iHRC: An AR-Based Interface for Intuitive, Interactive and Coordinated Task Sharing Between Humans and Robots in Building Construction

Felix Amtsberg [a], Xiliu Yang [a], Lior Skoury [a], Hans Jakob Wagner [a], Achim Menges [a]

[a] Institute for Computational Design and Construction, University of Stuttgart, Germany
E-mail: felix.amtsberg@icd.uni-stuttgart.de

Abstract

The research presented in this paper introduces a novel method for Augmented Reality informed human-machine collaboration in the context of timber prefabrication. The concept is based on the craftsman controlled instructive interaction between a High Level of Automation (robotic) fabrication setup and a human co-worker. It argues that by enabling the craftsmen to coordinate or take over specific process parts, a significant increase in flexibility and robustness of automated workflows becomes feasible. This is highly relevant within the project-based construction industry where efficient and flexible production of one-off components is predominant.

A novel approach to integrate human and robotic co-workers in a joint fabrication setup that we call "Instructive Human Robot Collaboration" is introduced. With Vizor, a computational framework was developed for this purpose. It provides an intuitive interface between human and robotic fabrication units via a mixed reality head-mounted display (HMD).

Finally, the proposed method is tested with an initial case study in which a 14-Axis fabrication setup is connected with human craft. The HMD gives a craftsman without any knowledge in robot programming direct control over the fabrication setup and extends its individual skill set. Fabrication tasks can be shared freely and between human and robotic units, enabling a dynamically adaptive workflow.

Keywords –

Augmented reality; instructive Human-robot collaboration; Digital Twin; project-based, Task-Skill comparison

1 State of the Art

1.1 Requests in building industry

In recent years, the building industry and here especially the timber-based manufacturers are investing in prefabrication lines with a high Level of Automation (LoA) for a higher accuracy and process reliability. Bespoke fabrication lines are installed to produce slab and especially wall elements [1] within predefined constraints of the product portfolio. Recent developments introduce industrial robots to replace human craftsmen for another step, the wall assembly process of frame and plate elements [2]. This trend even suggests a shift to a fully automated human free prefabrication environment [3] and new specialized High LoA concepts introduce new machines to carry out tasks, which previously relied on the execution of human labor or extend the possibilities and qualities of fabrication through integrative computational design and robotic fabrication [4].

In industry, this approach is often related to a conceptual understanding of the building as a product rather than a unique project. This is motivated by the goal of standardization of building components [5] and results in a restriction of the architectural freedom. Hence, such solutions are often not sufficient to solve the demand for the housing market, especially in the inner cities, where solutions adaptive to the various onsite conditions are requested, to fill the vacant spaces or extend the building vertically by adding new stories on the existing ones. Compared to the whole market only 13 % of the upcoming projects fall under the concept of modular building solutions [6]. To address this challenge, more flexible automation approaches are necessary to be investigated [7].

In addition, the recent results of fully automated "lights-out factories" in the high batch size production of the car industry (TESLA 3) showed a lower overall production speed [8], demonstrating the need for better integration of manual processes and automated systems. For the small and medium sized enterprises in the building industry with their request for an efficient short-term production of bespoke building elements, the human co-worker remains an essential part not just for the execution but the planning of the fabrication as well.

1.2 AR in AEC research

Augmented Reality-Technology (AR) was presented more than five decades ago [9] and introduced to the aircraft industry three decades ago [10]. As robust and affordable AR headsets became more accessible in the last decade, this technology is gaining focus within the Architecture, Engineering and Construction (AEC) field. The concept of complementing the real world with digital representation of otherwise not visible data has opened a new path for a great variety of applications in AEC.

While there is a clear and obvious use case for shared model visualization to enhance design communication and collaboration [11] and another use case in visualizing hidden parts like water or electric conduits in facility management [12,13], first efforts are undertaken to implement AR-devices in the environment of prefabrication and on the construction site to improve and extend the skillset of craftsmen via the precisely located delivery of information on-time. Here two different major directions can be observed.

1.3 AR-enhanced craft

Research in the field of AR-enhanced craft investigates how human augmentation enables the construction of geometrically complex structures by craftsmen, a task previously reserved to computer numerically controlled technology (e.g. industrial robots). This approach was presented in visually guided pick and place procedures of bricks for the assembly of uniquely shaped brick walls [14], the manual bending of structural elements (i.e. steel tubes) to erect one-off structures and their quality check [15]. The system informs the human about the next step in an instructive one-directional information flow.Potentials for AR -enhancement of craft for assembly sequences have been further investigated in relation to the replacement of instruction manuals to enable the assembly of complex structures by untrained or unskilled persons [10, 16, 17]. Investigations in other fields focus on the introduction of alternative feedback concepts like acoustic [18] and haptic feedback or the combination of several feedback systems [19], which could be used to explore their potential of training the craftsmen due to the provision of a more intuitive feedback. And the integration of sensors and additional motors has been used to actively readjust hand steered toolpaths, compensating for human imprecisions, and enabling sub-millimeter accuracy thus CNC-comparable results with hand-held tools (I.E. Shaper) [20].

1.4 AR-based human-machine collaboration

Research in the field of AR-based HRC shows high potential to integrate human labor and industrial robots to join their forces for smarter, more flexible, intuitive fabrication sequences, combining their individual strength and extending the setup's skill sets.

In many fields of production this potential is discussed to explore novel and more flexible automation processes [21]. In car industry for example, the level of collaboration is deeply discussed to identify potential scenarios [22] based on the proximity of collaboration and the related safety issues. The International Federation of Robotics defines 4 levels of collaboration: The coexistence, sequential collaboration, cooperation, and responsive collaboration [23].

High efforts are undertaken to bring human and robot closer together, such as precise scanning systems and sensitive sleeves for the robot [24]. The level of collaboration is defined by the mode in which the robots run if the human and machine share the same workspace or if there are physical barriers [21].

Recent work in architectural research focuses on novel human robot collaboration in experimental fabrication processes, instead of functionally driven implementations in the industrial environment.

For the contextualization of this paper, we propose a differentiation of existing modes of HRC in AEC and research along 3 scenarios:

1.4.1 Humans and robots as separate units

In this scenario, humans and robots work alongside each other as separate units executing pre-determined tasks. Various examples can be found where the precision of industrial robots for pick and place or holding in space is used, while the human screws [25] or welds [26] to fix the workpiece.

Even though this sequential task sharing demonstrates the benefit of a collaborative workflow already, studies mainly have been focusing on the robotic processes, using human labor to execute tasks, which are either hard to be executed by industrial robots or out of scope of the research. Interaction or even just organized and automated communication between human and robot fabrication units is usually not considered. This applies also to processes in which human and robot do not share the same workspace, i.e. material supply, workpiece unloading [4].

1.4.2 Human as an instructor, robot as an augmenting tool

A deeper collaboration between human and robot has been introduced via the integration of sensors and emitters. Humans instruct the robot through gestural instructions. Sensors are used to identify and localize the human intervention and special programs convert these instructions to physical actions executed by the machine.

For example a Kinect RGB-D camera attached to the end effector of an industrial robot was used for the project “Iterative clay forming” to localize the finger position of the craftsman and to deform a piece of clay based on its position [27], a combination of motion capture markers, a pressure sensor and an external camera system enabled a direct and more intuitive description of shaping a sheet of plastic using the concept of thermoforming [28] and third research uses the torque sensors of a KUKA iiwa to readjust the robot arm manually during the fabrication process if requested [29]. Concepts like these require a direct and distinct communication between human instructor and the machine. If well designed the robot becomes a tool directly attached to the craftsmen and intuitively usable, which extends their skill set significantly, without any knowledge in coding or communication design.

1.4.3 Human and robot as collaborative units

Just recently HRC is becoming a focal point in AEC research. The implementation of sensors in High LoA fabrication setups in combination with novel interfaces and communication strategies support the collaboration between robots and humans in achieving the same fabrication goal within a dynamic process.

Being an important research topic in car industry for many years, sensitive small-scale low payload industrial robots (e.g KUKA iiwa, Universal Robots) have been developed as tools for low-risk hand in hand collaboration between human and robot. These machines were adopted to establish a collaborative prefabrication setup and experiment new concepts of HRC [30, 31]. The project “CROW” [31] successfully established a collaborative task sharing of robot and craftsman enabling the cooperative fabrication of bespoke timber structures.

2 Instructive Human robot collaboration and Multi-Unit Task Sharing

Despite these developments, true human robot collaboration in the building industry has significant room for further investigation. Typically, AR technology is envisioned for the construction site predominately, while prefabrication aims for full automation. The roles of the human and machine fabrication units in prefabrication typically are seen as separate, static and not interchangeable, once the workflow is planned. This often results in an over-defined digital system, that leaves the worker unable to intuitively interact with the automation workflow. Current State of the Art lacks adaptive, fabrication concepts, suitable for the flexible project-based demands in the building industry.

This research presents a novel method for the integration of humans and High LoA technology in a collaborative fabrication setup, combining their individual strengths to extend its skill set.

2.1 From Task-skill analysis to Multi-Unit Task-sharing

Multi-unit Task-sharing is a method which derives from the conceptual approach, of Task-Skill based fabrication planning [4]. In this concept a set of Tasks which must be executed to produce a building system is formulated. These requests are compared with the skill sets of adaptive and modular and therefor flexible fabrication setups. Such fabrication setup can consist of several fabrication units, which can be industrial robots and other automated machines, but also human workers. Accuracy, payload, and tools among others define the skill set of each unit individually and/or in collaboration with others. If the tasks required and skills provided match, the fabrication setup is suitable for the fabrication of this specific building system (Fig. 1). The fabrication tasks are distributed, based on the individual skill set of these units. If the skill set required by a task is satisfied by more than one unit, the task can be flexibly redistributed among these units depending on other criteria such as availability. If it can only be satisfied with a combination of multiple units, it can be distributed among these units for collective execution.

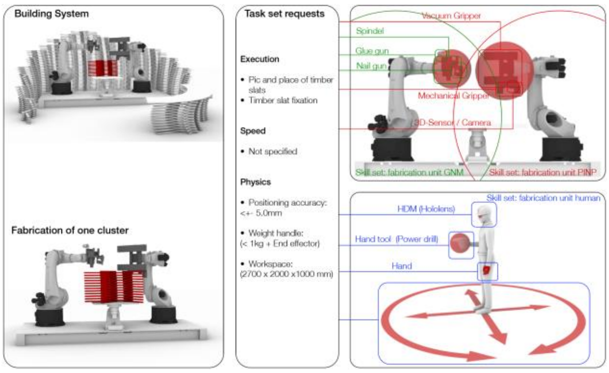

Figure 1. The building system leads to a set of requested tasks for its fabrication, which is aligned with the skill set of the different units of the fabrication setup

2.2 Instructive Human Robot Collaboration

With instructive Human Robot Collaboration (iHRC) this paper introduces an additional layer to the existing levels of collaboration. An intuitive communication interface, which provides the human worker with essential process and task- relevant data from the digital model as well as the possibility to control and interact with the robotic workflow is established.

This extends the concept of sequential collaboration, enabling the craftsmen to instruct the automated fabrication units e.g. industrial robots. With the tools described in the following chapter a communication protocol is proposed, which connects the machine controllers with the human craftsmen via AR-technology. The developed Hololens interface “Vizor” is used as the central facilitator and doesn’t request any programming skills from its user. Providing a digital twin of the work piece, it further extends the users skill in terms of positioning accuracy. This enables a craftsman-controlled fabrication process, breaking free from the constraints of a linear predefined workflow (Fig. 2). Tasks can be taken over, corrected or reassigned, depending on various conditions, such as the unit’s skill set (tool, reach, payload, etc.), resulting in a dynamically adaptive fabrication process and an extremely flexible fabrication system.

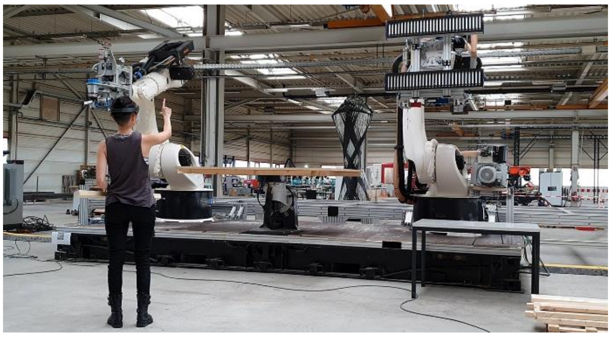

Figure 2. Human wearing an HMD controls the robotic fabrication setup

3 Setup

A communication strategy and an interface for the HMD were developed, to connect the human being with the robotic fabrication setup.

3.1 Communication Strategy

A communication system is implemented through a server that can read the tasks and communicate the fabrication data to the units for execution. Furthermore, the server also allows the units to share the fabrication data and the task's progress with each other (Fig. 3).

Three elements support implementing this case study of human-robot collaborative workflow: a server that dispatches tasks, two KUKA robot controllers connected to the server by KukaVarProxy via TCP/IP connection, and a Hololens Version 1 HMD connected to the server by rosbridge via a WebSocket connection.

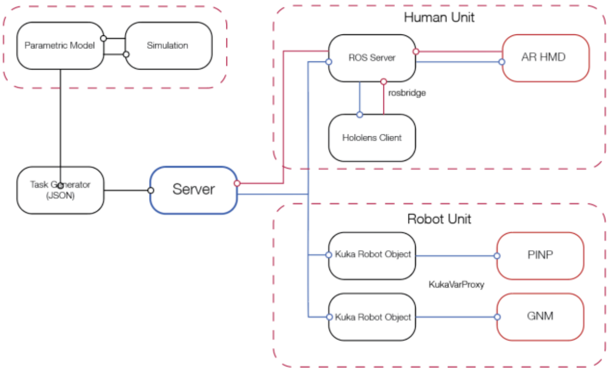

Figure 3. Communication strategy

3.1.1 Robotic fabrication unit

Each one of the robots is defined as a ‘Kuka-Robot’ unit in the server. The server is communicating with the robots using the Python KukaVarProxy library [32]. When starting a fabrication process, the server initiates the communication channel to each of the robot units and will keep it open through the process. According to the specific task, the server knows which data it needs to send for the task execution. For the robot to know what to do with the received information, a unique KRL code is used. In this KRL some global variables are defined at the beginning of the program. Then an infinite loop is triggered, and according to the received data, it causes a switch case to execute the desired task. Using the KukaVarProxy also allows the robot to send some data such as robot position and tool activation while running the task and informing the other units in the system on the progress. When the entire fabrication process is done, a particular signal is sent from the server to stop the loop and the communication.

3.1.2 Human fabrication unit

Information to the human unit is communicated through messages, and rendered via a Hololens app. This Hololens application is developed to work in sync with the Vizor plugin in grasshopper but can also communicate more generally with servers using the roslibpy library [33]. The information related to each task, namely description, deadline, and geometric information is sent to the human worker as the server dispatches them. At the event of a task reassignment action through Hololens, the server registers the change upon receipt of the user message and modifies the unit to which the task is dispatched.

3.1.3 Workflow and Human control

When initiating the fabrication process, setup functions for robot controllers and Hololens run to ensure all units are connected to the system. The server then broadcasts a task list, rendered on Hololens display for the operator to review. In the case of our proof-of-concept workflow, this is a list of pick, place, nail, and screw tasks that lead to the assembly of a spiral structure composed of timber slats.

When the robot is executing a task, the human sees the target frame for the robot in the current motion, a timer documenting the duration of task, and the name of the task being executed. When the human chooses to execute such a task, the display shows specific action instructions, highlighted geometry, as well as a deadline for the task being executed.

As the process unfolds, the human may step in at any time and modify the designated unit to complete a given task. This introduces flexibility of human intervention during a high level of automation process. In the proof-of-concept workflow, this flexibility allows quick resolution of issues in robot paths (e.g. collisions) or contingent events such as material inconsistencies (e.g. knots in the wood that could prevent nails from being inserted).

3.2 AR Interface Vizor

Second corner stone is the developed application "Vizor ". Vizor facilitates bi-directional communication between multiple fabrication units. The Grasshopper plugin allows users to prototype workflows directly using GH components. The companion HoloLens application is built using Unity (Fig. 4). It includes a digital twin of the TIM setup as well as modular user interface components that let a user interact with tasks, markers, model geometry and system status. The information is provided and visually presented in four components on the Head Mounted Display, in this case a Hololens (Fig.5).

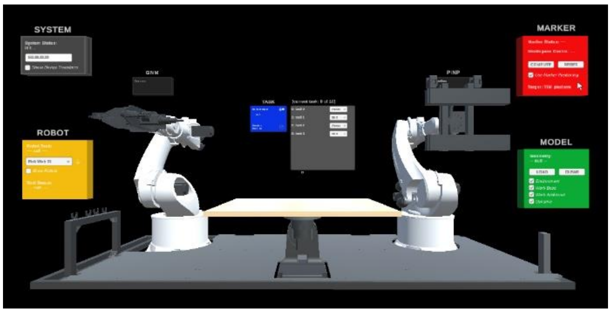

Figure 4. Platform representation in Unity

3.2.1 Display of the Digital Twins

A digital twin of the fabrication setup is built within Grasshopper using the plugin Virtual Robot and the plugin developed within this research Vizor to support simulation of the fabrication process (Fig. 6).

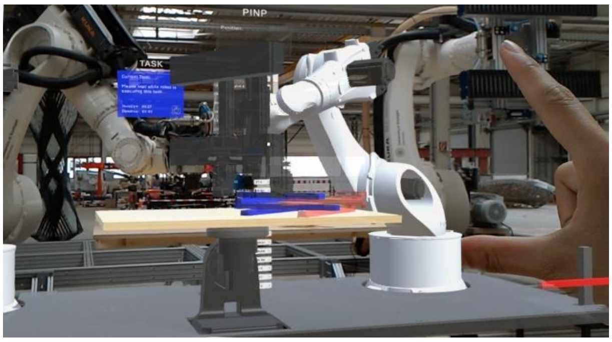

Figure 5. Hololens-Visualized forecast of the fabrication sequence and gesture-based instruction of the robotic fabrication platform

Digital twin (work object): The digital twin shows the virtual representation of the model. It shows where to place the timber slat for the robot to pick it and its final position, if the placing is executed manually. Color coding is used to show, if the task was executed by the robot (blue) or the craftsman (red). It also contains the information if a screw or nail was used, a crucial factor for disassembly and recycling. The successful use of this information relies on a precise localization in the work environment, to provide accurately projected information in-situ to the craftsmen. Therefore, accuracy required by the task must match the accuracy of augmentation from the AR device. This is an important consideration when selecting which fabrication steps will benefit from this approach.

Digital twin (robot): The digital twin builds the virtual representation of the High LoA system. It shows the execution of a specific task. It also keeps the craftsman informed of the robot's next movement. For an operator unfamiliar with pre-programmed robot paths, this allows them to be better aware of fabrication contexts and easily intervene in case problems arise.

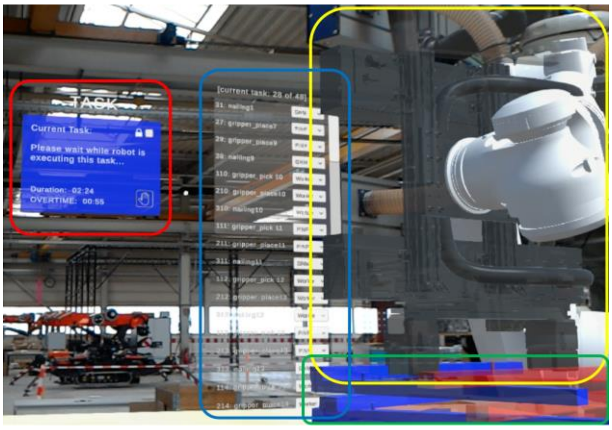

Figure 6. Visualization of the task window (red) and task list (blue) and the digital twins of the robots (yellow) and the work object (green)

3.2.2 Display and control of Tasks

Starting with a digital design model, the fabrication process is broken down into the different tasks, which are then assigned to each unit according to its tools and a generic task assignment logic (in this case a ping-pong scenario). The CAD design information is deconstructed into general fabrication data, which can then be tailored to each unit to facilitate robotic and manual tasks.

Task window: The Task window provides information on the fabrication process. The "Current Task" shows which task is currently executed or if the system is paused for the craftsman to execute. A clock shows the runtime of the current job. This timer is especially useful for time sensitive operations e.g. gluing to prevent the exceedance of its pot life. Additional messages can be sent to inform about successful fabrication steps, or issues, which must be corrected.

Task list: The Task list gives the human control over the upcoming task and their executing unit. By default, this task will be executed as defined in the script. Whenever the human decides to take over a specific task, they can interfere and change the fabrication sequence and assign a specific task to themselves. The script will be updated, and the workflow continues seamlessly.

4 Case Study

The case study chosen for this research is based on a pervious project which was produced with the TIM-Platform [4]. The building system was represented by a trade show stand which consists of a geometrically complex, but simple arrangement of 36 Clusters of prefabricated 22-50 timber (in total 1860) slats (Fig. 7).

Figure 7. Trade show stand surrounding the robotic fabrication platform which fabricated it

4.1 Specific task description

The requests were defined as followed:

- **Execution**
  - Pic and place of timber slats
  - Timber slat fixation.
- **Physics**
  - Positioning accuracy: <+- 5.0mm
  - Weight handle (< 1kg + End effector)
  - Workspace (~ 2700 x 2000 x 1000 mm)
- **Speed**
  - Not specified

This collaborative process exposed two potential sources of failures:

1. The wooden nails cannot penetrate the timber if the nailing spot is at a knot hole, resulting loose connections.
2. Several programmed positions cause singularities between pic and place of a slat, requesting a stop and potential reprogramming of the toolpath.

4.2 Specific setup description

In this case study, four fabrication units share the workload of the fabrication: The robotic fabrication platform TIM is a 14-Axis fabrication setup, which consist of 2 KUKA KR-500 industrial robots and a tilt-turn table [4].

The industrial robots used in this case study have a reach of 2830 mm (+ End effector), payload (500 kg – End effector) and a position accuracy (pose repeatability of +- 0.08 mm. There are 3 end effectors each (PINP: mechanical gripper, pneumatic gripper, 3D-Camera and GNM: Nail gun, spindle and Glue gun) to define their skill set. In this case study the PINP robot uses the mechanical gripper to pick and place the slat and hold it in place, while the GNM robot uses the nail gun to fix it in place. The tilt-turn table extends the reach of the individual robots via repositioning of the work pieces (Fig. 8).

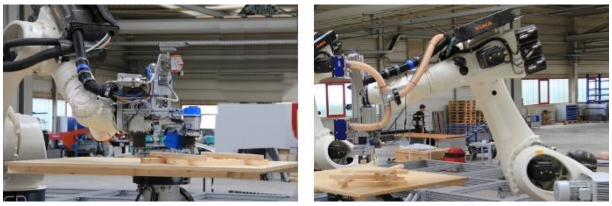

Figure 8. Pick and Place procedure executed by an industrial robot and slat fixation by nailing

The human craftsman skillset is partially defined by the labor law of the individual country. For example, the load a human is allowed to carry. Other skills depend on the individual physical (i.e. reach) and training (usage of tools) and additional tools available. The weight of the individual pieces with 1 kg is within these constraints and every spot of the prefab clusters is in reach. The positioning accuracy is ensured through an Augmented Reality head-mounted display. The craftsman is equipped with a Hololens, enabling a manual positioning accuracy within the requested +- 5 mm. An electric screwdriver is used, to fix the slats with 4 x 60 mm screw, while the craftsman holds the slat in place (Fig. 9).

Figure 9. Same tasks executed with a different skill set by a Hololens-equipped human (slat fixation by screwing)

4.3 Evaluation of the fabrication sequence

The interface and communication strategy developed in this research successfully transfers the supervision and direct control of a heavy-payload 14-Axis fabrication setup to the human co-worker. The coordination works fully Hand gesture-based and requires no understanding in robot coding. Additional information like digital twins of the model augment the human skill set.

As a result, in this particular scenario, every task can be executed by one human, or the industrial robots collaboratively. The human can take over every part of the fabrication sequence and replace each industrial robot. The combination of the different skill sets for the same task provides an opportunity for changing fabrication strategy on the fly. Toolpaths which would result in singularities can be avoided, nails which failed to join the slats can be replaced with screws.

5 Discussion and Outlook

With instructive Human Robot Collaboration, the developed setup introduced a first step into a new level of HRC. It is currently restricted to the coordination of whole linear task sequences which means only one task happens in one point of time. Next steps aim for in depth control within the sequence for higher adaptivity. This will allow the human to pause a running sequence, intervene in the process (e.g. update target position, correct errors), and then continue fabrication. Such granular control will require further software development. The development of a generalizable ontology will be necessary to enable skill set descriptions of more complex fabrication setups and of humans for the coordination of several human and robotic units for fabrication sequences with higher complexity.

The developed interface can be applied to tasks requiring hybrid human and robotic labour to execute, though it has certain limitations at the current stage. First, the interface needs user studies with untrained labour for validation and improvement. Second, the holograms have limited positional accuracy, for which combined outside-in tracking can be useful. Third, interface cues rely on programmed triggers, and object recognition can be integrated in the future to render it context-aware.

The AR-device Hololens 1 is suitable for applications in the controlled research environment, but still shows limits to be operational in the environment of construction halls and sites due to its heavy weight and the presence of view blocking holographic projections. Alternative strategies for human augmentation (e.g, or haptic devices) can be used for a partial implementation until further developments.

6 Acknowledgements

The research has been partially supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany‘s Excellence Strategy - EXC 2120/1 - 390831618.

The presented research was partially developed within the master’s program “Integrative Technologies and Architectural Design Research” (ITECH) at the University of Stuttgart.

References

[1] Orlowski K. Automated manufacturing for timber-based panelised wall systems. *Automation in Construction*, 109(2020):1–12, 2019.

[2] HOMAG. The first WEINMANN smartPrefab at WeberHaus. Online: https://www.homag.com/en/news-events/news/article/the-first-weinmann-smartprefab-at-weberhaus, Accessed: 20/07/2021.

[3] Randek. Zerolabor Robotic Systems. Online: https://www.randek.com/en/wall-floor-and-roof-production-lines/zerolabor, Accessed: 20/07/2021.

[4] H. J. Wagner, M. Alvarez, O. Kyjanek, Z. Bhiri, M. Buck, and A. Menges, “Flexible and transportable robotic timber construction platform – TIM,” *Automation in Construction*, vol. 120, p. 103400, Dec. 2020

[5] Katerra. Transforming construction through innovation of process and technology. Online: https://katerra.com/, Accessed: 20/07/2021.

[6] Bertram N. and Fuchs S. Modular construction: From projects to products https://www.mckinsey.com/businessfunctions/operations/our-insights/modular-construction-from-projects-to-products#, Accessed: 20/07/2021.

[7] H. J. Wagner, M. Alvarez, A. Groenewolt, and A. Menges, “Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and co-design of the BUGA Wood

Pavilion," *Construction Robotics*, 2020

[8] Putzier K. and Brown E. How a SoftBank-Backed Construction Startup Burned Through $3 Billion. Online. How a SoftBank-Backed Construction Startup Burned Through $3 Billion – WSJ, Accessed: 20/07/2021.

[9] Sutherland I.E. A head-mounted three dimensional display. *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I,* 757-764, 1968.

[10] Thomas, P. C., and W. M. David. Augmented reality: An application of heads-up display technology to manual manufacturing processes. *Hawaii international conference on system sciences*. 1992.

[11] Unity Reflect, https://unity.com/products/unity-reflect#unity-reflect-products--2, Accessed: 20/07/2021.

[12] Webster, A., Feiner, S., MacIntyre, B., Massie, W., & Krueger, T. (1996, June). Augmented reality in architectural construction, inspection and renovation. In *Proc. ASCE Third Congress on Computing in Civil Engineering* (Vol. 1, p. 996).

[13] Bock, T., Meden, H., & Ashida, S. Embedded System and Augmented Reality in Facility Management. *Advances in Building Technology:* (ABT 2002), 351.

[14] Mitterberger, D., Dörfler, K., Sandy, T., Salveridou, F., Hutter, M., Gramazio, F., & Kohler, M. (2020). Augmented bricklaying. *Construction Robotics, 4(3),* 151-161.

[15] Newnham, C., van den Berg, N., & Beanland, M. (2018). Making in mixed reality. In Proceedings of ACADIA (pp. 88-97).

[16] Chu, C. H., Liao, C. J., & Lin, S. C. (2020). Comparing augmented reality-assisted assembly functions—a case study on dougong structure. *Applied Sciences*, 10(10), 3383.

[17] Lharchi, A., Ramsgaard Thomsen, M., & Tamke, M. (2020). Connected Augmented Assembly-Cloud based Augmented Reality applications in architecture.

[18] Larsson, M., Yoshida, H., & Igarashi, T. (2019, June). Human-in-the-loop fabrication of 3D surfaces with natural tree branches. In *Proceedings of the ACM Symposium on Computational Fabrication* (pp. 1-12).

[19] Webel, S., Bockholt, U., Engelke, T., Gavish, N., Olbrich, M., & Preusche, C. (2013). An augmented reality training platform for assembly and maintenance skills. *Robotics and autonomous systems*, 61(4), 398-403.

[20] https://www.shapertools.com/en-gb/ Accessed: 20/07/2021.

[21] Shi, J., Jimmerson, G., Pearson, T., & Menassa, R. (2012, March). Levels of human and robot collaboration for automotive manufacturing. In *Proceedings of the Workshop on Performance Metrics for Intelligent Systems* (pp. 95-100).

[22] Wang, L., Liu, S., Liu, H., & Wang, X. V. (2020). Overview of human-robot collaboration in manufacturing. *In 5th International Conference on the Industry 4.0 Model for Advanced Manufacturing, AMP 2020; Belgrade; Serbia; 1 June 2020 through 4 June 2020* (pp. 15-58). Springer.

[23] International Federation of Robotics. Demystifying Collaborative Industrial Robots. https://web.archive.org/web/20190823143255/https://ifr.org/downloads/papers/IFR_Demystifying_Collaborative_Robots.pdf. Accessed: 20/07/2021.

[24] Bdiwi, M. (2014). Integrated sensors system for human safety during cooperating with industrial robots for handing-over and assembling tasks. *Procedia CIRP*, 23, 65-70.

[25] Graser, K., Baur, M., Apolinarska, A. A., Dörfler, K., Hack, N., Jipa, A., ... & Kohler, M. (2020). DFAB HOUSE: A Comprehensive Demonstrator of Digital Fabrication in Architecture. *Fabricate 2020: Making Resilient Architecture*, 130-139.

[26] Parascho, S., Gandia, A., Mirjan, A., Gramazio, F., & Kohler, M. (2017). Cooperative fabrication of spatial metal structures. *Fabricate 2017*, 24-29.

[27] Amtsberg, F., Raspall, F., & Trummer, A. (2015). Digital-material feedback in architectural design.

[28] Mueller, S., Seufert, A., Peng, H., Kovacs, R., Reuss, K., Guimbretière, F., & Baudisch, P. (2019, March). Formfab: Continuous interactive fabrication. *In Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (pp. 315-323).

[29] Stumm, S., Devadass, P., & Brell-Cokcan, S. (2018). Haptic programming in construction. *Construction Robotics*, 2(1-4), 3-13.

[30] Johns, R. L., Anderson, J., & Kilian, A. (2019, September). Robo-Stim: modes of human robot collaboration for design exploration. *In Design Modelling Symposium Berlin* (pp. 671-684). Springer, Cham.

[31] Kyjanek, O., Al Bahar, B., Vasey, L., Wannemacher, B., & Menges, A. (2019). Implementation of an augmented reality ar workflow for human robot collaboration in timber prefabrication. *In Proceedings of the 36th International Symposium on Automation and Robotics in Construction* (Vol. 36).

[32] (https://github.com/linuxsand/py_openshowvar) Accessed: 20/07/2021.

[33] https://roslibpy.readthedocs.io/en/latest/ Accessed: 20/07/2021.