Collaborative design and construction of reconfigurable wood structures in a Mixed Reality environment

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Abstract. Mixed Reality tools offer new possibilities for cyber-physical design and construction and promote novel collaboration protocols. This work tackles a multi-user open-end design and construction of reconfigurable timber structures in Mixed Reality by introducing a computational workflow, physical setup and custom-designed interface. The developed procedures are demonstrated in the design and making of a real-scale architectural mock-up based on a discrete construction kit that allows for numerous assembly combinations. The results show that such a construction system that is characterized by rich design and assembly data is processed faster and with fewer mistakes by the builders using Mixed Reality. This opens the possibility to execute, change and update the construction directly in the physical environment in real-time. Moreover, the projected holographic analytics and construction data allowed for more structured decision-making and understanding of the impacts that each building action had.

Keywords: Mixed Realities, Reconfigurable Timber Construction, Collaborative Design, Collaborative Assembly, Wood Architecture Automation

1 Introduction

Mixed Reality (MR) tools are opening possibilities for real-time engagement with digital design and construction data within the physical space and supporting the experimentation of novel human/machine collaboration protocols (Alizadehsalehi et al. 2020, Zolotová et al. 2020). In digital timber construction in particular, MR has been involved in facilitating the interaction with complex material behaviour (Jahn et al. 2020), to enable the design of structural systems with wood logs of irregular forms (Lok and Bae 2022), to support data-driven assembly (Gramazio Kohler Research 2019), and to advance carpentry procedures (Settimi et al. 2022).

Figure 1. The collaborative assembly process of reconfigurable timber structures by two users wearing Microsoft Hololens 2 headsets © CREATE

Furthermore, MR has been coupled with robotic fabrication processes to investigate opportunities for human-robot interaction, where robot simulation in physical space (Hughes et al. 2021) and online operation (Kyjanek et al. 2019, Amtsberg 2021) are enabled through augmented interfaces and interactive human-robot processes for co-design and assembly are unfolded (Atanasova et al. 2021).

In this paper, complex robotic operations for the assembly of reconfigurable timber structures, which were previously developed by the authors (Kunic et al. 2021a, 2021b; Naboni et al. 2021), are translated into MR-supported human processes. In particular, we describe an experimental study for an immersive in-space and open-end collaborative *design* and *construction* of timber frame structures that can be reconfigured in real-time. A custom User Interface (UI) is designed to facilitate human interaction with complex and rich construction data effortlessly and foster the integration of human decision-making into automated processes (Fig. 1).

2 Methodology

In this research project, reconfigurability is seen as a central concept of circular construction, which promotes material reuse and the evolution of structures over time, unlike typical construction processes which lack flexibility, openness, and capacity to adapt to unpredicted external circumstances

(McKinsey 2017). The following methodological procedures are developed to enable an easy-to-follow, flexible and adaptive process that allows non-expert users to conceive, modify and update circular building structures (Fig. 2):

- Cyber-physical MR workflow for an adaptive *design* and *assembly* of reconfigurable wood structures that rely on discrete building blocks with a large number of connections
- A custom-designed UI for managing the navigation between the design and building phases in MR, interaction with their related data and the setup through *holographic projections* and direct *holographic instructions*
- A *physical setup* for collaborative MR assembly

Firstly, reconfigurable wood structures are conceptualized collaboratively among multiple users, directly observing their choices' spatial and material implications. Secondly, starting from a prefabricated construction kit, the designed structure is assembled by the same users in the form of distributed-task construction. The users engage with holographic projections of the analytical structure data and direct construction instructions through the developed UI.

The established workflow, MR functionalities and the UI are developed within Grasshopper, using the Fologram plug-in, and showcased in the design and making of an architectural mock-up, namely *ReconWood Proto 01*. The developed processes and features are evaluated in terms of communication between the phases and between the users, the construction time and users' interactivity with the complex assembly data.

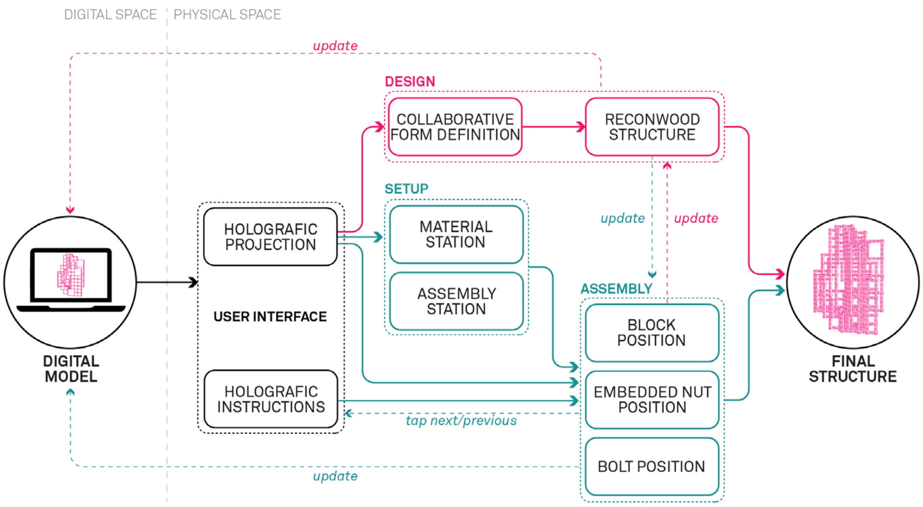

Figure 2. Cyber-physical collaborative design-construction workflow in MR
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2.1 Collaborative Design of ReconWood Proto 01 in MR

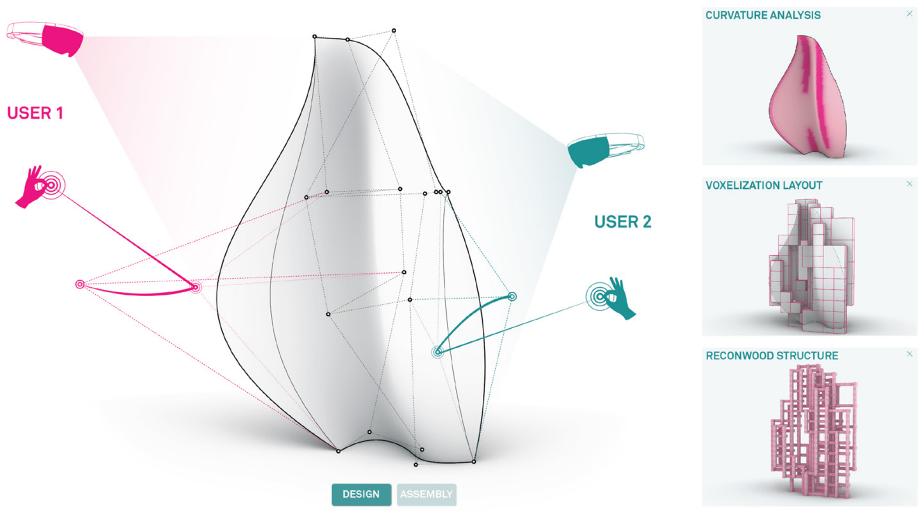

Figure 3. Multi-user collaborative design conceptualization in MR environment © CREATE

The design of the *ReconWood Proto 01* is developed through algorithmic procedures that start from a user-defined three-dimensional geometry, which is subsequently discretised into a multi-resolution voxel-based layout in response to a determined scalar field. Voxels are translated into a timber frame system with an optimized structural density, which takes into account the reusability of the discrete building blocks. Inspired by the properties of a LEGO "building brick" (Christiansen 1961), such as (1) the vast variety of assembly combinations achieved with (2) a few block typologies that are (3) interlocked together through a male-female joint, the discrete *ReconWood* blocks are assembled and re-assembled in a layered fashion to achieve a targeted formal configuration.

The immersive shaping of the ReconWood Proto 01 resulted in a doubly curved surface collaboratively manipulated by two users. More specifically, by tracking their hand gestures, the designers first defined the spatial boundaries in the physical environment that were referenced in the digital design algorithm as the bounding box within which to operate. In the following phase, a doubly-curved surface was conceived within the bounding box and further manipulated by dragging its control points (Fig. 3a). As the users changed the surface design, they could track algorithmic, structural and material data, such as:

- Dimensional data of the defined form such as width, height and surface area
- Gaussian *curvature analysis* which has been used as a scalar field to inform the voxelization algorithm (Fig. 3b)

Figure 4. ReconWood Proto 01 © CREATE

- Multi-resolution *voxelization layout* based on the Gaussian curvature values (Fig. 3c)
- *ReconWood frame structure* (Fig. 3d) derived from the voxelized layout
- The resulting structure statistics such as total wood length, number and types of employed *ReconWood* blocks, the amount of the required connections and total weight.

As the input surface design is collaboratively updated, the voxels distribution and subdivisions are constantly re-computed according to the Gaussian curvature values. The resolution range of the used voxel grid is determined by the dimensions of the selected construction elements (i.e. cross-section and length).

With this method, two users conceived a wall-like structure with a differentiated distribution of reconfigurable timber frames (Fig. 4), parametrized on significantly variable Gaussian curvature values of the input surface.

2.2 Collaborative MR Construction

Experiment Setup. The setup for collaborative MR construction of reconfigurable timber structures consists of three main areas (Fig. 5). The *Assembly area* has a plan size of 3000x1500 millimeters with two QR codes placed on opposite corners for accurate referencing between the digital model and the physical setup.

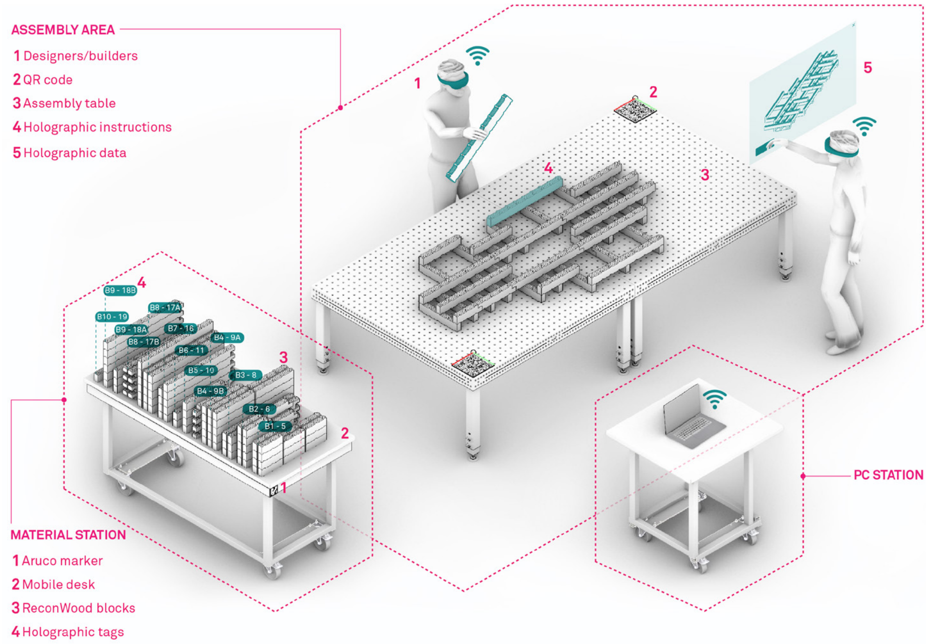

Figure 5. Cyber-physical setup for multi-user collaborative MR construction
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The *Material station* hosts timber blocks, steel bolts and insert nuts. It is mobile and tracked through an Aruco marker which is also used as a reference point for the holographic tags of the discrete blocks. This allows for the material station to be freely moved around while preserving an accurate alignment of the materials to their digital twin. The *PC station* provides bi-directional communication between the builders' physical actions and the digital construction model. Each builder is equipped with Microsoft Hololens 2 headset and a cordless electric screwdriver. To enable communication between them, the PC and the two Hololens devices were connected to the same Wi-Fi network.

Collaborative assembly. Two users carried out the collaborative assembly of the *ReconWood Proto 01*. The process consists of (1) block preparation and the application of steel insert nuts; (2) block placement and alignment to their final position within the structure; and (3) insertion of two different types of steel bolts into the assigned joints, according to a statically determined configuration. The two users cooperated within a shared MR environment and accessed the same construction data. They could collaborate on construction tasks of higher complexity, e.g. placing and screwing a long cantilevering block with a large number of bolts or simultaneously executing consecutive operations, e.g. one user places and screws one block while the other user embeds the insert nuts into the next one.

During the construction, consecutive blocks are highlighted through the UI both within the physical assembly space and in the three-dimensional projection of the assembly sequence, providing users with an intuitive overview of their reciprocal actions. For each assembly phase, sequential instructions and data are visually superimposed onto the physical setup. For instance, for each block that is being assembled, its precise position, the types of bolts to be inserted and their corresponding locations are visualized (Fig. 6). As the users modified the design during the construction process, their decisions and building actions were consequently digitalized in real-time, updating the further assembly instructions and data.

Assembly feedback. In particular, once the block is physically taken from the material station, it is synchronized and "solidified" as a Rhino object, and its position is tracked. In case the wrong block has been picked, or the tracking process should be interrupted for any other reason, the implementation of a “delete block” button allowed for the cancellation of the corresponding active Rhino object.

When the two designers decide to place the blocks differently from the initial layout and change the structure's design, the new layout is synchronized with the digital model, and the virtual configuration is updated. Attempts to place the blocks in positions that are not compatible with the system connectivity logic result in a red component highlight, requiring the designer to modify its position.

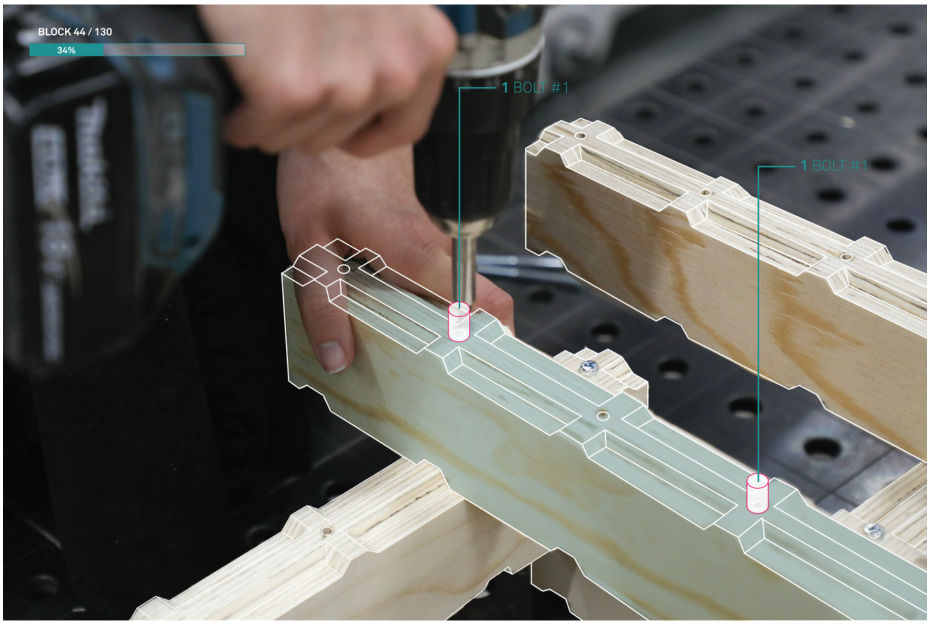

Figure 6. Augmented assembly and screwing of a ReconWood block © CREATE

2.3 User Interface Design

To assure smooth interoperability between two users and their physical operations with the digital model, a custom UI was designed (Fig. 7). This allows the assembly instructions to be dynamically updated based on human actions and superimposed on the ongoing physical activities, as previously described.

In the developed UI, three sets of holographic interactive panels are distinguished. (1) *Assembly instructions panels* were used to provide specific guidance for each *ReconWood* block in action (e.g. bolts and nuts layout and types), the assembly sequence and general construction progress (e.g. position of the current block in the overall construction; percentage of completion regarding bolts, nuts and blocks). (2) *Assembly data panels* show general construction information such as cross-sections, weight, total material length, number of required connections, percentage of each block's recurrence in the structure etc. This data is updated in real-time during the assembly phases and upon emergent design modifications. The holographic panels are interactive and can be dragged by the users, placed anywhere in the augmented space or switched on and off according to their needs or preferences. (3) *Interactive buttons* are used to facilitate specific process navigations (e.g. selection and cancellation of a building block, proceeding to the next block or going back to the previous one, etc), the transition from the design phase to the construction one, and increase interactivity in each phase without the need to consult a 3D model from a PC screen.

Figure 7. Custom-designed UI for the adaptive construction of ReconWood structures © CREATE

3 Results

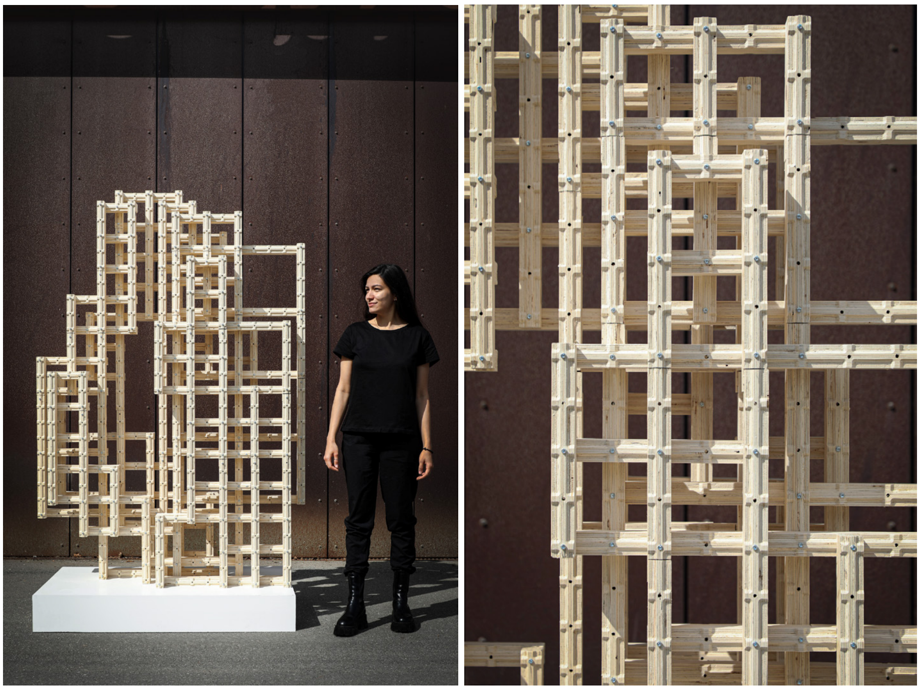

Figure 8. Views of the completed ReconWood prototype © CREATE

The MR collaborative design and assembly of the *ReconWood Proto 01*, a 2000X1400X500 mm wall-like structure with graded material density (Fig. 8), have been successfully carried out by two users who mutually interacted through a custom-designed UI.

The use of Fologram plug-in allowed for achieving seamless communication and interactive dependency between the digital design environment and physical setup, enabling full operational autonomy without the need for time-intensive software implementation. Various gesture-tracking possibilities assured design freedom and interactive decision-making by the users, which would otherwise be complicated to run in a fully manual mode, or with the use of automated robotic processes. The established bi-directional synchronization of actions and geometries was highly relevant for the adaptiveness and openness of the whole design-build workflow. The UI was easily modified and refined several times based on the user experience, leading to better performance over time.

The 130 *ReconWood* discrete blocks, prefabricated out of LVL battens with a 39x66 mm cross-section and varying lengths, were assembled over six hours following complex assembly instructions.

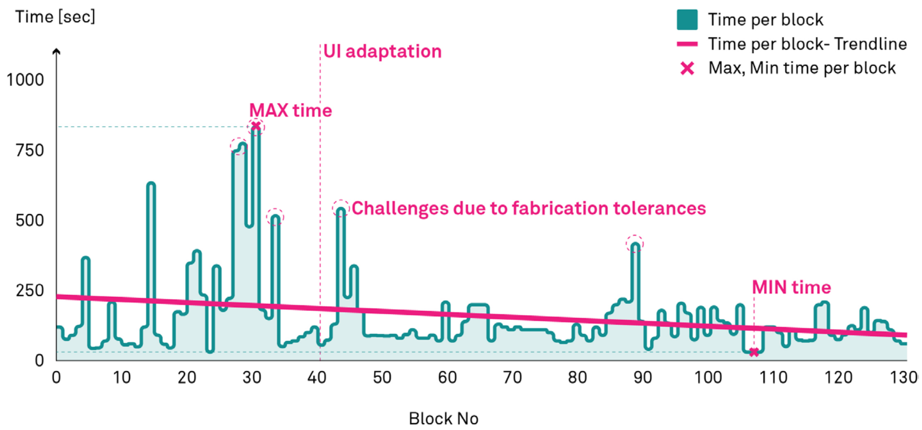

Figure 9. Assembly time tracking of ReconWood prototype in MR © CREATE

The complexity of the assembly data, indeed, increases by the use of a large number of identical blocks within the structure, while the distribution of the bolts and nuts is broadly varying, as well as by the periodical re-configurations based on instantaneous designers' decisions, and the corresponding design updates.

The average time needed to assemble a single block was about 2.5 minutes. Fabrication tolerances in some of the blocks have caused misalignments between the holes of two superimposed blocks which required more time and fatigue for a bolt to be screwed in. This resulted in significant delays in some cases, reaching up to 14 minutes of assembly time required for a single block. However, the general time/block trendline decreased as the construction progressed (Fig. 9), with a minimum time of 30 seconds registered for the assembly of shorter blocks with a few bolts. The reason for this was the adaptation of the UI and the introduction of "previous block" and "delete block" interactive buttons, which initially were not implemented, but became necessary for the two users to control their reciprocal actions better and eventually retrieve precedent operations when needed. Moreover, the designers developed confidence in the process and interaction with the interface over time.

4 Discussion

The presented research introduced an approach for collaborative, open-end design and assembly of reconfigurable wood structures in an MR environment, immersing nonlinear human actions into digital design-construction loops. Two users equipped with MR headsets played the role of both designer and builder to conceive an architectural demonstrator of reconfigurable timber structures designed for automation-prone assembly and re-assembly.

The data-rich construction of the *ReconWood Proto 01* has significantly benefited from the use of MR and custom-designed UI, which reduced space for mistakes and quickly increased productivity. The building actions were driven by human reasoning and intuition, which are the crucial features that the machines still lack and are highly needed in unpredicted and unstructured environments such as building sites. As opposed to the assembly feedback of previously studied robotic assembly (Kunic et al. 2021), this MR process extends design negotiation and brings human creativity and spontaneous decision-making into the digital and automated processes.

Future work will investigate new UI functionalities to render the design/construction process more inclusive to non-skilled users and favour the integration of more relevant real-time construction information, such as structural feedback and data from the material passport (MP) of each building element. Furthermore, a new workflow for human-robot collaborative construction aided by MR will be explored, considering the advantages and challenges of both individual processes.

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