Mixed Reality Interactive Representations for the Assembly of a Custom Timber Tower

Sarah Blahut[1], Marie-Therese Harnoncourt-Fuchs[2]
[1,2]University of Kassel
[1]{blahut|harnoncourt-fuchs}@asl.uni-kassel.de

In recent years, many projects have emerged testing the use of augmented reality (AR) and mixed reality (MR) systems in the custom design and fabrication of architectural projects at a variety of scales using digital and analog tools. This paper presents a series of MR systems for key modes of interactive representations in the assembly process of a custom timber tower, intending to expand an area of research on the use of MR as a critical medium for architectural representation in design customization. The series of MR systems were developed to assist and expedite the physical assembly of customized timber parts and connections for the large-scale tower with a small team of students and carpenters. The MR systems are built as interactive representations of the 3D digital design model, allowing the user to see connections in real-time on physical materials in order to perform collaborative preparation and assembly tasks with analog tools. Each MR system relied on a single user, wearing a HoloLens 2, to use hand gestures to place and interact with 3D Rhino model representations of the tower and individual parts overlaid in the physical context at 1:1 scale. The MR systems deployed as interactive 3D representations were evaluated at three key stages in the material preparation and assembly processes. The project tested the use of MR systems created for a series of tasks that enabled the fast assembly of the tower, which is almost 10 meters high. The outlook explores the perspective of how MR systems augment modes of architectural representation through human interaction, collaboration, and accessibility (also for non-expert users), using digital and analog tools, and how these systems provide greater agency for customization and variety in design and building.

Keywords: *Mixed Reality, Interactive Representation, Customization, HoloLens2, Head-Mounted Display, Digital and Analog, Augmented Reality.*

INTRODUCTION

The use of augmented reality (AR) and mixed reality (MR) systems in architectural projects are increasing, with many projects currently emerging that explore the use of AR/MR technology as new tools in experimental design and custom fabrication areas of the architecture, engineering, and construction (AEC) industry (Lharchi et al. 2020; Mitterberger et al. 2020). AR/MR tools have been developed recently that reduce the learning curve for users to visualize and interact with digital 3D models in physical space. Commercially available MR software plug-ins, like Fologram, are used to create a real-time connection link between a digital Rhino model and a user wearing a HoloLens2 head-mounted display (HDM) or using mobile-based AR-enabled devices (Jahn et al. 2019; Jahn et al. 2020). The real-time 'live stream' of 3D model data enables users to experience and interact with the digital model spatially at any scale in a physical context. This enhances the user's ability to understand geometric complexities and spatial qualities simultaneously with the physical environment; merging digital and analog information together (Figure 1). This hybrid workflow enhances the user's agency in the fabrication with the ability to make intuitive decisions and create novel collaborations in the process. The variety of applications of AR/MR systems developed for experimental designs and fabrication processes points to its expanded use in creating novel modes of architectural representation that augment users' abilities to understand digital geometry in parallel with physical conditions (Chun et al. 2020; Goepel et al. 2020). These tools enable users to perform a range of tasks in a digital and analog hybrid workflow, which is not possible with standard modes of representation.

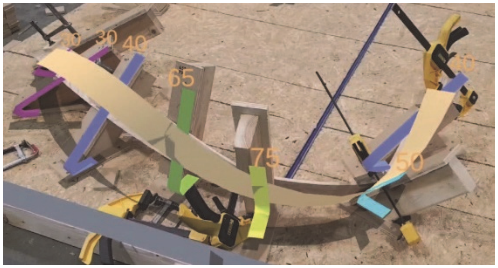

Figure 1
3D Model overlaid with a completed steam bent panel using AR platform Fologram (Jahn et al. 2019).

BACKGROUND

Two-dimensional orthographic projections, like plans, sections, elevation elevations, as well as linear perspectives, are traditional modes of representation used by architects for hundreds of years to describe both painterly and mathematical components of three-dimensional spaces and geometry (Witt 2021). They are created as a means to communicate the design and construction to other actors in a project. The legibility of the representations is based on an understanding of architectural drawing conventions, which today can be produced quickly using digital CAD and BIM software to extract spatial, mathematical, and other qualities from a 3D digital model. Despite the role of parallel projections as a tool for design, being replaced largely by digital technology and computer 3D modeling (Carpo 2017), these modes of representation are still produced as a standard convention in most projects, despite their geometric complexity.

The research leading up to this project has questions the modes of representation used in standard architectural practice. Despite the advanced technology available, there could be a greater increase in customization in design and fabrication in order to bring more variety to the built environment. Looking beyond standard practices of optimization, the research conducted in this project posits that architectural representation still plays a critical role in the design and building process, and could gain new agency by exploring advanced technology of MR systems as a new medium critical for further expansion of novel uses.

PROJECT

The project presented in this paper demonstrates the use of an experimental series of MR Systems for interactive representations (MRIR) created for the fabrication and assembly of a custom timber tower. The tower was designed by architecture students at the University of Kassel, Germany. The required key stages for physical assembly were based on tasks for the foundation installation, material fabrication, and guided assembly of the custom tower. A hybrid workflow was developed for the physical tasks carried out by team members in collaboration with an MR-enabled user wearing an HMD (MR user) deploying MRIR created for each key stage of the project.

The research seeks to establish AR/MR systems as an emerging critical medium for architectural representation and design customization that offer agency in the design process through novel forms of interaction and collaboration. The goal was to test the MRIR in their effectiveness in carrying out tasks, as well as different ways of interacting with digital and analog information in collaboration with a team for the expedited assembly of the tower's heavy and awkward parts. The physical assembly time was limited to three days during a week dedicated to a building workshop in the seminar with three carpenters to assist the team.

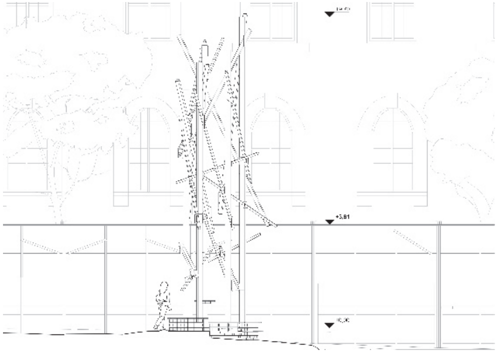

Figure 2
Conventional elevation drawing of the tower structure in front of existing advertising wall by students that describes both painterly and mathematical components of three-dimensional spaces and geometry (Witt 2021).

Tower design

The tower was designed for an urban art and cultural area in Kassel's city center as part of an art exhibition coinciding with the opening of documenta 15 in June 2022. The project began as design studio with students who created the concept for the proposed tower through a series of design phases in the winter semester of 2021/2022. The design was later adapted and modified based on skilled worker and material costs and site area restrictions, as well as adjustments for structural calculations and tests carried out by the structural design department. In the following summer semester of 2022, a seminar assisted by MR systems, with a small team of 7 students, 1 student assistant, 1-2 teaching supervisors, and 3 professional carpenters, was held for the tower implementation and for the material fabrication leading up to and for its assembly.

The tower's custom design required the use of laminated and solid spruce members for columns, mounted on top of steel screw foundations drilled into the ground, and diagonal beams connected by a complex system of customized CNC-fabricated birch plywood plates screwed onto the columns. The design consisted of five screw foundations, five columns, 17 diagonal beams, and 34 plywood connection plates (CP), with a height of 9.4 meters and a base area of six square meters.

Site and context

The site is located where an old hospital building use to exist and was destroyed during World War II. The remaining parts of the masonry foundation were buried over time by soil, foliage, and trees that have accumulated over time, hiding any visible trace; therefore, their exact location was unknown prior to construction. The tower position was situated on the central northern edge of the site, adjacent to an existing four-meter-high advertising wall that encloses the site. The tower design sought to achieve high visibility from outside the advertising wall between existing trees and a position where the ground topography was most even. For construction, site access was limited to the street for some equipment.

Figure 3
MRIR of the digital 3D model of the timber tower and connections plates, viewed through the HMD on site.

Interactive representations

Standard representations in architecture are static 2D projections of geometry and data representing specific parts or a whole structure within its context that are printed on paper and read by a user. They are created by extracting this information from a digital 3D model (Figure 2). In a similar way, MRIR are created by extracting this information from a digital 3D model using MR systems. However, they allow MR users to deploy any part of (or a whole) structure into the physical environment, where they can experience and interact dynamically with the overlaid digital representations in a variety of ways. By wearing a HMD, the user can immerse themselves in the digitally projected geometry and data, viewing it from countless perspectives while standing or walking around it (Figure 3). The representations are interactive with the ability of the MR user to select, manipulate, and change the scale and visibility of the extracted information with simple hand gestures. When the MR user can interact with the digital information in real-time, combined with the physical environment, they have more agency with an enhanced ability to collaborate with other team members using analog tools to execute tasks (Figure 5).

Figure 5
MR user with enhanced ability while using the MRIR for collaborative fabrication tasks with a team member (Chun et al. 2020; Goepel et al. 2020).

METHODS

Digital and analog set-ups for a hybrid workflow were used for this experiment in order to test and evaluate the use of MRIR developed for key stages of the project in order to carry out collaborative tasks. The MRIR tools developed follow the same principles described in the previous section.

Digital set-up

A complete digital 3D model of the timber tower was created using Rhino, containing essential 3D geometry of the tower foundations, columns, beams, connections, and immediate site context. The 3D model was organized using a detailed layer structure, which allowed for maximum sorting of tower parts and connections. Each part was given a label indicating the part number, side number, and orientation within the overall structure, following a system of annotation developed for digital and analog referencing.

Figure 4
3D wireframe of angled connection deployed onto the timber beam with a QR code, enabling the MR user to see complex conditions (Jahn et al. 2019).

The MR systems developed in this project used a digital set-up of a laptop running Windows 10, Rhino7 with Grasshopper (GH) and Fologram plug-ins, a portable Wi-Fi device, and a HoloLens 2 HMD (Fologram 2022; Rhino 7 2022). The user wearing the HMD deployed the digital 3D model by scanning a QR code (fixed at a reference point corresponding with the digital and physical part position) with integrated sensors in the front of the HMD, placing the digital geometry in a consistent location and overlaying the digital representation with the physical context (Figure 4). This established a real-time connection between the MR user and the Rhino 3D model over the Wi-Fi signal, allowing them to interact with the model using the digital menu seen through the HMD. The user could open a digital menu at any time using hand gestures detected by the HMD to deploy, select, scale, rotate, or move the MRIR of the digital model or individual parts (Figure 6). MRIR were created for all parts of the 3D model corresponding to different collaborative hybrid tasks.

Figure 6
MR user selecting side 2 of column 5 (C5/S2) with an interactive digital menu.

Analog set-up

The tower timber materials were delivered on-site, which included five laminated spruce timber

Figure 7
MR user collaborating with a team member in the analog set-up and CNC-fabricated plate.

columns (one 16 cm x 16 cm, four 12 cm x 12 cm) and three beams (10 cm x 10 cm), nine solid spruce beams (6 cm x 6 cm), and three sheets of 21 mm thick multiplex birch plywood (150 cm x 300 cm).

The laminated spruce timber columns and beams were pre-cut to the approximate length required in the design prior to delivery. The solid spruce timber beams were cut to length on-site with an electric jigsaw according to the required length. Each column and beam size and length were double-checked with standard measuring tape devices, then labeled with tape and marker with a part number corresponding with the digital 3D model. In addition, each side of the part was also numbered on one end to establish the lower and upper ends (or top and bottom) of each part.

The CNC-fabricated plywood CP were produced using two birch plywood sheets. After the plates were cut off-site, they were returned for sanding and sealing and checked during a manual trial fitting onto their corresponding diagonal beams. Each CP was engraved with a label that indicated the column number, beam number with orientation, and mounting position height and direction. These labels were engraved onto the outward timber face of the plywood CP during the CNC fabrication process. All timber parts were hand-sealed with a protective oil or waterproof coating to help preserve the wood.

Hand-held tools like hammers, levels, string, pencils, metal stakes, and straight edges were used to set out the foundation and mark columns and beams with guidance from MR users on different locations on site during fabrication (Figure 7), as demonstrated in similar projects (Jahn et al. 2020). During the assembly, the MR provided guidance for the physical assembly team from the overlaid digital model, even climbing up a ladder into higher parts of the tower of the structure. The physical assembly team moved around and inside the tower with ladders, platforms, and climbing, passing a cordless drill to screw the CP onto the column based on the instruction of the MR user.

Hybrid workflow in key stages

The project's key stages were established by identifying the necessary tasks for building the tower in a hybrid workflow that test MRIR used to assist their completion. Using the digital set-up, an MR user deployed extracted digital 2D and 3D MRIR of the 3D model onto the physical environment and objects during each stage. Using the analog set-up, team members were provided guidance from the MR user for collaborative physical fabrication and assembly tasks in each stage.

- Position on site and foundation setting-out
- Column & diagonal beam connection mark-ups
- Physical assembly guidance

The tasks were based on the structural logic and suitable assembly sequence of the tower columns and complex system of diagonal beams and connections, beginning with the installation of the foundations for each column. Three key stages of the fabrication and assembly of the tower were identified based on these tasks (Figure 8).

1. Tower foundations
2. Timber fabrication
3. Tower assembly

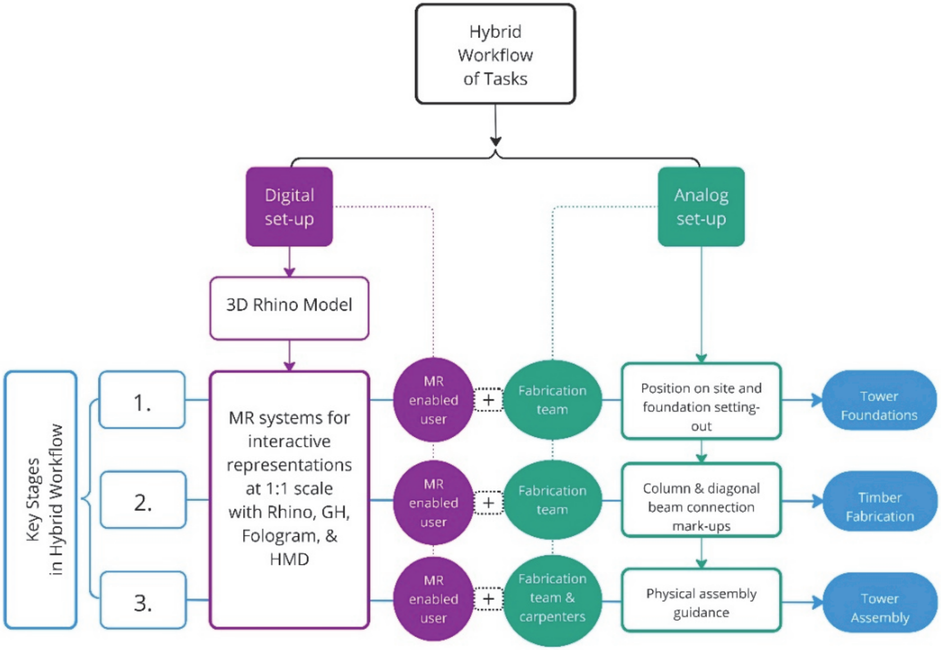

Figure 8
Diagram of hybrid workflow in three key stages.

Figure 9
MR user viewing the digital plan of the foundation plate C5 in position at 1:1 scale, overlaid on red string and metal stakes.

Setting out tower foundations

Stage one. The tower foundations on site consisted of five 1.8-meter-long steel screws with a top plate required for mounting the base of each column. The proposed positions of the tower columns (C5 and C4) were parallel and closest to the existing wall. The other three columns were angled in different positions with varied distances. A digital plan was drawn in Rhino with lines that triangulated and dimensioned the location of each foundation plate from its center. The MRIR allowed an MR user to deploy the 1:1 scale digital plan of the tower foundations on site. A common reference point was established by a QR code placed in a fixed position perpendicular to the adjacent wall, also referencing the ground elevation height level at zero. The MR user deployed the digital plan drawing in the correct position and orientation on-site using the HMD to scan the QR code.

The digital plan was made interactive when the MR user selected and choose layers to change their visibility. In the deployed digital plan, the MR user could see the center positions of the plate, the plate outline and orientation, as well as the height of the top of the plate in relation to the ground condition and wall (Figure 9). The MR user instructed the other team members who were tasked with installing metal stakes at the center point of each plate, then wrapping a red string around the stake, also following the digital triangulation lines drawn between the center point of each stake, marking the center of each plate and corresponding distance.

Timber part fabrication

Stage two. The tower design consisted of five columns that are connected with 17 diagonal beams through a complex system of 34 individually CNC-fabricated plywood CP. A series of MRIR were created for the fabrication of the columns and beams. The MR systems extracted the intersecting geometry between the CP and the surface of a column or diagonal beam in the digital 3D model. Each column and diagonal beam was referenced using GH to extract a 3D wireframe of the part and intersecting geometry. The 3D wireframe was deployed onto a physical column or beam using the same digital origin point referenced physically with a QR code. The MR user could select the part from an interactive menu using hand gestures detected while wearing the HMD. After the MR user selected the part and its corresponding side, they used a metal straight edge to indicate the angle and position of the connection visualized through the HMD. This provided a guide for the other team members to mark it on the surface of the column or beam with a pencil (Figure 11). Each column and beam on site was checked and marked using MRIR.

Figure 11
MR user viewing of plate connection angle position overlaid with the timber beam, holding a metal straight edge for another team member to mark with a pencil (Jahn et al. 2020).

Tower physical assembly guidance

Stage three. An articulated platform with a telescopic arm was required for the assembly of the tower due to difficult access on site. The close proximity of the tower position adjacent to the existing advertising wall could be accessed from above the wall from the platform operating outside of the site. The platform was parked between the street and sidewalk adjacent to the wall. Two carpenters operated the platform during the assembly to help lift, guide, and position timber columns and beams from the above, as well as mount and drill CP with screws in high areas. The third carpenter and the rest of the team moved the parts from below the platform with various means, bringing the top of each member within reach of the carpenters in the platform above.

Figure 10
3D model and annotation overlaid with the physical tower and platform lift during assembly, viewed through the HMD by the MR user.

After the columns were mounted on top of their screw foundations at their base and laterally stabilized, the MR user provided guidance for the assembly of the complex system of diagonal beams and CP. The MR user deployed an interactive 3D digital model with annotation labels created with an MR system (Figure 10). The MR user indicated which beam number would follow in the sequence, allowing the team to locate the correct part and orientation based on its matching physical label. Team members screwed on the corresponding CP and began to bring the diagonal beam through the plate opening to its pencil-marked position. The MR user then provided further guidance in approximating the position of the diagonal beam in relation to its second CP (also where it is attached to another column) and the next diagonal beam to be installed in the assembly sequence.

RESULTS AND ANALYSIS

The project tested the use of MRIR created for a series of tasks that enabled the expedited assembly of a custom timber tower in three days, which is 9.4 meters high with a final built base area of six square meters. The acceptable tolerance for the built tower was a maximum average of about two centimeters.

The experimental MRIR created for the series of tasks were evaluated for their effectiveness in a hybrid workflow to complete tasks in key stages of the fabrication and assembly process.

Tower foundations

For the setting out of the foundations, the MRIR allowed the MR user to deploy 2D plan information from the digital model on-site representing the orientation and center of each foundation plate (one for the base of each of the five columns) using triangulation lines drawn from the center of each plate. This allowed the MR user to adjust the strings to the correct height to set the same level for the top of each plate, as well as guide the rotated position of the physical plates after the foundation screws were installed. In the original position of the tower on site, columns C5 and C4 would have stood parallel to the existing wall (Figure 12A).

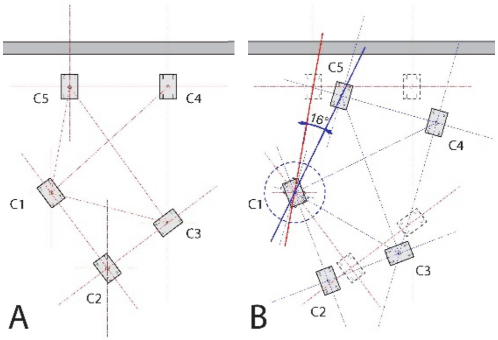

Figure 12
A) Plan diagram of proposed tower foundation positions on site, with columns C5 and C4 parallel to the existing wall on site.
B) Plan diagram of built tower foundation positions on site rotated 16 degrees from the center of column C1.

The process of drilling the foundation points began with column C1. The second drill point was C2, however, the drill became stuck in a part of an old masonry foundation wall that was discovered in the ground below, The logical solution was to rotate the entire set of foundation points to accommodate the full length of the steel foundation screw. The result of the rotation of the tower was 16 degrees (Figure 12B), repositioning the entire structure at an angle to the existing wall. The unexpected built result led to a more dynamic position on-site that created more space for movement around the tower, which ended up creating a better spatial presence on site. MR systems were not used during the drilling process and the rotation of the foundation points. The 3D digital model was updated to reflect the manually recorded rotated position and verified with the updated MRIR after the foundation screws were installed.

In order to evaluate the foundation setting-out with metal stakes and string, a printed scaled plan drawing of the digital information was used to manually verify the dimensions between each foundation centers, which showed accuracy within 5 mm compared to what was seen through the HMD. The strings' height was accurate within a 2mm, verified with a level.

Timber fabrication

The tower's complex system of column and diagonal beam connections with CNC-fabricated plywood pates were marked onto the parts during the fabrication process relying on MRIR. The intersecting geometry extracted from the digital model varied at each customized connection in the tower, creating different angles on each part of diagonal beams and columns. The angles displayed as a 3D wireframe overlaid on the beams reflected the position at which the beam uniquely intersects with the opening of the plywood plate. The digital model deployed onto the physical beam was easy to read out of direct sunlight. During the column fabrication, the CP profile was traced with a pencil onto each corresponding side. The engraved labeling system on each CP provided information to locate the correct position on the column with a standard measuring tape. The MRIR was used to verify the position of each plate on each column, also providing an opportunity to double-check positions, make some corrections, or add missing information. This also provided and means for evaluating the accuracy of the MRIR that showed an average of 10-20 mm maximum difference to the manually measured CP positions marked on the columns.

Tower assembly

An MRIR representing the digital 3D model with annotation was deployed by the MR user onto the physical tower at 1:1 scale, who provided guidance to the team during its assembly. The deployed digital 3D model was sometimes difficult to see clearly in sunny conditions and lost connection to the digital 3D model when the HMD was above four meters in height. Despite these limitations, the MR user helped the team locate the correct diagonal beams and orientation in the assembly sequence before they were installed within the complex physical arrangement of parts and connections (Figure 14).

Figure 14
MR user shown on the right side providing guidance to the team during the assembly process.

The use of the articulated platform with a telescopic arm was essential in completing the tower assembly due to its large scale. The laminated timber columns were extremely heavy and long, making it challenging to maneuver parts in high positions. The skilled knowledge of the carpenters was critical in the logistical handling and installation of the heavy awkward timber parts.

The overall tower construction was evaluated by measuring the height of the installed positions of the 34 CP on site, using a laser-measuring device, from the base of each column to the bottom of the engraved reference on each CP. The installation heights of the CP were compared with the heights taken from the digital 3D model used in the MRIR. The resulting differences in accuracy were recorded; 68 percent (23 CP) with less than 10 mm, 12 percent (4 CP) between 10-20 mm, 15 percent (5 CP) between 20-40 mm, six percent (2 CP) having 78 mm and 185 mm due to errors while measuring.

DISCUSSION AND CONCLUSION

Considering the difficulty of the site and scale of the tower, the installation of the 79 percent of the CP (27) were within an acceptable tolerance of 20 mm of their intended height. The MRIR were successful in creating a hybrid workflow for performing fabrication and assembly tasks in key stages of the project. The MRIR were easily deployed and operated by student MR users throughout the process, who were considered non-expert with less than three months of experience with the technology (making it highly accessible). The MRIR deployed onto the physical environment and objects made complex conditions of the tower position, foundation points, and connecting parts easier to understand. This experiment proved to have similar benefits as in other project using MR systems (Chun et al. 2020; Goepel et al. 2020).

The MRIR were effective for the original foundation setting-out process and provided sufficient accuracy for the screw installations. Once the positions of the foundations were established in a triangulated system on site, the rotated position and distances were again easy to verify with MRIR. The MR user provided assembly guidance, but site conditions made it sometimes difficult to use higher up. The MRIR, using a HoloLens2 and Fologram (Fologram 2022), were most advantageous when used for deploying a 3D wireframe of the complex geometric conditions with accuracy within 10-20 mm at close range, in normal lighting conditions, and within six meters away from the Wi-Fi signal. More tests on ways to improve the accuracy of digital 3D model deployment should be conducted in further research experiments.

Future work will explore ways of using MR systems (possibly other platforms too) to provide greater design agency for customization and variety in design and building by using more HMDs for more MR users. Further studies will explore more ways to evaluate the outcomes and accuracy of using MRIR with more detailed comparisons with conventional modes of representation and consulting expertise in hand craft fabrication and assembly procedures for bespoke designs.

ACKNOWLEDGMENTS

The project was planned and realized by the department of design and building theory in cooperation with the department of structural design at the University of Kassel, Germany, with the help of the carpentry firm Holzwerk Energie. Client: Hugenottenhaus GmbH Silvia und Lutz Freyer. Sponsors: Sprengwerk Architektur, HELIX Schraubfundamente GmbH & Co. KG., Mateco GmbH, J.W. & L Jordan GmbH, Hugenottenhaus GmbH, Pfeifer Stiftung Uni Kassel, Studienkommission Uni Kassel. Additional support was received from Brandthaus Uni Kassel, Guido Brinkmann and PERLE Café + Bar, Marén Freyer.

REFERENCES

Carpo, Mario. (2017). The Second Digital Turn: Design Beyond Intelligence. Cambridge, MA: MIT Press.

Chun, J., Fong, H., Long, A., Poon, W., Sze, W., Ho, C., Goepel, G. and Crolla, K. (2020). 'Augmenting Craft with Mixed Reality' Available at: http://papers.cumincad.org/data/works/att/acadia20_436.pdf [Accessed 14 Oct. 2022].

Fologram (2022). Available at: https://fologram.com/. [Accessed 25 March 2022].

Goepel, G. and Crolla, K. (2020). 'Augmented Reality-Based Collaboration - ARgan, a Bamboo Art Installation Case Study.' in Proceedings of 25th CAADRIA Conference. 5-6 August 2020, Bangkok, Thailand, Vol.2 pp. 313-322. Available at: doi:10.52842/conf.caadria.2020.2.313.

Jahn, G. and Wit, A. (2019). '[BENT] Holographic Handcraft in Large-Scale Steam-Bent Timber Structures', In Conference: ACADIA 2019. Austin, Texas: ACADIA 2019, 2019. Available at: https://doi.org/10.52842/conf.acadia.2019.438.

Jahn, G., Newnham, C. and van den Berg, N. (2020). 'Collaborative Fabrication In Mixed Reality' in Melendez, F., Diniz, N., Del Signore, M. (eds.) Data, Matter, Design: Strategies in Computational Design, New York: Routledge, pp.239–247. Available at: doi:10.4324/9780367369156-82.

Jahn, G. Newnham, C., van den Berg, N., Iraheta, M., and Wells, J. (2019) 'Holographic Construction' in Gengnagel C, Baverel O, Burry, J., Ramsgaard Thomsen, M., Weinzierl, S. (eds.) Design Modelling Symposium, Springer International Publishing, Berlin, pp 314-324. Available at: https ://doi.org/10.1007/978-3-030-29829 -625

Lharchi, A., Ramsgaard Thomsen, M. and Tamke, M. (2020). 'Connected Augmented Assembly - Cloud based Augmented Reality applications in architecture' in eCAADe 38 2020 proceedings, Vol.1 pp.179-186. doi:https://doi.org/10.52842/conf.ecaade.2020.1.179. [Accessed 01 Feb. 2023].

Mitterberger, D., Dörfler, K., Sandy, T., Salveridou, F., Hutter, M., Gramazio, F. and Kohler, M. (2020). 'Augmented Bricklaying Human-Machine Interaction for in Situ Assembly of Complex Brickwork Using Object-Aware Augmented Reality', Construction Robotics, 4, pp. 151–161. Available at: doi:10.1007/s41693-020-00035-8.

Rhino 7 (2022). Available at: https://www.rhino3d.com/. [Accessed 25 March 2022].

Witt, Andrew. (2021). Formulations, Cambridge, MA: MIT Press.