ADDRESSING COLLABORATIVE CHALLENGES IN HUMAN-ROBOT TEAMS THROUGH THE DEVELOPMENT OF AN IMMERSIVE VIRTUAL ENVIRONMENT

Adetayo Onososen[1], Innocent Musonda, Ramabodu Molusiwa and Christopher Dzuwa

Centre for Applied Research and Innovation in the Built Environment, Department of Construction Management and Quantity Surveying, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, 2092, South Africa

Technological innovations in construction, like robots, pose a challenge in collaborating effectively with humans. An immersive virtual environment (IVE) addresses this by simulating human-robot interactions safely. This study developed an IVE that accurately represents the real-world setting for human-robot teams. It integrates essential elements like equipment, tools, and objects for construction tasks. The virtual environment depicts real-time interaction between human operators and virtual robots as typical of construction environments and scenarios. It effectively enhances construction workers' and operators' interaction and collaboration with robots, familiarising them with capabilities, limitations, and behaviour. Moreover, it facilitates testing and evaluating different human-robot interaction methods, interfaces, and control approaches to precede implementation on construction sites. Overall, the IVE provides a controlled and safe platform for training, allowing operators to become proficient in working with construction robots while optimising their performance and safety in real-world construction settings.

Keywords: collaboration; human-robot teams; virtual reality

INTRODUCTION

The use of collaborative robots teaming with humans in future industrialised networks is inevitable in delivering sustainable and quality infrastructure to meet socio-economic demands. The adoption of robots is hinged on their characteristics to be highly skilled in performing physically repetitive tasks, which abounds in the built environment (Malik and Brem, 2021). With the potential to cut down waste, reduce injuries and perform work better and faster, design and development in collaborative robots are progressing very fast with optimism and concerns about what it connotes for the future of work between workers and robots (Lucas, 2018). However, effective collaboration between humans and robots remains a significant challenge due to the differences in their capabilities, skills, and cognitive processes. Developing immersive virtual environments can help address these challenges by providing a

[1] Onososen@outlook.com

Onososen, A, Musonda, I, Molusiwa, R and Dzuwa, C (2023) Addressing Collaborative Challenges in Human-Robot Teams Through the Development of an Immersive Virtual Environment *In:* Tutesigensi, A and Neilson, C J (Eds) *Proceedings of the 39th Annual ARCOM Conference,* 4-6 September 2023, University of Leeds, Leeds, UK, Association of Researchers in Construction Management, 75-82.

platform for training, testing, and optimising human-robot team performance (Adami *et al.,* 2021). This article presents an overview of collaborative challenges in human-robot teams. It showcases how they can be addressed through human-robot collaborative learning in an immersive virtual environment as a solution to these challenges.

Background to Study

The construction industry has been vulnerable to high rates of deaths and fatal injuries than any of the other main industries because of the unstructured and dynamic nature of building sites and the significant physical demand that construction labour places on workers (Kurien *et al.,* 2018; Wang *et al.,* 2021). This has led to increased interest in the development of robots. Yet, due to the unstructured and complicated nature of construction settings and the relatively loose tolerances of building projects, construction robots confront various problems, which may lead to frequent robot failures while executing duties on-site. In addition to collaboration issues, this poses myriad challenges to human-robot teams' collaboration.

Immersive Virtual Environments

Immersive virtual environments (IVEs) are computer-generated environments that simulate real-world scenarios and allow humans and robots to interact in a controlled setting (Lucas, 2018). IVEs provide a platform for training, testing, and optimising human-robot team performance, as they allow researchers to manipulate various parameters and observe their effects on team dynamics (Albeaino and Eiris, 2021). IVEs can also be used to evaluate new communication protocols and interfaces and to identify potential sources of errors and misunderstandings (Onososen, Musonda and Ramabodu, 2022).

IVEs can be designed to simulate various scenarios, such as manufacturing, healthcare, and disaster response. In a manufacturing setting, for example, an IVE can simulate a production line where humans and robots work together to assemble products (Dallel *et al.,* 2023). In a healthcare setting, an IVE can simulate a hospital ward where robots assist nurses in patient care (Bermúdez I Badia *et al.,* 2022). In a disaster response setting, an IVE can simulate a rescue mission where robots and humans work together to locate and rescue victims (Sermet and Demir, 2022). In the built environment, their applications range from site visits/education, training for rooftop workers, human-machine skills development training, health, and safety training on-site, and recently on, human-robot collaboration simulations and training. They are also extensively used for design visualisation in communicating project concepts and progress (Albeaino and Eiris, 2021).

Constructing New Future

Developing IVEs for human-robot teams represents a significant step towards creating a future where robots and humans can collaborate effectively and safely. IVEs can help bridge the communication gap between humans and robots and provide a platform for testing and optimising new communication protocols and interfaces (Alisadehsalehi and Hadavi, 2021). Moreover, IVEs can enable researchers to identify potential sources of errors and misunderstandings before deploying robots in real-world settings (Matsas *et al.,* 2017). However, developing IVEs is the first step to achieving effective human-robot collaboration. Further research is needed to explore the effects of different communication protocols, modalities, and interfaces on team dynamics and performance. Moreover, researchers need to develop new methods for evaluating the effectiveness of IVEs and transferring the lessons learned in virtual environments to real-world settings.

Therefore, the development of IVEs for human-robot teams is an exciting and promising field that has the potential to revolutionise the way humans and robots work together. IVEs can help create a future where robots and humans collaborate seamlessly and safely by addressing the collaborative challenges in human-robot teams.

METHOD

To examine how the immersive virtual environment can address the collaborative challenges associated with human-robot teams, an immersive VR interface for human-robot interaction for construction task execution was developed. This approach is an experimental study followed by a post-experiment discussion based on the participants' perceptions (Matsas *et al.,* 2017)). The result for this paper is drawn from piloted experiments with robots and human participants to simulate real-life construction environments (Kurien *et al.,* 2018). Seven student participants who were postgraduate construction management students were recruited for the experiment. All the respondents had completed several subjects related to construction project management and gained basic construction industry experience through internships at construction companies. Before the experimental sessions commenced, they were briefed on the study's purpose and process, and their background information was collected through a survey. A group post-experiment question was asked to examine their perception of an immersive virtual environment and how it can address the collaborative challenges associated with human-robot teams. Their responses were categorised and summarised into themes, as presented in Table 2. The immersive VR interface, developed on the Unity platform, allows users to interact with robots and other humans in the environment (Bermúdez. *et al.,* 2022). It consists of the robot, construction workspace, and humans in the environment. Humans can perform environmental tasks such as site inspection, progress monitoring and interacting with drones.

Already-built structures, such as static building components and temporary structures, were included inside the workspace. The environment was implemented in Unity 2022.1.16 using the C# programming language. Following the importation of the model into unity, parameters to measure the participant's task performance and ability to collaborate with robots in the environment were included. This included the safety of colliding with materials and robots in the environment, the number of tasks performed, the position of the participants at every point in the environment, the command prompts sent to the VR, and other parameters. Scripting involves simulating the rotor animations, object gripping, grip retraction and extension, switching between cameras, robot motion control, robot powering and starting, collision tracking, and payload delivery logging. The robot was controlled using a controller with a display screen. The flight environment was a construction site with four uncompleted buildings. Other objects commonly found on construction sites were also added to the scene (Figure 1).

Virtual reality was utilised in the running of the simulation so that the experience could be as lifelike as feasible (Dallel *et al.,* 2023). The simulation included virtual reality capabilities thanks to the XR interaction tools. This involves moving around, turning, and conversing with other characters or things in the scenario. Because it supports various virtual reality devices, including SteamVR, Oculus Quest 2, Oculus

Rift, HTC Vive, and others, the XR interaction toolkit was selected as the best option. The motion speed was kept at 1.5 meters per second, and the turning speed was kept at 1.0 degrees per second because these speeds proved effective in preventing motion sickness while using virtual reality. The Oculus Quest 2 was utilised in user testing, which took place. Ten minutes were allotted to every user for them to perform the tasks assigned in the virtual environment.

Figure 1: Images showing the VR environment and a participant using the system

FINDINGS

Collaborative Challenges in Human-Robot Teams

The main questions/issues addressed in this paper are what are the collaborative challenges construction workers are likely to face in working with robots, and how can VR be utilised to address these challenges? The findings reveal that human-robot teams' success depends on effective collaboration, which requires a shared understanding of tasks, goals, and communication protocols (Liang *et al.,* 2021). However, humans and robots have different capabilities and limitations, leading to misunderstandings and errors. For example, humans rely on social cues and nonverbal communication, while robots may not recognise or respond to these cues (Liu *et al.,* 2016). Similarly, humans have cognitive flexibility and can adapt to new situations, while robots may struggle to handle unexpected events (Yazdani, Brieber and Beetz, 2016).

The challenges identified in the post-experiment group discussion are the communication gap between humans and robots, as they use different languages and modalities (Groom and Nass, 2007). Humans use natural language, gestures, and facial expressions, while robots use programming languages, sensors, and actuators (Bainbridge *et al.,* 2011). Bridging this gap requires developing new communication protocols that allow humans and robots to understand each other's intentions and actions. Other challenges identified and described in the table 1 are; Role confusion (Berx, Decré and Pintelon, 2022), trust and confidence (Hancock *et al.,* 2021), Adaptability (Malik and Brem, 2021), Task allocation (Tsarouchi *et al.,* 2017), Decision-making (Le, Sajtos and Fernandez, 2022), Technical difficulties (Atabay, Pelin Gurgun and Koc, 2020), Safety concerns (R. Wang *et al.,* 2021), Compatibility issues (Faber, Bützler and Schlick, 2015), Ergonomics in Human-robot interaction (Onososen and Musonda, 2022).

Table 1: Collaborative Challenges in Human-Robot Teams

S/N	Collaborative Challenges	Description	Sources
1.	Communication	Differences in communication styles, modalities, or languages can create misunderstandings and hinder effective collaboration.	(Akiho and Sugaya, 2016)
2.	Role confusion	Lack of clarity about team members' roles and responsibilities can lead to duplication of effort or gaps in task completion.	(Berx, Decré and Pintelon, 2022)
3.	Trust and confidence	Building trust and confidence between humans and robots can be challenging, as robots may be perceived as unpredictable or untrustworthy.	(Hancock *et al.,* 2021)
4.	Adaptability	Human-robot teams must be able to adapt to changing circumstances, such as unexpected events or changes in the environment.	(Malik and Brem, 2021)
5.	Task allocation	Assigning tasks and responsibilities to the appropriate team member can be complex, especially when considering task difficulty, robot capabilities, and expertise.	(Tsarouchi *et al.,* 2017)
6.	Decision-making	Human-robot teams may face challenges in decision-making, particularly when dealing with complex or ambiguous situations.	(Le, Sajtos and Fernandez, 2022)
7.	Technical difficulties	Technical issues, such as malfunctions or software bugs, can impede collaboration and cause delays or errors.	(Atabay, Pelin Gurgun and Koc, 2020)
8.	Safety concerns	Ensuring the safety of human team members when working with robots is crucial, as robots may pose physical risks or hazards.	(Wang *et al.,* 2021)
9.	Compatibility issues	The compatibility of hardware, software, and other technologies used by human-robot teams must be carefully considered to ensure seamless collaboration.	(Faber, Bützler and Schlick, 2015)
10.	Ergonomics Human-robot interaction	Designing interfaces and interaction modalities that enable effective and natural human-robot interaction can be challenging, as humans and robots have different capabilities and limitations.	(Onososen and Musonda, 2022)

How Virtual Reality Addresses Collaborative Challenges in Human-Robot Teams

One of the most natural ways humans and robots work together is to lead the robot through physical touch. This method calls for human operators to apply physical forces directly to the robot or the object the robot is carrying to guide the robot to comparable places (Wang *et al.,* 2021). Virtual reality applications offer an immersive environment for human workers to virtually rehearse such contact and use scenarios with the robot to enhance safety and human-robot interaction learning. In the virtual environment developed, the robot executes the physically demanding task to enable the human workers to pay more attention to the task execution details. The human worker is responsible for high-level task planning and supervision, and the robot undertakes detailed workspace sensing and monitoring, path planning, and physical execution of the work.

Moreso, the workspace can be visualised from the building information model for human workers to understand workflows associated with the robot's movement and task performance. The reaction of the robots to tasks and commands can also be tested in the VR environment before actual work on-site to build trust. Collision-free motion plans can be visualised in the virtual environment and rehearsed to evaluate safety.

Identified challenges, such as communication factors, can utilise haptic and audio-visual systems to reflect operator and robot responses (Adami, 2021). This includes using vision-based systems to identify human gestures for robot guidance. Other studies have also identified using wearable sensors, inclinometers, orientation sensors, and rotary encoders to detect human arm movement to operate a robot. As suggested by the participants, collaboration challenges in human-robot teams can also be addressed using VR through robot role plan preview and evaluation, simulating realistic scenarios, and testing the performance of robots in various situations, helping to build trust and confidence in their capabilities, simulating complex tasks and allocate responsibilities among team members based on their expertise and capabilities. Also, Table 2 suggests that users should simulate dangerous situations, allowing team members to practice safety procedures and minimise risks to humans. Other factors stated that the environment should provide a simulated scenario that allows team members to test and optimise the compatibility of different hardware and software components.

Table 2: Role of VR in Collaborative Challenges in Human-Robot Teams

S/N	Collaborative Challenges	Role of Virtual Reality
1.	Communication	Virtual reality can provide a shared visual and auditory environment that can help overcome language and communication barriers. For example, virtual reality can create a shared workspace where team members can communicate through avatars, overcoming differences in communication styles and modalities.
2.	Role confusion	Virtual reality can provide an immersive simulation environment that allows team members to experience different roles and responsibilities. This can help clarify expectations and promote a better understanding of each other's roles. Robot role plan preview and evaluation
3.	Trust and confidence	Virtual reality can be used to simulate realistic scenarios and test the performance of robots in various situations, helping to build trust and confidence in their capabilities. For example, virtual reality can simulate dangerous or high-stress situations, allowing team members to test robots' ability to perform under pressure.
4.	Adaptability	Virtual reality can provide a flexible and dynamic simulation environment that can be easily modified to reflect changing circumstances. This can help human-robot teams practice and develop adaptability skills in a safe and controlled environment.
5.	Task allocation	Virtual reality can simulate complex tasks and allocate responsibilities among team members based on their expertise and capabilities. This can help optimise task allocation and improve task completion times. Robot motion plan review and evaluation.
6.	Decision-making	Virtual reality can provide a realistic and immersive environment that allows team members to practice decision-making in complex and ambiguous situations. For example, virtual reality can simulate emergencies, allowing team members to practice decision-making in a safe and controlled environment.
7.	Technical difficulties	Virtual reality can provide a simulated environment that allows team members to practice troubleshooting and problem-solving during technical difficulties. This can help minimise delays and errors caused by technical issues.
8.	Safety concerns	Virtual reality can simulate hazardous situations, allowing team members to practice safety procedures and minimise risks to human team members.
9.	Compatibility issues	Virtual reality can provide a simulated environment that allows team members to test and optimise the compatibility of different hardware and software components. This can help ensure seamless collaboration and reduce technical issues caused by incompatible technologies.
10.	Ergonomics Human-robot interaction	Virtual reality can be used to design and test interfaces and interaction modalities that promote effective and natural human-robot interaction. This can help overcome the challenges of designing intuitive and user-friendly interfaces for both humans and robots.

CONCLUSIONS

This paper developed an immersive virtual environment approach to addressing challenges associated with collaboration in human-robot teams. First, it highlights how the environment was developed and demonstrates how the environment can enable collaboration amongst human-robot teams. The study's findings imply that VR can enhance collaboration by providing a virtual environment where human team members and robots can interact and work together seamlessly. This can lead to better coordination, increased efficiency, and overall team performance. The study suggests that collaborative robots will play a crucial role in future industrialised networks, and immersive virtual environments can help overcome the communication gap between humans and robots, leading to effective collaboration. The findings also indicate that these environments can enhance safety, optimise robot performance, and facilitate skill development and training for construction team members, while further research is needed to explore communication protocols and transfer virtual environment lessons to real-world settings. Overall, immersive virtual environments have the potential to revolutionise human-robot collaboration in the construction industry. Also, these help us to understand enhanced training and skill development in the learning process for construction team members and robots. By simulating realistic scenarios, individuals can gain valuable experience and develop the necessary skills to navigate complex collaborative challenges. This can lead to faster skill acquisition, reduced training costs, and increased readiness for real-world deployments.

REFERENCES

Adami, P, Rodrigues, P B, Woods, P J, Becerik-Gerber, B, Soibelman, L, Copur-Gencturk, Y and Lucas, G (2021) Effectiveness of VR-based training on improving construction workers knowledge, skills and safety behaviour in robotic teleoperation, *Advanced Engineering Informatics*, **50**.

Akiho, O and Sugaya, M (2016) *Impression Evaluation for Active Behavior of Robot in Human-Robot Interaction*, Cham: Springer International Publishing, 83-95.

Albeaino, G and Eiris, R (2021) DroneSim : A VR-based flight training simulator for drone-mediated building inspections, *Construction Innovation*, **22**(4), 831-848.

Alisadehsalehi, S and Hadavi, A (2021) Assessment of AEC students performance Using BIM-into-VR, *Applied Sciences*, **11**(3225).

Atabay, S, Pelin Gurgun, A and Koc, K (2020) Incorporating BIM and green building in engineering education: Assessment of a school building for LEED Certification, *Practice Periodical on Structural Design and Construction*, **25**(4), 04020040.

Bainbridge, W A, Hart, J W, Kim, E S and Brian, S (2011) The benefits of interactions with physically present robots over video-displayed agents, *International Journal of Social Robotics*, **3**(1), 41-52.

Bermúdez I Badia, S, Silva, P A, Branco, D, Pinto, A, Carvalho, C, Menezes, P, Almeida, J and Pilacinski, A (2022) Virtual reality for safe testing and development in collaborative robotics: Challenges and perspectives, *Electronics*, **11**(11), 1-14 doi 10.3390/electronics11111726.

Berx, N, Decré, W and Pintelon, L (2022) Examining the role of safety in the low adoption rate of collaborative robots, *Procedia CIRP*, 106, 51-57.

Dallel, M, Havard, V, Dupuis, Y and Baudry, D (2023) Digital twin of an industrial workstation: A novel method of an auto-labeled data generator using virtual reality for human action recognition in the context of human-robot collaboration, *Engineering Applications of Artificial Intelligence*, **118**, 105655.

Faber, M, Bützler, J and Schlick, C M (2015) Human-robot cooperation in future production systems: Analysis of requirements for designing an ergonomic work system, *Procedia Manufacturing*, **3**, 510-517.

Groom, V and Nass, C (2007) Can robots be teammates? *Interaction Studies Social Behaviour and Communication in Biological and Artificial Systems*, **8**(3), 483-500.

Hancock, P A, Kessler, Theresa T, Kaplan, Alexandra D and Szalma and James L (2021) Evolving Trust in Robots : Specification through sequential and comparative meta-analyses, *Human Factors*, **63**(7),

Kurien, M, Kim, M K, Kopsida, M and Brilakis, I (2018) Real-time simulation of construction workers using combined human body and hand tracking for robotic construction worker system, *Automation in Construction*, **86**, 125-137.

Le, K B Q, Sajtos, L and Fernandez, K V (2022) Employee-(ro)bot collaboration in service: An interdependence perspective, *Journal of Service Management*, **34**(2), 176-207.

Liang, C, Wang, X, Kamat, V and Menassa, C C (2021) Human-Robot collaboration in construction : Classification and research trends, *Journal of Construction Engineering Management*, **147**(1994), 1-23.

Liu, D, Wu, You, Li, S and Sun, Y (2016) Automation in Construction A real-time monitoring system for lift-thickness control in highway construction, *Automation in Construction*, **63**, 27-36.

Lucas, J (2018) Immersive VR in the Construction Classroom to increase student understanding of Sequence, assembly and Space of Wood Frame Construction, *Journal of Information Technology in Construction*, **23**(November 2017), 179-194.

Malik, A A and Brem, A (2021) Digital twins for collaborative robots: A case study in human-robot interaction, *Robotics and Computer-Integrated Manufacturing*, **68**, 102092.

Matsas, E and Vosniakos, G.C (2017) Beware of the Robot : A Highly Interactive and Immersive Virtual Reality Training Application in Robotic Manufacturing Systems, *In*: A*dvances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services: IFIP WG 5.7 International Conference,* Rhodes, Greece, September 24-26.

Onososen, A O and Musonda, I (2022) Ergonomics in construction robotics and human-robot teams in the AEC domain: A review, *In*: *IOP Conference Series: Earth and Environmental Science,* IOP Publishing, **1101**(5), 052003).

Onososen, A O, Musonda, I and Ramabodu, M (2022) construction robotics and human-robot teams research methods, *Buildings*, **12**(1192), 1-33.

Sermet, Y and Demir, I (2022) Computers and Geosciences GeospatialVR : A web-based virtual reality framework for collaborative environmental simulations, *Computers and Geosciences*, **159**, 105010.

Tsarouchi, P Michalos, G, Makris, S, Athanasatos, T, Dimoulas, K and Chryssolouris, G (2017) On a human-robot workplace design and task allocation system, *International Journal of Computer Integrated Manufacturing*, **30**(12).

Wang, R Nakhimovich, D, Roberts,, F.S and Bekris, K.E (2021) Robotics as an enabler of resiliency to disasters: Promises and pitfalls, *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, Cham: Springer International Publishing.

Wang, X, Liang, C J, Menassa, C C and Kamat, V R (2021) Interactive and immersive process-level digital twin for collaborative human-robot construction work, *Journal of Computing in Civil Engineering*, **35**(6), p.04021023.

Yazdani, F, Brieber, B and Beetz, M (2016) Cognition-enabled robot control for mixed human-robot rescue teams, *In*: *Intelligent Autonomous Systems 13: Proceedings of the 13th International Conference IAS-13*, Cham: Springer International Publishing, 1357-1369.