

# A Virtual Reality-Based Learning Environment for Human–Robot Collaboration Training in Construction 4.0

1<sup>st</sup> Khadija Sabiri

*Laboratory Collaborative Mountains of Research*

*Institutio CeDRI - Research Centre in Digitalization and Intelligent Robotics, Polytechnic Institute of Bragança*

Bragança, Portugal

<https://orcid.org/0000-0002-1237-8719>

ksabiri@morecolab.pt

2<sup>nd</sup> Luís Afonso

*Laboratory Collaborative Mountains of Research*

Bragança, Portugal

<https://orcid.org/0000-0003-0956-7065>

lcafonso@gmail.com

3<sup>rd</sup> Caio Camargo

*Laboratory Collaborative Mountains of Research*

Bragança, Portugal

<https://orcid.org/0000-0001-5913-9814>

caioorafael@gmail.com

4<sup>rd</sup> Estefânia Gonçalves

*Laboratory Collaborative Mountains of Research*

Bragança, Portugal

*University of Leon, Spain*

<https://orcid.org/0000-0002-9596-8369>

egoncalves@morecolab.pt

5<sup>th</sup> Rui Fernandes

*Laboratory Collaborative Mountains of Research*

Bragança, Portugal

<https://orcid.org/0000-0002-8611-7706>

rfernandes@morecolab.pt

**Abstract**—The rapid digitalization of the construction sector under the Construction 4.0 paradigm demands new training approaches for human–robot collaboration (HRC). Integrating HRC with Virtual Reality (VR) offers a powerful means to enhance workforce competence, safety, and efficiency through immersive and realistic simulations of construction scenarios. This paper presents the design and evaluation of a VR-based Virtual Learning Environment (VLE) developed in Unity 3D to train construction professionals for safe and effective human–robot teamwork. The platform comprises four integrated modules: (i) safety fundamentals, (ii) robot familiarization, (iii) immersive collaboration scenarios, and (iv) performance assessment. A virtual prototype of a construction robot and typical interaction workflows were modeled to simulate real-world operations. An experimental study involving 10 construction professionals evaluated the system using a mixed-methods approach grounded in the Technology Acceptance Model (TAM) and objective task performance metrics. Results demonstrate strong perceived usefulness and ease of use, with participants reporting improved communication, safety awareness, and trust in robotic co-workers. The findings highlight the potential of VR-based training to enhance workforce readiness and advance safe, collaborative practices in the era of Construction 4.0.

**Index Terms**—Virtual reality, human–robot collaboration, Construction 4.0, immersive training, safety, workforce development.

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## I. INTRODUCTION

The construction industry is undergoing a major transformation under the Construction 4.0 paradigm, characterized by the integration of digitalization, automation, and robotic technologies into everyday work practices. While these advancements promise substantial improvements in productivity, safety, and efficiency, their widespread adoption is hindered by persistent labor shortages, an aging workforce, and limited technical skills among workers [1], [2]. To address these challenges, the sector is increasingly turning to automation and robotics to supplement human labor and enhance operational safety [3]–[5]. However, successful adoption requires a workforce equipped to operate collaboratively with robotic systems, particularly in dynamic, unstructured environments.

VR has emerged as a promising solution for workforce training in such high-risk, complex environments. Unlike traditional instruction [6], VR provides full immersion in a simulated environment, enabling users to engage in realistic, risk-free task execution and spatial interaction [7], [8]. VR-based training has been shown to improve spatial understanding, enhance safety awareness, and facilitate behavior change among learners [9]. These features make VR particularly valuable for developing the skills necessary for safe and effective HRC in construction, where direct physical

training can be hazardous, time-intensive, and costly [10].

Despite growing interest in VR applications for construction education and safety training, few existing Virtual Learning Environments (VLEs) address the unique demands of HRC. Current systems often lack realistic simulation of robot behavior, task coordination, and interaction dynamics between humans and robotic agents [11]. This gap highlights the need for an interactive, user-centered, and scalable VR framework tailored to construction-specific collaborative scenarios. To address this gap, this paper presents the design and evaluation of a VR-based training platform for Construction 4.0 workforce development within the RobetArmé project [12]. The system integrates four complementary modules: (i) safety fundamentals, (ii) robot familiarization, (iii) immersive collaborative task scenarios, and (iv) performance assessment. The platform was developed using a user-centered design approach and validated through a pilot study involving construction professionals. Evaluation was conducted using the Technology Acceptance Model (TAM) and objective task performance metrics to assess usability, perceived usefulness, and learning outcomes. The key contributions of this work are threefold:

- Development of an integrated VR training framework specifically designed to support human–robot collaboration in construction.
- Implementation of a modular, scalable learning platform that supports extensibility for future features such as AI-driven scenario generation and multimodal feedback.
- Empirical evaluation with industry participants, demonstrating the system’s usability, effectiveness, and potential to improve safety awareness and collaborative task performance.

The proposed system contributes to advancing workforce readiness for Construction 4.0, supporting the safe and effective integration of robotic systems in the construction sector. The remainder of this paper is organized as follows:

- **Section II** outlines the project context, methodology, and system architecture.
- **Section III** presents the experimental evaluation and discussion of results
- **Section IV** concludes the paper with key findings, limitations, and directions for future research.

VR has been extensively investigated as a tool for construction safety training, consistently demonstrating the superiority of immersive, simulation-based learning over traditional, passive methods such as lectures or printed manuals [9], [13]. The effectiveness of VR is grounded in the “learning-by-doing” paradigm, which enables trainees to engage with high-risk scenarios in a controlled, risk-free environment, thereby improving knowledge retention, hazard recognition, and behavioral safety performance. Beyond general safety applications, VR has been successfully applied

to equipment operation and task-specific training. Studies have developed VR-based simulators for heavy machinery such as cranes [14] and excavators [15], showing measurable improvements in both operational accuracy and safety awareness. In construction robotics, VR-based teleoperation training has been shown to enhance users’ skills and situational awareness during robot-assisted tasks [16]. These applications highlight VR’s potential to improve technical competence and task execution efficiency in high-risk construction environments. However, the successful deployment of robotics on construction sites extends beyond technical proficiency. Human factors, including trust, perceived safety, and user acceptance, play a decisive role in HRC effectiveness [17], [18]. Research indicates that workers are more likely to engage effectively with robotic systems when they trust the robot’s behavior and perceive the environment as safe. Consequently, training programs must not only teach operational procedures, but also foster confidence and trust in collaborative robotic systems. Despite significant progress, existing VR-based training systems remain fragmented in scope. Most focus on isolated aspects such as safety awareness, equipment familiarization, or task-specific operations, without offering an integrated framework that combines these critical elements. To the best of our knowledge, no prior work provides a comprehensive, modular VR training platform that unifies safety fundamentals, robot familiarization, immersive collaborative scenarios, and performance assessment within a single system. As summarized in Table I, previous studies address individual components of HRC training but lack a holistic approach aligned with the needs of Construction 4.0. In contrast, the proposed system introduces an integrated VR-based training framework that encompasses all four dimensions. This unified approach supports both the technical and human-centric aspects of workforce development, representing a novel contribution to the advancement of safe and effective HRC in the construction industry.

## II. PROJECT CONTEXT: ROBÉTARMÉ

The central objective of The RoBétArmé project [12] aims to design and evaluate a VR-based training platform that could leverage real-time interaction with virtual robots, dynamic hazard generation, and embedded assessment tools, enabling users to experience both preventive safety measures and collaborative task execution. The novelty lies in combining these features within a unified training pipeline specifically tailored to HRC in construction environments. Developed in Unity 3D and deployed on Meta Quest 3 headsets, the platform offers a portable and highly immersive experience. Users are placed in realistic simulated scenarios where they can train essential skills related to workplace safety and robotic equipment handling.

As shown in figure 1, illustrates the architecture of the VR-based training platform. Its modular architecture separates content design, simulation logic, and analytics, ensuring flexibility and adaptability to new equipment and tasks. The

TABLE I  
SUMMARY OF RELATED WORK ON VR FOR SAFETY AND OPERATION TRAINING IN CONSTRUCTION, HIGHLIGHTING THE GAP ADDRESSED BY OUR RESEARCH.

Study / Year	Application Area	Training Scope	Technology / Hardware	Reported Benefits	Limitations Relative to Our Work
[13] / (2013)	Construction Safety	Hazard recognition in static environments (e.g., fall hazards)	Desktop-based VR	Improved hazard identification vs. traditional methods.	Focus on generic hazards, not robot-specific risks. Lacks interactivity and close-quarters HRC dynamics.
[9] / (2014)	Construction Safety	Hazard recognition using augmented virtuality	High-fidelity AV environment	Enhanced ability to recognize and assess safety hazards.	Passive observation training. No active interaction or operation of machinery/robots.
[17] / (2018)	Human-Robot Collaboration	Measuring and enhancing perceived safety near robots	Immersive VR (e.g., CAVE)	Framework to improve perceived safety and trust in robots.	Focuses on perception only, not on operational procedures or complex tasks.
[15] / (2019)	Equipment Operation	Excavator operation and safety algorithms	Virtual Reality	Development of safety algorithms; improved operational awareness.	Focused on a single, standard piece of equipment. Not for collaborative robotic systems.
[14] / (2020)	Equipment Operation	Critical lift planning and simulation with cranes	Gaming environment (Unity3D)	Effective for planning complex lifts and identifying spatial conflicts.	Focused on planning, not on real-time operation training or worker-robot interaction.
[16] / (2021)	Robotic Teleoperation	Training for robotic arm teleoperation tasks	VR Headset	Improved worker skills, safety behavior, and knowledge in teleoperation.	Focuses on <b>teleoperation</b> , not on <b>close-quarters collaboration</b> with autonomous robots.
<b>Our Work</b>	<b>Human-Robot Collaboration</b>	<b>Integrated safety and operation for HRC</b>	<b>Meta Quest 3 (Standalone VR)</b>	<b>Holistic environment combining safety, operation, and task simulation.</b>	<b>N/A (This work addresses the listed limitations)</b>

architecture highlights a bidirectional flow of information between the trainee and the system in which immersive VR environments deliver visuals, behaviors, and hazards, while user interactions (e.g. task times, errors, safety compliance) are captured for real-time assessment and adaptive training.

#### A. Methodology

The development of the VR training application was guided by a user-centered methodological approach, aimed at ensuring that the needs, expectations, and limitations of construction workers were considered from the earliest stages of the project. This approach involved the following steps:

##### A-User-Centred Design

Development followed a user-centered methodology, incorporating feedback from construction engineers, safety experts, and workers through iterative workshops. Five main phases guided the process:

- 1) **Requirements Gathering with End Users:** active listening sessions were conducted with construction professionals, engineers, and safety technicians to identify the main challenges faced on construction sites, as well as the critical skills required for safe interaction with robotic systems

- 2) **Iterative Prototyping:** usability testing is done at each stage. allowing feedback to be gathered on the interface, interaction mechanics, clarity of training objectives, and realism of the simulated scenarios.
- 3) **Pedagogical Validation** of content by safety experts. This validation ensured the clarity, accessibility and effectiveness of the concepts as well respecting users' levels of technological literacy.
- 4) **Workshop-based evaluation** collecting both quantitative (execution time, number of errors, protocol compliance rate) and qualitative (perceived usefulness, comfort, suggestions for improvement) data.
- 5) **Continuous improvement based on user feedback**, allowing for continuous adjustments to the interface, simulation scenarios, and application functionalities. This approach ensured that the final product was not only technically robust but also intuitive and effective from the user's perspective.

#### B. Virtual Reality Training System

The training system is structured into four pedagogically sequenced modules, ranging from safety fundamentals to immersive task simulations (figure 3). This approach breaks down the complexity of HRC into four main modules, each

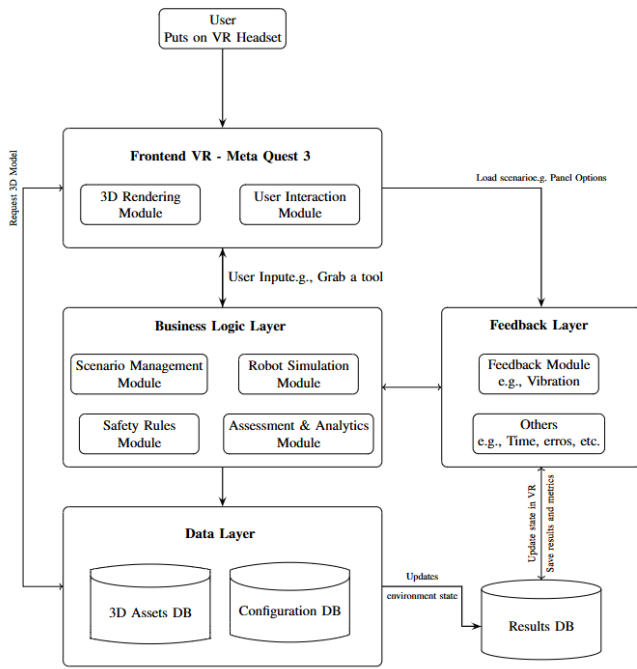


Fig. 1. System Overview.

building on the knowledge of the previous one. It guides users from fundamental safety concepts to the execution of complex operational tasks. From the main menu of the application, we have access to the learning modules (figure 5) (figure 2). The structure and purpose of each module are detailed below.

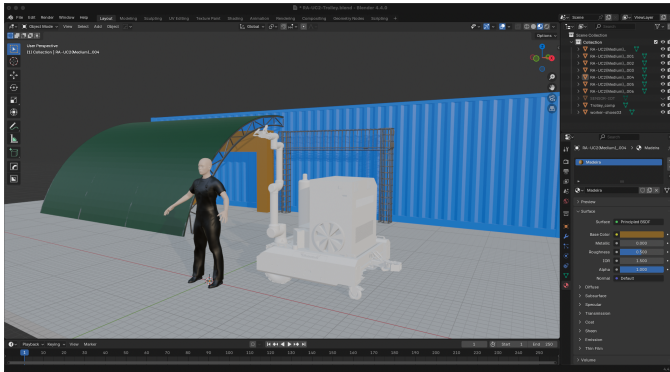


Fig. 2. Initial training scenario.

**Initial Training Scenario** For example, users must physically pick up and equip virtual Personal Protective Equipment (PPE) before starting a task, or use a virtual controller to guide the IRR robot through a scanning procedure. The system provides real-time feedback through visual cues (e.g., highlighting a correctly positioned object) and spatialized audio alerts (e.g., a warning sound if a user enters a restricted safety zone). To ensure an effective and progressive learning path, the VR training system was designed with a modular architecture (figure 3). This approach breaks down the complexity of

human-robot collaboration into four main modules, each building on the knowledge of the previous one. It guides users from fundamental safety concepts to the execution of complex operational tasks.

From the main menu of the application, we have access to the learning modules (figure 4). The structure and purpose of each module are detailed below.

1) *Module 1: Fundamentals of Safety in the Automated Worksite*: This initial module serves as the foundation for the entire training experience, focusing on indispensable safety knowledge. Its objective is not only to reinforce safety protocols already known in civil construction but also to introduce the new paradigms and risks associated with the presence of autonomous and collaborative robotic systems such as, safety principles, exclusion zones, and emergency protocols using interactive multimedia.

2) *Module 2: Familiarization with the Robotic Platforms (IRR & SFR)*: allows users to explore and manipulate 3D models of the IRR and SFR robots, understanding their functions and limitations (figure 3), where IRR aims at high-precision 3D modeling and rebar reinforcement, and SFR is responsible of the autonomous application and finishing of concrete. Users can virtually manipulate the robots, view their main components, and understand their operational capabilities, limitations, and specific purposes (figure 3).

3) *Module 3: Immersive Simulation of Tasks and HRC*: simulates realistic construction tasks requiring joint human-robot operation, such as wall construction and reinforcement. Users are immersed in realistic construction scenarios where they must directly interact with the robots to perform specific tasks, aligned with the use cases of the RoBétArmé project.

4) *Module 4: Performance Assessment* : The final module is to assess the proficiency acquired by the user and to collect data about the training platform itself through collecting task completion times, number of errors, safety compliance, and qualitative feedback for user evaluation.

### C. Feature overview of the VR training system

The VR training system incorporates multiple interactive features—such as object manipulation, real-time feedback, and immersive environments—whose complete technical descriptions are provided in Table II.

1) *Object Interaction: Grabbing, Dropping, Activating, and Assembling Tools*: This mechanic allows users to manipulate virtual objects intuitively using the VR headset’s and assembling tools are designed to mirror the movements a worker would perform on the construction site.

2) *Real-Time Feedback: Visual and Audio Cues*:

- What it is: The system provides immediate responses to the user’s actions, indicating whether they were performed correctly or incorrectly, allowing for the immediate correction of errors, reinforcing awareness of safety procedures, while also keeping the user engaged and motivated.

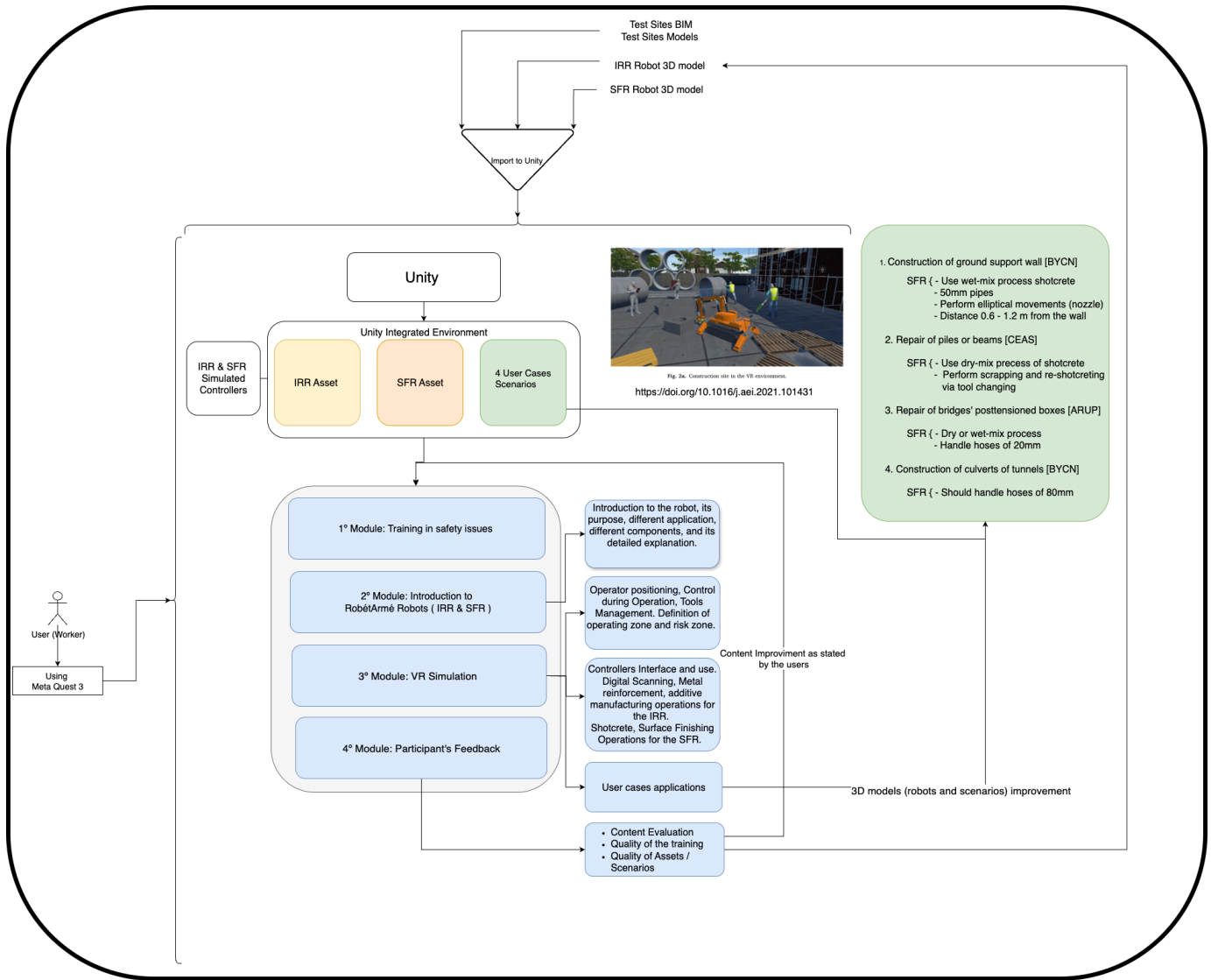


Fig. 3. Modular architecture of the VR training system.

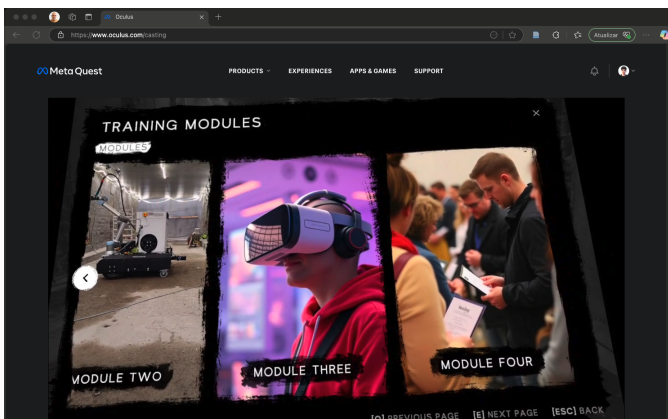


Fig. 4. The Main Menu VR training system.

### 3) Training Modes: Guided Tutorial, Free Practice, and Final Assessment:

- What it is: The application will be structured into different modes to cater to various skill levels and learning objectives.
- How it will work in practice:
  - Guided Tutorial: A step-by-step mode, ideal for beginners. The system will guide the user through tasks with clear instructions, highlighting the correct objects and the next steps to follow.
  - Free Practice: In this mode, the user has the freedom to explore the virtual environment and practice tasks at their own pace, without the pressure of an assessment.
  - Final Assessment: A test scenario where the user must complete a series of tasks without assistance. Their performance is measured based on criteria such as completion time, accuracy, and compliance with safety

TABLE II  
FEATURE OVERVIEW OF THE VR TRAINING SYSTEM

Feature	Brief Description
Object Interaction	Physics-based manipulation of virtual tools and mandatory PPE within the collaborative robot's workspace.
Real-Time Feedback	Immediate visual cues and spatialized audio warnings for unsafe proximity or incorrect procedures.
Training Modes	<ul style="list-style-type: none"> <li>• <b>Guided Tutorial:</b> Step-by-step instructions.</li> <li>• <b>Free Practice:</b> Unassisted task execution.</li> </ul>
Immersion and Realism	High-fidelity 3D reconstruction, accurate robot kinematics, and 3D spatial audio.
Unlimited Repetition	Repeat complex HRC tasks to build muscle memory without material cost or risk.
Performance Analytics	Tracking of key metrics for individual performance review and personalized feedback.
Adaptive Difficulty	AI-driven adjustment of scenario complexity based on trainee's real-time performance.

protocols.

- Why it is effective: The variety of training modes allows for a gradual learning progression. The user can start with the support of the tutorial, gain confidence in free practice, and finally demonstrate their competence in the final assessment.

#### 4) Immersion and Realism: Realistic Environments, Detailed Physics, and Spatial Audio:

- The goal is to create an experience as close to reality as possible to maximize the transfer of skills. This involves creating detailed virtual environments, simulating realistic physics, and using spatial audio. Providing a high level of immersion and realism increases user engagement and the sense of "presence" in the virtual environment. This makes the training more impactful and improves knowledge retention, better preparing the worker for the real conditions of the worksite.

#### 5) Unlimited Repetition: Repeating Tasks Until Mastery:

- The application allows users to repeat tasks and training modules as many times as necessary until they feel confident and demonstrate mastery of the skill.

### III. EXPERIMENTAL EVALUATION

#### A. Study Design

To assess the system's usability and perceived effectiveness, two interactive workshops were conducted with construction professionals (N = 10). Participants included engineers, site managers, and technicians with varying levels of prior exposure to robotic systems. Participants completed all four VR modules, after which data were collected through TAM questionnaires, task performance logs, and semi-structured interviews.

Regarding the measures adopted in this study, we outline the following:

- Quantitative: TAM constructs (Perceived Ease of Use, Perceived Usefulness, Attitude, Behavioral Intention).
- Assessment – real-time task performance tracking.
- Qualitative: Perceptions of realism, comfort, training relevance, and deployment feasibility.
- Observational: Task completion times, error frequency, and interaction fluency.

#### B. Quantitative Results

The questionnaire included items on user comfort with 3D glasses, intuitiveness of the interface, and difficulties encountered during interaction. Results showed that:

- 1) 83% of participants reported feeling comfortable or very comfortable using 3D glasses.
- 2) 92% found the interface intuitive, indicating a successful implementation of user-centered design principles.
- 3) 75% did not encounter any difficulties, while the remaining participants cited issues such as navigation commands, orientation in the virtual environment, and reading on-screen text.

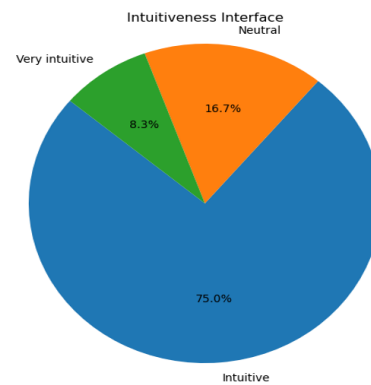


Fig. 5. Illustrates that most users found the interface intuitive.

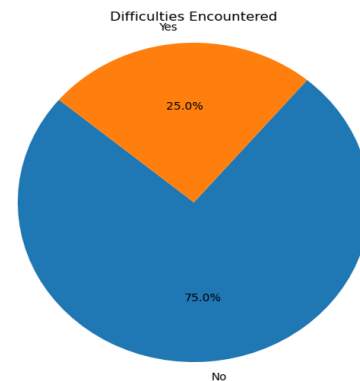


Fig. 6. Indicates that only a minority encountered difficulties during the interaction.

These findings support the effectiveness of the VR interface in delivering a smooth and engaging training experience.

### C. Qualitative Results

A qualitative study has been conducted through interviews to gather detailed perspectives and insights from participants to provide valuable suggestions in areas such as:

- 1) **Suggestions for improvement** included the addition of contextual pop-ups, clearer module titles, and a visible exit button in the main menu.
- 2) **Positive feedback** emphasized the value of VR in simulating hazardous environments safely and enhancing spatial awareness.
- 3) **Critical reflections** questioned the practical application of VR beyond technological novelty, highlighting the need for clearer communication of training objectives.

Participants also recommended resources such as online tutorials, instruction manuals, and peer support to facilitate onboarding.

### D. Implications for Future Development

The feedback gathered during the workshop will inform the next iteration of the VR training platform. Planned improvements include:

- 1) Enhanced onboarding through guided tutorials and kick-off sessions.
- 2) Refinement of interface elements for clarity and accessibility.
- 3) Expansion of training scenarios to include more diverse construction environments, such as tunnels and flatbeds.

This evaluation underscores the importance of continuous user engagement in the development of immersive learning tools and reinforces the potential of VR to transform workforce training in Construction 4.0.

### E. Discussion

The results validate the effectiveness of immersive VR in enhancing both cognitive and procedural learning for HRC. The integration of safety training, robot familiarization, and task execution within one environment addresses critical gaps in existing approaches. Importantly, participants' positive perceptions of usefulness and ease of use indicate readiness for adoption in professional training programs.

## IV. CONCLUSION AND FUTURE WORK

This paper presented the design and evaluation of a VR-based training platform for HRC in Construction 4.0. The system uniquely integrates four pedagogical components—safety, familiarization, immersive collaboration, and assessment—into a cohesive, modular framework. Experimental findings confirm high usability and perceived learning benefits, demonstrating VR's potential to bridge the gap between theoretical instruction and practical on-site readiness. These findings confirm that VR-based immersive training can serve as an effective bridge between theoretical safety instruction and practical on-site experience,

while mitigating risks inherent to construction environments. Future work will expand testing to larger participant groups, assess long-term retention, and explore AI-driven adaptive feedback for individualized learning. Ultimately, this research contributes to the advancement of safe, effective workforce training within the Construction 4.0 paradigm.

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