Usability Evaluation of an Augmented Reality System for Collaborative Fabrication between Multiple Humans and Industrial Robots

Xiliu Yang*
xiliu.yang@icd.uni-stuttgart.de
Institute for Computational Design and Construction, University of Stuttgart
Stuttgart, Germany

Aimée Sousa Calepso*
aimee.sousacalepso@visus.uni-stuttgart.de
Visualization Research Center, University of Stuttgart
Stuttgart, Germany

Felix Amtsberg
felix.amtsberg@icd.uni-stuttgart.de
Institute for Computational Design and Construction, University of Stuttgart
Stuttgart, Germany

Achim Menges
achim.menges@icd.uni-stuttgart.de
Institute for Computational Design and Construction, University of Stuttgart
Stuttgart, Germany

Michael Sedlmair
michael.sedlmair@visus.uni-stuttgart.de
Visualization Research Center, University of Stuttgart
Stuttgart, Germany

Figure 1: Photos taken during the workshop: (a) overall setup, (b) two users collaborating during manual task execution and (c) the assembled timber structure.

ABSTRACT

Semi-automated timber fabrication tasks demand the expertise and dexterity of human workers in addition to the use of automated robotic systems. In this paper, we introduce a human-robot collaborative system based on Augmented Reality (AR). To assess our approach, we conducted an exploratory user study on a head-mounted display (HMD) interface for task sharing between humans and an industrial robotic platform (N=16). Instead of screen-based interfaces, HMDs allowed users to receive information in-situ, regardless of their location in the workspace and the need to use their hands to handle tools or carry out tasks. We analyzed the resulting open-ended, qualitative user feedback as well as the quantitative user experience data. From the results, we derived challenges to tackle in future implementations and questions that need to be investigated to improve AR-based HRI in fabrication scenarios. The results also suggest that some aspects of human-robot interaction, like communication and trust, are more prominent when implementing a non-dyadic scenario and dealing with larger robots. The study is intended as a prequel to future work into AR-based collaboration between multiple humans and industrial robots.

CCS CONCEPTS

• **Human-centered computing** → **Mixed / augmented reality**; **Empirical studies in HCI**; **Usability testing**.

KEYWORDS

augmented reality, human-robot interaction, user experience, robotic fabrication

ACM Reference Format:
Xiliu Yang, Aimée Sousa Calepso, Felix Amtsberg, Achim Menges, and Michael Sedlmair. 2023. Usability Evaluation of an Augmented Reality System for Collaborative Fabrication between Multiple Humans and Industrial Robots. In *The 2023 ACM Symposium on Spatial User Interaction (SUI '23), October 13–15, 2023, Sydney, NSW, Australia.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3607822.3614528

*Both authors contributed equally to this research.

SUI '23, October 13–15, 2023, Sydney, NSW, Australia

ACM ISBN 979-8-4007-0281-5/23/10…$15.00
https://doi.org/10.1145/3607822.3614528

1 INTRODUCTION

Human-Robot Interaction (HRI) is a vast area that has been studied since robots were deployed in partnership with humans to carry out tasks. Augmented Reality (AR) emerged as a promising method to support such collaborations because it facilitates situated placement of information according to world referents [12]. In the context of the collaborative execution of physical tasks, AR provides an intuitive way for users to access in-situ information about the workpiece, robotic system, and the overall process. Compared to traditional display methods, AR Head-Mounted Displays (HMDs) provide additional advantages by allowing hands-free access and interaction with digital content. This is particularly relevant for fabrication tasks that require humans to remain mobile and where their hands are often occupied with tools [5]. Since AR devices have become faster, more portable, and of higher resolution, their use is increasingly feasible in real-world applications.

The use of AR for fabrication and construction tasks has grown over time, with significant advances in the areas of 3D instruction, data sharing, and human-computer interaction [27]. While many lab studies have shown ideas for enhanced safety, instruction guidance, and task performance, there is limited literature on the use of these systems in the wild [20, 29]. Real-world conditions involve diverse and non-expert users, unpredictable interruptions, and handling of costly physical equipment, which present barriers for studies to evaluate user experience. These issues limit the understanding of important pathways of interaction and, by extension, the usability of AR systems in these full-scale contexts.

Among existing works that highlight the potential of using AR in HRI, few have explored non-dyadic scenarios, that is, collaborations that go beyond one-to-one settings[24]. In fabrication and construction tasks, the participation of multiple humans is often a necessity because tasks involving large pieces or heavy materials require several people to work together in a synchronized or organized manner. Timber prefabrication also involves highly variant pieces, which means that workers need to adapt to new tasks by referring to the necessary information and communicating with their teammates. Given these factors, an effective HRI setup for these scenarios must account for the presence of multiple actors. Though non-dyadic human-robot teaming enables each member to participate with more flexibility and the team as a whole to achieve a greater diversity of tasks, new challenges also arise. How do users collaborate and synchronize their tasks with each other? What are the needs of the different users depending on the roles they take? How should the communication setup adapt to the diverse needs of the team and scale with the job requirement? Architecture and construction applications also require the use of heavy-payload robots to manipulate large building components, which are seldom used in lab-scale studies.

Toward exploring these research gaps, this paper presents an exploratory user study, where multiple participants with varying experience levels carried out fabrication tasks in collaboration with an industrial robot in a non-dyadic setting. The setup of the study is illustrated in Figure 1. Groups of four users wearing Microsoft HoloLens 2[1] devices work together with a KR420 KUKA robotic arm mounted on a linear axis. The system is based on a previously proposed setup [31] that leverages AR technology for collaborative timber prefabrication. The goal of our work is to better understand the usability of AR systems in fabrication setups where multiple humans interact with industrial robots. We also aim to shed new light on challenges regarding the use of AR interfaces for non-dyadic collaboration in the wild, and potential next steps to address them.

[1] https://www.microsoft.com/en-us/hololens

2 BACKGROUND AND RELATED WORK

We review related work on how AR has been used for human-robot interaction and in collaborative tasks, previous work on studies that attempted to study AR "in the wild", as well as background on our application domain, that is, how AR has been used in timber construction so far.

2.1 AR in Human-Robot Interaction

Much work has explored the interaction of humans and robots using AR, e.g., teleoperation cues [3, 6, 22], assembly instructions [10, 30], safety [8, 11, 14], and path planning [23]. Several surveys summarize these publications, for instance, Suzuki et al. proposed a taxonomy of AR interfaces for HRI [29]. The authors gave an extensive overview of existing literature and provided a taxonomy regarding the augmentation strategies, application domains, interaction modalities, and types of information conveyed in AR. Makhataeva and Varol [19] also reviewed recent developments in this area, distinguishing between augmented reality, mixed reality, and virtual reality for applications in robotic interaction and control. Both surveys highlight the important need for more research that moves studies from simulations and laboratory environments out into the real world. Our aim is to contribute to this identified need.

One example of such a study was conducted by Lafreniere et al., who investigated multi-user collaboration with UR10 robots through the concept of "crowdsourced fabrication" [17]. During a three-day period, over one hundred volunteers fabricated a 12' tall bamboo pavilion together with cobots. The AR system was based on smartwatches and indoor location sensing and garnered largely positive user feedback. However, the authors also noted the difficulty of interacting with the smart watch while both hands of the user were occupied. This points towards the need for hands-free visual guidance systems, such as HMDs, especially for fabrication use cases.

2.2 AR collaborative system

When it comes to collaborative scenarios, AR has been used, for example, to facilitate instruction sharing or virtually co-located collaboration between multiple users. Lukosch et al. [18] provide many examples of how AR has been used in these cases. Among the main benefits, we can cite improvements in the effectiveness of assembly tasks, as well as performance and lowering mental effort across different studies. However, challenges that are specific to the requirements of different use cases remain and thus demand a more targeted approach. For instance, investigating what type of interaction is more effective (hand vs. physical prop), or the influence of wearing headsets on the collaborative dynamics of people working together since the device blocks the gaze from the user. Also, studies of AR collaboration among larger groups and studies on AR-based collaboration "in the wild" (i.e., in more realistic work scenarios) are still scarce [20].

The Computer-supported cooperative work (CSCW) community has a long history of addressing these challenges and widely explored human-machine partnerships under different work conditions. Most of this work, however, does not focus on the role of AR. One general guideline that can be considered when developing multi-artifact interactions is the 4C framework (Communality, Collaboration, Continuity, and Complementarity) proposed by Sørensen et al. [28]. The authors explore what principles of interaction work well for certain scenarios, and how different types of interactions emerge from joint orchestration by multiple users. In the HRI context, a survey by Schneiders et al. [24] reviews HRI publications on non-dyadic scenarios, and points out, for example, that existing workplaces have a strong focus on simultaneous tasks over sequential ones shared between different actors. The survey uses the 4C framework to classify the papers and guide future researchers toward open questions. Although the framework was intended for digital ecosystems in general, the use of multiple AR devices in HRI can benefit from implementing such design recommendations.

2.3 Usability of AR systems in the wild

The use of AR in applied, real-world cases often addresses ways to enhance the efficiency and quality of processes by supporting the human with interactive and situated information. Chan et al. [9] explored the use of AR to simulate tasks for manufacturing industrial carbon-fiber-reinforced polymer, comparing the AR interface with a joystick controller. The study explored the interaction between multiple humans and larger-scale industrial robots. Among the findings, the results show that users found the AR interface easier, more intuitive, and faster to use. The completion time of the tasks was also significantly lower with the AR interface. However, the authors mention that the nature and complexity of the task likely has a big impact on user experience, which requires further study. They also mention that even though the study was done using an industrial robot, its scale still does not match the actual scale of the ones used in industry.

Mitterberger et al. [21] implemented a collaborative projection-based AR system for the design and fabrication of on-site robotic plastering. The system enabled users with limited robotic programming experience to manipulate complex designs for robotic fabrication using a hand-held motion controller. After several days of fabrication, users reported an overall positive experience. Despite a few studies which combine physical fabrication with user evaluation, in-the-wild experiments which also take into account user experience over a diverse group are scarce in the literature. We contribute to this body of work by studying a non-dyadic setup with large-scale industrial robots.

2.4 AR in timber construction

The application of AR in timber construction has been investigated by many researchers in the architecture and engineering community. Settimi et al. [25] explored how smart retrofitted hand tools can be combined with context-aware AR to facilitate complex drilling operations for augmented carpentry. The design and fabrication process can be opened up to improvisational human input by allowing live decisions to be registered into the digital system through an AR system with object tracking [4]. Head-mounted AR displays have also been used for human-in-the-loop robotic timber assembly, allowing the person to visualize and activate a collaborative robot to assemble a small timber structure [16]. Also, some initial applications are currently being tested in industrial setups e.g. Schaerholz AG developed with their partners a HoloLens application for AR-supported timber wall assembly [1].

Our work builds upon previous studies that used AR to support individual workers in timber prefabrication use cases, where some common tasks, such as picking and placing of elements, gluing, nailing, and general coordination with the robot, were explored (Fig. 2). Equipped with AR to visualize fabrication tasks, a worker was integrated into the process of fabricating a multi-storey timber pavilion, which extended the capacity of a high-level system automation by carrying out tasks the robotic system was not equipped to do [26]. Predefined task sequences were made more flexible using a reassignment mechanism accessible via AR. This allows a worker, who is untrained in robotic control, to take over tasks from the robot when unexpected situations occur [2]. These past studies paved the way to consider large-scale human-robot collaboration in prefabrication environments and facilitated the development and testing of a computational tool to integrate AR with robotic fabrication systems [31]. So far, no user-centered evaluations have been conducted in this environment, though.

3 METHODS

We first describe how we implemented the AR setup for the study, including the design of the AR interfaces and interactions, before we outline the methodological details of the study setup.

3.1 AR System Implementation

The AR system is implemented using Unity[2] on a Microsoft HoloLens 2 with a ROS-based backend and was built on top of a recent iteration of the VIZOR framework [31]. The AR information presented to the users during fabrication is generated using a plugin in the 3D modeling environment Rhinoceros and Grasshopper, which allows AR instructions to be authored within the same digital environment where the design model and robotic simulations are generated. This allows for the co-design of human and robotic tasks during the planning and design process by allowing rapid testing and iteration of the AR content.

The User Interface (UI) was updated from a previous HoloLens 1 implementation to HoloLens 2 and allows both near and far interaction with elements. The UI panels have two parts: (1) a *task list*, which presents a list of upcoming and completed tasks so that the user is aware of the fabrication process, and (2) a *task instruction*, which presents text-based fabrication instructions to the worker based on their roles (Fig. 3). In addition to the UI elements, task instructions are also complemented by projected 3D geometries in the workspace to indicate locations and guide the work steps where needed. Fig. 4 shows this UI together with the 3D geometries related to the work tasks used in the study.

[2]https://unity.com/

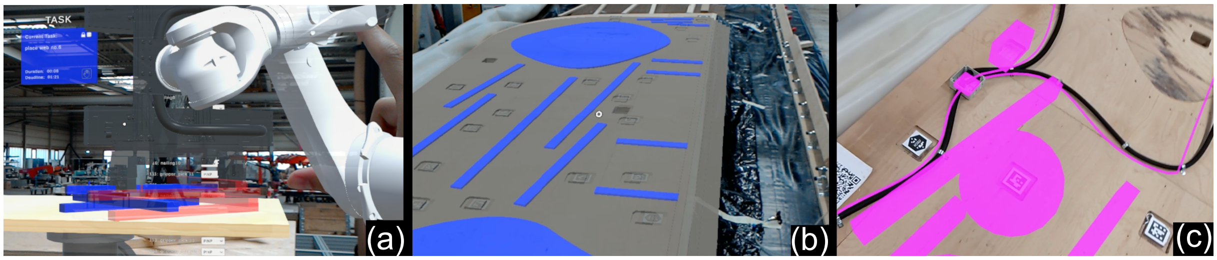

Figure 2: Three previous prototypes used for pilot testing with experienced users. (a) pick and place tasks, (b) highlight of primer application on surface and (c) visualization of path for conduit placement.

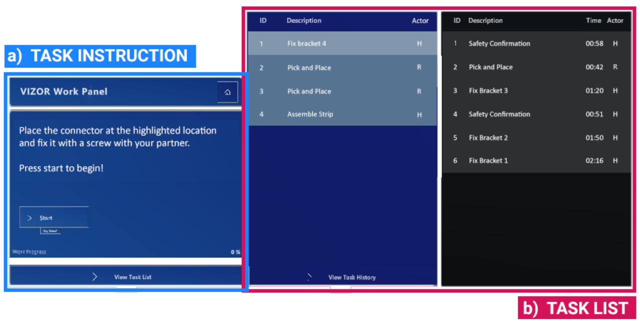

Figure 3: The task instruction UI is highlighted in blue (a) and the task list in red (b).

3.1.1 Task Instruction. The task instruction informs the user how and where a task should be carried out. It is presented through a UI panel and additional geometries in the AR environment to guide the task execution. The panel consists of a text description, and a button to allow users to accept and acknowledge the completion of the task as shown in Fig. 3(a). When a manual task starts, the instruction panel pops in front of the user and shows a brief text description. When the user accepts the task, a 3D model is shown in the AR space. For example, if the user needs to place an element, a colored mesh of the element appears at the correct location. When the task is completed, the user presses the button again to acknowledge. The positioning of 3D elements in AR space is provided through a marker placed on the robotic platform so that human and robotic tasks are displayed in the same coordinate system. The 3D element visualizations resemble similar designs in previous AR studies as in Fig. 2.

3.1.2 Task List. The task list informs the user of their progress in the fabrication sequence. In the case where one user takes over the shift from a previous one, this helps them understand the current state of the process and future tasks to come. The task list information is broadcast at the start of a task sequence and subsequently updated at each execution step. The visualization of the task list is illustrated in Fig. 3(b). The left panel indicates the upcoming tasks, where the task ID, title, and the intended executing actor (human or robot) for the next ten tasks are shown in a scroll frame. The right panel displays the task history, showing a summary of completed tasks with their titles, the actor who carried out the task, and the duration of execution.

3.1.3 AR Interaction. When a user is required to execute a task, the task instruction UI appears in front of the user with an audio cue to indicate the arrival of new tasks. As the user moves around the work area, they can recall this interface with a hand gesture. For the purpose of the study, the design of user interaction with the AR system was kept to the simplest, only allowing task acceptance and confirmation through the task instruction panel. During execution, the user can see geometries of the elements that are already fabricated but do not interact with these elements directly. Information about the robotic tasks was shown as a line item on the task list, but no simulation was included. Although in previous implementations, users were allowed to reassign execution actors or view robotic simulations via the task list [2], including these features would introduce additional factors that complicate a first understanding of user experience. The users also did not have to interact with robot actions directly because all motions were pre-planned and tested before the workshop for safety reasons.

3.2 Study setup

We organized our study in the form of a one-day workshop involving 16 participants. The main task for the participants was to fabricate a timber structure in groups of four people in collaboration with a KUKA KR420 industrial robot (max. reach 3.3m, max. payload 420kg) mounted on a linear rail (4.5m range). All users were equipped with a Microsoft HoloLens 2. The overall fabrication process coordination is based on a fabrication server that distributes a list of fabrication tasks to either the robotic platform or the AR system for human execution [26].

3.2.1 Preparation. To understand users' experience levels in technologies used in the experiment, we conducted a demographic survey prior to the workshop. Users were polled on their proficiency in timber fabrication tasks, robotic fabrication, and AR systems on a scale of 1 (no experience) to 5 (expert). To ensure all participants were capable of using the equipment, we offered training sessions for each required skill. These included basic instructions on how to operate a hand-held screwdriver and handle materials, as well as how to interact with holograms and UI elements on HoloLens 2. Participants were also briefed on the overall fabrication sequence and communication setup for the study, as well as a presentation

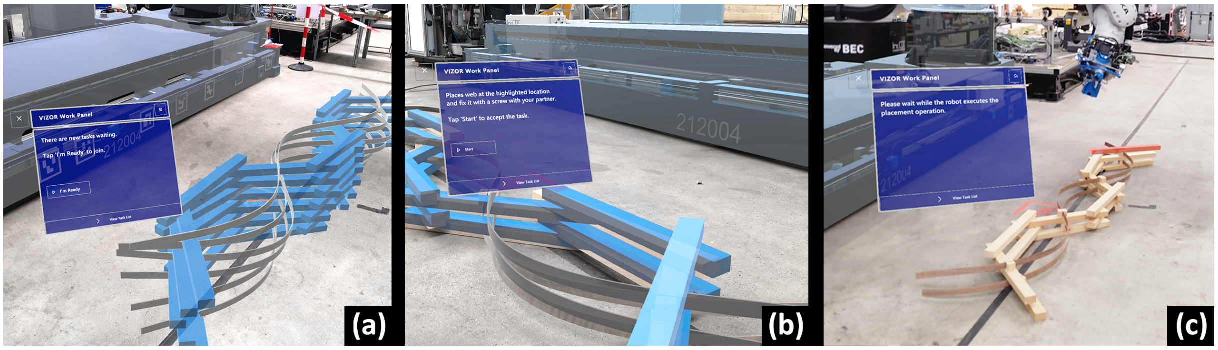

Figure 4: Three instruction interfaces shown to the user to provide task information. (a) initial prompt, (b) manual task execution prompt and (c) robotic task execution message.

Table 1: List of fabrication tasks, actors assigned, and the work areas for the fabrication of two layers (n, n+1) of the structure. Human tasks highlighted in grey were executed in parallel while the robot moved.

ID	Actor	Task	Work Area
1	Robot	pick, place, and nail slat A	All Areas
2	Robot	pick up slat B	Pick-up Area
	R1+R2	fix connector on slat A	Area 1
3	R1+R2+R3	safety confirmation	-
4	Robot	place and nail slat B	Area 1
5	Robot	pick up slat C	Pick-up Area
	R1+R2	fix connector on slat B	Area 1
6	R1+R2+R3	safety confirmation	-
7	Robot	place and nail slat C	Area 2
8	Robot	pick up slat D	Pick-up Area
	R1+R2	fix connector on slat C	Area 2
9	R1+R2+R3	safety confirmation	-
10	Robot	place and nail slat D	Area 2
11	R1+R2	fix connector on slat D	Area 2
	R3	fill storage	Pick-up Area
12	Robot	pick up slat A'	Pick-up Area
	R1+R2	fix and bend strip	Area 1 + 2
13	R1+R2+R3	safety confirmation	-
14	Robot	place and nail slat A'	Area 1
15	Robot	pick and place slat B', C'	All Areas

on the background of human-robot task sharing and its use in past timber fabrication projects.

3.2.2 Group assignment. After the preparation tasks, the 16 participants carried out the fabrication in four groups. Each group involved four humans and a robot mounted on a linear axis. When one group was finished, the next group continued building on top of the same structure. To distribute the number of experts within each group, we assigned participants manually to balance the skill levels and avoid too many experts and novices in the same group.

Two of the four users of a group were assigned primary manual fabrication roles (R1, R2). The third user acted as a supervisor of the fabrication process (R3), tasked with detecting issues during the

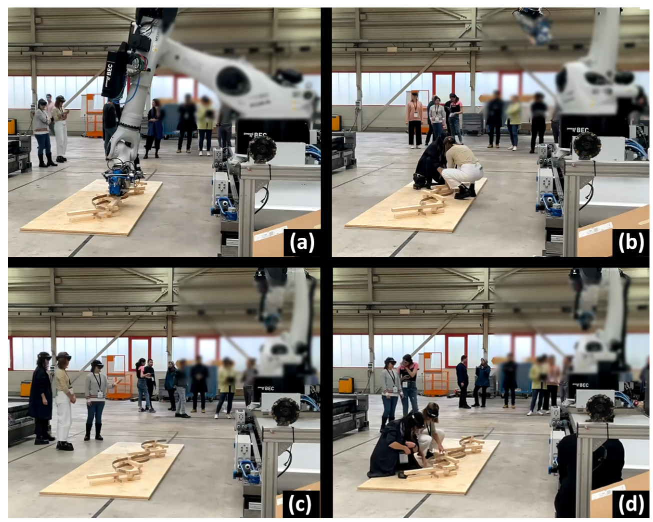

Figure 5: Photos during the study show the scale difference between humans and large industrial robots in the workspace. (a) robot placing slat A' and fixing it with nails (b) Human R1+R2 fix a connector on slat C (c) Human R1+R2+R3 safety confirmation (d) Human R1+R2 bend and fix strip.

process and refilling the storage when each layer is complete. Based on the demographic data, each group was assigned one expert user in robotic fabrication. This user is familiar with operating a large-scale robot for construction and fabrication tasks, and was tasked with operating the robot in the team (R4). The four roles (R1-4) are summarised below:

- R1 and R2: worker who carried out manual execution tasks;
- R3: supervisor who monitored process and safety conditions;
- R4: robot operator who held the KUKA pendant.

3.2.3 Task design. The tasks were designed based on a timber additive assembly process using different joining and element types. The structure is illustrated in Fig. 1(c) and spans 3m x 0.6m. It consisted of 14 layers built on top of each other and combined straight, linear timber elements (slats) and flexible, long, thin strips made of walnut wood. The slats were placed and nailed together

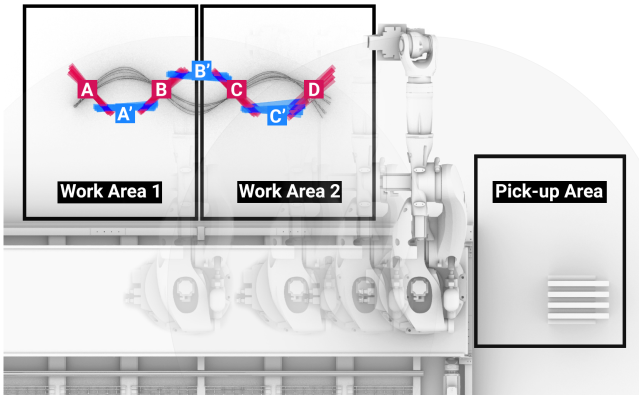

Figure 6: Illustration of the work areas around the robotic platform. Letters in red indicate slats on the even layers (A, B, C, D); and blue marks the odd layers (A', B', C'). On the even layers, human workers need to fix the connectors and insert the wood strip.

by the industrial robot equipped with a gripping and nailing end-effector. The strips were bent and fixed through custom connectors, which are screwed in place by humans. The human tasks require dexterity for inserting small screws and handling fragile thin wood strips which the robot cannot accomplish without a significantly more complex technical setup. The distribution of tasks is described in Table 1. The AR interface informed the users what task to execute and allowed them to signal task completion through a button when finished. When all participants involved in a task acknowledge completion, the system continues to dispatch the next one.

The workspace can be divided into three main areas (Fig. 6). The pick-up area is on the right side of the robotic platform where the timber slats are stored. The main work area is divided into two parts in front of the platform. When humans work in the assembly area, the robot can continue in the other. These tasks where humans worked in parallel with the robot are noted in Table 1. Since human and robot actors share these areas, the users need to perform a safety check before the robot moves into an area previously occupied by humans. This check was an additional task where users (R1,2,3) were shown a safety zone in AR, and a text prompt instructed users to move out of the dangerous area.

3.2.4 Feedback collection. Each group collaborated with the robotic platform in a 45-minute session. After each session, we collected questionnaire feedback including 1) a System Usability Study (SUS), 2) a questionnaire regarding the AR interface, and 3) open-ended questions regarding the interaction and fabrication experience. To conclude the workshop, we held a live discussion round involving all participants at the end of the day. Here, participants shared and discussed their experiences, thoughts, and insights.

4 RESULTS

In total, 16 participants completed the questionnaires, among which 13 participants were between 25-35 years old. Their previous technological experience was captured on a five-point Likert scale (1=no experience to 5=expert). All participants rated their existing experience with AR as moderate or low (M=1.8, SD=0.8). The experience levels with robotic fabrication (M=2.9, SD=1.4) and timber fabrication (M=3, SD=1.5) were more evenly distributed, with a handful of expert and novice users in both categories. Seven out of 16 people rated themselves as experienced (4 or 5) with robotic fabrication, and six rated themselves the same with timber fabrication.

Although the roles are pre-assigned (R1-4) according to the task design intent, during the workshop each person was free to talk to each other to exchange and try out other roles, which emulated the fluid exchanges in non-dyadic collaboration settings. At the end of the study, we asked the participants if they took part in the manual role, robotic control role, or both. For R1, R2, R3 there are no skill prerequisites beyond the training conducted in the preparation stage, so the users can switch freely. R4 required robotic operation experience, so only three respondents took both roles. Eleven participants took up manual roles only.

To ground our insights in the data from the users, we include direct verbal feedback of the participants as anonymous quotes in the presentation of the results below. The findings relate both to the overall usability of the AR system for HRI, as well as specific feedback on the task instruction and task list interface.

4.1 Usability feedback

The AR system received a mean score of 73.5 with a standard deviation of 12.2 from the SUS questionnaire. Correlation between the usability evaluation score and users' prior experience level in either of the three skill categories was low or negligible. Likewise, there was no correlation with which roles they took during the process. This indicates that the system was sufficiently easy to use regardless of background or activity. The result for each question is shown in Figure 7. All users agreed with the fact that "most people would learn to use this application very quickly". This matched our intention to keep the interface design and the interaction possibilities as simple as possible. The weakest criterion is whether they would "need the support of a technical person to be able to use this application". Because the process was very different from standard fabrication procedures and was controlled and supported by the research team throughout, we found it reasonable that users did not feel confident that the system can be used without the need for technical support.

4.2 Task Difficulty

We asked the users to rate the difficulty of tasks they performed from 1 (low) to 5 (high). The mean score is 1.4 with a standard deviation of 0.6. Regardless of the roles they carried out, the task difficulty was rated as "fairly low" (between 1-2). This fell within the expectation because the process was designed to be carried out by users of mixed-skill backgrounds. One user who gave the task difficulty the highest rating (3) also reported the lowest SUS score (50). This user carried out manual tasks only and was a novice in all three skill categories. There was unfortunately nothing notable in the written feedback to help us understand the issues he/she encountered.

4.3 Task Instruction Interface

The questions regarding the AR interface are listed in Fig. 8. The users were asked to rate the task instruction interface in terms of helpfulness and clarity. Seven participants gave a top score (5) for helpfulness and six gave a top score (5) for clarity. The mean score on the clarity criteria is 4.0 (SD=0.8) and helpfulness is 3.5 (SD=1.2). The lowest rating came from one participant who considered the task instruction "confusing" (1) and also found it "fairly unnecessary" (2). This was the only user who carried out robotic control tasks only, and was therefore exposed to only the message "Please wait while the robot executes the placement operation". This clearly points to the need to improve the design of the task interface for users who carry out robot control and monitoring roles.

4.3.1 I wish the Task Instruction was more ... Here, many participants gave feedback on having *"more visuals"*. Some mentioned that the instructions should take full advantage of the 3D interactive aspect of AR and display the instructions in more engaging ways. One participant also commented that the task instruction should be more *"precise"*. The precision of tracking is a known issue in augmented reality applications and was hinted at in several other responses. Another wrote they wished the instruction text itself was more *"descriptive"*. Since the textual description of how to execute a manual task can sometimes cause misunderstandings and be vague or time-consuming to read, a graphical representation of the task or animation of the process might be helpful.

4.4 Task List Interface

The participants generally rated the *task list* "helpful" (4). One participant gave it the lowest rating of 1 ("unnecessary"). This user was an expert in robotic fabrication *"I have been working alongside robots for 4+ years"*, but noted that the task list did not provide the information that they expected *"I would expect the Robot Controller to see trajectory, target, digital twins, etc."*. This brought in question our initial assumption of what was "strictly necessary" for the AR interface and echoed previous responses regarding the helpfulness of the current task instruction interface for users handling the robot control role. Overall the mean score for clarity is 4.1 (SD=0.9) and helpfulness is 3.9 (SD=1.2).

4.4.1 I wish the Task List was more ... A participant who exclusively carried out manual fabrication tasks commented that *"I did not check the task list, only direct instructions. It is interesting side info. I did not use it for fabrication"*. Most participants suggested the *task list* should be *"more 3D"*, *"interactive, colorful"*, or provide *"demo pictures"* or *"giving feedback or with graphics of what is happening"*. A few participants suggested that, although the task list aimed to present an overview of all the fabrication tasks, it should also show an overview of all current users participating in the process, given the multiple users involved.

4.5 HRI Experience with AR HMDs

During the study, the participants carried out tasks in the same environment as a heavy-payload robotic arm. The robot collaborated on the same workpiece and occasionally moved in parallel while humans executed tasks. Compared to smaller collaborative robots, industrial robots are loud when they move and appear imposing on humans by taking up large portions of the work area. This overall experience of using AR HMD for large scale human-robot collaboration was captured in the responses to two additional, open-ended questions.

4.5.1 How did you feel working while using AR HMD?. While the majority of participants expressed favorable impressions toward the experience, a few participants pointed out that it was uncomfortable when the device was worn over extended periods of time. One participant commented: *"in the beginning OK but I got [a] headache after 45 minutes. Would lift the glasses every time I wasn't working with it or take it off"*. Among the positive comments, we had *"Amazing experience! Also see the extended potential for constructing aided applications"*. The comments of the participants who had more experience with immersive fabrication systems addressed some technical aspects, such as *"I like the ability to be able to project 3d information; overlay them with reality. But this is not fully exploited in the demo"*. Although HMD's provide a more immersive and mobile experience, one must consider the ergonomics of wearing these devices over long periods, and appropriate interface designs that exploit the immersive visualisation capabilities.

4.5.2 How did you feel about working alongside a robot? One participant with extensive robotic operation experience commented that *"I feel safe in general if I can see/predict where they are about to go."*. Some participants noted their caution working alongside a robot – *"I didn't feel entirely comfortable being within the robot's reach when it was moving"*, particularly *"Sometimes scary when drilling and robot moved in parallel"*. This combination of divided attention and parallel motion is a critical scenario to consider in designing large scale HRI experiences. Many also noted that this was something that more training would resolve – *seems dangerous in advance* and *"It feels a bit strange but slowly you are getting familiar to it"*. However, even though users who have prolonged exposure to these work environments may grow to feel more comfortable, the system must guarantee the safety of the workers.

4.6 Limitations

During fabrication, participants could freely interact with each other, and the fabrication process was paused intermittently to address questions. Participants could also interchangeably perform the tasks by switching roles, which extended the execution time. Therefore, an overall time log of the fabrication process was not examined in this study. This is a major limitation for application in manufacturing or production environments, where timely execution is key. However, we chose to give users this freedom and did not apply time pressure so they could explore and interact as they saw fit. For the purpose of an exploratory study, this led to a more relaxed environment where users felt free to share their thoughts and ask questions.

Regarding hardware limitations, the Hololens 2 has a limited battery life, in addition to a built-in safety feature that turns itself off automatically when the device reaches a certain temperature. During the session, we experienced it happening with one device and quickly switched it to a backup device that was available. This meant a small interruption, which could be improved if a preemptive warning was issued and alerted a device change.

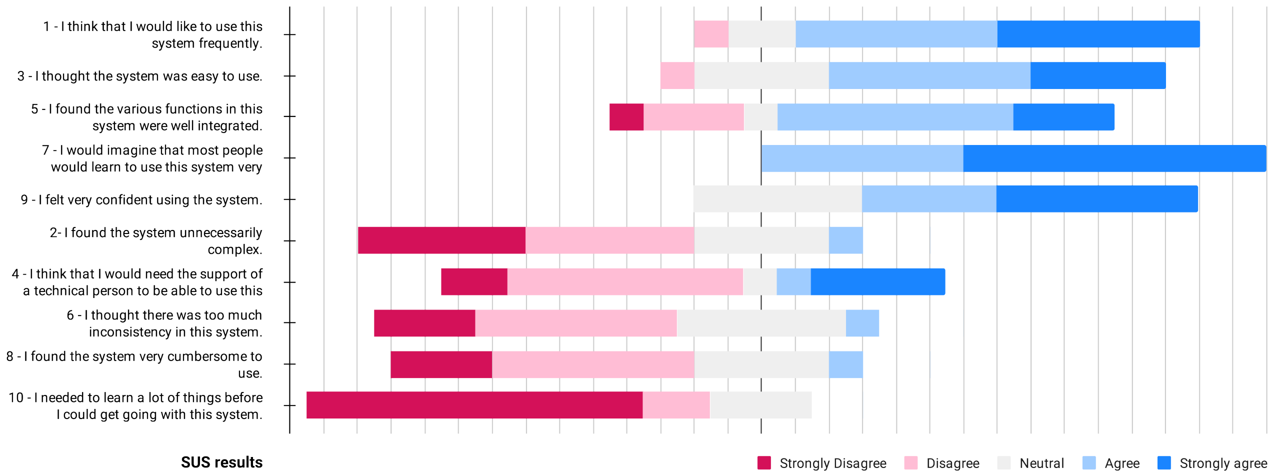

Figure 7: Results of the SUS questionnaire for the general system usability [7]. Positive questions are displayed in the upper part of the graph.

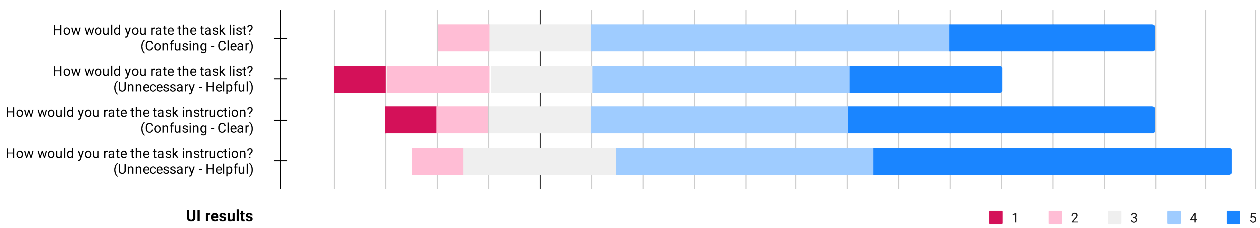

Figure 8: Results of the AR-UI evaluation. The numbers 1 to 5 represent the Likert Scale, and each question is described individually on the left.

The exploratory study focused on qualitative feedback and did not collect quantitative data on comfort levels or trust. Despite interesting insights on the overall user experience, quantitative methods would be necessary for further understanding, for instance, when considering the learning effects as users grow more accustomed to these settings, or understanding how unpredictable factors within in-the-wild environments may induce changes in user comfort levels.

Safety is a critical issue when it comes to putting humans in close proximity to robots. We ensured the safety of the study by 1) running the robot in T1 (manual mode with reduced speed, designed for the close proximity of humans and robots needed during testing) 2) simulating and testing all robotic motions prior and allowing no run-time changes to the sequence 3) having multiple supervisors from the organizing team that constantly monitored the situation. However, running robots at low speed conflicts the productivity benefits of using robots for fabrication in the first place. The only way to tackle this issue would be to adopt more robust and flexible safety systems that allow these studies to match production conditions. In production settings, safety is often guaranteed through control-based mechanisms such as speed and separation monitoring using light curtains or laser sensors. More experimental methods based on online motion planning or monitoring human presence and physiological states have been explored in research studies[13]. Although such flexible methods are not yet prevalent in real-life scenarios, they will be important components for the adoption of collaborative procedures demonstrated in this study.

5 CONCLUSION AND FUTURE WORK

This paper presents an exploratory user study for multi-human-robot collaboration through AR, conducted in the form of a workshop involving participants with varied skill levels ranging from expert to complete novice. The study aimed to establish a basic evaluation of head-mounted AR systems for multi-actor fabrication, enhance our understanding of the interaction between multiple humans and industrial robots in the wild, and outline open questions to be addressed in future work.

The workshop provided an opportunity to test the system's technical limitations (e.g., four AR participants simultaneously interacted with the system, the stability of the HoloLens tracking and connection functioned over a 3-hour period without manual intervention). Issues such as latency of the visualized information and precision of the holographic content can be improved in future implementations.

5.1 Key Insights

Based on the users' feedback from written questionnaires and in the discussion session at the end of the workshop, some key topics were noted as important questions to address for future work in HRI with industrial robots involving multiple participants. These are summarized below.

5.1.1 Issues of trust with large-scale robots. Trust is a well-known issue in HRI research, and with larger-scale robots, this effect is more pronounced. Many participants noted that they felt scared when the robot moved while they were executing a task in parallel, despite the robot moving at low speed and the participants knowing there is constant supervision. This was reported by five participants in the written response, and some mentioned that not knowing what the robot was about to do made them anxious. Some pointed out that if they had the means to predict the movements of the robot at the right moment, they would feel more comfortable sharing the same space. One could imagine that, with the correct information visualized over the robots, users' trust in the robot can be enhanced. During the discussions, we also observed multiple dimensions of trust at play in this scenario. Some relate directly to the physical motion of the robot, while others relate more to the technical system or the programmers behind the scenes. The full complexity of this issue needs to be examined in detail in future studies.

5.1.2 Exploiting 3D visual information in task interfaces. Given the capabilities of the HoloLens 2, the richness of the visualization in the current prototype is lacking. The ambiguity of textual descriptions sometimes incurs longer execution times and causes confusion. This points to the need to deploy more visual forms of task instruction using media such as arrows, images, and animations. However, the trade-off is that this might lead to a more complex content creation process and longer programming time during the design phase. In addition, since the fabrication tasks are somewhat repetitive, a few participants found the interface distracting after several iterations. It points to the importance to consider adapting the instruction details and finding the correct moment to trigger such visualizations. For instance, eye tracking data could be used to help determine the user's attention and provide guidance as to when might be a good time to be reminded of necessary instructions.

5.1.3 Communication support in non-dyadic collaborations. We observed that since at least three people simultaneously interacted with the system to perform tasks, communication issues between humans were a major concern. For example, the AR interface enforces that all participating actors acknowledge finishing the previous task so that the following ones can continue. Occasionally users finish a task and forget to indicate completion, causing unnecessary waiting times and prompting the users to check with each other verbally before the team can move on. Since humans naturally communicate with each other to ensure synchronization and also fluidly exchange roles as needed, AR systems to support these collaborations must take into account such characteristics. This is an area where we plan to explore new mechanisms, such as visualizations of collaborating actors' statuses, to support multi-human collaboration.

5.1.4 HRI in the wild with large-scale robots. Real-world building fabrication and construction environments can be chaotic and require people to adapt and communicate to solve problems as they arise. Prefabrication sites that deal with one-off building elements, as opposed to controlled factory automation, require similar flexibility given the high heterogeneity of the elements. During the study, these conditions were emulated by participants communicating with each other, figuring out how to complete the tasks as they go, at the cost of occasional interruptions and distractions. These conditions pose challenges to understanding the interaction scope and measuring task performance. Despite an increasing body of work that studies the interaction of humans with robots in complex social contexts [15], studies that address human interaction with large industrial robots are scarce. The main reason lies in the current safety limitations around industrial robots. This is an issue we plan to tackle by developing more flexible and robust safety systems that could allow for AR integration in more realistic production scenarios.

To the best of our knowledge, this is one of the first studies that tested a head-mounted AR system with simultaneous participation from multiple humans and an industrial robot to collaborate in real-world conditions. The uncertainties that remain when using such novel technology in an interdisciplinary environment are many, but we hope that our findings provoke future developments, unravel new challenges, and provide additional ecological validity to hypotheses that were previously investigated in controlled, small-scale HRI settings.

ACKNOWLEDGMENTS

This research is supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC 2120/1 – 390831618. We thank Lior Skoury and Thomas Wortmann, who contributed the robotic control system used in the study. The authors would also like to thank all the participants at the AAEC workshop, as well as the student assistants Maxime Fouillat and Eric Bossecker for their support during the study, and Alexandra Pittiglio for assisting in the UI mockups. The authors further thank the International Max Planck Research School for Intelligent Systems (IMPRS-IS) for supporting Aimée Sousa Calepso.

REFERENCES

[1] afca. AG. 2020. *Elementbau mit Hololens 2.* Retrieved August 21, 2023 from https://afca.ch/de/projekte/elementbau

[2] Felix Amtsberg, Xiliu Yang, Lior Skoury, Hans Jakob Wagner, and Achim Menges. 2021. iHRC: an AR-based interface for intuitive, interactive and coordinated task sharing between humans and robots in building construction. In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, Vol. 38. IAARC Publications, 25–32. https://doi.org/10.22260/ISARC2021/0006

[3] Stephanie Arevalo Arboleda, Franziska Rücker, Tim Dierks, and Jens Gerken. 2021. Assisting manipulation and grasping in robot teleoperation with augmented reality visual cues. In *Proceedings of the 2021 CHI conference on human factors in computing systems.* 1–14. https://doi.org/10.1145/3411764.3445398

[4] Lidia Atanasova, Daniela Mitterberger, Timothy Sandy, Fabio Gramazio, Matthias Kohler, and Kathrin Dörfler. 2020. Prototype As Artefact - Design Tool for Open-ended Collaborative Assembly Processes. In *Proceedings of the 40th Annual Conference of the Association for Computer Aided Design in Architecture: Distributed*

Proximities, ACADIA 2020. 350–359.

[5] Eleonora Bottani and Giuseppe Vignali. 2019. Augmented reality technology in the manufacturing industry: A review of the last decade. *IISE Transactions* 51, 3 (2019), 284–310. https://doi.org/10.1080/24725854.2018.1493244

[6] Filippo Brizzi, Lorenzo Peppoloni, Alessandro Graziano, Erika Di Stefano, Carlo Alberto Avizzano, and Emanuele Ruffaldi. 2017. Effects of augmented reality on the performance of teleoperated industrial assembly tasks in a robotic embodiment. *IEEE Transactions on Human-Machine Systems* 48, 2 (2017), 197–206. https://doi.org/10.1109/THMS.2017.2782490

[7] John Brooke et al. 1996. SUS: A quick and dirty usability scale. *Usability evaluation in industry* 189, 194 (1996), 4–7.

[8] Tathagata Chakraborti, Sarath Sreedharan, Anagha Kulkarni, and Subbarao Kambhampati. 2018. Projection-aware task planning and execution for human-in-the-loop operation of robots in a mixed-reality workspace. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 4476–4482. https://doi.org/10.1109/IROS.2018.8593830

[9] Wesley P Chan, Geoffrey Hanks, Maram Sakr, Tiger Zuo, HF Machiel Van der Loos, and Elizabeth Croft. 2020. An augmented reality human-robot physical collaboration interface design for shared, large-scale, labour-intensive manufacturing tasks. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 11308–11313. https://doi.org/10.1109/IROS45743.2020.9341119

[10] Oscar Danielsson, Anna Syberfeldt, Rodney Brewster, and Lihui Wang. 2017. Assessing instructions in augmented reality for human-robot collaborative assembly by using demonstrators. *Procedia CIRP* 63 (2017), 89–94. https://doi.org/10.1016/j.procir.2017.02.038

[11] André Dietrich, Michael Schulze, Sebastian Zug, and Jörg Kaiser. 2010. Visualization of robot's awareness and perception. In *Proceedings of the First International Workshop on Digital Engineering*. 38–44. https://doi.org/10.1145/1837154.1837160

[12] Philipp Fleck, Aimée Sousa Calepso, Sebastian Hubenschmid, Michael Sedlmair, and Dieter Schmalstieg. 2022. RagRug: A Toolkit for Situated Analytics. *IEEE Transactions on Visualization and Computer Graphics* (2022). https://doi.org/10.1109/TVCG.2022.3157058

[13] Roni-Jussi Halme, Minna Lanz, Joni Kämäräinen, Roel Pieters, Jyrki Latokartano, and Antti Hietanen. 2018. Review of vision-based safety systems for human-robot collaboration. *Procedia CIRP* 72 (2018), 111–116. https://doi.org/10.1016/j.procir.2018.03.043 51st CIRP Conference on Manufacturing Systems.

[14] Khoa Cong Hoang, Wesley P Chan, Steven Lay, Akansel Cosgun, and Elizabeth Croft. 2021. Virtual barriers in augmented reality for safe and effective human-robot cooperation in manufacturing. *arXiv preprint arXiv:2104.05211* (2021).

[15] Malte Jung and Pamela Hinds. 2018. Robots in the Wild: A Time for More Robust Theories of Human-Robot Interaction. *J. Hum.-Robot Interact.* 7, 1, Article 2 (may 2018), 5 pages. https://doi.org/10.1145/3208975

[16] Ondrej Kyjanek, Bahar Al Bahar, Lauren Vasey, Benedikt Wannemacher, and Achim Menges. 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, ISARC 2019*. https://doi.org/10.22260/ISARC2019/0164

[17] Benjamin Lafreniere, Tovi Grossman, Fraser Anderson, Justin Matejka, Heather Kerrick, Danil Nagy, Lauren Vasey, Evan Atherton, Nicholas Beirne, Marcelo H. Coelho, Nicholas Cote, Steven Li, Andy Nogueira, Long Nguyen, Tobias Schwinn, James Stoddart, David Thomasson, Ray Wang, Thomas White, David Benjamin, Maurice Conti, Achim Menges, and George Fitzmaurice. 2016. Crowdsourced Fabrication. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 15–28. https://doi.org/10.1145/2984511.2984553

[18] Stephan Lukosch, Mark Billinghurst, Leila Alem, and Kiyoshi Kiyokawa. 2015. Collaboration in augmented reality. *Computer Supported Cooperative Work (CSCW)* 24 (2015), 515–525. https://doi.org/10.1007/s10606-015-9239-0

[19] Zhanat Makhataeva and Huseyin Atakan Varol. 2020. Augmented reality for robotics: A review. *Robotics* 9, 2 (2020), 21. https://doi.org/10.3390/robotics9020021

[20] Leonel Merino, Magdalena Schwarzl, Matthias Kraus, Michael Sedlmair, Dieter Schmalstieg, and Daniel Weiskopf. 2020. Evaluating mixed and augmented reality: A systematic literature review (2009-2019). In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 438–451. https://doi.org/10.1109/ISMAR50242.2020.00069

[21] Daniela Mitterberger, Selen Ercan Jenny, Lauren Vasey, Ena Lloret-Fritschi, Petrus Aejmelaeus-Lindström, Fabio Gramazio, and Matthias Kohler. 2022. Interactive Robotic Plastering: Augmented Interactive Design and Fabrication for On-site Robotic Plastering. In *CHI Conference on Human Factors in Computing Systems*. 1–18. https://doi.org/10.1145/3491102.3501842

[22] Cristina Nuzzi, Stefano Ghidini, Roberto Pagani, Simone Pasinetti, Gabriele Coffetti, and Giovanna Sansoni. 2020. Hands-Free: a robot augmented reality teleoperation system. In *17th International Conference on Ubiquitous Robots (UR)*. 617–624. https://doi.org/10.1109/UR49135.2020.9144841

[23] C Perez Quintero, Sarah Li, Cole Shing, Wesley Chan, Sara Sheikholeslami, HF Machiel Van der Loos, and Elizabeth Croft. 2018. Robot programming through augmented trajectories. In *Proceedings of the 1st International Workshop on Virtual, Augmented, and Mixed Reality for HRI (VAM-HRI)*. https://doi.org/10.1109/IROS.2018.8593700

[24] Eike Schneiders, EunJeong Cheon, Jesper Kjeldskov, Matthias Rehm, and Mikael B Skov. 2022. Non-dyadic interaction: A literature review of 15 years of human-robot interaction conference publications. *ACM Transactions on Human-Robot Interaction (THRI)* 11, 2 (2022), 1–32. https://doi.org/10.1145/3488242

[25] Andrea Settimi, Julien Gamerro, and Yves Weinand. 2022. Augmented-reality-assisted timber drilling with smart retrofitted tools. *Automation in Construction* 139 (2022), 104272. https://doi.org/10.1016/j.autcon.2022.104272

[26] Lior Skoury, Felix Amtsberg, Xiliu Yang, Hans Jakob Wagner, Achim Menges, and Thomas Wortmann. 2023. A Framework for Managing Data in Multi-actor Fabrication Processes. In *Design Modelling Symposium Berlin*. Springer, 601–615. https://doi.org/10.1007/978-3-031-13249-0_47

[27] Yang Song, Richard Koeck, and Shan Luo. 2021. Review and analysis of augmented reality (AR) literature for digital fabrication in architecture. *Automation in Construction* 128 (2021), 103762. https://doi.org/10.1016/j.autcon.2021.103762

[28] Henrik Sørensen, Dimitrios Raptis, Jesper Kjeldskov, and Mikael B Skov. 2014. The 4C framework: principles of interaction in digital ecosystems. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. 87–97. https://doi.org/10.1145/2632048.2636089

[29] Ryo Suzuki, Adnan Karim, Tian Xia, Hooman Hedayati, and Nicolai Marquardt. 2022. Augmented Reality and Robotics: A Survey and Taxonomy for AR-enhanced Human-Robot Interaction and Robotic Interfaces. In *CHI Conference on Human Factors in Computing Systems*. 1–33. https://doi.org/10.1145/3491102.3517719

[30] Arthur Tang, Charles Owen, Frank Biocca, and Weimin Mou. 2003. Comparative effectiveness of augmented reality in object assembly. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. 73–80. https://doi.org/10.1145/642611.642626

[31] Xiliu Yang, Felix Amtsberg, Lior Skoury, Hans Jakob Wagner, and Achim Menges. 2022. Vizor, Facilitating Cyber-physical Workflows in Prefabrication through Augmented Reality. In *Proceedings of the 27th Conference on Computer Aided Architectural Design Research in Asia (CAADRIA) [Volume 2]*. 141–150. https://doi.org/10.52842/conf.caadria.2022.2.141