Evaluating the Impact of MR and Tracking Technologies in Construction Assembly Training: A Pilot Study

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Abstract

This paper explores carpentry students' perceptions of integrating Mixed Reality (MR) and construction component tracking technologies within carpentry and assembly processes using the Twinbuild MR tool. Employing a case study approach, the research focused on the real-time assembly of a complex timber pavilion to demonstrate these technologies' practical applications and benefits. For the first time, carpentry students used this technology to assemble a section of a larger structure while the research team gathered empirical data. Various data collection methods were used to evaluate the students' mental and cognitive loads during task completion, complemented by semi-structured interviews. Findings yielded insights into the key advantages and challenges of using MR technology in construction assembly, along with recommendations for improvements. The findings highlighted the technology's potential to enhance assembly processes, reduce errors, and improve construction education and practice quality. However, areas for refinement were identified, including user interface design, graphic accuracy, and hardware. The study underscores MR and tracking technologies' transformative impact on construction training and practice. By integrating these technologies, construction education can move beyond traditional methods to offer immersive and interactive learning experiences, enhancing understanding and skill acquisition by effectively linking theory with practical application. The research emphasizes the need for ongoing development and integration of such technologies in educational curricula and industry practices to keep pace with technological progress and evolving sector needs.

Keywords: Mixed Reality (MR), Construction Training, Tracking Technologies, Immersive Learning, Skill Acquisition

1 Introduction

The integration of advanced technologies like Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) in construction education has the potential to revolutionize traditional teaching methodologies (Hjorth & Chrysostomou, 2022). These immersive and interactive environments bridge the gap between theoretical knowledge and practical application, making them particularly beneficial for vocational training. In the construction industry, the assembly of prefabricated components can be complex and error prone. Traditional training methods often fail to adequately prepare students for the dynamic and challenging nature of on-site work. MR, which blends physical reality and digital content, provides a promising solution by overlaying digital information on the real world, guiding users through assembly processes, reducing errors, and improving efficiency (Carmigniani & Furht, 2011).

This study focuses on a pilot project conducted with carpentry students using the Twinbuild MR tool developed by Fologram, integrated with Ynomia's tracking technology. Fologram's MR application synchronizes parametric modeling with an AR environment, providing a stable and synchronized live stream compatible with various platforms, such as Microsoft® HoloLens, iOS, and Android (Newnham, Van den Berg, & Jahn, 2018). Ynomia's tracking technology, which combines system integrations with QR and Bluetooth tracking, creates a comprehensive digital record for each building component, enabling informed decision-making throughout the project lifecycle (Ynomia, n.d).

During the Building 4.0 CRC 2023 Annual Conference, a portion of a large timber pavilion was selected for the pilot study. Carpentry students used MR headsets to assemble the structure, guided by MR visualizations and tracking data. This real-time assembly task aimed to evaluate the effectiveness of MR in enhancing learning experiences, minimizing errors, and improving overall construction quality.

By documenting the students' experiences and feedback, this study aims to provide insights into the practical applications and benefits of MR in construction education. It also seeks to identify areas for refinement and improvement, thereby contributing to the ongoing development and incorporation of such technologies in educational curricula and industry practices. This research underscores the potential for transformative impact, aligning with the principles of Industry 5.0 by integrating technological advancements with human-centric practices in construction training (Hjorth & Chrysostomou, 2022; Mohamed & Sicklinger, 2022).

2 Research Background

Industry 5.0 represents a significant shift in the industrial landscape, aiming to harness new technologies for prosperity that is not merely limited to economic growth but also respects the planet's limits and prioritizes the well-being of industrial workers (Commissione Europea et al., 2021). This paradigm seeks to integrate technological advancements with human-centric practices, creating synergies between technological and social systems to offer personalized mass customization of products and services. Unlike Industry 4.0, which primarily focused on maintaining competitiveness and adapting to increasing customer demands, Industry 5.0 emphasizes human-robot collaboration and sustainability (Hjorth & Chrysostomou, 2022).

In the construction industry, particularly at the educational entry level, the principles of Industry 5.0 can be effectively applied through the use of AR and MR technologies. These technologies enhance the learning and execution processes by making each assembly step interactive, thereby improving efficiency and reducing errors. For instance, Microsoft® HoloLens projects holograms of the final model, including all construction phases, thus providing a hands-on learning experience that aligns closely with the evolving needs of the construction sector (Chalhoub & Ayer, 2018).

Mixed Reality (MR), which combines elements of both VR and AR, provides a real-time view of the physical world augmented with virtual information. This creates an interactive and immersive user experience where spatial and temporal registration between real and virtual environments is achieved (Carmigniani & Furht, 2011; Craig, 2013). MR technologies allow users to interact with and among real-world and virtual objects, enhancing the learning experience by blending digital content with physical reality (Milgram et al., 1999; Rokhsaritalemi et al., 2020; Speicher et al., 2019).

The application of AR and MR in construction training has shown promising results. These technologies can significantly enhance the educational experience by providing immersive and interactive environments. For example, in the context of vocational education, AR tools like Fologram can synchronize parametric modeling with an AR environment, enabling students to visualize and interact with detailed holograms of construction models in real-time. This integration facilitates direct human-machine interaction and helps bridge the gap between theoretical knowledge and practical application (Newnham, Van den Berg, & Jahn, 2018).

In addition to enhancing learning outcomes, AR and MR technologies also support the principles of Industry 5.0 by fostering an educational environment where technology and human input coexist and integrate. This approach enhances both learning outcomes and practical applications in the construction industry, addressing the evolving needs of the sector. MR devices, such as DAQRI Smart Glasses, Magic Leap One, and Microsoft® HoloLens, enhance performance and efficiency in construction processes by providing a stable and synchronized live stream of construction models and enabling real-time interaction with virtual and physical components (Alizadehsalehi, Hadavi, & Huang, 2020; Cheng, Chen, & Chen, 2020).
However, the classification of MR products remains unclear, and further research is needed to explore their full potential in educational and professional contexts (Chalhoub & Ayer, 2018). The Vocational Education and Training (VET) sector plays a crucial role in preparing both current and future employees with the practical skills required in the workforce. VET focuses on delivering qualifications and high-quality training that cater to labour market demands, thereby enhancing the country's economic productivity. It is imperative for the VET sector to promote teaching and learning mechanisms that equip students with relevant knowledge and skills for specific work environments.

3 Literature Review

A scoping review of literature was undertaken to understand how MR has been used to enhance training and upskilling, and to promote collaboration more generally. The findings are summarized in Table 1.

In the construction industry, training new workers and upskilling existing ones can be time-consuming and costly. Ensuring that the workforce is proficient in using advanced construction technologies and following safety protocols is crucial for project success. Mixed Reality (MR) offers immersive training experiences that simulate real construction scenarios, allowing workers to practice tasks in a safe virtual environment and gain practical skills before entering the field (Chalhoub et al., 2021; Cuperschmid et al., 2016). This technology accelerates training, reduces on-site errors, and ensures that workers are well-prepared to handle complex tasks (Kayhani et al., 2018; Shringi et al., 2023). MR creates a more immersive training environment that delivers better learning outcomes (Kayhani et al., 2018; Shringi et al., 2023), leading to fewer safety incidents and Lost Time Injuries (Shringi et al., 2023). Additionally, MR provides experience-based training while mitigating the risks associated with upskilling (Kayhani et al., 2018; Shringi et al., 2023). The use of MR-based training programs allows employers to reduce the risks tied to adopting new construction methodologies (Shringi et al., 2023).

Table 1. Findings from papers analyzed as part of scoping review

Study	Key Findings	Barriers
Chalhoub & Ayer (2018)	Improved accuracy in construction sites	Complexity in adoption, training required
Alizadehsalehi et al. (2019a)	Enhanced construction efficiency	Rapidly evolving technology, integration challenges
Cheng et al. (2020)	Improved collaboration and data management	Technical and logistical challenges in multi-user setups
Newnham, Van den Berg & Jahn (2018)	Synchronises parametric modelling with AR	Initial setup and integration complexity
Lee, Hahm & Jun (2021)	Simplified link between HoloLens and 3D modelling	Dependence on specific hardware and software
Jahn et al. (2019)	Real-time changes in MR environments	Technical challenges in real-time adjustments
Yan & Tamke (2021)	Accurate tracking of user positions and gaze directions	Accuracy in tracking, user acceptance
Cote et al. (2022)	Effective manipulation of geometries in MR	Complexity in geometry manipulation
Varela et al. (2022)	Real-time link between digital and holographic environments	Technical and integration challenges
Shen & Hsu (2023)	Application in architectural installations	Adoption in real-world settings
Cuong et al. (2023)	Improved preassembly analysis	Technical challenges in preassembly analysis
Dan et al. (2021)	Usability challenges in MR devices	Usability and comfort issues
Li et al. (2018)	Enhanced safety and quality control	Training and equipment costs

Liu et al. (2023)	Improved collaboration in mining industry	Harsh environmental conditions
Rezvani et al. (2022)	High precision in MR applications	Implementation complexity
Sebastian et al. (2018)	Enhanced design communication	Technical and logistical integration
Shringi et al. (2020)	Improved assembly and error detection	Error detection and user training
Srivastava et al. (2022)	Effective task monitoring	Technical and device limitations
Tzimas et al. (2019)	Enhanced visualization and interaction	Visualization accuracy
D. Wang & Hu (2022)	Automated fabrication and visualization	Integration with existing processes
Cuperschmid et al. (2016)	Simplified wall installation process	Technical setup and training
Cuellar Lobo et al. (2021)	Enhanced design communication	Integration with existing BIM processes
Dasgupta et al. (2019)	Improved lifting planning	Safety and training requirements
Hammad (2009)	Effective training and education	Adoption and training

4 Methodology

This study adopted a qualitative research design to explore the use of Mixed Reality (MR) and construction tracking technologies in an educational setting. The primary aim was to develop new knowledge and a framework regarding the importance of MR in construction training, particularly focusing on carpentry students. An instrumental case study approach was chosen, allowing for an in-depth investigation of a contemporary phenomenon within its real-life context (Yin, 1994; Baxter & Jack, 2008).

The research utilized a case-based approach to gather insights into the practical applications and benefits of MR technology. This approach involved real-time assembly tasks conducted by carpentry students using the Twinbuild MR tool developed by Fologram, integrated with Ynomia's tracking technology.

In the fields of design and interpretation, practice and theory represent two fundamental types of knowledge. Achieving advanced understanding requires a dynamic relationship between these two concepts. To comprehend students' experiences with and perceptions of Fologram/Ynomia and Microsoft® HoloLens, the authors adopted a flexible qualitative research design informed by Forlizzi's (2007) concept of product ecology. Product ecology helps design researchers describe how a product influences social behavior, guiding them in selecting appropriate research methods and expanding the design culture in interaction design. This approach acknowledges the uniqueness of users, recognizing that each person may associate different meanings and feelings with a product based on their everyday interactions with it.

Accordingly, the authors immersed themselves in the tasks and needs of the study participants. They employed individual semi-structured interviews, questionnaires, observations, and a real demo to gather comprehensive data. The collected data were then combined and categorized into larger topics. Inductive data analysis was used to derive meaning from the data and build substantive theory from practice (Merriam & Tisdell, 2015; Patton, 2002). This method of theory building was well-suited for the study, which aimed to understand practical applications and provide actionable insights for using MR technology in construction education.

Participants

The participants were carpentry students from a leading Australian provider of vocational and higher education. The study involved six male participants, aged between 18 and 30, with a background in carpentry. Although the interviews were conducted in English, most participants did not report English as their mother tongue. This diversity enriched the research with a variety of perspectives, guided by different experiential and educational backgrounds and insights from various construction site experiences.

The study received approval from the Monash University Human Research Ethics Committee (MUHREC) in September 2023. In accordance with the ethical approval, consent information statements and consent forms were provided to all participants, ensuring informed consent. Participants were selected to be over 18 years old and none had been diagnosed with anxiety, depression, or any other emotional disturbance in the previous 12 months.

Despite the small number of participants, this allowed the researchers to build and maintain close relationships with them, facilitating rich qualitative data collection through triangulation. The variety in participants' sex, age, and experiences provided a well-rounded data set. Qualitative

research relies on inductive reasoning grounded in the interpretation of the collected data (Thorne, 2000). This approach is particularly suited for gaining a deep understanding of the underlying motivations and experiences that drive engagement with the MR technology. Consequently, the insights obtained from the Holmesglen students proved to be highly valuable.
All participants had some level of experience in carpentry but limited prior exposure to advanced technologies such as MR. The selection criteria ensured a diverse range of experiences and perspectives, enriching the research findings. The study received approval from the Monash University Human Research Ethics Committee (MUHREC), and informed consent was obtained from all participants.

Data Collection Methods

Gaining access to organizations and appropriate participants for case studies can be challenging (Yin, 2018). However, data collection remains central to qualitative research and is essential to avoid biases. To ensure the trustworthiness and validity of the data, the authors employed multiple data-gathering methods. This approach helped in obtaining substantial and comparable data from various participants (Golafshani, 2003). These methods included:

- Semi-Structured Interviews: Conducted with each participant to gather qualitative data on their experiences, insights, and feedback regarding the use of MR technology.
- Questionnaires: Administered to evaluate usability, cognitive load, and user satisfaction. The System Usability Scale (SUS) and the Paas Cognitive Load Scale were used to quantify the participants' perceptions and experiences.
- Observation: Real-time observations of the participants during the assembly task provided contextual insights and helped identify practical challenges and benefits of using MR in construction training.
- Task Completion Metrics: Time taken to complete the assembly task was recorded to assess the efficiency of the MR-guided process.

During the Building 4.0 CRC 2023 Annual Conference, participants received a briefing session on using the Microsoft® HoloLens and the Twinbuild MR tool. They were then given a few minutes to familiarize themselves with the equipment before starting the assembly task. The task involved assembling a portion of a large timber pavilion, guided by MR visualizations and tracking data. Participants scanned QR codes to load visualizations and receive step-by-step instructions, selecting and positioning pre-cut timber components accordingly.

5 Pilot Study

During the Building 4.0 CRC 2023 Annual Conference hosted by Monash College in Docklands, Australia, participants first attended a briefing session on using the Microsoft® HoloLens and the associated technology workflow. Following this briefing, participants had a few minutes to familiarize themselves with the equipment through practical training. This phase was particularly exciting for the participants, as it marked their first hands-on experience with the MR technology before they began constructing the timber pavilion.

For the user test, a portion of a large, complex timber pavilion structure was selected to minimize participant engagement time (please see Figure 1). The Fologram/Ynomia workflow was established, requiring participants to scan a QR code to load the visualization of the structure and receive instructions on how to build it. Specifically, participants used the model to identify the next required part and select the correct pre-cut timber components, which were serialized with QR codes.

Additionally, a parallel workflow was set up for participants to cut other parts using a mitre saw. This workflow utilized MR to display the correct angle for setting the saw blade and positioning the stops, ensuring precise cuts. The MR technology also displayed the correct orientation for each part, enabling participants to screw it in place accurately. This structured approach allowed participants to effectively use MR technology to guide their construction tasks, demonstrating the practical applications and benefits of MR in a real-world setting.

Figure 1. Participants constructing the selected portion of the timber complex structure

6 Results

In sum, the entire process—from briefing the participants, testing the equipment, to completing the task by the participants—took approximately two hours. This process, which would typically take a team of students up to three days to complete without the use of this technology, demonstrates the time efficiency of the new method. Despite some participants having previous experience with MR through gaming, the quick briefing was sufficient for all participants to start building the timber structure immediately. This suggests that a basic, brief training session might be enough to enable carpentry students to use this technology regularly. This could help address the need for skilled workers, contribute to safer construction sites, and provide updated training courses.

Participants reported enjoying the experience and appreciated the technology's ability to facilitate quick and accurate work. However, they highlighted the need for regular use of MR technology in educational settings to improve familiarity and efficiency. Participants also noted that wearing the MR headsets for extended periods was uncomfortable, often leading to task interruptions due to the weight of the headsets. They suggested that lighter, more breathable materials should be used, especially for non-traditional environments or hot-weather conditions. Several further improvements to the MR software were also suggested, such as enhancing the colours used in visualizations and implementing alerts to indicate mistakes. These enhancements would help users perform tasks more accurately and efficiently.

These findings were consistent across all data-gathering phases and are summarised in Table 2. Despite the small number of participants in this pilot study, the results were used to design a framework and guidelines for effectively adopting MR technologies in construction education (see Table 1). Therefore, further research in this area is needed to continue improving the technology and its applications in educational settings.

All the participants had some level of experience in carpentry, with limited prior exposure to advanced technologies such as MR. Despite their initial unfamiliarity, the majority found this MR technology relatively easy to learn and use, despite their commonly preferring interfaces like everyday tools like carpentry-related smartphone applications, general smartphone user-interface design, and laptop computers. When evaluating the MR technology workflow, participants rated their overall satisfaction at a median level of 7 out of 10.

The participants suggested improvements in several areas: enhancing the graphical interface by adding more colors and alerts to reduce errors during tasks, and increasing the accuracy and tolerance levels of the technology. Additionally, they suggested making wearable components (such as goggles) in lighter materials to improve comfort and usability during extended use or in extreme weather conditions (e.g., lean construction site versus traditional construction site, hot weather temperatures typically experienced in some Australian zones). These insights point to a generally positive reception but also highlight significant opportunities for refining the technology to better meet user needs along with providing guidelines to manufacturers to enhance the products' quality.

Table 2 – Results' Summary of User Study

Participants/Demographic	NASA	SYSTEM USABILITY SCALE	PAAS SCALE
Student A 25 years old Education: Certificate 3 Years of Experience on site: 2 Previous Experience with AR/VR Technology: No	Task needed a Very Low Mental and Physical demand Medium/High concern in time demand to execute the task Medium/Low effort and stress requested to complete the task	Still unsure to use this system frequently This system is easy to use and user-friendly The system is a bit too cumbersome to use	Low mental effort needed to complete task High mental effort needed to understand how the tech worked High mental effort requested to interact with tech High excitement in using this tech but high concerns about the impact of tech on privacy
Student B 36 years old Education: High Years of Experience on site: 3 Previous Experience with AR/VR Technology: No	Task needed Medium to Low Mental and Physical demand Medium concern in time demand to execute the task Medium/Low effort and stress requested to complete the task	Medium interest in using this system frequently This system is very easy to use and user-friendly The system is slightly cumbersome to use	Very low mental effort needed to complete task and understand how the tech worked Very low mental effort requested to interact with tech Low excitement in using this tech and very low concerns about the impact of tech on privacy
Student C 32 years old Education: Master's degree Years of Experience on site: 1 Previous Experience with AR/VR Technology: No	Task needed Medium to Low Mental and Physical demand Low concern in time demand to execute the task Medium/Low effort and stress requested to complete the task	High interest in using this system frequently This system is easy to use and user-friendly The system is slightly cumbersome to use A lot of things learnt before to use this system	Low mental effort needed to complete task and understand the technology Low mental effort requested to interact with tech High excitement in using this tech and very low concerns about the impact of tech on privacy
Student D 31 years old Education: Bachelor Years of Experience on site: 2 Previous Experience with AR/VR Technology: No	Task needed Medium Mental and Physical demand Low concern in time demand to execute the task Low effort requested to complete the task Very high level of stress and frustration experienced	Very high interest in using this system frequently This system is very easy to use and user-friendly The system is slightly cumbersome to use A few things learnt before to use this system	Low mental effort needed in completing the task and to understand how the tech worked Very low mental effort requested to interact with tech High excitement in using this tech and very low concerns about the impact of tech on privacy

7 Discussion

The results of this pilot study indicate that mixed reality (MR) technology has the potential to enhance the efficiency and accuracy of construction training. Students quickly adapted to the MR-guided assembly process, demonstrating the technology's intuitiveness and ease of learning. The visual guidance provided by MR reduced assembly errors and increased task accuracy, highlighting its potential to improve practical skills development in a hands-on learning environment. The substantial reduction in task completion time suggests that MR can make training processes more efficient, enabling students to complete complex tasks more quickly with greater confidence. These findings align with existing literature on the benefits of MR and augmented reality (AR) in construction education. Previous studies have highlighted these technologies' ability to provide immersive and interactive learning experiences that bridge the gap between theory and practice (Chalhoub & Ayer, 2018; Mohamed & Sicklinger, 2022). They enhance learning outcomes by making abstract concepts more tangible and engaging (Carmigniani & Furht, 2011; Craig, 2013; Newnham et al., 2018). Additionally, the observed increase in task accuracy and reduction in errors support findings that MR can enhance the precision of construction processes (Alizadehsalehi et al., 2020; Cheng et al., 2020). However, this study also highlights the need for ergonomic improvements in MR headsets, echoing concerns about the physical comfort of these devices during extended use (Chalhoub & Ayer, 2018). Future research should focus on refining the user interface and exploring interactive virtual displays to enhance the MR experience further.

While promising, this pilot study had limitations, including a small sample size, short duration, potential participant bias, and varying levels of technology familiarity among participants. Larger-scale, longer-term studies with control groups and blind testing are needed to provide more robust data and definitive conclusions. Despite these limitations, this study provides valuable insights into the potential of MR technology in construction education. It underscores the significant benefits of immersive learning environments and the need for ongoing development and refinement of MR tools to enhance their usability and effectiveness in vocational training.

This pilot study reinforces the need for more research in this area, as the MR technology utilized seems appropriate for offering updated construction training courses, especially for carpentry students. Further investigations should explore employing this technology with a broader range of vocational education and training (VET) students, where efficiency, productivity, and time management are core skills for lean construction sites. Moreover, as MR technology advances, interactive virtual displays are expected to play a significant role in delivering immersive experiences. Recent advances in big data, cloud computing, and artificial intelligence (AI) are making MR capabilities more affordable and accessible. Future research should focus on how this methodology can support the manufacturing process, aiming for greater integration of new technologies to develop custom programs that guide workmanship for specific product realization.

New technologies represent the keystone for creating human-machine connections, allowing for interaction and feedback from both actors. Similar methodologies could be implemented for different manufacturing processes, resulting in powerful tools for workers. This study identified a need for such technologies in the construction field, where available tools can further improve their functions but are not yet regularly utilized. Technologies like Microsoft HoloLens and Ynomia could be introduced at the educational level, enabling beginners (e.g., carpentry and trade students) to familiarize themselves with these innovative approaches early on.

8 Conclusion

This pilot study explored the use of mixed reality (MR) technology in construction training for carpentry students assembling a timber pavilion. The findings demonstrated that MR technology significantly enhances training efficiency, accuracy, and student engagement. Students quickly adapted to the MR tools, resulting in reduced assembly errors and faster task completion times. The interactive and immersive nature of MR boosted students' motivation, making the learning process more appealing and effective.

The results suggest several avenues for future research:

1. Larger-scale and longitudinal studies to validate findings, assess long-term skill acquisition/retention, and enhance generalizability.
2. Ergonomic design improvements for MR headsets to improve comfort and usability during prolonged use.
3. Examining the role of prior technology familiarity on the effectiveness of MR training.
4. Exploring the integration of MR with other advanced technologies like AI and IoT to further enhance capabilities.

Based on the findings, several recommendations can be made:

1. Incorporate MR technology into educational curricula to provide immersive and interactive learning experiences.
2. Encourage regular use and familiarization with MR tools in educational settings.
3. Develop more intuitive and user-friendly MR interfaces to streamline the learning process.
4. Promote ongoing research and development to refine MR technology and explore new applications in construction training.

This study captures an innovative human-computer interface approach guided by Industry 5.0 principles, immersing users in an MR environment where construction steps are visualized as holograms overlaid on the real world. The interoperability of Microsoft HoloLens, Grasshopper, Ynomia, and Fologram enabled hologram generation, real-time interaction, and evolution of the virtual structure based on the physical environment. The case study research design facilitated the development of new knowledge and a qualitative approach emphasizing richness over generalizability. While positive participant responses were obtained, further research is needed to promote user-centered design innovation in construction education. Specifically, there is potential for the study's framework to be implemented in developing more MR equipment for vocational education and training (VET) students. This study filled a gap in existing knowledge by increasing the importance attributed to the needs of MR tool users in VET education and discussing the necessity of revising their applications. The research findings demonstrate that design-led innovation is crucial for a user-centered approach in this field, confirmed by the lack of literature on this topic, prompting further investigation.

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