can serve as a foundational framework, supporting researchers and practitioners in the development, standardization, and evaluation of XR-HRI designs and prototypes. Third, we discuss the implications of these interaction designs based on the literature review.

2. Background

2.1. XR for HRI and Existing Taxonomies

Our work builds upon and extends related taxonomies in the domain of XR for HRI, focusing on areas such as the functional role of AR [10], the design spaces of AR-enhanced HRI [11], and the Virtual Design Elements (VDEs) of Virtual, Augmented, Mixed reality (VAM) [2]. This section provides an overview of these relevant taxonomies, construction methodologies, and their relation to the taxonomy proposed in our study.

In the field of AR and HRI, Phaijit et al. [10] proposed a multidimensional taxonomy of AR’s function in HRI. They focused on three key aspects of AR-for-HRI: the type of perception augmentation, the functional role of AR, and the augmentation artifact type. Suzuki et al. [11] also presented a comprehensive taxonomy of this field based on an extensive survey of 460 research papers. Their work systematically analyzed key design strategies, common practices, and open research questions in AR and robotics research. While these taxonomy can serve as an assessment tool for the functionality of AR in HRI, it does not extend to the broader spectrum of XR technologies, such as VR or MR, which have recently been the topic of workshops [11] and serve as a critical tool for designing HRI in construction.

Expanding the scope of taxonomy in the field of XR and HRI, Walker et al. [2] presented a taxonomy for VAM-HRI. Although this taxonomy provides a shared, descriptive basis for characterizing VDEs developed and deployed in mixed and virtual reality systems, the direct application of these VDEs to HRI scenarios in construction is not always feasible. This taxonomy includes VDEs designed for general tasks that may not always be useful in construction contexts, such as entity appearances virtual alterations. Additionally, VDEs such as robot sensor readings (e.g., robot temperatures, actuator data, and numerical joint angles) that rely heavily on technology-specific interpretations might need to be simplified or adapted to distinct forms of presented information and virtual elements effective for construction such as color-coded alerts [12] or intuitive status display [13]. Moreover, the abovementioned taxonomies either do not include construction tasks in the target task types [2,10] or reference construction as a future research opportunity [11], without considering them in the development of the taxonomy and being too generic to address any specific applications in construction [14]. In contrast, our taxonomy not only builds upon these existing taxonomies, but also addresses the construction-specific design spaces including interface, interaction, and contextual aspects relevant to XR-HRI in construction.

2.2. XR for HRI in Construction

This section provides the scope of our topic in more detail and clarifies what is included and what is not.

2.2.1. XR in Construction

The definition of XR can vary depending on the context [11,15]. In this study, we adhere to the XR spectrum as outlined in the reality-virtuality continuum by Milgram and Kishino [16], which includes VR, AR, MR, and augmented virtuality (AV).

There has been a notable increase in the use of XR technologies in the construction industry, where it is integrated with BIM [5]. The industry has witnessed substantial advancements by employing XR technologies in areas such as construction management, safety management, machine operation, steelwork, and surveying [5]. However, our focus is on the application of XR in HRI, thus we specifically investigate systems in which XR is used in the context of robotics.

2.2.2. HRI in Construction

In this paper, the term HRI is used to refer to all the exchange of information and actions between humans and robots, as well as between humans and traditional construction machinery, including excavators, pavers, bulldozers, and cranes, which are fully operated by humans. Although it is challenging to categorize some construction machinery as “robots”, transitioning from the perspective of human-machine interaction (HMI) to HRI can significantly expand opportunities for design innovation and enhance the application of new technologies such as XR [17]. Designing interaction between humans and construction machinery as interactions between humans and robotic systems naturally facilitates the integration of technological advances in artificial intelligence (AI) and robotics into construction. Considering the increasing autonomy and intelligence of construction machines, this broader scope of HRI allows for a more comprehensive understanding of related studies in the current research landscape.

Additionally, we do not limit the scope of HRI to on-site interactions between human workers and construction robots, but also include any type of interactions that take place off-site, as large body of construction robotics literature focus on robotic applications in off-site construction, such as timber fabrication [8,13,18] and modular construction [12].

3. Methods

To investigate the current state of XR applications for HRI in the construction industry, we reviewed relevant literature in a structured way. The selection process for publications for our review follows the PRISMA (Preferred Reporting Items of Systematic reviews and Meta-Analyses) [19] guidelines, as shown in Fig. 1. First, to identify papers about XR-HRI in construction, we queried articles and proceedings on the online search engine. The Scopus search engine was used to query journal and conference papers from major publishers including ASCE, Elsevier, Springer, ACM, and IEEE [14]. This involved a keyword search using AND / OR operators across the categories: “virtual, augmented, mixed, extended reality”, “construction”, and “human-, robot, machine, equipment, collab*”. The publication year was limited to 2010 or later and only papers in English were considered. This search identified a total of 1198 papers. Further screening involved assessing titles and abstracts of papers for relevance to XR-HRI systems, resulting in 168 papers. We also excluded 117 papers which are not relevant to the construction domain. The remaining total of 51 were included in full review and for taxonomy construction.

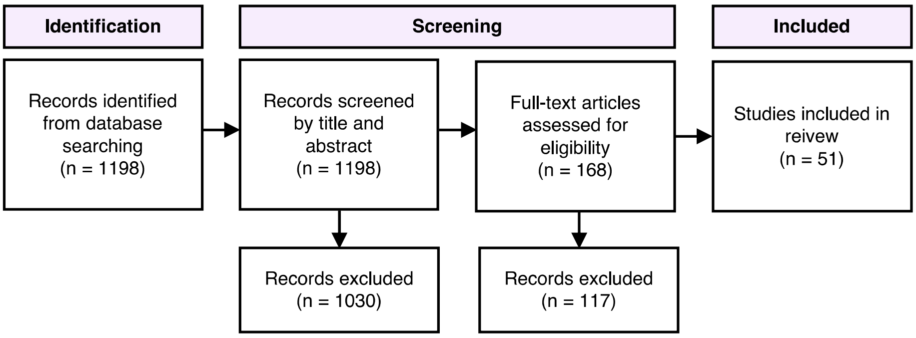

Fig. 1. PRISMA Flow diagram [19] illustrating the paper selection process.

Drawing upon the taxonomy development method proposed by Dey et al. [20], we developed taxonomy in three major iterations. In Iteration 1, we developed the dimensions based on previous works on VAM-HRI [2], AR-HRI [11], and HRI in construction [14]. The literature pertaining to XR technologies [21] was also taken into consideration. This initial taxonomy comprised 16 dimensions covering key attributes of XR-HRI in construction. We then refined the taxonomy in two succeeding iterations, Iteration 2 and 3, to ensure that the list of subcategories within each dimension was grouped or separated based on their alignment with the context of HRI in construction and the interrelations among key terms [14]. For each iteration, a subset of 10 papers was randomly chosen and independently categorized by the two authors using the established taxonomy dimensions, following the method proposed by Dey et al. [20]. After completing their individual categorization, they collaboratively refined the taxonomy by adding, removing, merging, and reorganizing dimensions as needed. This procedure was iteratively repeated twice, resulting in two refinement iterations (Iteration 2 and 3) in total.

The remaining literature was then reviewed and categorized based on the updated dimensions. Following the taxonomy development process, the authors finally revised the 12 dimensions by re-examining the appropriateness of the classification criteria. Finally, the entire literature set was re-categorized according to the revised dimensions.

4. Taxonomy of XR for HRI in Construction

Based on the literature analysis described above, we constructed our taxonomy for XR for HRI in construction (see Fig. 2). The resulting taxonomy consists of 12 dimensions, which are grouped into three design spaces: interface, interaction, context, according to the three main components of the HRI model proposed by Frijns et al. [22]. The first design space, Interface, indicates how XR interfaces are constructed, implemented, and presented in construction HRI. The second design space, Interaction, describes the various interaction attributes of human-robot communication within XR environments. The third design space, Context, covers the applications and evaluation methodologies of XR-HRI systems in construction.

1. Interface

Milgram Continuum
- Augmented reality (AR) (5)
- Augmented virtuality (AV) (15)
- Virtual reality (VR) (29)

Display Hardware
- Head-mounted displays (HMDs) (33)
- Monitor video displays (9)
- Projectors (2)
- Mobile devices (2)
- Cave automatic virtual environments (CAVEs) (2)

Coordinate Frame Rectification
- Fiducial marker (7)
- Motion capture sensor (10)
- Manual alignment (4)

Presented Information
- Robot status/capability (6)
- Operating environment (42)
- Task plan/target (26)
- Supplementary information (37)

2. Interaction

Form Factor
- Robotic arms (16)
- Mobile robots (4)
- Drones (3)
- Mobile manipulators (8)
- Cranes & Construction equipment (21)

Relationship (H:R)
- 1:1 (34) / 1:m (7) / n:1 (5) / n:m (2)

Proximity
- On-board (5) / Co-located (34) / Remote (8)

Interaction Modality
- Controller (23)
- Gesture (8)
- Mouse & Keyboard (2)
- Touch (3)
- Gaze (1)
- Tangible (2)

Interactivity
- No interaction (14) / Explicit (33) / Implicit (2)

3. Context

Purpose
- Robot manipulation (24)
- Robot training (4)
- Human training (18)
- Safety enhancement (6)
- Information visualization (9)
- Intent communication (1)

Task Type
- Progress monitoring (2)
- Earthworks (11)
- Lifting (5)
- Concrete works (1)
- Fabrication (15)
- Interior & Exterior finishing (6)
- Maintenance & Demolition (5)

Setting
- On-site (34)
- Off-site (5)
- Laboratory (11)
- Simulation (30)

Figure 2. Taxonomy of extended reality for human-robot interaction in construction

4.1. Interface

In this section, we classify research projects based on the characteristics of XR interfaces.

Dimension 1: Milgram Continuum. This category addresses the Milgram continuum, also known as the reality-virtuality continuum, that categorizes XR technologies implemented in interfaces (see Section 2.2.1). These technologies include VR, AR, and AV. These can be employed either independently or in combination to support communication in shared virtual construction environments.

Dimension 2: Display Hardware. XR interfaces can be implemented by various display hardware [2]. In the most common case, head-mounted displays (i.e., optical see-through HMDs, video pass-through HMDs, and VR HMDs) are utilized for display hardware, but the existing research in construction also explores the use of monitor video displays [23], projectors [24], mobile devices [25], and Cave Automatic Virtual Environments (CAVEs) [12].

Dimension 3: Coordinate Frame Rectification.

Coordinate frame rectification refers to a process of aligning virtual and real-world coordinates, ensuring the appearance of XR imagery in its correct position and orientation [2]. In HRI in construction, where multiple dynamic agents (e.g., workers, robots, vehicles) are involved, each with different perspectives, real-time tracking within such an environment is crucial for accurate overlays and interactions [2]. To achieve this, a large majority of XR-HRI research in construction uses traditional methods such as fiducial markers [24] or motion capture sensors [26] to rectify multiple coordinate frames. Alternatively, some interfaces require manual placement of virtual objects onto physical targets with known poses to the robot, such as a workpiece [25,27] or a reference point of a building component [28].

Dimension 4: Presented Information. This dimension classifies the types of information that are displayed through XR interfaces for HRI in construction. The information can vary across applications, with key categories identified in construction research being *robot status/capability*, *operating environment*, *task plan/target*, and *supplementary information*.

- Robot status/capability: Examples include fabrication system status [13] and crane loading capacity [12].

- Operating environment: Examples include virtual site scenes [29], real-time 2D images [9], real-time 3D point clouds or reconstructed scenes [30], and environmental data such as temperature [31] and pressure [32].
- Task plan/target: Examples include task sequence and progress [13], target positions for tasks such as beam attachment [33] and window panel installation [7], and simulation visualizations [8].
- Supplementary information: Examples include User Interfaces (UIs) [6,25], safety areas and boundaries [34], and virtual agents [35].

4.2. Interaction

Next, we categorize the interaction aspects of XR within the context of HRI in construction.

Dimension 1: Form Factor. Form factor refers to the various types of robots involved in HRI scenarios. The form factor reflects the extended definition of robots (see Section 2.2.2), which include: robotic arms [7,27], mobile robots [24], drones [36], cranes [12], construction equipment [23,26,31], mobile manipulators [37], and other types such as guide rail machines [38].

Dimension 2: Relationship. Research addresses various human-robot relationships. As seen in the general HRI studies, one person interacting with a single robot (1:1) is the most common case. However, in construction, HRI scenarios often involve construction equipment operating in a collaborative manner, such as a team of an excavator and a dump truck [31], requiring one person to interact with two or more robots (1:m) or n-people to interact with m-robots (n:m). Existing research also explores scenarios in which multiple people interact with a single robot (n:1). A typical example is a crane lift operation, involving roles like a lifting supervisor, signaller, crane operator, and rigger [12].

Dimension 3: Proximity. Proximity refers to the distance between the user and robots during interaction [11]. In construction, the proximity can fall into three categories: *on-board*, *co-located*, and *remote*. While the large majority of XR-HRI research in construction focuses on co-located scenarios, there are examples of on-board scenarios. These on-board scenarios provide an interaction experience within the equipment, such as the crane operator’s view inside a tower crane cabin [39].

Dimension 4: Interaction Modality. In terms of interaction modality, most active research in construction is done within the controller category, as the controllers are a common mode of interaction for HMDs [7,40]. Gestures are another common modality [8,35] in construction HRI. Additional interaction modalities include: mouse and keyboard [41], touch [25], gaze [42], and tangible [43]. These modalities are often utilized to complement the controller or the gesture.

Dimension 5: Interactivity. As noted by Suzuki et al. [11], interactivity in HRI can be classified into three categories: *no interaction*, *implicit interaction*, and *explicit interaction*. Interfaces in the no interaction category focus on visualization aspects, such as task target position [33], virtual components [24], and safety hazards [44], without processing user input. Implicit interaction enables robot responses through the prediction or interpretation of the user’s implicit input, such as proximity to the robot [45], while explicit interaction focuses on the user’s direct input, such as manual teleoperation [46] and physical demonstration [43].

4.3. Context

Finally, we categorize prior research based on the application context of the XR-HRI technology.

Dimension 1: Purpose. This dimension classifies previous works according to the function of XR in terms of developing certain aspects of human-robot interaction. In HRI research, one of the most significant and challenging parts is developing effective methods to control robots [47]. To address this challenge, numerous scholarly investigations employ XR as an interface for improving robot manipulation [29]. More specifically, current state-of-the-art research in construction robot manipulation is aimed at enhancing the flexibility and level of intelligence to adapt to unexpected working conditions [7]. The solution includes training robots in a virtual environment to learn the policy for achieving goals

[30]. Training is also necessary for humans [6] to safely operate robots in controlled environments. XR technology is frequently employed to create personalized and cost-effective training environments [2]. Beyond worker training, XR can play a role in enhancing safety [45] across various robotic tasks within the construction industry. Additionally, it proves beneficial in tasks involving the visualization of information [48] that is not perceptible in the physical world, such as Computer-Aided Design (CAD) drawings or BIM. The utilization of XR interfaces further extends to improving bidirectional communication of intentions [8] between the robot and the user by leveraging spatial information [11].

Dimension 2: Task Type. Construction tasks of diverse types can be executed through XR-HRI. Common terminology has been established to categorize human-robot systems, with a specific focus on construction applications. The following 14 cases highlight recent works that incorporate XR into HRI across various construction activities: progress monitoring, earthworks, lifting, concrete works, fabrication, interior & exterior finishing, maintenance & demolition.

Dimension 3: Setting. Setting denotes the location where the application task is performed. On-site [28,49] studies entail the utilization of XR-HRI systems in active job site scenarios, whereas off-site [33] investigations concentrate on applications within factories and warehouses situated away from the ultimate installed location [14]. Experiments can also be carried out to observe the system's performance under controlled laboratory conditions [27]. Furthermore, real-world working environments are often replicated and simulated [31] in virtual environments for experimentation and analysis.

5. Discussion

5.1. Main Findings

In this study, we aim to develop a taxonomy of XR-HRI in construction, with a focus on three design space dimensions: (1) interface, (2) interaction, and (3) context. Existing taxonomies have not specifically addressed XR-HRI in construction, particularly in terms of interface, interaction, and contextual aspects of HRI in construction. In this section, we discuss common approaches and identify gaps within the selected dimensions.

Interface – Dimension 4: Presented information. We observed that *virtual site scenes* (26 papers), *UIs* (16 papers), and *virtual agents* (15 papers) are the most commonly presented types of information in XR interfaces. This is because of the frequent use of VR (29 papers) in XR technologies, suggesting a possible relation between the choice of XR technologies (i.e., VR) and the presented information (i.e., virtual site scenes, UIs, virtual agents). Examples of UIs include an interactive billboard that displays XR functions and robot commands [30], and floating menus and instructions [34]. Furthermore, *robot's task targets* are also commonly displayed (12 papers). However, *robot status visualization* appears less frequently (3 papers), possibly implying that robot's status is not yet commonly accepted information for users in construction, compared with safety boundaries and areas.

Interaction – Dimension 5: Interactivity. In terms of interactivity, we observed that *explicit interaction*, where user directly inputs commands, is the most common context in XR-HRI in construction (33 papers). Here we would like to point out that this result aligns with some previous studies in general HRI in construction. For example, Zhang et al. [50] showed that manual and teleoperation interfaces that allows direct control of the robot is the most common interaction interface in construction HRC systems. In contrast, *implicit interaction* has been less explored, with only one paper, by Sun et al. [45], investigating the safety risks of proximal and distant interaction scenarios through VR visualization. This highlights potential opportunities for future research in this area.

Context – Dimension 1: Purpose. Regarding the purpose of XR-HRI interfaces in construction, *human training* (18 papers) and *safety enhancement* (6 papers) are the most common applications. This indicates that XR's safety-oriented features, including realistic yet cost-effective training environments and virtual safety envelopes, seem to be effective for enhancing safety in construction HRI. However, we observed a gap in utilizing XR for *intent communication* (1 paper). Again, this aligns with the lack of implicit interaction in the interactivity dimension.

5.2. Practical Implications

Recently, the construction research has increasingly focused on enhancing HRI using advanced technologies such as XR. However, unlike in Human-Computer Interaction (HCI) and robotics, XR-HRI in construction lacks a synchronized taxonomy. This gap makes it difficult for practitioners and researchers, both within and outside the construction domain, in deciding which design spaces to consider when developing XR interfaces for construction robots. Our proposed taxonomy aids this by providing a foundational framework for the systematic design and integration XR interfaces in construction HRI settings.

5.3. Limitations and Future Works

This taxonomy focuses on identifying characteristics including interface, interaction, and context, which are directly related to XR interfaces in construction. Thus, not all aspects of HRI have been covered. For example, in the *purpose* dimension, although robot navigation is a well-established area in construction robotics, our review found no existing papers that specifically use XR for the purpose of “navigating robots.” Future work should include regular updates and revisions of the taxonomy, considering that XR-HRI in construction is still an emerging field with significant potential for technological advancements.

Acknowledgements

This research was supported by Brain Pool program funded by the Ministry of Science and ICT through the National Research Foundation of Korea (RS-2023-00284237).

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