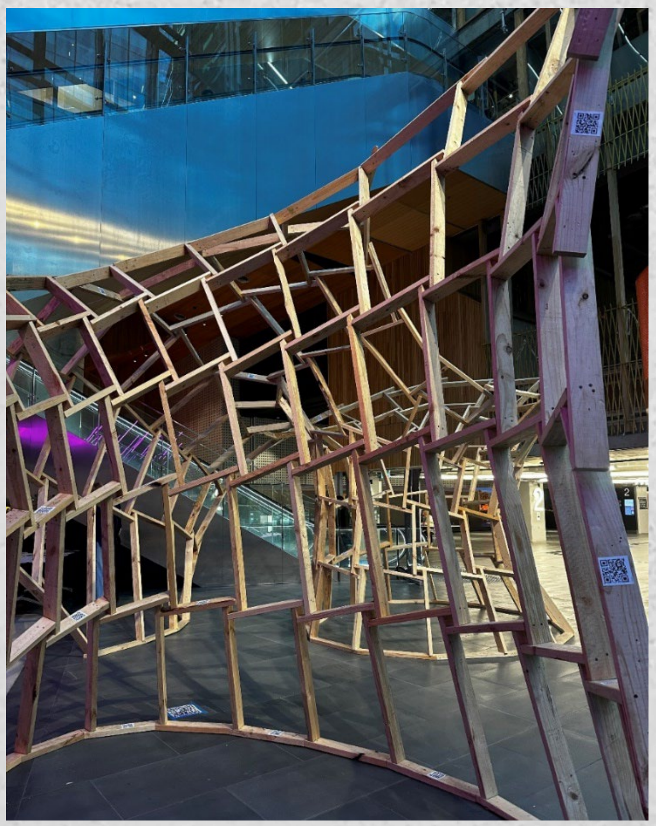
LIGHTHOUSE PROJECT #13: MIXED REALITY CARPENTRY DEMONSTRATION

FINAL REPORT



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CONFIDENTIAL:	☐ Yes ☒ No
Author/s of this report:	Dr Sahar Soltani, Dr Lisa Giusti Gestri, A/Prof. Duncan Maxwell and Darcy Zelenko
Date of this report:	20 December 2023
Project completion date:	19 December 2023
Program Leader reviewer:	A/Prof. Duncan Maxwell
Project title:	Mixed Reality Carpentry Demonstration
Project duration:	4 months
Partners:	• Ynomia • Fologram • Holmesglen Institute
Project team members:	• Dr Sahar Soltani • Dr Lisa Giusti Gestri • Dr Duncan Maxwell • Darcy Zelenko
Acknowledgements:	

EXECUTIVE SUMMARY

The integration of mixed reality (MR) and construction tracking technologies aims to address several key issues. Traditional training methods, while foundational, often fall short in preparing students for the complexities of modern construction practices, which increasingly incorporate advanced technologies. MR offers a safe, immersive learning environment where students can practise carpentry skills without the physical risks associated with traditional training. By providing real-time feedback and enabling practising of complex tasks in a controlled setting provided by tracking technologies, MR fosters a deeper understanding and retention of carpentry skills. This innovative educational approach is important in preparing a skilled workforce that is adaptable, proficient in digital tools and ready to meet the challenges of the contemporary construction sector. Through achieving the aim and objectives, the following findings emerged.

Summary of key findings

Technological evolution in construction:

- **Advancements fuelling accessibility**: The growing fields of big data, cloud computing and artificial intelligence (AI) are making MR more accessible and cost effective. This evolution is poised to revolutionise human-computer interactions, particularly in the traditionally conservative construction industry, which is now gradually opening up to these advanced technologies.
- **Human-centric approach**: Our research focused on keeping humans at the core of the process. The integration of tools like Microsoft HoloLens, Grasshopper, Ynomia and Fologram created an immersive, interactive environment. This not only enhanced the user's real-time interaction with virtual elements but also improved comprehension and engagement in construction tasks.
- **Positive participant feedback**: The enthusiastic response from participants underlined the need for more in-depth research in this area, particularly in construction education, to leverage these technologies for user design innovation.

MR's multifaceted benefits in construction:

- **Enhancing design and reducing errors**: The ability of MR to overlay virtual elements onto real environments is instrumental in reducing critical task errors and elevating design and communication processes.
- **Collaboration and assembly efficiency**: MR has shown significant potential in fostering effective collaboration, despite some limitations in multi-user capabilities. It enhances assembly performance, offering more efficient and interactive visualisation, thereby simplifying construction-related tasks.
- **Revolutionising training and upskilling**: The immersive nature of MR tools has led to improved training outcomes, emphasising experience-based learning. This approach not only reduces safety incidents but is effective in de-risking the upskilling process for construction workers.

Insights from the user study:

- **Efficiency and rapid adoption**: The pilot study demonstrated that participants could quickly adapt to MR technology, completing tasks in hours that would traditionally take days. This highlights MR's potential for efficiency and ease of adoption in educational and practical settings.
- **User experience feedback**: Participants valued the speed enhancements brought by MR. They recommended improvements such as more ergonomic design for equipment, better visual elements in MR and real-time feedback mechanisms for error correction. From an educator’s perspective, providing a real-world scale perception for students was a crucial advantage of technology.

Recommendations for future research and implementation

- **Targeted enhancement of MR content for carpentry education**: Develop specific MR modules or content tailored to carpentry skills and techniques. This content should include interactive tutorials and simulations that mimic real-life carpentry challenges, focusing on areas where trainees had the most difficulty or expressed the most interest.

- **Incorporation of feedback mechanisms in MR tools**: Integrate real-time feedback mechanisms into MR tools to provide immediate guidance and correction during tasks. This mechanism could involve using AI-driven analysis to assess the accuracy of carpentry tasks and offer personalised tips for improvement.
- **Expansion of MR applications to advanced carpentry skills**: Explore the use of MR in teaching advanced carpentry skills and complex construction concepts. This activity could involve higher-level tasks like structural design interpretation, advanced joinery techniques, or precision measurements.
- **Longitudinal study on skill retention and workplace application**: Conduct a long-term study to assess how effectively skills learned through MR are retained over time and how they translate to real-world job performance. This study could track participants over several months or years to evaluate the long-term impact of MR training.
- **Collaborative projects with industry partners for real-world testing**: Partner with construction companies to test the applicability of MR-trained skills in real-world scenarios. This testing could involve pilot projects where trainees work on actual construction sites, using their MR-acquired skills under supervision.
- **Ergonomic optimisation of MR hardware for prolonged use**: Focus on improving the ergonomic design of MR hardware to make it more comfortable for prolonged use in educational settings. This activity could involve collaborating with hardware manufacturers to develop lighter, more comfortable headsets or harnesses.
- **Cost-benefit analysis for MR integration in construction training**: Perform a detailed cost-benefit analysis to evaluate the financial feasibility of integrating MR technology into carpentry training programs. This analysis should consider the cost of technology, training for instructors and potential returns in terms of improved learning outcomes and job readiness.
- **Development of a scalable MR training model**: Create a scalable and adaptable MR training model that can be implemented in various educational institutions, from vocational schools to apprenticeship programs. This model should be flexible enough to accommodate different levels of expertise and learning styles.
- **Investigation of the impact of MR on collaborative learning and teamwork**: Study how MR technology affects collaborative learning and teamwork in construction education. This research could involve designing MR scenarios that require group problem solving and cooperation, mimicking real-world construction team dynamics.

PROJECT OVERVIEW

Lighthouse Project 13 was a small scale 4-month study that explored the potential of construction tracking and MR visualisation technologies to address challenges assembling prefabricated components in carpentry and construction. The project demonstrated the practical application of these technologies through a real-time assembly of a complex timber pavilion, showcasing their effectiveness in overcoming various construction challenges. The project focused on demonstrating the capabilities of the Twinbuild MR tool developed by Fologram integrated with Ynomia's tracking technology in a real-world scenario, emphasising its potential to enhance assembly processes, reduce errors and improve overall construction quality.

Aims and objectives

The project aimed to achieve the following objectives:

- **Demonstrating MR technologies**: Showcasing how tracking and MR visualisation can effectively track and visualise construction components
- **Understanding benefits for assembly and installation**: Gaining insights into the advantages of MR in prefab component assembly and the overall construction process
- **Exploring broader applications**: Identifying potential wider applications of these technologies in the construction industry.

Key deliverables and method of delivery

The research approach involved a thorough literature and market analysis in addition to the user study. The review involved a detailed examination of existing MR visualisation and tracking tools, and assessing their features and applicability specifically to carpentry assembly challenges. A literature review was conducted, focusing on prefab component assembly techniques and training using MR visualisation and tracking technologies.

A key aspect was the live demonstration at the Building 4.0 CRC Annual Conference 2023 (11 October 2023), in collaboration with Holmesglen, Ynomia and Fologram. To enhance the realism and effectiveness of the demonstration, Microsoft HoloLens was integrated with Twinbuild to create a digital overlay of real-time instructions and 3D component locations. The team assembled a small, bespoke complex timber pavilion, guided by the MR tools. This process not only highlighted the seamless integration of digital and physical assembly processes but also used QR code and Bluetooth component tracking technology provided by Ynomia.

The demonstration involved a user study where pre-apprentice volunteers from Holmesglen Institute and their educator, participated in a live assembly task using MR technology:

1. **Technology demonstration (15 minutes)**: Participants received a hands-on demonstration of the MR technology, which included an introduction to its features and capabilities, and instructions on how to use it for assembly tasks.

2. **Questionnaire (15 minutes)**: After engaging with the technology, participants completed questionnaires that probed their impressions of the technology, its ease of use, perceived benefits and any immediate feedback they might have.

3. **Interview (30 minutes)**: Participants were interviewed to gather more in-depth insights into their experiences with the MR technology. They discussed challenges, offered suggestions for improvements, and expressed their overall satisfaction with the MR system.

This demonstration provided a comprehensive view of the assembly's full lifecycle, from preparation to disassembly. Conference visitors could also directly experience and understand the assembly process through MR tools, fostering insights and discussions on the potential of MR tools in addressing broader construction challenges.

Researchers collected data on various metrics such as task completion time, a usability evaluation survey using the System Usability Scale (SUS) questionnaire and Cognitive load evaluation (e.g. the Paas scale). Researchers also conducted a semi-structured interview with participants, to gather qualitative data about their experiences, insights and observations during the demonstration.

The project findings were refined based on the literature and market review, user feedback, conference interactions and data analysis. This phase culminated in the compilation of a report into a Building 4.0 CRC White Paper and an academic conference paper. These documents aimed to not only validate the commercial partner technologies but also to provide empirical evidence about MR performance in real-world scenarios with a focus on workforce skills and training.

CONSTRUCTION TRACKING AND MR TECHNOLOGIES

This section synthesises the findings from an extensive literature and market review, highlighting the benefits and challenges of construction tracking and MR technologies.

MR and related technologies in construction

MR is a multidimensional term that refers to a user environment in which physical reality and digital content are mixed in a way that enables interaction with and among real-world and virtual objects or scenarios. This creates a technology-augmented environment, that blends elements of augmented reality (AR) and virtual reality (VR) to enable a merging of real and virtual environments on a spectrum with varying degrees of blending and interaction, and to provide an immersive user experience (Milgram et al., 1999; Rokhsaritalemi et al., 2020; Speicher et al., 2019). MR is fundamentally informed by AR and can be defined as a real-time view of a physical environment, augmented through the addition of virtual information (Carmigniani & Furht, 2011). This virtual information can be interactive and is overlaid in real time on the physical world in such a way that both spatial and temporal registration between the 2 is achieved (Craig, 2013).

Table 1 summarises and compares many related technologies used in a MR context.

Table 1. Key terms and technologies related to MR

Technology	Cons	Pros
VR (virtual reality)	- Isolated experience - User is detached from real surroundings and colleagues	- Complete flexibility in building digital experiences - True immersion - Ability to create endless virtual scenarios and experiences
AR (augmented reality)	- Limited in complexity compared with VR or MR	- Portable and usually wireless - Lower cost compared with MR - Enables interaction with surrounding reality - Usable outdoors in the field - Ideal for simple content like information overlays
AI (artificial intelligence)	- High cost - Potential for human job displacement - Lacks emotion and creativity - Ethical concerns - Limited self-improvement capabilities	- Reduces human error - Timesaving and always available - Helps eliminate biases - Automates repetitive tasks and jobs - Practical for daily applications
MR/XR (mixed reality)	- Larger, heavier devices - Tethered, requiring a dedicated environment for usage	- Immersive environment matching real-world scenarios - Ideal for simulations reflecting real situations - Combines virtual world flexibility with real-world reliability - Unlimited computing power
ML (machine learning)	- Susceptible to high error rates - Resource and time-intensive for training and implementation	- Efficiently identifies trends and patterns - Improves over time with data input - Capable of instantaneous adaptation - Automates processes

Construction-specific application of MR

The field of MR is relatively new in construction. This section highlights the different definitions of MR offered by the review of 23 papers. The analysis led to 7 major themes summarised in Table 2.

Table 2. Summary of MR major themes analysis

	Theme name	Summary
1	A blending of elements from a spectrum of real and virtual integration	MR perceived as real by humans (Chalhoub & Ayer, 2018; Riexinger et al., 2018; Shringi et al., 2020) MR provides different experiences to the user (Rezvani et al., 2022; Shen & Hsu, 2023)
2	Visualisation and interaction	MR as a facilitator for interaction with virtual objects (Chalhoub & Ayer, 2017b; Dasgupta et al., 2019; Wang & Hu, 2022)
3	Anchoring virtual objects	MR shows virtual objects as essentially ‘anchored’ to the real world to facilitate user interaction (Rezvani et al., 2022)
4	Telepresence and immersion	MR leads the user who is imbued with a sense of telepresence (Liu et al., 2023; Srivastava et al., 2022)
5	Use of technology	MR supports the experience and interaction with the environments (Cuong et al., 2023; D. Wang & Hu, 2022)
6	Continued relevance of the work of Milgram	Milgram on the significance MR holds in the development of technology (Chalhoub & Ayer, 2017b, 2017a, 2018; Delgado et al., 2020; Liu et al., 2023; Shringi et al., 2020; D. Wang & Hu, 2022) Companies using Milgram on MR as part of marketing activities (Delgado et al., 2020)
7	Application to a construction-specific context and beyond	MR as a potential incrementor to understand assembly processes and influence the update of human/robot collaboration (Cuong et al., 2023; Riexinger et al., 2018; Shen & Hsu, 2023)

Construction tracking technologies

In the construction sector, data quality and visibility have been significant challenges due to manual processes and fragmented data management, hindering accurate project tracking, particularly in large and complex projects. The advent of Industry 4.0 introduced a new era of connectivity and integration in construction, shifting the focus to ‘smart logistics’. This approach uses advanced technology for material transport, storage and delivery, integrating information sharing and resources through Internet of Things (IoT), AI and big data. It results in a more responsive and adaptive construction process.

Raza (2013) identified 7 outcomes of construction tracking: detection and identification of objects, location information, object tracking, properties, memory representation and application-specific processes. Wireless sensor networks (WSNs), as discussed by Dargie and Poellabauer (2010), bridge the physical and digital worlds, capturing real-world occurrences for digital processing. These sensors are crucial in construction, covering 12 established categories. Hightower and Borriello (2001) anticipated mobile computing would increasingly rely on localisation, a concept validated by recent advancements. Tracking solutions are essential for providing automated location data, with significant technological progress reducing device size, cost and power consumption.

In construction logistics tracking, prevalent technologies include Global Positioning System (GPS), Radio Frequency Identification (RFID) and Bluetooth. GPS, widely adopted, offers global coverage but is limited to outdoor functions and is costlier. RFID provides excellent accuracy but faces challenges with construction site materials. Bluetooth, especially with the development of Bluetooth Low Energy Aware Tracking (BLEAT), offers a balanced cost-effective solution. No single tracking solution is universally superior for construction logistics; each technology has its trade-offs. Ynomia, an Australian IoT company, addresses construction industry challenges by tracking building components throughout the project lifecycle, combining system integrations, QR and Bluetooth tracking, and a user-friendly mobile app. Their goal is to create a comprehensive digital record for each building component, enabling construction teams to make informed decisions.

Benefits of MR technology in construction

Enhanced assembly processes

MR significantly enhances construction assembly by providing real-time visual guidance, enabling workers to accurately fit components and visualise assembly steps, thereby reducing guesswork and assembly time. Cuong et al. (2023) introduced an MR-based system for prefabricated bridge component assembly. Cuperschmid et al. (2016) described 'montAR,' an AR application aiding precast wood-frame wall installation with full-scale visualisations and step-by-step instructions. Shringi et al. (2023) developed a context-aware safety training framework for prefabricated building assembly processes. Conversely, Wang & Hu (2022) focused on automating steel bar cage production in concrete rebar construction.

Reduced errors

MR shows significant potential in reducing errors in construction processes, as evidenced by various studies. MR's real-time visualisations can substantially minimise measurement, placement and alignment mistakes, enabling early detection and correction of issues like misalignments. This proactive approach is key to preventing costly errors, improving accuracy, reducing rework and ultimately enhancing construction quality and cost efficiency.

Chaloub & Ayer (2018) found MR technology led to a 75% error reduction in electrical conduit installation, credited to MR's display of full-scale assembled component models. Supporting this, Cuperschmid et al. (2016) noted AR-based technology's superimposition of virtual models onto real environments can significantly mitigate errors. They also suggested AR's usefulness in less accuracy-dependent tasks, like positioning electrical outlets. Extending MR's application, Kayhani et al. (2018) discussed its role in planning heavy mobile crane operations, a critical factor in on-site error reduction. Riexinger et al. (2018) emphasised MR's capability in creating self-instruction tools for workers, aiding in preventing and promptly correcting mistakes. Similarly, Sebastian et al. (2018) demonstrated how MR integrated with 4D building information modelling (BIM) can address the construction sector's knowledge fragmentation, using self-instruction models and error highlighting for effective on-site problem solving.

Improved construction quality

MR enhances construction quality by improving decision making and coordination among stakeholders. It supports collaborative reviews and assessments of design plans and progress, enabling quick identification and resolution of potential issues to meet higher quality standards. Chalhoub & Ayer (2018) showed participants using MR for an electrical conduit installation made 75% fewer errors and required 72% less rework compared with those using paper plans. Liu et al. (2023) described how MR in the mining industry improved system operations quality, as agreed by most participants in their study.

Safety

Through MR simulations, construction workers can undergo realistic training exercises in a virtual environment. They can practise safety protocols, emergency responses and hazardous scenarios without actual risk exposure. This hands-on training enhances their preparedness and responsiveness on real construction sites, reducing accident and injury likelihood. Kayhani et al. (2018) developed a VR-based heavy lift planning simulator, allowing trainees to virtually experience cranage processes. Crane operation, a complex and potentially risky task, benefits from VR

	technology by providing a safe training environment before on-site operations. Shringi et al. (2023) expanded this by combining a VR training environment with BIM, creating a context-aware training environment for crane operators. They used Unity3D to integrate these technologies into a gamified training program that imposes penalties based on risk severity.
Design and communication	MR technology significantly enhances design and collaboration in construction projects, as evidenced by studies like Chalhoub & Ayer (2017a, 2018) and Cuellar Lobo et al. (2021). It fosters effective team collaboration, facilitates the visualisation of complex design concepts and streamlines communication among stakeholders. Moreover, MR reduces the time needed to convey intricate design ideas and serves as an enabler for participatory design, further supported by findings from Chalhoub & Ayer (2017b, 2018) and Dasgupta et al. (2019).
Time efficiency	Implementing MR solutions in construction results in significant time savings across different project phases, as noted by Kayhani et al. (2018), Shringi et al. (2020), Tzimas et al. (2019) and D. Wang & Hu (2022). This technology streamlines essential tasks like layout planning, precise positioning, excavation operations and strategic decision making, as highlighted in Shringi et al. (2020).
Productivity and efficiency	MR has a positive impact on construction productivity and operational efficiency, as evidenced by Liu et al. (2023). It facilitates quicker error detection, improves quality control processes and offers valuable simulation capabilities, according to Chalhoub et al. (2021), Cuong et al. (2023), Hammad (2009) and Rezvani et al. (2022). These benefits not only boost on-site productivity but also enhance a company's image through the provision of new and improved services, as noted by Delgado et al. (2020).
Safety and risk management	MR can enhance construction safety and effective risk management. It provides immersive safety training, assisting in risk prevention, facilitating hazard recognition and enabling thorough safety inspections, as demonstrated by Li et al. (2018), Shringi et al. (2023) and Srivastava et al. (2022). Further, MR aids in managing complex design and construction scenarios, improving issue identification and reducing safety risks.

Barriers to implementing MR

The literature and market review identified several challenges in implementing MR technology. These challenges can be broadly categorised into 3 key areas: i) user comfort and ergonomics, ii) technical hurdles, and iii) technology immaturity. User comfort and ergonomics encompass issues related to the usability and physical discomfort of MR devices, while technical challenges include tracking errors, interoperability issues and limitations in hardware and software. Technology immaturity reflects the evolving state of MR technology and the resistance to change within the industry. Addressing these barriers is crucial for unlocking the full potential of MR in construction.

User comfort and ergonomics: Users often find MR headsets too heavy or uncomfortable for prolonged use. Issues such as limited battery life and a narrow field of view can impact the overall user experience. Additionally, ergonomic concerns, especially for design professionals who wear prescription glasses, may impede widespread adoption. Table 3 outlines key findings from the reviewed articles.

Table 3. User comfort and ergonomics

Findings from literature	Cited papers
User preference for traditional paper plans can be a barrier to MR adoption.	Chalhoub & Ayer, 2017; Chalhoub & Ayer, 2018
The comfort and weight of MR devices, such as HoloLens, may pose usability challenges for designers.	Dan et al., 2021
Visual confusion caused by superimposing virtual information over the real environment can be discomforting for users.	Cuperschmid et al., 2016
Battery life limitations and narrow field of view are technical challenges associated with MR devices.	Dan et al., 2021

Technical challenges: These include problems like drift errors in tracking and object alignment, as well as the reliance on external environmental conditions (e.g. sunlight and wind) for optimal MR performance. Achieving accurate marker recognition and precise alignment are additional technical difficulties. Table 4 outlines key findings from the reviewed articles.

Table 4. Technical challenges

Findings from literature	Cited papers
Drifting hologram BIM models can lead to inaccuracies in object tracking and spatial mapping.	Cuong et al., 2023
Lack of multi-user experience is a limitation that inhibits effective collaboration.	Delgado et al., 2020
The absence of industry standards poses challenges for consistent implementation.	Delgado et al., 2020
Technical challenges encompass hardware, software and data interoperability issues.	Sebastian et al., 2018
QR marker limitations and geo-spatial drift impact the accuracy of MR applications.	Rezvani et al., 2022
Challenges in snapping tools and limited colour representation can hinder measurement functionality.	Rezvani et al., 2022
Custom software development is often required to suit specific construction tasks.	Wang and Hu, 2022

Technology immaturity: This category encompasses obstacles related to the current state of MR technology. These include the immaturity of both MR hardware and software. Users may encounter difficulties due to the lack of model accuracy required for precise construction applications. Visual confusion resulting from the superimposition of virtual information and discomfort during extended use are also prevalent challenges. Table 5 outlines key findings from the reviewed articles.

Table 5. Technology immaturity

Findings from literature	Cited papers
Immature technology can be a barrier to the successful implementation of MR in construction projects	Delgado et al., 2020
Resistance to change, particularly in adopting new technology and workflows, can hinder the adoption of MR in the construction industry.	Delgado et al., 2020
The lack of national and international regulations covering the use of MR tools on construction sites or within factories poses a challenge to MR implementation.	Riexinger et al., 2018
The Hawthorne Effect and Practice Effect can influence user behaviour when using MR technologies.	Li et al., 2018

While MR offers transformative possibilities for construction (Figure 1), it faces significant barriers (Figure 2). These barriers, ranging from user comfort and technical challenges to technology immaturity, need to be overcome to fully harness the benefits of MR in construction projects. By addressing these issues through ongoing research, development and industry collaboration, the construction sector can pave the way for a future where MR plays a pivotal role in enhancing efficiency, safety and productivity in the field.

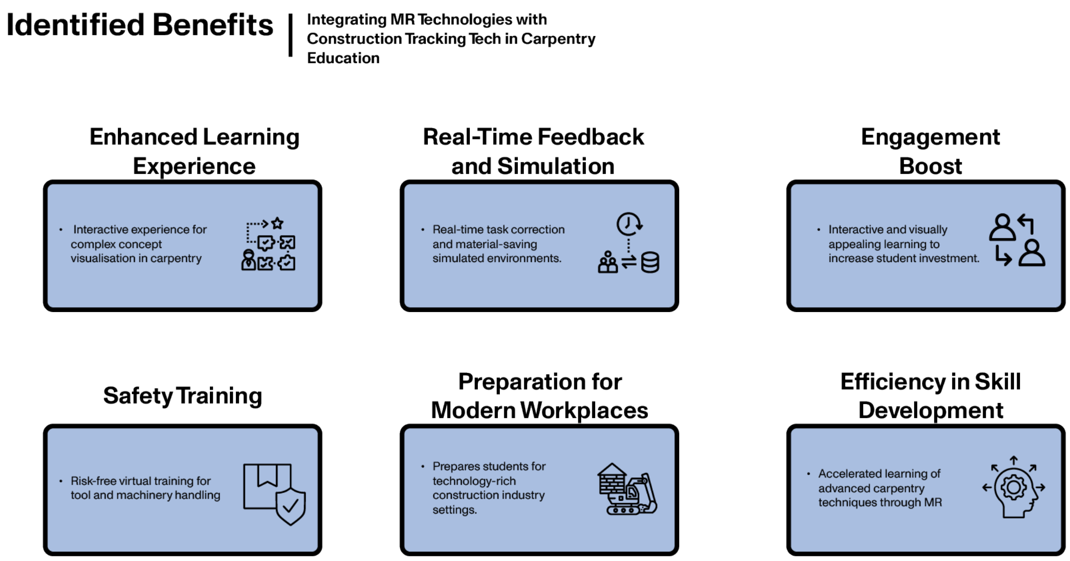

Figure 1. Benefits to integrating MR identified in literature

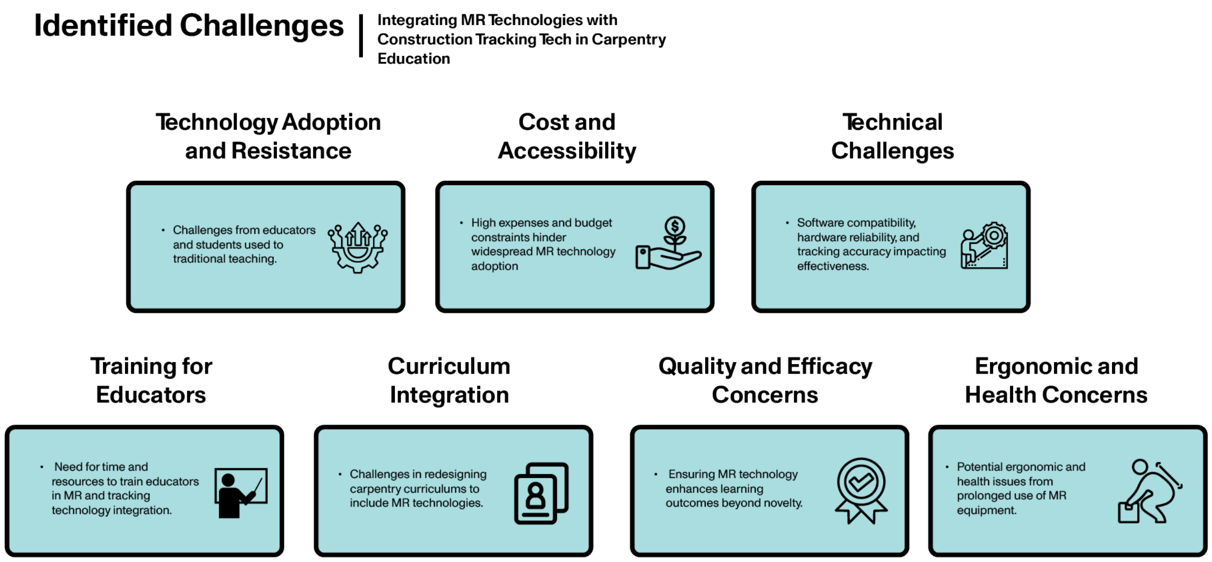

Figure 2. Barriers to integrating MR identified in literature

TECHNOLOGY DEMONSTRATION – A USER STUDY

The adoption of technology is complex, requiring input and feedback from various stakeholders. To understand these diverse perspectives, individual semi-structured interviews and questionnaires were conducted, supplemented by observations, particularly during participants' use of HoloLens, Ynomia and Fologram technology in building a timber pavilion structure. Participants underwent a brief training session on the use of the MR equipment, followed by immediate hands-on experience.

This approach allowed them to start constructing the timber pavilion in less than 2 hours, a task that would typically take up to 3 days without such technology.

This section provides the results of the user study that was conducted during the Building 4.0 CRC Annual Conference, held 11 October 2023.

User study design and approach

This research project was conceptualised as a small-scale, preliminary study, primarily aimed at evaluating the feasibility and refining the research design for future, more extensive investigations in this domain. The user study provided invaluable insights, enabling the collection of diverse data to enhance the understanding of the case, in line with Baxter & Jack (2008, p 556).

Employing a qualitative research method with an instrumental case-research design, the study aimed to develop new knowledge and establish a framework concerning the significance of using MR in educational contexts, particularly within construction. Understanding this unique group was possible only through an instrumental case approach, using the case as a comparative point across others where similar technologies (e.g. Fologram and HoloLens) were implemented. This strategy was crucial in confirming the lack of literature covering carpentry students.

This study applied a qualitative research method and used inductive theory building, reflecting the paucity of literature. The research progressed from specific observations to the formulation of broader propositions for the explanatory framework. A holistic approach was employed to understand participants within their social and cultural contexts. Notably, the study employed an ethnographic approach in the qualitative research, allowing for the observation of participants with the aim of immersing in their culture and viewing them as active contributors to the research. Semi-structured interviews, questionnaires, observations and real demonstrations were used to gather data. The collected data were then synthesised and organised into broader themes: inductive data analysis produced meaning from the data and built substantive theory from practice (Merriam & Tisdell, 2015; Patton, 2002). This theory-building method was apt for this study, which sought to understand practice and offer practical benefits for applying AR/VR to students and in the construction field. Findings are presented as problems, guidelines and propositions to promote future research.

To comprehend participants' experiences with and perceptions of Fologram and HoloLens as a basis for proposing recurrent use, a flexible qualitative research design was employed, informed by Forlizzi's (2007) concept of product ecology. Product ecology assists design researchers in understanding how a product evokes social behaviour, guiding the choice of the most appropriate research methods and expanding the design culture in interaction design. Recognising users are unique and may associate various meanings and feelings with a product due to everyday use, the study progressed from specific observations to broader explanatory framework propositions, coupled with a holistic approach to better understand the users.

Participants

The participants were students and educators from Holmesglen Institute, specialising in carpentry (Figure 3). The group was predominantly male, aged between 18 and 30. Although English was not the first language of most participants, it was the language used for interviews. The diversity in participants' backgrounds enriched the research with varied perspectives, influenced by different experiences and educational backgrounds, as well as their visions of construction sites. The group consisted of 7 individuals, of whom 80% were students and 20% were tutors and educators.

Figure 3. Carpentry students working on structure

Selecting Holmesglen students and their tutors and educators as participants was crucial for conducting semi-structured interviews, questionnaires and observations. Their involvement, particularly during real fabrication tasks at the Building CRC Annual Conference 2023 (Figures 3 and 4), allowed for independent critique and assessment of design topics directly impacted by the study's findings, as detailed in Table 6.

Table 6. Results of user study

<table>
<tr><th>Participants</th><th>Demographic</th><th>NASA</th><th>System Usability Scale</th><th>PAAS Scale</th><th>Summary of findings</th></tr>
<tr><td>Student A</td><td>25 years old
Education: Certificate 3
Years of experience on site: 2
Previous experience with AR/VR technology: No</td><td>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</td><td>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</td><td>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</td><td rowspan="3">All the participants had experience as carpenters.
All the participants had limited experiences with technologies.
Most of the participants prefer to use the Carpenter App, Phone and laptop.
Majority of the participants found this technology easy to learn and use.
All the participants suggested to review the tolerance/ accuracy of this technology.
On a scale between 1 to 10, all the participants scored their satisfaction with this technology as a 7.
All the participants suggested improving the graphics by introducing more colours or alerts in case of mistakes during the tasks.
All the participants suggested reviewing the wearability of the goggles by introducing lighter materials.</td></tr>
<tr><td>Student B</td><td>36 years old
Education: High
Years of experience on site: 3
Previous experience with AR/VR technology: No</td><td>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</td><td>Medium interest in using this system frequently
This system is very easy to use and user-friendly
The system is slightly cumbersome to use</td><td>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</td></tr>
<tr><td>Student C</td><td>32 years old
Education: Master’s degree
Years of experience on site: 1
Previous experience with AR/VR technology: No</td><td>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</td><td>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</td><td>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</td></tr>
</table>

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

User study results

Despite minimal prior experience with MR, participants positively adapted to its use, appreciating its assistance in efficient task completion. This result suggests basic training might suffice for regular MR use, especially for carpentry students. All recognised the importance of MR in their educational routines. Participants enjoyed the MR experience, noting its contribution to accuracy and speed. However, they called for regular use in education for better proficiency and raised concerns about the comfort of MR goggles, suggesting improvements like lighter materials for diverse environments. Enhanced colour quality and error-alert features were also recommended.

Figure 4. Participants completing sample structure

Facing challenges like skill shortages and rapid technological changes, the construction industry, including in Australia, needs to adapt. This study advocates for the increased application of MR in construction training. Further research is suggested, involving broader data collection and diverse audiences, to test MR's practicality and feasibility in carpentry education across various settings.

Technology preferences	A significant finding was the participants' preference for more conventional tools like the Carpenter App, smartphones and laptops. This preference underscores a comfort level with more traditional, familiar technologies and suggests a potential learning curve or initial hesitation in adopting newer, more advanced systems like AR/VR.
Ease of learning and usability	A positive aspect of the findings was the general ease of learning and using the AR/VR technology. Participants reported that despite their limited background in such technologies, they found the tools easy to comprehend and use. This ease of learning is a promising indicator for the potential integration of AR/VR technologies into carpentry education,

	suggesting that even those with limited tech experience can quickly adapt to these advanced tools.
User satisfaction	Uniformly, participants rated their satisfaction with the technology at a 7 out of 10. This score reflects a moderate level of satisfaction with the AR/VR experience, indicating both a positive reception and room for improvement. The consistent rating across different participants provides a clear benchmark for assessing the technology's current standing and areas for enhancement.

Participants' suggestions for Improvement

Participants provided valuable feedback for enhancing the AR/VR experience (Figure 5):

- Review the tolerance and accuracy of the technology, which is crucial in the precision-oriented field of carpentry.
- Improve the graphics, such as introducing more colours and alerts to signal mistakes during tasks.
- Using lighter materials could enhance comfort and usability, which is essential for prolonged use in educational or professional settings.

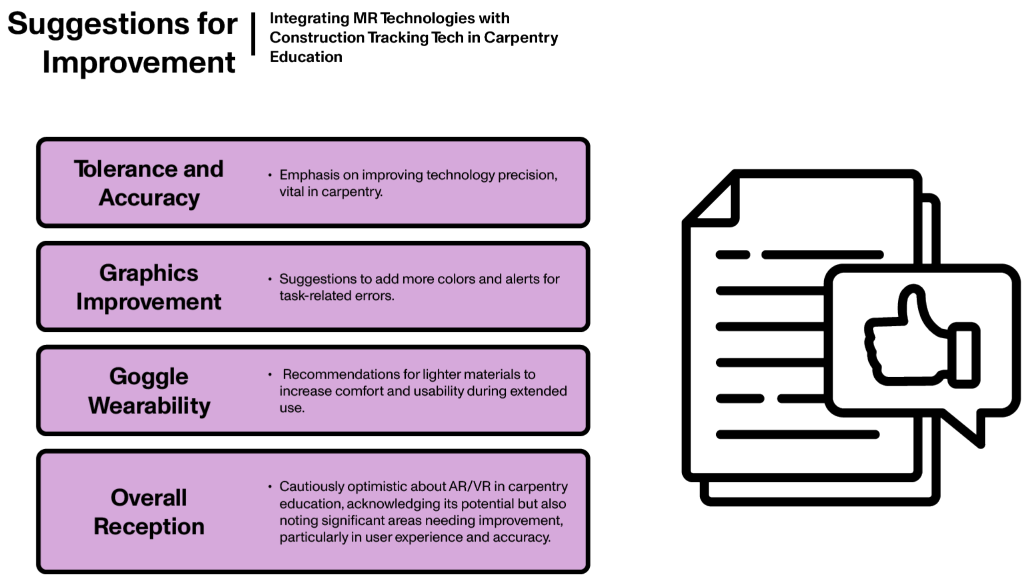

Figure 5. Participants' suggestions

The findings from the user study revealed a cautiously optimistic reception of AR/VR technology in carpentry education. Participants recognised the potential of these tools in enhancing learning and practice in their field. However, they also highlighted critical areas for improvement, especially concerning user experience, comfort and accuracy.

The results also highlighted that the used technology is simple enough to be easily understood and used, however users might like some graphic updates to deliver a better and quicker job. Hence, this pilot study reinforces the need for more research in this area because the technology used seems to be appropriate for offering updated construction training courses, especially to carpentry students.

PROJECT FINDINGS AND OUTPUTS

New findings and developments

This project, encompassing both literature and market review and a user study, led to several pivotal findings and developments in applying MR in construction education and practice:

- **Integration of MR in construction**: The project highlighted the utility of MR to be seamlessly integrated into construction processes, enhancing both educational and practical aspects.
- **Advancement in educational methods**: A significant development in educational methodologies using MR was demonstrated, promoting more effective and engaging learning experiences.
- **Industry benefits**: The findings underscored MR's potential to improve efficiency, accuracy and safety in construction practices, benefiting the wider construction industry.

In summary, benefits and challenges of integrating MR technologies with construction tracking tech in carpentry education are as follows:

Benefits

- **Enhanced learning experience**: Integrating MR with construction tracking technology offers carpentry students a highly interactive and immersive learning experience. Complex carpentry concepts can be visualised and understood more effectively through this augmented environment.
- **Real-time feedback and simulation**: Students can receive immediate feedback on their carpentry tasks, allowing them to correct mistakes in real time. Simulated environments also enable students to practise skills without the need for physical materials, reducing costs and waste.
- **Increased engagement**: MR technologies can significantly increase student engagement. By making learning more interactive and visually appealing, students are likely to be more invested in their education.
- **Safety training**: MR allows students to practise in a virtual environment where they can learn to handle potentially dangerous tools and machinery without the risk of actual injury, improving overall safety awareness.
- **Preparation for modern workplaces**: As the construction industry increasingly adopts new technologies, integrating MR and tracking tech in education ensures students are well prepared for modern, technologically advanced workplaces.
- **Efficiency in skill development**: With MR and tracking technologies, students can rapidly develop skills and understand complex carpentry techniques, leading to a more efficient learning process.

Challenges

- **Technology adoption and resistance**: There may be resistance to adopting new technologies from both educators and students, particularly those accustomed to traditional teaching methods.
- **Cost and accessibility**: The high cost of MR and tracking technology can be a barrier to widespread adoption in educational institutions, especially those with limited budgets.
- **Technical challenges**: Technical issues such as software compatibility, hardware reliability and the accuracy of tracking systems can impact the effectiveness of these technologies in an educational setting.
- **Training for educators**: Educators need adequate training to effectively use and integrate MR and tracking technologies into their teaching. This requires time and resources that may not always be readily available.
- **Curriculum integration**: Effectively integrating MR technologies into existing carpentry curriculums can be challenging, because it requires a redesign of teaching methods and materials.
- **Quality and efficacy concerns**: Ensuring MR and tracking technology effectively enhance learning outcomes and do not simply become a novelty is crucial.
- **Ergonomic and health concerns**: Prolonged use of MR headsets and equipment may raise health and ergonomic concerns among students, such as eye strain or discomfort.

Outputs

- **Comprehensive reports**: Detailed reports from the literature review and user study, outlining key findings and recommendations.
- **Conference paper**: A conference paper to submit in mainstream international construction technology outlets.

Deliverables

- **Validation of commercial partner technologies**: Assessed and validated the practicality and effectiveness of partner technologies in real-world construction scenarios.
- **Empirical evidence on MR performance**: Provided empirical evidence regarding the performance of MR tools in real-world scenarios, with a focus on workforce skills and training.

R&D gaps and opportunities

The research highlighted several gaps and opportunities for future development:

- **Customisation for construction needs**: The need for MR solutions that are specifically tailored to the unique challenges of the construction industry.
- **Scalability and accessibility**: Opportunities to scale MR tools for wider adoption in the construction industry.
- **Long-term impact studies**: Research into the long-term impacts of MR integration in construction practices and education.

Skills, training and education outcomes

The project's findings have significant implications for skills development, training and education in the construction sector:

- **Enhanced training techniques**: MR offers new ways to train construction professionals, providing a more interactive and engaging learning experience.
- **Integration into curricula**: Support for integrating MR into construction education curricula at various educational levels.
- **Professional development**: Need for ongoing professional development for educators and industry professionals in the use of MR technologies.

FUTURE RESEARCH PLANS

Building on the initial insights gained from the current project, a comprehensive plan for future research has been outlined. This plan aims to expand the scope of investigation beyond educational applications and delve into broader implications for the construction industry. It encompasses a series of strategic initiatives, including workshops, subsequent research phases and academic publications.

Further research should focus on how this methodology can support the manufacturing process, aiming for greater integration of the innovative technologies available to develop custom programs to guide workmanship to realise specific products. Latest technologies represent the keystone to creating human-machine connections, allowing for interactions and feedback from both actors in the process. Similar methodologies could be implemented for diverse kinds of manufacturing processes, resulting in powerful tools for workers. Specifically, we found a need for this in the construction field, where technologies are available and can only improve their functions, yet most are not used regularly. Additionally, technologies such as HoloLens, Fologram and Ynomia have potential applications at the educational level, particularly for beginners such as carpentry and trade students, as demonstrated in our pilot study.

Educators' workshop

As one of the primary future research plans, this workshop will bring together educators from various construction disciplines. This workshop has the following objectives:

- **Sharing insights**: Educators will be presented with the findings from the student user study, offering them a comprehensive understanding of how students interact with and benefit from MR technologies.
- **Gathering feedback**: The workshop will serve as a platform for educators to provide feedback on the user study results, share their experiences and discuss the practicality of integrating MR technologies into their teaching methodologies.
- **Collaborative development**: Participants will collaborate to develop strategies for effectively incorporating MR into the construction education curriculum. This will include brainstorming sessions on course design, pedagogical approaches and assessment methods.
- **Identifying research gaps**: The workshop will also focus on identifying gaps in current research and exploring potential areas for future studies. Educators will play a crucial role in shaping these research directions based on their expertise and classroom experiences.

Expansion of research phases

Post-workshop, the research can integrate the insights gained from both students and educators. Future research phases will include the following phases:

- **Curriculum development**: Develop and test new curricula incorporating MR technologies, based on workshop outcomes.
- **Longitudinal studies**: Assess the impact of MR-integrated teaching methods on student learning and engagement.
- **Industry applications**: Explore how educational findings can translate into practical skills that benefit the construction industry.

Publications and dissemination

A key component of the future research plan is publishing and disseminating findings. A conference paper has already been drafted, marking the first step in this process. The publication strategy includes:

- submitting the drafted conference paper, detailing initial findings and theoretical implications
- developing additional academic papers focusing on various aspects of the research
- planning for journal articles aimed at a broader audience, including industry professionals
- presenting at industry conferences and academic forums to share insights and foster discussions.

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