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Cooperative augmented assembly (CAA): augmented reality for on-site cooperative robotic fabrication

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Abstract

Recent years have witnessed significant advances in computational design and robotic fabrication for large-scale manufacturing. Although these advances have enhanced the speed, precision, and reproducibility of digital fabrication processes, they often lack adaptability and fail to integrate manual actions in a digital model. Addressing this challenge, the present study introduces cooperative augmented assembly (CAA), a phone-based mobile Augmented Reality (AR) application that facilitates cooperative assembly of complex timber structures between humans and robots. CAA enables augmented manual assembly, intuitive robot control and supervision, and task sharing between humans and robots, creating an adaptive digital fabrication process. To allocate tasks to manual or robotic actions, the mobile AR application allows multiple users to access a shared digital workspace. This is achieved through a flexible communication system that allows numerous users and robots to cooperate seamlessly. By harnessing a cloud-based augmented reality system in combination with an adaptive digital model, CAA aims to better incorporate human actions in robotic fabrication setups, facilitating human–machine cooperation workflows and establishing a highly intuitive, adaptable digital fabrication process within the Architecture, Engineering, and Construction sector.

Keywords Human machine collaboration · Human machine cooperation · Augmented reality · Distributed systems · User interface interaction · Adaptive digital fabrication

1 Introduction

During the last two decades, computational design and robotic fabrication have advanced significantly, leading to improved speed, precision, and reproducibility for digital fabrication in architecture (Gramazio et al. 2014; McGee and Ponce de 2014; Bock and Linner 2016; Menges 2015). Most conventional digital fabrication workflows are primarily linear, aiming for full automation, where the work environment, materials, and parameters remain constant throughout the process. In these linear workflows, users are required to complete a digital design before translating the geometry into fabrication instructions. Subsequently, these parameters are sent to a machine to fabricate a building part. If the user needs to adjust any parameters or refine the outcome, the entire process must be repeated until the final result aligns with design, fabrication, performance, and aesthetic criteria.

While linear robotic workflows can indeed produce precise building parts, particularly in a prefabrication setting

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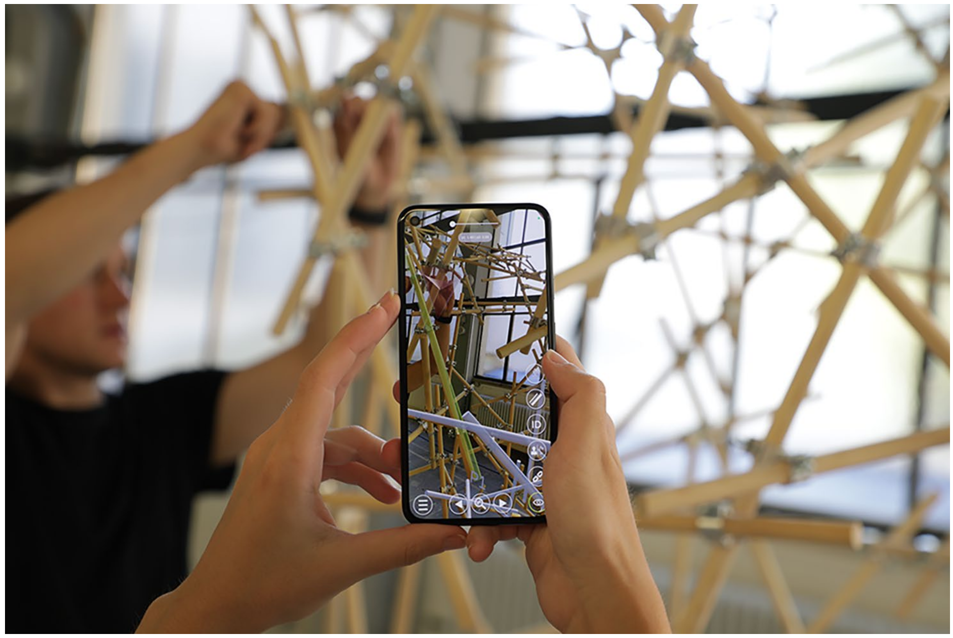

Fig. 1 Cooperative assembly of a timber structure with the guidance of CAA

where the work environment, materials, and processes remain constant, they come with significant drawbacks. These drawbacks include the need for extensive time, effort, and material resources to define all discrete steps in the fabrication process. Moreover, the inherent inflexibility of linear workflows restricts human interaction with machines during fabrication, making it challenging to adapt parameters on the fly or engage in computationally informed manual actions within digital fabrication processes (Han et al. 2021). This exclusion of humans from the loop not only makes the processes less adaptive, but it also hinders the autonomy of robots. Despite advancements in robotic systems, robots have not yet achieved full autonomy in handling all aspects of complex fabrication tasks due to their lack of advanced cognitive abilities (Johannsmeier and Haddadin 2017). The necessity of human inclusion in digital fabrication is evident, as robotic processes often require humans presence. Examples of this are seen in the fabrication of spatial metal structures (Parascho et al. 2017) or bespoke timber assembly (Thoma et al. 2019), where humans are still involved in the fabrication process. However, while manual human actions complemented robotic actions, humans were not digitally informed or guided, and their actions were not included in the digital model.

To establish adaptive robotic fabrication processes involving human-in-the-loop workflows, it is vital to utilize adaptive computational models and data structures linked to visual interfaces for inputting human actions. Recent research has demonstrated the effectiveness of augmented reality (AR) technologies as a preferred interface in this context (Amtsberg et al. 2021; Mitterberger et al. 2022). AR allows real-time overlay of task-specific information onto the physical workspace, enhancing precision and accuracy (Nee et al. 2012; Lavric et al. 2021) . It also facilitates collaborative work by allowing multiple users to view and interact with the same digital information simultaneously (Atanasova et al. 2023). Furthermore, AR serves as an intuitive tool for supervising (Wang et al. 2023) and controlling robots (Song et al. 2021), and enhancing safety measures by allowing users to monitor and cooperate with robots in real-time and space (Arévalo et al. 2020) (Chadalavada et al. 2020). Additionally, it enables the visualization of digital models aligned with physical structures, aiming in identifying and preventing errors in an early fabrication stage (Gruenefeld et al. 2020; Tian and Paulos 2021).

Therefore, Cooperative Augmented Assembly (CAA) aims to address current limitations of digital fabrication workflows by developing an AR-assisted adaptive workflow that enables human–machine cooperative processes (Fig. 1). More specifically, it investigates adaptive models of task sharing between manual human actions and robotic follow-up actions through a flexible “task-shop”. The “task-shop” is a concept that refers to a repository of tasks that can be performed by either humans or robots, and it is linked to a computational model. It is available to users via a phone-based AR application, enabling them to visualise the structure, interact with robots and receive fabrication instructions. This allows humans to take on tasks that require dexterity and complex motions and facilitates precise robotic follow-up actions. Such robot actions include element placement in 3D space without additional reference points, or the stabilization of a structure without time limitations.

Consequently, the key outcomes of this research encompass: 1) a phone-based AR application that facilitates the supervision and control of robots, and enables human instruction during assembly processes, and 2) a data structure that streamlines the interaction between design, fabrication, and user input, thereby fostering an adaptive and efficient fabrication process. To evaluate the benefits and advantages of such systems, this research used two experimental case studies evaluated through user studies.

The remainder of this paper is structured as following: Sect. 2 provides an overview of the state of the art of AR-assisted manual fabrication, AR-assisted robotic fabrication, and task distribution for cooperative human-robot fabrication in Architecture, Engineering, and Construction (AEC). The method section introduces the system walk-though, the task distribution logic and data structure of the digital model. The paper then continues by presenting the User Interaction and Interface of the phone-based application as well as how the system works, the required hardware and software components. Section 4 presents the two experimental studies that were conducted. Experimental study 1 evaluated the usability of the AR application in a large-scale assembly through a user-study with a group of AR-guided architecture and civil engineering students. Experimental study 2 investigated the usability of functions related to supervision and control of robotic actions through the phone-based AR application. For this, users assembled a small scale timber structure. The last Sect. 5 discusses the findings of the experimental studies and concludes with current limitations and outlook.

2 Background

The following sections describe how our research builds on previous investigations. In particular, this section focuses on AR-assisted manual and robotic fabrication, along with task distribution for cooperative human-robot fabrication.

2.1 AR-assisted manual fabrication

AR applications can advance manual fabrication workflows and facilitate novel digital fabrication processes. These advancements include guidance through difficult assembly tasks (Lafreniere et al. 2016) (Chidambaram et al. 2021), task specific fabrication instructions (Kyaw et al. 2023) and fabrication supervision (Portalés et al. 2018; Zhou et al. 2011; Ramakrishna et al. 2016). AR applications that provide guidance can be used on various devices such as smartphones (Atanasova et al. 2023), smartwatches (Lafreniere et al. 2016), external monitors (Mitterberger et al. 2020), projection-based AR systems(Chen et al. 2021), or head-mounted displays (HMD) (Fang et al. 2023; Jahn et al. 2022). AR instructions find applications in both prefabrication settings and on-site scenarios (Jahn et al. 2022, 2020). An example of AR-assisted fabrication instructions for prefabrication is the research experiment by Bartuska et al. (2023). It uses a projector-based spatial AR system to improve spatial understanding and instruct craftspeople in space for a faster and more precise assembly of timber-frame wall elements. An example of on-site AR assistance using external monitor systems is “Augmented Bricklaying” (Mitterberger et al. 2020). “Augmented Bricklaying” uses a visual inertial object tracking to instruct masons on how to place bricks in space by tracking their current location and their desired position. Both examples show how the use of AR can improve a manual craft through digital means. However, both examples have one-directional user interaction functionalities, focusing mainly on user instructions, and do not allow craftspeople to adjust an existing design or intervene in the fabrication or assembly cycle. Such flexibility might be desirable for adjusting a structure based on visual cues during the fabrication process or for purposes related to craft making practices. Furthermore, in these projects and similar AR instruction projects (Aguilera et al. 2023; Song 2020; Kim et al. 2022; Atanasova et al. 2020), humans can not dispatch fabrication tasks to other machines or robots cause their AR systems focus solely to manual fabrication tasks. A project that tackles this limitation is “Prototyping as Artefact” (Atanasova et al. 2020). The project enables users to design on the fly, as the design is not predefined and results from the user’s decisions during fabrication. Humans use the phone-based AR application to visualize cues for possible element placements and register manually placed elements. Additionally, the project showcases the advantages of AR-assisted interactive fabrication (Mueller et al. 2019; Willis et al. 2010; Peng et al. 2018) in architecture; however, it lacks task-specific user interfaces, and it’s limited to singular users. Another project addressing multi-user assembly processes is “Collective AR-Assisted Assembly of Interlocking Structures”, but it does not facilitate the distribution of tasks between both humans and robots.

2.2 Augmented reality in robotic fabrication

Robotic applications in digital fabrication is a well-explored field in academia, resulting in processes characterized by high levels of customization and precision (McGee and Ponce de 2014; Gramazio et al. 2014; Bock and Linner 2016). Due to the challenges associated with automation, there has recently been a growing interest in integrating AR systems in robotic fabrication to facilitate a more intuitive and streamlined supervision and control of the robots (Suzuki et al. 2022; Makhataeva and Varol 2020; Dianatfar et al. 2021). These AR-assisted robotic processes mostly either focus on visual feedback and supervision or intuitive control during the fabrication process. A project that focuses on visual supervision of robots for multiple users is "Crowd-sourced Fabrication" (Lafreniere et al. 2016). This project provides a wearable guidance system to inform untrained volunteers about robotic actions and facilitate safe interaction between them. Other examples are the researches of Hughes et al. (2021) and Cao et al. (2019). Both projects use AR-HMD to inform users about the behavior of robots by visualizing their trajectories. Two products in industry focusing on visual robot supervision are "Kuka.MixedReality",[1] a recently launched software product by "KUKA Robotics", and "RobotStudio AR Viewer",[2] a software product of "ABB Robotics". All of the above-mentioned projects show how we can use AR to ease the interaction between humans and machines. However, they don't provide users with the flexibility of controlling them. Achieving control through AR systems requires tracking user intentions, either through spatial tracking like gesture recognition or alternative user interfaces. "*IRoP*" (Mitterberger et al. 2022) utilizes projection-based AR to translate human gestures into precise robotic motions during a robotic plastering process. While the project introduces an intuitive interface for programming and controlling robots through motions, it does not employ AR to visualize the spatial aspects of robotic actions in real-time. Additionally, it does not facilitate multiple users simultaneously and projection-based AR either confines the working space or necessitates relocating the equipment in large construction sites. Meanwhile, "PinpointFly" (Chen et al. 2021) and "KineticAR" (Fuste et al. 2020) are two projects that offer the freedom to control and supervise drones and robots, respectively, through AR applications on mobile devices. However, the usability of these solutions remains untested in complex fabrication processes.

2.3 Task distribution for cooperative human–robot teams

Task distribution is a pivotal research topic for well-functioning cooperative systems in digital fabrication, describing a system that defines which actions are allocated to humans for manual fabrication and which ones are designated for machines. Researchers have proposed multiple approaches for task distribution in cooperative processes (Mahadevan et al. 2021; Fiebich et al. 2015), including assigning actions based on each agent's unique strengths and capabilities (Haddadin et al. 2011) (Ranz et al. 2017) or adopting a turn-taking approach in which distribution occurs during task execution(Roncone et al. 2017). To visualize task distribution some researchers have experimented with the use of AR interfaces. Examples that combine task distribution with robotic assembly processes for timber structures are "Tie a Knot" (Mitterberger et al. 2022), "CRoW" (Kyjanek et al. 2019), and "iHRC (Amtsberg et al. 2021)". In the first project, phone-based AR is used to inform humans about the turn-taking task distribution. In this system, challenging-to-automate tasks are allocated to humans while task requiring precision and stability are distributed to industrial robots. "iHRC" is a project that uses AR-HMD to inform users about a flexible set of actions, such as pick, place, nail, and screw actions. These actions can be reassigned and corrected via AR and throughout the fabrication process. "CRoW" proposes an AR-HDMD as a tool that can help the user plan robotic trajectories, influence production sequencing, and view superimposed diagnostic feedback. These projects propose a workflow for combing AR with task distribution, but they do not link a data model with the AR visualization. Furthermore, "Tie a Knot", "CRoW" and "iHRC" lack multi user support.

3 Methodology

CAA aims to facilitate an adaptive and efficient digital fabrication process based on task distribution for cooperative human-robot teams combining AR assisted manual fabrication with AR enabled robotic fabrication. For this, CAA uses a phone-based AR system, consisting of a process-specific user interface for manual assembly of bespoke building parts and an interface to supervise and control multiple mobile robots. The instructions for AR-assisted manual assembly enable users to preview a 3D model in space, provide fabrication instructions and interact with a task-shop. The instructions for AR supported robotic fabrication allow users to preview and calculate robotic toolpaths, visualize current robot positions and control robot actions. To enable multiple users to fabricate in parallel, CAA employs flexible communication protocols. To include manual human actions in a digital model a shared computational datastructure linking geometric information with task distributions is necessary.

3.1 System walkthrough

In the overall system workflow, users first prepare their design with the appropriate datastructure in a CAD

[1] https://www.kuka.com/en-ch/products/robotics-systems/software/simulation-planning-optimization/kuka_mixedreality.

[2] https://new.abb.com/products/robotics/robotstudio/ar-viewer-app.

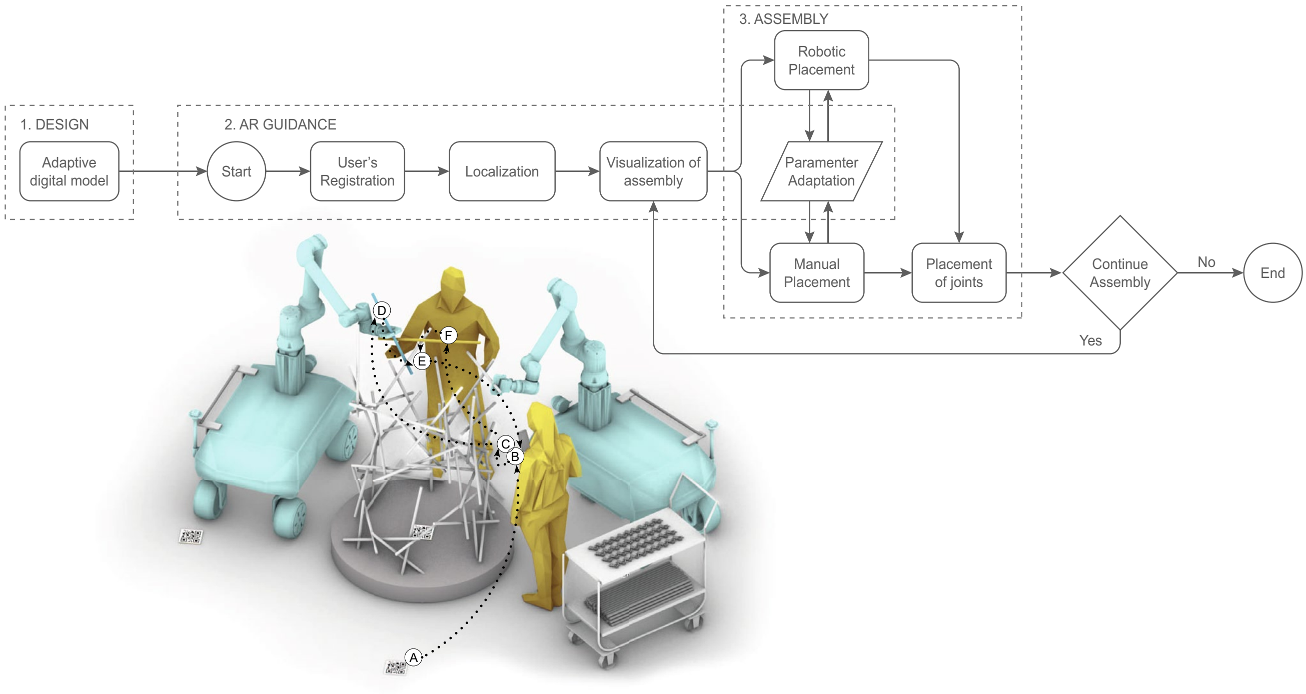

Fig. 2 System walkthrough and AR-guided assembly workflow that consists of six main steps (**A**) Localization, (**B**) Visualization, (**C**) Parameter Adaptation, (**D**) Robotic Placement, (**E**) Joint Placement, (**F**) Manual Placement

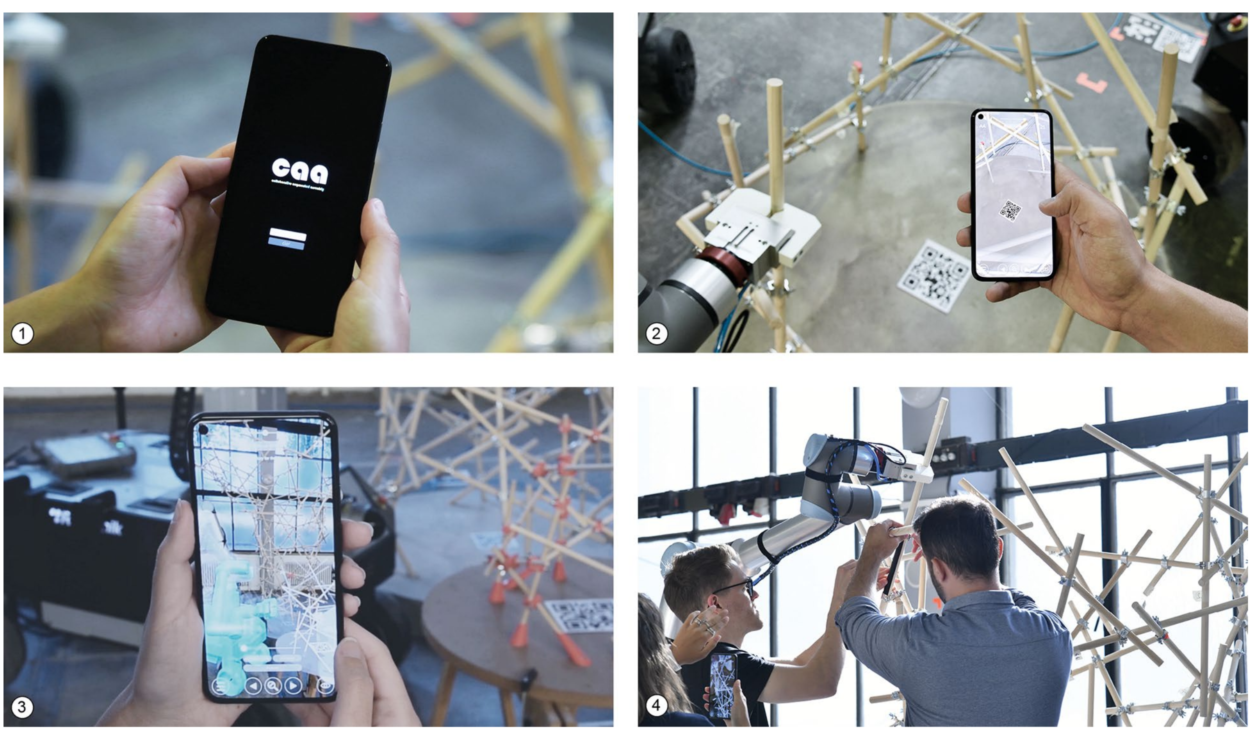

Fig. 3 (**1**) Registration Screen (**2**) Localization of the digital model by tracking one of the QR code markers (**3**) Visualizing the robot's trajectory on the AR application for robotic placement (**4**) AR manual placement of next element

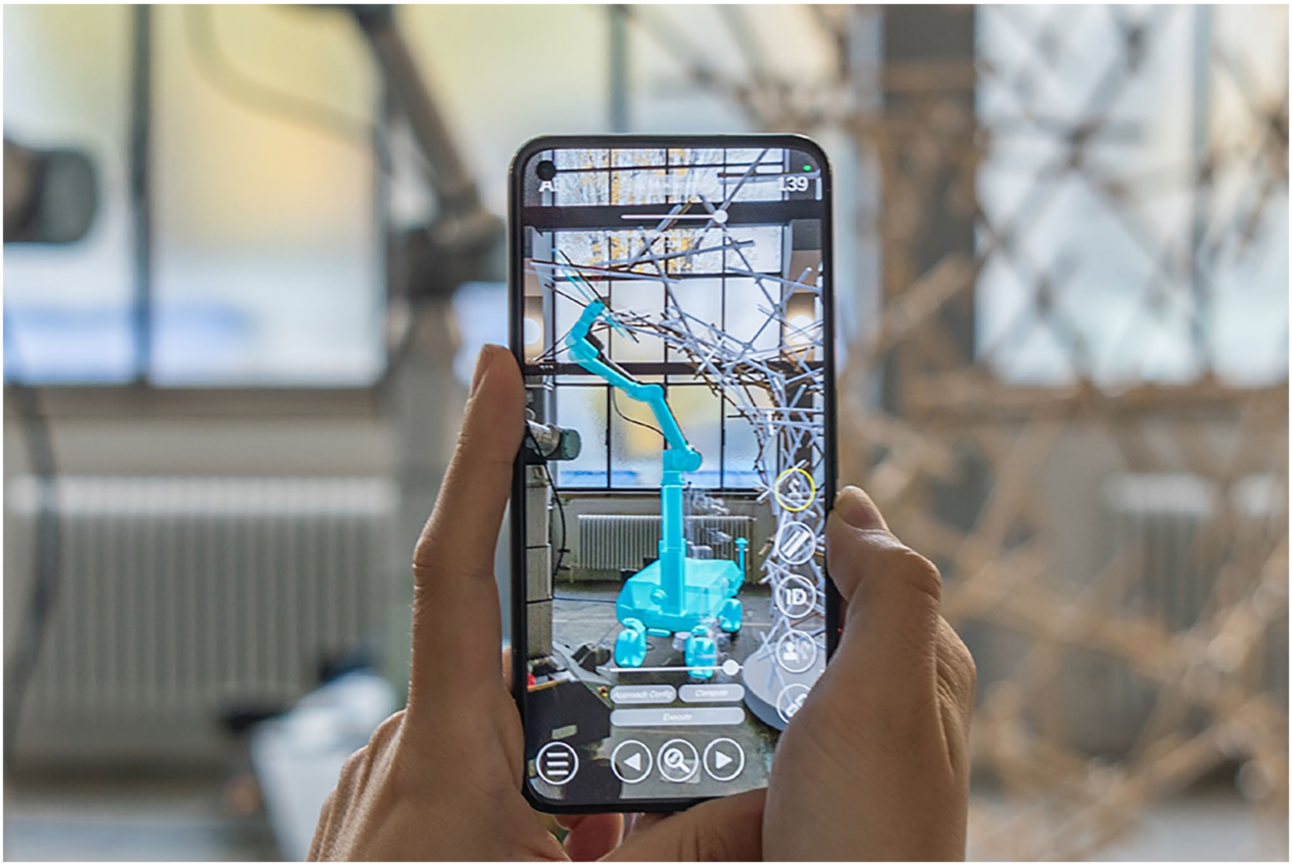

Fig. 4 Visualization of robot's place configuration

environment and then they upload it to the cloud based server (as explained in Sect. 3.5.2). Subsequently, they initiate the CAA application on a smartphone, activating an intuitive interface for working with the robots. The overall functionalities that CAA provides them can be split in five distinct parts, which are *User Registration, Localization, Visualization, Parameter Adaptation* and *Fabrication* (Fig. 2). First, users register themselves (Fig. 3(1)), allowing multiple users to fabricate collectively, by linking devices' identification number (ID) with timestamps. After registration, users localize their phones by scanning pre-measured physical 2D markers (QRcode markers) to track the device's position[3] (Fig. 3(2)). Following localization, users can preview the geometry of the structure and its related fabrication parameters, as well as the order in which the discrete elements should be assembled. As the application targets specifically human–machine cooperative assemblies, it also provides information on which elements should be assembled by humans and which should be assembled by robots. The assembly order and task distribution are algorithmically determined before fabrication starts during the design phase (see Sect. 3.3). However, users retain the flexibility to adapt these parameters at any point during the assembly process. During the Fabrication step, when an element is assigned to the user, they receive clear instructions and assistance to complete the assembly task. When the placement of an element is assigned to one of the robots, they need first to make sure that the robot is at the right location or if it needs repositioning in space. Once assured of its position, they can send the command to the robot to execute the placement (Fig. 4). At the end of each cycle, all instances of the AR application and the CAD model are updated since they are all linked through the cloud-based server (Sect. 3.5.2). To integrate and synchronize these functionalities while linking the devices and the CAD model to the cloud, an adaptive data structure is necessary.

[3] The QR code markers were generated using the online website https://qr.io/.

3.2 Data structure for human–robot cooperative assembly

Conventional digital design models for digital fabrication typically only describe the geometric attributes of a structure. To facilitate a shared digital-physical workspace between humans and robots, incorporating manual human actions in the digital model, a shared and adaptive datastructure is necessary. This shared adaptive datastructure combines task descriptions with geometric description, linking the design model with the multiple instances of the AR visualization through a flexible network system. For this, the research uses the COMPAS open source library[4] (Van Mele et al. 2023), generating an Assembly Information Model (AIM) for design and robotic fabrication. This model encompasses all essential information required to describe assembly sequences, with the objective of bridging different tools and stakeholders. The data structure used for the application is based on the *compas.datastructures.Network* class.[5] This datastructure represents a geometric graph, illustrating the connections of elements described through “nodes” and “edges”. In this framework, individual elements are represented as “nodes” and “edges” capture the relationships between them. Information about the elements is stored in the “nodes” themselves, while information about the relationship is stored in the “edges”. A similar approach can be found in “Prototype as artefact” (Atanasova et al. 2020), “Collective AR-Assisted Assembly of Interlocking Structures” (Atanasova et al. 2023), and “Tie a knot” (Mitterberger et al. 2022). All parameters used in the datastructure of this research are shown in the Table 1. Attributes are predefined[6] and then set, assigned, or reassigned in the CAD environment during the design process. These attributes include geometric information such as “frames”[7] and fabrication attributes such as “is_built”, “placed_by”. The attribute “placed_by” indicates whether this element’s placement is assigned to a human or a robot, determined by the task distribution logic (Sect. 3.3).

As this application enables multiple users to collaboratively fabricate with multiple robots, each element has the additional parameter “robot_name” to indicate to which of the robots an element is distributed to. Additionally, robotic parameters include the “robot_base_frame” to guide the user on where to place the mobile robot to reach the end position an element has to be placed to. Once the design with the adaptive digital model is complete, all information related to the fabrication and visualization of the structure, including the mentioned attributes, is saved to a JSON file. This file is then published to a cloud-based server directly from the CAD environment with a click of a button. Every instance of the AR application has access to the cloud-based server and can read and rebuild the data structure as a dictionary in real-time, as explained in Sect. 3.5.2. The fabrication attributes of “is_built”, “placed_by” can be adjusted via the AR application to achieve a flexible task distribution as discussed in Sect. 3.3. Manual setting of attributes and troubleshooting is also possible from the digital design environment due to the real-time communication with the cloud-based server.

Table 1 Table showing the required parameters for the geometrical representation of each element and task distribution

Attributes	Type	Unit
“element”		
“frame”:		
“point”	float [x, y, z]	m
“xaxis”	float [x, y, z]	m
“yaxis”	float [x, y, z]	m
“type”	integer	–
“is_built”	boolean	–
“placed_by”	string: “human”/ “robot”	–
“robot_name”	string: “AA”/ “AB”	–
“robot_AA_base_frame”		
“point”	float [x, y, z]	m
“xaxis”	float [x, y, z]	m
“yaxis”	float [x, y, z]	m
“robot_AB_base_frame”		
“point”	float [x, y, z]	m
“xaxis”	float [x, y, z]	m
“yaxis”	float [x, y, z]	m

3.3 Task distribution for humans and machines

One of the key aspects of the AR application is the adjustment of the task distribution and specific parameters for each element of the structure. This increases the flexibility of the application to accommodate on-site decisions by allowing the users to decide on-the-fly if an element should be reassigned to a machine or a human for assembly.

During the algorithmic design with the adaptive digital model, the distribution of tasks is determined and stored as an attribute in the data structure. In the following experimental case studies described in Sect. 4, the task distribution (Fig. 5) is based on the geometry of the structure, but

[4] COMPAS is an open-source Python-based framework.

[5] https://compas.dev/compas/1.0.0/api/generated/compas.datastructures.Network.html.

[6] e.g The “is_built” attribute is set to *True* for the starting elements needed to provide a base of the structure and set to *False* for the subsequent pieces.

[7] Instances of the *compas.geometry.Frame* class https://compas.dev/compas/1.14.1/api/generated/compas.geometry.Frame.html.

Fig. 5 Task distribution for human and machines

the system is built flexible enough to include different task distributions. More specifically, in this research, robots undertake tasks that humans either cannot perform or are not as efficient. They execute spatially complex pick-and-place routines with high accuracy, and without the need for reference points. Additionally, robots are used to stabilize the structure for extended periods. On the other hand, human operators tackle tasks that require high dexterity and are challenging for robots, such as positioning and tightening of a joint (Figs. 6, 7(3)), and fast yet approximate placement of an element onto existing structures with the guidance of the AR application. Moreover, they make intuitive decisions, and reassign tasks during the active fabrication process to address unexpected challenges.

Even though tasks are assigned beforehand in the digital model according to a specific logic, tasks can be reassigned to a robot or a human during fabrication. One reason why reassignment might be necessary is due to the complexity of spatial structures, time constraints or accuracy discrepancies. Complex spatial structures may have hard-to-reach elements that might not be reachable by the current position of the robot or result in hard-to-compute robotic toolpaths due to collisions. These elements can be nested within a structure or fixed on the floor or walls. In some cases, a faster conclusion of the assembly of a structure is more favorable than a sub-centimeter accurate structure. In these cases, the user can switch from robotic mode to manual assembly. Conversely, when higher precision is required to prevent accumulation of errors, manual assembly tasks can be redistributed to a robot. In these scenarios, users have the option to switch the task distribution of an element from human to robot, or vice versa, as many times as they desire (Figs. 8n, 9B). This feature enables dynamic allocation of tasks based on real-time considerations, ensuring optimal task sharing and efficient utilization of available resources throughout the construction process.

Fig. 6 Connecting two elements with the zoom in feature of the AR application

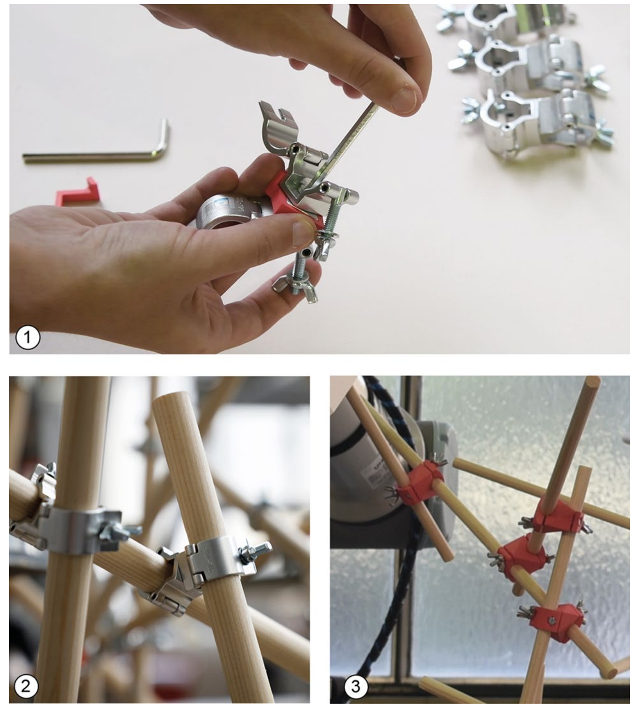

Fig. 7 (**1**) The process of fixing the rotation angle of the clamps at 60 degrees (**2**) Off-the-shelf coupler clamps were used in the Study 1 (**3**) Fixed 3D printed joints were used in the Study 2

3.4 User interaction and interface for the AR application

The user interface (UI) of the phone-based AR application allows users to interact with the datastructure discussed in Sect. 3.2 providing access and visualization of the data (geometry and attributes). Additionally, it offers instructions on manual assembly actions such as placing elements and joints, as well as communication and control over the mobile robots.

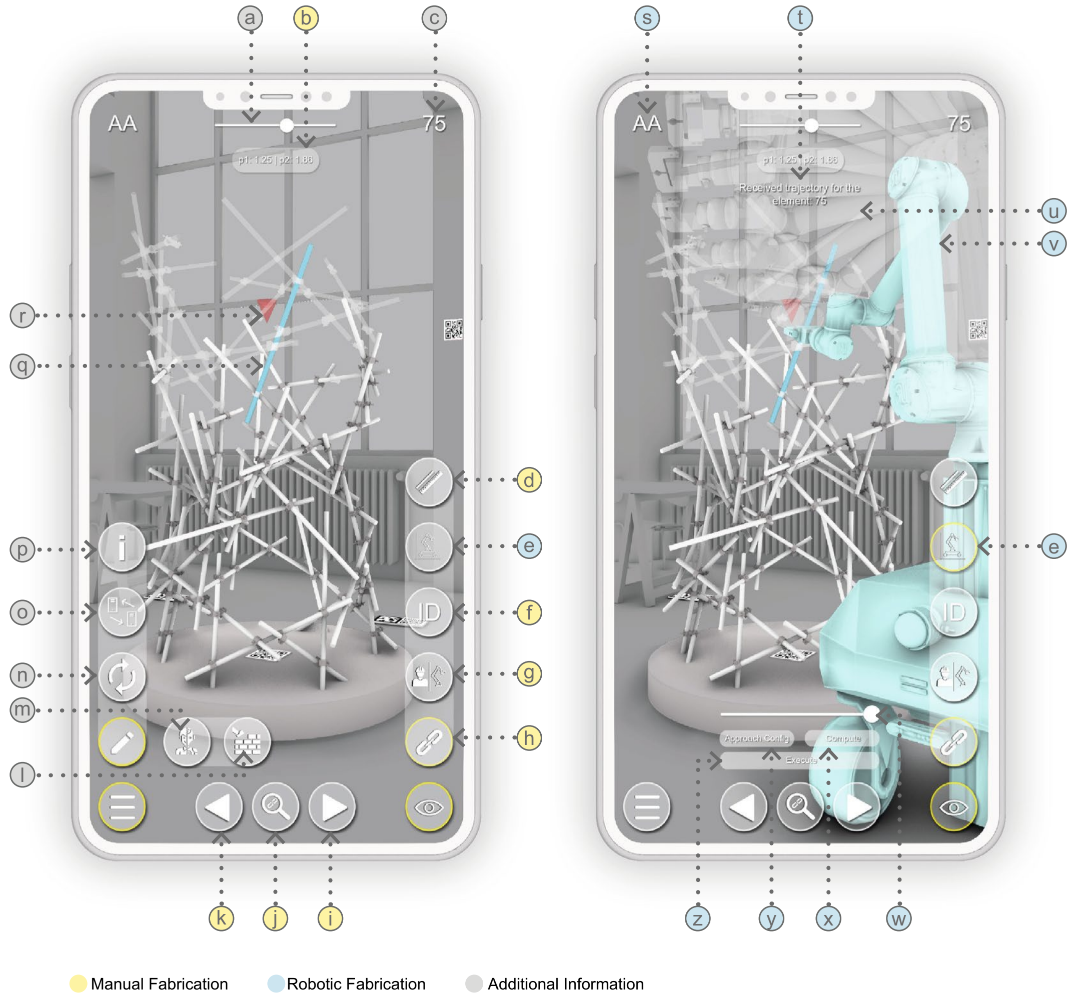

Fig. 8 Comprehensive user interface of the AR application

Fig. 9 (**A**) Visualizing the index and type of each unbuilt element, along with the assigned executor for its placement, (**B**) Adjusting the executor of an element by enabling the "Parameter Adaptation Menu" and selecting the preferred element, (**C**) Modifying the "Built Status" of an element

3.4.1 Visualization of the datastructure

Elements with the “is_built” value True are visualized in solid white while the remaining elements are visualized in yellow or cyan based on the “placed_by” attribute (Fig. 8q). Yellow indicates to the user that this element should be placed by a human while cyan shows that this is a robotically placed element. Users can control the number of the remaining elements displayed with a slider (Fig. 8a). The ID of the current element is displayed on the top right corner of the screen(Fig. 8c), while a red arrow highlights its location in space (Fig. 8r). On the top left corner, the robot’s name appears when an element is assigned for robotic placement (Fig. 8s). Users can visualise information about the assigned executor (Fig. 8g), the lengths (Fig. 8d) and the IDs (Fig. 8f) of all elements.

Manual assembly instructions: For the manual assembly of a complex timber structure, users require guidance on which element to place and where to place it. This is achieved by visualizing a digital twin of each element (Fig. 8q). Before moving to the next element (Fig. 8i), users can manually validate the position of two points on the placed object(p1: the lower end and p2: the upper end of the strut). By that, they can cross-check the distances from these points to the floor with the ones displayed on the AR application (Fig. 8b). This measuring system aims at preventing discrepancies and the accumulation of inaccuracies of AR assisted manual placement. Users can also edit the attributes of previous elements at anytime if necessary (Fig. 8k). *Joint assembly instructions*: Joints have the potential to be geometrically quite complex for manual assembly. To assist the humans in this process, the AR application features a visual representation of all joints (Fig. 8h), a “how-to” video (Fig. 8p), and a zoom in on a selected joint feature (Figs. 6, 8j) for a quicker comprehension of the connecting system.

Robotic assembly instructions: The AR application provides essential features for requesting the calculation of a robot’s place configuration for a specific element (Fig. 8y), path planning (Fig. 8x), and execution of a selected trajectory (Fig. 8z). A successful calculation of a place configuration results in a visualization of the robot in the specific configuration (Figs. 4 and 8v). Similarly, once a trajectory is calculated, a partially translucent image of the robot movement appears (Fig. 8u). Users can inspect this movement with a slider (Fig. 8w). Messages regarding the success or failure of every action are displayed on the screen (Fig. 8t), informing the user how to proceed. Typically, in robotic fabrication workflows, users preview robotic actions on a computer. However, this research suggests an approach, wherein the preview occurs in the physical space through augmented reality. This allows individuals to remain on the construction site, reducing reliance on computers.

3.4.2 Parameter adaptation

As mentioned in Sect. 3.3, users can dynamically switch the task distribution of an element between human and robot, using the application. Additionally, they can modify the built status of an element, toggling between “built” and “unbuilt” states as necessary. This feature allows users to register elements that were placed without the application or to inform the system when an element is removed and needs to be placed again. To access this adaptation feature, users must navigate to the “Parameter Adaptation Menu” and then activate either the “Executor Adaptation” (Fig. 8m) or the “Built Status Adaptation” (Fig. 8l) selecting the desired element on the screen for adaptation. Upon changing the assigned executor or the built status of an element, its color adjusts accordingly (Fig. 9B and C).

3.5 System architecture

The system architecture consists of a hardware and a software setup, and a communication workflow enabling seamless interaction among multiple users and their devices during the fabrication process.

3.5.1 Hardware architecture

The hardware setup (Fig. 10) consists of two 6-DoF cooperative robotic arms (UR10e) mounted on mobile *Robotnik* platforms. Mobile robots are well-suited for in-situ fabrication due to their freedom of movement, which extends their static reach and facilitates the construction of larger structures. Furthermore, the integration of a vertical axis enables the robotic arms to achieve a total height of approximately 3.5m. To ensure a secure grip on the timber rods, both robotic manipulators are equipped with pneumatic grippers and custom 3d printed gripping fingers. Each mobile *Robotnik* platform has attached a custom 3D-printed pickup station for feeding and collecting timber elements. Two Google Pixel 5 mobile devices are used, and a Windows PC is used for visualization and running the CAD enviroment to generate the adaptive digital model.

3.5.2 Software architecture

A comprehensive software architecture and communication system is employed to (1) design an adaptive digital model with the above-mentioned datastructure, (2) develop the AR application, (3) calculate the robotic toolpaths and (4) enable usage of the AR application for multiple users and robots (Fig. 11).

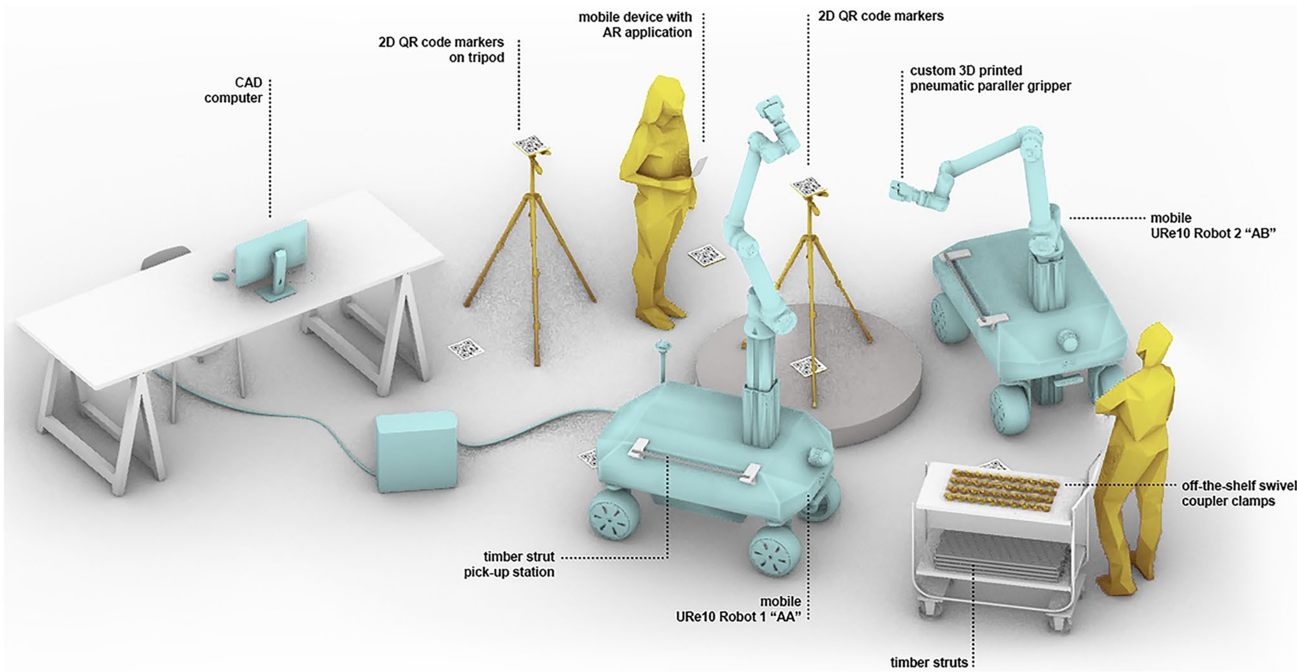

Fig. 10 Hardware setup of the system

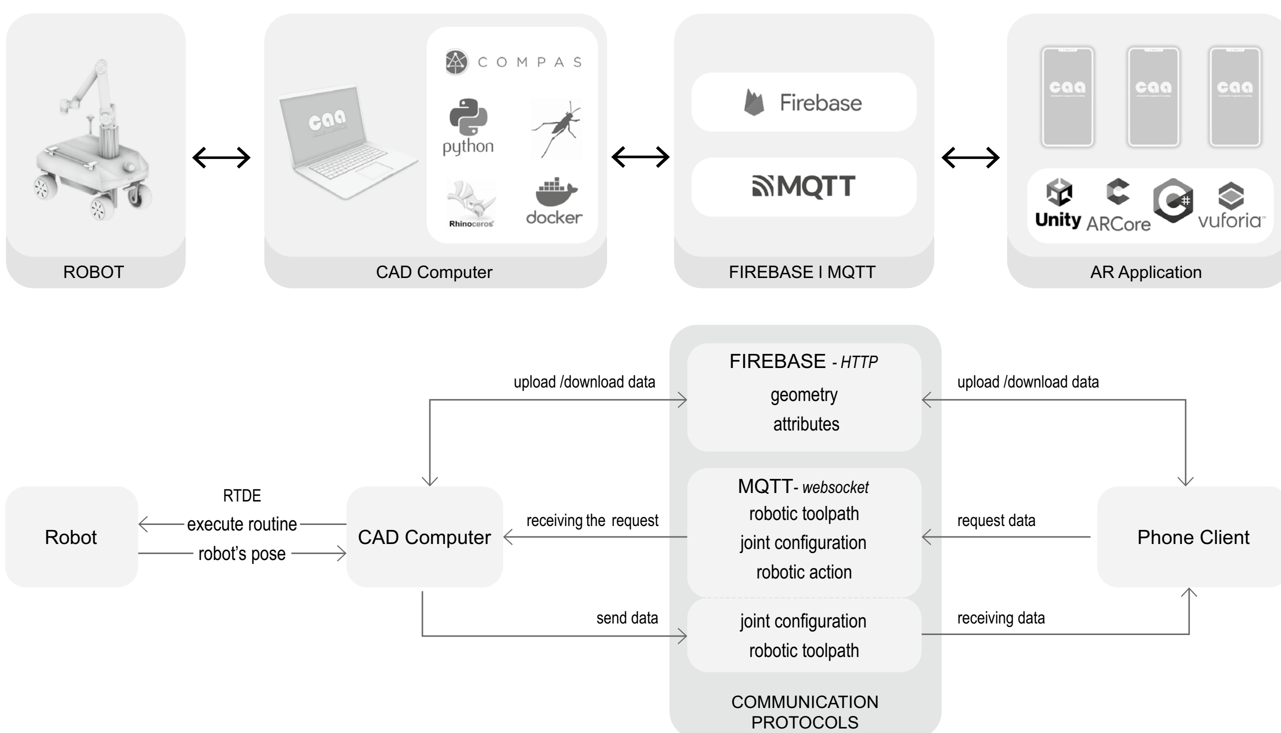

Fig. 11 Software and communication setup of the system

Design of an adaptive digital model: The adaptive digital model (Fig. 12) is designed in *Rhino3D*[8] and *Grasshopper* (GH)[9] using *COMPAS* and *Python* (Fig. 11).

Development of the phone-based AR application: The application is designed in *Unity Game Engine*,[10] using *ARCore*[11] and *ARFoundation*[12] to access AR functionalities such as placing and interacting with objects in AR environments through Ray-casting. In addition, the *Vuforia Engine* library[13] is used for localization and synchronizing the digital and physical space by tracking Image Targets, more specifically 2D QR code markers (Fig. 11).

Registration of QRcode markers: The relative positions of these markers in terms of distance and orientation to the exact origin point of the design in the real world are crucial for achieving accurate alignment. Their position is first determined in the same Rhino3D model as the design of the structure. Then, 2D QR code markers are manually placed in space as accurately as possible, and their position are measured using a high-precision measuring tool, such as a total station. The obtained measurements are used to update the corresponding planes within the digital model.

Robotic Fabrication: The planning of the robotic toolpaths and their preview in the CAD environment is achieved with the use of *MoveIt*,[14] *COMPAS FAB* (Casas et al. 2023) and Python. Customized *Docker*[15] containers are used to run ROS system, composed by a *ROS core*, rosbridge server, *MoveIt*, (Crick et al. 2017) and their dependencies on the Windows PC. The communication with the UR controller of each robot is achieved over a standard TCP/IP connection. More specifically, because UR robots are employed, a Real-Time Data Exchange (RTDE)[16] interface is used to transfer a planned pick-and-place routine, including target frames, I/O control, and robot parameters. To preview a planned toolpath on a mobile device *MQTT*[17] is utilized. *MQTT* was selected because it's a lightweight protocol. The phone has to be connected via WIFI to the same *MQTT Broker*. Then, the system uses *MQTT* topics to request and receive trajectories. More specifically, upon establishing this connection, the CAD subscribes to three *MQTT* topics while also functioning as publisher for two *MQTT* topics. Concurrently, each instance of the application operates as a publisher for the initial three *MQTT* topics and subscribes to the subsequent two *MQTT* topics. These topics are essential for users to request and receive a robot's placement configuration for a specific element, obtain a valid trajectory from the current state to the target placement position, and ultimately execute the robotic placement process.

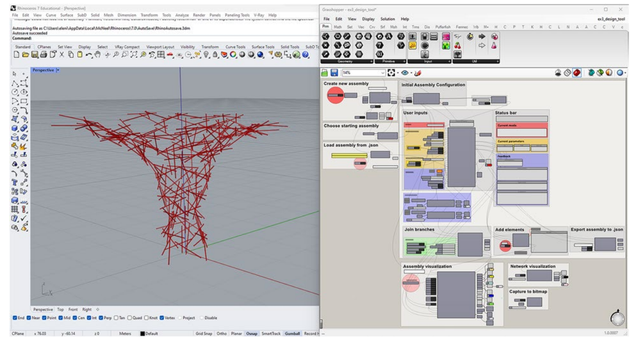

Fig. 12 The adaptive digital model

Cloud-based communication: The application utilizes a flexible network system, specifically a cloud-based server, to enable collaborative assembly among multiple users and ensure real-time synchronization across all connected devices and the CAD model (Fig. 11). For this, *Firebase*[18] is utilized, a cloud-hosted database, that synchronizes the stored data in real-time across all clients. The assembly datastructure is uploaded to the *Google Firebase Realtime Database* from Rhino and GH, using Python and the *Pyrebase Python wrapper*[19] for the Firebase API. Once the uploading is finished, every instance of the AR application reads and rebuilds both the datastructure and the geometry within its environment. All instances of the app and the CAD model maintain continuous synchronization, ensuring that any updates made to the built status of an element within the app are promptly communicated to the CAD model, which is then updated accordingly. The measurements of the 2D QR code markers during their registration is uploaded to *Firebase* as well, so that the data associated with the QR code markers aligns with the broader dataset used in the application. By centralizing this information in *Firebase*, it becomes readily accessible

[8] Rhinoceros is a 3D computer graphics and computer-aided design (CAD) software developed by McNeel and Associates.

[9] Grasshopper is a visual programming language and environment that runs within the software Rhinoceros.

[10] Unity Game Engine is a real-time development platform developed by Unity Technologies.

[11] ARCore is Google's software development kit (SDK) for augmented reality (AR) applications on Android devices.

[12] Unity's AR Foundation is a cross-platform framework enabling developers to create augmented reality applications that run on both Android and iOS devices with no need for platform-specific adjustments.

[13] Vuforia Engine is an augmented reality (AR) software development kit (SDK) developed by PTC.

[14] MoveIt is an open-source software framework for motion planning and manipulation in robotics developed by PickNik Robotics.

[15] Docker is a platform for creating and running containers that package applications and their dependencies across different environments.

[16] https://www.universal-robots.com/articles/ur/interface-communication/real-time-data-exchange-rtde-guide/.

[17] https://docs.oasis-open.org/mqtt/mqtt/v5.0/mqtt-v5.0.html.

[18] https://firebase.google.com/.

[19] Pyrebase. https://github.com/thisbejim/Pyrebase

Table 2 Comparison of data between experimental study 1 and experimental study 2

	Study 1	Study 2
Duration	5 days	Half-day
Participants	17	15
Elements		
Design	200	45
Built	153	28
Manually placed	128	27
Robotically placed	25	1
Structure's size	$4.03 \times 4.03 \times 3.18$ m	$0.89 \times 0.84 \times 0.64$ m
Main focus of AR visualization	Data structure, manual assembly instructions, parameter adaptation	Toolpath visualization, robot's control

and consistent throughout the development process, enhancing the efficiency and accuracy of the localization and interaction components within the application.

4 Experiments and results

To evaluate the functionalities of CAA and assess the UI of the AR application, as well as its potential and drawbacks in fabrication processes, two experiments in the form of assembly workshops were conducted. The design was created in both workshops through the designated data workflow using the appropriate data structures. Both case studies looked at complex reciprocal frame structures which defined the sequence-dependent task distribution (Table 2).

The primary focus of the first experiment was on the functionalities related to visualizing the data structure, manual assembly instructions, and parameter, as explained in Sects. 3.4.1 and 3.4.2. Users could also visualize the approximate positions of the two robots for every element, enabling them to determine if repositioning them was needed before calculating a robotic toolpath through the CAD environment. The second case study extended upon these concepts, additionally incorporating toolpath visualizations of the robot and robot control through the MQTT communication protocol. This decision arose from the observation of significant back-and-forth between computers, phones, and robots to send and receive robot's commands. Differences between both workshops include the scale of the structure and fabrication time. In the second experiment, we deliberately scaled the overall structure and the size of the elements to decrease the building time, increase the complexity of robotic fabrication and challenge the robot control system and workflow. Moreover, we closely observed users' behavior and their opinions throughout the fabrication process. Following both experiments, participants were asked to provide ratings and qualitative evaluations of the application's usability in user studies.

4.1 Experimental study 1: large-scale assembly

The first case study constituted a 5-day-long fabrication workshop conducted in Munich, with participation from 17 students, between the ages of 21–31 from different disciplines, such as Civil Engineering, Architecture, Structural Engineering, Mechanical and Software Engineering, representing the Technical University of Munich (TUM). Throughout this workshop, students worked in pairs, with one student designated to use the AR application and the other student responsible for physically placing the elements (Figs. 13, 14). The main objective of the workshop was to collaboratively assemble a complex structure, which the students had previously designed.

The timber structure was designed using a prototype of a custom-developed fabrication-aware design tool. Based on a user's initial design intent (input geometry) and predefined design and fabrication-related criteria, users control the step-wise growth of the assembly structure. Considering the structure's stability at each assembly stage, fabrication constraints such as robot availability or reach and the initial distribution of human and robot tasks ensure the structure's feasibility. This happens by evaluating design options based on the criteria above to provide the users with feedback and support their design decision whether a design option will be approved or a new one will be generated. The final structure consisted of individual interlocking pieces within a system of reciprocal frames. The placement of these elements requires a sequential order, thus influencing the task distribution between humans and robots. The initial task distribution was defined by the skills of the involved agents (humans and robots) and the requirements needed to place an element in space, such as robot reachability, collision-free robot trajectory, and robot availability. The adaptive digital model, encompassing geometry, fabrication-related data, initial distribution of human and robot tasks, and "built" "unbuilt" states (for tracking assembly progress), was stored in a graph data structure as explained in Sect. 3.2. Storing the design in an adaptive digital model allowed for the task distribution to be adapted to the given building conditions during assembly using the AR application. A similar approach to "Tie a knot" (Mitterberger et al. 2022) was taken, where each assembly cycle consists of adding a timber triplet (see Fig. 15) made of three struts—one from a previous triplet, another assembled by a robot, and a third manually assembled by a human. This process ensures that the robots consistently stabilize the structure while humans perform a more intricate placement.

The designed timber structure consisted of individual elements where each three were mechanically connected in a

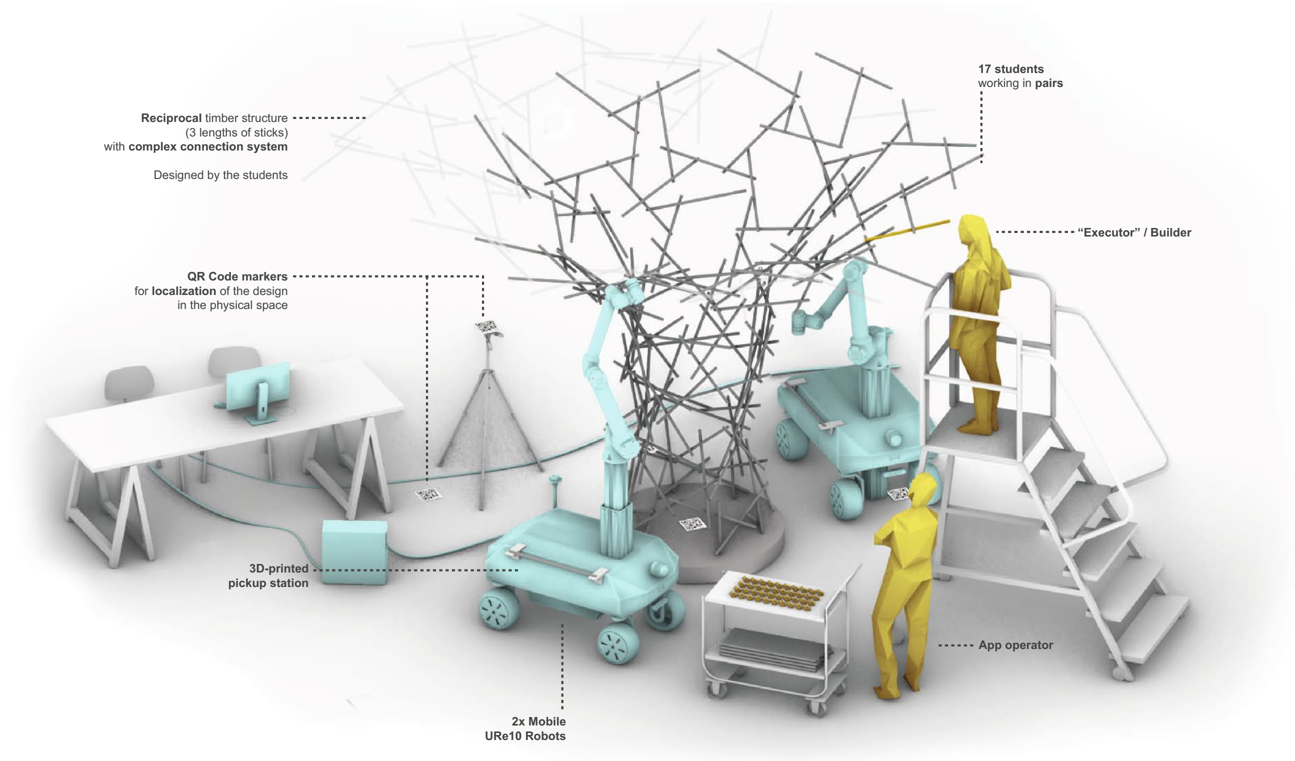

Fig. 13 Fabrication setup that was used for study 1

Fig. 14 Hardware setup of the system in Study 1. **(A)** CAD computer, **(B)** mobile UR10e robot 1 ("AA"), **(C)** mobile UR10e robot 2 ("AB"), **(D)** timber strut pick-up station, **(E)** 2D QR code markers, **(F)** 2D QR code markers on a tripod, **(G)** mobile device with AR application, **(H)** custom 3D printed pneumatic parallel gripper

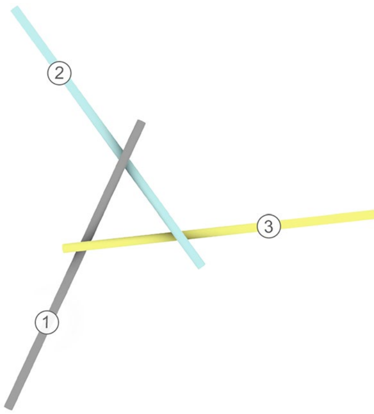

Fig. 15 (**1**) Already placement element from a previous triplet (**2**) Robotically placement element (**3**) Manually placed element

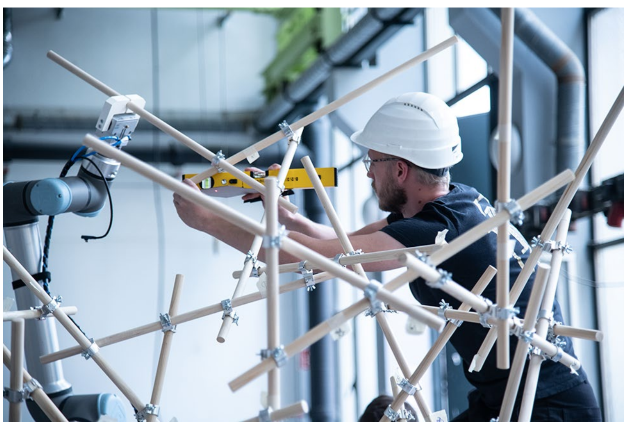

Fig. 16 The series of steps that the participants had to follow for the manual placement of struts

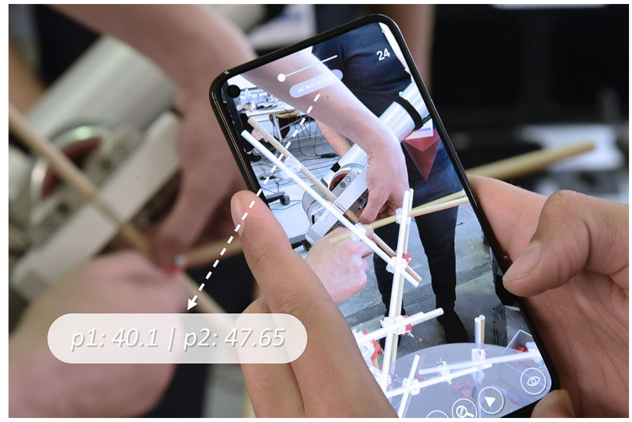

Fig. 17 The lengths of the vertical distances from the both ends of the current element

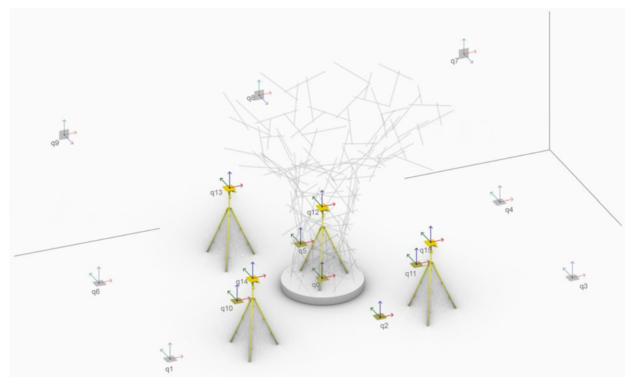

Fig. 18 Taking physical measurements to validate the placement of an element.

single reciprocal frame unit, showcasing intricate connecting system, and constructed with struts of 20 mm diameter and 600/700/800 mm length. Off-the-shelf swivel coupler clamps (see Fig. 7(2)) were used as connecting system and were manually locked in 60 degrees rotation prior to the assembly of the structure as shown in Fig. 7(1).

In preparation for the experiment, the students dedicated a day to familiarize themselves with the AR application and the sequential fabrication steps. A series of steps were devised to ensure the precise placement of each element and they are summarized in the Fig. 16. The operator, utilizing the AR application and guiding the assistant to place the strut in an approximate position that closely aligned with the augmented content displayed on the phone. The operator relied on the augmented visual cues to ensure an overlap between the digital model and the physical element. Subsequently, they positioned the required joints based on the augmented content's instructions, ensuring accurate alignment with the virtual representation.

At that stage, our system provided only visual information on tracking accuracy, making users dependent on visual cues, and more specifically, an overlay of the digital model onto the physical space, to determine if an object is placed correctly or if the phone is still tracking accurately. After an initial test round, we observed that some participants were very precise in following the instructions on the phone and overlaying the digital with the physical elements. However, some students lacked the patience or precision to pay attention to these visual cues and either did not restart the tracking algorithm when needed or placed elements correctly only from one perspective. This inaccuracy led to an increased accumulation of errors. Therefore, during experimental study 1, we developed a feature to allow users to cross-check their precision not just through visual cues but also by incorporating additional information for physical measurements on the UI (Figs. 8b, 17). Once a strut was secured in place, users could measure the vertical distance from each of its ends to the ground (Fig. 18) and

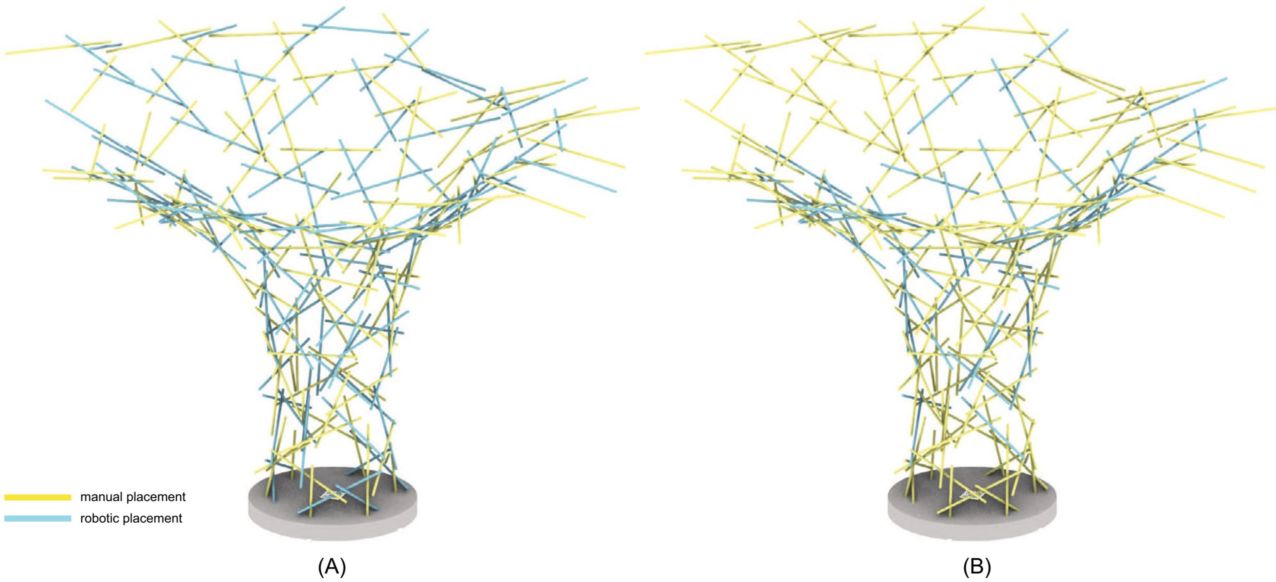

Fig. 19 The positions of the 2D markers for the localization of the digital model. **q0**: World coordinate system/textbfq1,q3,q4,q6–q9: Never used/**q0,q2,q5,q10–q11**: Used for the placement of elements 0–100 / **q12-q15**: Used for the placement of elements 101–153

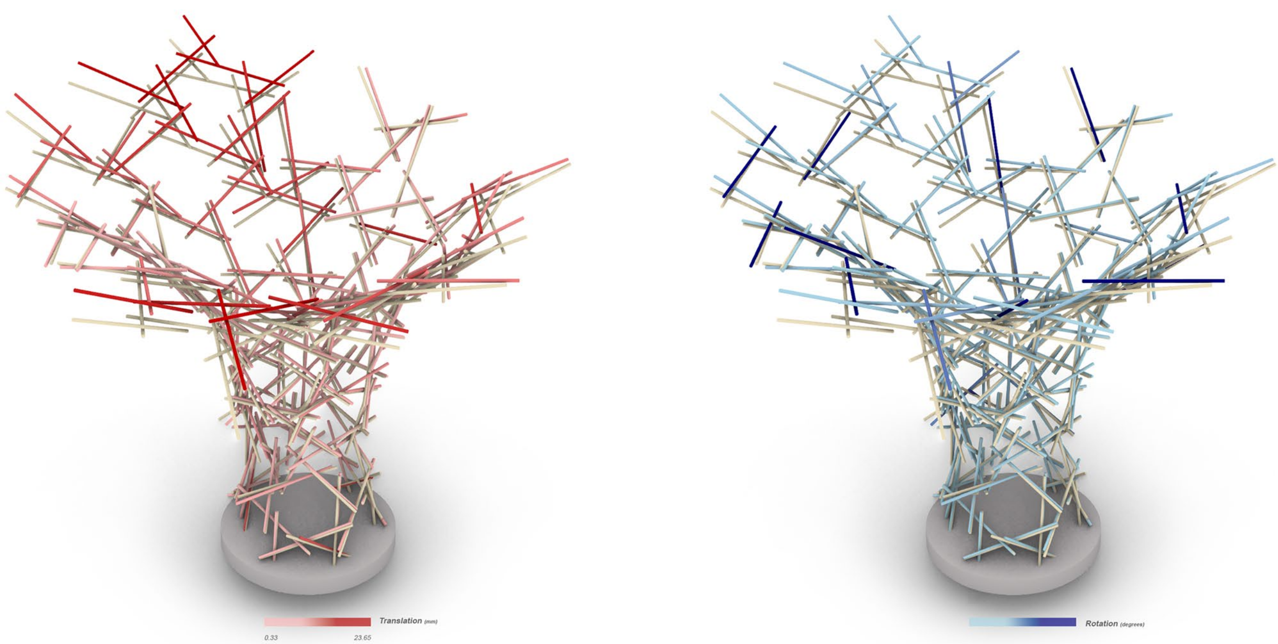

Fig. 20 (**A**) Designated placement type: Elements assigned for manual placement are highlighted in yellow, while those designated for robots are marked in blue. (**B**) Ultimately, 25 of the 72 elements assigned to robots (highlighted in blue) were placed robotically

then carefully adjust it to match the measurements of the digital model. Users could decide how often they wanted to use this feature; however, we observed that they checked the approximate precision in a fast manner (< 10s) for each element. These checks were not aimed at achieving sub-millimeter precision but rather to help users understand if they were accumulating larger errors and to fabricate the structure within an acceptable precision, as described in Sect. 4.1.1. Another very important observation was that for every element that was placed robotically, there was a noticeable back-and-forth between the assembly site and the computer station in order to request, receive, approve and execute a robotic action.

Tracking: To localize the digital model in physical space we placed a 2 × 3 grid of unique QR code markers, each measuring 15 × 15cm, with uniform spacing of 3 ms (q1–q6, as shown in Fig. 19). Additionally, 3 QR code markers were placed on the wall (q7–q9) at a height of 1.8 ms in respect to the grid, with the expectation that they will be useful for the assembly of the higher sections of the structure. The center point of the structure's base was aligned with the center of the grid. Primarily, the two QR code markers nearest to the base were used, while those at the periphery of the grid and the wall-mounted markers saw no usage due to their distance from the assembly area. Attempts to integrate these less-utilized markers resulted in notable discrepancies between the digital model and the physical structure, because we observed a reduction in tracking stability when QR code markers were not within the phone's view and in close proximity to it. Consequently, by the second day, two more QR code markers (q10–q11) were strategically positioned around the base, each at a distance of 1.5 ms from the base's center, and one directly atop it (q0). However, as the structure's height increased, new challenges emerged due to the increasing distance of QR codes from the assembly area. Consequently, four additional QR code markers (q12–15) were strategically placed on tripods and their precise locations measured with the robots. Three of them (q13–q15) were positioned around the structure, while one (q12) placed internally to optimize localization accuracy.

4.1.1 Precision and accuracy of experimental study 1

The original design of experimental study 1 involved 200 elements, equally designated for manual and robotic placement. However, only 153 elements were ultimately placed, with only 25 assembled robotically, as seen in Fig. 20. For the remaining elements, users dynamically shifted the task distribution to humans while fabricating, by using the "Parameter Adaptation" feature of the application, as described in Sect. 3.4.2. This adjustment became necessary because placing those elements would have required repositioning the initially assigned robot to reach them. Such a process would have been time-consuming, increased the structure's deformation, and could have caused significant delays to the fabrication timeline.

At the conclusion of the first case study, we conducted a 3D scan of the final timber structure to enable a comparative analysis with the designed model. After 3d scanning the final structure, we extracted the precise positions and rotations of each timber strut, as depicted in Fig. 21. Notably, for 128 elements, the deviation fell below 10 mm, with 90 of them registering deviations below 5 mm. It is evident in the Fig. 21 that the element's translation and 3D rotation deviation were related; elements with high deviation in translation also exhibited high deviation in 3D rotation. Considering the accuracy expectations of the used AR technologies, which typically allow for a margin of error of 20 mm, our combined approach of integrating AR technologies with physical measurements had significantly minimized inaccuracies. This is also evidenced by the fact that only 6 values exceed this threshold. This values represented elements at the top of the structure, where not only the inaccuracy was higher but also the deformation of the structure due to the nature of its elements and connecting system.

4.1.2 Userstudy 1: architects and engineers

After the completion of the fabrication workshop, the participants and users of the AR application were asked to fill out a paper questionnaire following the Post-Study System Usability Questionnaire model (PSSUQ) (Lewis 1992) and extended it to include the following open-ended questions:

1. In what situations was the AR application most helpful, and in what situations was it difficult to use?
2. What functionalities or visualizations in the AR application did you find most helpful throughout construction?
3. What functionalities and improvements in the AR application would facilitate a better construction process?

Additionally the questionnaire offered a comment section for more open-ended notes by the participants. The PSSUQ (Version 1) consists of 18 items using a 7-point Likert Type Scala. The PSSUQ score starts with 1 (strongly agree) and ends with 7 (strongly disagree). The lower the score, the better the performance and satisfaction. The evaluation of the PSSUQ can further be broken into four categories: Overall score, System Usefulness (SYSUSE), Information Quality (INFOQUAL) and Interface Quality (INTERQUAL). To avoid social desirability bias, the survey was conducted anonymously and in solitude, and before the task, participants were informed about the anonymity of the quiz.

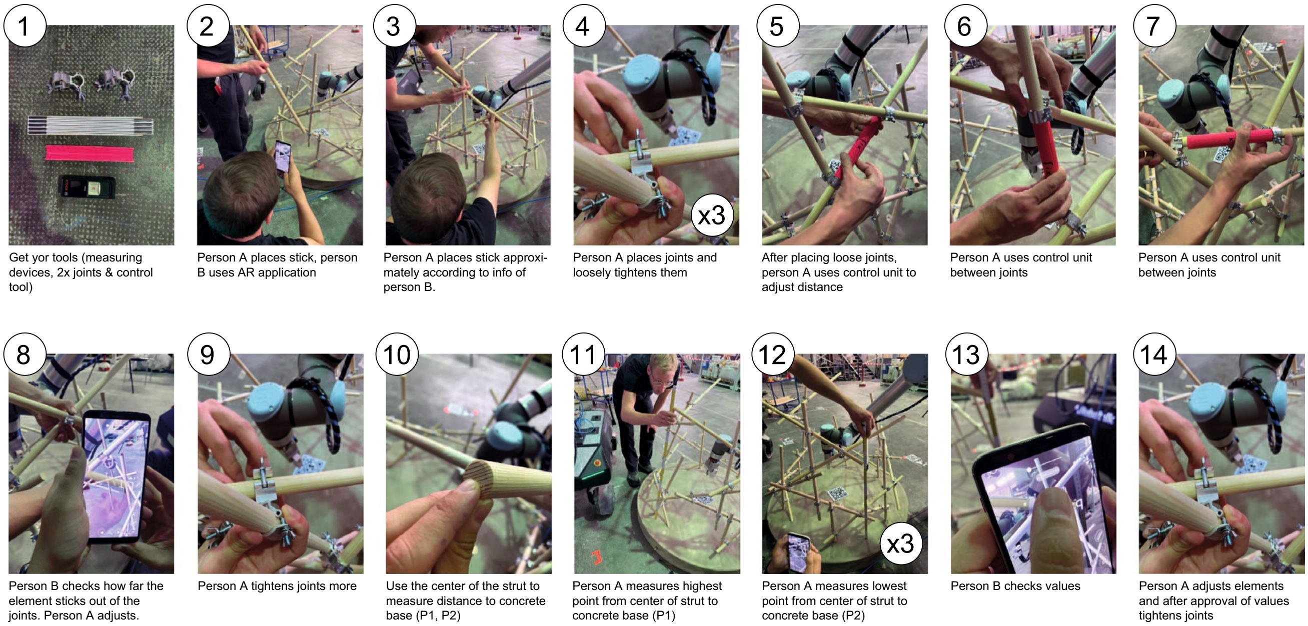

Fig. 21 The color gradient (red for translation and blue for rotation) illustrates the deviation between the final 3D scanned elements and their position in the 3d model

Overall system scored 2.8. Users were excited to engage with workflow instructed by the application. Overall, users enjoyed the simple user interface and described visualization options such as the assigned executor for each element, its ID, and joints, along with functionalities like adjusting attributes, very helpful. However, during fabrication, localizing was described as difficult for users, while new users required extra guidance and verbal instructions. As described by some, "*it was not very intuitive in the beginning, but learning it was quite simple in the end*". This frustration could be improved by including more explanatory systems within the application. Additionally, some suggested implementing a "search by key" method to find specific elements faster. They also recommended increasing the transparency of already placed elements, as the solid color made it difficult to check the overlay with their digital twins.

System Usefulness scored 2.8, and participants underlined the usefulness of the application as helpful for positioning objects in space accurately. However, users expressed frustration with accuracy and the need of continuous rescanning of QR code markers, particularly when the structure reached larger heights. Additionally, users found manual check measurements beneficial but suggested including additional measurements, such as distances between joint locations, as an area for improvement.

Information Quality scored 3.0. Users were pleased with how well the information was organized on the system screen and found it easy to locate the information needed to complete their tasks effectively. However, they expressed a desire for improved clarity regarding error messages. At that stage of the application's development verbal instructions from us were the sole means of informing users when an error occurred.

Interface Quality received a score of 2.40. Users noted that the system interface was pleasant and fulfilled their expectations by encompassing all the functions and capabilities they anticipated.

User engagement throughout the study remained constant. However confidence and ability in application interaction greatly improved with experience, which led certain users to have a better understanding and engagement than others. Notably, all participants were novices in digital fabrication processes, although they had prior experience with CAD programs and software used throughout the design of the structure. An additional study with users unfamiliar with the design process and CAD software might prove beneficial for the overall understanding.

4.2 Experimental study 2: small-scale assembly with AR-assisted robot interaction

The second case study extended upon results from Study 1, additionally incorporating toolpath visualizations of the robot and robot control through the MQTT communication protocol. This decision arose from the observation of

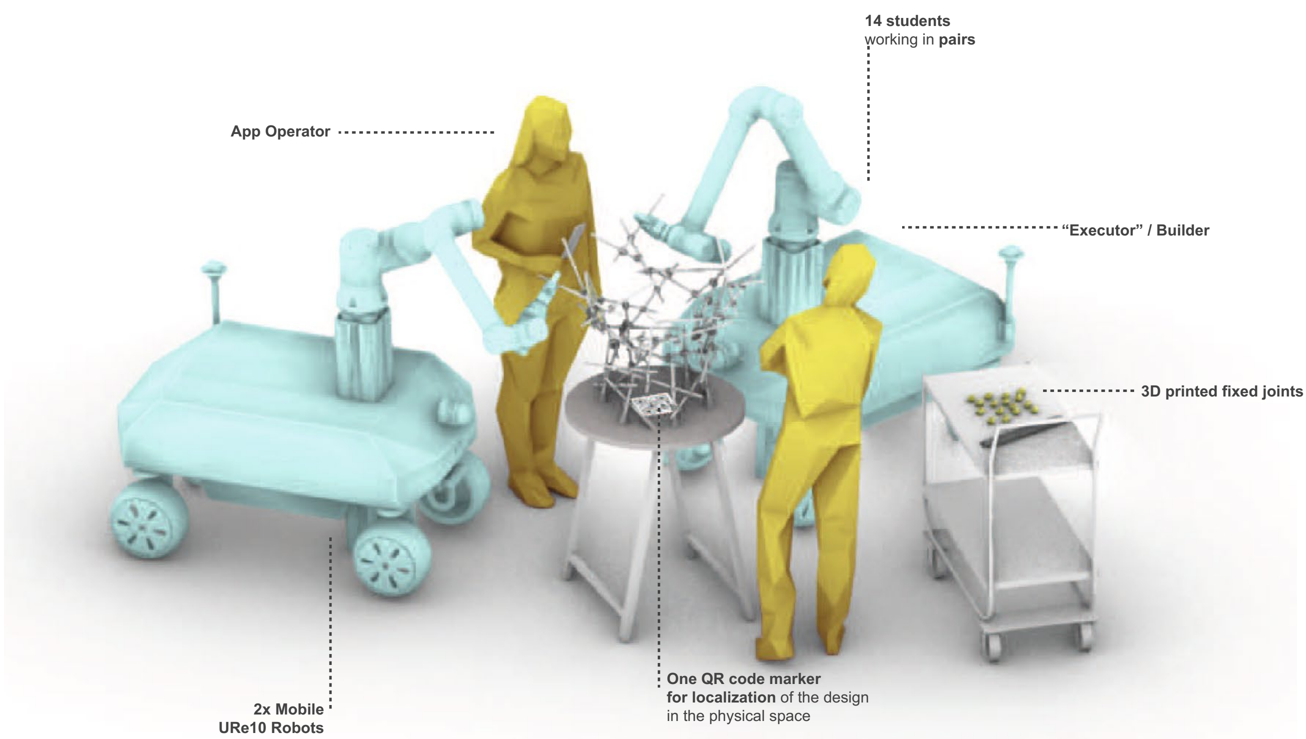

Fig. 22 The Fabrication setup that was used for Study 2

significant back-and-forth between computers, phones, and robots to send and receive robot's commands.

Study 2, titled "Augmented Collaborative Robotics Workshop" was a half-day workshop hosted as part of The Future of Construction Symposium at TUM in Munich. This workshop featured 15 participants between the ages of 23–33 from diverse backgrounds, including architects and researchers from various universities.

The workshop's setup (Fig. 22) closely resembled that of Study 1. However, one of the primary objectives was to assess the following new features of the AR application. Users were able to visualize in physical space not only the expected position of the robots for each element (Fig. 4) but also the trajectory of the robot for placing it (Fig. 3(3)). Through the AR application, they had the ability to control the robots' actions directly from the assembly area without the need to return to the computer.

In this study, the focus was on a smaller scale reciprocal timber system. This intricate structure required fixed 3D printed joints (Fig. 7(3)) and utilized struts measuring 350 mm in length and 10 mm in diameter. The design for this project was conceived by Lidia Atanasova. Due to the reduced scale of the structure, only one QR code marker was required for localizing the model of the structure in the physical space, and it was placed at the top and center of the base.

The workshop commenced with a comprehensive introduction to the AR application and its functionalities, as well as a walkthrough of the fabrication steps. Equipped with this knowledge, participants assembled the 20 elements of the structure, guided by the principles established in Study 1, as shown in Fig. 16. Following the assembly of the initial 26 elements, participants engaged in an additional assembly cycle of two elements, one placed by a robot and another one manually. In this cycle, that the participants repeated multiple times, they tested the application's feature that allows complete control of toolpath calculation and manual trigger the robotic placement through the application. The decision to place most of the elements manually in this cycle was primarily due to the limited duration of the workshop, ensuring

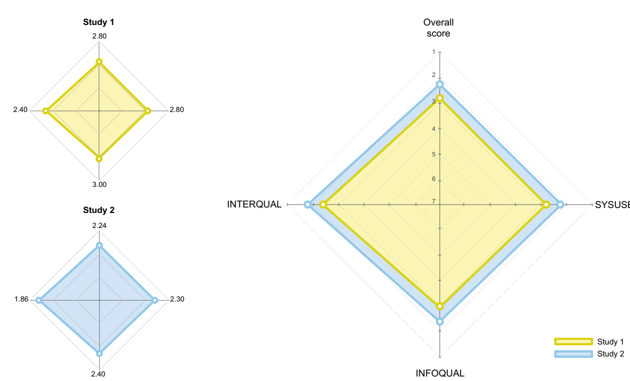

Fig. 23 Results of user-study 1: Architects and Engineers, and user-study 2: Architects and researchers in the field of digital fabrication

that all participants could gain hands-on experience in AR-assisted assembly.

4.2.1 Userstudy 2: architects and researchers in the field of digital fabrication

Following the completion of the workshop, participants were asked to provide feedback using the same paper questionnaire employed in Study 1.

The evaluation of the AR application in Study 2 revealed the following insights (Fig. 23).

The application received an *Overall System* Score of 2.24, indicating a generally positive reception among participants. Comments included acclaim for the clear and uncluttered interface. Users found it intuitive and easy to navigate.

System Usefulness scored 2.30. Participants highlighted the application's ease of use and intuitive interface. However, some users noted occasional difficulties in distinguishing between physical sticks and digital representations due to color and opacity similarities.

Information Quality scored 2.40, with participants acknowledging the clarity provided during the presentation. Some users suggested including explanatory text for application's buttons and a mandatory "tour" of functions would be beneficial for first time users.

The *Interface Quality* received a score of 1.85. Users enjoyed its UX design, highlighting its clarity and cleanliness. Despite this, some participants suggested improvements, such as the option to hide pieces that were already placed.

The users' feedback offered valuable insights into the usability and effectiveness of the application, particularly regarding the new feature. They appreciated the visualization of the robot's trajectory, noting its usefulness in understanding robotic construction in real space and scale. Additionally, they commented that the ability to choose between different robot configurations enhances the application's utility for safety and collision prevention with already-placed elements. Participants also valued the ability to adapt certain parameters within the application, providing them with greater control and flexibility during fabrication. However, they highlighted challenges, such as difficulties related to the instability of the current tracking methods. They also suggested the inclusion of a verification mechanism for the state of the QR code marker tracking, along with real-time feedback on stick placement accuracy.

5 Discussion on results

This section discusses the outcomes of our conducted experiments with a specific focus on the reasons behind the system's effectiveness, how beneficial it is for digital craft, and its potential success in larger real-world scenarios.

5.1 Effectiveness of CAA

Based on the results of both studies, CAA could be seen as a highly useful tool for complex assemblies, primarily due to its intuitive user interface that proved accessible to novices. In both scenarios, challenges related to localization with marker detection arose. To address the inaccuracies of the current tracking methods, physical measurements were incorporated into the assembly process. This adjustment not only increased fabrication speed but also offered a fast and pragmatic solution to a challenge inherent in current AR technologies. Notably, the system catered for different levels of expertise and was adaptable to the project's requirements. For first-time users, the system provided comprehensive information about each element, including dimensions, unique object IDs, and guidance for connecting different elements. In contrast, experienced users or those deeply involved in the design process could choose to focus solely on the position information of each element. An additional advantage lies in the system's ability to accommodate robotic control with multiple robots, providing users with complete control over the fabrication process. Users had the flexibility to intervene, reassign tasks, and make real-time judgments. In this method digital models were no longer static representations of a desired outcome, but serve as opportunities to record additional information that can serve as a live record of incremental decisions made throughout the construction process.

5.2 Benefits of CAA for digital craft

"Technological developments, tools, and processes have consistently expanded the creative horizons of craft practitioners, with digital technology being no exception" (Treadaway 2007). However, the current landscape of digital fabrication often follows a linear trajectory, primarily relying on automation over manual craftsmanship. This inclination towards automation, while efficient for repetitive and precise tasks handled by robots, tends to sideline the intricate and nuanced skills of human artisans. The introduction of CAA aims to address this challenge. By facilitating human-robot interaction, CAA aims to harness the strengths of both entities - humans excel at intricate tasks, while robots are adept at repetitive precision. This application introduces a human-in-the-loop approach, emphasizing the cooperation between digital techniques, such as robotic placement of elements, and craft skills, such as handling intricate joints. The goal is to demonstrate how the combination of technology and craftspersonship can enrich the creative process. While full automation of complex tasks currently has limitations, CAA aims to combine human dexterity with robotic efficiency, offering a more holistic and inclusive approach to digital craft (Fig. 24).

Fig. 24 The final pavilion, consisting of 153 timber struts, was assembled by 17 people working in pairs, cooperating with two robots

5.3 Real-world applications

Potential real-world applications of CAA can be found in robotic processes that require human involvement and flexibility, such as timber prefabrication with complex joint placement, custom robotic timber assembly and spatially complex on-site modular construction. In all of these scenarios, robots can be used to manipulate and place heavy elements such as beams and panels. At the same time, humans can take over the task of precise assembly and joint placement, finishing, quality control and monitoring. In such applications, CAA is a valuable tool that can be used for both manual and robotic tasks. Additionally to these potentials for real-world applications, CAA relies solely on smartphones or tablet devices, which can be seamlessly integrated into in-situ fabrication scenarios due to their cost-effectiveness and accessibility. The reason why we decided to use these devices is that they are not unfamiliar to construction workers, as they currently use them for construction supervision. Moreover, the application allows for loading, controlling, and supervising multiple robots and different types of robots on-the-fly, minimizing the back-and-forth between computers and the assembly site. However, depending on the scale of building elements and the overall project, the use of collaborative robots is recommended, as they enable users to work in close proximity and are well-suited for processes involving human cooperation and a wide array of applications. A solution for large industrial non-collaborative robots is not currently available and would require significant development on multiple fronts, such as safety. Lastly, the process demonstrated success in assisting the fabrication of a complex construction system with intricate joints, as showcased in the reciprocal timber frame structure. However, CAA is adaptable to various construction assembly systems, catering for a broad spectrum of potential practical use cases.

6 Limitations, challenges and outlook

Although our system shows promise, it is important to acknowledge its limitations and the challenges we faced during the development of the application. The biggest limitations of CAA are currently the used tracking methods such as the detection of Image Targets. Two main issues arise with this tracking method: Firstly, it relies on the user to ensure tracking accuracy, which can easily lead to errors. Secondly, it demands a time-intensive physical measurement of the images targets in space, as described in Sect. 3.5.2. To streamline this process, a more adaptable system for adding new image targets on the fly is necessary. This could be achieved through robotic measurement, as demonstrated in the integration of additional QR code markers in experimental study 1 (see Sect. 4.1). In the future, a feature to control the robotic measurement of points through the phone can be integrated into the AR application. This functionality would not only facilitate the measurement process but also assist users in validating key points of the structure.

Nevertheless, the deviations and inaccuracies of the tracking are currently mainly related to the low spatial resolution ability of the mobile devices that were used and not to the placement of the Image Targets. To mitigate this problem, the proposed solution involves integrating physical measurements into the workflow. This approach enables users to enhance accuracy beyond visual overlay. Moreover, to further improve accuracy, it would be possible to pair the system with another tracking algorithm providing more accurate positioning, such as Motion Capture techniques. However, it should be noted that newer generations of mobile devices with better AR technology may automatically improve the results of applying the exact same AR application with the same setup. In that case, the complexity of the system can remain low and easily transferable to a larger scale. A near-future next step would be to test the accuracy of the tracking system on a device with a Light Detection and Ranging scanner, as it enables more precise depth perception and improves depth sensing (Wang 2021).

Another area for improvement is related to security. At the moment, users weren't authenticated before accessing the application and the data. In the next iterations of the AR application more security requirements should be met to ensure data integrity.

Future research should also aim to include a more diverse user pool, both in terms of expertise and background, to better comprehend the broader implications of AR applications in digital fabrication processes.

Additionally, different assembly scenarios with various materials should be tested to understand the application's effectiveness across diverse design projects, assembly methods, and scales. This exploration will uncover opportunities for improvements tailored to specific assembly methods and materials, enriching design possibilities and applications.

During the course of this research, several challenges were encountered that are worth highlighting. One significant challenge related to the safety of humans working closely with robots. The research necessitated human-robot interaction, hence the selection of small collaborative robots. However, an operator always had to be present to stop the robot in case of an emergency. For taller and larger structures, industrial robots with a higher payload and larger reach might be preferred. This will require additional safety measures or features in the application to ensure a safe working environment for humans.

Lastly, another challenge pertains to the user interface of the application. Designing a comprehensive and self-explanatory interface is inherently difficult. Therefore, as mentioned in Sect. 4, while the application was easy to learn, a help section, possibly as a mandatory step-by-step guide for first-time users, should be included in the next update to further assist users.

7 Conclusion

This research explores an adaptive digital fabrication approach that leverages AR technologies to enable human–machine cooperative processes. A key output is an AR application for mobile devices that enables instructions for manual tasks, and supervision and control of robots during assembly processes, with an intuitive interface, eliminating the need for transitions between computers, phones and robots. The primary objective of the AR application is to infuse flexibility into digital fabrication processes by linking geometric information with fabrication attributes, structured in a task shop format. This allows users to intuitively adjust the distribution of tasks throughout fabrication. The second key outcome of the research is the development of a data-structure, that streamlines the interaction between design, fabrication, and user input.

Our experimental studies, which engaged architects, researchers, and engineers, provided valuable insights into the effectiveness of CAA. The system's intuitive user interface, demonstrated in both large-scale and smaller-scale assembly scenarios, proved accessible to users with varying levels of expertise. Noteworthy features include the system's flexibility in task allocation between humans and robots, real-time decision-making capabilities, and the dynamic nature of the digital model, all contributing to its adaptability.

In contrast to current digital fabrication processes, that often sideline intricate and nuanced skills of human artisans, CAA aims to a more holistic and inclusive approach to digital craft. The benefits of CAA for digital craft lie on its ability to harness the strengths of both human craftspersonship, such as intuition and dexterity, and robotic precision. The system introduces a human-in-the-loop approach, emphasizing cooperation between digital techniques and craft skills.

Upon examining the real-world applications of CAA, we acknowledge downtime during repositioning, and the need for optimization in on-site scenarios. The limitations of the current system include tracking accuracy challenges and low security on user's registration. Future developments could improve tracking accuracy, and explore applications across different construction methods and materials.

In summary, CAA emerges as a promising approach for enhancing human–machine cooperation in digital fabrication processes. As we continue refining and expanding this system, our goal is to develop user interfaces that incorporate humans' strengths and their actions into robotic fabrication processes, stimulating further discussions about the role of humans in the future of AEC.

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Data availability All data that support the findings of this study are included within the article. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no Conflict of interest.

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