Mixed Reality Hybrid Approach for Creating User and Material Affordances in Translating Digital and Physical Form

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This paper presents the outcomes of user and material affordances gained in a hybrid approach for students using mixed reality (MR) in the design process, combined with physical material fabrication, in various real-world contexts. The research uses a design-build studio project as a demonstrator, where students created two steam bent timber pavilions for a meditation at Buddhist center in Austria. The work contributes to a gap in research that studies MR uses and its potential impact in design education, by studying user and material affordances gained in a scalable hybrid design process. Also, how tacit knowledge informs the design process to afford a wider range of design outcomes. The methods used a hybrid approach for translating digital and physical models, carried out in three phases: 1) translating initial design concepts into iterative physical and digital models, 2) hybrid material translations building physical models and prototypes, and 3) hybrid fabrication and installation of both pavilions in separate locations. The work documents the process and design outcomes of both designs in each phase by collecting MR video recordings and 3D scanning the final design outcomes. Resulting observations of MR users reveal tacit learning and affordances in the design process. 3D scanned data is compared to the original 3D model to measure material affordances of the outcomes. This project tested MR used for translating design concepts into physical form and studies how tacit knowledge informed the hybrid design process in a real-world context. The hybrid design process supported students in designing and installing both pavilions, achieving the desired design outcomes for both projects. The project shows how MR hybrid approach affects user understanding and material affordances in translating digital and physical form through observations of tacit learning and 3D scan comparisons in the design process.

Keywords: *mixed reality, architectural representation, affordances, digital and physical, 3D scanning, design education, hybrid approach*

INTRODUCTION

This paper presents the outcomes of user and material affordances gained in a hybrid approach for students using mixed reality (MR) to overlay digital models in various physical environments in a design-build learning context. MR is used as a representation tool for design by spatializing and augmenting digital drawings and models in physical realms, enhancing student users' ability to design, interact with, and better understand

complex geometry (Goepel et al., 2020; Jahn et al., 2020). Despite the growing number of projects using augmented reality (AR) and MR for material fabrication (Song et al., 2021), there is still a need for more research on investigating its use and potential impacts in design pedagogy by learning through making (Loh et al., 2024).

The work contributes to this research by investigating the use of MR as a hybrid representational tool, combined with physical material fabrication, as an integral part of the design process. An MR hybrid approach is applied over two semesters using a design-build studio project as a demonstrator, where students designed, developed, and fabricated two steam bent timber pavilions for a Buddhist meditation center in Austria, in collaboration with local expert carpenters and using locally sourced timber. The goal was to install both meditation pavilions on site by early June 2024. The inquiry surrounds the research question: How does a MR hybrid approach affect user understanding and material affordances in translating digital and physical form?

BACKGROUND

The project builds on on-going research that leverages MR as an immersive spatial medium for architectural representation that fosters interaction, participation, and design agency. In addition, combined with the use of 3D scanning and other advanced technology, the work seeks to promote novel aesthetics in architectural design and education.

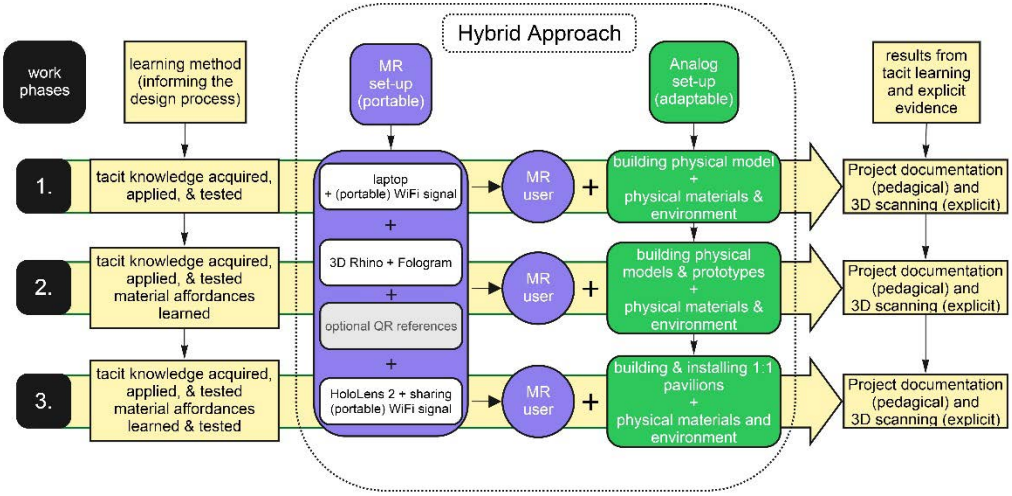
The hybrid approach presented in this paper is a subsequent study which tests a scalable version of the initial study (Blahut et al., 2024) conducted in a seminar in the winter semester (2023-24) and includes the same students. As the design-build design process of the two proposals (structures A and B) was carried out over the winter and summer semesters, where the initial phase in the winter semester ran parallel with the seminar research and tasks in the previous study. Both studies have the goal of students gaining tacit knowledge (first in the seminar tasks) to inform the design process in studio, as well as carry out material fabrication and installation on site, for both pavilions to achieve their intended design outcomes (Blahut et al., 2024).

Theoretical framework

Our previous study showed tacit skills learned in the seminar tasks, also in collaboration with one another, using advanced digital tools, such as MR and 3D scanning systems, and in physical model building (Böhm, 2021). This method offers the potential to collect data that can reveal both implicit and explicit evidence. Existing research on tacit knowledge (Polanyi, 1966) and skills learned through experiences in architectural design contexts (Schrijver, 2021) further support this approach to teaching design studios and seminars in architectural education.

The research explores how MR use enhances tacit knowledge and affordances (Barati et al., 2019) in education to allow more creative freedom in the design process while building tacit skillsets (Böhm, 2021). In addition, students' and material affordances in creating iterative and scalable design possibilities and their outcomes are analyzed, also where they learn and apply essential tacit knowledge (Schrijver, 2021) to inform the process in iterative physical and digital translations. This also further expands on research advocating for experiential and participatory learning methods in design education (Salama, 2015).

Figure 1
Diagram for the hybrid approach, applied in three phases.



Investigations in user and material affordances in the design, development, and installation processes, are supported by research based on how 'The Theory of Affordance' (Gibson, 1979) can be applied in architectural design, theory, and practice as an 'affordance-based approach' (Maier, 2009). Research conducted using similar technology, virtual reality (VR), in an architectural design studio to introduce affordance-based design methods found this to improve students' work, also revealing both positive and negative affordances in the design process (Agirachman et al., 2022). This study posits that tacit knowledge acquired is linked to the students' understanding of timber affordances physically, further enhanced by a MR hybrid approach, which also creates different feedback loops that inform the iterative design process.

METHODS

The hybrid approach uses a portable digital set-up for MR applied in three work phases (Figure 1), based on methods previously learned and tested in the prior study (Blahut et al., 2024). A laptop and Rhino 3D (Rhino, 2024) were used for digital modeling and with the MR plug-in Fologram (Fologram, 2024) to create a real time connection between users wearing a HoloLens 2 head-mounted display (HMD) and the 3D Rhino model from a laptop, over a shared (portable) WiFi signal. Four HMDs were available for users, allowing up to two MR users at a time for each design process, in collaboration with other team members, or to carry out individual tasks. The hybrid approach is applied in three phases.

1. Translating design concepts represented as iterative physical and digital models (in parallel with seminar study).
2. Hybrid material translations through building physical models and prototypes, remotely and on site.
3. Hybrid fabrication and installation processes on site.

Evidence of tacit knowledge and material affordances in the hybrid process is gathered through documentation video and images recorded with HMDs and 3D scanning the final

structures for comparison. The HMD footage is catalogued for each phase, also by making incremental screenshots in videos, showing how MR was used in tasks such as material fabrication, checking 3D model and proportions, anchor points and position on site, among others. The collected evidence is used to study learning, where a shift in skillset occurs, understanding physical material affordances related to 3D constraints, simplifying and/or adapting fabrication methods and 3D models, and checking explicit data for setting-out on site and locating final positions. 3D scans are compared with Rhino 3D models (as point clouds) to provide explicit evidence of material affordances of the physically installed structures.

Phase one

The design studio began by encouraging students to explore experimental ways of translating initial design ideas (about meditation) into spatial structures represented as physical models, using different materials that afford their physical geometric expressions and aesthetics (Figure 2). In subsequent physical model studies, students focused on designing further iterations based on material and fabrication research (from seminar), building physical models that explore potential material alternatives using different types of timber and/or fabrication techniques, also in combination with other secondary materials for structural support, such as metal wire frames and connections. The physical model studies and material prototypes built for both structures in parallel help to study different issues and material affordances to confirm the buildability of the proposed design geometry and fabrication method.

The decision was made by the students to use steam bending timber lamellae to fabricate both projects to achieve the complex curvature in timber geometry of both pavilion designs, after testing this along with two other feasible options, using willow or timber kerfing, in smaller physical models, as well as from structural feedback. They were asked to consider ways of using MR for steam bending fabrication and spatial location on site, considering their prior use of MR in the seminar study.

Figure 2
Initial design ideas and further translations into physical models for structure A (left) and structure B (right) in phase one.

Figure 3
Rhino 3D model translations and 3D scan site data, built during phase two, for structure A (left) and structure B (right).

Phase two

Subsequent design iterations informed by learning from phase one were carried out with the hybrid approach to integrate functional and spatial programmatic concepts, as well as incorporate 3D scans taken on site to test its location in relation to different structural systems and connections, translated from physical model studies (Figure 3). The plugin Kangaroo for material behavior simulation was used to compute the bending timber in structure A, as it would hang from a series of pre-selected trees in a forest. Material behavior simulations were not conducted for structure B, as it was more predictable based on physical behaviors of the

timber rings learned from building prototypes and structural feedback. This led to choosing an anchoring system of six screw foundations to support a timber platform (and substrate for the series of rings) on a gentle sloping topography. MR was used to deploy semi-developed 3D models in the physical context of each site to understand each structure's spatial location, form, and scale, as well as the positions of anchoring systems (Figure 5).

A workshop was conducted with local expert carpenters to test steam bending with samples of different types of locally available wood (beech, ash, and larch), cut in advance to desired thickness and sizes. MR was used to build form work for initial 1:1 prototypes to test fabrication with the samples. The students built an ad-hoc metal steam chamber with a steam device (temporarily) removed from a sauna. The use of a metal chamber was replaced by plastic tube sleeves, inspired by the methods used in the Steam Punk Pavilion (Jahn et al., 2022) to allow for steaming long strips of timber (Figure 4), necessary for both designs. Standard wallpaper steamers were also used in addition but did not provide enough steam alone. The fabrication set-up for both structures relied on timber formwork built to support the curved timber lamellae, held in place after steaming using clamps. Structure A formwork was developed to support twisting curvature in segments, first testing the form of a single strip. To create the individual timber 'rings' for structure B, long timber strips were wrapped around circular timber formwork and clamped into place for drying. The workshop led to the selection of Larch for the timber lamellae to use in both projects, as well as suitable dimensions and thicknesses. Not only could it be locally sourced, but also ideal for exterior construction and steam bending fabrication.

After building initial 1:1 prototypes, to simulate steam bent larch students built smaller scaled models in 1:5 scale using cherry wood veneer recommended by the expert carpenter. This was to further study MR combined with material fabrication and to test material behaviors before fabricating and installing at 1:1 scale in the final phase (Figure 5).

Figure 4
Steaming long timber lamellae in plastic tube sleeves.

Figure 5
Phase 2 MR hybrid model building and site studies for structures A (left) and B (right).

Phase three

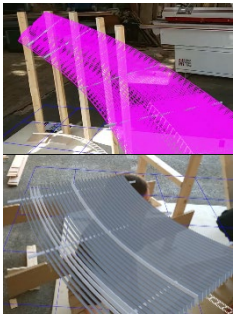
The hybrid approach is used for steam bending fabrication for both structures, carried out in parallel. Both structures relied on the same steaming method, having to take turns during fabrication.

For structure A, MR is used first to set out curving timber form work of four individual segments, including additional CNC fabricated timber templates that were horizontally mounted in various heights to hold the lamellae in position

after steaming (Figure 6). MR was also used to check the position of lateral threaded rods, and corresponding drill holes, in bent timber lamellae. The formwork was built to hold all steamed lamellae in place together in each segment while drying (Figure 7). After drying, holes were drilled and supporting rods and spacers were threaded through the lamellae, according to their marked locations to maintain different spacing between timber elements in each segment.

For the installation on site, the four prefabricated segments of structure A were combined by re-threading (weaving) the lamellae together on site, before suspending the entire structure. This required a stainless-steel hanging system made up of steel cables connecting to threaded rod anchors drilled directly into the trees with the ends of five lateral threaded rod supports, drilled (or threaded) through the twisting structure. MR was used in positioning the hanging structure in physical space between trees, also ensuring the intended seating area was set at the correct level. In addition, it was used to initially locate anchor points in the trees themselves, before drilling in threaded rods for suspending the structure.

The circular formwork used during steam bending fabrication for structure B relied on the fixed radius (built in phase two) for all rings, eliminating the need to use MR for building new formwork. It was learned that changing the radius would not make an impact on the material behavior of the different sizes of rings. After a timber ring dried, it was removed and further processed by hand nearby, freeing the formwork for a freshly steamed timber strip to be wrapped around, clamped for drying, and so on (Figure 7).



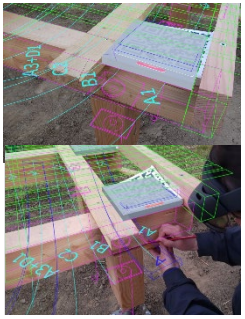


Figure 6
Phase 3 MR hybrid fabrication of formwork for structure A (left) and marking of ring locations on structure B (right).

MR was used for locating Structure B's six screw foundations on site, negotiating a sloping topography. These were connected to horizontal timber beams, serving as a base for mounting the timber rings and flooring. The steam bent rings were mounted to the underside of the main beams, which are beveled at an angle to make a better connection the curved lamellae. MR was used to mark the position of each individual ring in the correct location according to the digital 3D model (Figure 6). The structure is completed with the installation of larch flooring planks and attaching provisional timber horizontal connections with the installed timber rings to add further support for the overall structure.

Figure 7
Steam-bending formwork for fabrication of final structures A (left) and B (right).

RESULTS

The hybrid phases of both design processes, as well as improvements and adaptations to digital and physical models, were documented through recorded videos while using HMDs, showing how MR was used during the design process and in material fabrication tasks. The final design outcomes were 3D scanned with a FARO LiDAR scanner, from multiple points (five each) to retrieve as much 3D data of the built object as possible. The 3D scanned data was initially processed with the required FARO Scene software to align and combine the original scans into a single point cloud for each structure. The

combined 3D point clouds were exported as xyz file types for further processing and comparison.

Project Documentation and Observations from MR Use

The project was documented through recording videos from the HMDs while using MR for design, fabrication, and installation tasks. The videos and images taken during the process are used to analyze the use of MR in the process and to observe user and material affordances in both processes.

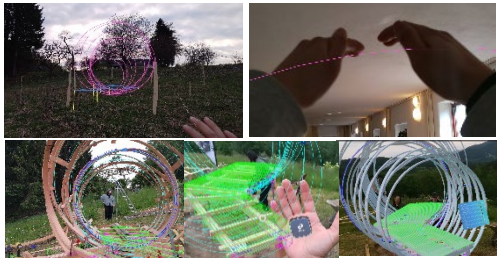


Figure 8
Screenshots of MR use for structure A site installation (phase 3).
Figure 9
Screenshots of MR use for structure B, setting out on site, checking proportions (phase 2, above) and installation on site (phase 3, below)

In phase one, MR use in hybrid process was initially tested in the previous seminar study (Blahut et al., 2024). This foundation helped to inform subsequent design iterations and fabrication methods through the rest of this study. MR videos and images taken from HMDs are focused on further developing both structures in phases two and three. The footage was analyzed to identify user and material affordances for both structures and how they informed later iterations. Observations are compared between the two processes, demonstrating different decisions made by the MR users to achieve the desired outcome.

The observations revealed that students used MR to understand physical material affordances related to 3D constraints, simplified and adapted fabrication methods and 3D models, and successfully verified explicit data for setting-out on site and locating final anchor positions (Figure 8). MR was repeatedly used to walk around digital 3D models to check scale and proportions, as well as ring heights and mounting positions in the physical environment (Figure 9). This body of evidence throughout all three phases allowed for understanding of where learning and shifts in skillset occurred in the iterative design process.

3D Scanning and Comparisons

The built design outcomes of both pavilions were 3D scanned with a LiDAR scanner. The design 3D model is compared with 3D scan of the built pavilions, also documenting the design outcomes.

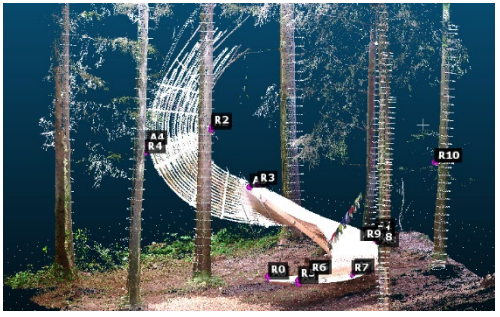


Figure 10
Ten equivalent point pairs for structure A were used to align both point clouds in CloudCompare.

CloudCompare was used to carry out further processing of the 3D scan point clouds of the final

built structures A and B to reduce the weight of the point clouds and excess noise. Excess points representing the surrounding environment were edited out of the cloud data, preserving the points representing the pavilions and their anchor points for comparison to the geometry of the design 3D model, a mesh exported from Rhino. The mesh vertices are sampled as a proxy point cloud which is used as a reference for aligning to the 3D scan point cloud for the comparison. The two clouds are aligned by picking equivalent point pairs on each cloud. For structure A, ten point pairs were used (Figure 10), while structure B used six.

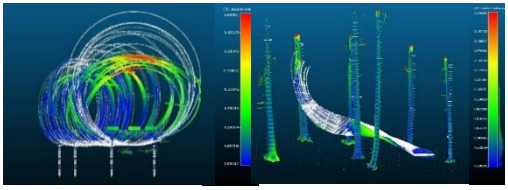


Figure 11
Material deviation for both structures A (right) and B (left).

Cloud-to-cloud (C2C) absolute distances between the 3D scan point cloud and the reference proxy point cloud of the design 3D model were calculated. The deviations between the 3D scans and the 3D design model were visualized as a color gradient (scalar value/ heat map). Red represents max. deviation and blue min. deviations (Figure 11). The overall resulting deviations of both structures are also summarized in a table (Table 1).

	Structure A	Structure B
Mean Deviation	**0.0924 m** (≈9.2 cm)	**0.2367 m** (≈23.7 cm)
St. Deviation	0.0682 m	0.1763 m
Min. Deviation	0.0002 m	0.0002 m
Max. Deviation	0.4999 m	0.6668 m

Table 1
Summary of C2C deviations for structures A and B.

DISCUSSION

This research tested a hybrid approach that relies on MR as spatial medium for architectural representation for the translation of digital and physical form. Using a design-build studio as a demonstrator, tacit knowledge and understanding of material affordances were learned by students, which also informed the design and material fabrication, as observed in recorded MR video footage taken in each work phase. Also, shifts in techniques and skillsets learned by students are shown through the design iterations developed in the process by testing proportions, scale, positions, and fabrication methods in combination with physical materials and contexts. The use of MR proved to be critical for installing tree anchors and suspending structure A in the correct position in the forest (Figure 12). Also, for setting out screw foundations and positioning the complex set of rings in structure B.

Figure 12
Tree climber (left) suspended above to drill at the location for threaded rod anchor using MR to find the location (right).

The 3D scan comparisons further confirm anticipated material affordances in both structures. This is further supported by the results of previous seminar case study (Blahut et al., 2024), which also showed tacit knowledge gained in the process, which follows similar methods at a smaller scale. The 3D scanning results were improved in this study by using professional LiDAR scanning equipment and point cloud comparisons carried out in CloudCompare. The material deviations calculated for structures A and B widely varied, visualizing the real-world material behavior of the installed pavilions compared to the digital model. This highlights that the geometry in the Rhino model of structure B did not account for physical material behaviors, providing evidence of the digital intent conflicting with real-world affordances. The Rhino model for

structure A accounted for bending behaviors simulated in Kangaroo, revealing a much lower overall material deviation. However, the real-world material affordances causing varied levels of deviation in both structures could be immediately observed when using MR during the final installation.

In terms of safety during fabrication tasks, students wore recommended safety gear, such as gloves and protective goggles, wherever necessary. HMDs were removed for heavy duty tasks and tools such as saws, drills, and sanders.

CONCLUSION

The hybrid approach was documented in three phases of the design process for structures A and B. This also provided evidence that could inform iterative improvements and adaptations to digital and physical models and prototypes, based on learned skillsets (Loh et al., 2024) and understanding material affordances (Barati et al., 2019) during fabrication.

By comparing digital design intent with actual material outcomes through MR observation and deviation mapping, this study reveals how material affordance, such as bend radius limitations and effects of hanging steam-bent timber components, reshaped the design process. Students learned where it was critical to follow overlaid digital geometry and to negotiate with the material itself, gaining tacit knowledge that informed the design development and physical prototyping, resulting in successful installation of both designs.

The hybrid approach presented was highly flexible and adapted to real-world applications, used in remote or local physical environments, having varying constraints. By further examining the approach on more scaled design iterations of only two pavilion structures (which include building scaled physical models, 1:1 material prototypes and installing the final pavilions on site), it is possible to gain closer insights on how user and material affordances can inform the design process and outcomes.

Future research should include user surveys or quotes from students. Also, a more rigorous study of MR observations throughout the process to better support new insights into MR's role in design education and its use as hybrid medium for representation, creating novel affordances for users and materials in the architectural design process.

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