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RESEARCH

Building (with) human–robot teams: fabrication-aware design, planning, and coordination of cooperative assembly processes

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Abstract
This research presents a comprehensive methodology for designing and fabricating spatial timber assemblies using cooperative human–robot workflows, enabling the on-site construction of complex structures that exceed the capabilities of humans or robots alone. At the core of this approach is a rule-based design method—termed assembly grammar—which defines not only geometric configurations but also sequences of interdependent physical tasks for assembling reciprocal frame-like structures cooperatively. This methodology integrates user-defined design intentions with equilibrium conditions and fabrication constraints specific to both robotic and manual processes. The design is stored using a graph-based assembly model, which captures geometric information alongside task-related data such as task assignments, robotic fabrication parameters, and assembly sequences. Complementing the design workflow, the methodology also includes strategies for effectively coordinating and distributing tasks between humans and mobile robots, supported by a custom-developed mobile augmented reality (AR) application. To validate the approach, a fabrication-aware design tool was created and applied for generating complex reciprocal-like timber structuresfor scaffold-free in-situ cooperative assembly. The coordinated assembly methodology was then demonstrated through the successful construction of two architectural-scale timber demonstrators built cooperatively by multiple humans and robots. Evaluation criteria such as assembly accuracy and the effectiveness of human–robot interaction demonstrated the practical benefits and applicability of the methodology for real-world construction scenarios.

Keywords Construction robotics · Human–robot cooperative assembly · Task distribution · Task assignment · Cloud data

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1 Introduction

Recent years have seen significant technological advancements in robotic assembly systems, both in prefabrication settings (Willmann et al. 2016; Apolinarska et al. 2016) and through in-situ fabrication scenarios (Dörfler et al. 2016, 2019). These developments have expanded architectural design possibilities, enabling the fabrication of highly complex geometries while improving productivity and precision. However, most in situ construction processes are still manually performed (Everett and Slocum 1994; Soto et al. 2018) raising essential questions about several barriers to technological adoption of robots directly on building sites. Some critical challenges lie in the unstructured nature of construction environments, directly affecting the complexity of construction tasks. These require long-horizon planning and real-time decision-making in unpredictable environments and constantly changing workspaces-conditions that differ significantly from prefabrication in controlled industrial settings. Construction workers typically must plan, gather tools and materials, and navigate the workspace while performing construction work (Everett and Slocum 1994) and constantly adapt their plans. As a result, many construction tasks remain challenging to automate and are likely to continue relying on manual execution (Zhang et al. 2023). For example, tasks requiring repetitive motions, spatial precision or physical endurance are better handled by robots, while those demanding dexterity, adaptability, and contextual judgment are better handled by humans (Everett and Slocum 1994). Robots may also struggle to adapt to complex situations or to unforeseen events that require flexibility, tasks that humans typically handle more effectively. These complementary strengths highlight the potential benefits of integrating both robots and humans in construction workflows (Skibniewski and Nof 1989). As the adoption of robotics and automation continues to grow, their successful implementation will increasingly depend on effective human–robot collaboration (HRC) (Yang et al. 2024).

The classical manufacturing domain has developed sophisticated HRC methods for assembly tasks (ElMaraghy and ElMaraghy 2016), including collaborative strategies where humans and robots share workspaces for hand-over tasks, sequential operations, and synchronized movements (Michalos et al. 2015). These approaches are supported by advanced interaction interfaces, from gesture-based control to augmented reality (AR) task guidance (Liu and Wang 2017; Wang et al. 2020), and have been implemented in both single- and multi-robot applications (Papakostas et al. 2011; Boschetti et al. 2021). However, despite these developments and their successful integration with humans (Wang et al. 2020), the robotic construction domain still struggles to adopt such approaches and effectively include humans in robotic processes. This challenge arises partly from the fundamental differences between manufacturing and construction environments. Unlike the controlled factory environment, where human workers, robots, and industrial assembly lines have predefined locations, construction sites are primarily unstructured working environments that pose unique challenges (Bock 2015). Robots must navigate through constantly changing spaces rather than remain in fixed positions, avoiding temporary obstacles and adapting to varying ground conditions (Lundeen et al. 2019). Materials and tools are often scattered across the site instead of being systematically arranged in predefined locations, requiring flexible logistics and handling strategies (Soto et al. 2018). Moreover, the scale of construction and payload requirements for construction tasks further distinguish construction from the manufacturing domain (Bock 2015), with elements often being too large or heavy to handle and requiring careful consideration of structural stability during assembly (Parascho et al. 2020a). Therefore, the construction environment poses significant challenges to the transfer of HRC methods.

To address these challenges, an integrated approach is needed—one that unifies design, planning, and execution by considering both the capabilities and constraints of human and robotic agents from the earliest stages. Such an approach requires the coordinated distribution of construction tasks across multiple agents—both humans and robots—using novel computational design-to-fabrication workflows that reflect the dynamic, non-linear nature of construction. These workflows must support versatile fabrication processes while incorporating the performative and temporal aspects of multi-agent assembly, particularly the definition, sequencing, and execution of interdependent human and robot tasks. Crucially, methods for adaptable task assignment must be developed and embedded from the early design stages, enabling resilient and responsive coordination within human–robot teams during construction.

Within this context, this paper presents two complementary methodologies: (a) A computational design methodology that considers and integrates human and robot capabilities already from the earliest design stages and (b) A cooperative fabrication workflow for the physical realization of spatial timber assembly structures by multiple agents—humans and robots (Fig. 1).

The proposed computational design methodology (a) expands existing fabrication-aware workflows, which typically focus exclusively on robot-only processes, by explicitly incorporating human–robot cooperation. It considers not only robotic fabrication constraints but also integrates the roles and capabilities of human agents, enabling the simultaneous generation of assembly geometry and task data for both. This fosters an integrated, cooperative design-to-fabrication process. The workflow uses graph modeling for both spatial (geometry) and temporal (human and robot tasks) representations, collectively referred to as the assembly model (AM). Each design generation step corresponds to a set of human and robot tasks, representing a structured yet adaptable plan that considers both agents' skills and fabrication affordances. Through an interactive digital design process, designers can generate spatial assembly structures that balance design intent with fabrication and equilibrium constraints. These principles are embedded in a prototypical interactive design tool that provides real-time feedback to support decision-making. As such, the outcome encompasses both the assembly model and a complete assembly sequence, ensuring process feasibility.

The multi-human–robot cooperative fabrication methodology (b) addresses the challenges of coordinating multi-agent teams in dynamic construction environments. While using the planned assembly sequence and task assignments from the design phase, it leverages the AM's graph structure to enable flexible in-process task reassignment when necessary.

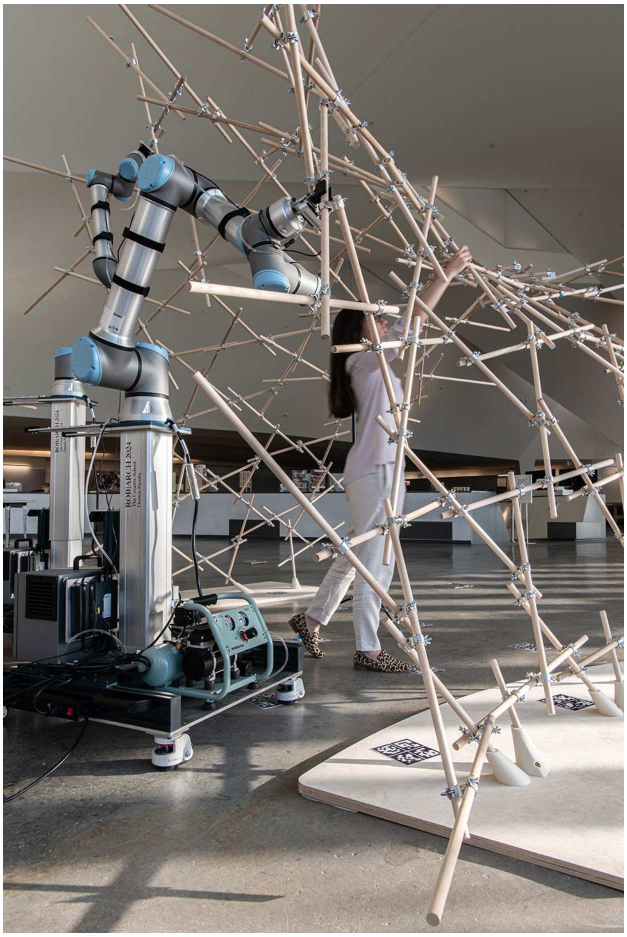

Fig. 1 Human–multi-robot cooperative assembly of a timber structure

This builds on our research on multi-user augmented reality for collective assembly (Atanasova et al. 2023) and hybrid human–robot cooperative assembly (Alexi et al. 2024), implementing a turn-taking coordination strategy and flexible reassignment by linking the AM with the shared physical workspace through an AR interface. The custom AR system accesses the cloud-hosted AM to provide real-time, context-aware instructions to multiple users and enable alternation of planned assignments, ultimately supporting human–robot interaction. Coordination is facilitated by overlaying digital content, such as human task guidance and robots' planned locations and trajectory previews, onto the physical environment, helping builders anticipate and control robotic tasks. Furthermore, the interface communicates reassigned tasks to all users by continuously synchronizing the AM and physical assembly process upon input. The process remains adaptable to changing conditions, such as robot unavailability, trajectory calculation failures, reachability limitations, extended robotic support durations, or cases where manual placement proves more efficient. These conditions require human judgment to strategically reallocate tasks among robots or dynamically reassign them between humans and robots, ensuring continuous assembly progression. This adaptive approach helps manage unforeseen events and promotes efficient use of resources by balancing the complementary capabilities of humans and robots.

The proposed computational design and cooperative fabrication methodologies encompass:

- **A graph-based assembly model (AM) for distributed human–robot assembly** storing and managing geometric and topological data of the architectural design, integrating design- and fabrication-related attributes along with assembly sequence dependencies.
- **A task representation and assignment strategy** for human and robot tasks combining skill-based task assignment during the design phase with affordance-based task reassignment during fabrication.
- **A fabrication-aware design methodology** employing growth-based, bottom-up design algorithms to generate complex assembly structures for multi-agent teams of humans and robots. This methodology refines the skill-based task assignments by simultaneously considering assembly logic, design criteria, and structural and fabrication constraints.
- **A task distribution and coordination strategy** implementing the planned task assignments through a cloud-hosted digital design model, accessible to multiple backend processes and devices, including the AR mobile interface to enable real-time human–robot interaction, turn-taking task coordination, and affordance-based reassignment.

The proposed methods are validated through two experimental case studies, demonstrating different approaches to scaffold-free assembly of full-scale reciprocal-like timber structures, with mobile robots assembling and acting as temporary structural supports. *Case Study* 1—*Turn-taking task distribution for assembling a double-curved funnel structure* explored a funnel-shaped structure assembled through turn-taking placement between humans and two mobile robots. Building on this approach, *Case Study 2—Turn-taking with mobile robotic support for assembling a double-curved shell structure*, introduced an arc-like shell structure where, besides placing elements, robots were essential for providing structural support during critical assembly steps. Both studies investigated this fabrication-aware design approach with two main objectives: designing geometrically stable assemblies (with or without additional structural support provided by a robot) and validating their assemblability through human–robot cooperation. The experimental setup for both case studies utilized a cooperative human–robot team featuring two mobile robotic systems and building teams of 2 people, guided via a custom AR mobile interface to assemble full-scale, complex timber structures. In sum, this research explores the architectural design possibilities enabled by multi-agent assembly systems, emphasizing the benefits of human–robot cooperation in achieving novel and improved results unattainable by humans or robots alone.

The remainder of the paper is structured as follows: Section 2 outlines existing research on multi-agent assembly processes, focusing on design for assembly and planning and coordinating of multi-agent assembly processes. Furthermore, this section identifies research gaps and motivates the proposed methods presented in Sect. 3. Section 4 describes the experimental case studies and the achieved results, followed by the discussion, limitation and future work in Sect. 5 and conclusions in Sect. 6.

2 Background

This section provides the background for the proposed research on fabrication-aware design for human–robot teams. We begin with an overview of multi-agent assembly processes in Sect. 2.1, examining the evolution from single-robot systems to human–robot collaborative teams in construction. This sets the context for understanding assembly challenges and opportunities. Section 2.2 then explores the Design for Assembly principles and their adaptation for HRC, particularly emphasising fabrication-aware design in architecture. Finally, Sect. 2.3 discusses methods for planning and coordinating multi-agent processes, highlighting current approaches and limitations in task planning and real-time coordination for human–robot teams.

2.1 Multi-agent assembly processes

Studies focusing on multi-robot systems for spatial assembly structures have demonstrated the benefits of cooperative fabrication workflows, where these approaches leverage cooperative maneuvers among robots to expand the capabilities of a single robotic agent (Parascho et al. 2017; Thoma et al. 2019). Such approaches have shown the scaffold-free assembly of complex geometries, including brick vaults (Wu and Kilian 2018; Parascho et al. 2020a, b), and discrete shell structures (Wang et al. 2023b). Current efforts in realizing such cooperative manufacturing workflows have also unveiled strategies for efficient assembly planning and complex motion planning to prevent collisions among robots or assembled structures, particularly in setups where robots remain stationary (Bruun et al. 2021). The application of mobile robots instead of stationary machines will additionally ease the adoption of robotic technology directly on construction sites and enable material-efficient construction (Bruun et al. 2024).

Current multi-robot assembly methods have recently also been expanded to multi-human–robot assembly methods to harness human expertise while leveraging the precision and repeatability of robots. Within the Architecture, Engineering, and Construction (AEC) sector, this integration has led to various collaborative fabrication approaches being explored and experimentally validated. Our previous projects like *Prototype as Artefact* (Atanasova et al. 2020) and *Tie a knot* (Mitterberger et al. 2022) demonstrate interactive design and fabrication workflows where multiple agents alternate in placing elements according to predefined rules. Further research has explored hybrid multi-agent collaboration through human–robot collective construction methods (Han et al. 2021; Han and Parascho 2023), digitally instructed human-human collective assembly (Atanasova et al. 2023), and investigations into human–robot collaboration (HRC) in timber prefabrication (Yang et al. 2024). These approaches have been tested through simulation studies for various construction tasks, including drywall installation, painting, bolting, welding, and concrete pouring (Brosque et al. 2020). Proof-of-concept implementations like *CRoW* (Kyjanek et al. 2019) and prefabrication scenarios proposed by *iHRC* (Amtsberg et al. 2021) further demonstrate the potential of hybrid multi-agent collaboration in construction settings.

Despite these advances in both multi-robot and hybrid human–robot systems, integrating design and fabrication processes remains challenging when considering multi-agent scenarios. Current digital design-to-fabrication workflows lack comprehensive methods to represent and plan for the complexity of human–robot interactions from the early design stages. This gap is particularly evident in the absence of integrated design tools that can simultaneously address design intent, fabrication constraints, and multi-agent coordination requirements. While existing approaches excel at either design optimization or assembly planning, they rarely bridge these domains effectively for hybrid teams of humans and robots working together. Therefore, future developments in this field must focus on creating unified frameworks that can seamlessly connect design decisions with their implications for multi-agent assembly processes, ensuring that both human and robotic capabilities are considered from the earliest stages of design through to final construction.

2.2 Design for assembly and graph-based modeling

Design for Assembly (DfA) is a systematic methodology that addresses material and fabrication considerations during the early design phase to optimize assembly efficiency and cost-effectiveness (Boothroyd et al. 2010). Traditional DfA principles emphasize three core strategies: minimizing part count through component consolidation, standardizing components to reduce variety, and ensuring straightforward handling and insertion operations (Boothroyd 1987). These principles have been adapted to accommodate robotic constraints, material behavior, and assembly sequencing within architecture and digital fabrication. In this context, DfA promotes early-stage integration of assembly logic into the design process, enhancing constructability and reducing the need for improvisation during fabrication.

Graph-based modeling has emerged as a key strategy to formalize and manage these assembly constraints. In the graph-based approach, components are represented as nodes while their interconnections form edges within the graph (Hu et al. 2011). This mathematical structure captures both physical connections and assembly dependencies, with the ability to represent hierarchical relationships through nested structures. Nodes carry comprehensive component information, including geometric properties (dimensions, volume, mass properties, centre of gravity), assembly specifications (mating surfaces, orientation requirements), and manufacturing constraints (tooling requirements, assembly times, accessibility needs). This detailed representation enables sophisticated analysis and optimization of assembly processes before physical implementation. The graph structure supports automatic generation and evaluation of assembly sequences (Wang and Tian 2016) as detailed in Sect. 2.3, early identification of potential issues, and optimization for efficiency and cost-effectiveness. Furthermore, nodes can store critical information about material specifications, surface finish requirements, and manufacturing methods, enabling virtual validation of assembly procedures.

While graph-based approaches originated in manufacturing contexts, their application has expanded into architectural design and construction. In architecture, these approaches serve two key purposes: representing assembly structures through components and their relationships (Frick et al. 2016), and describing robotic prefabrication processes through actions, tasks, and jobs (Wolf et al. 2022). To address fabricability challenges in the AEC sector, researchers have developed fabrication-aware and assembly-aware design approaches that build upon these graph-based representations (Pottmann et al. 2015; Kao et al. 2017). These computational methods incorporate fabrication and construction constraints directly into the design phase, such as for the shape-creation process (Pottmann 2012), ensuring manufacturability while preserving design intent. This integration of constraints has evolved from post-rationalization (modifying designs after conception) to pre-rationalization strategies where manufacturing constraints actively inform the initial design process (Austern et al. 2018).

Further recent advances in this field have produced significant developments in assembly-aware design methods. The Grasshopper plug-in *WASP*, developed in Python, enables flexible modular aggregation through various approaches, from random assembly to constraints and performance-driven configurations (Rossi and Tessmann 2017). Due to its discrete nature, the modules allow for a direct translation from design to robotic assembly sequence. The *Coupled Rigid-Block Analysis* (CRA) method enables stability-aware design processes and ensures structural integrity throughout the assembly (Kao et al. 2022).

However, current design approaches face significant limitations when addressing multi-agent scenarios, particularly in HRC. They lack comprehensive methods to represent and plan for human–robot interactions from the early design stages. While graph-based representations provide robust frameworks for assembly representation and planning, they require an extension to effectively visualize and adapt these models for dynamic HRC scenarios. These limitations highlight the need for more sophisticated approaches that can effectively capture and leverage both human and robot involvement while prioritizing the performative aspects of making processes (Knight and Vardouli 2015) rather than focusing solely on the final design. Therefore, this research aims to explore assembly as a series of sequential events with spatial and temporal dimensions, informing novel architectural expressions that arise from human–robot cooperation.

2.3 Planning and coordination methods for multi-agent assembly

The complexity of human–robot cooperative assembly necessitates sophisticated planning and coordination methods that can handle both the technical requirements of the assembly process and the dynamic nature of human–robot interaction. Current approaches address this challenge from multiple perspectives, ranging from bottom-up sequential design, through assembly sequencing, to task segmentation and real-time task coordination.

Traditional theoretical approaches to multi-agent task coordination have established several methods for planning and coordinating tasks across multiple agents. Hierarchical Task Networks (HTN) (Nau et al. 2003) decompose complex assembly operations into manageable subtasks with defined dependencies, enabling systematic planning for multiple agents. Behavior Trees (BT) (Colledanchise and Ögren 2017), with their modular structure, provide flexibility in adapting plans during execution—a critical capability for dynamic environments. These general frameworks have been extended for HRC through specialized planners like Hierarchical Agent-based Task Planner (HATP) (Lallement et al. 2018), which incorporates social rules and task-sharing preferences into the coordination process. The structured hierarchical nature of HATP makes it an ideal framework for embedding complex social rules while maintaining an efficient and organized task-planning process. This hierarchical structure actually serves as a precondition for creating flexible coordination strategies later in the process.

In the AEC sector, assembly sequence planning has seen significant advances, particularly in the context of scaffold-free construction. Wang et al. propose methods for determining assembly sequences that minimize structural deformation during partial assembly stages (Wang et al. 2023a). Their approach demonstrates adaptability to various fabrication setups, including manual assembly with mixed-reality tools and multi-robot systems. A multi-objective optimization process can determine a structurally optimal fabrication sequence by coordinating two to three robots (Bruun et al. 2021).

Task-based segmentation has emerged as a promising approach for managing complex multi-agent fabrication workflows. In prefabrication settings, Skoury et al. (2023) present a unified tasks data model that discretizes design-to-fabrication processes into individual tasks, maintaining links between design elements and fabrication procedures for multi-actor fabrication involving two industrial robots and one human worker. Similarly, Amtsberg et al. (2021) have developed an advanced interactive approach that manages task sharing between humans and industrial robots through AR interfaces and head-mounted displays. For on-site construction scenarios, recent work proposes the integration of 4D Building Information Modeling (BIM) with robot task planning to effectively account for dynamic construction conditions (Oyediran et al. 2024).

More flexible coordination approaches have emerged through our previous research on collective AR-assisted assembly (Atanasova et al. 2023). This work presents a dynamic sequencing method based on module states and their relationships in a graph data structure, enabled by a cloud-hosted digital model streamed on mobile AR devices for coordinating multiple people during assembly. Similarly, projects like *CRoW* (Kyjanek et al. 2019) demonstrate the potential of AR interfaces for facilitating direct human control over robot routines, enhancing the collaborative assembly process through digital data integration.

Despite these advances in multi-agent assembly coordination, significant challenges remain. Existing methods often lack comprehensive methodologies for integrating and managing human and robot actions and interactions into well-defined tasks, particularly in dynamic construction environments. Current sequence-based approaches typically consider either a single agent (human or robot) or multiple agents of the same type exclusively, without addressing the complexities inherent in hybrid human–robot teams, particularly regarding collision detection and agent coordination. Furthermore, human–robot task assignment and distribution approaches frequently rely on precalculated task sequences that cannot easily adapt to changing conditions. These limitations highlight the need for more flexible and adaptive methods for planning and coordinating human–robot teams in construction, potentially leading to more resilient and adaptable assembly processes.

3 Methods

This section presents a generalized methodology for the fabrication-aware design and coordinated assembly of reciprocal frame-like structures by hybrid human–robot teams. It begins by defining a consistent terminology, detailed in Sect. 3.1. Following this, Sect. 3.2 introduces the concept of the *Assembly Model* (AM) for distributed human–robot assembly, a graph-based modeling approach designed to manage digital design data, including geometric information, fabrication-related parameters, and task dependencies—fundamental elements for initiating and coordinating the assembly process between multiple humans and robots. The AM serves as both a representational and operational framework: it encodes the logical and spatial relationships between components and tasks, enabling the assignment and generation of executable tasks for agents involved in the assembly. Section 3.3 explores the performative and time-based aspects of assembly processes and how these are represented and operationalized through the AM, as well as how task sequences and responsibilities are dynamically assigned and reassigned to both robots and humans based on assembly logic, required skills, constraints, and local affordances. Building on the methodological foundations described above, Sect. 3.4 presents the concepts behind the proposed fabrication-aware design methodology, which serves as the basis for the design tool. Finally, Sect. 3.5 outlines a strategy for multi-agent coordination. It explains how fabrication- and task-related data are extracted from the cloud-hosted AM and distributed via a custom mobile augmented reality (AR) application, enabling real-time, on-site collaboration between humans and robots.

3.1 Terminology

The terminology used throughout the work is defined as follows:

Assembly—The process of connecting various parts to build a structure and the sum of the separate parts in one connected structure.

Agent—An individual participant in assembly, either human or robot.

Human–robot collaboration (HRC)—A joint activity involving multiple agents (humans and robots), where tasks are executed simultaneously and usually require direct physical interaction. This approach focuses on shared task execution, where humans and robots work together in close proximity, complementing each other's strengths.

Human–robot cooperation—A mode of interaction where tasks are performed either simultaneously or sequentially by humans and robots without direct physical contact. This type of cooperation emphasizes the sharing of physical, cognitive, and computational resources to achieve common objectives, enabling both human and robotic agents to complement each other's capabilities. As such, this research proposes a human–robot cooperative workflow.

Graph modeling—In the context of managing assembly processes, this refers to a method for representing components and their properties (nodes and node attributes) and their relationships or dependencies (edges) in a graph format. It is used to structure, analyze, and visualize the sequence and interactions involved in the assembly process. This approach helps manage dependencies between structure components, optimize assembly sequences, and encode assembly tasks.

Skills—Represent the agent's (human or robot) capabilities.

Affordance—Represents a possibility for action based on the environment and ongoing processes (Gibson 2014). These action possibilities serve as preconditions for dynamic task assignment, allowing humans to handle tasks previously assigned to robots when robotic assistance is not needed.

Task planning—The initial stage that defines the overall strategy, identifies tasks, sets objectives, and determines the sequence and dependencies of tasks.

Task assignment—The process of allocating individual tasks to specific agents. It involves matching tasks to agents' skills while considering affordances such as availability and following guidelines established in the task planning process.

Task distribution—Refers to the process of dispatching tasks to the assigned agent, both humans or robots.

Coordination—Refers to the process of managing the execution of tasks. The focus lies on synchronizing actions, handling dependencies between tasks, and ensuring agents do not interfere with each other. Coordination is often dynamic, adapting to changes in the environment or task progress.

Fabrication-aware design—A computational design approach combining shape design with essential aspects of function and fabrication (Pottmann 2013). In the context of this research, fabrication-aware design refers to a bottom-up design generation leveraging design criteria, structural and fabrication constraints and multi-agent task assignment.

Assembly grammar—An assembly logic that governs the arrangement and sequence of individual components to form large modular assembly structures. As such, it emphasizes spatio-temporal and performative aspects of assembly processes.

Growth algorithms—methods for controlling the sequential expansion of structures. In the scope of this work, these include the main assembly logic, assembly grammar, the design criteria, and structural and fabrication constraints.

3.2 Assembly model (AM) for distributed human–robot assembly

The proposed methodology introduces a digital data structure—AM—building on and extending *COMPAS Assembly* (Frick et al. 2016), a data structure developed with the open-source Python framework *COMPAS* (Mele et al. 2022), designed for managing and storing discrete element models in architectural contexts.

Utilizing graph theory, the AM integrates the *COMPAS Graph* data structure and allows for storing both geometric

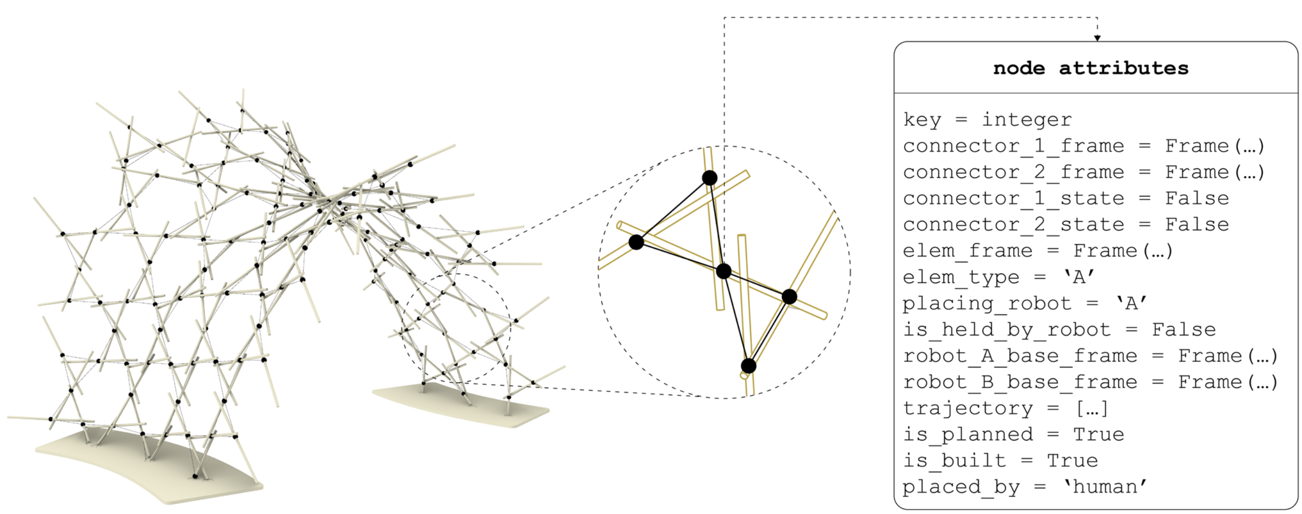

Fig. 2 The AM is stored as a graph data structure, containing geometric and topological information of the architectural design model, connectivity between building elements, and design and fabrication attributes accounting for human–robot task distribution

and topological data, capturing the architectural design and the connectivity and dependencies between individual building components (Fig. 2).

Each graph node corresponds to a distinct building element, identified by a unique ID and associated with design and fabrication parameters. During the design phase, the AM integrates with real-time calculation modules for structural evaluation and robotic fabrication feasibility, while during assembly, it enables progress tracking based on “as-built” states and dynamic adjustments to the stored parameters, such as task assignments and robot frames. Ultimately, the AM functions both as a design data repository and a guide for the physical assembly process, supporting the coordination of tasks among multiple agents.

Each connection between elements within the AM is represented as an edge connecting nodes in the directed graph, where the edge’s direction denotes task dependencies. For example, the placement of one building element may depend on the prior placement of another, as indicated by an incoming edge from another node. The sequential order of the node keys represents the inscribed assembly sequence and, as such, provides one possible ordering.

As the AM guides the physical assembly process, it is fundamental to managing and coordinating tasks within the human–robot cooperative assembly workflow. It supports hierarchical and dynamic planning, organizing tasks based on dependencies while enabling in-process adjustment.

The complete AM, encompassing building geometry, task planning, and fabrication-related data, is serializable as a JSON file and can be uploaded to a cloud-hosted server, enabling user interaction through various interfaces such as PCs, a web interface, and a custom mobile AR interface (Alexi et al. 2024). The AR interface extrapolates data and partially reconstructs the AM data structure within its environment and serves as a communication, task distribution, and coordination interface, as detailed in Sect. 3.5.1.

3.3 Task representation and assignment

The computational representation of tasks is integrated into the AM. Within the graph data structure, nodes represent building element placement, with node attributes storing the task assignment, while edges represent connector placement, with their direction indicating task dependencies (Fig. 3a). This representation encapsulates both spatial relationships and task dependencies required for assembly. By applying topological sorting (Cormen et al. 2022) to the directed graph of the AM, alternative assembly sequences can be computed. This enables flexible ordering of tasks or the parallelised placement of multiple elements based on in-process conditions (Fig. 3b), making it possible to adapt the sequence to unforeseen events.

Building on this representation, the task assignment strategy in the proposed workflow involves two key dimensions: skill-based task assignment during design and affordance-based task reassignment during execution. During the design and planning phase, task assignment relies on identifying the specific skills required for each task and matching them to the inherent capabilities of humans or robots. Tasks requiring dexterity (such as positioning, joining, or feeding elements) or relying on human judgment (such as task verification, confirmation, and reassignment via the AR app) are assigned to humans, while repetitive, spatial precision-based, or stabilization tasks are assigned to robots (such as positioning or supporting). While some tasks are agent-specific based on their skill sets, others may be performed by

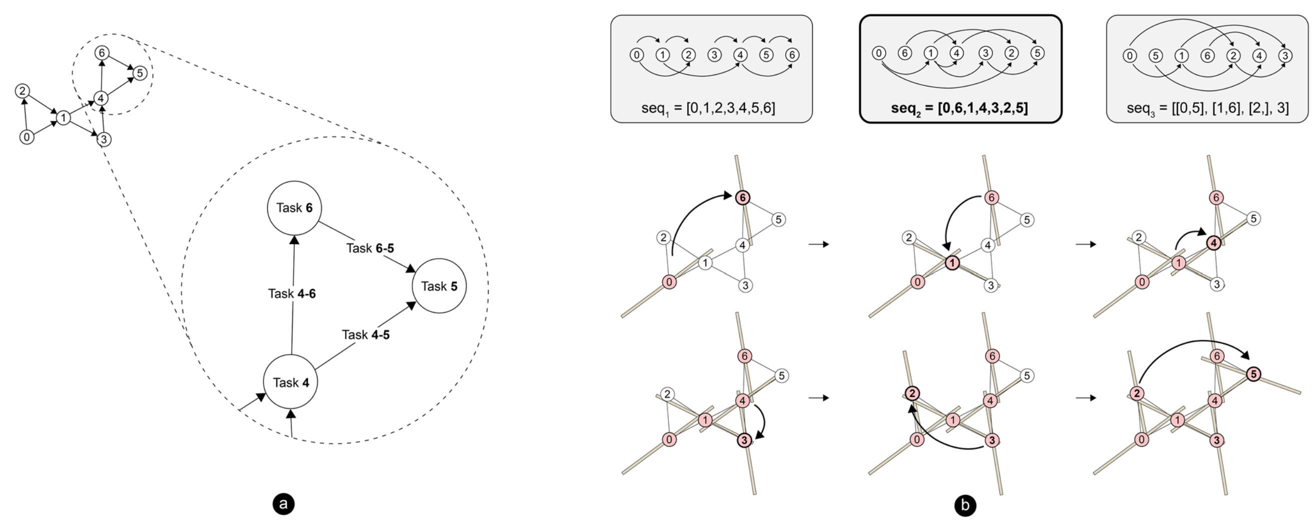

Fig. 3 Task representation and sequencing: **a** The graph represents placement tasks through both nodes and edges, where the edge direction encodes dependencies between tasks. **b** The graph’s topology enables the generation of multiple valid task sequences

Table 1 List of tasks, their description and assignment based on skills

Task	Task description	Assignment
Handling	Feeding material to the robot	Human
Positioning	Element placement	Robot OR human
Positioning and supporting	Precise element placement and temporally supporting	Robot
Joining	Placing connectors	Human
AR device operation	User guidance and task verification, confirmation, and reassignment	Human

either humans or robots, providing initial flexibility during the planning phase. Table 1 lists the tasks, their descriptions, and assignments used in this work.

During the fabrication process, affordances become crucial in refining these initial task assignments. This refinement concerns tasks that can be executed from different types of agents. As defined by Gibson (2014), affordances represent the possibilities for action based on environmental conditions and ongoing processes. These affordances enable dynamic task assignment based on spatiotemporal factors such as physical setup, resource availability (material, humans, or robots), robot reachability, and assembly state. For example, an element placement task initially assigned to a robot can be reassigned to a human based on evolving spatial and temporal affordances, such as when the robot is manually steered to a location that no longer aligns with the planned setup and can no longer reach the target position. Such reassignment mechanisms allow the system to flexibly adapt to real-world deviations during construction.

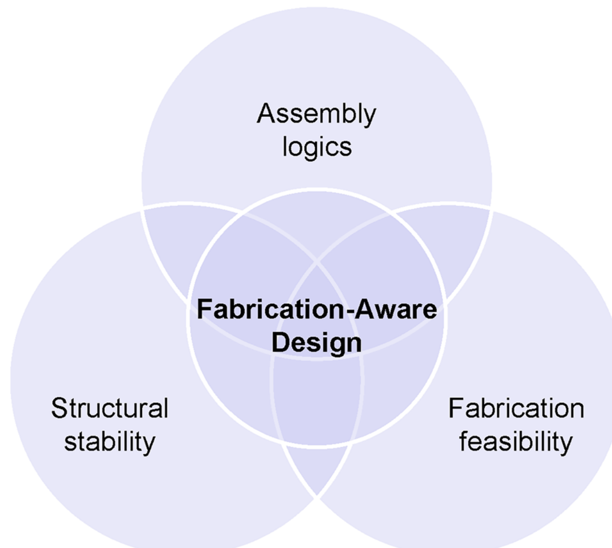

Fig. 4 The fabrication-aware design methodology integrates assembly logic, structural and fabrication constraints

3.4 Fabrication-aware design methodology

This research introduces a fabrication-aware design methodology that utilizes the AM and the proposed task assignment strategy to integrate fabrication information and considerations within the design phase (Fig. 4). At the core of this approach is a growth-based algorithmic process, where the design evolves incrementally following a set of predefined local geometry and connectivity rules referred to as *assembly grammar*. By adhering to the assembly logic of the assembly grammar and incorporating global design criteria and constraints, including a target geometry, static equilibrium condition, fabrication feasibility, and a human–robot task assignment, this method enables the generation of assemblable structures composed of discrete elements. These structures are designed to leverage the complementary strengths of humans and robots, enabling a cooperative assembly workflow involving multiple human and robotic agents.

This approach enhances design adaptability to the available human and robotic agents and their skills, enabling the construction of complex configurations and the execution of tasks that would be infeasible for a single agent.

3.4.1 Assembly grammar

The proposed assembly grammar formalizes the incremental sequence of physical making actions that generate complex timber structures composed of individual Reciprocal Frame (RF) units. Rather than describing only the final result, the grammar encodes the assembly process itself, specifying the sequential actions, assigned agent roles (human or robot), and the conditions required for each step. The assembly logic is structured around two primary rules: *Rule A: Local growth rule* and *Rule B: Global growth rule* (Fig. 5).

Rule A: Local growth rule defines how a Reciprocal Frame (RF) unit is formed through a sequence of actions. When a rod is placed (the *guiding rod*, E0), it creates the condition for attaching two additional rods (E1 and E2), thereby completing an RF unit. The new rods are added in such a way that all three rods overlap and interlock at 60-degree angles, forming an equilateral triangular configuration. This geometric arrangement ensures stable configurations and consistent interlocking throughout the assembly.

Rule B: Global growth rule defines how the structure expands by leveraging *connectors* at the rod ends. Each

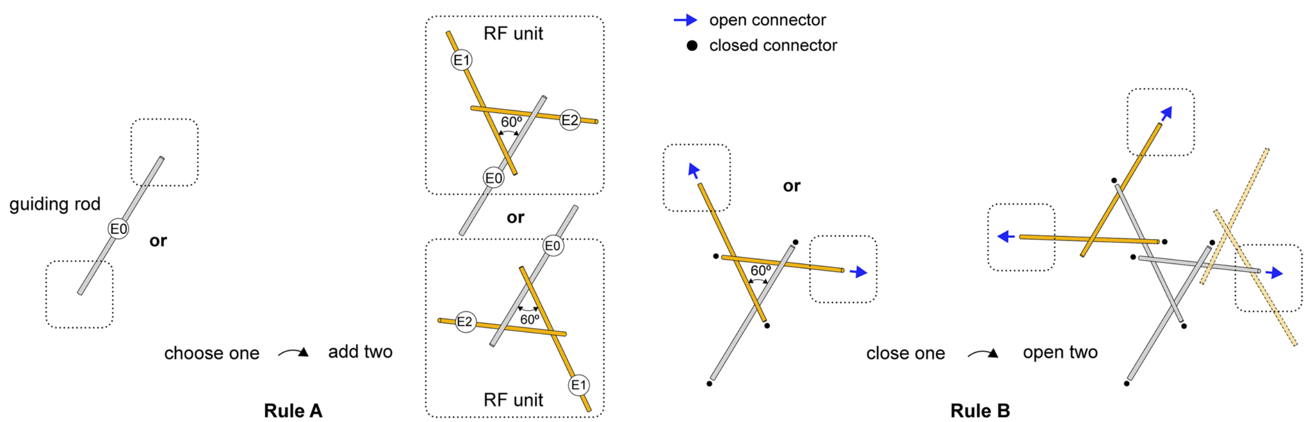

Fig. 5 The primary rules of the assembly grammar: ***Rule A***—formation of RF units via overlapping rods by attaching two rods to an existing guiding; ***Rule B***—structural expansion via open connectors

rod end functions as a connector that can be either *open* (available for attachment) or *closed* (occupied or restricted). When a new RF unit is assembled at an open connector, the process closes the existing connector but simultaneously generates two new open connectors. This ongoing creation of attachment points drives the continuous growth of the overall structure.

As a branching system, the assembly grammar defines a geometric framework that expands through iterative bifurcation. By repeatedly applying Rule A and Rule B, the structure grows outward from an initial guiding rod, generating branches that diverge in different directions without forming closed loops. Each newly created RF unit facilitates further branching. To better understand and control the geometrical behavior of the assembly, two aspects are introduced below: *Random growth and branching behavior* and *Directed growth through unit parameters*.

Random growth and branching behavior: While the structure can originate from a single guiding rod, it is also possible to use multiple starting points. In such cases, each guiding rod acts as the root of an individual branch (Fig. 6a). The implications of this branching behavior for design generation, as well as methods for joining branches, are further explored in Sect. 3.4.2.

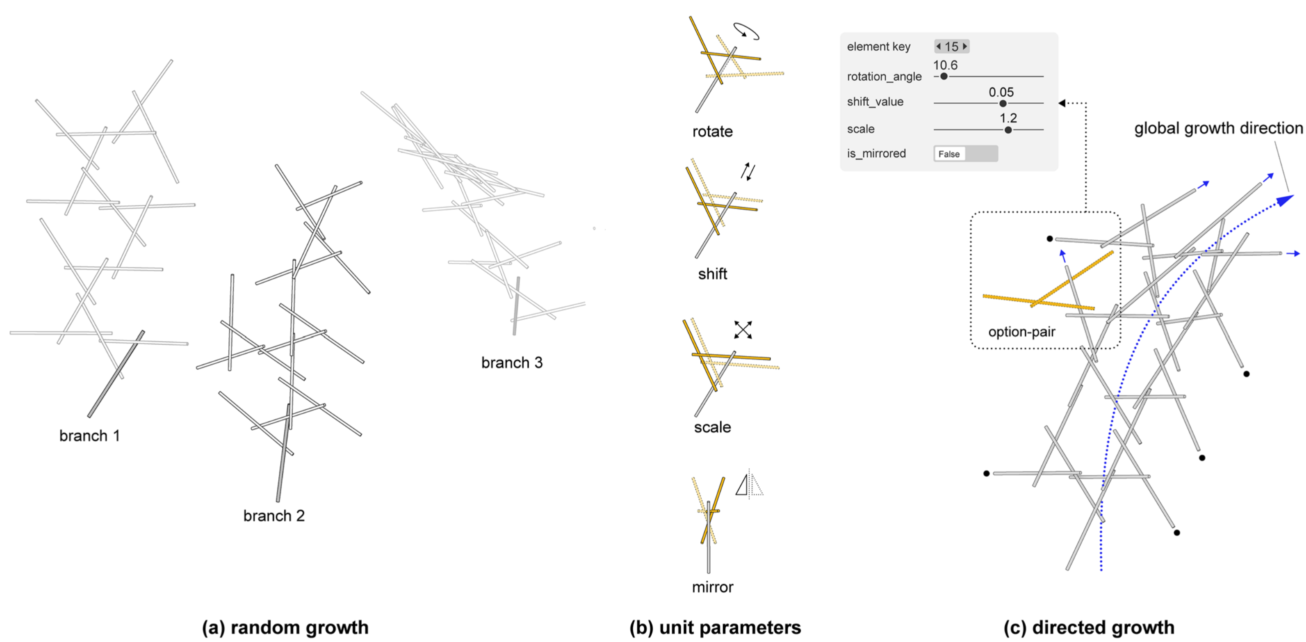

Fig. 6 Assembly grammar growth: **a** random growth and branching behavior: When expanding a structure from multiple starting points, each guiding rod acts as the root of an individual branch. **b** By introducing adjustable unit parameters of the option-pair, including rotate, shift, scale, and mirror, one can follow a **c** predefined growth direction, enabling the creation of highly customized forms

Directed growth through unit parameters: To achieve greater control over the structure's branching behavior and growth direction—and to facilitate the joining of branches—a set of unit parameters is introduced (Fig. 6b):

- `key`: specifies which rod to attach to, identified by its element key.
- `rotation_angle`: defines the rotational orientation of the new rods in relation to the guiding rod, influencing the directionality of branching.
- `shift_value`: adjusts the positional offset of the new rods, enabling the structure to take different forms and adapt to space constraints.
- `scale`: alters the size of the equilateral triangle formed by the three rods in each RF unit.
- `mirror`: enables mirrored unit generation to facilitate directional switching during growth.

These parameters can be freely adjusted to enable precise positioning and orientation of new rod pairs, referred to as *option-pairs*, relative to the guiding rod. By modifying these parameters, the structure's growth can be directed to achieve specific outcomes. For instance, curvature control can be achieved by varying the rotation angle and shift value, enabling growth along different curves. Smooth shape transitions can also be implemented by mirroring a unit, enabling shifts between concave and convex geometries as needed. Additionally, density adjustments using the shift value and scale unit can enhance stability or reduce weight by modifying the density of the rods. These flexible adjustments provide precise control over the structure's shape and stability, enabling the creation of highly customized forms (Fig. 6c).

3.4.2 Design criteria and constraints

The rules of the assembly grammar incorporate multiple design criteria and constraints to ensure functional and feasible designs. Specifically, designs develop within four key constraint categories: target geometry constraints controlling the overall form, branching constraints managing element connections, equilibrium conditions ensuring stability, and robotic fabrication constraints including reachability, collision-free robot trajectory, and robot availability for placing elements and supporting the structure.

By embedding these constraints directly into the design process, the system achieves two key objectives: maintaining control over design generation while ensuring constructability. This integrated approach minimizes the gap between design and assembly by guiding the generation process through predefined requirements.

Target geometry: The target surface geometry defines both the global design space and the desired final shape of the assembled structure. Through the application of assembly grammar rules and unit parameter adjustments at each step, large structures can be generated that conform to this predefined geometry. This approach gives designers control over the outcome while maintaining systematic growth. At each step of the assembly growth, the system calculates how option-pairs align with and relate to the target surface, producing a score that informs design decisions (Fig. 7).

The implementation evaluates potential element positions in relation to the target geometry through distance and orientation calculations. For each option-pair's frame of a selected element, the system computes its distance from the target geometry and its alignment. The distance calculation transforms the option-pair's frame by a given rotation angle around the element's x-axis, then determines the closest point on the target geometry to this transformed position, providing both the minimal distance and the corresponding vector between these points.

The orientation analysis uses a similar transformation but focuses on the alignment between the connector's z-axis and the direction vector to the closest point on the target geometry. This alignment is quantified through a dot product calculation, normalized to a percentage where higher values indicate better alignment. These complementary measurements enable informed decisions about how well potential element positions conform to the desired target geometry.

Branching constraints: Following the rules of the assembly grammar results in branching in multiple directions, leading to two distinct cases: open loops and multiple branches. Both configurations result in non-enclosed structures, posing stability challenges. Open loops arise from a single branch that extends in different directions, affecting overall structural integrity. Growth initiated from multiple support points creates separate branches that enhance initial stability without requiring additional ground connections. However, these branches often develop as independent structures requiring their own support systems.

To enable branching or starting from multiple support points—while still treating the entire system as a single, interconnected structure—geometrical methods for closing loops and joining individual branches are explored. These strategies aim to address stability challenges during assembly and minimizing the need for external structural support. These methods rely on first geometrically describing the connectivity range of rods with open connectors as ruled surfaces and then identifying an intersection between a ruled surface and a rod or an intersection between two ruled surfaces. Depending on the intersection case, the approach distinguishes between two scenarios (Fig. 8). The first scenario involves closing a loop or joining branches by adding one option pair, where one of the rods connects to an existing rod at the intersection point. The second scenario requires adding two option pairs

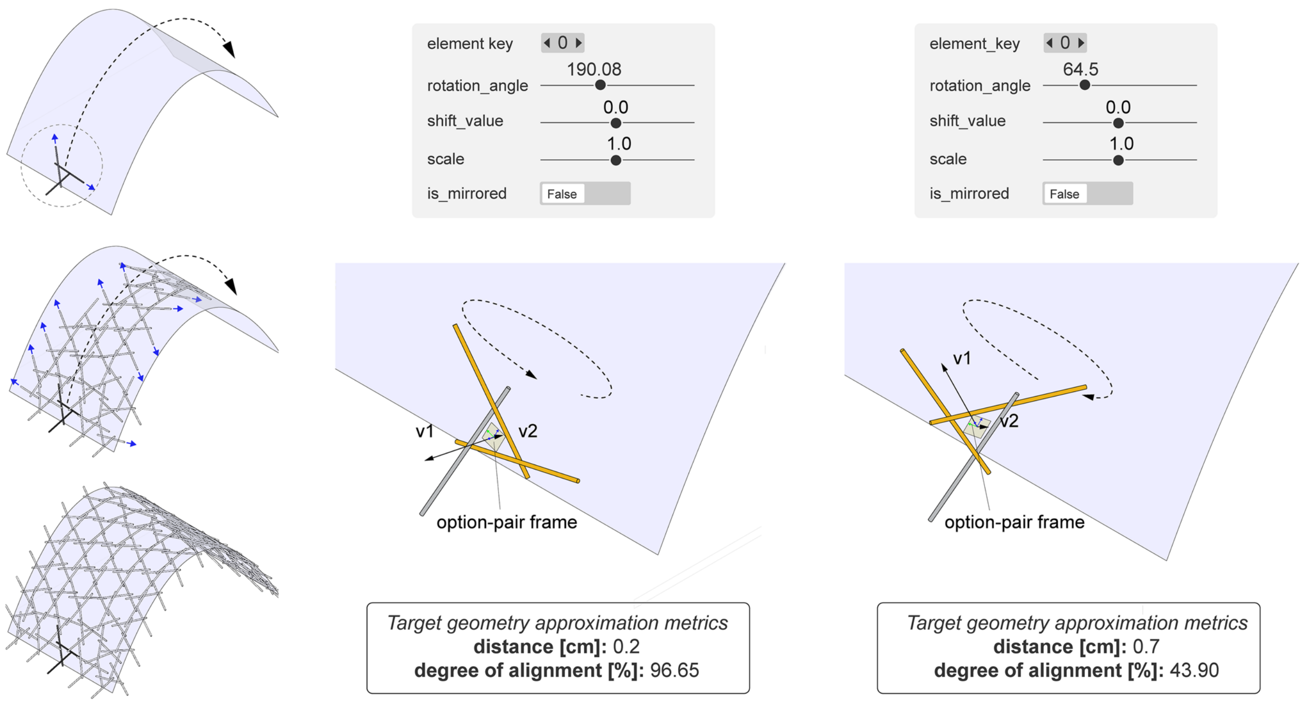

Fig. 7 Target geometry constraint: adjusting unit parameters based on distance and degree of alignment to conform to a predefined geometry

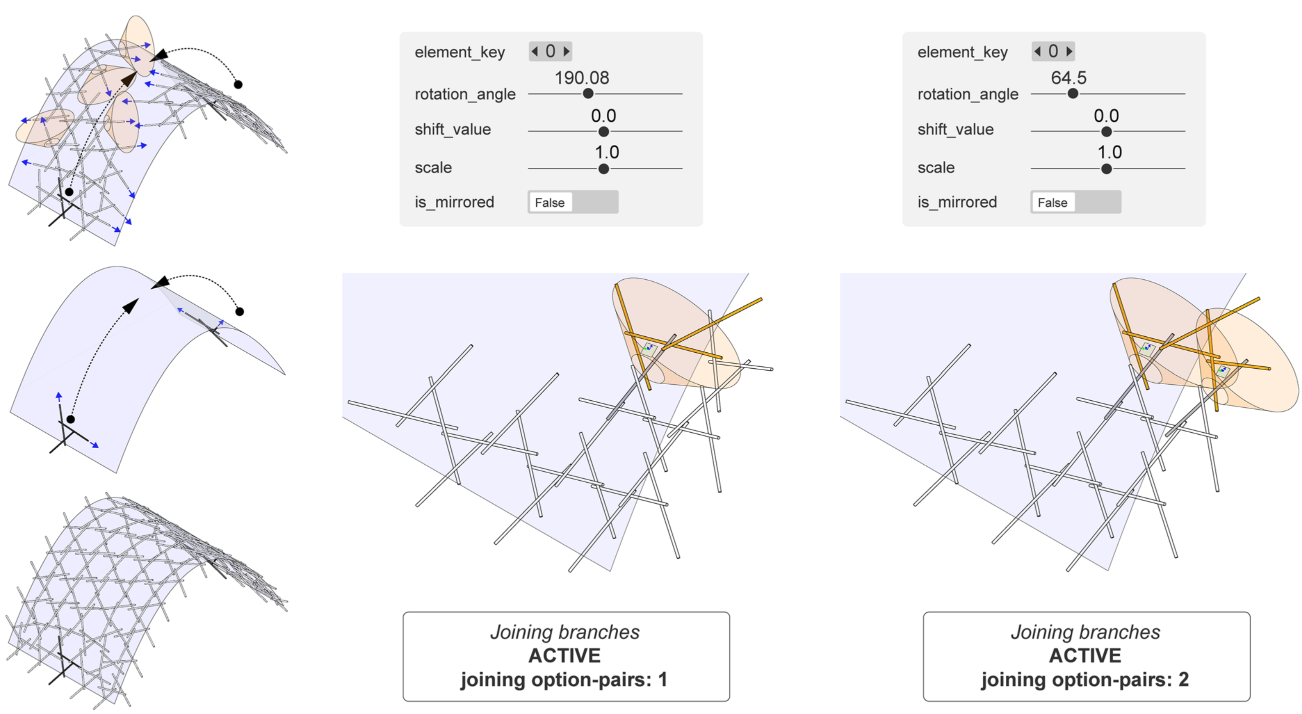

Fig. 8 Branching constraints: Multiple branches and open loops are generated when growing from multiple locations. These can be closed by identifying intersections between the ruled surfaces of open connectors, determined by the rod arrangements within modules

that connect at an intersection point on the intersection curve of the two ruled surfaces. In both cases, the unit parameters of each new option-pair are determined by first identifying the intersection points and then calculating the necessary unit parameters.

Branch-wise equilibrium conditions: To ensure stability throughout the assembly process, a simplified analysis determines static equilibrium for an incrementally growing structure, where elements are added sequentially to a support base. Every branch is treated as a distinct structural entity until it is joined with another branch, at which point the connected branches are considered together in the equilibrium analysis. The analysis determines stability by checking whether the resultant center of gravity, considering all elements of the branch in the current fabrication state together with the support base, falls within the support base's footprint. The overall center of gravity is computed by projecting the individual centers of gravity of all elements onto the ground plane and calculating their weighted average, using the volume of each element representing its self-weight (Fig. 9a).

The implementation distinguishes between three cases:

- *No additional support required:* The branch-wise center of gravity lies within the support area, eliminating the need for additional support (Fig. 9a).
- *Single temporary support required:* A single temporary support, such as robotic assistance, is required to maintain stability during assembly (Fig. 9b).
- *Multiple temporary supports required:* The center of gravity of a branch falls outside the support area, necessitating multiple temporary supports (Fig. 9c).

If any of the branches is not satisfying the equilibrium condition independently, methods to join it with other branches to form a larger, more stable configuration are applied.

This approach aims to minimize the need for additional supports to maintain structural integrity at each assembly stage, ideally reducing it to a single temporary support. The algorithm uses this simplified analysis to provide in-process feedback on the assembly's stability state, as well as a rough estimation of when and where temporary robotic support is necessary during the construction process.

Robotic fabrication constraints: In the design and fabrication workflow, two mobile robotic systems are employed. These robots are used for both element placement and temporary structural support during assembly. Their positioning, reach capabilities, and availability are critical factors for both design and successful assembly. The deployment locations for temporary robotic support are determined based on the stability analysis (Fig. 9) and are later used in the task assignment (Sect. 3.4.3).

ÅThe mobile robot system's reachability is approximated by a sphere with a 1.3 m radius, vertically extendable by 0.72 m through the vertical linear axis (Fig. 10). Due to their dual role in placement and support, next to the positioning and reachability, the availability of both robots is considered a key constraint already in the design process as detailed in Sect. 3.4.3.

3.4.3 Human–robot task assignment

The initial task assignment is an integral part of the computational design model. It complies with the skill-based task assignment, is represented in the logic of the assembly grammar, and is further refined based on the equilibrium

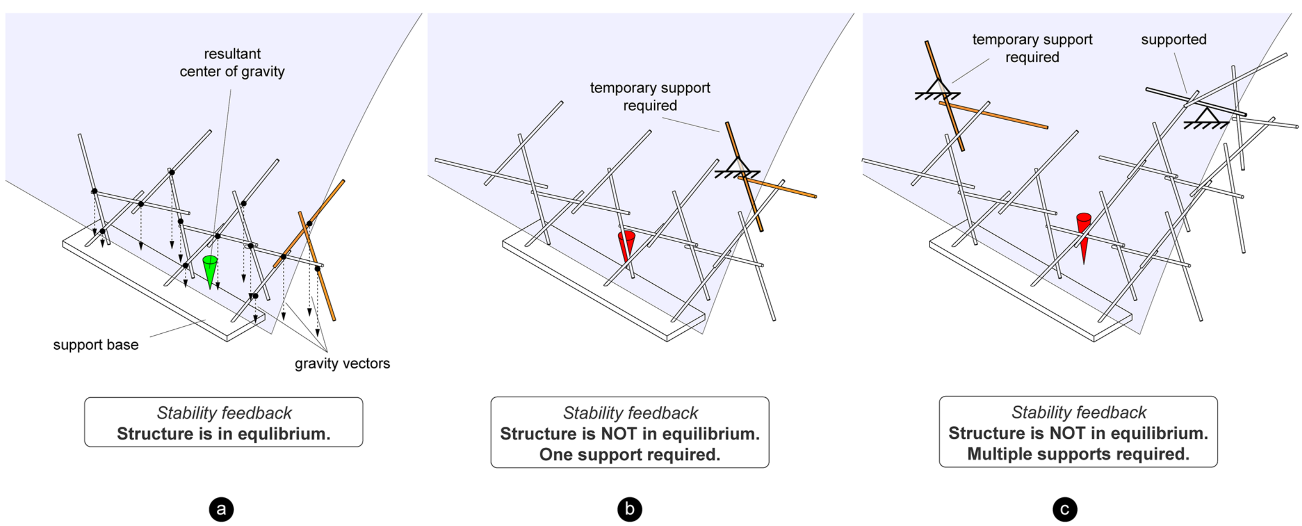

Fig. 9 Equilibrium condition: stability is determined by verifying whether the resultant center of gravity, accounting for all elements of the branch in the current fabrication state along with the support base, falls within the support base's footprint

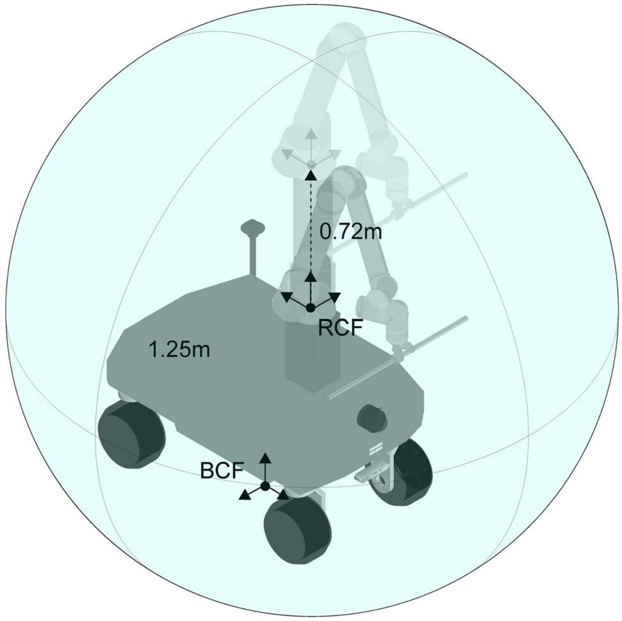

Fig. 10 Robot reachability approximation: a sphere with a 1.3 m radius represents the robot arm's range, combined with a 0.72 m vertical extension enabled by the mobile system's linear axis

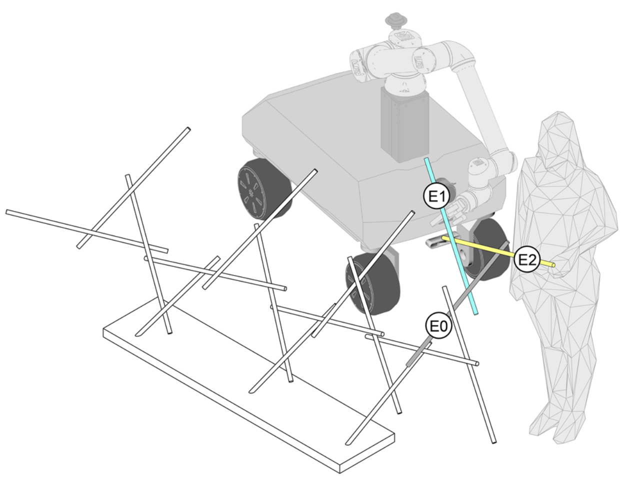

Fig. 11 Human–robot task assignment: The guiding rod (E0) is pre-assembled first. The robot then places and holds the second rod (E1) steady until the human adds the third rod (E2), completing the RF unit

condition and robotic fabrication constraints. According to the initial rule, the guiding rod (E0) is pre-built, followed by one robot placing the second rod (E1), and a human placing the third rod (E2), completing the RF unit (Fig. 11). After each rod placement, humans install mechanical connectors to secure the connections. This initial rule defines one assembly cycle that begins with a single robot.

As the structure grows and stability becomes a concern, a second robot is introduced to provide temporary support. Between cycles, based on the simplified static equilibrium analysis and the task assignment in the previous cycle, the two robots swap their roles as placer and holder; the robot that has lastly placed a rod remains temporarily stationary, and the second robot is used to place another rod. This alternating pattern of placing and supporting between the two robots maintains static equilibrium by utilizing one robot as a temporal support of the structure (Fig. 12).

3.4.4 Design tool

To further investigate this design approach, the presented concepts were implemented in a proof-of-concept interactive fabrication-aware design tool using *Rhino* and *Grasshopper* CAD software and the *COMPAS* computational framework (Mele et al. 2022). The latter interfaces with backend processes, including a robot path planning environment for generating collision-free trajectories.

Built on the assembly grammar rules (Sect. 3.4.1) and incorporating design criteria and constraints (Sect. 3.4.2), the design tool implements a user-controlled design methodology. The design workflow consists of four key steps: (1) *Initialize the design process with boundary conditions*, (2) *Design generation through different growth control modes*, (3) *Feedback and assembly growth* incorporating target geometry approximation, stability feedback, robotic fabrication constraints, and branch joining evaluation (Fig. 13), and (4) Final AM.

Step 1: Initialize design process: The design process begins with setting the main user-defined parameters, which define the boundary conditions of the intended design (Fig. 14). These parameters include global parameters such as the target geometry, which represents the desired overall shape to be approximated by arranging RF units along and close to the input geometry; the material dimensions (e.g., rod length and radius) and the distance between connected rods; the foundation, which refers to the shape and dimensions of the support(s) and is critical for determining the equilibrium condition of the structure; and the starting configuration, which specifies the number and position of the initial rods, establishing the starting point for the design generation.

Step 2: Design generation: One placement cycle follows the growth rules A and B as defined in the assembly grammar and works as follows: an existing, placed rod is selected, and a new option-pair is displayed. This option-pair is generated based on unit parameters which can be manually defined or computed. The designer can choose between three modes of option generation: *Manual*, *Automatic*, and *Branch joining* (Fig. 15).

In *Automatic* mode, option-pairs, by default 100, are generated based on a random or user-defined selection of a

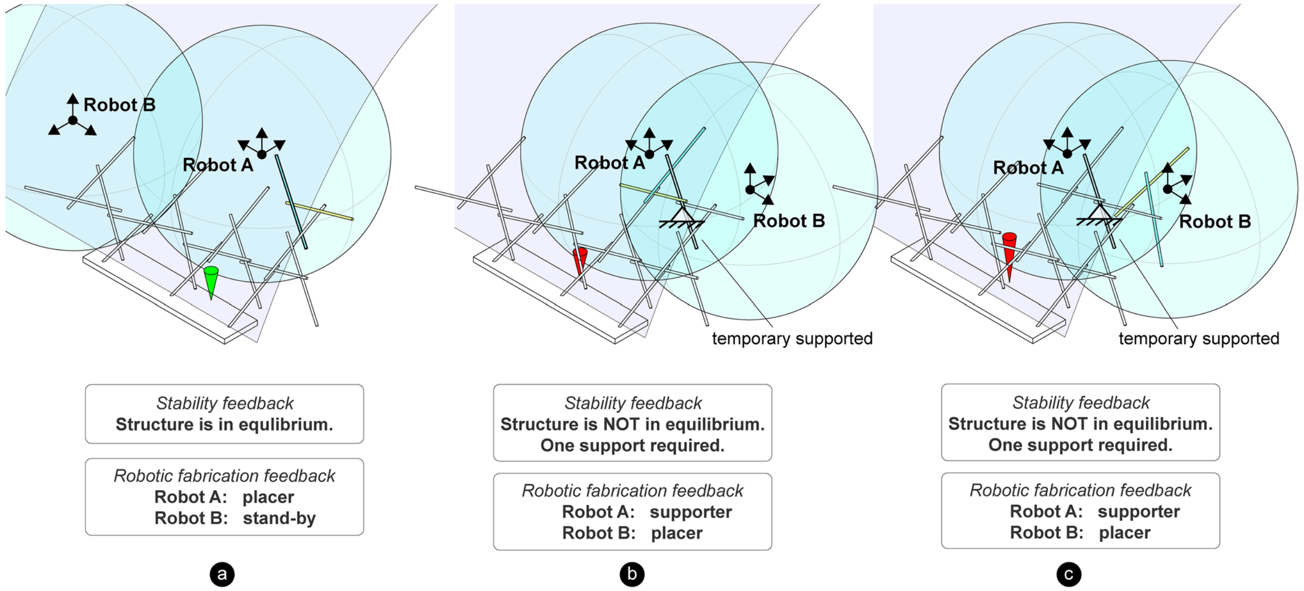

Fig. 12 Robot task assignment: Tasks are allocated based on availability and reachability, with the robots alternating between placer and supporter roles

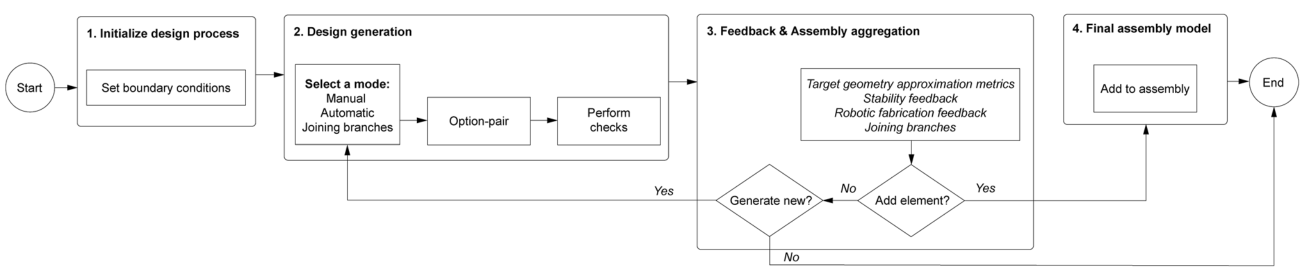

Fig. 13 Overview of the fabrication-aware computational design workflow, illustrating the key steps: (1) initialize design process, (2) design generation, (3) feedback and assembly growth, and (4) final AM

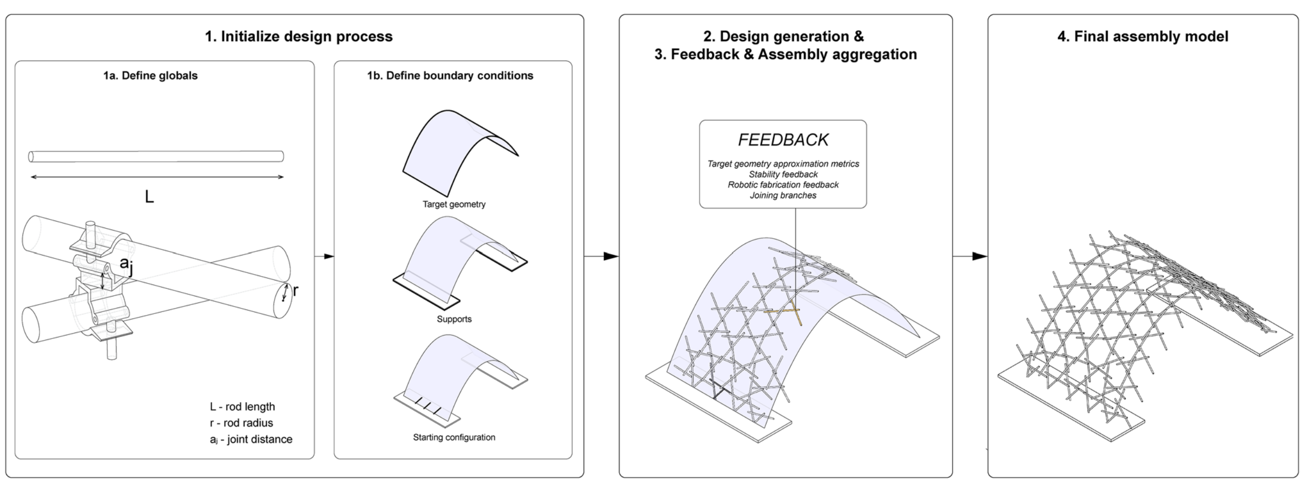

Fig. 14 The design process starts by defining the (1) boundary conditions of the intended design: these include the (1a) *assembly globals* and (1b) *goal condition* represented by the target surface geometry, supports, and the starting configuration, followed by (2) *design generation*, and (3) *feedback and assembly growth*, and ends with (4) *final AM*

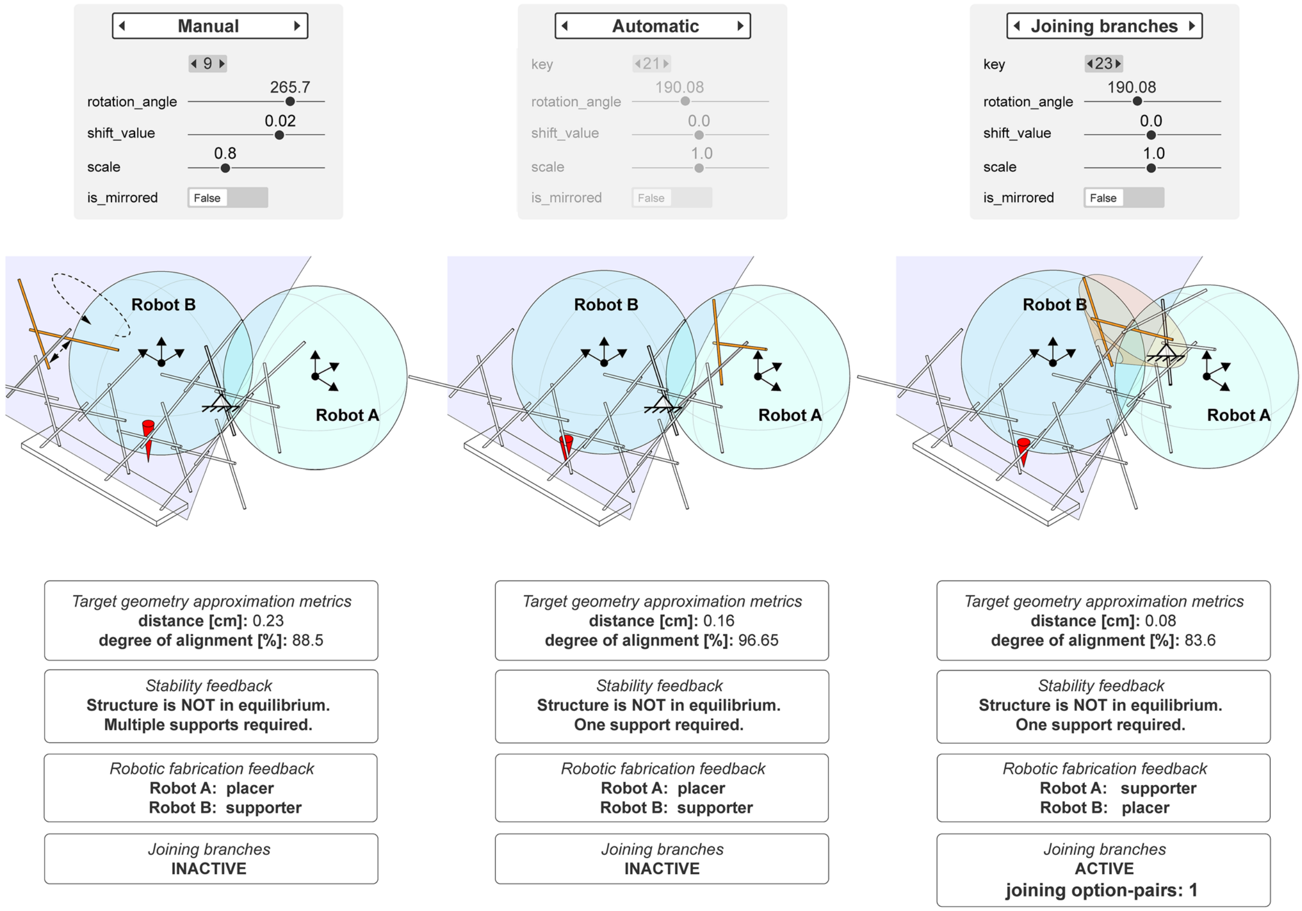

Fig. 15 Three modes of design generation: manual, automatic, and branch joining

parent rod and randomized unit parameters for shift_value, rotation_angle, scale and mirror.

These option-pairs are then evaluated against stability and design criteria to determine the best candidate. The designer can choose to accept the proposed option-pair, generate a new one, or switch to Manual mode to manually set the parameters. The *Manual* mode extends the tool's capabilities by providing full control over rod placement through direct manipulation of position and orientation parameters. This mode gives designers precise control over specific design decisions when computational suggestions fulfill the constraints but fail to satisfy subjective design criteria that are difficult to formalize algorithmically. It allows designers to apply visual preferences at critical connection points such as when surface curvature changes or when element connection is required. In *Branch joining* mode, the system helps the designer connect open loops or connect two branches of the structure to reduce multiple support requirements to just one support.

Step 3: Feedback and assembly aggregation: Whether an option-pair is placed or not is determined by the designer, guided by comprehensive feedback on the design's performance. Each generated option-pair triggers visual and textual feedback on geometrical stability (including resultant force vector), target geometry approximation (distance and alignment), and robotic fabrication constraints (robot positions and reach limitations). Geometrical stability is maintained either through the structure's self-supporting geometry or by deploying one robot as temporary support until either sufficient stability is achieved or until unstable branches are connected into stable formations. During assembly, the robots alternate between support and placement roles based on stability requirements, with their positions (*robot_A_base_frame* and *robot_B_base_frame*) determined by each robot's availability and reachability. These base frames are stored as attributes in the AM to inform trajectory simulation and guide the robot positioning during construction.

Step 4: Final AM: Upon completion of the design process, all computed fabrication parameters - robot positions and task assignments - are stored in the final Assembly Model (AM). During each design step and with each newly added option-pair, these fabrication parameters are determined and stored in the AM. When the design process is completed, the

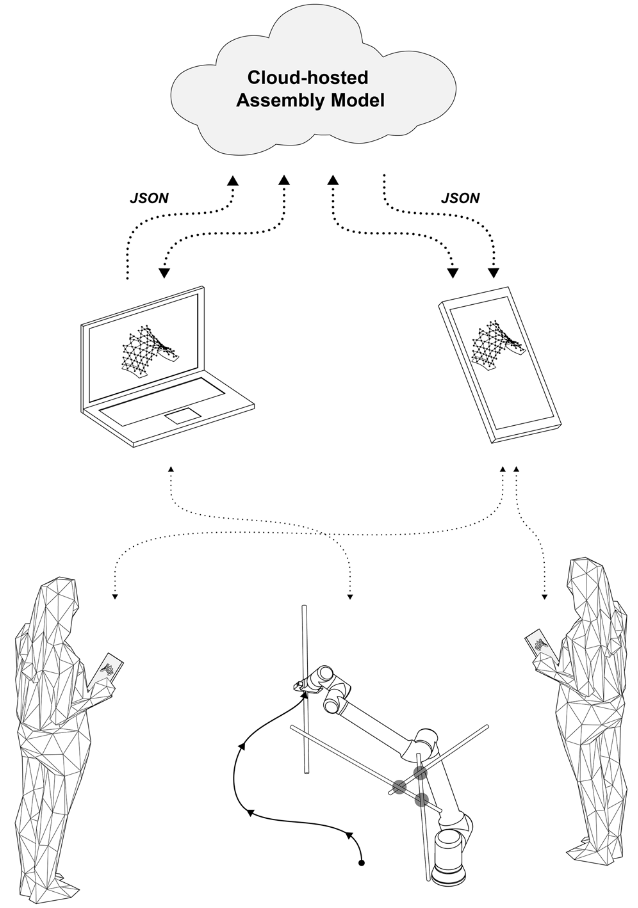

Fig. 16 Participating entities communicate and coordinate over a cloud-hosted AM

AM is serialized to JSON and uploaded to a cloud-hosted database. This database is accessed from various platforms, and data is dispatched through different interfaces to the building team, which consists of two mobile robots and a varying number of human builders.

3.5 Task distribution and coordination strategy

For the actual assembly process, this research introduces an assembly workflow based on a turn-taking coordination strategy between humans and robots, where human and robot tasks are executed sequentially or in parallel, creating mutual interdependence. This approach requires a robust task management system capable of dynamic task assignment and flexible task distribution in space. The proposed solution utilizes a centralized, cloud-hosted AM, enabling communication between all participating agents (Fig. 16). Section 3.5.1 details the data flow between the CAD environment, cloud-hosted database, robotic systems, and the mobile AR device. Section 3.5.2 explains the implemented

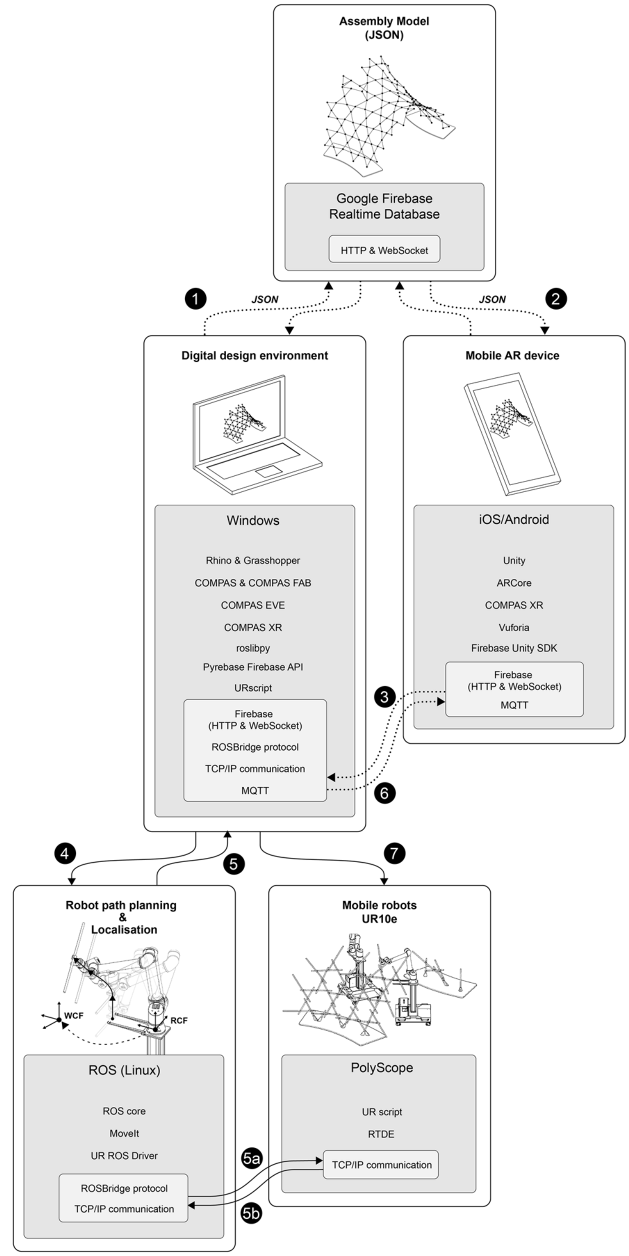

Fig. 17 System backend architecture illustrating communication and data flow between digital design environment, cloud-hosted AM, robotic planning and simulation environment, and robot controller

robot and phone localization methods, while Sect. 3.5.3 describes the in-process robot motion planning and control.

3.5.1 Data exchange and visualization

Once the design is completed, the AM is serialized to JSON format and uploaded to the *Firebase Realtime Database*,[1]

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

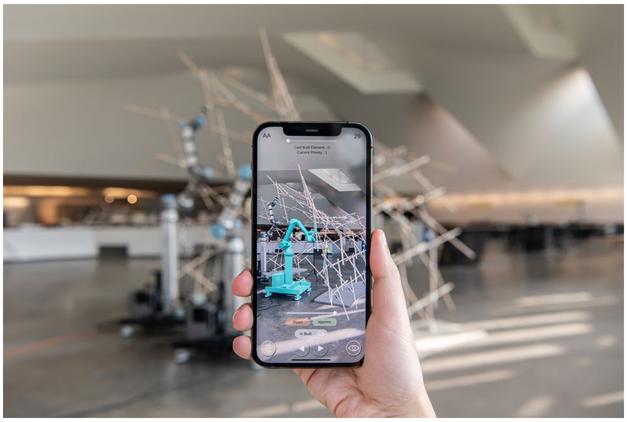

Fig. 18 The custom AR phone-based application serves as a communication interface between the cooperating agents—human and robots—in the assembly process

a cloud-hosted server that functions as a central data hub. This hub can be accessed and visualized across multiple interfaces, including hand-held devices, the CAD environment, and the web interface. The system enables real-time communication between all agents through a custom AR phone-based application that utilizes the *COMPAS XR* library (Kenny et al. 2024) to integrate the cloud-hosted AM, the CAD environment (interfacing with the motion planner), and the physical construction space (Fig. 17).

The AR application accesses fabrication-related data from the cloud-based AM, including task assignment, *built* state, priorities, and geometric details. It augments the human workspace with essential digital information, allowing users to:

- visualize the final locations of building rods,
- visualize current task assignments and assembly progress,
- update the cloud-hosted AM in real-time (e.g., confirming rod placement with *is_built* = True) or reassigning tasks between agents with *is_placed_by* = “human”.

The user interface allows customization of views to support efficient human–robot cooperation for complex assembly tasks.

To maintain system consistency and real-time synchronization, the interface implements specific interaction protocols. Humans must communicate task completion and manually trigger robot tasks through the AR interface (Fig. 18). The system ensures continuous synchronization of parameter changes across all app instances and the CAD model, immediately updating the built status of rods across all connected devices.

Next to visualizing the digital model, assembly sequence, and all data necessary for executing manual assembly tasks, additional app features help users directly interact with the robots:

- request robot placement configurations for specific rods,
- preview planned robot location,
- requesting robot trajectories based on newly estimated robot position,
- preview, verify, and confirm planned trajectories,
- and send planned trajectories for execution.

The technical implementation integrates with the *ROS*[2] environment and *MoveIt*[3] to facilitate localization (Sect. 3.5.2) and collision-free trajectory computation for the mobile robots as explained in Sect. 3.5.3. For further details on the mobile AR app implementation, refer to *CAA* (Alexi et al. 2024) and *COMPAS XR* library (Kenny et al. 2024).

3.5.2 Localization

For effective human–robot cooperative assembly, all agents and devices must share a synchronized digital-physical workspace. Building on established localization techniques using fiducial markers, our implementation uses two methods for robot localization: manual point measurement with known spatial coordinates and marker tracking using fiducial markers and image-based recognition (as implemented in the *Vuforia Engine* library[4]) for localizing the mobile phones and correctly mapping visual objects in the camera feed (Fig. 19). These approaches were selected for their reliability and compatibility with the system architecture, where mobile robots require frequent repositioning during assembly. To ensure consistent tracking performance, we conducted tests to determine the optimal size and distribution of markers throughout the workspace.

Manual point measurement and iterative closest-point (ICP) algorithm: Robot localization is achieved through a two-step process. First, when a robot is moved, a custom measurement tip is used to capture points that are aligned with known spatial coordinates relative to a mixed marker frame ***MCF***. Second, these measured points are then aligned with the digital model using the iterative closest-point (ICP) algorithm, which calculates the robot coordinate frame ***RCF*** with millimeter precision. For the phone localization, the phone’s camera coordinate frame $\boldsymbol{CCF}_1$ is also determined relative to the same marker frame ***MCF***. This process ensures accurate registration of all agents’ positions within

2 Robot Operating System (ROS or ros) is a framework for writing robot software.

3 MoveIt is an open-source framework for motion planning and manipulation in robotics, developed by PickNik Robotics.

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

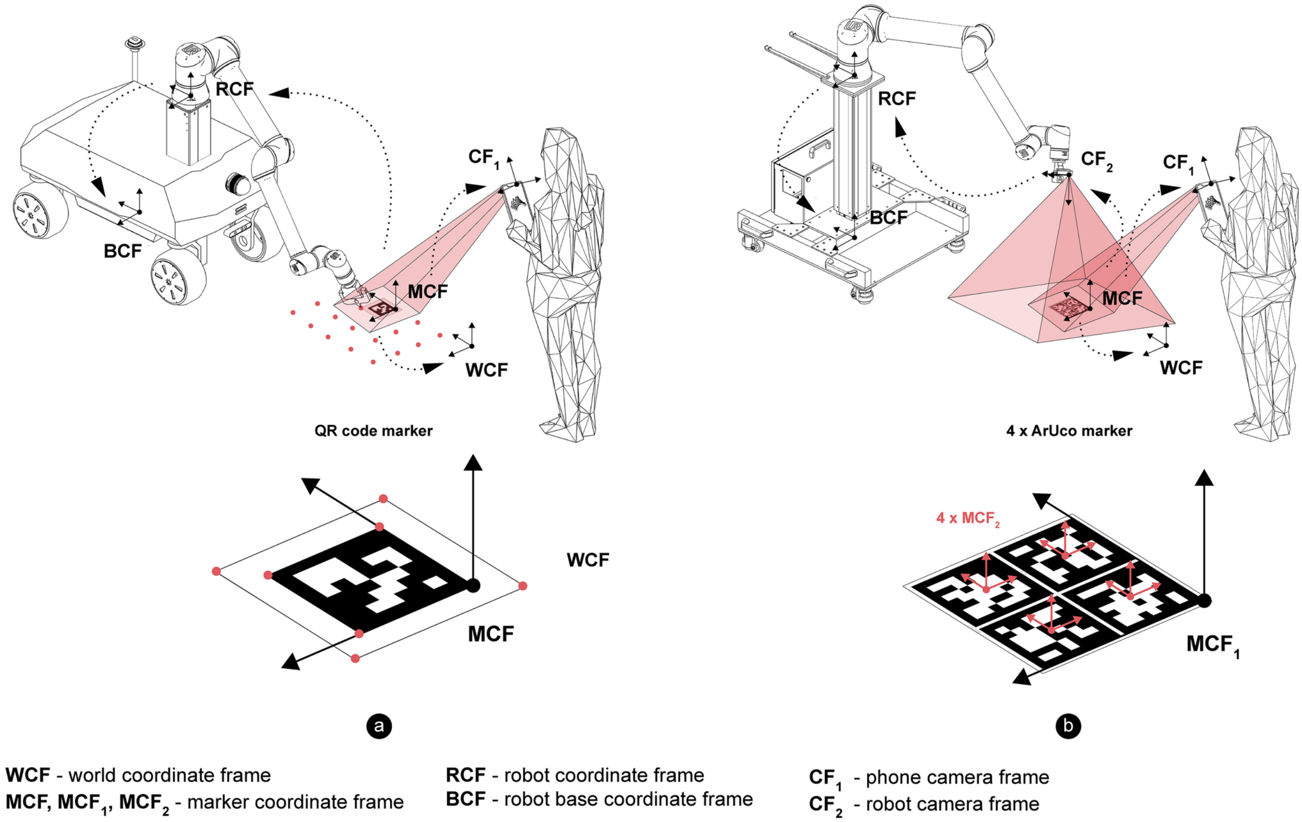

Fig. 19 Localization methods for synchronized digital-physical workspace: **a** Manual point measurement with ICP algorithm for robots, **b** Marker-based tracking for robots and mobile devices

both the physical workspace and the CAD model's world coordinate frame and correct overlay of the digital content.

Marker tracking using fiducial markers: The system uses fiducial markers to establish a shared coordinate system for all agents. To localize the mobile robots, their positions (robot coordinate frame ***RCF***) are captured relative to a fixed marker frame ***MCF***, which is then transformed into the world coordinate frame ***WCF***. Similarly, the phone's camera coordinate frame $\boldsymbol{CCF}_1$ is determined relative to the same marker frame ***MCF***, thereby bringing both robots and phones into a shared coordinate system. For precise tracking, the system employs two types of markers: a detailed marker $\boldsymbol{MCF}_1$ combining 4 ArUco markers for accurate phone camera tracking, and four simpler markers $\boldsymbol{MCF}_2$ for robot localization.

3.5.3 Robot motion planning, simulation, and control

For the assembly, three main robot routines were executed: *release*, *pick-and-place*, or a combination of both (Fig. 20). Each routine consists of several motions. The release routine involves a Cartesian motion to a safe target frame and a free motion to the home position. The pickup routine includes a Cartesian motion to the pickup point, returning home, free motion to the safe target frame, and linear motion to the target frame. To validate the feasibility of the generated plan, all trajectories can be calculated and simulated before fabrication using the fabrication parameters stored in the digital model. During assembly, these trajectories are computed upon request and based on the robots' estimated position after each repositioning of the mobile robots.

The robotic toolpaths are planned using a combination of *MoveIt*, *COMPAS FAB* (Mele et al. 2022), and Python and are previewed both within the CAD environment and via the mobile AR app. The *ROS* system, which includes *ROS core*, rosbridge server, and *MoveIt*, is run on a Windows PC using custom *Docker*[5] containers. Communication with each robot's UR controller is established over a standard TCP/IP connection. The *Real-Time Data Exchange* (RTDE)[6] interface is used to transfer planned pick-and-place routines, including target frames, I/O control, and robot parameters.

[5] Docker is a platform for creating and managing containers that package applications with their dependencies for different environments.

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

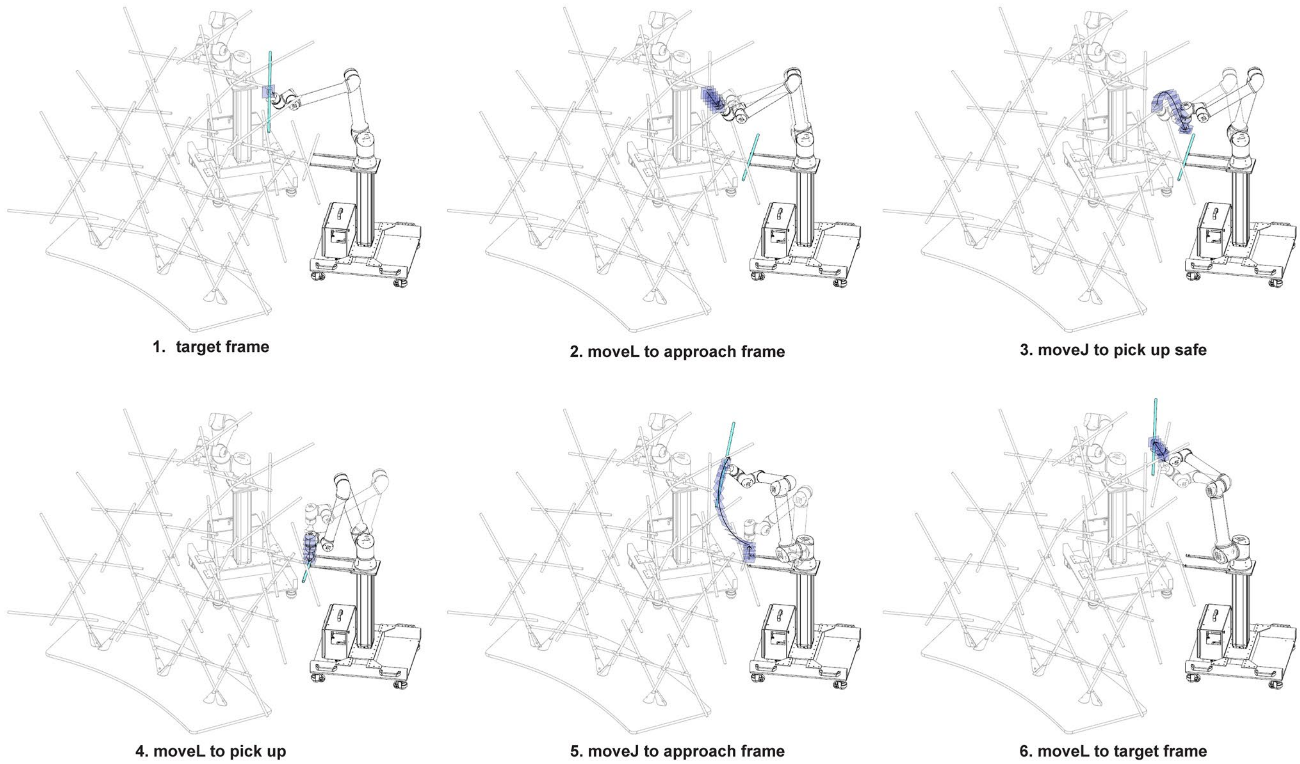

Fig. 20 Robot motion planning: In-process computation of robot trajectories based on updated positions after mobile robot repositioning

3.5.4 Assembly workflow

The proposed cooperative assembly workflow involves multiple teams of two or more human agents and two collaborative mobile robots, as illustrated in Fig. 21. Only one team is actively assembling at a time. Within each team, one person operates the mobile phone and follows instructions via an AR app, while the second places rods or connectors accordingly. Optionally, a third person may assist by handing over materials or supervising the system via the CAD interface on a laptop. All agents—human and robotic—are coordinated through the cloud-hosted AM and visually guided via the custom mobile AR interface, which streams real-time instructions directly from the AM.

The assembly sequence follows the numbered steps shown in the figure: **(1)** It begins with the AR operator scanning a QR code marker to localize the phone and initialize the process, **(2)** The interface overlays the geometry and task information onto the camera feed, highlighting the rod to be placed: yellow for human-assigned and blue for robot-assigned rods. In the coordinated turn-taking sequence, robots and humans alternate in placing rods. **(3)** For robot-assigned rods, provided the robot localization has already been performed, the system computes a placement configuration and a pick-and-place trajectory, which are visualized in the AR interface. The phone operator reviews and confirms the plan before execution. **(4)** Upon the operator's request via the AR interface, the assigned robot (Robot A) places a rod and holds it in position. **(5)** The second person then installs the next rod, completing the RF unit, and adds the corresponding joints. **(6-7)** The phone operator requests a trajectory for the subsequent rod, which is then placed by Robot B. **(8)** Robot B remains in position to provide structural support, allowing the human to assemble the next RF unit. **(9)** Afterward, Robot A releases its hold and returns to its initial position, ready for the next placement, while Robot B maintains support.

Alternatively, if structural support is not required, human agents can access the cloud-hosted AM through the app's interface and reassign tasks originally allocated to robots.

4 Case studies and results

To demonstrate the proposed fabrication-aware design methodology and the associated task distribution and coordination strategy, two full-scale experimental case studies were conducted. These experiments illustrate the feasibility of scaffold-free, multi-human–robot cooperative assembly for geometrically complex timber structures (Fig. 22). In this setup, two mobile collaborative robots were employed not only for element placement but also as

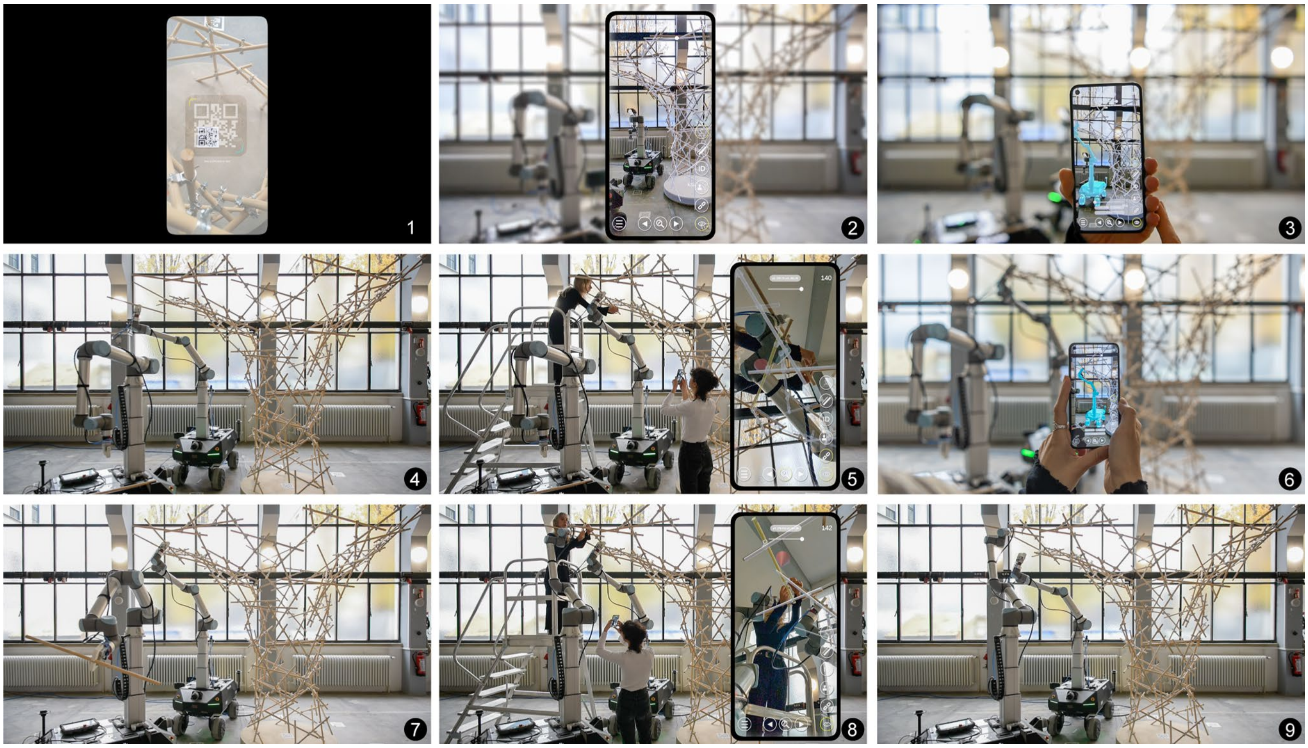

Fig. 21 Steps of the cooperative assembly workflow involving a human–robot team consisting of two people and two collaborative mobile robots: **(1)** initialize the app, **(2)** visualize the geometry with the next element highlighted, **(3)** request the placement trajectory, **(4)** execute robotic placement with the assigned robot, **(5)** human places rod and connectors, **(6)** visualize the next element and request the trajectory, **(7)** execute robotic placement with Robot B, **(8)** human places rod and connectors, **(9)** Robot B supports, Robot A releases and is free to place

Fig. 22 Two case studies demonstrating coordinated multi-human–robot cooperative assembly using custom AR interface. Left: *Case Study 1—Turn-taking task distribution for assembling a double-curved funnel structure*. Right: *Case Study 2—Turn-taking with mobile robotic support for assembling a double-curved shell structure*

mobile, temporary supports, minimizing structural deviation and ensuring structural stability without relying on traditional scaffolding. The cooperative assembly workflow was supported by the custom mobile AR interfaces.

Each case study was designed to demonstrate the adaptability, robustness, and versatility of the proposed approach, focusing on distinct robot deployment strategies tailored to specific structural conditions and assembly requirements based on different input geometrical topologies. *Case Study 1* involved a double-curved funnel-shaped structure, in which humans and robots alternated in element placement following a turn-taking task execution logic. As an extension of this approach, *Case Study 2* focused on a double-curved arc-like shell structure where robotic support was essential during specific assembly steps. In this scenario, both robots were responsible not only for placing elements but also for providing temporary structural stabilization at locations predefined during the design phase. An overview of the setup and task distribution for each case study is presented in Table 2.

These case studies provided a structured environment to validate the design-to-fabrication workflow, including fabrication-aware design, task coordination, communication, and on-site execution. Both experiments utilized a standardized material system comprising spruce timber rods (22 mm diameter) and swivel couplers fixed at a 60-degree angle via a tightened connecting screw. This predefined angle ensured a semi-rigid connection, maintaining geometric consistency throughout the assemblies. The material logic enabled consistent testing of robotic handling, modularity, and repeatability, while also supporting both assembly and disassembly processes.

Quantitative and qualitative results were collected to evaluate the performance of the system (Table 3). Metrics include total assembly duration, number of elements placed by human and robotic agents, frequency of robot repositioning, and deviations between planned and as-built geometries. These indicators reflect the effectiveness, precision, and task distribution dynamics of the cooperative assembly process.

The following sections detail the two case studies used to validate the proposed methodology, describing their experimental setups, the generation of fabrication-aware design models, and the execution of coordinated human–robot assembly workflows tailored to distinct structural typologies.

4.1 Case Study 1: turn-taking task distribution

4.1.1 Experimental setup

The experimental setup comprises two 6-DoF *UR10e* collaborative robotic arms mounted on mobile *Robotnik* platforms, with an added vertical axis that increases the combined height of the robotic arms to approximately 3.5 m (Fig. 23). Each robotic arm is equipped with a pneumatic parallel gripper and custom 3D-printed gripping fingers for handling the timber rods. The mobile platforms have custom-manufactured pickup stations mounted, allowing timber rods to be fed directly to the robots. For the robot and mobile

Table 3 Summarized results of the case studies

	Case Study 1	Case Study 2
Participants	17	13
Duration		
Days (approx. 7 h)	5	3
Structural elements		
Total rods	178	141
Total couplers	315	220
Placement details		
Robot-placed rods	25	42
Human-placed rods	153	99
Robot parameters		
Robot positions	4	12
Accuracy [mm]		
Based on 3D scan	5–60	–
Based on marker tracking	–	20–50

Table 2 Elements of the conducted case studies

	Case Study 1	Case Study 2
Cooperating agents	2 mobile robots and 17 human builders	2 mobile robots and 13 human builders
Human tasks	Place a rod, material handling, place a joint, operate AR app, operate AR app	Place a rod, material handling, place a joint, operate AR app, operate AR app
Robot tasks	"Pick & place" routine, hold in place, "release" routine	"Pick & place" routine, stabilize structure, "release" routine
Task execution	Turn-taking/sequential	Turn-taking/sequential
Sensing	Human perception, localization via manual point measurements and ICP algorithm and marker tracking	Human perception, localization via marker tracking
Communication	Custom mobile AR app, Rhino-Grasshopper user interface, digital twin, cloud services	Custom mobile AR app, Rhino-Grasshopper user interface, MQTT, cloud services
Coordination	Via an AM stored in the design environment and a cloud-hosted AM, custom mobile AR app	Via a cloud-hosted AM, custom mobile AR app

This is an example of table footnote

[1] A human–multi-robot cooperative assembly of a double-curved, funnel-shaped timber structure

[2] A human–multi-robot cooperative assembly of a double-curved, arc-like shell timber structure

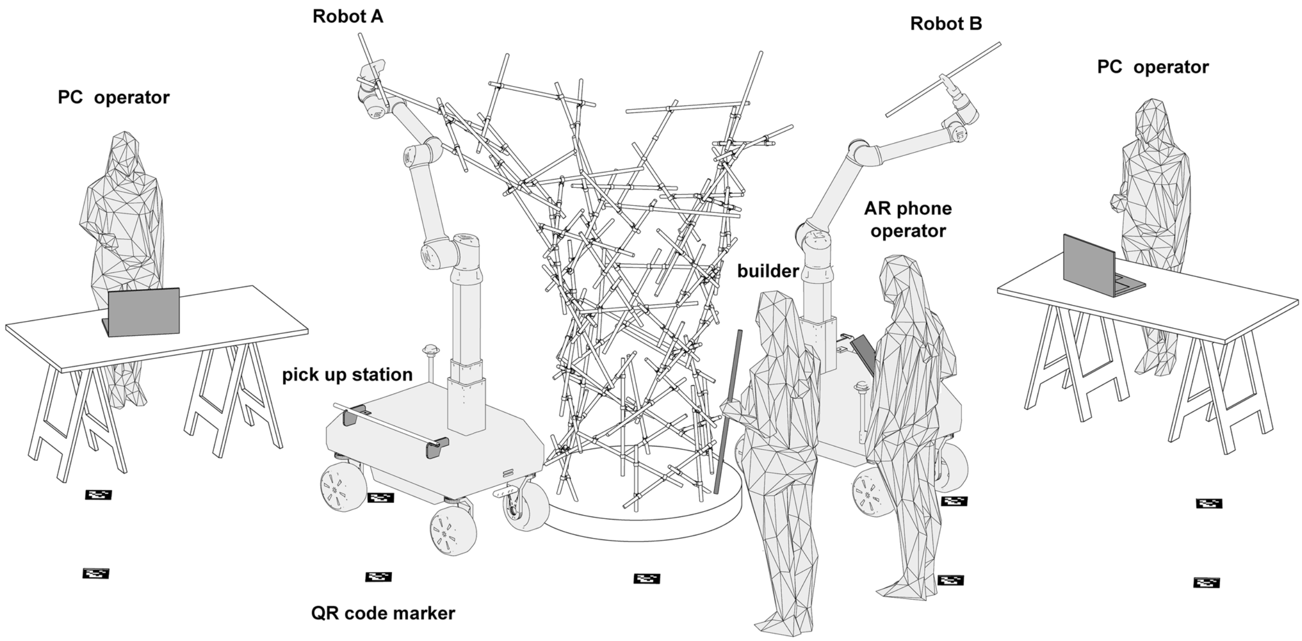

Fig. 23 Experimental setup of the cooperative assembly workflow for Case Study 1

phone localization, a total of 10 QR code markers were used, 8 located on the floor and 2 on tripods for better tracking and alignment at higher elevations.

Two Windows PCs were used for data visualization, CAD model generation, robot path planning, and control, each managing one robot setup to prevent errors during the assembly process. Additionally, two Google Pixel 5 devices ran the custom AR app to guide and instruct the assembly process.

4.1.2 Design generation

Case Study 1 explores a funnel-shaped structure spanning approximately 22.5 m^2 with a height of 3.2 m at its highest point.

Target geometry: Case Study 1 employs *Combinatorial Equilibrium Modelling* (CEM) (Ohlbrock and D'Acunto 2020) to generate a structurally informed target geometry tailored to the properties of the selected material system. CEM is a form-finding method based on *Vector-based Graphic Statics* (VGS) (D'Acunto et al. 2019) that produces spatial networks in static equilibrium using only axial elements. By directly controlling internal force magnitudes, CEM enables the design of material-efficient geometries that respond to specific structural requirements.

The equilibrium network, which forms the basis for generating the target geometry, is defined through radial trail edges extending from circularly arranged origin nodes toward fixed supports, and deviation edges that form concentric rings to redistribute forces and shape curvature (Fig. 24).

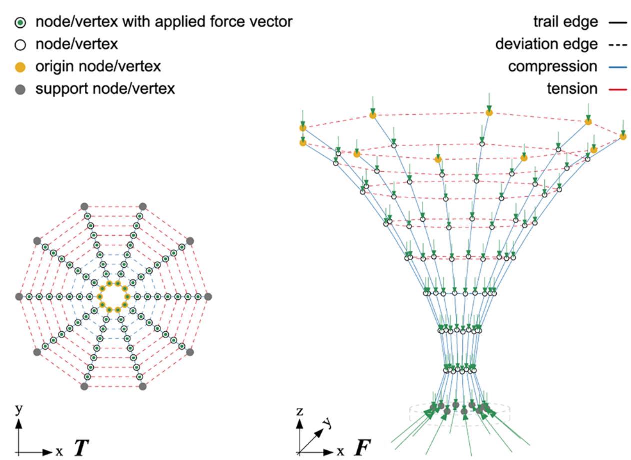

Fig. 24 Form-finding of the target geometry using CEM: the topology diagram (***T***) defines connectivity, while the form diagram (***F***) represents the equilibrium geometry. Curvature is controlled by adjusting trail lengths and internal forces in deviation edges

This ring-based logic not only informs the geometry but also guides the robotic assembly sequence: by progressively closing each ring, local structural stability is maintained throughout the assembly. The resulting network is converted into a mesh geometry, which serves as the reference for design generation and assembly sequence. The objective of the design generation was to closely approximate the target geometry, thereby aligning with the intended structural system (Fig. 25).

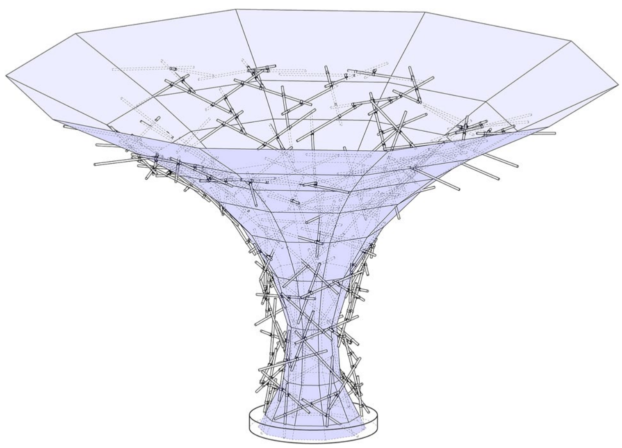

Fig. 25 Final design of the timber demonstrator, including a visualization of the target funnel-shaped geometry

Timber structure: The final timber structure comprised 178 timber rods of varying lengths connected by 315 swivel couplers. Three rod lengths—60, 70, and 80 cm—were used: shorter rods enabled tighter curvatures in the lower sections, while longer rods formed the overhanging parts. Of the 178 rods, 141 were assigned to humans and 37 to two mobile robots operating from 8 positions (Fig. 26). To ensure sufficient support and anchoring, the structure was mounted on a circular concrete base weighing 400 kg (125 cm diameter, 13.5 cm height), with custom 3D-printed holders embedded into it to secure the rods.

4.1.3 Assembly process

The demonstrator was assembled by teams of two people—one operating the mobile phone and one placing elements—supported by two mobile collaborative robots, which effectively operated from 4 instead of the originally planned 6 positions. Humans and robots alternated in placing rods. Human agents received placement instructions through a custom mobile AR interface, guiding the manual assembly of rods and connectors. In addition to placing elements, the robots took turns holding rods in their final position until they were mechanically fixed to the structure. Robotic support proved particularly valuable in areas prone to larger deflections, as it stabilized the structure and helped reduce cumulative deviations resulting from misalignments between the AR overlay and the physical assembly.

Due to the reduced number of robot repositionings, 12 rods initially designated for robotic placement were reassigned to human agents. To accommodate this limitation and maintain progress, the assembly tasks were parallelized after completing the lower portion of the structure and closing the initial rings, which enabled stable assembly from two locations at a time without bringing the structure out of equilibrium. This allowed two human–robot teams to operate simultaneously. As a result, in the final physical demonstrator, humans placed a total of 153 rods, while the mobile robots placed 25. Beyond providing temporary structural support to prevent large deflections, robotic placement also served to establish a spatial ground truth based on the digital model, helping to accommodate

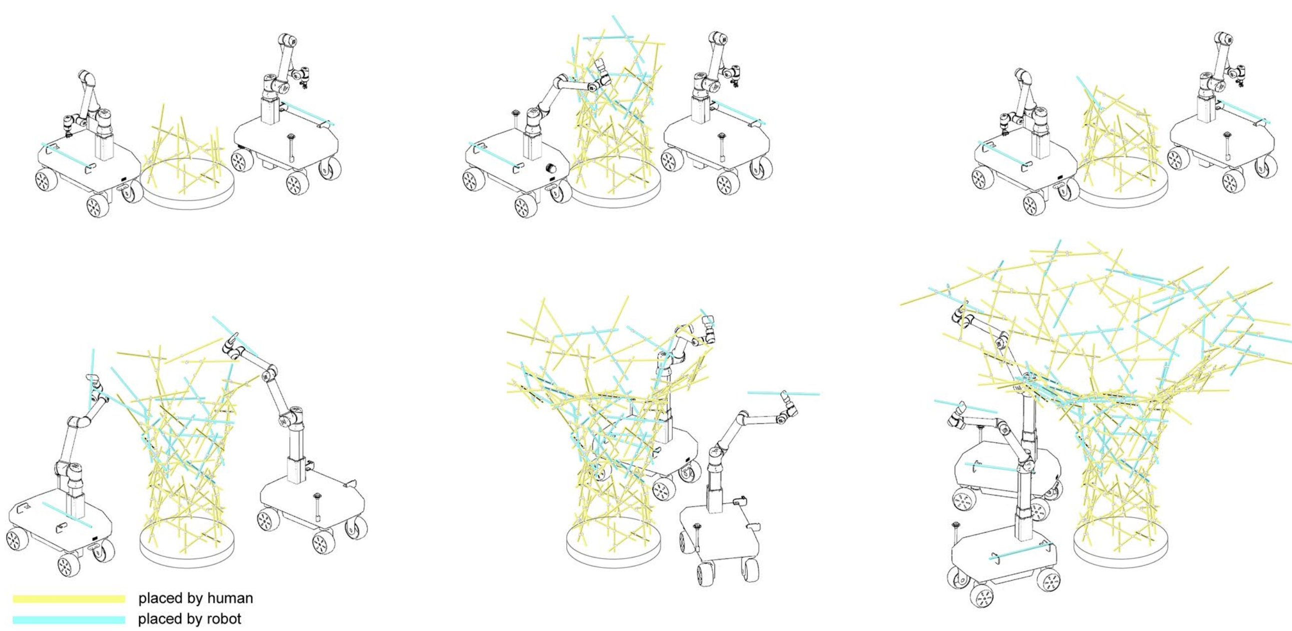

Fig. 26 Assembly sequence generated during the design phase, illustrating the planned task distribution between two mobile robots and human agents. Color coding indicates which agent is responsible for placing each element

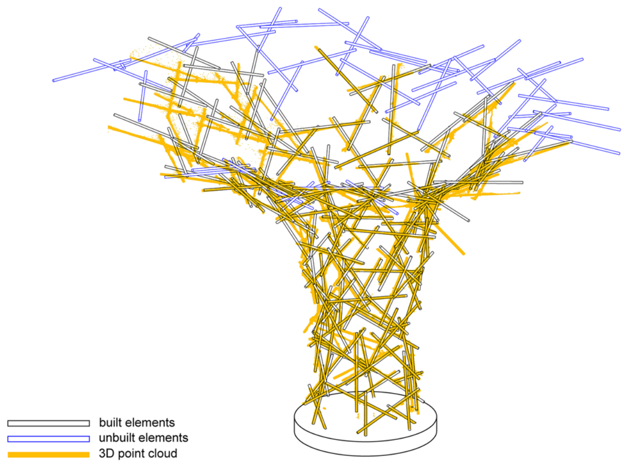

Fig. 27 3D laser scan of the partially assembled structure

deviations introduced by human placement. A 3D laser scan of the partially assembled structure was conducted to maintain geometric consistency, enabling the digital model to be updated prior to continued robotic placement (Fig. 27). Based on this scan, deviations between the digital and built structures ranged from 5 to 60 mm, with the most significant deviations occurring at the overhang due to the structure's self-weight.

The structure was disassembled to enable the reuse of the swivel couplers in Case Study 2 (Fig. 28).

4.2 Case Study 2: turn-taking with mobile robotic supports

4.2.1 Experimental setup

Similarly to Case Study 1, the experimental setup comprises two 6-DoF UR10e collaborative robotic arms mounted on custom mobile carts with integrated vertical axes and air compressors. The added vertical axis increases the combined height of the robotic arms to approximately 3.5 m (Fig. 29). The mobile carts had custom-manufactured pickup stations mounted, allowing timber rods to be fed directly to the robots. Each robotic arm was equipped with pneumatic parallel grippers and custom 3D-printed gripping fingers for handling the timber rods. Each gripper also features an *Intel RealSense Depth Camera* D435i for robot localization within the workspace, using marker tracking. For the robot and mobile phone localization, a

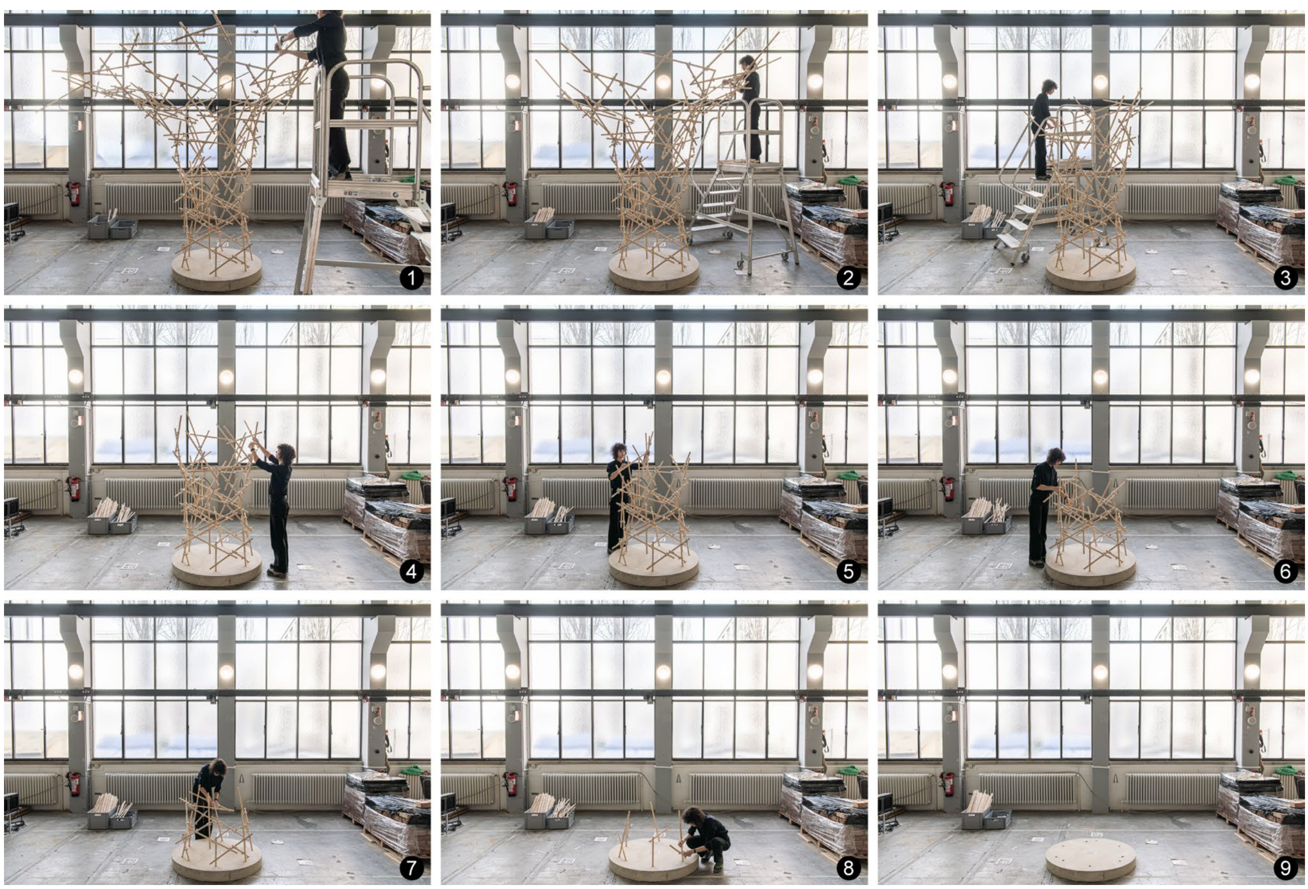

Fig. 28 Disassembly sequence in Case Study 1 showing the breakdown of the structure into its main components

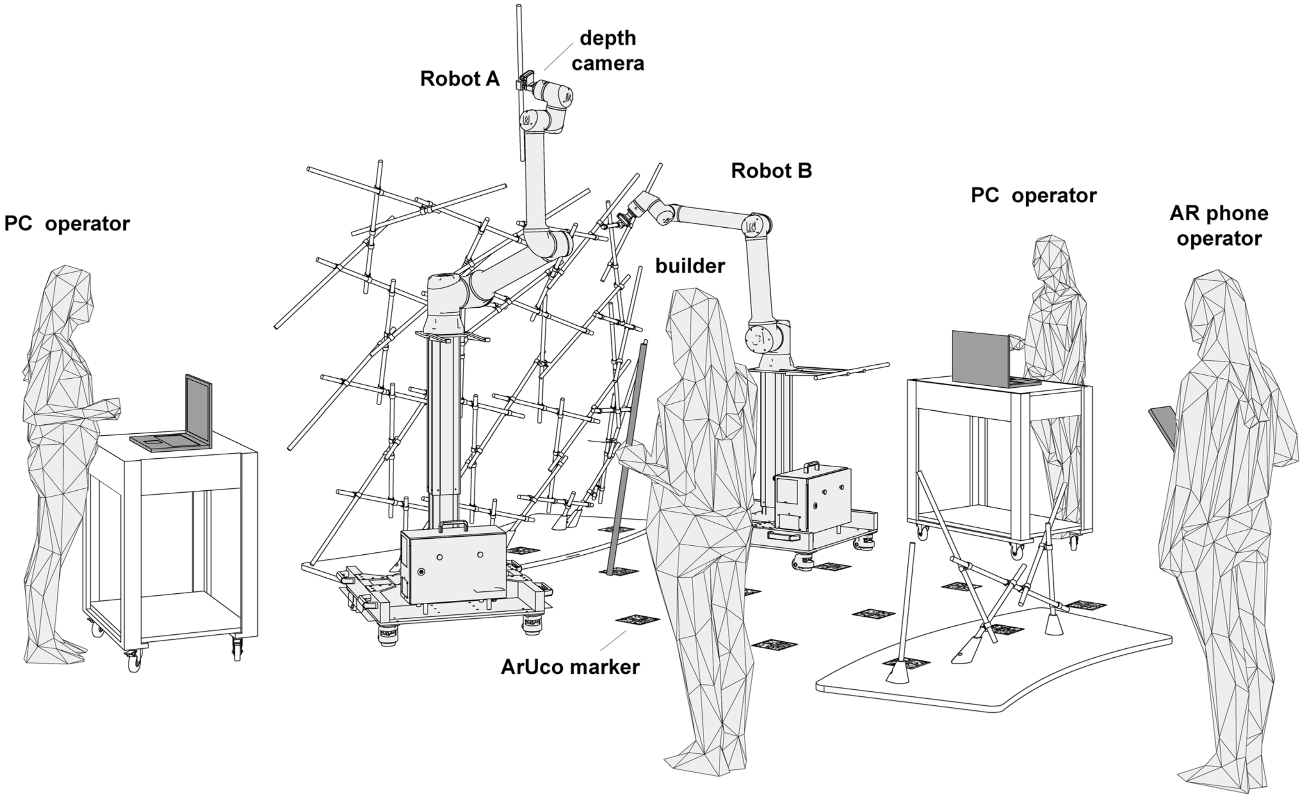

Fig. 29 Experimental setup of the cooperative assembly workflow for Case Study 2

total of 18 ArUco markers were used, 15 on the floor and 3 mounted on tripods. Two Windows PCs were used for data visualization, CAD model generation, robot path planning, and control, each managing one robot setup to prevent errors during the assembly process. Additionally, between 2 and 4 *Apple iPhones* ran the custom AR app to guide and instruct the assembly process.

4.2.2 Design generation

Case Study 2 explores an arc-like shell covering approximately 17 m^2 with a height of 3.2 m at its highest point (Fig. 30).

Target geometry: The target geometry was generated through lofting input curves and designed to accommodate both mobile robot systems and at least two people during assembly. The target geometry's curvature was optimized to allow approximation using rods of uniform length.

Timber structure: The final timber structure comprised 141 timber rods of the same length (80 cm) connected by 220 swivel couplers. Two milled plywood bases (20 mm thickness) incorporating custom 3D-printed "feet" to fix the first rods served as the foundation for the demonstrator.

4.2.3 Assembly process

The demonstrator was assembled by teams of two or more people—one operating the mobile phone and one placing elements—supported by two mobile collaborative robots, which effectively operated from 12 positions. Only one team was actively building at a time. Humans and robots alternated in placing rods. Human agents received placement instructions through the custom mobile AR interface, guiding the installation of rods and connectors. In addition to placing elements, the robots alternated in holding rods at their final position until they were mechanically secured to the structure, providing temporary stabilization. To maintain equilibrium at critical stages of the assembly, additional supports were applied.

This case study focused on turn-taking task distribution between the two mobile robots, where dynamic, temporal support was critical for maintaining equilibrium and ensuring the successful progression of the assembly. The robots placed a total of 42 rods and served as temporary supports throughout the assembly, enabling humans to safely place the remaining 99 rods. The entire structure was completed over a three-day period (Figs. 31 and 32).

To assess system accuracy, the marker-based tracking system used for robot localization was compared to point

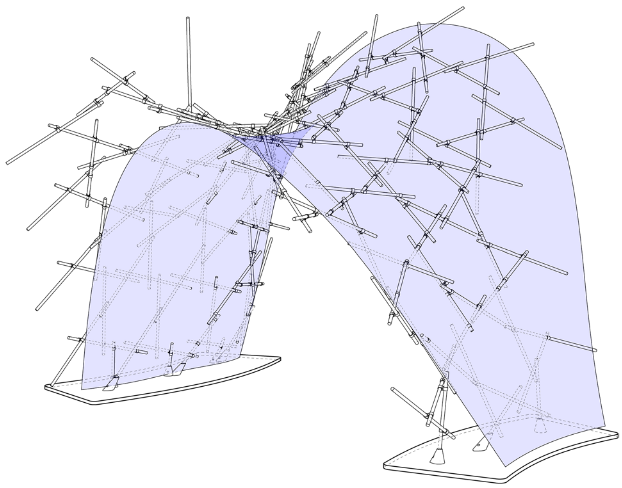

Fig. 30 Final design of the timber demonstrator, including a visualization of the target geometry

measurements, revealing a vertical deviation of 1–1.5 cm in the z-axis of the marker frame. The same system was also used to measure local structural deviations at a specific location, where markers were attached to both ends of a rod at the start of assembly. Two measurements taken during the process showed deviations between planned and as-built rod positions ranging from 20 to 50 mm, with deviations decreasing as more rods were placed by the robot.

5 Discussion

This section discusses and analyzes the outcomes of the case studies presented in Section 4. The discussion is organized around key aspects of the proposed human–robot collaborative assembly system, including current limitations and corresponding directions for future work: design for cooperative assembly, fabrication-aware design tool, task sequencing and parallelization, communication and coordination, perception and estimation.

5.1 Fabrication-aware design

The proposed fabrication-aware design methodology successfully supported the creation of two distinct assembly structures, demonstrating its flexibility in handling different geometric configurations and assembly requirements. Considering robotic limitations during the design phase proved crucial for successful assembly realization. The methodology enables human intervention without disrupting the digital fabrication workflow by segmenting the workflow into tasks based on agent competencies while maintaining interchangeable tasks where possible. This approach ensures that the generated structures not only meet geometric and structural requirements but are also tailored to cooperative assembly, where humans and robots complement each other's skills—robots providing precise placement and temporary

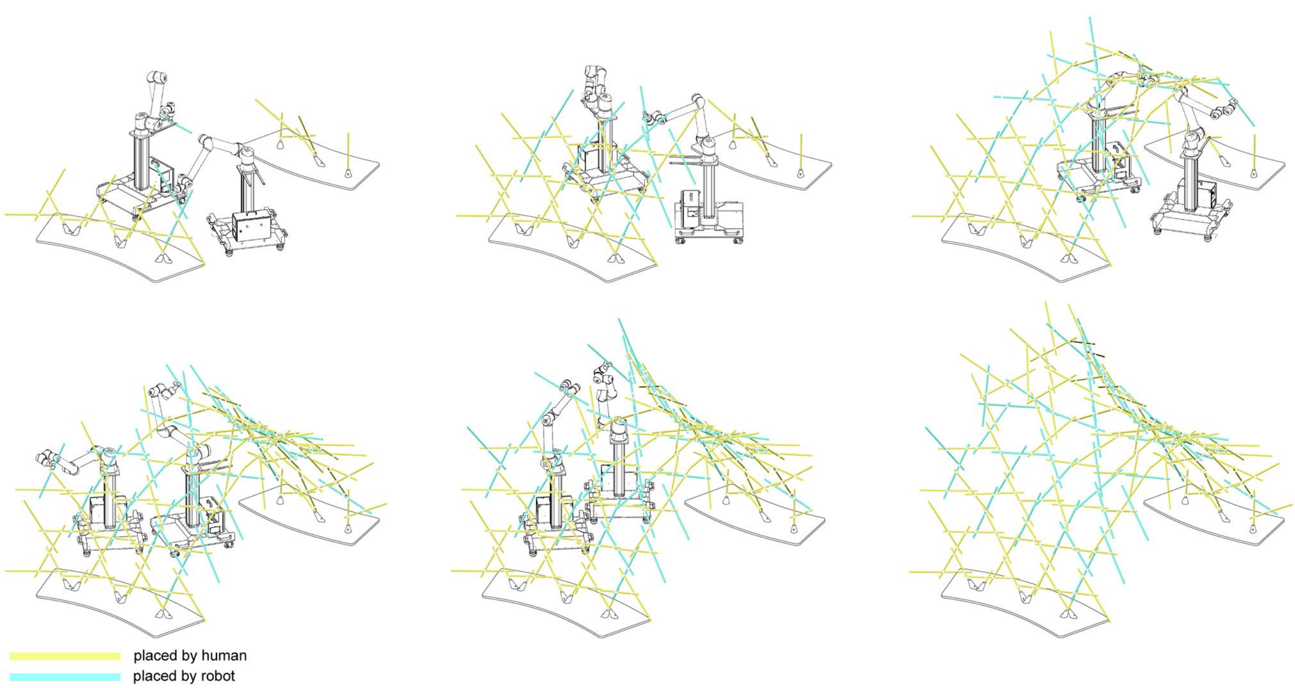

Fig. 31 Assembly sequence generated during the design phase, illustrating the planned task distribution between two mobile robots and human agents. Color coding indicates which agent is responsible for placing each element

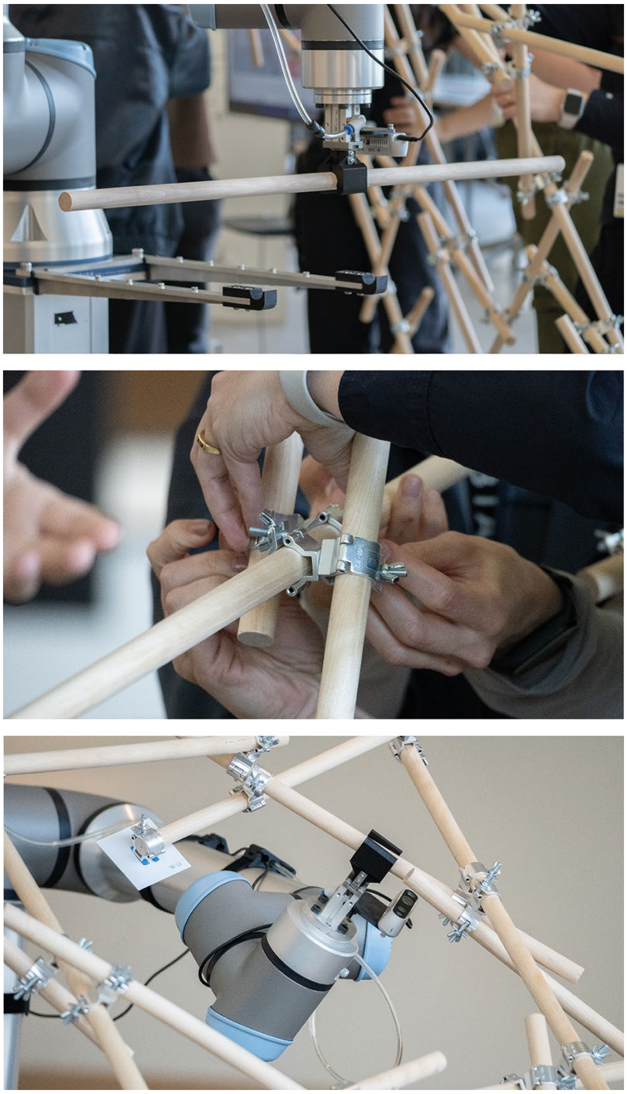

Fig. 32 Humans and robots share the task of placing rods and supporting each other in their specific roles

support while humans handle complex assembly operations and decision-making. Furthermore, the integration of the digital design environment with a robotic planning framework, simulation environment, and the cloud-hosted AM strengthened the connection between design and execution.

A sequential design generation approach incorporating fabrication constraints was implemented as part of the design methodology. Throughout design generation, static equilibrium was continuously analyzed to help determine optimal robot positions to temporarily support the structure at each assembly step. This approach provided a first approximation for determining support requirements. However, as the proposed method essentially assesses equilibrium conditions, it does not account for advanced structural analysis and resulting deformations in the individual elements. Therefore, it should be considered a gross estimation tool rather than a comprehensive structural analysis. A more detailed structural evaluation, assessing deformation and potential failure modes, would be required for precise structural verification. An advanced structural analysis could inform an automated robot position computation.

Additionally, expanding the design generation to produce multiple configuration options consisting of more elements rather than a single option-pair would enable better anticipation of how parameter changes affect the final shape. This would allow designers to more effectively balance local adjustments with global design intentions.

Central to the proposed design methodology is the AM, which currently represents spatial relationships between physical components. A natural next step in the evolution of this model would be a transformation from a geometry-centric assembly graph towards a more abstract, process-oriented task graph. While the current approach uses nodes to represent parts with spatial relationships, future extensions could shift towards representing building missions, where nodes correspond to discrete task primitives in expansion to geometry and topology, and edges encode dependencies, sequencing, or resource constraints. This transformation would allow such a model to better encode what and how is to be assembled with higher resolution, enabling a more flexible, high-level representation of construction logic. Such a representation would better support task allocation, human–robot role distribution, re-planning, and mission-level optimization.

5.2 Task sequencing and parallelization

Each design produced an AM containing a feasible assembly sequence, including task assignments and robotic fabrication parameters, to guide the process and ensure equilibrium during assembly—either through self-supporting geometry or with robotic assistance when needed. However, during assembly, these task assignments required adaptation. Robot tasks were occasionally swapped or reassigned to humans due to robot reachability limitations, demonstrating the value of dynamic task reassignment across both robot-robot and human–robot interactions. While robot locations were preplanned in the AM, in-process task swapping between Robot A and Robot B, based on reach capabilities, minimized the number of robot repositionings and reduced the frequency of mobile system localization, thus improving operational efficiency. The human–robot turn-taking approach, where robots share placement tasks alongside humans when not required for support, created a balanced system in which high-precision robotic placements compensated for less precise human actions. This task assignment strategy successfully accommodated local deviations, including material variations such as non-uniform rods, structural deflection, and imprecise human placement—factors not accounted for during the design phase.

While task parallelization was feasible in Case Study 1, it was not achievable in Case Study 2 due to its frequent reliance on robotic support at each step. This limitation arises because the current system operates under a sequential execution model, requiring each agent to wait for the completion of preceding tasks, thereby constraining the assembly process and limiting opportunities for parallelization. Future developments could address this by leveraging the graph topology of the assembly to generate multiple viable assembly sequences while preserving equilibrium. Such an approach would enable the system to adapt assembly plans to varying numbers of human agents and support the parallel execution of tasks. By implementing flexible task distribution through graph-based buildable element computation, the system could efficiently coordinate multiple human builders working simultaneously, significantly enhancing construction speed and resource utilization.

5.3 Communication and coordination

The system employed a centralized coordination strategy with communication managed through a cloud-hosted AM. The AR application played a crucial role in facilitating human–robot interaction. The system successfully implemented task reassignment decisions across all connected devices, with human assessment and judgment providing essential input for the decision-making process.

While functional, the current communication and task monitoring system relies heavily on manual processes that could be automated. The AR interface requires a verbal relay of information from the operator to assembly personnel, and task completion depends on manual confirmation. These limitations could be addressed through the implementation of automated task completion recognition systems and more sophisticated human instruction methods based on the deviation between planned and estimated object poses that utilize object tracking capabilities. Such improvements would streamline the communication flow and reduce potential bottlenecks in the assembly process.

5.4 Sensing and estimation

The perception and estimation components of the system revealed several important findings regarding accuracy and practical implementation. While marker-based tracking for robot localization provided lower precision compared to manual point measurement with the robot, it achieved significantly faster execution times. This trade-off between accuracy and speed proved beneficial for maintaining overall workflow efficiency, as the achieved precision remained within acceptable tolerances for successful assembly operations.

Structural deflections of up to 10 cm were observed depending on robot support positions. Two successful solutions were implemented to handle these variations: 3D scanning to update the digital model in Case Study 1, and direct measurement of built rods using the robot's measurement tip after marker-space localization in Case Study 2. By updating the digital model with actual built geometry, these approaches ensured accurate robot positioning and successful element attachment throughout the assembly process..

Several limitations were identified that affected both quality control and system scalability. The reliance on human visual inspection and manual measurements could be overcome by integrating advanced sensing and tracking systems. These systems could enable quantitative quality control through real-time measurement of positional deviations between as-planned and as-built rods and automated detection of assembly sequence violations. Additionally, load-bearing capacity could be continuously assessed, comparing actual versus predicted structural behavior. Human motion tracking could enable both dynamic task distribution and enhanced safety through human-aware collision avoidance, while real-time object detection could continuously monitor structural deflection. The development of automated feedback mechanisms could create a closed-loop system where physical adjustments are seamlessly transferred to the design environment, maintaining precise alignment between the digital model and physical construction. These comprehensive improvements would enhance the integration of design and cooperative assembly and provide more reliable and consistent quality assurance throughout the assembly process.

6 Conclusions

To achieve meaningful human–robot cooperative assembly workflows for on-site construction, the distinct capabilities, constraints, and interactions of human and robot agents should be integrated from the design phase through to fabrication. Beyond planning, effective cooperative workflows rely on the ability of agents to coordinate their actions within a shared environment. This research proposes a holistic computational design-to-fabrication methodology that integrates a graph-based assembly model, supporting multi-agent task representation, adaptive task planning, and reassignment with fabrication-aware design, and multi-agent task coordination for designing complex timber assemblies—embedding these elements already at the design stage to enable flexible, cooperative human–robot assembly workflows.

The proposed methodology is implemented through a process-oriented design approach that integrates these considerations directly into the design workflow, enabling the generation of flexible execution plans alongside geometry and allowing the system to adapt to the dynamic, unpredictable nature of in-situ construction environments. Rather than focusing solely on the final artifact, our method emphasizes the performative and temporal dimensions of multi-agent assembly, particularly the definition, sequencing, and execution of interdependent tasks between human and robotic agents. The proposed assembly grammar formalizes geometry as a sequence of coordinated physical tasks distributed across agents with complementary capacities. This geometric and procedural reasoning integrates the physical and operational constraints of both humans and robots; in particular, robotic limitations—such as reachability—were considered alongside the equilibrium of the partially assembled system during design generation to ensure both constructability and assembly feasibility. The generated AM was hosted on a cloud server and made accessible to a custom AR app, which served as a visual and interactive interface: it generated manual instructions for human builders, coordinated robotic routines, enabled synchronized human–robot task execution in dynamic construction environments, and supported task reassignment when on-site conditions prevented task executions originally assigned.

To validate this approach, we conducted two experimental case studies that demonstrated how this integrated design-to-fabrication methodology can be applied for different geometrical conditions and how flexible assembly plans can support turn-taking task execution between humans and robots. By combining the problem-solving capabilities of humans with the precision, consistency, and structural support functions of robotic systems, the proposed workflow contributes to more resilient and adaptable robotic assembly processes, where human intervention enhances rather than disrupts progress. While these cooperative methods may not yet match the speed of traditional manual construction, they offer clear advantages in managing complexity, ensuring spatial precision, and distributing physically demanding tasks across agents. These benefits stem from robots' ability to maintain precise positioning and provide temporal structural support—tasks that are physically demanding for humans. Moreover, the dual functionality of robots in both placing and stabilizing elements introduces workflow efficiencies that are difficult to achieve through manual labor alone.

Future work could expand this process-oriented approach by evolving the assembly model beyond geometry-centric representations toward more abstract, mission-level task graphs, enabling higher-resolution modeling of task dependencies, dynamic resource allocation, and optimization of human–robot cooperation across increasingly complex construction scenarios. Ultimately, the strategies presented in this work demonstrate how human–robot cooperation can help advance robotic construction technologies by enabling higher levels of automation alongside more adaptable, context-aware construction processes—capable of addressing the unique challenges of real-world building environments.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

References

Alexi EV, Kenny JC, Atanasova L, Casas G, Dörfler K, Mitterberger D (2024) Cooperative augmented assembly (CAA): augmented reality for on-site cooperative robotic fabrication. Constr Robot 8(2):28. https://doi.org/10.1007/s41693-024-00138-6

Amtsberg F, Yang X, Skoury L, Wagner H-J, Menges A (2021) IHRC: an AR-based interface for intuitive, interactive and coordinated task sharing between humans and robots in building construction. In: Proceedings of the 38th international symposium on automation and robotics in construction (ISARC). https://doi.org/10.22260/ISARC2021/0006

Apolinarska AA, Knauss M, Gramazio F, Kohler M (2016) The sequential roof. Routledge, London, pp 45–59. https://doi.org/10.4324/9781315678825-4

Atanasova L, Mitterberger D, Sandy T, Gramazio F, Kohler M, Dörfler K (2020) Prototype as Artefact. Acadia 2020, 2010, 350–359

Atanasova L, Saral B, Krakovská E, Schmuck J, Dietrich S, Furrer F, Sandy T, D'Acunto P, Dörfler K (2023) Collective AR-assisted assembly of interlocking structures. In:Towards radical regeneration.Springer International Publishing, pp 175–187. https://doi.org/10.1007/978-3-031-13249-0_15

Austern G, Capeluto IG, Grobman YJ (2018) Rationalization methods in computer aided fabrication: a critical review. Autom Constr 90:281–293. https://doi.org/10.1016/J.AUTCON.2017.12.027

Bock T (2015) The future of construction automation: technological disruption and the upcoming ubiquity of robotics. Autom Constr 59:113–121. https://doi.org/10.1016/j.autcon.2015.07.022

Boothroyd G (1987) Design for assembly—the key to design for manufacture. Int J Adv Manuf Technol 2:3–11. https://doi.org/10.1007/BF02601481/METRICS

Boothroyd G, Dewhurst P, Knight WA (2010) Product design for manufacture and assembly. CRC Press, Boca Raton. https://doi.org/10.1201/9781420089288

Boschetti G, Bottin M, Faccio M, Minto R (2021) Multi-robot multi-operator collaborative assembly systems: a performance evaluation model. J Intell Manuf 32:1455–1470. https://doi.org/10.1007/s10845-020-01714-7

Brosque C, Galballyt E, Khatib O, Fischer M (2020) Human–robot collaboration in construction: opportunities and challenges

Bruun EPG, Parascho S, Adriaenssens S (2024) Cooperative robotic fabrication for a circular economy. Springer, Cham, pp 129–149. https://doi.org/10.1007/978-3-031-39675-5_8

Bruun EPG, Pastrana R, Paris V, Beghini A, Pizzigoni A, Parascho S, Adriaenssens S (2021) Three cooperative robotic fabrication methods for the scaffold-free construction of a masonry arch. Autom Constr 129:103803. https://doi.org/10.1016/j.autcon.2021.103803

Colledanchise M, Ögren P (2017) Behavior trees in robotics and AI: an introduction. In: Behavior trees in robotics and AI. https://doi.org/10.1201/9780429489105

Cormen TH, Leiserson CE, Rivest RL, Stein C (2022) Introduction to algorithms, 4th edn. MIT Press, Cambridge

D'Acunto P, Jasienski J-P, Ohlbrock PO, Fivet C, Schwartz J, Zastavni D (2019) Vector-based 3D graphic statics: a framework for the design of spatial structures based on the relation between form and forces. Int J Solids Struct 167:58–70. https://doi.org/10.1016/j.ijsolstr.2019.02.008

Dörfler K, Sandy T, Giftthaler M, Gramazio F, Kohler M, Buchli J (2016) Mobile robotic brickwork. Robo Fabr Archit Art Des 2016:204–217. https://doi.org/10.1007/978-3-319-26378-6_15

Dörfler K, Hack N, Sandy T, Giftthaler M, Lussi M, Walzer AN, Buchli J, Gramazio F, Kohler M (2019) Mobile robotic fabrication beyond factory conditions: case study mesh mould wall of the DFAB HOUSE. Constr Robot 3(1):53–67. https://doi.org/10.1007/S41693-019-00020-W

ElMaraghy H, ElMaraghy W (2016) Smart adaptable assembly systems. Procedia CIRP 44:4–13. https://doi.org/10.1016/j.procir.2016.04.107

Everett JG, Slocum AH (1994) Automation and robotics opportunities: construction versus manufacturing. J Constr Eng Manag 120:443–452. https://doi.org/10.1061/(ASCE)0733-9364(1994)120:2(443)

Frick U, Mele TV, Block P (2016) Data management and modelling of complex interfaces in imperfect discrete-element assemblies

Gibson JJ (2014) The ecological approach to visual perception. Psychology Press, London. https://doi.org/10.4324/9781315740218

Han IX, Parascho S (2023) Improv-structure: exploring improvisation in collective human–robot construction, pp 233–243. https://doi.org/10.1007/978-3-031-20241-4_16

Han IX, Meggers F, Parascho S (2021) Bridging the collectives: a review of collective human–robot construction. Int J Archit Comput 19:512–531. https://doi.org/10.1177/14780771211025153

Hu SJ, Ko J, Weyand L, Elmaraghy HA, Lien TK, Koren Y, Bley H, Chryssolouris G, Nasr N, Shpitalni M (2011) Assembly system design and operations for product variety. CIRP Ann 60:715–733. https://doi.org/10.1016/J.CIRP.2011.05.004

Kao GTC, Körner A, Sonntag D, Nguyen L, Menges A, Knippers J (2017) Assembly-aware design of masonry shell structures: a computational approach. https://doi.org/10.3929/ethz-b-000554318

Kao GTC, Iannuzzo A, Thomaszewski B, Coros S, Mele TV, Block P (2022) Coupled rigid-block analysis: stability-aware design of complex discrete-element assemblies. CAD Comput Aided Des. https://doi.org/10.1016/J.CAD.2022.103216

Kenny J, Mitterberger D, Casas G, Alexi E, Gramazio F, Kohler M (2024) COMPAS XR: extended reality workflows for the COMPAS framework. https://github.com/compas-dev/compas_xr/. ETH Zürich, Princeton University. https://doi.org/10.5281/zenodo.12514526

Knight T, Vardouli T (2015) Computational making. Des Stud 41:1–7. https://doi.org/10.1016/j.destud.2015.09.003

Kyjanek O, Bahar BA, Vasey L, Wannemacher B, Menges A (2019) Implementation of an augmented reality AR workflow for human robot collaboration in timber prefabrication. In: Proceedings of the 36th international symposium on automation and robotics in construction (ISARC). International Association for Automation and Robotics in Construction (IAARC). https://doi.org/10.22260/ISARC2019/0164

Lallement R, Silva L, Alami R, Lallement DR (2018) HATP: hierarchical agent-based task planner. In: ACM reference format. https://doi.org/10.34894/VQ1DJA

Liu H, Wang L (2017) An AR-based worker support system for human-robot collaboration. Procedia Manuf 11:22–30. https://doi.org/10.1016/j.promfg.2017.07.124

Lundeen KM, Kamat VR, Menassa CC, McGee W (2019) Autonomous motion planning and task execution in geometrically adaptive robotized construction work. Autom Constr 100:24–45. https://doi.org/10.1016/j.autcon.2018.12.020

Mele TV, Casas G, Beverlylytle Rust R, Liew A, Li, Tetov A, Pastrana R, Rippmann Lee J, Xydis A, Bernhard M, Robin-oval, Mattiskoh, He X, Leung V, Nizartaha, Wenqian, Ania A, Godwyll R, Deviezeviking, Du C, Dörfler K, Robinjodon, Ranaudo F, Kao GT-C, Nikeftekhar, Huang Y, Ghensi A, Dimitrova E (2022)

compas-dev/compas: COMPAS 1.14.1. Zenodo. https://doi.org/10.5281/zenodo.6108431
Michalos G, Makris S, Tsarouchi P, Guasch T, Kontovrakis D, Chryssolouris G (2015) Design considerations for safe human-robot collaborative workplaces. Procedia CIRP 37:248–253. https://doi.org/10.1016/j.procir.2015.08.014
Mitterberger D, Atanasova L, Dörfler K, Gramazio F, Kohler M (2022) Tie a knot: human–robot cooperative workflow for assembling wooden structures using rope joints. Constr Robot 6:277–292. https://doi.org/10.1007/s41693-022-00083-2
Nau D, Au TC, Ilghami O, Kuter U, Murdock JW, Wu D, Yaman F (2003) SHOP2: an HTN planning system. J Artif Intell Res 20:379–404. https://doi.org/10.1613/JAIR.1141
Ohlbrock PO, D'Acunto P (2020) A computer-aided approach to equilibrium design based on graphic statics and combinatorial variations. Comput Aided Des 121:102802. https://doi.org/10.1016/j.cad.2019.102802
Oyediran H, Turner W, Kim K, Barrows M (2024) Integration of 4d BIM and robot task planning: creation and flow of construction-related information for action-level simulation of indoor wall frame installation
Papakostas N, Michalos G, Makris S, Zouzias D, Chryssolouris G (2011) Industrial applications with cooperating robots for the flexible assembly. Int J Comput Integr Manuf 24:650–660. https://doi.org/10.1080/0951192X.2011.570790
Parascho S, Gandia A, Mirjan A, Gramazio F, Matthias K (2017) Cooperative fabrication of spatial metal structures. UCL Press, London, pp 24–29. https://doi.org/10.2307/j.ctt1n7qkg7.7
Parascho S, Han IX, Walker S, Beghini A, Bruun EPG, Adriaenssens S (2020a) Robotic vault: a cooperative robotic assembly method for brick vault construction. Constr Robot 4:117–126. https://doi.org/10.1007/s41693-020-00041-w
Parascho S, Han IX, Beghini A, Miki M, Walker S, Bruun EPG, Adriaenssens S, Parascho S, Han I, Beghini A, Miki M, Walker S, Bruun E, Adriaenssens S (2020b) LightVault: a design and robotic fabrication method for complex masonry structures
Pottmann H (2012) Freeform architecture and fabrication-aware design. Comput Graph 36:306. https://doi.org/10.1016/J.CAG.2012.04.003
Pottmann H (2013) Architectural geometry and fabrication-aware design. Nexus Netw J 15:195–208. https://doi.org/10.1007/S00004-013-0149-5/METRICS
Pottmann H, Eigensatz M, Vaxman A, Wallner J (2015) Architectural geometry. Comput Graph 47:145–164. https://doi.org/10.1016/j.cag.2014.11.002
Rossi A, Tessmann O (2017) Geometry as assembly—integrating design and fabrication with discrete modular units, pp 201–210. https://doi.org/10.52842/conf.ecaade.2017.2.201
Skibniewski MJ, Nof SY (1989) A framework for programmable and flexible construction systems. Robot Auton Syst 5:135–150. https://doi.org/10.1016/0921-8890(89)90006-7
Skoury L, Treml S, Opgenorth N, Amtsberg F, Wagner HJ, Menges A, Wortmann T (2023) Towards data-informed co-design in digital fabrication. https://doi.org/10.1016/j.autcon.2023.105229
Soto BG, AgustíJuan I, Hunhevicz J, Joss S, Graser K, Habert G, Adey BT (2018) Productivity of digital fabrication in construction: cost and time analysis of a robotically built wall. Autom Constr 92:297–311. https://doi.org/10.1016/j.autcon.2018.04.004
Thoma A, Jenny D, Helmreich M, Gandia A, Gramazio F, Kohler M (2019) Cooperative robotic fabrication of timber dowel assemblies. De Gruyter, Berlin, pp 77–88. https://doi.org/10.1515/9783035620238-008
Wang Y, Tian D (2016) A weighted assembly precedence graph for assembly sequence planning. Int J Adv Manuf Technol 83:99–115. https://doi.org/10.1007/S00170-015-7565-5/METRICS
Wang Z, Kennel-Maushart F, Huang Y, Thomaszewski B, Coros S (2023a) A temporal coherent topology optimization approach for assembly planning of bespoke frame structures. ACM Trans Graph 42:1–13. https://doi.org/10.1145/3592102
Wang J, Liu W, Kao GT-C, Mitropoulou I, Ranaudo F, Block P, Dillenburger B (2023b) Multi-robotic assembly of discrete shell structures. De Gruyter, Berlin, pp 261–274. https://doi.org/10.1515/9783111162683-020
Wang L, Liu S, Liu H, Wang XV (2020) Overview of human–robot collaboration in manufacturing. pp 15–58. https://doi.org/10.1007/978-3-030-46212-3_2
Willmann J, Knauss M, Bonwetsch T, Apolinarska AA, Gramazio F, Kohler M (2016) Robotic timber construction—expanding additive fabrication to new dimensions. Autom Constr 61:16–23. https://doi.org/10.1016/j.autcon.2015.09.011
Wolf M, Kaiser B, Hügle S, Verl A, Middendorf P (2022) Data model for adaptive robotic construction in architecture. Procedia CIRP 107:1035–1040. https://doi.org/10.1016/j.procir.2022.05.104
Wu K, Kilian A (2018) Robotic equilibrium: Scaffold free arch assemblies. In: ACADIA
Yang X, Amtsberg F, Sedlmair M, Menges A (2024) Challenges and potential for human–robot collaboration in timber prefabrication. Autom Constr 160:105333. https://doi.org/10.1016/J.AUTCON.2024.105333
Zhang M, Xu R, Wu H, Pan J, Luo X (2023) Human-robot collaboration for on-site construction. Autom Constr 150:104812. https://doi.org/10.1016/J.AUTCON.2023.104812