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Building (with) Human-Robot Teams

Enabling Cooperative Assembly Processes for Building Construction

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Abstract

The objective of this research is to develop a design-to-fabrication methodology for coordinated assembly processes performed by human-robot teams within the Architecture, Engineering, and Construction (AEC) sector. This methodology is used to experimentally investigate the possibilities and implications of human–robot cooperation in robotic building construction.

Robotic assembly techniques have advanced beyond the limitations of manual construction, enabling the realization of structures with highly complex geometries, offering increased design freedom and productivity. However, while robots are versatile and spatially precise tools that are programmable for various assembly procedures, they also bring limitations such as reduced dexterity, limited adaptability to unforeseen events, and reduced reach compared to human builders. While robots may struggle to respond to unexpected fabrication conditions—challenges that humans typically manage intuitively—the integration of both humans and robots holds the potential to combine the spatial precision and machine intelligence of robots with the adaptability and contextual awareness of human builders. Despite the development of novel Human-Robot Collaboration (HRC) methods in the classical manufacturing domain, the robotic construction domain still faces challenges in integrating these approaches and defining the role of humans in robotic processes. These challenges are partly due to the differences between manufacturing and construction environments, including, but not limited to, task complexity and heterogeneity, evolving worksite environments, and construction scale. To address the complexities of human-robot cooperation in building construction, novel approaches and their integration into a computational design-to-fabrication process are required.

Hence, this research aims to develop a comprehensive methodology for designing and constructing complex spatial assemblies that leverage the cooperation of multiple human and robotic agents to achieve tasks that neither can accomplish alone. The methodology explores the performative, temporal, and architectural dimensions of spatial assemblies and investigates adaptable team configurations capable of responding to changing environmental and task-specific conditions. Assembly workflows are decomposed into spatial and temporal events, and coordinated through task allocation strategies and real-time interfaces that link physical and digital domains via sensors and actuators. The proposed methods are validated through an experimental case study approach involving architectural-scale prototypes constructed by various human–robot team configurations. The insights gained from these experiments aim to inform new applications for robotic workflows in architecture and construction, ultimately demonstrating how human–robot teams with complementary capabilities can unlock new potentials in the built environment.

Zusammenfassung

Diese Forschung entwickelt eine Design-to-Fabrication-Methodik für koordinierte Montageprozesse, die von Mensch-Roboter-Teams in den Bereichen Architektur, Ingenieurwesen und Bauwesen (AEC) ausgeführt werden. Diese Methodik untersucht experimentell die Möglichkeiten und Implikationen der Mensch-Roboter-Kooperation im robotischen Bauen.

Robotische Montagetechniken haben die Grenzen manueller Bauweisen erweitert und ermöglichen die Realisierung von Strukturen mit hochkomplexen Geometrien, und bieten damit erhöhte Gestaltungsfreiheit und Produktivität. Roboter sind vielseitige und räumlich präzise Werkzeuge, die für verschiedenste Montageverfahren programmierbar sind. Gleichzeitig bringen sie Einschränkungen mit sich: reduzierte Fingerfertigkeit, begrenzte Anpassungsfähigkeit an unvorhergesehene Ereignisse und eine geringere Reichweite als Menschen. Auf unerwartete Fertigungsbedingungen zu reagieren – Herausforderungen, die Menschen meist intuitiv meistern – fällt Robotern oft schwer. Genau hier liegt das Potenzial der Mensch-Roboter-Integration: die räumliche Präzision und maschinelle Intelligenz der Robotik mit der Anpassungsfähigkeit und dem Kontextbewusstsein menschlicher Bauausführung zu verbinden. Obwohl im klassischen Fertigungsbereich bereits neuartige Methoden der Mensch-Roboter-Kollaboration (HRC) entwickelt wurden, bestehen im robotischen Bauen weiterhin Herausforderungen – bei der Integration solcher Ansätze ebenso wie bei der Definition der Rolle des Menschen im Prozess. Ursache dafür sind strukturelle Unterschiede zwischen Fertigung und Bauwesen: Aufgabenkomplexität und -heterogenität, wechselnde Baustellenbedingungen und der größere Maßstab von Bauprozessen. Um diesen Anforderungen zu begegnen, sind neue Ansätze erforderlich, die in einen rechnergestützten Design-to-Fabrication-Prozess integriert werden.

„Die vorliegende Arbeit entwickelt daher eine umfassende Methodik zum Entwurf und zur Realisierung komplexer räumlicher Strukturen, bei der menschliche und robotische Akteure im Bauprozess kooperieren, um Aufgaben zu bewältigen, die weder Mensch noch Maschine allein ausführen können. Die Methodik untersucht die performativen, zeitlichen und architektonischen Dimensionen räumlicher Montageprozesse und erprobt flexible Teamkonfigurationen, die auf wechselnde äußere und aufgabenspezifische Bedingungen reagieren. Montageabläufe werden in räumliche und zeitliche Vorgänge unterteilt und durch Aufgabenzuweisungsstrategien sowie Echtzeit-Schnittstellen koordiniert, die physische und digitale Umgebung mittels Sensorik und Aktorik miteinander verbinden. Die Methoden werden durch einen experimentellen Fallstudienansatz validiert, bei dem architektonische Prototypen im Maßstab 1:1 von verschiedenen Mensch-Roboter-Teamkonfigurationen gebaut werden. Die gewonnenen Erkenntnisse sollen neue Anwendungsfelder für robotische Prozesse in Architektur und Bauwesen aufzeigen – und demonstrieren, wie Mensch-Roboter-Teams mit komplementären Fähigkeiten neue Potenziale in der gebauten Umwelt erschließen können.

Acknowledgments

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Contents

1 Introduction

1.1 Motivation

Robotic assembly techniques have expanded beyond the limits of manual construction, enabling the realization of structures with highly complex geometries and offering greater design freedom and productivity [1]–[3]. Robots act as versatile, spatially precise tools that can be reprogrammed for a range of assembly procedures and excel at tasks requiring high positional accuracy, repeatability, and endurance. These capabilities have opened up new architectural possibilities that would be difficult or impossible to achieve with traditional manual construction.

However, these advantages are accompanied by limitations, especially when robots are deployed in construction environments. Compared to human builders, robots have reduced dexterity, agility, and reach. They often struggle to adapt to unforeseen events or irregularities during assembly—situations that humans routinely handle through situational awareness, tactile feedback, and real-time problem-solving. Beyond perception, many robotic fabrication processes still rely on humans performing manual tasks such as joining components, drilling, or screwing, even if such human involvement is not explicitly reflected or integrated within digital workflows. Research on human-robot collaboration methods (HRC) for assembly tasks [4] addresses these complementary capabilities to develop collaborative strategies that extend what individuals can achieve on their own. Today, humans and robots share workspaces for handover tasks, execute sequential and simultaneous tasks, and are able to perform synchronized movements [5]. These approaches are supported by advanced interaction interfaces, from gesture-based control to augmented reality (AR) task guidance [6], [7], and have been implemented in both single- and multi-robot applications [8], [9]. Despite their significant progress in the manufacturing sector, the construction domain still struggles to meaningfully integrate such approaches and clearly define the role of human workers in robotic assembly processes.

This challenge arises in part from the fundamental differences between manufacturing and construction environments. Manufacturing processes are designed for controlled, repetitive operations in highly structured settings where spatial relationships between components, tools, and machines remain constant, and each action is preplanned. Construction sites, by contrast, are dynamic, open-ended, and characterized by low levels of standardization [10]. Workspaces evolve continuously as projects progress: materials arrive at unpredictable times, scaffolding and temporary structures are erected and removed, and external factors such as weather and site topography introduce further variability [11]. Unlike manufacturing assembly lines with predetermined component flows, building assembly involves managing tolerance accumulation across multiple joints, positioning large structural elements in three-dimensional space, and adapting continuously to changing conditions that may affect assembly sequences, component accessibility, or create collision risks for robots during motion execution. These realities explain why construction robotics, despite decades of research and experimentation, has not achieved the level of implementation seen in manufacturing and why most building assembly work continues to rely heavily on manual labor [12], [13].

The complexity of construction assembly further amplifies these challenges. Building assembly requires managing multiple interdependent operations—joining, placing, holding—that must be coordinated across various agents, including machines, human workers, cranes, and material handlers operating simultaneously in shared, often constrained workspaces. Automated approaches struggle with these realities, particularly when continuous quality assessment and adjustment are needed during assembly. Humans excel at detecting subtle indicators such as resistance during joining or slight misalignments—issues that remain difficult for robotic systems to detect and resolve autonomously.

Prefabrication offers one strategy to mitigate some of these challenges by shifting portions of the construction process into controlled environments. However, it introduces its own constraints, including transportation limits, component size restrictions, and integration complexities on-site. Certain architectural forms and material systems require in-situ assembly to achieve structural continuity or meet design intent [14]. Overreliance on prefabrication risks narrowing architectural possibilities without fully addressing the core challenges of onsite construction assembly.

Within this context, HRC emerges as a promising strategy for construction assembly. Rather than treating human involvement as a fallback when automation fails, cooperative assembly intentionally combines the complementary strengths of human and robotic agents. Robots contribute precision, endurance, and repeatability; humans bring dexterity, contextual understanding, and real-time adaptability. Together, human-robot teams can address on-site construction challenges that robots alone cannot resolve independently. However, this requires integrated frameworks that can systematically embed HRC into design-to-fabrication processes to enable system flexibility and adaptability. Most current systems either focus on robotic workflows or rely on simple human supervision without providing mechanisms for dynamic task sharing, real-time task adjustment between humans and robots, or even meaningful inclusion of human participation in digital workflows.

To advance human-robot cooperative assembly in construction, new approaches are needed that address the complexities of task assignment between human and robotic agents, enabling flexible, dynamic allocation as conditions change; support spatial coordination systems for safe and efficient concurrent operations; develop shared control interfaces that facilitate seamless handoffs and parallel task execution; and incorporate real-time feedback mechanisms that leverage human assessment to maintain construction quality. Such cooperative assembly frameworks should treat human-robot teams as the fundamental design unit for construction, embedding cooperation into computational design and fabrication workflows from the earliest stages. By doing so, they can enable superior assembly outcomes, support novel architectural expressions, and help bridge the gap between robotics research and practical building assembly.

In light of these considerations, the questions that arise are as follows: How can assembly workflows be designed to integrate the combined strengths of human and robotic agents in construction environments? What coordination methods are required to support real-time cooperation and dynamic task allocation in shared workspaces? How can cooperative assembly processes be embedded in computational design-to-fabrication workflows to enable outcomes beyond the reach of either humans or robots alone?

Through the development of integrated methods, computational models, coordination strategies, and experimental validations, this research aims to establish human-robot cooperation as a core strategy for construction assembly and contribute to the broader adoption of robotics in building practice.

The following sections articulate the specific problems this research addresses, the research questions that emerge from them, and the objectives pursued in response. The chapter concludes with the applied research strategy and an overview of the thesis structure.

1.2 Problem statement

Multi-agent assembly systems integrating cooperative robotics and humans show promise for addressing critical technology adoption challenges in building construction. By enabling flexible fabrication workflows, such systems could support higher levels of automation on construction sites while maintaining the adaptability required for real-world building scenarios. However, practical implementation reveals a fundamental mismatch between how we currently plan robotic construction processes and how human-robot teams actually need to efficiently work together to handle assembly operations. Current digital fabrication methods follow a rigid, linear workflow—departing from architectural design, then planning, and finally construction execution. While such workflows successfully function in prefabrication settings, their lack of adaptability makes them impractical in an environment whose conditions continuously evolve. To fully leverage the potential of human-robot cooperation, these approaches require flexible, real-time adaptation possibilities integrated within their system workflows, which allow for planning adjustments, design decision-making, and error handling without disrupting the entire fabrication process.

This creates a core problem: our design tools and fabrication methods lack opportunities to systematically generate assembly processes that harness mutual dependencies between humans and robots while being computationally precise and adaptively responsive to the dynamic conditions encountered across both prefabrication and in-situ assembly contexts. This mismatch manifests in three specific areas that require new theoretical frameworks and practical methods:

- **Linear digital design-to-fabrication workflows**
- **Object-based representation limitations**
- **Multi-agent coordination challenges**

Linear digital design-to-fabrication workflows. Current computational design methods cannot systematically account for performative requirements of multi-agent coordination, including how to embed task distribution logic that leverages complementary human-robot capabilities for complex operations. Existing design software lacks the capability to generate adaptive workflows where design, planning, and assembly inform each other continuously, preventing architects and engineers from algorithmically designing assembly processes that systematically utilize tasks that exceed what either agent type can handle alone.

Linear workflow vs **Adaptive workflow**

Design → **Plan** → **Assemble** vs **Design** ↔ **Plan** ↔ **Adapt**

sequential vs **simultaneous (iterative)**

Object-based representation limitations. Current computational models focus primarily on geometric data while missing critical information about temporal sequences, performative requirements, complementary skill sets, and mutual dependencies between different agent types. These representation gaps prevent systematic modeling of how humans and robots can support each other in assembly processes and how their interdependencies affect coordination effectiveness across different construction contexts.

Multi-agent coordination challenges. Current coordination approaches lack flexible task assignment mechanisms that can allow for the redistribution of work, leveraging complementary capabilities during assembly. Existing methods either impose rigid role assignments or require constant supervision, lacking systematic approaches for seamless cooperation that can expand the application area of collaborative robotics in construction through shared workspaces that support complex assembly operations.

1.3 Research questions

The outlined research challenges highlight a central gap in current digital construction practices: while cooperative human-robot assembly systems could offer great potential, existing tools and methods fail to support their integration. Addressing this requires rethinking how we design, represent, and coordinate construction processes across multiple agents-both humans and robots. To explore this, the research is guided by the following key questions:

1. ***How can we develop integrated design-to-fabrication workflows that are inherently adaptive and support multi-agent cooperation?***
   What new methodologies emerge when fabrication is not a downstream consequence of design, but part of a continuous, feedback-driven process that enables real-time adjustments and shared task planning between humans and robots?

2. ***How can computational models represent the spatial, temporal, and constructive interdependencies of human-robot teams?***
   What new forms of representation are needed to capture and operationalize the mutual dependencies, sequencing, and complementary skills involved in cooperative assembly?

3. ***How can dynamic coordination between multiple agents be achieved during assembly processes?***
   What mechanisms and systems can enable effective, real-time task negotiation, redistribution, and responsiveness to changing construction conditions?

4. ***How do different material systems and construction contexts influence the coordination strategies and architectural potential of multi-agent assembly?***
   How do the properties of materials and the nature of site conditions shape the roles, interactions, and capabilities of human-robot teams?

5. ***What are the transferable principles of multi-agent coordination that apply across diverse architectural-scale fabrication systems?***
   Can we identify generalizable strategies or models that transcend specific material systems and inform broader applications of human-robot collaboration in construction?

1.4 Research objectives

This research aims to extend the digital process chain of robotic assembly to an integrated design-to-fabrication methodology for adaptive human-robot cooperative assembly processes. It investigates whether and how humans and robots can leverage their complementary skills to support each other in assembly operations that exceed single-agent capabilities, and explores new opportunities for the AEC domain. Furthermore, this research investigates the establishment of shared digital-physical workspaces—continuously updated using object tracking and augmented reality systems—that enable seamless coordination between heterogeneous human and robotic agents. This research focuses particularly on the cooperative assembly of complex timber structures, which exemplify the design and fabrication challenges of adaptive multi-agent assembly processes.

Specific objectives of the proposed research include:

- **Develop design-to-fabrication methodology for cooperative assembly processes**, focusing on how design decisions, planning adjustments, and execution feedback can inform each other simultaneously rather than sequentially. This includes embedding task distribution logic directly within the design process to systematically plan assembly operations that leverage heterogeneous abilities. This objective advances understanding of adaptive design-to-fabrication workflows $design \rightarrow plan \rightarrow adapt$ that move beyond linear workflows to enable responsive and adaptive assembly processes.

- **Develop computational methods for representing and modeling multi-agent participation** within assembly design systems that can capture both human and robot physical actions and their interdependencies, considering their complementary skill sets. This objective advances theoretical understanding of how diverse agent characteristics and mutual dependencies can be formally represented within computational models to enable the computational design of complex assembly structures across different construction contexts rather than ad-hoc coordination approaches.

- **Develop coordination strategies for multi-agent assembly** through task assignment mechanisms and seamless coordination interfaces using augmented reality systems within continuously synchronized workspaces. This includes investigating sequential versus parallel coordination approaches and pre-planned versus adaptive task distribution strategies. This objective contributes to understanding coordination approaches for adaptive multi-agent assembly processes to take advantage of the complementary strengths of both humans and robots in collaborative construction.

- **Explore and demonstrate the developed methods** through implementation across distinct team configurations to realize architectural scale demonstrators focusing on complex timber structures. This includes comparing design outcomes across various material systems, joint configurations, and construction scenarios in different construction contexts.

1.5 Research design

To investigate the outlined research objectives, this dissertation adopts a case study approach combining computational development with empirical, full-scale prototyping. The research is structured around four experimental case studies, each exploring different configurations of human–robot cooperation and addressing specific design-to-fabrication challenges.

Case Study 1: Human-human cooperative assembly focuses on human–human collaboration mediated by augmented reality (AR). It establishes the baseline logic of distributed manual construction using topologically interlocking modules, coordinated through an AR system accessing data from a cloud-based assembly model. It explores a collective construction process between multiple humans supported by a custom mobile AR application. The app distributes and visualizes step-by-step building instructions in 3D space, enabling real-time coordination among multiple human participants on-site. Through cloud-based services and user-specific AR content, the construction progress is synchronized across all users. The material system consists of topologically interlocking wooden modules that assemble without mechanical fasteners, allowing for reconfigurable and fully disassemblable full-scale architectural structures.

Case Study 2A: Human-robot cooperative assembly with one robot introduces the first level of human–robot cooperation with a single robot operating alongside two human agents. Termed *Prototype-as-Artefact*, this study explores emergent, in-situ design processes, where human and robotic actions alternate in a hybrid, reactive workflow. Central to this approach is the development of an assembly grammar—a set of local assembly rules that guide construction while allowing the overall form to emerge adaptively within a rectilinear grid. This grammar supports a hybrid process that combines intuitive, spontaneous human actions with rational, rule-based robotic coordination. Interaction is facilitated through a context-aware mobile AR device, which enables real-time registration, evaluation, and augmentation of human input with robot-executed building actions in a shared augmented workspace.

Case Study 2B: Human-robot cooperative assembly with two robots builds on the interaction principles and non-linear design established in *Case study 2A*, extending the system to support a team of two mobile robots and two human participants. This project explores the cooperative assembly of a spatial wooden reciprocal frame structure with rope joints, progressively designed during construction based on an expanded assembly grammar that is no longer limited to a rectilinear grid. Within the shared digital-physical workspace, spatial information provides real-time feedback on design boundaries and fabrication constraints, guiding human placement decisions. Human agents position elements manually in accordance with a set of design rules, which shape the evolving structure. In direct response, the robots continue the assembly cycle, precisely placing components and stabilizing the configuration in real time.

Case Study 3: Multi-human-robot cooperative assembly synthesizes the learnings from all prior studies into a fully predefined, architectural-scale cooperative assembly process. It integrates design, structural logic, and fabrication constraints within a cloud-connected model, coordinating multiple human and robotic agents through a centralized system. The design is determined prior to fabrication, incorporating fabrication-related constraints to ensure feasibility and structural stability. Cloud-based tools support centralized coordination between multiple human and robotic agents on-site. A comprehensive *assembly grammar* guides the design process, defining both geometric configurations and the interdependent sequence of tasks required to assemble a reciprocal timber frame. This approach integrates design intent with equilibrium and fabrication constraints, enabling the cooperative execution of assemblies beyond the capabilities of humans or robots alone.

These case studies collectively serve both as validation of the proposed methodology and as iterative design experiments. Each case expands the complexity of the cooperative assembly scenario, scaling the material system, team configuration, sequencing logic, and interaction model. Together, they demonstrate how a computationally driven, human–robot cooperative framework can support adaptive, constructible, and scalable spatial assemblies.

1.6 Structure of the thesis

The thesis is structured into five chapters following this introduction.

Chapter 2 establishes the conceptual and technological foundations for this research. It introduces computational theories of making and argues for integrating human agency into robotic construction as an alternative to full automation. The chapter reviews advances in multi-agent assembly, assembly-aware design, and coordination methods, highlighting key gaps in current approaches, particularly in integrating human participation, dynamic planning, and real-time adaptability. These gaps directly inform the problem statement and research objectives presented in the next chapter.

Chapter 3 outlines the research methods and presents a dual approach combining computational and empirical methods to develop and evaluate a design-to-fabrication methodology for human-robot cooperative assembly. It introduces rule-based design strategies grounded in *assembly grammars*, which define both the geometric logic and sequential actions of construction. The chapter presents the *Assembly Model* (AM), a graph-based data structure that encodes geometry, fabrication constraints, and task dependencies to support multi-agent workflows. It further details coordination strategies and AR-based user interfaces that facilitate real-time task distribution and interaction. The methods are validated through a series of case studies, each testing different team configurations, sequencing strategies, and levels of autonomy, culminating in the architectural-scale construction of a complex timber structure.

Chapter 4 describes the developed case studies and their evaluation. It provides the implementation and validation of the developed methods with regard to their applicability to distinct human-robot cooperative teams.

Finally, **Chapter 5** presents the overall conclusion. It synthesizes findings, discusses implications, and concludes the thesis by presenting future directions.

Appendix A presents *"Diversifying construction"*, the publication and documentation of an exhibition contribution, addressing human-robot cooperative workflows where a mason and a collaborative robot share physical labor in constructing a brick structure.

Appendix B presents the documentation of a study on *"Cooperative mobile brickwork"*, bringing bricklaying apprentices of a mason's school and a mobile collaborative robot together.

2 Background and related research

2.1 Background

This section lays the conceptual foundation for this research through two key concepts: computational theories of making that emphasize temporality and openness to emergent formation (see Section 2.1.1), and second, cross-domain perspectives that advocate for more inclusive robotic construction by positioning human participation as an integral part of digital fabrication processes, suggesting an alternative paradigm to fully automated systems (see Section 2.1.2).

2.1.1 Computational modelling of making

Contemporary architectural practice often separates conceptual design from fabrication planning, creating a hierarchical workflow where construction methods are determined after design concepts are established. This contrasts with craft practices where design decisions evolve continuously through direct engagement with materials and making processes during production. Craft practitioners maintain plans that adapt during physical production, accommodating unexpected events such as material property changes, design modifications, or production errors. This adaptive approach affords craft processes inherent openness and flexibility, preserving space for creative discovery throughout making. In architectural construction, such adaptability becomes essential as projects inevitably encounter site-specific conditions, material variations, and assembly challenges that cannot be fully predicted during design phases. To embed this openness in digitally-informed processes, it must be explicitly defined and requires representing processes beyond their final results. Recognizing this challenge, Knight and Stiny's computational theory of making—termed *making grammar*—builds upon Stiny's and Gips' generative design theory on shape grammar [15], seeks to capture the temporal and perceptual dimensions of craft practice, moving beyond static product representation to encompass the dynamic processes of creation [16]. This approach challenges traditional hylomorphic design thinking[1], privileging material-driven, emergent formation processes [17].

Knight and Stiny apply *making grammar* to describe the kolam pattern, a South Indian practice of drawing intricate geometric patterns on the ground using rice powder, as a set of *seeing* and *drawing* rules (see Fig. 2.1).

By conceiving craft as *"doing and sensing with stuff to make things,"* Knight and Stiny articulate creative practice through rule-based systems that govern both physical making and sensory engagement across spatial and temporal dimensions [16]. These generative rules resist predetermined outcomes, maintaining an open approach throughout the creative process. This flexibility enables practitioners to respond dynamically to emergent design opportunities re-

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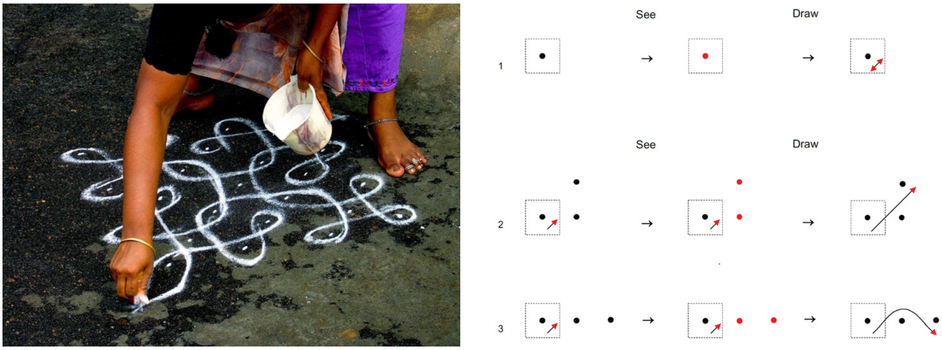
[1] In design and making contexts, hylomorphism describes the model where *"practitioners impose forms internal to the mind upon a material world 'out there'"* [17].



(a) Woman drawing a kolam pattern [18] **(b) The rules of *making grammar* [19]**

Figure 2.1: Kolam pattern making

vealed through work in progress, adapting to unexpected material behaviors or discovering new creative possibilities that emerge from the making process itself [20].

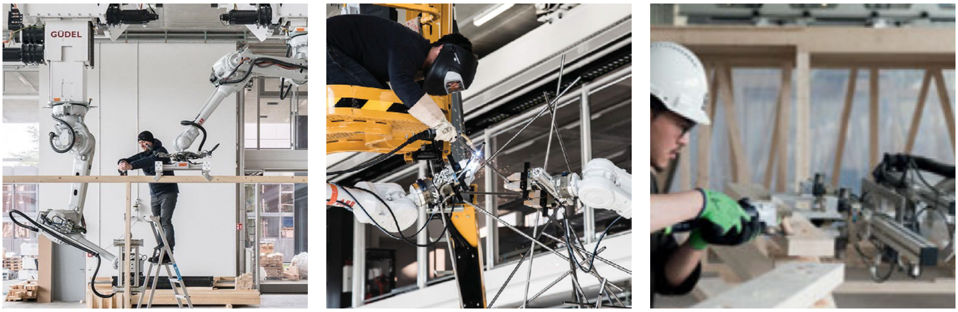
Similarly, Richard Sennett's interpretation of Ruskin reinforces this perspective of craft by characterizing craft processes as *"lost spaces of freedom"* where makers engage in experimental practice, embrace productive failure, and willingly *"lose control"* [21]. Within contemporary industrial contexts, Sennett's reading of Enlightenment thought suggests pathways for recovering such creative autonomy: *"The enlightened way to use a machine is to judge its powers, fashion its uses, in light of our own limits rather than the machine's potential. A machine ought to propose rather than command, and humankind should certainly walk away from the command to imitate perfection"* [21]. Rather than positioning human and machine capabilities in opposition, the intersection between rationalized industrial methods and traditional craft practices suggests new possibilities for architectural fabrication. To realize these possibilities, computational methods must capture not just the precision of digital fabrication but also the temporal, adaptive qualities that define craft practice.

2.1.2 Diversifying robotic construction

Research in diversified farming systems argues that cooperation between humans and robots often produces superior results compared to automation alone in variable, heterogeneous conditions [22]. Like construction sites, diversified farms present unstructured environments where emergent interactions resist predetermined automation sequences, pointing to the need for automation that does not aim to eliminate human involvement but rather create opportunities for higher-value human activities like observation, assessment, and strategic decision-making.

Ditzler and Driessen's exploration of *"pixel cropping"* automation reveals how practitioners generate *"a spectrum of imaginations for how automated tools might—or might not—be appropriately used, ranging from fully automated visions, to collaborative scenarios, to fully analogue prototypes."* [22] This spectrum directly parallels the needs of construction robotics, where different project phases, site conditions, and safety requirements demand varied levels of automation. The authors document a particularly instructive example of human-robot collaboration where *"the farmer walked behind the robot as it weeded... The robot was imprecise and missed weeds periodically, which the*

Figure 2.2: A farmer walks behind a prototype weeding robot and pulls out the weeds it missed [22]



(a) Manually bolting timber beams together that have been jointly placed by the two robots [23]

(b) Manually welding metal tubes, held by two robotic arms, at their connection point [3]

(c) Manually inserting, cutting and watering timber dowels [24]

Figure 2.3: Examples of human participation in robotic fabrication processes

farmer then pulled himself." This represents what they term a "co-bot scenario" that transcends traditional supervised control, demonstrating how humans and robots can work in dynamic partnership rather than hierarchical supervision.

Perhaps most importantly, their framework shifts focus from *"aiming to achieve a singular end goal (A: How to automate system x?) and rather towards a feedback process driven by the underlying ethos of the desired system (B: How to facilitate the processes and outcomes we want?)."* In construction contexts, this suggests designing robotic systems not merely to automate specific tasks, but to enhance overall fabrication workflow capability instead of automating the entire workflow.

In AEC, the challenges from struggling to answer question A inevitably lead to looking for an answer to question B, which naturally calls for manual task execution as the *immediate* problem solution 2.3.

2.2 State of the art

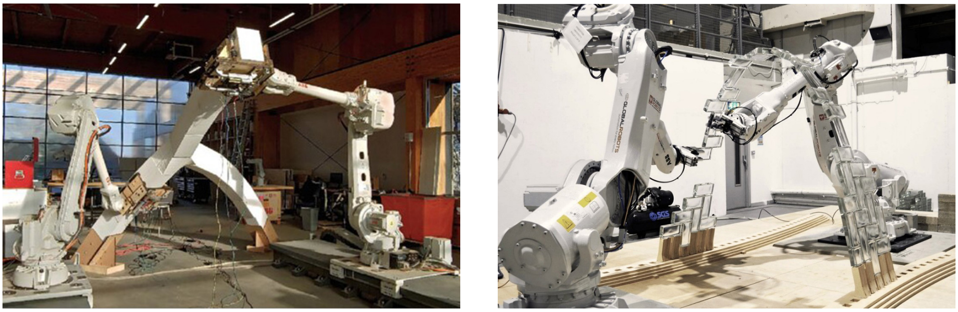
This *State of the art* Section reviews technological and methodological developments that form the foundation for this research on human-robot cooperative assembly in construction: first, the evolution from single-robot to multi-robot and hybrid human-robot systems, through the perspective of extended design possibilities and flexibility (see Section 2.2.1); second, the principle of design for assembly through assembly-aware design approaches and graph-based computational representations (see Section 2.2.2); and third, existing multi-agent planning and coordination methods, assembly sequencing to task-based coordination (see Section 2.2.3).

2.2.1 Cooperative assembly processes

Research on multi-robot assembly systems has demonstrated significant advantages over single-robot approaches by enabling cooperative operations where multiple robots work together to handle components and assembly tasks that exceed individual robot capabilities [3], [23]–[29]. These systems leverage distributed execution to expand both physical workspace coverage and functional capabilities beyond what single robotic agents can achieve. The cooperative nature of multi-robot assembly enables new construction possibilities, particularly for large-scale structures and complex geometries that require simultaneous manipulation from multiple positions. These advantages have been validated through the assembly of bespoke spatial frame structures from metal bars [3], [26], timber frame modules [23], and timber dowel assemblies [24], showcasing how multiple robots can simultaneously and precisely position building elements in three-dimensional space.

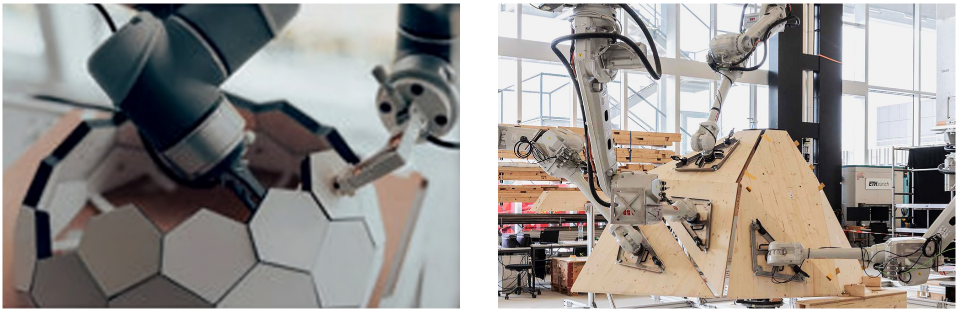
Recent implementations have further explored the application of robots beyond achieving high spatial precision for enabling scaffold-free assembly of non-planar geometries. Instead of temporary supporting frameworks, these methods rely on the robots themselves to provide temporal support to enable the construction of complex spatial geometries. Such a strategy was exemplified by Wu and Kilian, who employed two stationary industrial robots that alternate in supporting and placing foam blocks to assemble an arch structure [25] (Fig. 2.4a). Building on this sequential coordination technique, the *LightVault* project [27], [28] demonstrated the cooperative construction of a doubly-curved vault using two stationary industrial robots performing simultaneous positioning and support operations (Fig. 2.4b). Similarly, Wang et al. utilize two collaborative robotic arms for the proof-of-concept assembly of a discrete shell structure [29] (Fig. 2.4c). Scaling up the number of coordinated agents, the *Semiramis* installation by Gramazio Kohler Research showcases a multi-robot assembly using four industrial robot arms on an overhead gantry system to handle complex spatial arrangements of timber plates [30] (Fig. 2.4d). These implementations reveal that multi-robot systems can achieve assembly precision and complexity that significantly exceeds single-robot capabilities, particularly for operations requiring temporal structural support, simultaneous manipulation, and precise spatial positioning from multiple directions. Additionally, by minimizing the need for temporary scaffolding, cooperative assembly methodologies have the potential to reduce resource input [31].

Building upon the proven advantages of multi-robot assembly, recent research in cooperative



(a) Assembly of an arch [25]

(b) *LightVault:* utilises two cooperating robots to construct complex doubly-curved vault [28]



(c) Multi-robotic assembly of discrete shell structures [29]

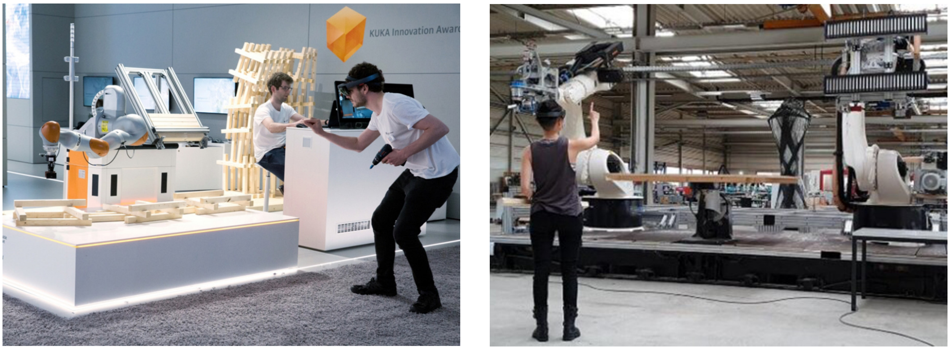
(d) *Semiramis*: robotic assembly with four robot arms by Gramazio Kohler Research, ETH Zurich [30]

Figure 2.4: Examples of scaffold-free assembly enabled by multi-robot systems

fabrication processes for AEC has begun to increasingly frame topics of interest related to design and fabrication in human-robot teams to leverage the knowledge and expertise of humans while taking advantage of robot's precision and task repeatability in cooperative workflows, to support more flexible and adaptable workflows. Within the AEC sector, this has led to various studies exploring the relationship between humans and robots through theoretical frameworks and experimentally validating collaborative fabrication approaches.

Human-robot collaborative assembly approaches have been explored in proof-of-concept projects for timber prefabrication, such as *CRoW* [32] and *iHRC* [33]. In *CRoW*, an interactive robotic assembly process is facilitated through an augmented reality (AR) user interface that augments the human worker with digital data and provides direct access to robot control routines (Fig. 2.5a). *iHRC*, on the other hand, proposes a human-robot collaborative system for managing and sharing tasks between humans and an industrial robot in the prefabrication of complex building components. In this system, precomputed tasks are stored in a task manager and distributed upon execution confirmation of previous tasks, with communication mediated via an AR interface on head-mounted displays (Fig. 2.5b).

Recent research seeks to move beyond isolated demonstrations of human-robot interaction by formalizing theoretical frameworks that propose systematic frameworks for human-robot collaboration in construction. These studies position the collective synergy between humans and robots as a strategic opportunity to enhance design potential and address key challenges in robotic fabrication [34]. Rather than focusing solely on technical implementation, they frame HRC as an integrated design problem—one that requires consideration of system, task, and human factors alike [35].



(a) *CRoW*: interactive robotic assembly through AR [32]

(b) *iHRC*: human-robot collaborative system for timber prefabrication [33]

Figure 2.5: Proof-of-concept demonstrations of human-robot collaborative assembly for timber prefabrication

(a) *Improv-Structure*: humans and robotic arms collaboratively assemble an unplanned bamboo rod structure [36]

(b) Design space explorations in a cooperative fabricating scenario informed by robotic constraints [31]

Figure 2.6: Design space explorations through cooperative assembly workflows

This evolving field has been complemented by experimental work that illustrates the expanded design possibilities afforded by multi-robot systems in collaboration with human workers. These projects embed fabrication constraints while enabling intuitive human design decision-making during construction. For example, *Improv-Structure* [36] explores an improvisational fabrication workflow where humans and robotic arms collaboratively assemble an unplanned bamboo rod structure (Fig. 2.6a). Similarly, in preliminary work, Bruun et al. [31] have conducted a design space exploration study in a cooperative fabricating scenario informed by robotic constraints and human input for fabricating aggregated structures, shifting the robot's role from passive tool to active, creative participant (Fig. 2.6b).

Although substantial progress has been made in both multi-robot and hybrid human-robot systems, current approaches remain fragmented—each demonstrating isolated techniques without integrating them into a cohesive design-to-fabrication methodology suited for human-robot collaboration. In particular, existing cooperative workflows often fall short in capturing the role of human actors within digitally informed processes or in addressing the intricacies of human-robot interaction from the outset of the design process. This gap is especially apparent in the lack of integrated design tools capable of simultaneously addressing design intent, fabrication constraints, and multi-agent coordination requirements. While these hybrid assembly approaches significantly expand architectural possibilities, the complexity of planning multi-agent workflows introduces considerable challenges compared to single-robot systems. Current efforts, including some of the research mentioned above, have developed a range of strategies for multi-agent planning and coordination, which are introduced in Section 2.2.3. To better understand how such considerations can be systematically embedded in design workflows, the following section reviews foundational principles of Design for Assembly and computational representations of assembly processes.

2.2.2 Design for assembly and computational representations

The word *assembly* encompasses both the process of connecting components and the resulting assembled product—a dual meaning that emphasizes its inherently temporal nature. Assemblies are therefore defined not only by *what* is being assembled, but also by *when* each part is added. Design for Assembly (DfA) represents a methodological approach that integrates these manufacturing and assembly considerations into the earliest stages of product development to enhance efficiency and reduce costs [37]. Graph theory provides a powerful framework for formalizing assembly relationships and constraints through node-edge models, where components are represented as nodes and their physical or logical dependencies as edges [38]. Nodes encapsulate detailed data on geometry, connections, positional requirements, and process constraints such as tooling, timing, and accessibility. This enables advanced computational analysis, supporting automated sequence generation and evaluation [39], conflict detection, and systematic optimization for efficiency and constructability.

Within architectural and robotic assembly contexts, DfA principles have undergone significant adaptation to address robotic limitations, material characteristics, and assembly sequence requirements. This adaptation facilitates the integration of assembly considerations directly into design workflows, thereby improving constructability and minimizing the reliance on ad-hoc solutions during the fabrication phase [40]. In response to fabrication challenges within the AEC industry, researchers have further looked into fabrication-aware and assembly-aware design methodologies [41], [42]. These digital design methods embed fabrication and construction limitations directly within design development phases, particularly during geometry generation processes [43], thereby ensuring producibility while maintaining design objectives. This constraint integration has progressed from retrospective design modification (post-rationalization) toward proactive approaches where manufacturing limitations directly influence initial design generation [44].

Further developments show the integration of various fabrication-related constraints into open-source assembly-aware computational design tools. The Python-based WASP Grasshopper plugin facilitates adaptable modular growth through diverse strategies ranging from stochastic placement to constraint-driven and performance-optimized arrangements [45], enabling the conversion from design configurations to robotic assembly instructions. Similarly, the Rigid Block Equilibrium Analysis library (compas_rbe) supports stability-informed design processes that maintain structural performance throughout assembly design progression [46], illustrating how computational frameworks can simultaneously address design objectives and assembly requirements.

Although graph-based methodologies originated within manufacturing environments, their application has expanded significantly into architectural design and construction domains. Within architectural contexts, these computational methods fulfill dual functions: modeling assembly configurations through component-relationship mapping [42], [47], and characterizing robotic fabrication workflows through action-task-operation hierarchies [48].

Despite advances in assembly-aware and fabrication-aware design methodologies, current techniques face significant limitations when addressing multi-agent scenarios, particularly in HRC. Existing computational frameworks lack comprehensive methods for representing and planning human-robot interactions from the early stages of design, leading to fragmented workflows that struggle to meaningfully integrate human agency alongside robotic execution. While graph-based representations offer robust structures for modeling assembly relationships and planning robotic operations, these frameworks require extension to effectively visualize, simulate, and adapt to the dynamic, interactive conditions inherent in HRC scenarios. Moreover, prevailing approaches tend to focus on the final design outcome, overlooking the performative and procedural aspects of making that are central to cooperative construction processes [19]. These limitations highlight the need for more sophisticated methods capable of capturing and leveraging both human and robot involvement, while addressing the sequential, spatial, and temporal dimensions that define cooperative assembly.

2.2.3 Multi-agent assembly planning and coordination

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. A range of methodologies has emerged to address this challenge, spanning from bottom-up design logic and structured assembly sequencing to task partitioning techniques that enable real-time coordination.

In the AEC sector, assembly sequence planning has seen significant advances, particularly in the context of scaffold-free construction. A multi-objective optimization process can determine a structurally optimal fabrication sequence by coordinating two to three stationary robots [49]. Research by Wang et al. introduces techniques for sequencing assembly operations to limit deformation during transitional construction stages [50]. Their method exhibits adaptability to various fabrication setups, including manual assembly with mixed-reality tools and multi-robot systems, and experimentally validates the AR-instructed manual assembly. However, none of these applications consider hybrid multi-agent teams.

Task-based segmentation has emerged as a promising strategy for managing complex multi-agent fabrication workflows. In prefabrication settings, Skoury et al. [51] present a unified tasks data model that discretizes design-to-fabrication processes into individual tasks, maintaining links between design elements and fabrication procedures for a single robot fabrication setup.

Expanding this approach to hybrid agents, iHRC decomposes digital designs into discrete tasks that are matched to the skill sets of both robotic and human fabrication units [33]. The system enables flexible task reassignment during execution through AR interfaces, allowing humans to take over, correct, or reassign tasks based on unit capabilities. However, while this approach demonstrates dynamic workflow adaptation, the tasks remain derivatives of predetermined design models rather than being integrated into the design process itself. Additionally, the system exhibits limits on parallelized task execution.

The use of AR in such workflows is particularly promising, as it facilitates real-time guidance and coordination between human and robotic agents. Beyond task visualization, AR enables networked and collaborative interactions by integrating with cloud services and wireless communication technologies, supporting scenarios such as computer-supported collaborative work [52], multi-user AR environments [53], and mobile collaborative AR systems [54]. In architectural fabrication contexts, AR has been used to assist craftspeople through projection-based guidance [55], [56], holographic spatial instructions [57], [58], and interfaces for human–robot collaboration [8]. Custom AR systems now support high-accuracy object tracking and real-time as-built measurement [59], [60], while mobile AR apps stream digital models directly to connected devices, enhancing the adaptability and precision of manual construction workflows [57], [60].

Research by Oyediran et al. [61] underscores the need for integrated workflows when deploying robots on construction sites. Their work explores how robot task planning and simulation can be embedded within broader construction planning processes, proposing 4D BIM-based frameworks for context-aware robotic operations. These frameworks represent a significant step toward aligning robotic behavior with site logistics and project timelines. However, while they enhance robot–environment integration, the role of human workers remains largely peripheral. In particular, questions of how human–robot collaboration should be jointly planned, sequenced, and adapted from the design stage onward remain insufficiently addressed.

Despite advanced sequence planning methods leveraging multi-agent scenarios, these methods typically consider multi-robot cooperative workflows or manual assembly following predefined sequences, without addressing shared roles for hybrid human-robot teams. Recent frameworks for streamlined design and digital fabrication processes deliberately exclude representing human tasks within their structure, although the fabrication workflow relies on humans performing manual tasks. Although iHRC proposes an interactive workflow liberating builders from prescribed sequences, the system supports timber prefabrication while still assuming predetermined assembly orders, structured conditions, and stationary industrial robot systems.

2.2.4 Summary and open challenges

The state-of-the-art review highlights a research domain undergoing significant transition, where foundational developments have enabled new possibilities, but key challenges remain unresolved. Multi-agent assembly processes have shown clear potential to overcome single-agent limitations, with successful implementations in several key areas: multi-robot systems, hybrid human-robot collaborations, equilibrium-aware sequencing methods, and interactive task distribution between humans and robots. Graph-based design methods provide robust foundations for assembly representation, while advances in task planning and real-time coordination offer promising directions for complex construction scenarios.

However, three fundamental gaps prevent the realization of this potential in real-world construction applications. Current design-to-fabrication workflows remain disconnected from multi-agent coordination requirements, lacking the integrated frameworks to bridge design intent with assembly execution. While sophisticated in geometric and structural domains, assembly representation systems require extensions to capture the performative and temporal dimensions essential for dynamic human-robot cooperation. Finally, existing coordination methods rely on static, precalculated sequences that cannot adapt to the unpredictable conditions of construction environments.

These gaps collectively limit the field's ability to move beyond prototype demonstrations toward systematic, scalable deployment of cooperative assembly systems on building sites. The challenge lies not in individual technical components, which show considerable promise, but more in their integration into cohesive frameworks capable of addressing the complexity, adaptability, and scale required for real-world construction scenarios.

The limitations of current approaches presented in the *State of the art* Section identify the following research gaps:

- Design workflows that consider multi-agent participation
- Integrated design-to-fabrication workflows gap for multi-agent participation
- Assembly representation systems requiring extensions beyond geometry
- Task coordination and assignment limitations

The following chapters detail the methodological development and case study implementation of this research.

3 Methodology

This research aims to establish a new design-to-fabrication methodology for cooperative assembly in building applications performed by human-robot teams. To support and inform the proposed methodology, the method of this research is two-fold: (a) an *algorithmic-computational approach*, and (b) an *empirical-materialist approach*. To this end, abstract representations of human-robot cooperative assembly processes, appropriate data models, interfaces for real-time fabrication-related data exchange, and digital methods for multi-agent team coordination will be investigated and synthesized into key components. Different strategies for discretizing cooperative assembly processes and for managing, distributing, and allocating tasks among multiple agents will then be explored as part of an experimental case study approach.

To address the research objectives outlined in Section 1.4, the following methods are investigated:

Design for human-robot cooperative assembly where design, planning, and execution feedback inform each other simultaneously to enable adaptive human-robot cooperative assembly processes (Section 3.2).

Assembly data modelling and representations for human-robot cooperative assembly to formally model human-robot interdependencies and complementary skills within assembly design systems, enabling systematic rather than ad-hoc coordination for complex construction tasks (Section 3.3).

Multi-agent coordination strategies and user interfaces through task assignment mechanisms and augmented reality interfaces, investigating different sequencing approaches to leverage complementary agent strengths (Section 3.4).

Validation through multiple team configurations testing to systematically analyze the relationships between material systems, algorithmic design approaches, and cooperating agents in producing different design outcomes (Section 3.5).

To implement this dual approach effectively, a comprehensive research strategy has been developed that integrates both computational development and empirical validation within an iterative framework.

3.1 Research strategy

This research adopts a *Research through Design* (RtD) methodology, where design practice itself serves as a method of knowledge generation. Prototyping functions both as a means of testing and refining theoretical ideas and as a tool for developing new conceptual frameworks. The work proceeds through iterative cycles between conceptual frameworks and material implementations, with physical demonstrators acting simultaneously as research outcomes and as tools for validation.

The study employs a mixed-methods framework that combines computational development, experimental validation, and both qualitative and quantitative analysis. The computational development includes computational design methods, data structure implementation, and interface prototyping. Experimental validation involves physical assembly tests, human-robot interaction studies, and performance measurements. Qualitative analysis focuses on observing cooperative assembly processes and assessing workflow effectiveness. Quantitative assessment addresses team metrics such as team size and type of cooperating agents, task load, performance metrics including production times, accuracy, and scalability.

An iterative development process guides the progression of the work, allowing insights from each cycle to inform the next. The method supports cross-case study learning, knowledge transfer between experiments, and the continuous integration of findings into the evolving methodology. Feedback loops between theoretical models and practical implementations ensure that both domains advance together.

The scaling strategy of the research is structured in phases. Phase 1 focuses on proof-of-concept experiments in simplified scenarios, while Phase 2 advances to architectural-scale validation with full system integration. Across these phases, the complexity of tasks, team size, and environmental variables are progressively increased to assess system robustness and adaptability.

This work emphasizes interdisciplinary integration, bridging architectural design, robotics, and human-computer interaction. The research involves collaborative development with domain experts and actively translates insights between theoretical and practical domains.

Participatory design elements are embedded throughout the project. The development of coordination interfaces follows a human-centered design approach, integrating user feedback throughout the process. Stakeholders are involved in the design and validation of scenarios to ensure relevance and usability.

Finally, a validation framework supports systematic evaluation. This includes testing multiple team configurations (human-human, human-robot, and multi-human-robot teams), enabling cross-case comparison and pattern identification. The framework ensures systematic documentation of system capabilities and limitations, contributing to the generalizability of the findings.

3.1.1 Research scope and limitations

This research focuses on the development and validation of cooperative assembly methodologies for architectural-scale spatial structures involving human–robot teams. The scope is limited to prototyping and controlled experimental case studies, using mobile robots and augmented reality systems to explore digital-physical workflows. The primary focus is on fabrication-aware design, task modeling, and human–robot coordination, rather than the development of custom robotic hardware or deployment in uncontrolled, real-world construction environments.

The work investigates cooperative assembly processes through four case studies, each testing specific aspects of the proposed methodology—from real-time decision-making in open-ended design to task planning in predefined sequences. These studies are designed to simulate relevant architectural construction scenarios while maintaining experimental control.

The scope includes:

- Rule-based and generative design methods for spatial structures,

- Data models for representing sequencing, dependencies, and agent tasks,
- Augmented reality (AR) interfaces and mobile applications for in-situ guidance and task coordination,
- Cloud-based communication systems for synchronizing user actions, element states, and system feedback across devices,
- Evaluation of workflows through full-scale physical prototypes.

The research excludes:

- The design or fabrication of new robotic hardware,
- Real-world site deployment under construction site conditions,
- Long-term performance and durability testing of assembled structures.

Instead, the research prioritizes methodological development, computational integration, and empirical validation through iterative prototyping in structured experimental setups. The resulting findings are intended to inform future applications in construction robotics, design computation, and digital fabrication.

3.2 Design for human-robot cooperative assembly

This research develops rule-based design methods for spatial assembly systems co-performed by human and robotic agents. The approach models building tasks through their performative and temporal characteristics, considering agent capabilities, spatial affordances, and their implications for process-oriented design strategies that enable the systematic generation of collaborative assembly workflows.

At the core of this approach is the development of computational methods capable of formally representing these cooperative assembly processes. In the context of architectural design and digital fabrication, this research proposes a synthesis of bottom-up principles of craft with computational design methods, enabling fabrication processes governed by rule-based geometric logic, human decision-making, and material constraints. This leads to the formulation of what is termed an *assembly grammar*—a computational framework that defines not only the geometric configuration of a structure but also the sequential logic of its assembly. Rather than merely describing the final form, the *assembly grammar* represents the construction process itself by specifying a sequence of making actions, agent roles, and spatial conditions at each step. For instance, the grammar includes:

- **Local growth rule**, which defines how a module is assembled. A guiding rod is placed first, enabling the subsequent placement of two more rods to complete a module in a predefined geometric arrangement. This sequence encodes the precise temporal and geometric logic of component placement.
- **Global growth rule**, which governs how the structure expands through available *"open connectors"* at the ends of rods. Once a module is completed, it generates new attachment points for further growth, embedding a recursive and expandable logic directly into the *assembly grammar*.
- **Attributes and parameters** including assigned agent roles (e.g., human for positioning and joining, robot for positioning/support), conditional requirements (e.g., the presence of an "open connectors"), and geometric parameters (e.g., rotation, shift, scale, mirror). These attributes and parameters determine how and where the next component can be added

and provide a mechanism for growth control and variation across the overall geometry.

These encoded actions and preconditions allow the grammar to generate not only spatial configurations but also an executable plan for human–robot cooperative assembly (see Sec. 3.3.

To explore and operationalize this concept, the four case studies conducted examine two contrasting design paradigms for modular structures:

1. **Open-design systems**, *design-on-the-fly*, in which the built outcome emerges through interactive, in-process decision-making by human agents during construction, and
2. **Predefined design systems**, in which the design and assembly sequence are fully determined prior to construction.

Regarding material systems, *Case study 1* employs geometrically identical interlocking modules, enabling a regular and repeatable assembly logic. By contrast, *Case studies 2A*, *Case study 2B*, and *Case study 3* utilize modular units composed of discrete timber elements—blocks or rods—that belong to the same typological family but incorporate local variation, allowing for adaptive geometric articulation while maintaining systemic consistency.

In *Case study 1*, the design is predetermined, yet the assembly process is guided by human decision-making within a constrained rule set.

Case study 2A and *Case study 2B* explore open-ended design processes, where structures emerge incrementally through cycles of human input and robotic execution.

Case Study 3 adopts the same material and assembly logic as *Case study 2B* but utilizes *assembly grammar* to top-down generate buildable discrete structures by introducing design, fabrication, and equilibrium constraints and encoding the assembly plan in a flexible computational model. This model enables the task coordination between multiple human and robotic agents while allowing for in-process adaptation during execution.

The implementation of rule-based design methods across these case studies demonstrates how assembly grammars can structure collaborative human-robot assembly processes through both predefined and open-ended design approaches. However, to support such processes computationally, these grammars must be encoded in robust, adaptable data structures capable of capturing not only geometric configurations but also temporal sequences, agent roles, and physical constraints.

The following section outlines the computational logic that underpins this approach, detailing the representational frameworks, rule-encoding mechanisms, and task modeling strategies that enable the generation, adaptation, and execution of collaborative assembly workflows.

3.3 Assembly Data Modeling for Human-Robot Cooperation

For the assembly data modelling and representations, a digital data structure—referred to as the *Assembly Model* (AM)—is developed, building upon *COMPAS Assembly*[1] [47], a module

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[1] COMPAS Assembly is a lightweight data structure for representing Discrete Element Models (DEMs), including individual elements and their interactions. It is part of the open-source Python framework COMPAS. See: `https://blockresearchgroup.github.io/compas_assembly/latest/index.html`

of the *COMPAS* framework [62]. *COMPAS Assembly* is designed for managing and storing discrete element models in architectural contexts. It encodes both geometric and topological information using a directed edge graph, where nodes represent parts and edges represent physical connections or joints between them.

The AM is not only adapted to represent the state of the physical assembly but is expanded as a hybrid *data–method container* that encodes design logic from Sect. 3.2 and supports coordination routines and task sequencing methods discussed in Sect. 3.4.

Each node in the AM stores a range of attributes, including:

- **Geometrical data** (e.g., part shape and position),
- **Design parameters** (related to the algorithmic growth logic),
- **Fabrication-related parameters** (robot frames),
- **Task annotations** (e.g., task type, assigned agent, task priority, role in sequence),
- **Build-state tracking** (e.g., `is_built`, `is_support`, `is_removable`, `is_accessible`). Edges in the graph store topological constraints and physical interdependencies between parts, such as attachment conditions, required mechanical connections, or mutual exclusion in design generation and sequencing.

Beyond its role as a static data container, the AM embeds a set of dedicated *methods* that operate on this structure to support computational design and coordinated construction:

- **Design generation**: The AM provides methods for the generative creation of complex assemblies using local attachment rules (*local growth rule*), spatial constraints (e.g., desired shape approximation), and recursive part placement—where each added element generates new valid attachment points, enabling the structure to expand incrementally according to the *global growth rule* defined by the *assembly grammar*.
- **Equilibrium validation**: To ensure stability during incremental construction, the AM integrates simplified equilibrium analytics by evaluating whether the current center of gravity of a branch lies within its support area, enabling dynamic structural validation and informing task generation and robotic role assignment.
- **Task sequencing**: The AM provides methods for the analysis of topological dependencies to compute valid task sequences. It supports both global sequencing strategies and local re-sequencing in response to runtime changes (e.g., delays or errors).
- **Task distribution and role assignment**: The AM includes logic for distributing and assigning tasks dynamically to different agents (human or robot) to provide personalised AR or robotic instructions.

Finally, the AM interfaces directly with various entities, including robotic planning environments, AR devices, and robot controllers, through its linkage to various backends from within the CAD modeling platform. This integration enables:

- Collision-free robot path planning,
- Dynamic task allocation,
- Runtime adaptation based on physical feedback (e.g., AR-confirmed `is_built` flags).

In *Case Studies 2A*, *2B*, and *3*, this integration facilitated real-time synchronization between digital assembly status and physical robot execution, including safe switching between human and robot installation steps.

3.4 Multi-agent coordination strategies and user interfaces

This section details the task planning and allocation strategies developed for multi-agent teams. It includes the discretization of tasks into spatial-temporal components, dynamic and hierarchical planning routines, and the design of craft-specific user interfaces. These interfaces, based on AR-enabled mobile and wearable devices, support real-time fabrication data sharing, guidance, and interaction between human participants and robots.

Task dependencies are encoded via the directionality of the graph's edges, enabling a structured representation of sequential logic within the assembly process. This directed graph topology is designed to reflect both the modular design logic and the cyclical or adaptive workflows characteristic of human-robot collaboration.

In each case study, the AM—introduced in Sec. 3.3—encodes construction logic as event chains, where each node functions both as a placement task and as a representation of the corresponding physical part. The AM is customized per scenario to reflect specific requirements related to assembly sequence specification and workflow coordination:

1. **Predefined assembly sequence:** *Case study 3* implements a fully predefined sequence, stored as edge direction and node attributes.
2. **Adaptable or emerging assembly sequences:** *Case Study 1* and *Case study 2A* and *Case study 2B* support dynamic, open-ended workflows in which sequencing is updated during construction.

In *Case Study 1*, the AM introduces additional element state attributes. These, combined with directed edges representing task dependencies, enable real-time tracking of construction progress and allow builders to act independently of a predefined sequence, supporting greater flexibility.

In *Case studies 2A*, *Case study 2B*, and *Case study 3*, predefined task assignments (e.g., *"human task"* or *"robot task"*) are stored per node. These assignments, alongside dependency information stored in the directed graph, support coordinated sequencing of human and robotic actions.

Case study 3 further extends the AM's functionality by computing and storing robot-specific task assignments (e.g., robotA, robotB) dynamically, based on current robot positions (also stored in the AM) and a corresponding geometric approximation of each robot's reachability. Additionally, the AM interfaces with stability-checking algorithms that verify static equilibrium at each stage of assembly. This enables not only the sequential generation of structurally valid designs but also ensures their constructability during physical realization.

The AM also integrates with robotic simulation environments through its connection to the CAD modeling system, allowing the computation of collision-free robot trajectories in real time—used in *Case studies 2A*, *2B*, and *3*. Assembly progress is tracked via a dedicated attribute (*is_built* = True/False) stored per node, enabling continuous synchronization between physical actions and their digital representation.

Finally, the AM supports in-process plan adaptation. As actual building conditions and spatial affordances may deviate from the initial plan, part attributes within the AM can be modified at runtime to reflect:

- Human agents taking over robotic tasks,

- Robots switching roles or task sequences,
- Repositioning and re-localization of robots within the workspace.

This adaptability makes the AM a central coordination layer between design, simulation, and execution, enabling real-time responsiveness and decision-making in collaborative construction scenarios.

3.5 Validation through multiple team configurations testing

This section outlines the team constellations used in a series of prototypical scenarios designed to validate the framework. The experiments involved 1:1 scale architectural assemblies with varying configurations of human participants and mobile robotic systems. The following list summarizes the composition of each team:

Case study 1: 2-4 human agents

Case study 2A: 2 human agents & 1 robotic agent

Case study 2B: 2 human agents & 2 robotic agents

Case study 3: 2-4 human agents & 2 robotic agents

4 Case studies

This chapter presents four studies that demonstrate the application of the methodology described in Chapter 3. Each case study highlights different aspects of the research and provides empirical evidence for the effectiveness of the proposed approach.

4.1 Case Study 1: Human-human cooperative assembly

4.1.1 Summary and contribution to the thesis

This case study contributes to the research objectives of the thesis by implementing a **collective, digitally coordinated assembly process using a multi-user mobile AR system.** It implements a cloud-hosted AM that encodes geometric, topological, and procedural data, module states, of the structure. The AM is accessed and manipulated via custom AR interfaces, enabling participants to view and interact with real-time construction data in a shared digital-physical workspace. A cloud-based communication framework ensures continuous synchronization of module states and user actions across multiple devices, supporting distributed coordination and seamless task transitions. The system facilitates the modeling of multi-agent participation, capturing interdependencies between human actions through dynamically updated *built*-state logic. Custom coordination strategies, delivered through the AR interface, support **asynchronous, parallelized workflows** and empower participants to make local decisions without disrupting global progress. The full-scale pavilion case study validates the system's effectiveness in enabling adaptive, cooperative design-to-fabrication processes. The resulting demonstrator enabled the evaluation of multi-agent coordination mechanisms, distributed task handover, and interaction design within a synchronized collaborative environment involving two to four human participants.

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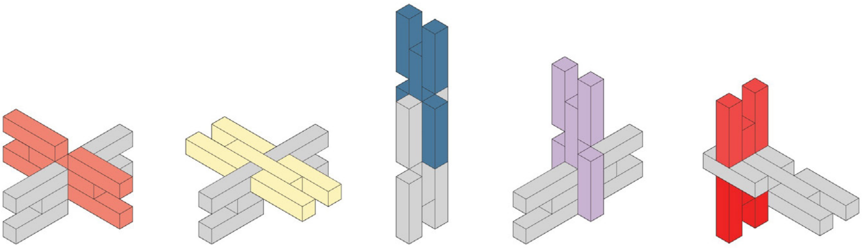

4.1.2 Publication

Collective AR-Assisted Assembly of Interlocking Structures

Lidia Atanasova[1], Begüm Saral[1], Ema Krakovská[1], Joel Schmuck[1], Sebastian Dietrich[1], Fadri Furrer[2], Timothy Sandy[2], Pierluigi D'Acunto[1], Kathrin Dörfler[1]

Abstract

Research on mobile Augmented Reality (AR) technologies has proven many potentials and benefits for assisting craftspeople in various building applications within the AEC domain. However, little research has been done on the use of multi-user mobile AR systems coordinating several people at the same time. This paper examines the potentials of a collective construction process enabled by AR technology that distributes and guides manual assembly tasks for multi-user participation. For this purpose, a custom mobile AR app is developed that uses cloud services and allows multiple people to participate in the construction and be coordinated with each other at the same time. In the proposed setup, digital building instructions for the stepwise assembly of a physical building structure can be retrieved by multiple users via the app. The app positions these building instructions in 3D space, visually superimposed on the building site, where the building structure is being assembled. Methods are proposed for synchronizing the construction progress via user-specific AR content visualization over the app's user interface (UI). Based on the principle of topologically interlocking structures, the material system developed for this research offers several form-fitting connections with one modular wooden component without the need for mechanical fasteners for their assembly. This principle enables the manual implementation of various complex building structures at full architectural scale, which are reconfigurable and fully disassemblable. The proposed methods were experimentally validated in a 1:1 scale demonstrator. A pavilion was assembled collectively by students and researchers over two days, and the UI was evaluated through a qualitative user study. As an outlook, the paper discusses the potential of such AR systems to make digitally-driven construction processes more tangible and accessible to laypersons and unskilled people and thus encourage community participation.

Keywords: Augmented Reality · Multi-user mobile application · Topological interlocking · Cloud data · Participatory digital fabrication

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Introduction and context

In the past decade, the availability of mobile handheld devices and their increasing use for AR applications have led to a vast rise in the adoption of AR technologies in the AEC domain. Although these applications have already proven to be useful for managing construction processes, the potentials of the AR technology are not yet fully exploited and appropriate application areas will continue to expand [63]. The rapidly growing capabilities and features of mobile devices combined with the ubiquity of Internet access as well as the multitude of embedded sensors make the development of mobile AR applications utilizing remote servers possible [64]. In combination with existing technologies such as cloud technology and wireless communication, AR shows a large potential for collaborative and networked applications. In this regard, recent research developments have investigated AR approaches for computer-supported collaborative work [52], the possibility to use handheld devices for massively multi-user AR [53] and mobile collaborative augmented reality [54].

The possibilities of using AR to support craftspeople in manual production processes in architecture have recently been highlighted by a growing number of research efforts. In early projects, AR technologies were used to guide human actions via projection-based mapping [55], [65]. More recently, AR headsets were used by people to interface with robots enabling collaborative fabrication processes [32], as well as to instruct craftspeople for various manual tasks via holographic 3D models in space [57], [58]. Custom-built AR systems providing extended features such as the 3D registration of discrete objects together with highly accurate pose estimation [59] have shown the real-time guidance of construction tasks using craft-specific user interfaces, as well as the ability to register and measure the as-built structure with sub-centimeter accuracy [60]. Recently developed mobile AR apps for the visual guidance of manual construction processes provide virtual information based on exported building plans [60] or a real-time stream of digital models over Wi-Fi from the design environment to connected mobile devices [57].

Available AR methods generally constrain fabrication to prescribed sequences, and streamed models provide users with uniform visual content, thus limiting the deployment of these systems for multi-user task coordination, in which user-specific information must be supplied. Instead, we propose an AR app that uses a centralized design model to synchronize solely fabrication-related data between multiple users employing cloud services. Asynchronous multi-user assembly tasks are coordinated in real-time via the cloud by providing user-specific AR content over a custom-developed user interface (UI). The proposed workflow has been explored and evaluated via the AR-assisted collective assembly and disassembly of a complex wooden structure consisting of identical interlocking modules.

Methods

Material and structural system

Material system. As part of the overall concept, a material system consisting of discrete wooden units, offering a variety of form-fitting connections was developed. The units can be assembled and reassembled into various configurations, and eventually disassembled. One unit is composed of five wooden pieces, cut from a square timber member with a 45 × 45 mm cross-section, and mechanically fastened with screws. The length and arrangement of the pieces in the unit follow a square grid defined by the timber member's cross-section. Three of such units are then organized into a module. By introducing an asymmetric module shape and following a defined assembly logic, the modules are topologically interlocking, allowing building structures to be assembled without the need for mechanical fasteners, even for complex structural configurations such as openings or overhangs. During the assembly, these modules are not only used as structural components of the building structure but also as temporary support – for configurations such as overhangs and openings – that can be removed subsequently and reused in another part of the structure. Several module iterations and their interlocking properties were examined to satisfy the conditions for both a structural system and ease of manual assembly, to finally select an asymmetric module composed of three units (Fig. 4.1).

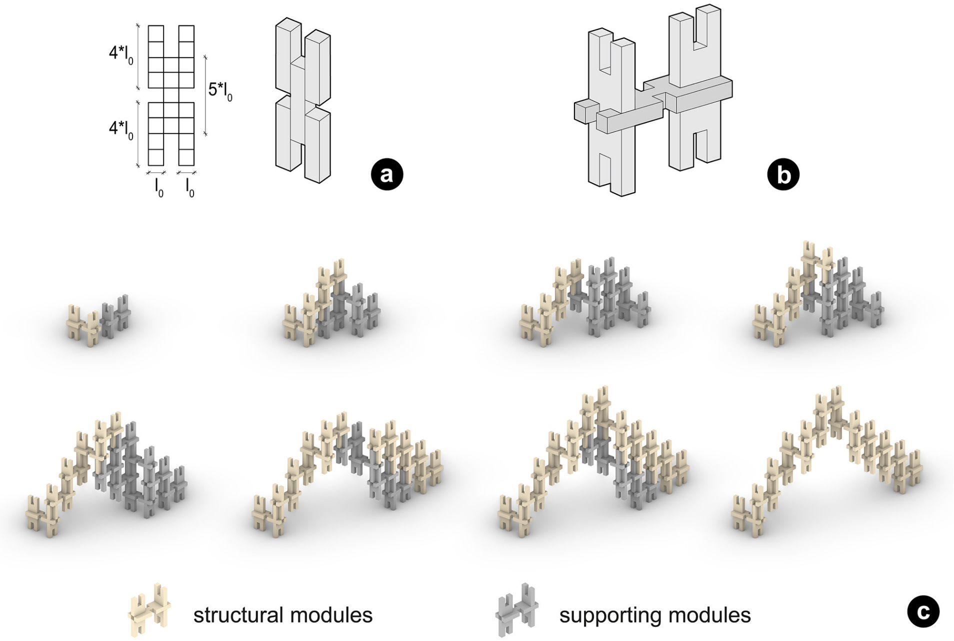


Figure 4.1: a) The length and the arrangement of the timber pieces in the unit follow a square grid defined by the cross-section dimension of the square timber; b) each discrete wooden module consists of three units. c) Due to their asymmetric geometry the modules interlock with each other and eliminate the necessity for additional mechanical connectors. Modules can also be used as a temporary support during assembly and removed after.

Structural system. The units are designed to generate horizontal and vertical interlocking mechanisms by connecting the individual units in various directions in space. Due to this topologically interlocking configuration, compression force transmission between units is made possible. A distinctive feature of the interlocking mechanism is that it allows some tolerance in the connection between the various units, thus facilitating the assembly and disassembly process. In terms of the static system, this means that slight movements between the units are allowed without affecting the overall stability of the structure. An FEM model allows for the structural analysis of a cluster of modules with respect to its overall stability and deformation behavior across different design iterations. This model reproduces the interlocking mechanism by taking into consideration the stacking configuration and the tolerance between connected modules (Fig. 4.2).

In the FEM model, each unit is modeled as a cluster of beam elements and fully rigid connection elements. While the beam elements reproduce the timber members of a unit, the rigid connection elements are used to model the eccentricity between the individual timber members and thus connect the timber members together. The interlocking mechanism between the individual modules of three units is modeled via customized joints. Based on the position of the joints within the unit, the six degrees of freedom of each joint are individually defined either as fixed, released or with a non-linear mechanical behavior, such as compression-only or with localized slippage (Fig. 4.3). The parameters for local slippage are estimated from material tests on 1:1-scale physical models.

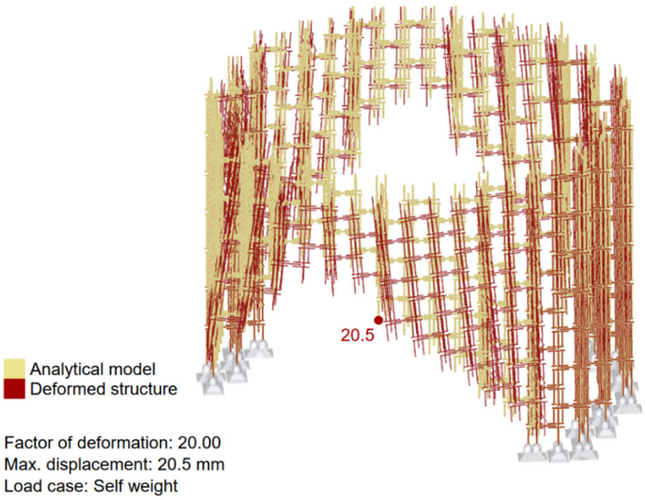
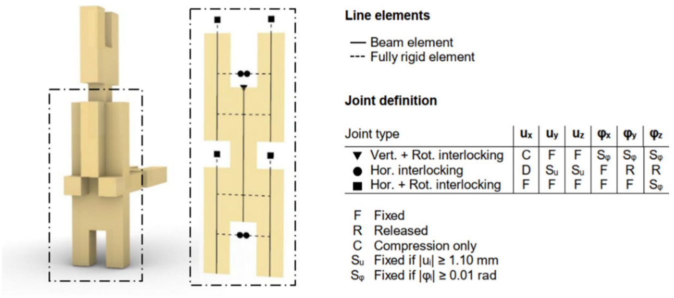


Figure 4.2: The FEM structural model showing the predicted deformation behavior of an assembly of units.



Line elements

— Beam element
--- Fully rigid element

Joint definition

Joint type	u_x	u_y	u_z	φ_x	φ_y	φ_z
▼ Vert. + Rot. interlocking	C	F	F	S_φ	S_φ	S_φ
● Hor. interlocking	D	S_u	S_u	F	R	R
■ Hor. + Rot. interlocking	F	F	F	F	F	S_φ

F Fixed
R Released
C Compression only
S_u Fixed if $|u_i| \geq 1.10$ mm
S_φ Fixed if $|\varphi_i| \geq 0.01$ rad

Figure 4.3: Detailed model view of a single unit illustrating the implementation of the local interlocking mechanism in the FEM structural model.Multi-user AR-System setup.

Fabrication setup and workflow

Experimental system setup. In the experimental workflow, user-dependent inputs and a digital model hosted on a cloud can be synchronized across multiple devices via a custom-developed mobile AR app (Fig. 4.4). The building actions of individual participants are updated and continuously synchronized via the app in real-time. This synchronization makes it possible to simultaneously coordinate and visually guide several people involved to complete assembly tasks, thus enabling the proposed collective assembly process. As an extension to existing AR-guided fabrication systems, the task sequence is not entirely specified a priori but results from user-based decision-making processes during assembly.

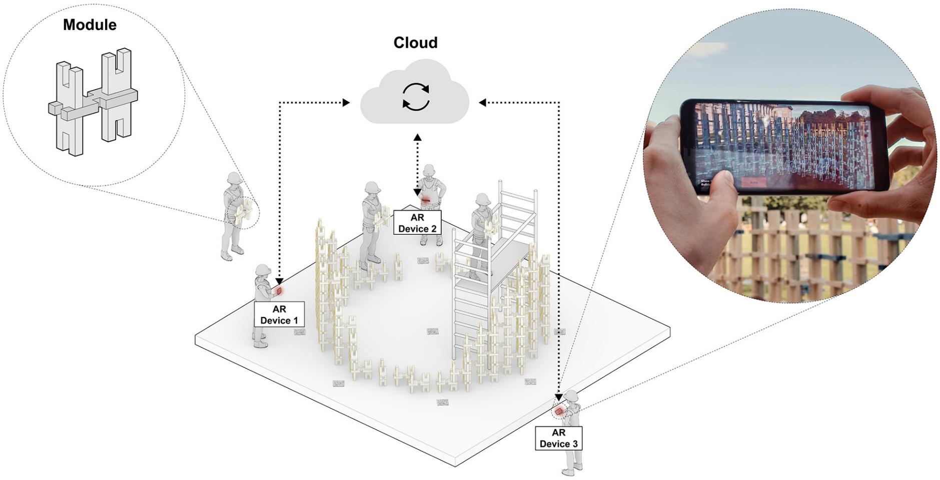


Figure 4.4: In the experiment, the proposed multi-user AR-System setup features three mobile devices communicating with a central cloud database over the mobile AR app.

The prototype of the AR app was developed in the Unity game engine [66] using 2D marker-based tracking with the Vuforia Engine library [67]. Vuforia handles both the spatial positioning of the digital model projection and the pose calculation based on the markers including extended SLAM (Simultaneous localization and mapping) tracking for continuous content visualization after the marker has left the field of view.

Assembly information model. The designed assembly structure is stored as a graph data structure, where each module is represented by a node of the graph (Fig. 4.5). The digital model, referred to as the Assembly Information Model (AIM) [68], is implemented using the data structures available through the open-source Python-based COMPAS framework [62] within the computer-aided design environment of Rhino-Grasshopper [69]. Alongside the module's geometrical representation, each module's states, i.e., *built*, *buildable*, *is_support*, *removable*, and *selected*, are stored as Boolean variables inside the node attributes. The edges of the graph store topological data about the connectivity of the individual modules, where physically connected modules are referred to as neighbors and are interfaced via an edge in the digital model (Fig. 4.5). The topology and individual module's states allow to continuously compute the states of other modules according to their assigned states: a module is assigned the state *built* if it is already built in the structure; a module has the state *buildable* when both lower neighbors's state is set to built; the state of a module that temporally serves as supporting structure is defined as *is_support*. As the structure gradually gains sufficient structural stability during construction, the *removable* state of the supporting modules, which are not required anymore, changes such that these modules can then be removed and used further in the building process.

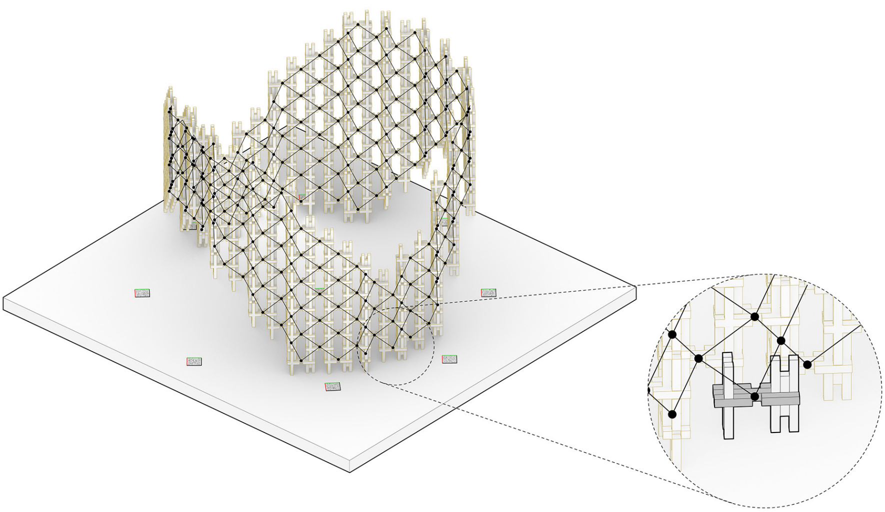


Figure 4.5: The digital model includes a graph data structure that stores topological data (edges) about the connectivity and state of the modules (nodes).

A set of geometrical rules based on the module's shape is developed and organized into design patterns, allowing for larger configurations and various design possibilities emerging from the discrete aggregation of a single module.

Data Exchange and Synchronization. To transfer the AIM data structure from the architectural design and planning environment to the mobile app, the assembly model is serialized to a JSON file format and later deserialized to reconstruct the data structure and the geometry in the app's environment. For this purpose, a custom implementation of the Pyrebase Python wrapper for the Firebase API [70] is utilized to enable the transfer of the assembly model directly from the design environment in Rhino-Grasshopper to the Google Firebase Cloud Storage. To then synchronize the model's parameters – i.e., a continuous update of the elements' states and the indication of already selected buildable elements – across multiple connected devices, a cloud-hosted real-time database – Firebase Realtime Database – is used (Fig. 4.6).

The cloud storage stores a JSON file containing the keys of all planned modules. Each time a newly built module is confirmed by a user over the app's interface by pressing the "Build"-button, the state of the respective module's key is updated in the real-time database. In addition to modules' states, the activity of the user is continuously tracked by storing the key of the currently selected module as part of the stored user data. Each client, i.e., connected mobile device, listens to

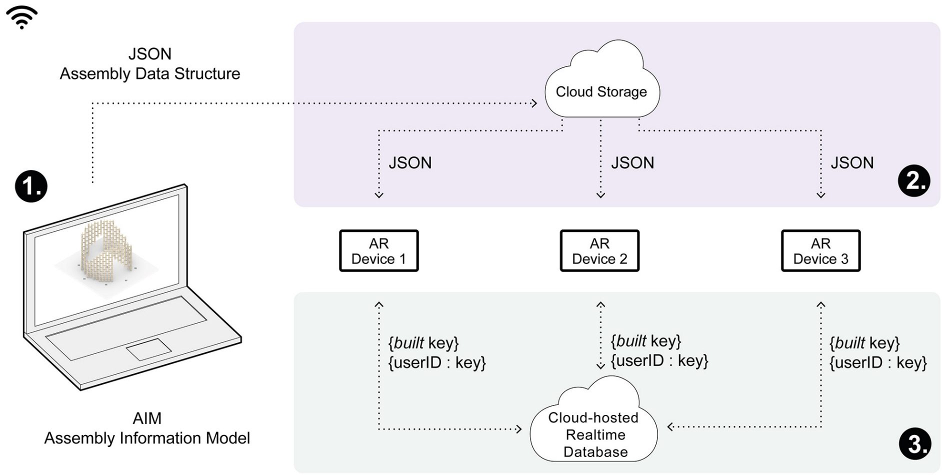


Figure 4.6: Connected devices successfully exchange building data utilizing wireless communication and Google cloud services. The design model is first exported to JSON (1) and then uploaded to the cloud storage (2). Each connected device is downloading the assembly data structure – a JSON file – upon starting the app to store it locally. Via the app's interface, modules states, and user selections are updated and synchronized over the cloud-hosted real-time database (3).

changes on the real-time database. As soon as a change is detected, it is instantly forwarded to all clients triggering UI actions such as the display of a text notification or updating the visualization of the elements according to their changed states and users' current selections.

User Interface. The UI was designed to promote both personalized user experience via user input and inclusiveness in a collective endeavor. The custom UI elements include three input controls and one informational component (Fig. 4.7). The input controls are shown as a drop-down list to choose the desired display mode, a slider to select a desired buildable module and a "Build"-button to confirm a newly built module. Users can choose between four pre-programmed display modes – *show all*, *show built + current phase*, *show all + buildable*, *show only built* – to display the assembly structure based on the modules' states and to keep track of the overall building progress. Since the digital model is stored locally on the phone and the app does not rely on the streaming of a single digital model, the app interface supports different display modes on each connected device at a time.

As module states are continuously computed, users are informed about which modules can be assembled at the current building stage. By allowing users to select modules to assemble via the slider, the proposed workflow aims to liberate participants from prescribed assembly sequences and procedural instructions and promote their decision-making and participatory engagement instead [71] (Fig. 4.8).

Case study

Assembly process. The proposed approach was applied to construct a pavilion collectively. For this purpose, 945 timber units – a total of 315 modules – were prefabricated to be later assembled

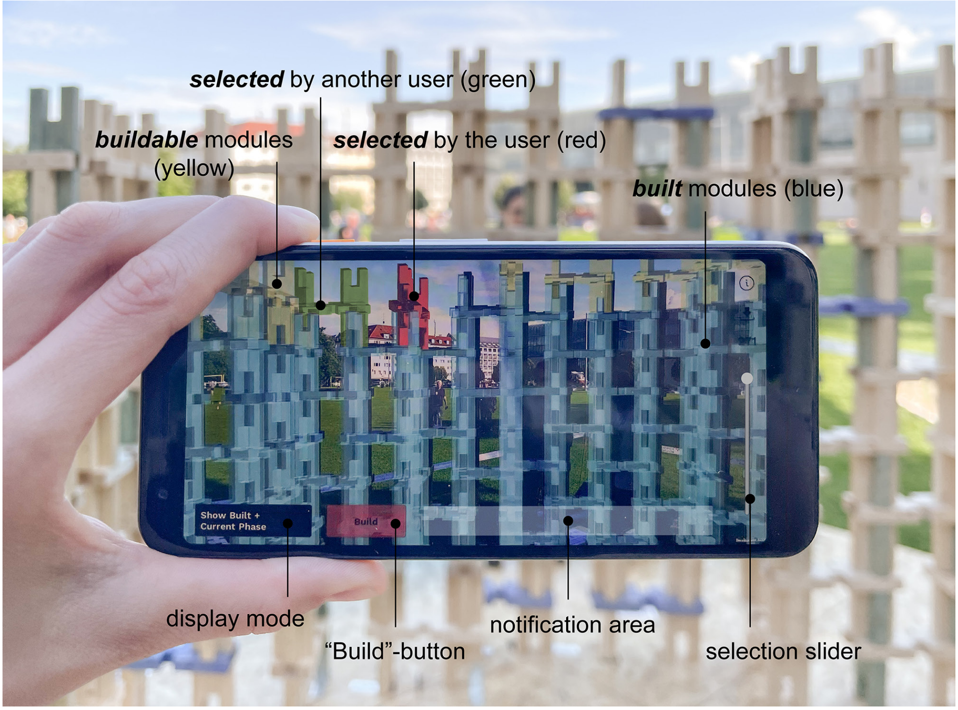


Figure 4.7: The elements of the custom UI include three input controls – a display mode drop-down list, a selection slider for selecting a buildable module, and a "Build" – button to confirm a just built module – and a notification area. A color-coding according to the module's state guides the users during assembly: *built*=blue, *buildable*=yellow, *selected* by the user=red, *selected* by another user=green.

on-site over two days. Sixty modules were built to support the structure temporally and were gradually removed and reused as a part of the final design. The final design had a circular shape with an outer diameter of 4.26 m and a total height of 3.0 m.

For the marker-based tracking, nine fiducial markers were distributed around the base of the planned structure to ensure that at least one will remain in the field of view during assembly. To prevent positioning errors and discrete jumps of the AR content due to misplacement of the markers, a precise measurement of them using a total station was performed before construction. The measured location coordinates and the orientation of the individual fiducial markers were then embedded into the app's final version.

The app was used and explored by eight different participants using up to three Android smartphones connected to a public Wi-Fi network to enable data transfer to and from the cloud simultaneously. The participants assembled modules of the entire structure either independently or in teams of two – i.e., one person was assembling modules following the instructions displayed on the mobile device, which was held, and operated by a second person (Fig. 4.9).

User study. A qualitative survey in the form of a user questionnaire with five of the eight participants of the case study was performed to evaluate the AR app's usability and the custom UI. The answer given to the questionnaire confirmed the potential of the custom UI to improve

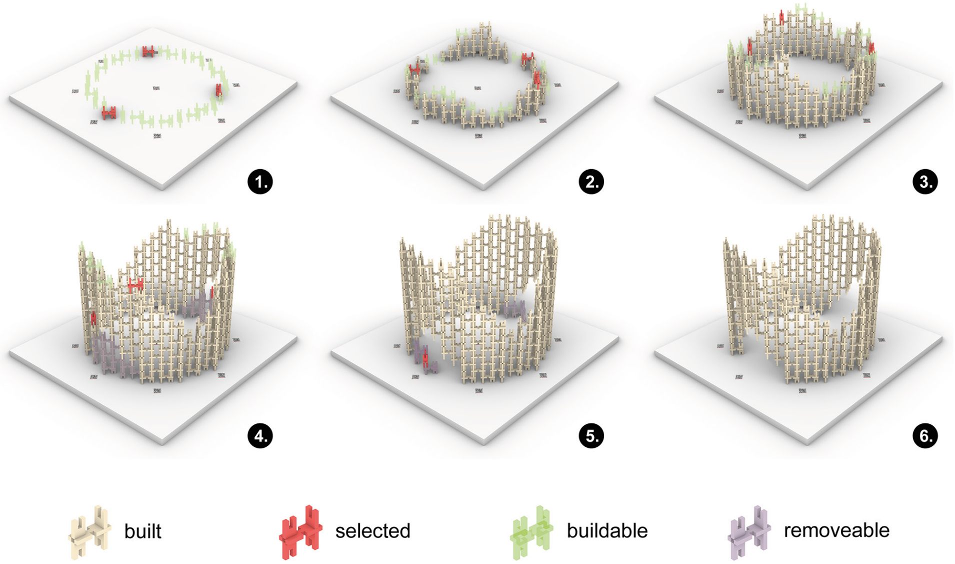


Figure 4.8: The assembly order is not specified. Instead, the participating users select and place any module from a subset of *buildable* modules or remove from *removable* modules, defining the order of assembly on the fly.

task coordination during construction by providing individual guidance. According to the participants' feedback, this resulted in a spontaneous and playful experience enabling them to start or stop building or take turns at any time without obstructing the digitally coordinated workflow. The integration of communicative features, namely being informed about the actions of other participants via the UI, such as being visually informed about other participants selecting a module to build or completing a task, led to an indirect interaction between all participants via the app and was perceived as motivating.

Conclusion and future outlook

This research has explored and developed methods for a mobile AR app enabling multi-user participation in a digitally-driven construction process. The collective construction of a pavilion structure enabled the experimental validation of the material and structural system using the AR app and its custom-developed functionalities Fig. 4.10).

Concerning the applied AR technology, the proposed system could greatly benefit from an extended context-awareness, featuring direct object-tracking instead of marker tracking as introduced by [59], as well as the automated recognition of user actions instead of active user interaction via the app, e.g., automatically registering added modules instead of pressing the "Build" button once a module has been added.

With respect to community involvement and participation, well-conceived, people-centered public spaces have vast potential to become assets that cities can leverage to transform the quality of urban life and improve city functioning. The presented research could allow people in the future to design and build their co-created multi-purpose structures, engaging the public in

Figure 4.9: To test the proposed methods and evaluate the multi-user AR app, a pavilion was assembled collectively with students over the course of two days.

establishing a profound sense of belonging and responsibility for our built urban environment.

Acknowledgments

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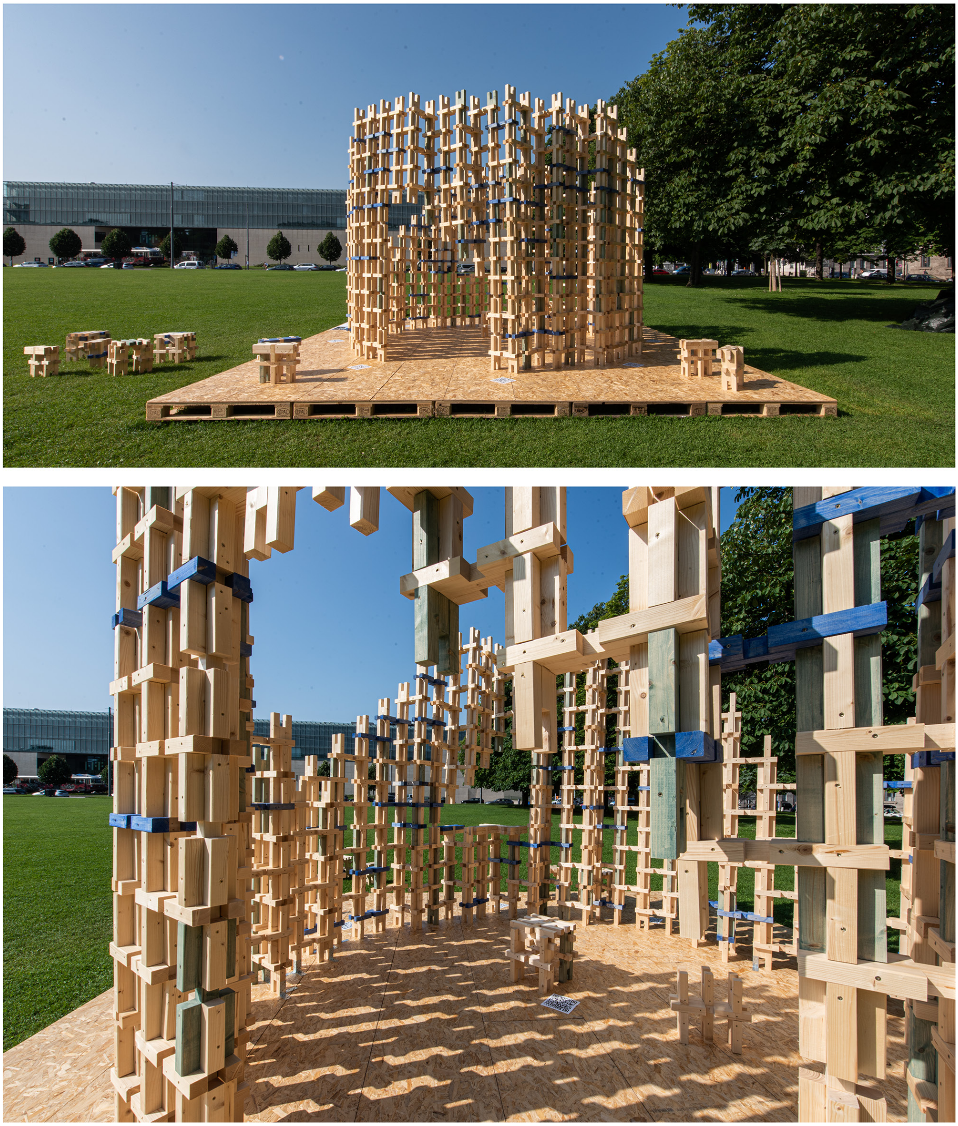
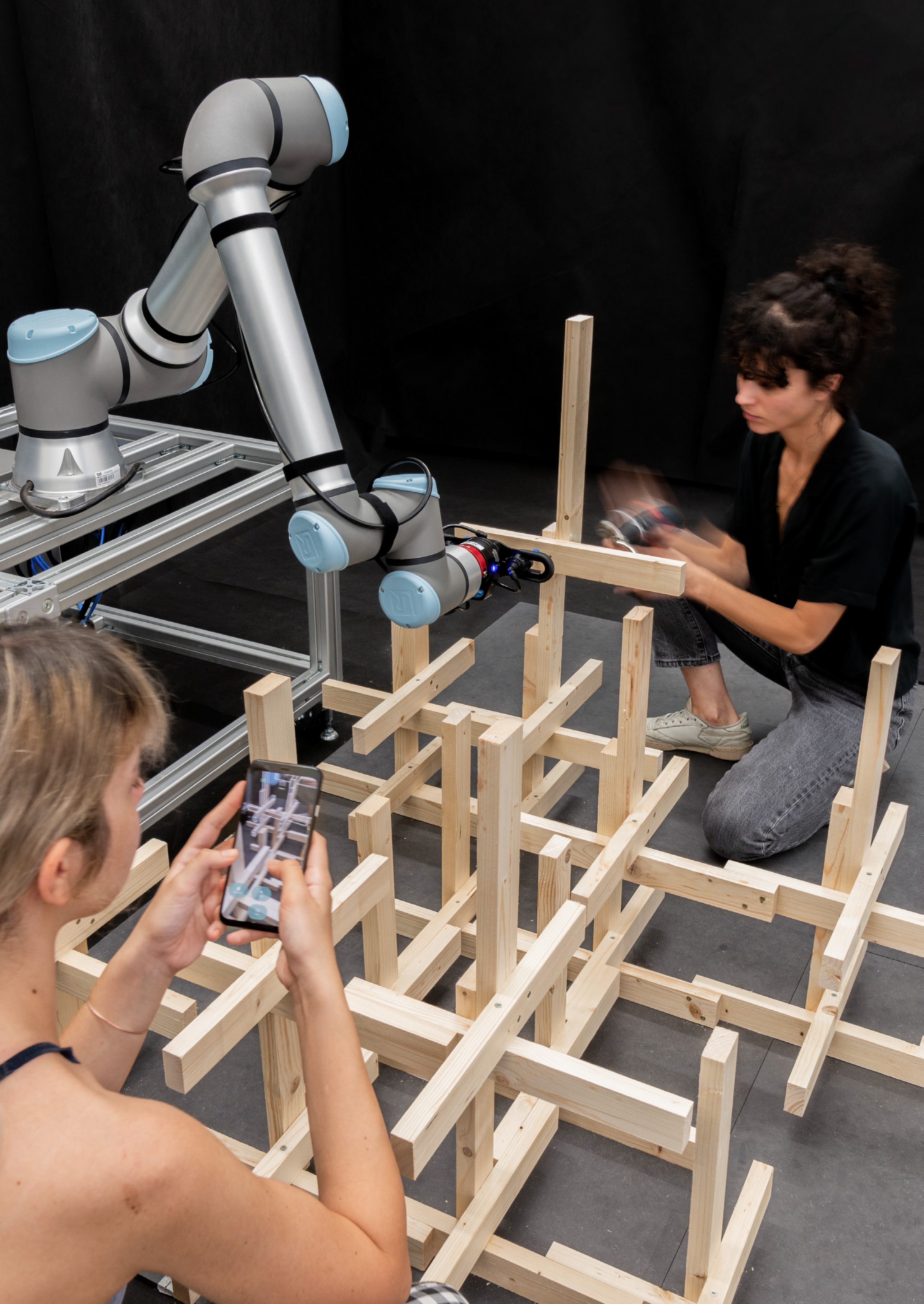


Figure 4.10: Final pavilion.

4.1.3 Author's contribution

The contributions by the author of this thesis to the realization of this case study can be summarised as follows: First, the author led the preliminary conception, development, and testing of the collective, AR-assisted human fabrication workflow between 2020 and 2021. Second, the AM was customized to manage not only geometric and topological data but also procedural assembly information, such as module states. The AM served as a central data structure containing all construction-related information, including the data required for exchange and synchronization across devices. The author implemented bi-directional communication between the CAD design environment and the Firebase Realtime Database to enable real-time coordination. A set of computational tools was developed to encode module states and assembly logic. Third, the author implemented key functionalities within the custom mobile AR application, including the continuous evaluation of module states to support user decision-making during construction. As one of the designers, the author also contributed to the architectural design of the full-scale physical demonstrator and coordinated its realization, overseeing fabrication, tracking setup, and the live construction experiment. To evaluate the proposed methods, the author conducted a prototypical user study and analyzed system performance and interaction patterns.



4.2 Case Study 2A: Human-robot cooperative assembly with one robot

4.2.1 Summary and contribution to the thesis

This case study contributes to the research objectives of the thesis by introducing an open-ended, human–robot collaborative assembly workflow that enables dynamic integration of design and construction processes. At its core is an assembly grammar that encodes temporal and geometric rules for combining discrete timber elements into modules to form larger spatial structures. Rather than prescribing a fixed design outcome, the assembly grammar defines a constrained design space within which users make real-time design decisions during construction. These decisions are supported by an AR interface that visualizes the current state of the structure and suggests feasible directions for growth based on geometric and robotic constraints. The process is mediated through a shared digital–physical workspace: using the mobile AR device's object-tracking capabilities, human input is registered and transmitted to the computational design environment. In response, robot actions are computed to execute the complementary steps required to complete each module. The assembly process involves a team of two human participants and one robotic arm. Both humans and the robot actively place structural elements, working collaboratively in alternating roles to incrementally construct a branching timber prototype. This interactive workflow demonstrates the potential of adaptive, multi-agent design-to-fabrication processes and offers new coordination strategies for human–robot construction, validated through the collaborative realization of a spatial timber structure.

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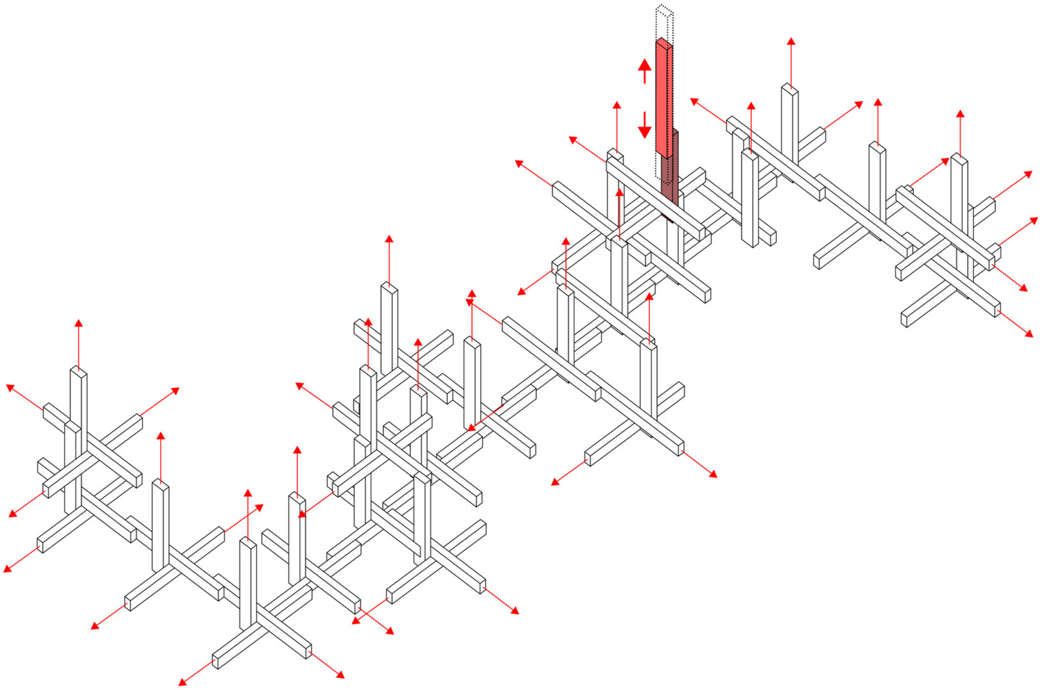

4.2.2 Publication

Prototype as Artefact

Design Tool for Open-ended Collaborative Assembly Processes

Lidia Atanasova[1], Daniela Mitterberger[2], Timothy Sandy[2], Fabio Gramazio[2], Matthias Kohler[2], Kathrin Dörfler[1]

Abstract

In digital design-to-fabrication workflows in architecture, in which digitally controlled machines perform complex fabrication tasks, all design decisions are typically made before production. In such processes, the formal definition of the final shape is explicitly inscribed into the design model by means of corresponding step-by-step machine instructions. The increasing use of Augmented Reality (AR) technologies for digital fabrication workflows, in which people are instructed to carry out complex fabrication tasks via AR interfaces, creates an opportunity to question and adjust the level of detail and the nature of such explicit formal definitions. People's cognitive abilities could be leveraged to integrate explicit machine intelligence with implicit human knowledge and creativity, and thus to open up digital fabrication to intuitive and spontaneous design decisions during the building process. To address this question, this paper introduces open-ended Prototype-as-Artefact fabrication workflows that examine the possibilities of designing and creative choices while building in a human-robot collaborative setting. It describes the collaborative assembly of a complex timber structure with alternating building actions by two people and a collaborative robot, interfacing via a mobile device with object tracking and AR visualization functions. The spatial timber assembly being constructed follows a predefined grammar but is not planned at the beginning of the process, it is instead designed during fabrication. Prototype-as-Artefact thus serves as a case study to probe the potential of both intuitive and rational aspects of building and to create new collaborative work processes between humans and machines. The resulting demonstrator enabled the evaluation of the proposed workflow and design logic through a multi-agent construction process carried out by two human participants and one collaborative robot within a structured, synchronized collaborative environment.

Keywords: Architectural design · Augmented reality · Collaborative robots · Computer aided design · Computer architecture · Knowledge management · Robots

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Introduction

In contemporary digital workflows from design to fabrication in architecture, the formal definition of the final shape is explicitly inscribed into the design model, and all design decisions are made prior to production. This applies in particular to digital fabrication processes, in which digitally controlled machines require such formal definitions for the execution of fabrication tasks by means of detailed and step-by-step machine instructions [72]. While useful for fully automated applications in typical industrial settings, the recent surge in the use of novel augmented reality (AR) technology for digital fabrication workflows, in which users carry out complex fabrication tasks instead of a machine [73], [60], this approach does not allow the users to contribute creatively to the fabrication process in any meaningful way. The involvement of users in digital fabrication raises questions about the level of detail and the nature of such explicit formal definitions. One such question is to which extent digital fabrication processes could be opened up to intuitive and spontaneous decisions by humans during fabrication, in order to integrate explicit machine intelligence with implicit human knowledge and creativity, and, thus, to create novel human-robot collaborative workflows.

To address this question, this paper proposes Prototype-as-Artefact fabrication workflows [74], which challenge the notion of a top-down linearity of design-to-fabrication workflows and explore the possibilities of making bottom-up design decisions while building in a human-robot collaborative setting. This paper describes the development of an assembly grammar which defines a set of rules on how to assemble elements into local configurations, but which leaves the overall design open to branch out in various directions and shapes over the course of construction. This grammar sets the basis for the collaborative assembly of a complex spatial timber structure constructed with alternating building actions by two users and a collaborative robot, featuring both intuitive and rational aspects. Recent technological advancements in AR technology and sensor-enabled context-awareness [59] serve to establish a shared workspace between the users and a collaborative robot via the visual interface of a mobile device. This context-aware AR technology makes it possible to iteratively register intuitive and spontaneous human building actions with a high geometric precision, to evaluate them in the computational design engine, and to supplement these actions with robot-controlled building tasks. The robotic tasks are computed in response to the user's intuitive building choices by using the explicit rules and geometric boundary conditions of the assembly grammar defined. This approach ultimately leads to the emergence of a final shape as a result of this interactive process.

In this paper, we then finally present the results of the spatial timber assembly being constructed by humans and a robot, and their complementary role in creating and building. The remainder of the paper is structured as follows. The Context Section outlines the contextual background of prototype-as-artefact fabrication workflows and the current state of the art in this area of research. The Method Section presents the method of the design tool and the fabrication workflow between humans and robots in a shared geometric workspace. It elaborates on the developed assembly grammar and the collaborative building process this grammar enables, including task distribution strategies between the two users and the robot. In the Results Section, the results of the case study of the complex timber structure enabled by the developed workflows and interaction concepts is described. The Conclusion and outlook Section presents the conclusion and gives a future outlook of this research. In closing, this paper discusses if such a balanced integration of robotic fabrication processes in coordination with humans could open up new avenues for design and digital fabrication in architecture.

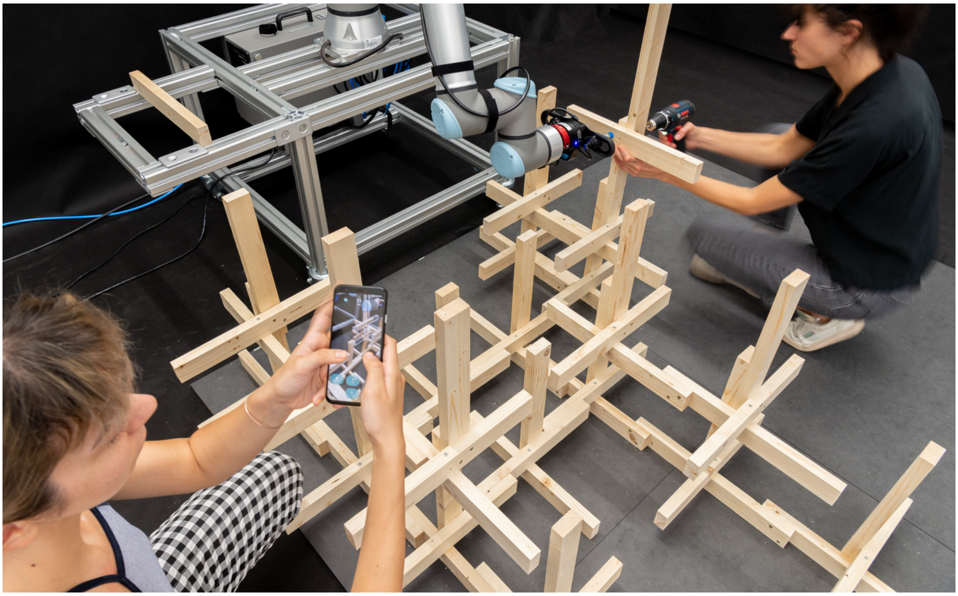

Figure 4.11: Prototype-as-Artefact fabrication workflow: Thanks to novel augmented reality technologies, two users and a robot collaborate in the assembly of a complex wooden structure in alternating physical actions. The spatial timber assembly being constructed follows a predefined assembly grammar but is not planned at the beginning of the process, its configuration is instead designed during fabrication

Context

Towards non-linear digital design to fabrication workflows

The computational theory of making grammars, presented by Knight and Stiny in 2015, has extended the theory of shape grammars for the study and the digital representation of the temporal performance of craft in contrast to representing solely the product [19], ultimately aiming at replacing top-down hylomorphic thinking by bottom-up material processes of formation [17]. By understanding the act of making in craft “as doing and sensing with stuff to make things”, they described its underlying creative processes by segmenting their spatial and temporal properties of applying rules for both actions of making and sensory perception. Such processes are open and do not fully determine the outcome in advance. They allow practitioners and users to change plans on-the-fly, for example, to pursue new design ideas that are triggered by the pattern in progress, or to accommodate for mistakes [20]. Also, in Sennett’s observations on Ruskin’s worldview [21], he advocates for craft processes as "lost spaces of freedom", in which craftspeople experiment with ideas and techniques, risk mistakes and delays, and “can at least temporarily lose control”. In the context of contemporary industrialized production, the early Enlightenment thinking summarized by Sennet can give clues as to how such spaces could be regained: "The enlightened way to use a machine is to judge its powers, fashion its uses, in light of our own limits rather than the machine’s potential. A machine ought to propose rather than command, and humankind should certainly walk away from the command to imitate perfection.” Rather than competing against the machine, exploring the relationship between rationalized industrial production techniques and traditional craft could show us entirely new ways in which we make and build architecture. Our proposed geometric aggregation strategy therefore aims to combine the bottom-up principle of making in craft with computational methods in design and fabrication. While the final configuration of the spatial timber assembly is unplanned, the process of assembly is governed by a simple rule-based geometric process (described in the Method Section) in combination with human decision-making and physical constraints. As such, this strategy aims to integrate physical boundary conditions of material processes in architecture (robotic reach) into the open-ended design process, which often cannot be anticipated directly by human intuition. In this scenario, in which the final geometric result is not explicitly determined before fabrication, computation strategies are used to inform the user about possible design spaces and the feasibility of their design intent by making physical and material constraints explicit during the fabrication process. The novelty of this project lies in the creation of a collaborative fabrication framework between humans and robots for unplanned structures, in which both creativity (since users have a certain influence on the final result of the physical structure) and rationalization (since the machine computes and performs fabrication steps in response to the actions by the user) are fostered. This type of open-ended construction advantages over a conventional top-down digital fabrication process: For example, it combines global target definitions with local connections between parts and ensures the constructability of each part during the course of construction.

State of the art

Various concepts and methods for non-linear and open-ended digital fabrication workflows in architecture via different direct and indirect user input technologies have been demonstrated in recent years. For example, Interactive Fabrication shows how a user can direct the fabrication of a physical form by using real-time user input [75]. In Interlacing, camera tracking allows for the

2D observation of a robot workspace, enabling a robot to process various material inputs and to make design decisions within a constrained design space during fabrication [76]. In RoMa, an interactive fabrication system provides an in-situ modeling experience for users [77]. As a designer creates and adapts a model using the RoMA CAD editor in AR, a 3D printing robotic arm sharing the same design volume concurrently constructs the designed features. In FormFab: Continuous Interactive Fabrication, the interactive manipulation of a thermoplastic sheet allows for shape explorations directly in the physical space [78]. While novel technology and approaches have allowed for a major leap forward in this area of research, the demonstrated processes to date still show various trade-offs. For example, few investigations have been performed on how to utilize user input as a feedback to the computational design engine directly via the built structure. While the input of sensors is defining the robot actions for manipulating an object in Interactive Fabrication, RoMa, and FormFab, the physical result of the robotic manipulation procedure is not registered and is therefore not directly part of an interactive loop. While Interlacing aimed to provide such feedback directly via the built structure, it was highly constrained by lacking adequate sensor and 3D registration technology and intuitive human-machine interfaces. Most importantly, all described processes have been performed at object scale and have not tested and evaluated the principles of interactive fabrication at the architectural scale and in the context of architectural production. In Prototype As Artefact, the user input is processed directly via the built structure by tracking elements which are placed spontaneously by users and by feeding this information back to the digital model. This approach allows for an interactive and collaborative workflow between humans and robots at architectural scale.

Method

The aim of the research was to develop a set of workflows and technologies to facilitate an interactive human-robot collaborative workflow for assembly tasks, with a particular consideration for the unique needs and circumstances of architecture and construction. The following sections describe the various building blocks and implemented methods necessary for realizing this research project.

Assembly grammar

In reference to Terry Knight's *making grammar*, this research proposes an *assembly grammar*, which allows for the description of rules for temporal processes next to geometrical ones. The design rules of the proposed assembly grammar allow for building spatial structures by mechanically connecting discrete elements in subsequent fashion. In the digital model, referred to as the Assembly Information Model, each element is represented by a node of a graph; the edges of the graph correspond to the connections between the elements. Each element features two connectors on both endings on the long side representing two options where a new element can be mechanically attached, defining an open design space of discrete and variable structures [45]. The Assembly Information Model was implemented by using the data structures available through the open-source Python-based COMPAS framework [62]. The initial design rule that directly affects the geometrical outcome is described by the geometrical configuration of three perpendicular elements into a module with a predefined range of connection possibilities. Due to the module's perpendicular spatial arrangement, each element has a different type assigned to it – each module consists of one element of type X, one of type Y or and one of type Z. These also refer to the orientation of the elements along a respective axis in the digital design model (Fig. 4.12).

The connection between two modules (but not the connection between elements within a single module) is represented as a parent-child connection, in which the module that is already mounted is referred to as the parent and the newly mounted one as its child. The first element of the child module inherits the type of its parent: parent type X -> child type X, Y -> Y and Z -> Z. The type of the parent module's first element and correspondingly of its child determines the type and sequence of the placement and mounting of the subsequent two elements. Depending on the type of the parent, the sequence can have the following order: if the parent is of type X, the mounting sequence is [X, Y, Z], if the parent is of type Y, its sequences is [Y, X, Z], if the parent is of type Z, its sequence is [Z, X, Y]. There exist a few exceptions to these rules, for example, the mounting sequence for type Y changes to [X, Y, Z] when building on the ground, due to otherwise reduced accessibility of the space underneath previously mounted elements and the base of the structure.

To introduce a differentiation in the design space where a structure can be built with higher or lower density, parent-child connections are fixed in angle but leave some variability in the range of the mounting distance along the element's axis. For this, two conditions must be satisfied: 1) Sufficient contact surface must be provided between the child and the parent where the mechanical connectors are installed but also allowing for the remaining two elements to be placed. With elements of 40 cm in length and a minimum overlapping length of 4 cm of the connected pieces, this results in a range of 15 cm within which an element can be freely placed along the respective axis. 2) The child must always be mounted on the same side of the parent element (either on the left or on the right side), otherwise the initial design rule cannot be fulfilled. If the mounting position within the structure differed, the spatial arrangement of the module would alter and prevent the modules from connecting, which would affect its overall structural performance and stability.

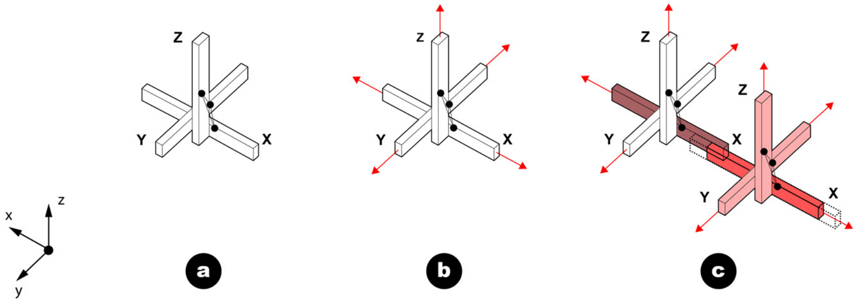

Figure 4.12: Assembly Grammar: a) module of three discrete elements represented by three nodes of a graph, b) arrows displaying all possible directions in which the assembly can be continued, and c) placing new module within a range

User input

The assembly grammar stipulates that the placement of the first element of a new module, referred to as the keystone element, is carried out via a spontaneous user input within the given design space, i.e., the free range and direction of an element's placement at open connector locations (Fig. 4.13).

The boundary conditions constraining the design space can be subject to various performance criteria such as to stability criteria of the overall structure, target conditions of growth directions, workspace limitations of a robot, or the collision avoidance between elements (Fig. 4.14). After a user determines the orientation and location of the keystone element, the design algorithm computes the subsequent two elements of the module as a response to the user's choice. If the computed elements were to collide with the existing structure, any colliding objects are detected and omitted by the algorithm and thus not added to the assembly. With each added module, the potential design space, represented by the amount of open connectors, can grow.

Material system

For realising the prototype, same sized timber elements with dimensions of 24 x 48 x 400 mm were used, which were pre-drilled and could later in the process be mechanically connected into

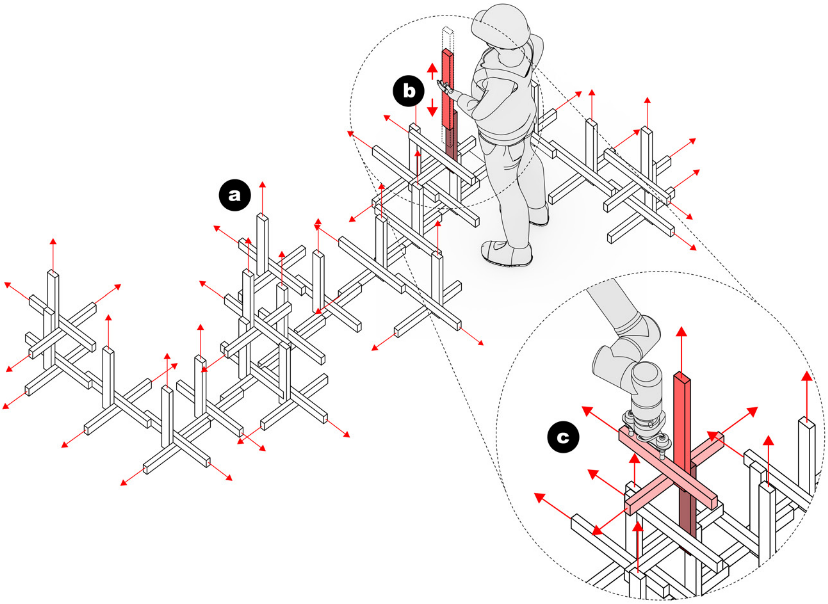

Figure 4.13: Assembly steps distributed between users and a collaborative robot according to a set of design rules and options: a) arrows displaying the design options, b) keystone element is placed freely at a chosen location within a possible domain, c) complementing elements 2 and 3 are computed based on the location of the keystone element and placed by the robot

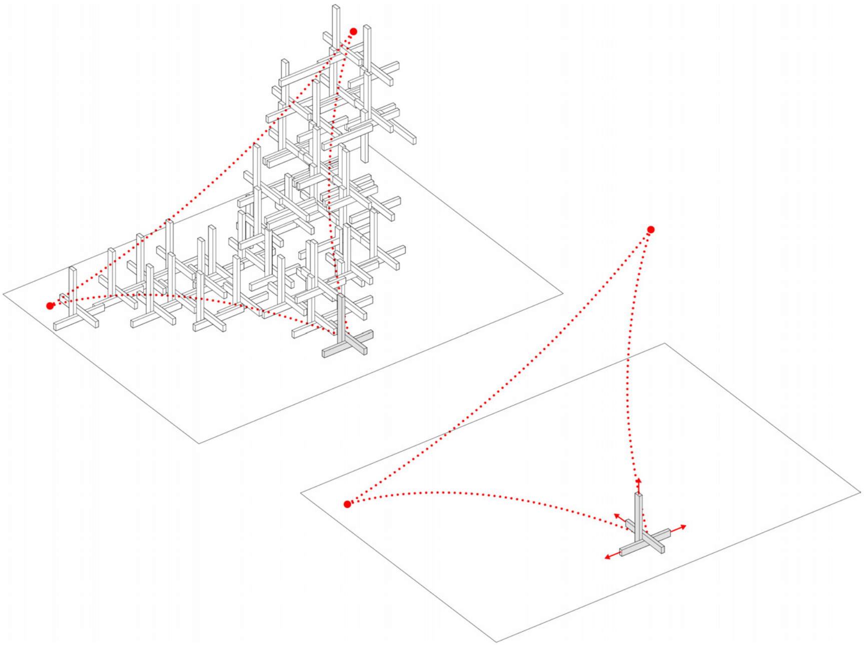

Figure 4.14: At the start of the process an origin, described by one module, and a global growth directions of the structure, specified by target points in space, are defined by the users. The inscribed design space and according building options are based on these initial constrains and are continuously calculated throughout the process according to the users' input

an overlapping shear connection by using wood screws (Fig. 4.15). The spatial arrangement of the elements within a module results in three different drilling patterns for each element type. These patterns enable a separate mechanical connection of each element to the other two elements whereas the hole pattern necessary for the connection between modules remains the same for each element. The choice for the single shear screw connection type was entirely influenced by the requirement of enabling variable placement of the mechanical connectors along the longitudinal side of the elements. For fastening the elements, torx stainless steel wood screws with countersunk and lengths of 40 and 60 mm were used. The screws are inserted through the holes of the predrilled element that is to be attached to the structure and screwed in the desired member of the structure with a portable electric screwdriver. By inserting two rather than only one screw at the lap joint sufficient stiffness of the connection has been reached. The screw connection also enables an easy disassembly of the structure and reuse of both timber and screws.

Collaborative human-robot assembly setup

The setup of the proposed collaborative workflow for assembling the timber structure in alternating physical actions consists of two users, which are equipped with a mobile AR device and complemented by a semi-mobile collaborative robot (Fig. 4.16). The mobile AR device enables both the users and the robot to build on the same workpiece, which is enabled by two key features: 1) The visual display of the AR device can superimpose cues on the real world video stream designed to assist the builders with information, in this particular case with visual cues on the

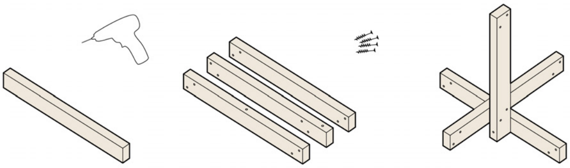

Figure 4.15: Material System: one module consists of equally sized pre-drilled timber elements mechanically connected with wood screws

design space in which they can make their design choices, and 2), the simultaneous visual-inertial tracking capabilities of the AR device [59] allow the users to continually digitize their building actions (i.e., design choices); this is achieved by tracking and registering the precise position of newly placed keystone elements of the timber structure, and by feeding this information back to the design engine (Fig. 4.17).

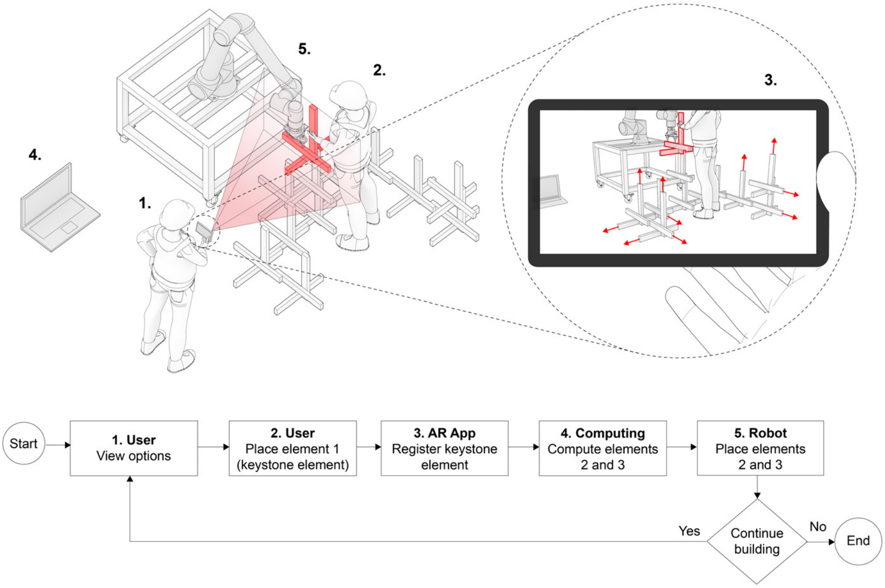

Figure 4.16: Setup and flowchart of the open-ended collaborative human-robot assembly workflow, enabled by novel assistive AR technology and sensor feedback

Open-ended assembly workflow

The collaborative assembly workflow consists of alternating user and machine actions of assembling timber elements into the spatial structure, in which each spontaneous user action is followed by a robot action. The combination of the timber elements into modules of three thereby

Figure 4.17: The visual display of the AR device can superimpose cues on the real world video stream designed to assist the builders with information, in this particular case with visual cues on the design space in which they can make their design choices

represents the alternating assembly sequence between the user (keystone element, freely placed by hand) and the robot (second and third element, computed and placed by the robot). One iteration starts with the user tracking the built structure and observing the design space visualized via the AR interface (Fig. 4.18). The design space is visualized in the representation of arrows superimposed onto the built timber structure, in which the arrows indicate the open connectors and possible directions where the structure can continue to be built and branched out. The location of the arrows are subject to various boundary conditions, in this case, the definition of initial target locations to where the structure should grow towards, as well as the current robot workspace. The user can then choose any location within the current given design space to place the keystone element (Fig. 4.18a); while the chosen connection is then fixed in angle, the distance along the parent element's axis is subject to the user's decision. After having the element placed and mechanically fixed, its precise location (position and orientation) is then registered by the user via the AR device (Fig. 4.18b) and fed back to the design engine (Fig. 4.18c). In response to the user's freely placed element, the design engine then computes the location of the two subsequent elements to complement the module (Fig. 4.18d). For robotically placing the two computed elements, their corresponding robotic pick-and-place routines need to be calculated. The planning scene creation and the motion planning are done through COMPAS FAB, the robotic fabrication package for the COMPAS Framework [79], by using the MoveIt! Package from the Robot Operating System (ROS) backend. In the closing of one iteration, the two elements are placed according to the computed robot motions (Fig. 4.18e).

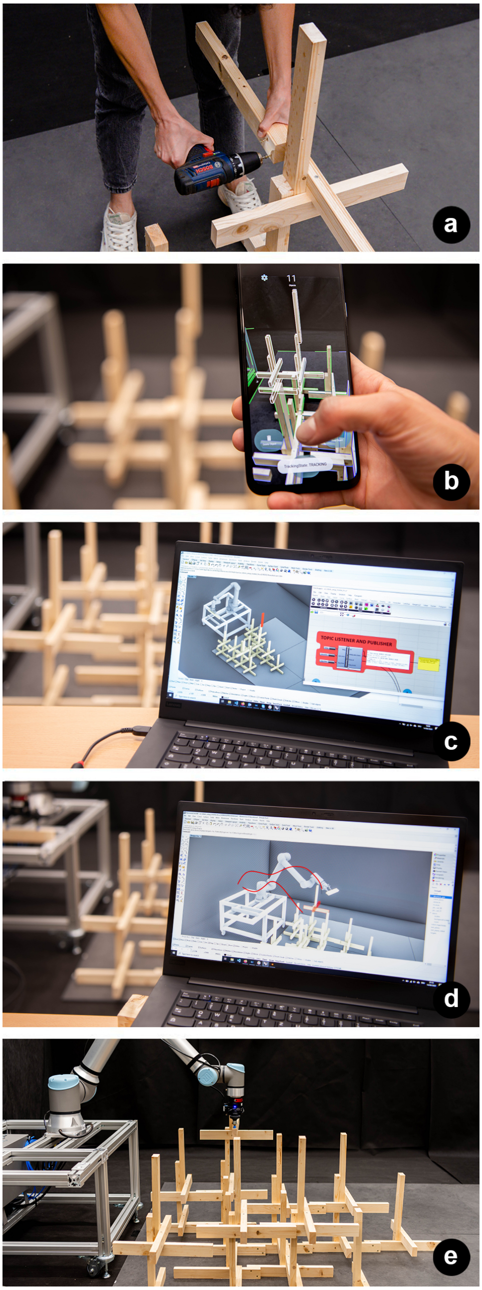

Figure 4.18: Assembly workflow: a) The user can place an element freely within the boundaries of the AR-visualized design space. b) After placing, the user must register the pose of the manually placed element via the tracking feature of the mobile AR app. c) The registered pose is then transmitted to the CAD design environment of the mobile AR app. d) The two subsequent elements of one module and their respective robotic pick-and-place routines are then computed in response to the registered pose. e) Finally, the robot places the computed two elements. At their target location, the user can fix the elements with screws

Interoperability and cross-platform communication

To ensure the interoperability between the multiple devices and back-end computational processes for the collaborative assembly process, a necessary component is a scalable middleware technology as the communication infrastructure for the distributed system. In this case, this was achieved by using ROS, which is currently the state-of-the-art in robot middleware, providing a simple socket-based programmatic access to robot interfaces and algorithms, that external processes can access through the rosbridge package and roslibpy of COMPAS Fab. Here, the ROS system architecture is utilized to connect the multiple instances of a) the design computation process embedded within the computer-aided design (CAD) design environment Rhino/Grasshopper, b) the mobile AR app for visualization and tracking, c) the ROS MoveIt! Planner, and d) the collaborative robot. The associated hardware consists of a) a Windows PC (running the design computation process and a rosbridge client), b) a Linux PC (running the ROS master, Moveit! and a rosbridge server), c) an Android phone (running a rosbridge client within the AR app), and d) the UR robot controller. For a viable communication, all devices have to be connected within the same Wifi network.

Results

To test the developed workflow and toolsets, a case study was conducted, whereby two users and one Universal Robot (UR10e) collaborative robot interactively constructed a medium-scale architectural prototype. The prototype was realized on a building floor area of 2 x 3 m consisting of 6 MDF boards with dimensions of 1 x 1 m each and 6 mm thickness. This MDF flooring served both as a base for mounting the prototype with the elements placed on the ground to it and as a neutral background for the tracking. Additionally, dark light proof and non reflective fabric was suspended around the building area to exclude unnecessary surface edges from the tracking scene. To provide constant lighting conditions and thus uniform tracking results, only artificial light was used over the entire building process. A free space described by a rail of 120cm between the base of the prototype and the black coverings was used for the robot to be moved around within, as well as to allow for enough space for the robot motions. A total of 102 timber elements were installed over the course of three days (Fig. 4.19), of which 16 were freely placed and tracked by a user, 56 were placed by the robot from three different locations, and 30 were placed by a user which could have been placed by the robot but were placed manually instead. This manual placement was also made possible via the app, as the elements calculated by the design algorithm were visualized and the user could follow the superimposed outlines of the digital model over the real video stream when placing them. At each of the three robot's locations, the robot's origin was determined by matching manually recorded corner points of the built structure with the robot's measurement tip with their point location in the digital model. The tracking accuracy was observed to be well between 3mm as indicated by ground truth measurements with the robot's measurement tip. The color gradients in the error plot (Fig. 4.20) indicate the deviation in distance (red) and rotation (blue) from the estimated object poses to the poses of the planned elements which follow a rectilinear grid as defined by the design algorithm.

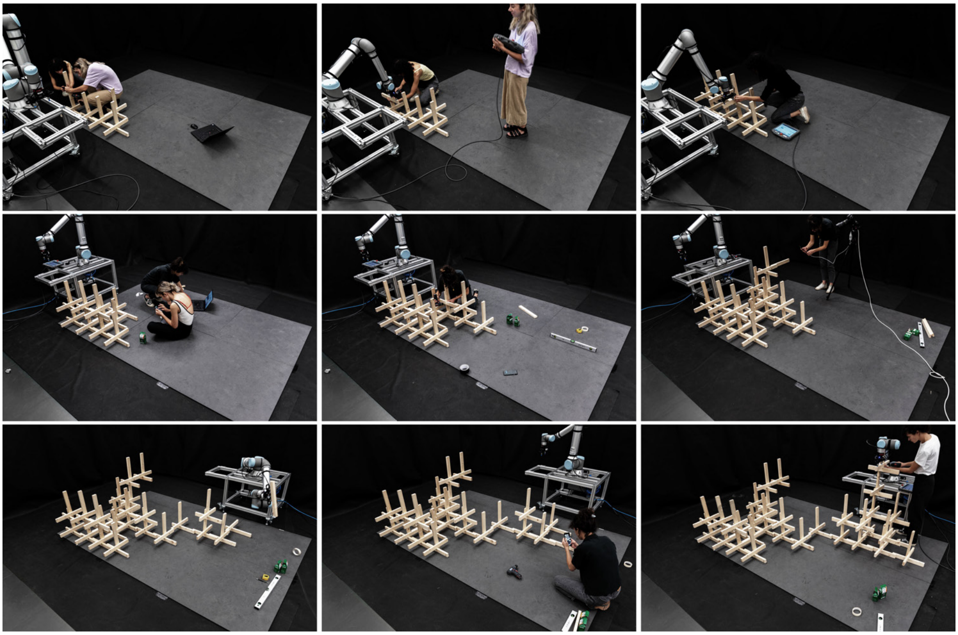

Figure 4.19: Snapshots from the time lapse of the open-ended collaborative fabrication process.

Conclusion and outlook

Conclusion

The research presented in this paper has explored a novel open-ended digital fabrication workflow by introducing non-linear principles of craft into a usually linear design-to-fabrication process. On the basis of an implemented design tool for the sensible distribution of tasks between humans and robots, this novel workflow could be carried out by two users and a collaborative robot. They all worked together in designing and assembling an unplanned spatial structure, combining explicit machine intelligence and implicit human knowledge and creativity. The realization of this concept was facilitated by state-of-the-art object tracking technology of an AR app, which provided the facility to register single objects precisely in 3D space and in relation to the built structure. The concepts and methods have been successfully evaluated and validated on behalf of one case study, the collaborative assembly of a branching spatial timber structure. In this study, the global growth directions and local branching rules of the structure to be constructed were defined by the users at the start of the process. During the process, the users could follow the suggested directions that were visualized to them as design options via the AR app, but make individual and spontaneous decisions within these suggested options. As such, the process facilitated the creative participation of humans in a digital building process by integrating creative decisions during the ongoing process. Design computation in this case was utilized not only to calculate a finished structure ready to be fabricated, but to continually calculate a potential design space and according building options based on the users' decisions/input, as well as its corresponding robotic fabrication procedures. The result of this project was a timber structure

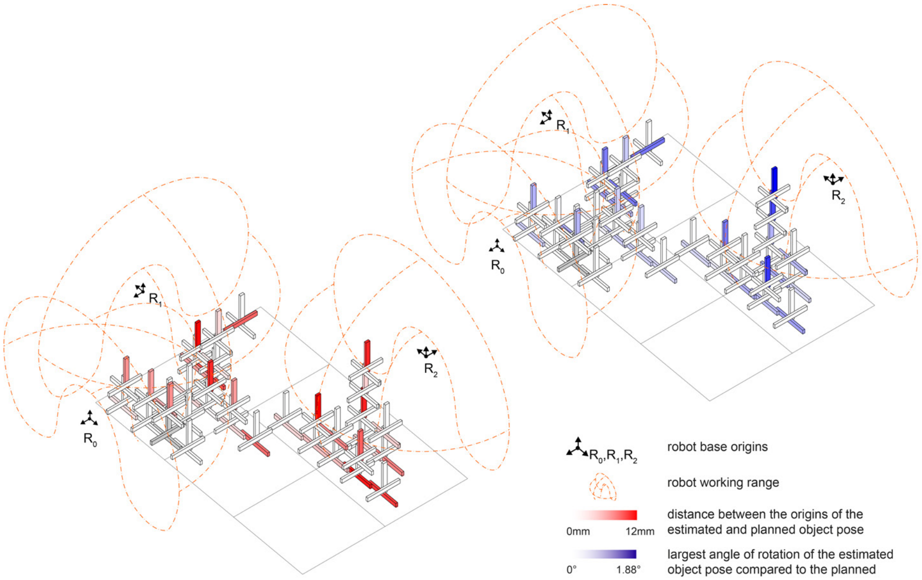

Figure 4.20: The color gradients in the error plot indicate the deviation in distance (red) and rotation (blue) from the estimated object poses to the poses of the planned elements if there were to follow the rectilinear grid

— a complex 3D branching structure with varying densities — sequentially designed and built collaboratively on the basis of the user's design input and physical boundary conditions. In summary, the project has made it possible to question the typical roles of designers, builders and robots. It also lays the foundation for future scenarios in which humans could actively intervene, physically or cognitively, supporting or steering automated processes towards higher levels of robustness and efficiency in complex or unforeseen scenarios.

Outlook

While this research has allowed to demonstrate the core concept of non-linear and open-ended digital design-to-fabrication workflows, many directions for future work have been identified: Structural evaluation: While structural evaluation is usually important for the final shape, in this research, maintaining structural stability during production is of great importance in order to ensure its equilibrium without further support. Due to the rather small number of built elements and the scale of the built prototype, its structural behaviour could be intuitively anticipated by the users and thus affect their design decisions during building. This reduced the necessity for structural feedback through the design engine. Instead, locations were selected for new elements to be placed on the existing structure that were intuitively viewed as stable to continue building; e.g., by being viewed close to the center of mass of the overall structure. However, the intuitive decision making of the user will require additional methods for evaluating the structure's stability such as real-time structural analysis as an integrative part of the design generation and computation of the design possibilities once the complexity of the structure increases, e.g., by introducing cantilevering modules.

Mobile robot: The setup featured a semi-mobile robot manipulator on a wheeled base which was relocated manually to three subsequent locations. A mobile robot on an automatically movable base could be used for future work. Further, the localization of the robot's origin in reference to the built structure has been performed by manually recording a set of points and matching these points with their digital location. In future work, the object registration capabilities of the mobile AR app could also be utilized to automate the mobile robot's localization.

Variability: The implemented bottom-up design strategies could in the future be applied to variable building elements, which vary in size and shape, e.g., in the case of found material.

Scale: For future development, the process could be scaled up to enable the fabrication of larger structures to validate the stated concepts for fabrication at full architectural scale.

Gamification of construction: Future research will also look more closely at the notion of gamification in construction and its impact on the professions of architects and builders.

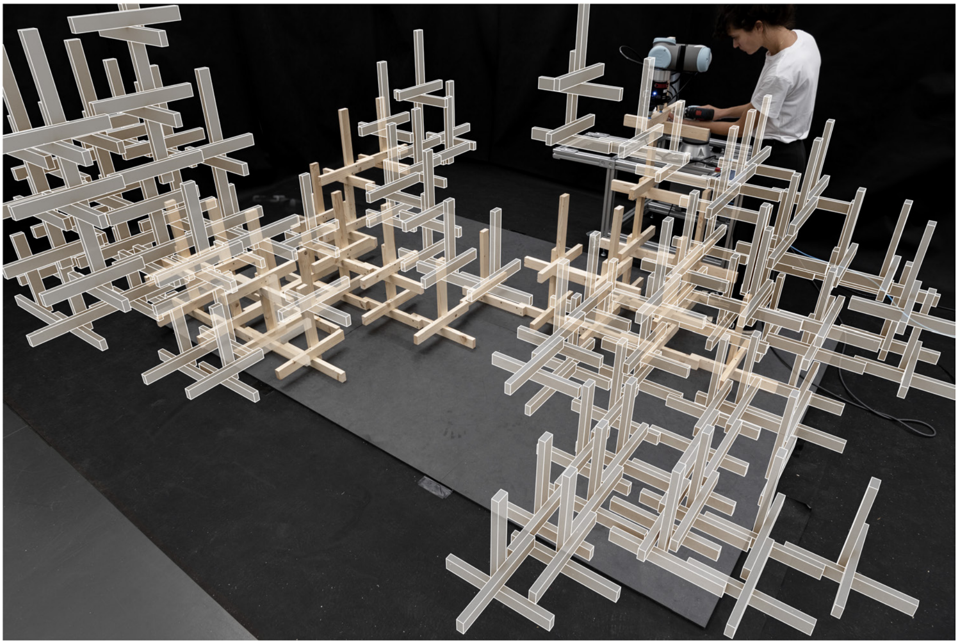

Figure 4.21: One out of countless potential design outcomes of the open-ended collaborative fabrication workflow if the building process would be continued by placing more modules. The overlaid structure, consisting of 290 timber elements (the total number of elements including the prototype is 392), was generated by randomly placing new modules within the design spaces defined by the realized prototype and following the branching directions specified by the user

Acknowledgments

This paper and the research were supported by incon.ai who provided the AR tracking technology. We thank Begüm Saral for helping with the fabrication of the prototype.

4.2.3 Author’s contributions to the paper

The contributions of the author to the realization of this case study can be summarized in three main areas: First, the author developed the computational design logic by formulating the *assembly grammar* that governs both the spatial configuration and temporal sequencing of the collaborative construction process. This included extending the AM to encode not only topological relationships but also embedded assembly instructions and task assignments derived from the grammar. Second, the author designed and tested the human-robot collaborative workflow using off-the-shelf AR tools. This involved defining the interaction sequences and coordinating mechanisms for real-time cooperation between human and robotic agents. Third, the author contributed to the integration and testing of all system components required for a medium-scale spatial frame prototype validation. This encompassed the material system, AR tracking and visualization, robotic motion planning, and the orchestration of the experimental setup to ensure robust interoperability between hardware and software systems throughout the construction of the prototype.


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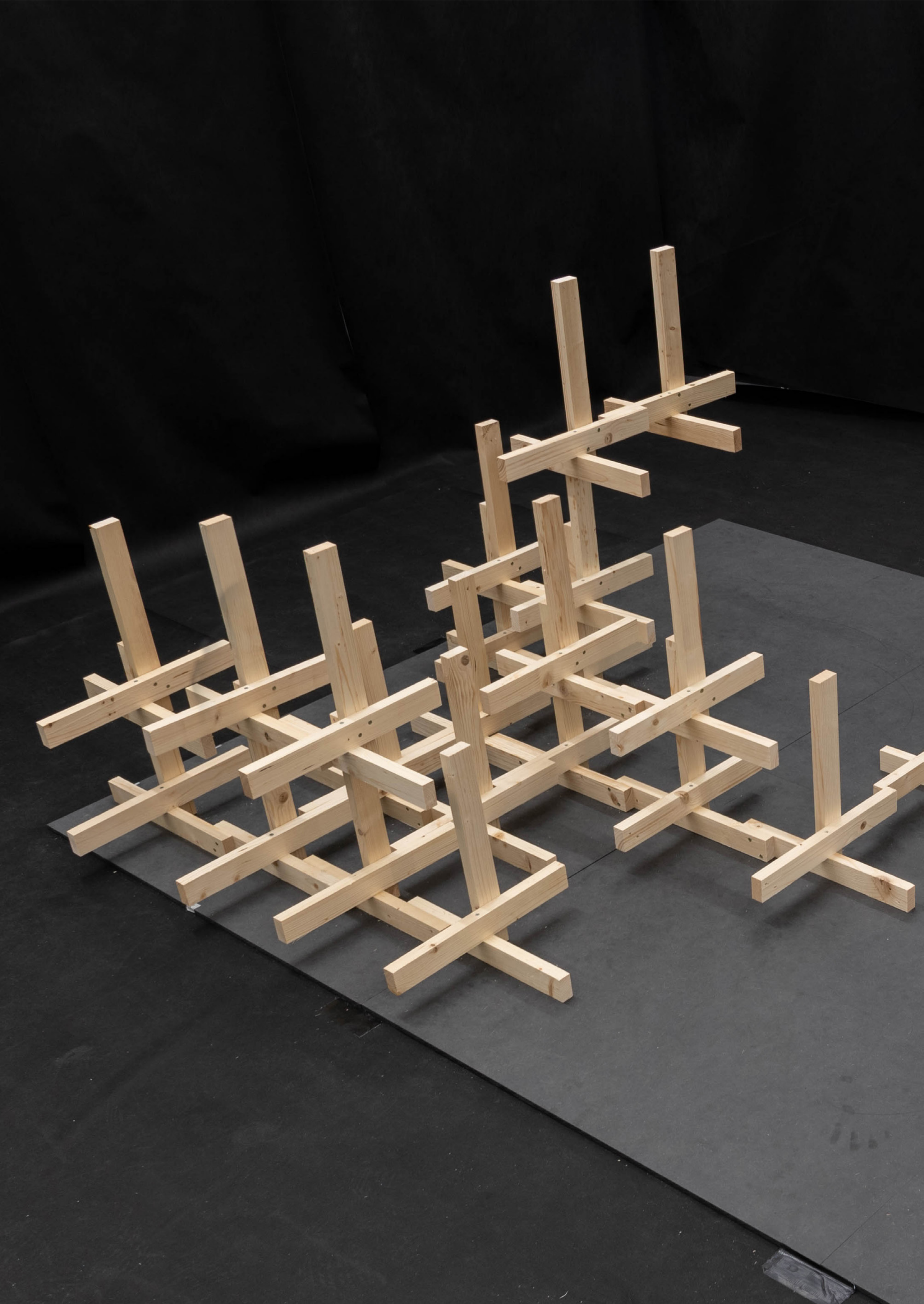

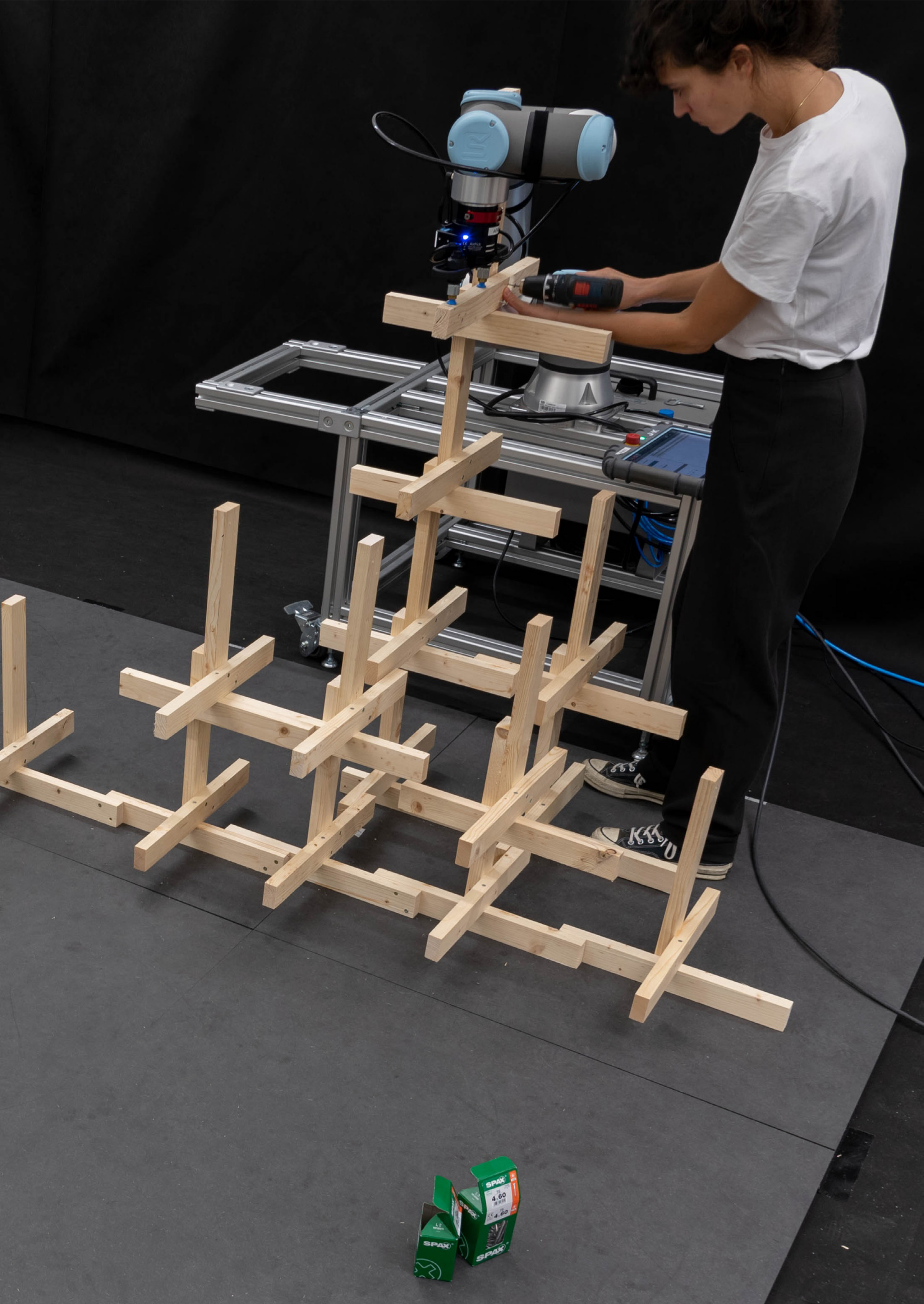
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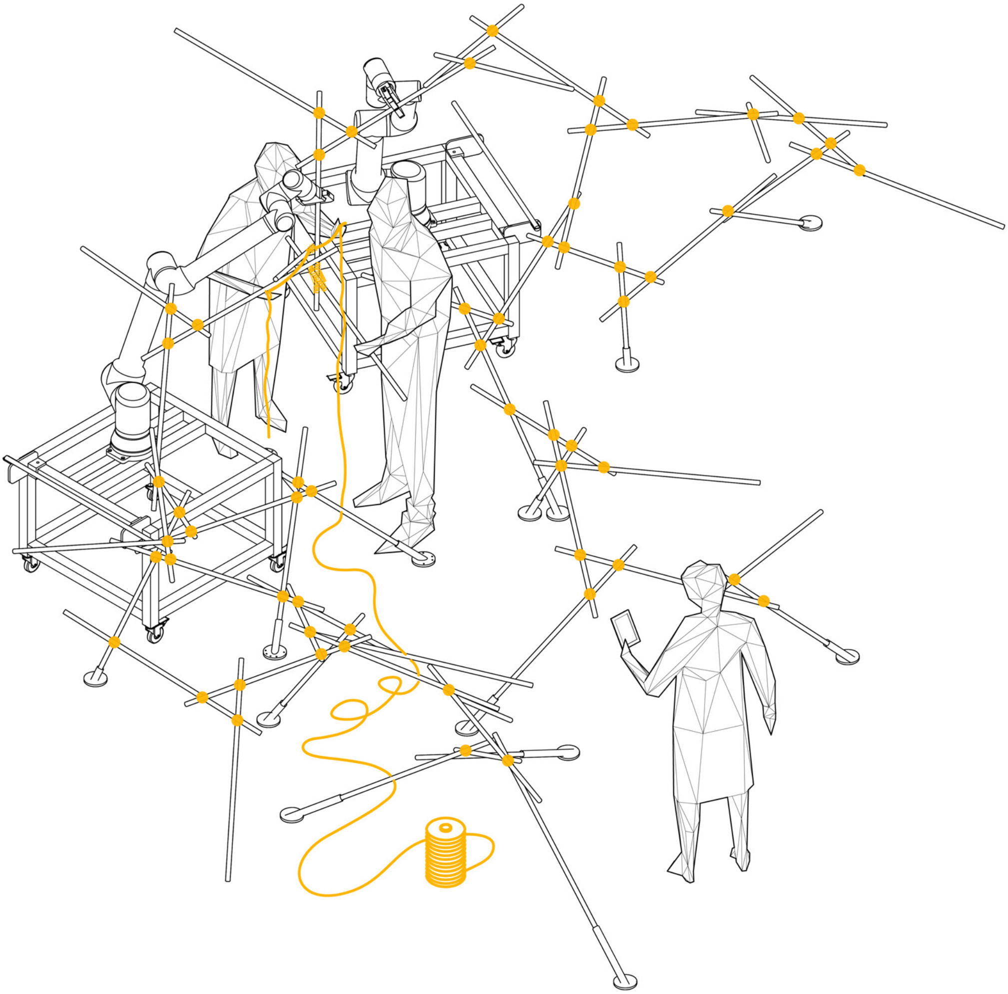
4.3 Case Study 2B: Human-robot cooperative assembly with two robots

4.3.1 Summary and contribution to the thesis

This case study expands on insights gained from Case Study 2A and contributes to the research objectives of the thesis by presenting a turn-taking human–robot cooperative assembly workflow for discrete timber structures, involving two human agents and two mobile collaborative robots. The study investigates how humans and robots can co-construct complex spatial configurations by alternating roles within a synchronized digital–physical workspace, where human actions are registered, interpreted, and used to dynamically update the system state. The workflow integrates visual–inertial tracking, point-probing via robotic end-effectors, and augmented reality interfaces to maintain a real-time connection between physical actions and their digital representation in the AM. Human and robotic tasks are generated in response to ongoing changes, allowing construction, design intent, and computational planning to evolve in parallel. The assembly process was validated through a full-scale physical prototype that tested the system's performance under real construction conditions, including alignment, stability, and material variability. This case study directly supports the thesis objectives by implementing and evaluating cooperative, multi-agent assembly strategies that foreground reciprocity and interdependence between agents. It demonstrates how computational design logic, embodied interaction, and real-time coordination can be integrated into a shared workflow, enabling adaptable construction processes where human agency, robotic precision, and material behavior are jointly negotiated.

This section has been published as:

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. Construction Robotics. https://doi.org/10.1007/s41693-022-00083-2



4.3.2 Publication

Tie A Knot

human–robot cooperative workflow for assembling wooden structures using rope joints

Daniela Mitterberger[1], Lidia Atanasova[2], Kathrin Dörfler[2], Fabio Gramazio[1], Matthias Kohler[1]

Abstract

In recent years, research in computational design and robotic fabrication in architecture, engineering, and construction (AEC) has made remarkable advances in automating construction processes, both in prefabrication and in-situ fabrication. However, little research has been done on how to leverage human-in-the-loop processes for large-scale robotic fabrication scenarios. In such processes, humans and robots support each other in fabrication operations that neither of them could handle alone, leading to new opportunities for the AEC domain. In this paper, we present *Tie a knot*, an experimental study that introduces a set of digital tools and workflows that enable a novel human–robot cooperative workflow for assembling a complex wooden structure with rope joints. The system is designed for a dually augmented human–robot team involving two mobile robots and two humans, facilitated by a shared digital-physical workspace. In this shared workspace, digital spatial data informs humans about the design space and fabrication-related boundary conditions for decision-making during assembly. As such, humans can manually place elements at locations of their choice, following a set of design rules that affect the gradual evolution of the structure. In direct response to such manually placed elements, the cooperating robots can continue the assembly cycle by precisely placing elements and stabilizing the overall structure. During robotic stabilization, humans make rope connections, which require high dexterity. The concept and workflow were physically implemented and validated through the cooperative assembly of a complex timber structure over five days. As part of this experimental investigation, we demonstrated and evaluated the performance of two tracking methods that allowed the digitization of the manually placed elements. In closing, the paper discusses the technological challenges and how a hybrid human–robot team could open new avenues for digital fabrication in architecture, accelerating the adoption of robotic technology in AEC.

Keywords: Human–machine cooperation · Human–robot cooperation · Interactive fabrication · Open-ended design · Augmented reality · Context-awareness

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Introduction

In the last 17 years, research in computational design and robotic fabrication in architecture, engineering, and construction (AEC) has made remarkable advances. These advances have introduced a variety of approaches using diverse robotic and material systems, ranging from complex timber construction [80], [81], 3D printing with concrete [82], [83], to autonomous brick assembly [2], [84] both on and off-site construction scenarios. Robotic fabrication has enabled rapid and precise production with increased construction customization, accuracy, and process reliability in various work environments and scales [72]. Since construction robots have been designed and programmed for relatively static work environments and predefined processes, most robotic processes require the robots to run in work cells, free from humans and unpredictable disturbances. Once the robot is programmed, the environment and objects that the robot interacts with are expected to remain within the same range of variance that the robot was programmed to. Therefore, especially in unstructured environments, such as construction sites, the level of robustness and autonomy of such robotic processes is still remarkably low [85]. Due to this low level of robustness and autonomy, these robots still rely on human operators to make critical decisions or assist the robotic fabrication process [86]. Moreover, the lack of autonomy limits the robots' ability to seamlessly and reliably interact and collaborate with humans, thereby missing out on the benefit of leveraging complementary skills. Research has not yet focused enough on complementary workflows and human-in-the-loop processes in AEC, leading to a lack of working and intuitive interfaces for robotic fabrication processes that enable seamless communication and data exchange between humans [87]. This deficiency, in turn, limits new design and manufacturing opportunities and delays the wider adoption and integration of robotic fabrication into AEC.

This research addresses this limitation by examining how to leverage the development of cooperative and semi-autonomous manufacturing systems between humans and robots. It focuses on hybridizing robotic fabrication with traditional manual workflows, developing a balanced human–machine collaboration system that can enable novel, intelligent and economical workflows for AEC. Such workflows make equal use of human and machine capabilities—the autonomous and interactive capabilities of robots, such as robotic precision and computational iterations, and human cognitive and physical abilities, such as manual dexterity, material knowledge, and intuition. The research findings of this paper emerged through physical experimentation and a proof-of-concept prototype of a complex wooden structure with rope joints (Fig. 4.22).

The cooperative assembly workflow is designed for a dually augmented human–robot team involving two mobile robots and two humans. A shared digital-physical workspace is established to facilitate cooperative assembly tasks distributed between humans and robots. Humans can initiate assembly cycles and take turns with the robot to construct wooden Y-triplet units. These units are made of three struts—one from a previous triplet, one assembled by the robot, and one manually assembled by a human. The manually assembled element can be placed freely, following a set of local rules that influence the design of the structure on the fly. These additions made by humans to the built structure need to be continuously digitized and fed into the digital model, from which robot routines can be derived successively. Therefore, this research utilizes recent advancements in mobile augmented reality (AR) technology and sensor-enabled context-awareness [59] to track and detect such manually added changes to the built structure automatically and precisely. Alternatively, the collaborative robots themselves are utilized as precision instruments that are used by humans to track and register manual changes. In this

Figure 4.22: Cooperative assembly scenario by human–robot teams

paper, we evaluate the accuracy of both tracking methods to understand how humans and robots can collaborate in assembling a large-scale structure.

The remainder of this paper is structured as follows. Section Background provides an overview of the state of the art of non-linear design-to-fabrication workflows and hybridized robotic and manual fabrication processes in AEC. Section Case study—Tie a knot introduces a set of digital tools enabling a novel cooperative assembly workflow of a wooden structure in a shared geometric workspace between humans and robots. It presents a system walkthrough and the hardware and software components. Section Results and limitations presents the results and current limitations. Section Conslusion concludes the research, addresses the technical challenges of the case study, and concludes with an outlook on future research directions. In summary, this paper discusses how—by getting humans and machines to communicate with one another—the notion of a hybrid human–robot work team could open new avenues for digital fabrication in architecture.

Background

The following sections illustrate how our study expands on previous work by investigating non-linear design-to-fabrication workflows and cooperative fabrication processes in digital fabrication. Specifically, this research focuses on hybridizing robotic and manual construction techniques by human–robot teams.

Nonlinear design-to-fabrication workflows

Most digital design-to-fabrication workflows in architecture are linear due to the explicit nature of machine instructions, thus requiring most design decisions to be made prior to fabrication. Traditional craft processes, on the contrary, are not necessarily linear but rather encourage practitioner creativity by not entirely specifying the path of execution [20]. To incorporate this non-linear approach, Knight and Stiny [16] introduced a computational theory of making grammars, which has expanded the theory of shape grammars [19] for the study and digital representation of the temporal performance of craft. They articulated the fundamental creative processes of craft by segmenting spatial and temporal aspects and by applying rules to both the act of creation and sensory perception. They understood crafting as "doing and sensing with stuff to make things". Such procedures are open and do not entirely predetermine the result. Ultimately, through sensory perception, they enable practitioners to make changes to plans, for instance, to make design adjustments, pursue new design ideas, or accommodate mistakes. Further concepts for non-linear digital fabrication workflows utilizing user input technologies have been demonstrated in the last few years. *Interactive Fabrication* [88] presents how users can control the digital fabrication of a physical form using real-time input devices. Another example of such a process is *IRoP* [89], an interactive augmented robotic plaster spraying process. In *Interlacing* [76], a robot makes a design decision within a constrained design space based on 2D camera tracking. *Prototype-as-Artifact* [90] presents core concepts of non-linear design-to-fabrication workflows. This research explores the possibilities of making bottom-up design decisions while building in a human–robot cooperative setting. However, the task distribution allocated to humans and robots was interchangeable and not explicitly tuned to their unique strengths.

Toward hybridizing robotic and manual fabrication

As has been explored in previous research, humans and robots have different strengths [91], [92], and cooperative processes should make the most of this by tailoring the role each agent plays. There are diverse strategies for such task distribution in cooperative processes [93]. In this research, we focus mainly on task distribution, where a machine assists a human while fabricating, a process we define as *machine-assisted human fabrication*[1]. In this case, human fabrication or "human-made" no longer applies only to handcrafted objects. Rather, *machine-assisted human fabrication* also incorporates partially automated processes whose physical output is still dependent on the human craftsperson who oversees and participates in the fabrication [94]. Only a few research projects combine difficult-to-automate manual fabrication tasks with robotic fabrication tasks. The research, *iHRC* [33], introduces a workflow that enables workers to decide actively on the human–machine cooperative task distribution. The human worker can take over specific process parts, such as picking and placing timber slats or slat fixation, or give these tasks to the machine. Another human–robot cooperative building process is the *Hive* pavilion [95], [96]. The live building process coordinates multiple human workers via a phone-based app that provides humans with instructions to locate materials and respond to commands like tightening mechanical ratchets, placing finished elements, and supervising fabrication quality. Another example of combining robotic and manual processes is *CRoW* [32]. In turn-taking tasks, a user

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[1] This case study focuses on "machine-assisted human fabrication" as humans are predominately fabricating, and require guidance and tools to assist them during fabrication. The difference to traditional manual manufacturing is that humans are enabled to fabricate geometrically complex and digitally informed objects.

equipped with an AR headset can plan the placement of wooden elements by assessing the fabrication data beforehand. Subsequently, the robotic arm places the wooden plank, and the operator nails it manually. These projects show how such hybridization of automated processes and manual construction techniques can increase the flexibility and robustness of automated workflows. However, in these projects, the tasks selected for the human operator do not require extensive dexterity or elaborated context perception.

Hybridizing robotic fabrication with manual tasks also includes the combination of manual esthetics with automated processes. Projects such as *RobotSculptor* [97] or *Adaptive Robotic Carving* [98] allow the results of an automated process to achieve a handcrafted look. These researches show the potential of combining predefined robotic processes with human dexterity. However, the design in these projects is finished before fabrication starts, and therefore, these processes do not fully embrace the potential of combining human–machine collaborations with interactive fabrication.

Case study—Tie a knot

Overview

This research aims to combine non-linear design with an interactive fabrication process to facilitate a human–robot cooperative workflow for assembling a complex wooden structure using rope joints. The cooperative assembly workflow consists of turn-taking tasks between two humans and two robots according to predefined rules and action sequences. A shared digital-physical workspace enables the cooperation between humans and robots, in which tracking systems are used to update the digital-physical workspace continuously. An extended reality system informs the cooperating humans about the design space and fabrication-related boundary conditions. Humans can initiate design and assembly cycles that are continued, assisted, and completed by the cooperating robots. These assembly cycles are composed of five turn-taking steps: (A) interactive design, (B) robotic assembly, (C) manual assembly, (D) rope jointing, and (E) registration of manually assembled elements (Fig. 4.23).

Each assembly cycle consists of adding a wooden Y-triplet made of three struts, one from a previous triplet, one assembled by the robot (B), and one manually assembled by a human (C). At the beginning of each assembly cycle, users change global constraints such as growth direction and density (A). Then they move the robots within reach of the first element of the Y-triplet, which is already assembled and part of a previous Y-triplet. The second element is robotically assembled and held in place by *robot one* (B) until *user one* places the third element and closes the Y-triplet (C). The manually assembled element can be placed freely following a set of local rules that affect the design of the structure on-the-fly. After all the struts are placed, they are connected via rope joints by *user two* (D). After placing the joints, the manually placed element is tracked by *user two* and included in the digital model (E). While *robot one* stays in place to stabilize the structure, *robot two* is used to continue the building cycle in direct response to the manually assembled strut. To test the feasibility of the concept, a large-scale proof-of-concept timber structure was built with this open-ended design process (Fig. 4.24).

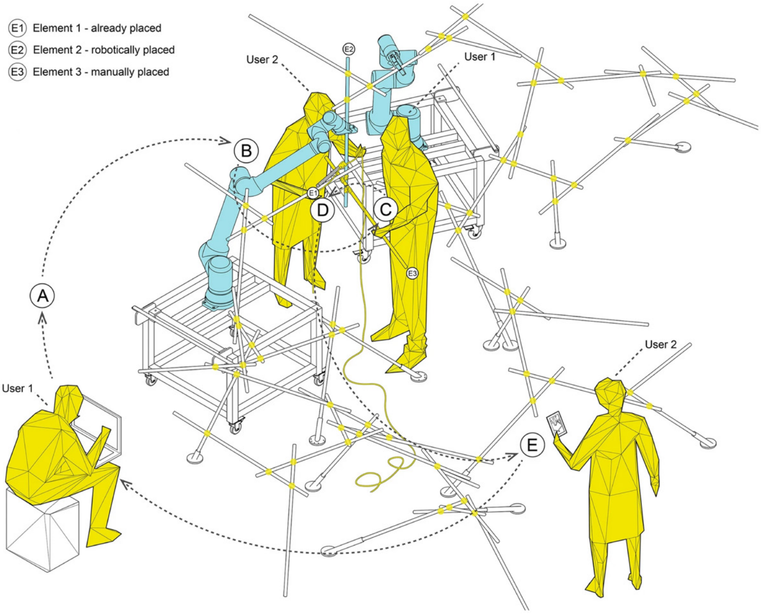

Figure 4.23: Overview cooperative assembly cycle, consisting of five main components (A) interactive design, (B) robotic assembly, (C) manual assembly, (D) rope jointing, (E) tracking of elements

Collaboration and task distribution

A meaningful task distribution between humans, robots, and computational processes should fit the unique strengths of the cooperating agents. Based on the known set of higher level actions (i.e., planning, picking, placing, stabilizing, joining), the assembly process is formulated as a *flexible task shop*. The task distribution is sequence-dependent and incorporates spatial dependencies. The turn-taking task distribution presented in Fig. 4.25 shows the combination of human tasks assisted by follow-up robotic tasks.

Humans perform physical tasks that are difficult for the robot, such as positioning elements that dock onto existing structures and tying knots. Humans also perform cognitive and intuitive tasks such as spontaneous design decisions and adjustments, as well as the digitization of manually placed elements. The robots perform precise spatial operations, i.e., spatially complex pick-and-place routines, as well as structural stabilizations to aid in assembling the Y-triplets as fully stable configurations, which is a difficult task for humans. A continuously updated digital model is necessary to enable a mutual distribution of tasks between humans and robots. Human actions, such as manually assembled elements, must be digitized and fed into the digital model to enable a direct reaction of the cooperating robots. We use and compare two different methods of digitizing human actions; an inertial visual object tracking method using the mobile AR device and a point-to-point localization method using the robots (refer to Section Cooperative assembly logic for more technical details).

Material system

Timber struts: As building elements, we use timber struts with a length of 1000 mm and a radius of 20 mm. Three interconnected timber struts form a Y-triplet, and multiple interlocking Y-triplets define a reciprocal space frame (Fig. 4.26). The first timber strut in a Y-triplet is built-up from an already placed space frame (E1), a robot assembles the second strut (E2), and a human assembles the third strut (E3). Timber struts touching the existing context, i.e., ground or walls, are fixed with 3D-printed flexible joints.

Rope joints: To join the interconnected timber struts, rope joints are used. The advantages of rope joints are that they are reversible, lightweight, and flexible, allowing for a higher error margin during construction. Furthermore, the flexible connection by rope avoids the cutting and opening of holes in the material, which would weaken their cross-section. However, a rope joint connection requires a high level of dexterity in placement, making this method of joining very difficult to be carried out by a robot. Therefore, this task is assigned to be carried out by humans. In this research, we use the *God's Eye* rope joint (Fig. 4.27). This joint is typically used in basket weaving to join a pair of sticks together. We chose it because the knot can easily be converted to cover whole surface areas and can be used to define different spatial articulations. Different colors of thread were used to indicate the origins of the assembly, whether one strut was placed manually or robotically.

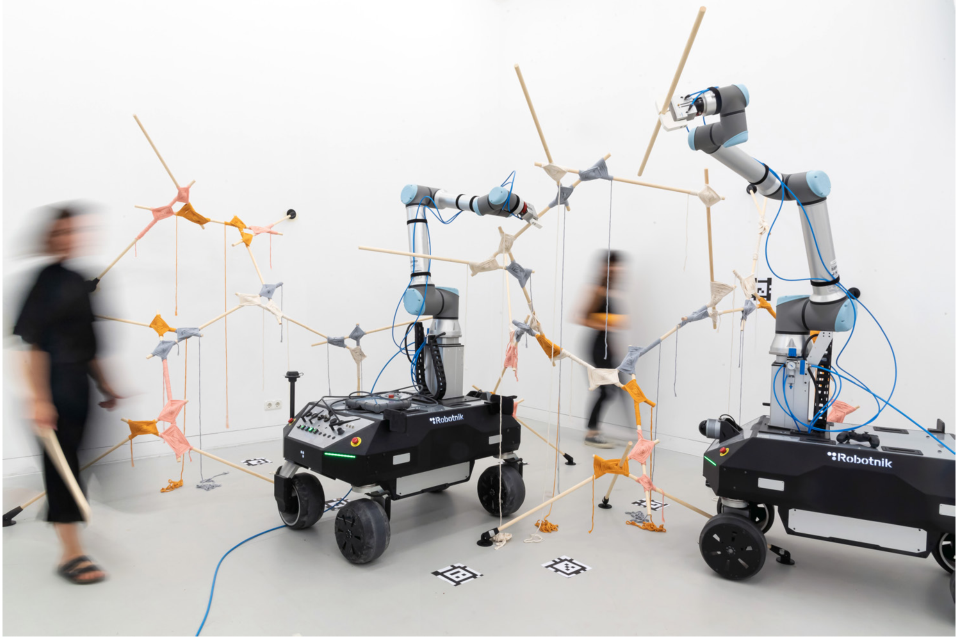

Figure 4.24: Proof-of-concept prototype to test the system's design principles and workflow

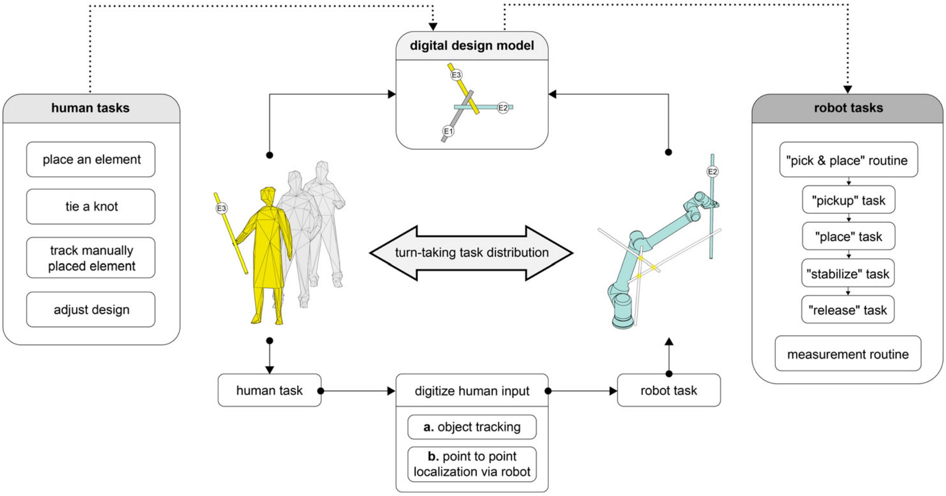

Figure 4.25: Turn-taking task distribution between humans and robots

Cooperative assembly logic

As previously introduced in the Overview Section, the assembly logic incorporates five main turn-taking tasks distributed between humans and robots. These tasks are (A) interactive design, (B) robotic placement, (C) manual placement, (D) rope joints, and (E) registration of manually placed elements, comparing the use of (E1) a mobile AR device for automatic registration, and (E2) a robot's measurement tip for manual registration of manually placed elements (Fig. 4.28).

A) Interactive design: The interactive design environment builds upon algorithmic modeling methods open for user input during assembly. The computational logic of the interactive design model is based on the *Assembly Information Model*, which expands on a serializable network data structure available through the open-source Python-based *COMPAS* framework [62] within *Rhinoceros* and *Grasshopper*.

In the assembly model, each discrete element (strut) is stored as a node in a graph data structure. The edges of the graph represent the connections between the elements whose spatial arrangement is organized within global and local design rules. Three elements are combined into a Y-triplet featuring three connection options located on its open ends, referred to as connectors. Each connector is stored in the node's attributes as a frame, describing the position and orientation of the following triplet and a corresponding Boolean variable indicating whether the connector is closed or open. Therefore, each element in one already assembled triplet has one open and one closed connector.

At each assembly cycle, humans can interactively generate design options abiding by specific local and global design rules, influencing the growth direction and geometry of the overall structure. To define growth direction, the user freely picks a starting element in the CAD environment that is an already-built element in the structure (Fig. 4.29—E1). After picking the first built element, the user visualizes the corresponding two elements to complete the Y-triplet and specifies their

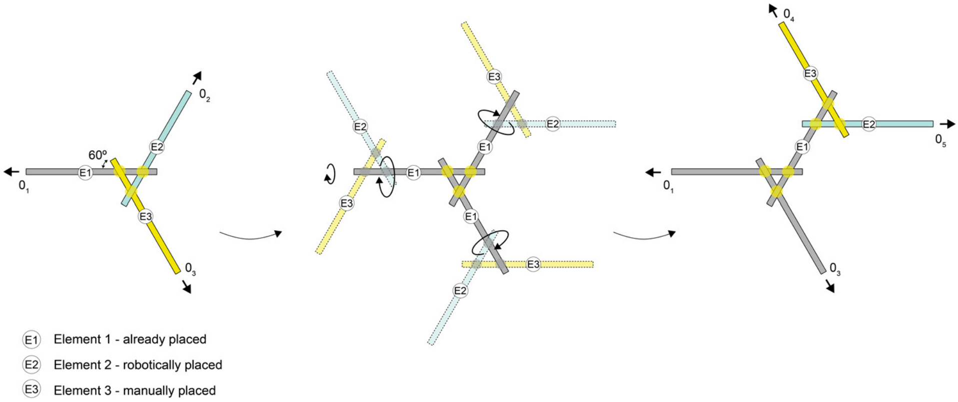

Figure 4.26: Reciprocal space frame structure from interlocking struts, referred to as Y-triplet

rotation angle around the starting element. After that, the user chooses which element will be placed robotically (Fig. 4.29—E2) and which one manually (Fig. 4.29—E3). The visualized position of the third element, which will be placed manually (Fig. 4.29—E3), is used only as guidance. Its actual position will be chosen by the human when being manually placed and updated in hindsight through registration.

B) Robotic placement: After the user decides on the first element of a triplet (E1) upon the preview of the computed consecutive two elements (E2, E3) in the CAD design environment, the robot is used to place the next element (E2). The robotic assembly requires the calculation of a valid and collision-free trajectory for the associated pick-and-place routine according to the current robot's location in the workspace. We use *Grasshopper* and the *COMPAS FAB* library in combination with the *MoveIT* motion planner for the robot's trajectory planning. Each already placed strut, the mobile platform of the robot, and the robot manipulator are uploaded as collision objects to the planning scene, allowing for trajectory planning and taking the collision objects of the workspace into account. After computing a valid trajectory, the user sends the planned pick-and-place routine (target frames, IO control, and robot parameters) via a custom TCP/IP connection from the CAD design environment to the robot. Following, the robot picks up the wooden strut from the picking station, drives into a safe position, and then toward the target position. After the successful robotic placement of the consecutive element, the robot stabilizes the element in place, waiting for the third element to be manually placed and joined into a stable reciprocal frame configuration.

Since the robots are mobile, they can be remotely controlled by humans within the workspace and always moved to where they are needed. Therefore, after each movement, the robots must be localized in relation to the assembled structure. Reference points with known coordinates in physical and digital environments are used for their localization, which are first probed manually with the robot's measurement tip and aligned with an iterative closest-point algorithm (ICP) to estimate the robot's position.

C) Manual placement: After the second strut has been placed and the structure is stabilized by the robot, the human places the third element (E3). The aim is to complete the triplet, with respect to the local design rule, and thus close the structural triangle in the overlapping area

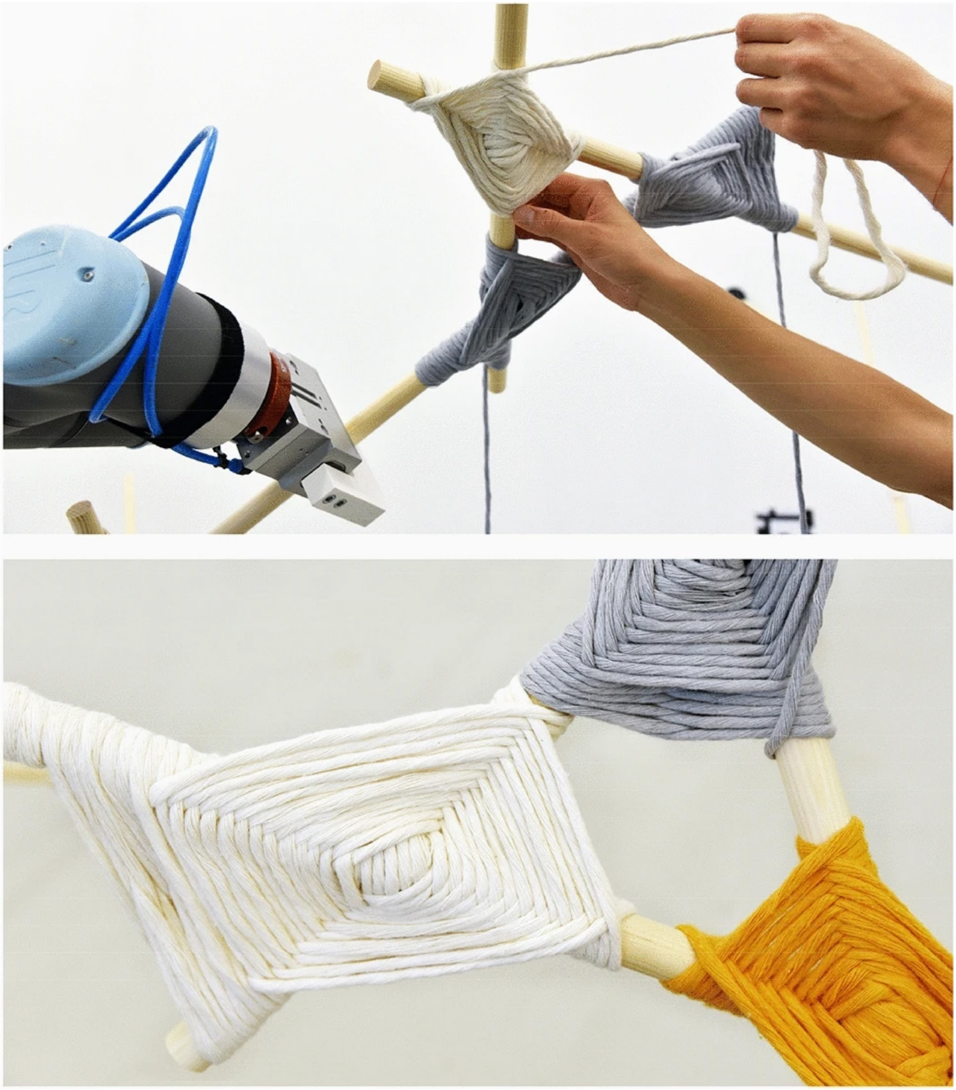

Figure 4.27: ***God's Eye*** **rope joint**

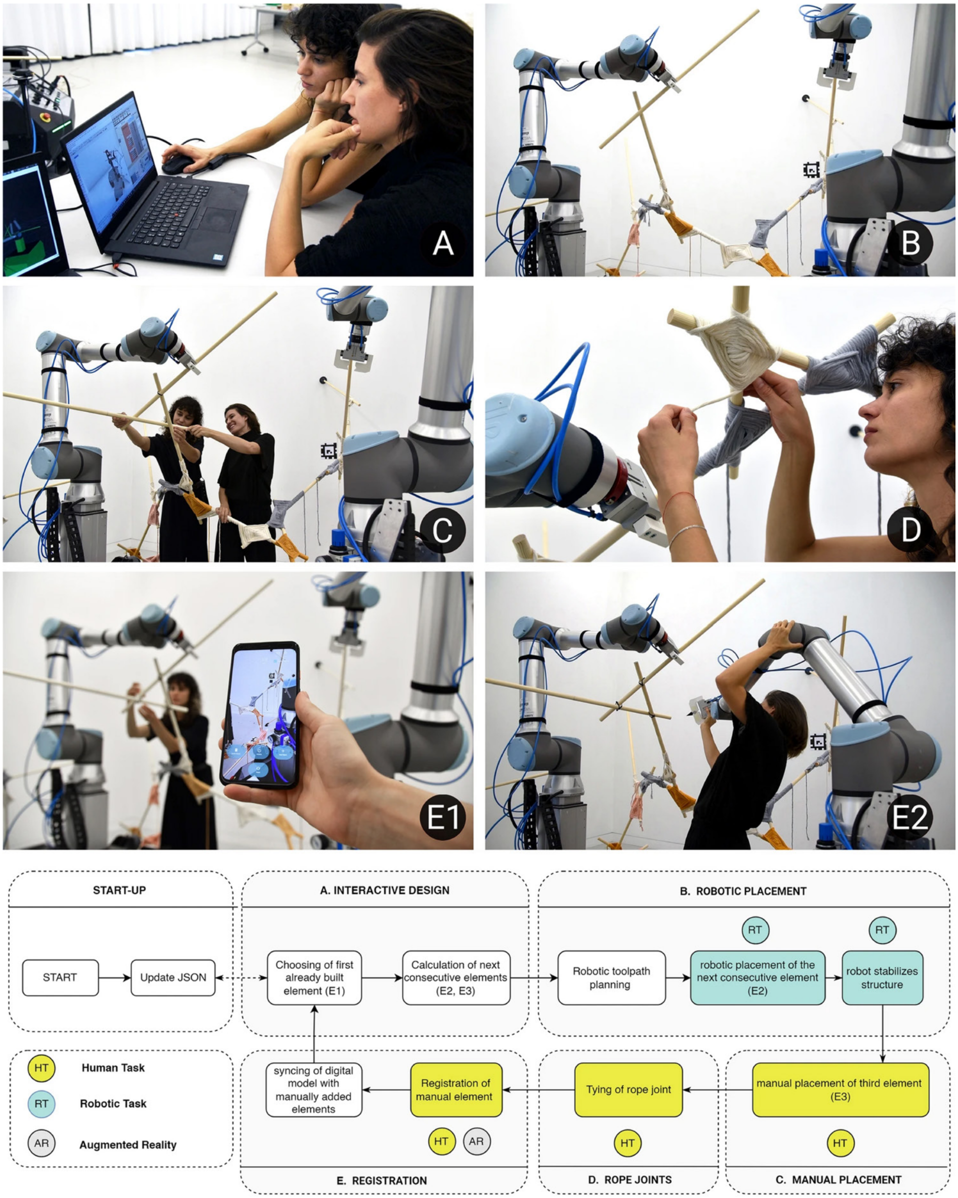

Figure 4.28: System walkthrough: (A) interactive design, (B) robotic, (C) manual, and (D) rope joint placement (E1) tracking with the phone, (E2) tracking with the robot

Figure 4.29: The user interface of the interactive design model provides input controls for selecting a starting element for a new triplet and defining the triplet's rotation angle via a number slider

of the three elements. When placing the third strut manually, the humans can test the ideal position for the element to stabilize the whole space frame. They can consider structural options, such as expanding the structure toward the floor or walls if needed. Furthermore, humans can interactively change spatial articulations of the structure, such as densities and openings of the space frames.

D) Rope joints: After finishing the manual placement, the second user connects the struts and places all three rope joints. During assembly and joining, a robot always stays in position to stabilize the structure until the next Y-triplet is built or equilibrium is reached. The other robot not used for stabilization is free to be used for further assembly of the structure.

E) Digitization of manual physical interventions: Before choosing the next Y-triplet, the manually placed strut needs to be registered in reference to the already built structure. The user has two options for registering the exact position of the strut.

The first (automated) option is via a custom AR-app on a mobile device. The AR-app uses the visual-inertial object tracking software by *incon.ai* in combination with message-passing capabilities allowing for information exchange with the CAD design environment. The tracking system uses edge detection to detect the position and orientation of the struts in relation to known geometry and pre-registered QR-Codes. For further technical details and implementations of the *incon.ai* software, refer to [59]. The message-passing capabilities are further explained in Sect. 3.5. After registration, the AR-app updates the digital model with the as-built data and adds the strut to the assembly model.

The second (manual) option is via the robot, where reference points are manually probed and used to fit the strut geometry. This registration is achieved by probing four points on the wooden struts required to define their exact position and rotation. Consecutively, the tracked location is sent to the digital model to update it with the as-built data.

After registration and syncing of the digital model with manually added elements, the user can pick the next Y-triplet to continue building and initiate a consecutive robotic action. The assembly cycles are repeated until the structure is finished (Fig. 4.30).

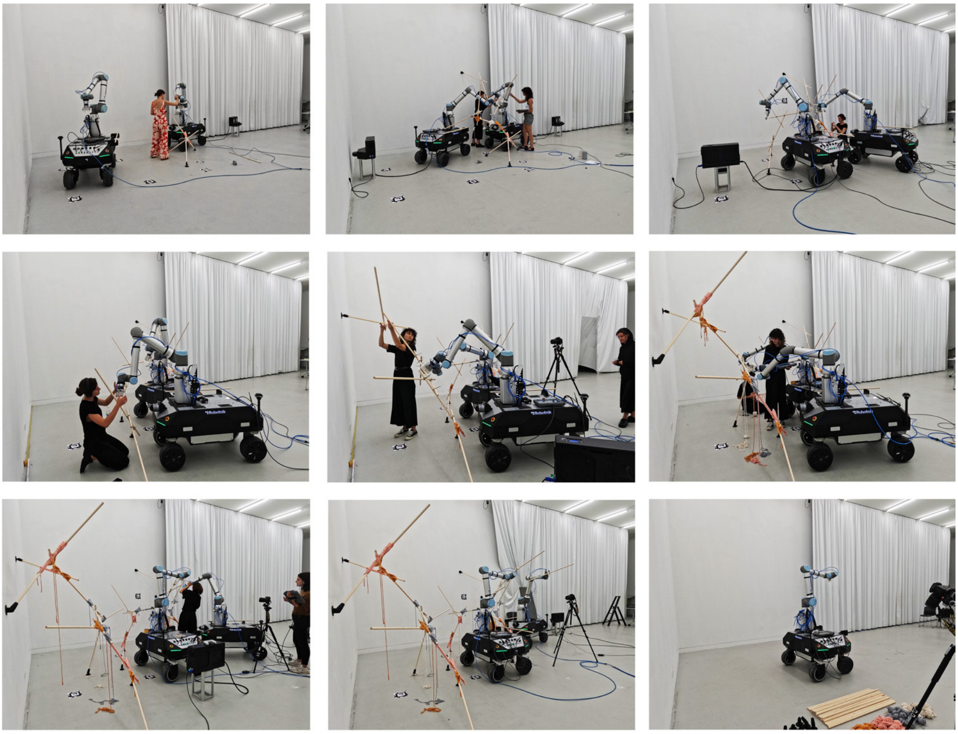

Figure 4.30: Time-lapse recordings of assembly and disassembly of the experimental prototype

System architecture

The system architecture consists of a hardware setup (Fig. 4.31) and a communication system (Fig. 4.32) that allows for interoperability between all devices used in the experiment.

Hardware setup: The hardware setup consists of two 6-DoF cooperative robotic arms *(UR10e)* with custom 3D-printed pneumatic grippers. To extend the working space of the *UR10e*, the robots are placed on mobile platforms, allowing humans to reposition the robots manually. Each robot has a timber strut pick-up station to collect wooden elements. For the mobile AR device, we use a *Google Pixel 4*. The hardware used for communication between all devices includes a *Linux PC* and a *Windows PC* used to run the interactive design model.

Communication workflow: A necessary component for an augmented human–robot cooperative process is a scalable communication system for connecting multiple devices and back-end compu-

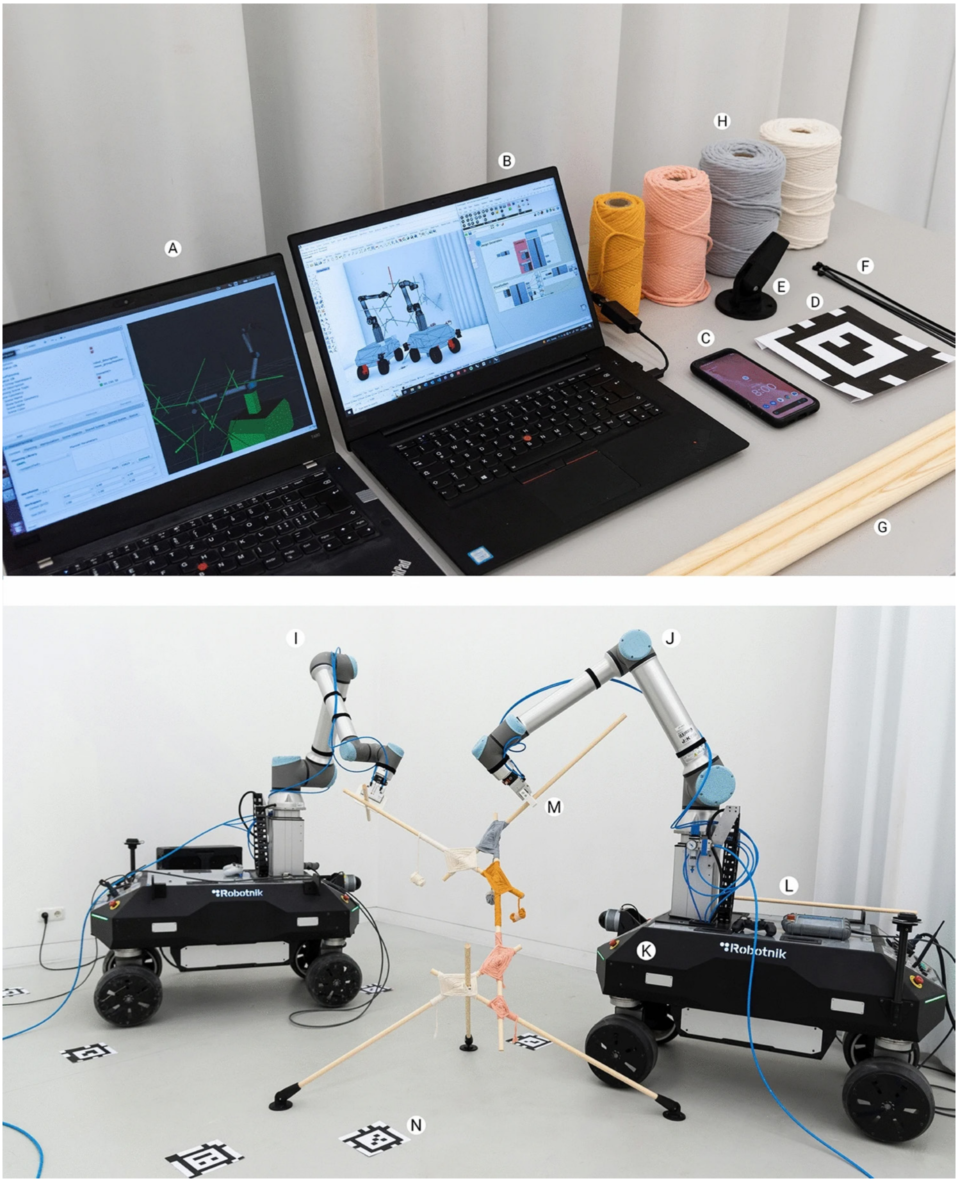

Figure 4.31: Hardware setup of the system. (A) *Linux* computer, (B) CAD computer, (C) mobile AR-device, (D) QR-codes, (E) adjustable 3D printed feet, (F) zip-ties, (G) wooden struts, (H) wool, (I) robot 1, (J) robot 2, (K) mobile platform, (L) timber strut pick-up station, (M) pneumatic parallel gripper with custom 3D printed gripper fingers, and (N) measured-in fix points (QR codes)

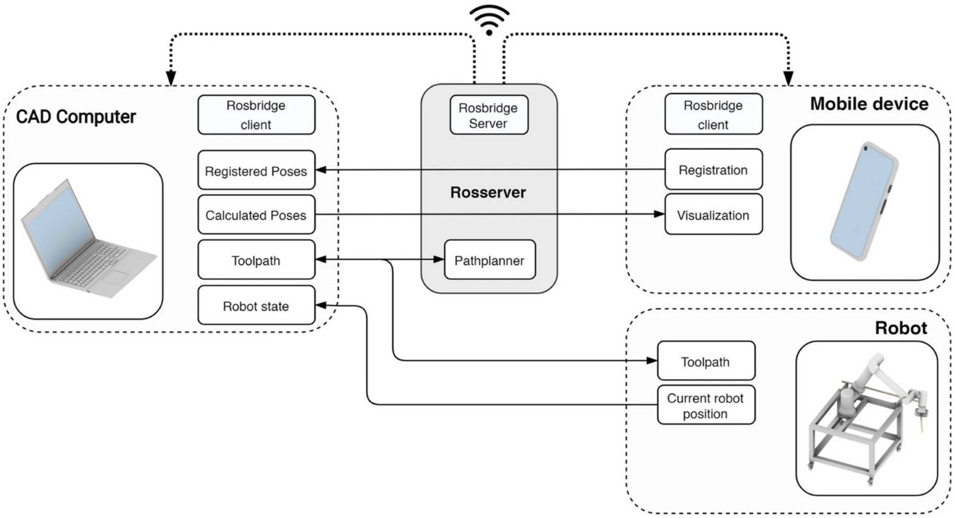

Figure 4.32: Communication workflow diagram showing the system setup consisting of 1) a computer with a CAD design environment, 2) a mobile AR-app, and 3) a robotic unit

tational processes, which in this case is achieved utilizing a ROS publish-and-subscribe architecture and the rosbridge package [99]. Here, the *ROS system* architecture connects all devices (Fig. 4.32), the AR-app, the interactive algorithmic model, and the *MoveIT* simulation. The AR-app is a custom version of the *incon.ai* software, providing visual inertial object tracking while also providing *ROS* functionalities such as the publish-and-subscribe architecture and data structure. The *Linux PC* runs the *ROSmaster*, the *rosbridge server*, and the *MoveIT* simulation. The second PC runs the interactive design model, which uses Python, *COMPAS*, and *Grasshopper* and visualizes the data structures within *Rhinoceros*. As depicted in Fig. 11, the computational units and the AR devices are connected via WIFI to the same ROSmaster and rosbridge server. A direct TCP/IP communication is established between the CAD environment and the robots.

At the beginning of a work session, the user uploads the initial assembly model as JSON into the CAD environment and publishes it via *ROS service*. The mobile AR-app subscribes to this service via the *rosbridge server*. Once the CAD design environment and the mobile AR-app are in sync, the uploaded assembly model is visualized on the AR-app. The user can initialize the object tracking when the assembly model aligns with the physical model. After a new element has been tracked and registered, its position and orientation are published via the *ROS topic*. The CAD design environment subscribes to this *ROS topic* and updates the digital model of the assembly with the received as-built data. In a consecutive step, the next assembly cycle can be initiated, that is, Y-triplets can be calculated and published again via a *ROS service* to sync the AR phone.

Results and limitations

We tested and validated our computational setup and assembly strategy by producing a proof-of-concept prototypical architectural structure over a period of 5 days. The floor area of the prototype was 6 × 4 m. As described in Section Cooperative assembly logic, two humans

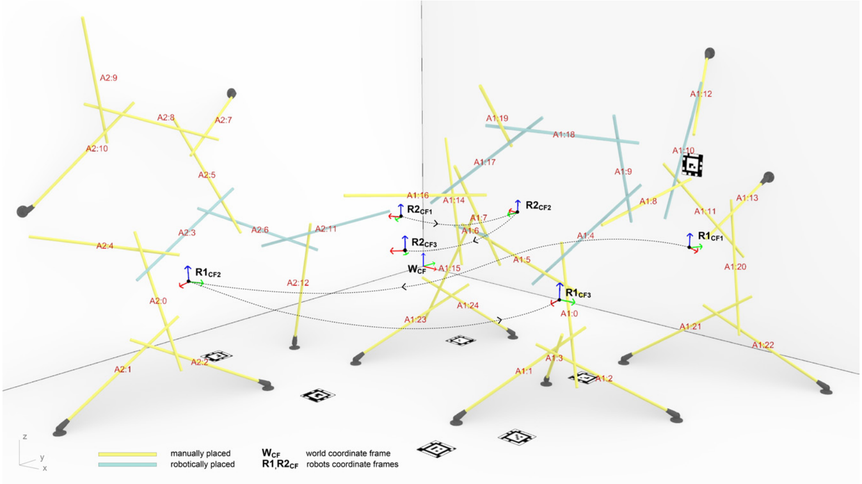

Figure 4.33: Screenshot of the digital model showing in blue the robotically placed elements and in yellow the manually placed elements

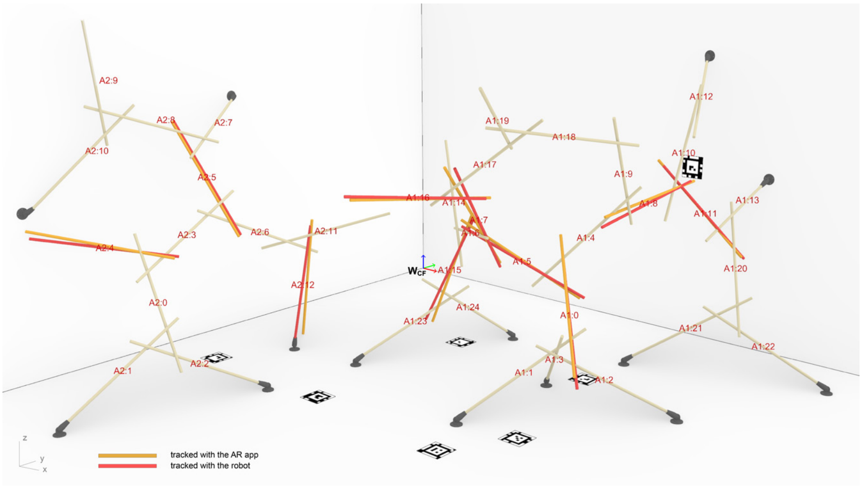

Figure 4.34: Different tracking results of manually placed elements: orange: tracked with the AR-capable phone, red: tracked with the robot

in collaboration with two mobile robots cooperatively and interactively assembled a wooden structure in turn-taking actions. The hybrid human–robot assembly process was initialized with three pre-assembled elements fixed to the ground. A total of 38 wooden struts were assembled, of which 29 were manually placed and tracked by a user. Nine were placed by the robot (Fig. 4.33).

The design setup focused on the space frame logic due to the inherent rigidity of the triangle. Rope joints connected the different elements of the triplet. Over the period of 5 days, we placed 53 knotted joints, and the whole structure was disassembled within two hours (Fig. 4.30).

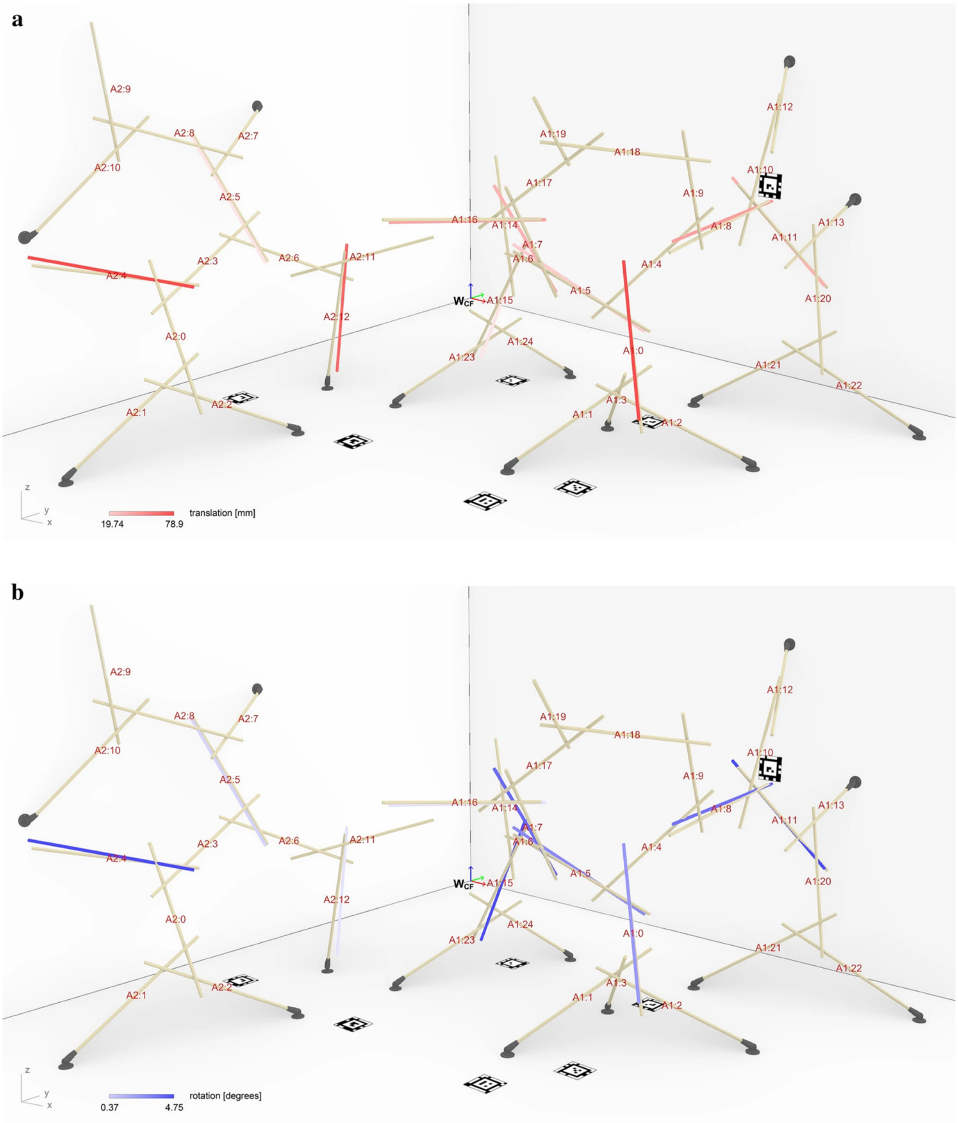

Figure 4.35: a The color gradient (red for translation) visualizes the deviation between the tracking results of the AR-app with those from the measurement executed with the robot. b The color gradient (blue for rotation) visualizes the deviation between the tracking results of the AR-app with those from the measurement executed with the robot

In this experimental study, more struts were placed manually than robotically because many connections to the walls and floors were required as "special scenario struts" to ensure structural stability. 10 of the 29 manually placed struts were registered with both the app and the robot. Not all manual struts were registered because only those used to continue the assembly robotically were tracked and included in the physical-digital model (Fig. 4.34). Another eight struts were registered during assembly as the structure deformed over time, and an updated version of the struts was required to continue a precise building process. The tracking discrepancy between struts registered by the AR-app and the robot was measured by comparing the registered element frame located in the center of the cylinder; the tracking discrepancy ranged between 19.74 and 78.9 mm positional difference and 2.81 degrees to 7.83 degrees rotational difference. The color gradient in the error plot (Fig. 4.35) indicates these deviations. The registration via visual inertial object tracking reached its technological limits due to the distinct geometry of the struts. The long and thin wooden struts were not ideal for edge-detection-based algorithms as they were only marginally constrained in one direction, which led to a shift along the strut's axis of the digital model. The alternative registration method of the manually placed struts using the robot's manipulator for probing reference points fulfilled the accuracy requirements. However, both methods proved to be time-consuming to use.

Discussion

Human–robot cooperation

This experimental study has explored how the combination of manual and robotic actions might open new opportunities for future crafts and lead to new workflows for human agency in robotic construction. Examples of such human agency are tasks that are difficult to be carried out by robots. In this experiment, for example, such a task refers to the joining of the wooden elements using ropes. Most joining processes in robot manufacturing have focused on systems that can be automated and avoid such complex connections. On the contrary, *Tie a knot* is characterized by the intentional incorporation of manual joining techniques into robotic processes, thus aiming to combine advanced robot-based methods with traditional craftsmanship knowledge. In addition, such human agency is also reinforced by the fact that the system presented is designed so flexibly that spontaneous design decisions and adjustments are made possible. The flexibility of a system to be open to spontaneous changes is particularly important for special situations, for example, when the elements have to be attached to the floor or the wall. However, a prerequisite for featuring such flexibility in a robotic construction process is the ability to continually feed human-induced changes into a digital model, here presented as the shared digital-physical workspace.

According to Shi's categorization [100], our system falls into the category of human–machine cooperation because it supports an intermediate level of human–machine collaboration. Both cooperating entities, humans and robots have the autonomy to achieve a common goal and to make use of the knowledge and skills of the other system. Both entities share the same workspace, and the human interacts directly with the robots in their workspace. The human assembles and joins the elements synchronously, while the robot holds single elements and thereby stabilizes the overall structure. Currently, the robot's position relative to the human's position cannot be detected. Therefore, the robot did not continue the next pick-and-place task until the human initiated it and moved outside the robot's workspace. Tighter and more responsive sensor systems would be needed to enable parallel task execution with humans within the workspace.

Potential for future work

Tie a knot incorporated complexity on multiple levels involving mobile robotic systems, structures that deform over time, and non-predefined design. These systems require continuous localization of the robots, tracking of built elements over more extended periods of time, and registration of manual physical interventions. Currently, only a relatively small architectural installation was fabricated with the workflow and tools developed here. Future research aims to assemble a larger scale structure to test a broader range of spatial articulations. As scale increases, more robust computational support needs to be implemented for humans to guide decision-making processes, i.e., intelligent computational processes capable of observing, predicting, and controlling quantifiable performance targets such as structural stability and robot range. Such a real-time structural analysis would be required to ensure that spontaneously made decisions are statically valid, also considering future load cases.

Furthermore, the automatic object tracking workflow and implementation needs substantial modifications and improvement. Future development needs to combine and automate the same object tracking for manually placed objects with the tracking system for locating the mobile robots in relation to the built structure. Additionally, it is critical to speed up the tracking of manual changes made to the built structure.

Regarding the AR interface, in the future, we will focus on the visualization of additional data such as design possibilities, robot reachability, and robot toolpath simulation, which will be shown overlaid on the physical world. AR could also be used in the future to inform people about the structural feasibility of currently selected options. These spatial visualizations could better support people collaborating to make more informed design decisions.

Conslusion

Instead of supporting a workflow that is object and end-product-oriented, *Tie a knot* furthers the idea that traditional craft fulfills a deep-seated human need for direct engagement with material production [101]. The workflow developed here allows for intuitive interaction and direct tacit engagement with the material and process, thus deviating significantly from linear design-to-production workflows. At the same time, back-end computational processing combined with highly precise tracking algorithms provides new possibilities for human augmentation.

While it is common to include human collaborators in semi-autonomous processes, in which the human undertakes specific tasks such as manually loading the robot's material, placing and tightening joints, or manually drilling robotically placed elements, in these processes, human interaction is not linked with a digital model and happens outside supervision. In our workflow, human interventions are used strategically for decision-making, corrections, and tacit engagement with a physical process, while still being assisted by computational logic assuring quality.

Tie a knot is a system that allows humans to negotiate the levels of task distribution and coordination and thereby reinvent the fundamental relationship between humans, skilled workers, and designers—machines and robots. Such a system reinforces human agency by increasing the social sustainability of automation, allowing humans to make decisions throughout fabrication procedures and interactively decide on task distribution. This workflow enables explicit machine intelligence (parameters, work range, structural boundary conditions) to be integrated with implicit human knowledge (creativity, intuition, fast reaction to complex situations), thus enabling a new cooperative workflow and building strategy. These cooperative strategies could be harnessed to extend robotically automated workflows to materials and construction scenarios that have resisted automation, including unpredictable and unstructured material processes or working within complex existing building structures. In such cases, humans could actively intervene, physically or cognitively, supporting or steering automated processes toward higher levels of robustness and efficiency in complex or unforeseen scenarios.

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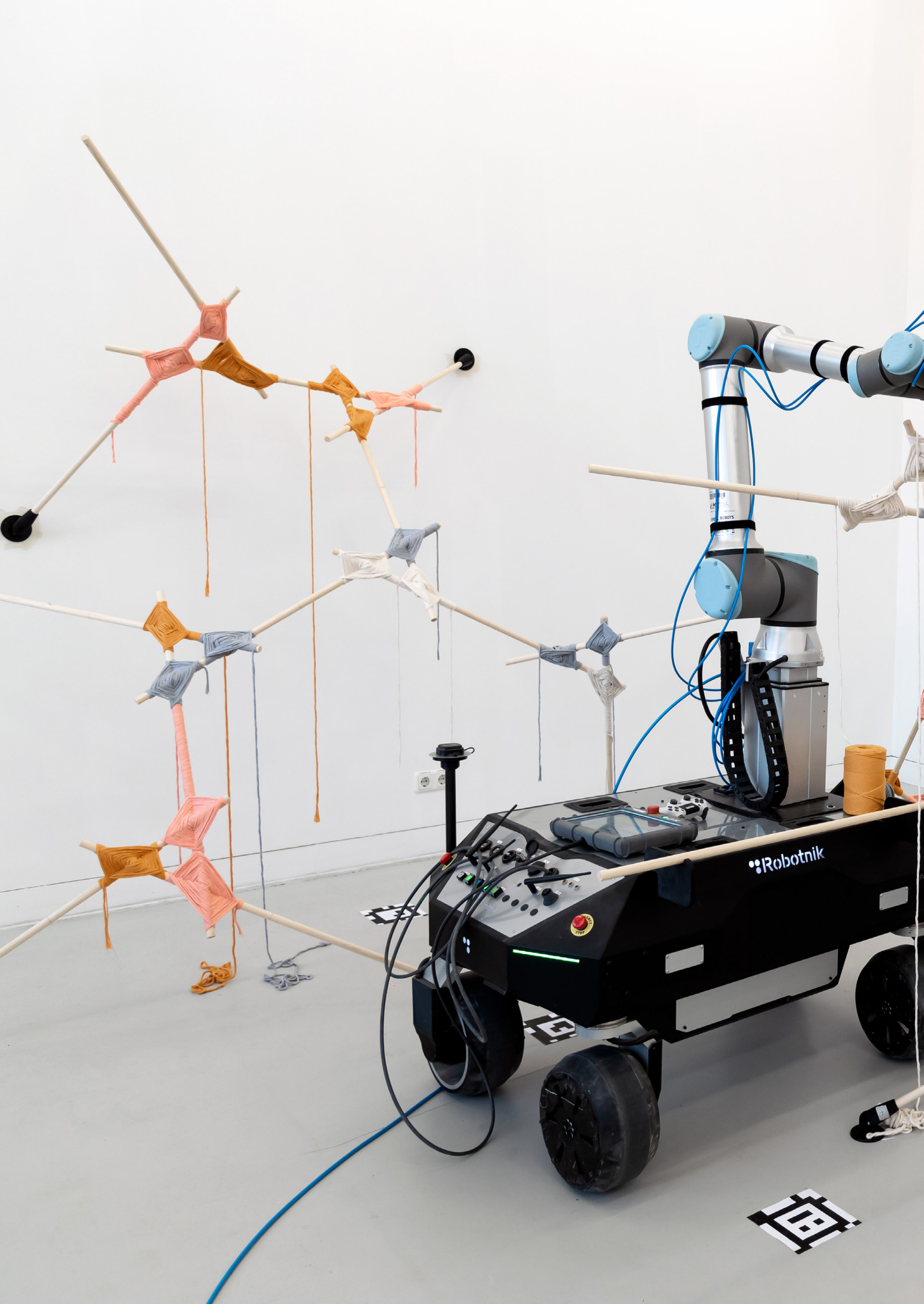
4.3.3 Author's contribution

The contributions by the author of this thesis to the realization of this case study can be summarised as follows: The author led the computational design development, including the extension of the *assembly grammar* to enable the generation of more complex spatial modules and to incorporate turn-taking task assignments and execution between humans and robots. The AM was further extended by the author to encode task assignments for two robotic agents and to represent human task assignments, facilitating coordinated interaction within a shared assembly process. The author also implemented the interface between the AM and the robot path planner and integrated the robot control interface into the system. In addition, the author co-conceived and implemented the architectural application scenario and collaboratively designed the full-scale physical prototype alongside the first author of the publication.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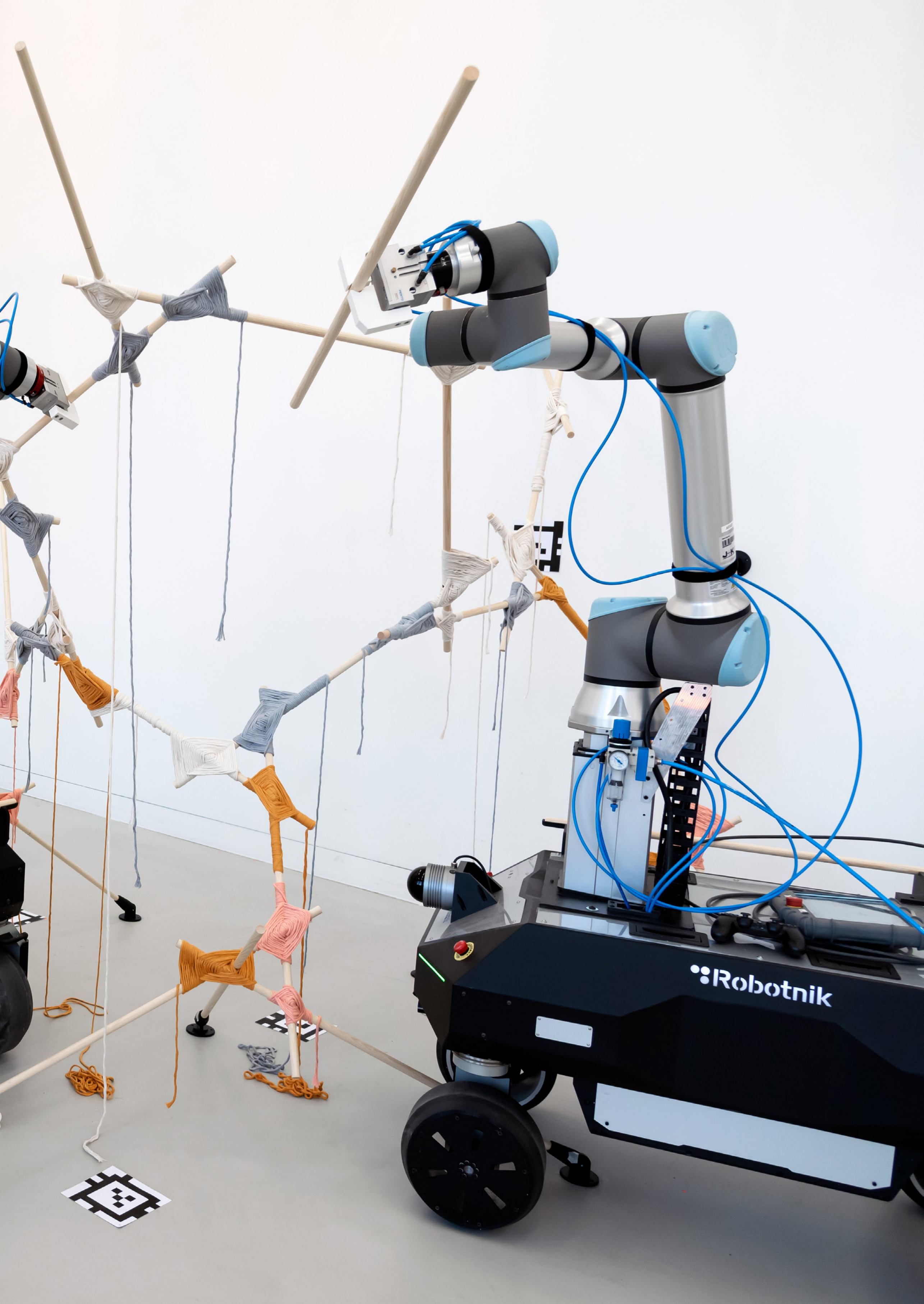
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4.4 Case Study 3: Multi-human-robot cooperative assembly

4.4.1 Summary and contribution to the thesis

This final case study contributes to the thesis by proposing an integrated, fabrication-aware approach to human–robot cooperative assembly that combines computational design, planning strategies, and coordination mechanisms in real-world construction scenarios. It presents two experiments involving full-scale timber assemblies carried out by human–robot teams operating within shared digital–physical workspaces. These workflows arechat supported by an extended AM that encodes geometric, topological, and procedural data, including task assignments and agent-specific actions. The study introduces a workflow in which task distribution is embedded directly into the design logic, enabling real-time adaptation and coordination between human and robotic agents. Task logic and construction state are accessed through external interfaces, including a custom mobile AR application used to visualize fabrication data and guide local decision-making. Human and robot actions are executed in turn-taking cycles based on sequencing rules, geometric constraints, and dynamic state updates. The system was validated through two full-scale construction experiments involving two human participants and two mobile collaborative robots. The system was tested through full-scale construction experiments designed to evaluate its capacity to support adaptive, sequential cooperation in multi-agent workflows under varying geometric and structural conditions. This case study directly supports the four research objectives of the thesis by advancing adaptive design-to-fabrication workflows, formalizing computational models for human–robot participation, evaluating coordination strategies through AR-mediated interfaces, and validating the proposed system in real construction scenarios.

This section has been published as:

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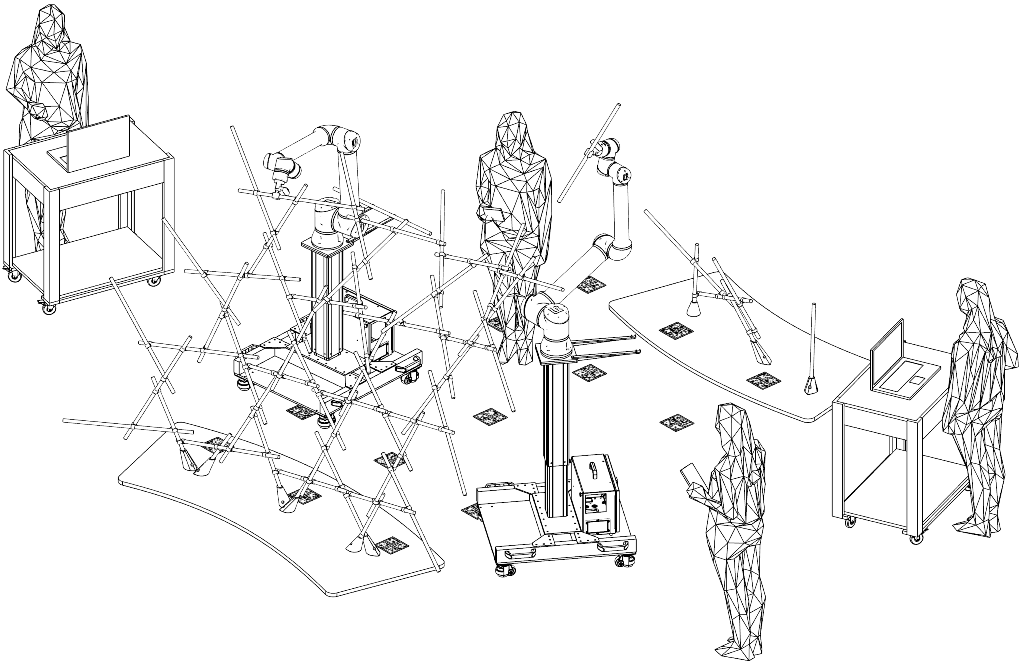

4.4.2 Publication

Building (with) Human-Robot Teams

Fabrication-Aware Design, Planning, and Coordination of Cooperative Assembly Processes

Lidia Atanasova[1], Joseph Kenny[2], Eleni Vasiliki Alexi[2], Frederic Chovghi[3], Daniela Mitterberger[2], Kathrin Dörfler[1]

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 structures for 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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Introduction

Recent years have seen significant technological advancements in robotic assembly systems, both in prefabrication settings [1], [102] and through in-situ fabrication scenarios [2], [14]. 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 [11], [103] 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 [11] and constantly adapt their plans. As a result, many construction tasks remain challenging to automate and are likely to continue relying on manual execution [13]. 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 [11]. 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 [104]. As the adoption of robotics and automation continues to grow, their successful implementation will increasingly depend on effective human–robot collaboration (HRC) [35].

The classical manufacturing domain has developed sophisticated HRC methods for assembly tasks [4], including collaborative strategies where humans and robots share workspaces for hand-over tasks, sequential operations, and synchronized movements [5]. These approaches are supported by advanced interaction interfaces, from gesture-based control to augmented reality (AR) task guidance [6], [7], and have been implemented in both single- and multi-robot applications [8], [9]. However, despite these developments and their successful integration with humans [7],, 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 [105]. Robots must navigate through constantly changing spaces rather than remain in fixed positions, avoiding temporary obstacles and adapting to varying ground conditions [106]. Materials and tools are often scattered across the site instead of being systematically arranged in predefined locations, requiring flexible logistics and handling strategies [103]. Moreover, the scale of construction and payload requirements for construction tasks further distinguish construction from the manufacturing domain [105], with elements often being too large or heavy to handle and requiring careful consideration of structural stability during assembly [27]. 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

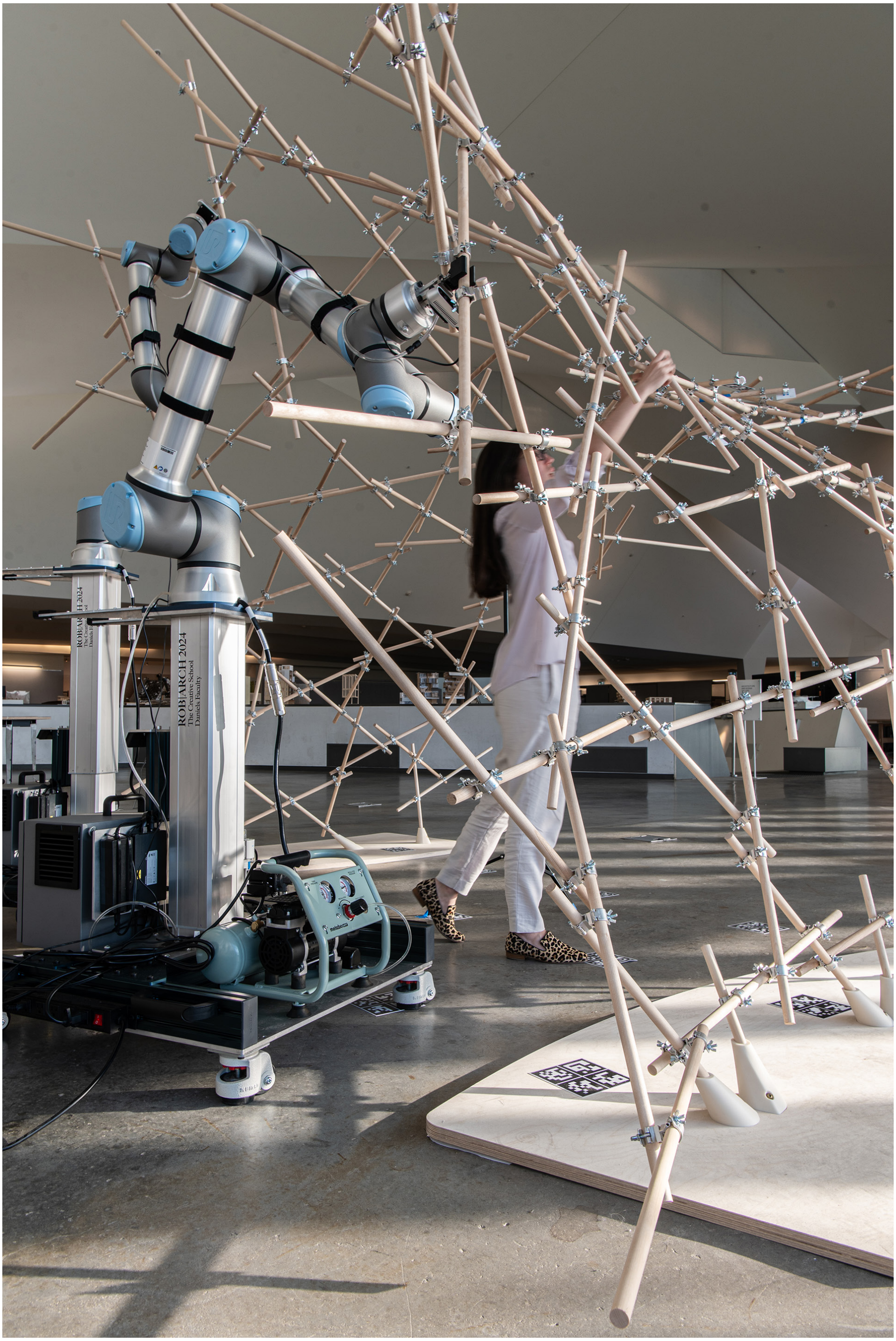


Figure 4.36: Human-multi-robot cooperative assembly of a timber structure

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. 4.36).

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. This builds on our research on multi-user augmented reality for collective assembly [107]and hybrid human–robot cooperative assembly [108], 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 Background 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. Methods. Section Case Studies and results describes the experimental case studies and the achieved results, followed by the discussion, limitation and future work in Sect. Discussion and conclusions in Sect. Conclusions.

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. Multi-agent assembly processes, 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 Design for assembly and graph-based modelling then explores the Design for Assembly principles and their adaptation for HRC, particularly emphasising fabrication-aware design in architecture. Finally, Sect. Planning and coordination methods for multi-agent assembly 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.

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 manoeuvres among robots to expand the capabilities of a single robotic agent [3], [23]. Such approaches have shown the scaffold-free assembly of complex geometries, including brick vaults [25], [27], [28], and discrete shell structures [29]. 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 [49]. 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 [109].

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 [90] and Tie a knot [89] 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 [34], [36], digitally instructed human-human collective assembly [107], and investigations into human-robot collaboration (HRC) in timber prefabrication [35]. These approaches have been tested through simulation studies for various construction tasks, including drywall installation, painting, bolting, welding, and concrete pouring [110]. Proof-of-concept implementations like CRoW [32] and prefabrication scenarios proposed by iHRC [33] 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.

Design for assembly and graph-based modelling

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 [37]. 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 [111]. 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 [38]. 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 [39] as detailed in Section Planning and coordination methods for multi-agent assembly, 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 [47], and describing robotic prefabrication processes through actions, tasks, and jobs [48]. 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 [41], [42]. These computational methods incorporate fabrication and construction constraints directly into the design phase, such as for the shape-creation process [43], 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 [44].

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 [45]. 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 [46].

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 [19] 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.

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) [112] decompose complex assembly operations into manageable subtasks with defined dependencies, enabling systematic planning for multiple agents. Behavior Trees (BT) [113], 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) [114], 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 [50]. 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 [49].

Task-based segmentation has emerged as a promising approach for managing complex multi-agent fabrication workflows. In prefabrication settings, Skoury et al. [51] 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. [33] 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 [61].

More flexible coordination approaches have emerged through our previous research on collective AR-assisted assembly [107]. 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 [32] 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.

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. Terminology. Following this, Sect. Assembly model (AM) for distributed human-robot assembly 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 Task representation and assignment 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. Fabrication-aware design methodology presents the concepts behind the proposed fabrication-aware design methodology, which serves as the basis for the design tool. Finally, Sect. Task distribution and coordination strategy 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 cooperation between humans and robots.

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 modelling - 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 [115]. 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 [43]. 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.

Assembly model (AM) for distributed human-robot assembly

The proposed methodology introduces a digital data structure - AM - building on and extending *COMPAS Assembly* [47], a data structure developed with the open-source Python framework *COMPAS* [62], designed for managing and storing discrete element models in architectural contexts.

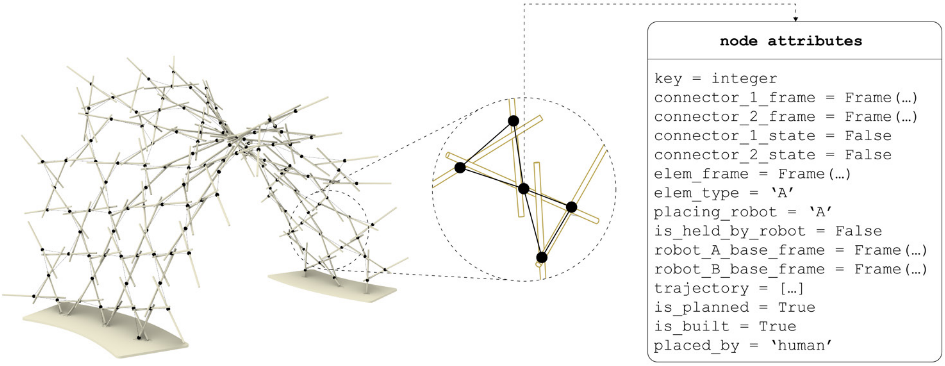
Utilizing graph theory, the AM integrates the *COMPAS Graph* data structure and allows for storing both geometric and topological data, capturing the architectural design and the connectivity and dependencies between individual building components (Fig. 4.37).

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



```
key = integer
connector_1_frame = Frame(…)
connector_2_frame = Frame(…)
connector_1_state = False
connector_2_state = False
elem_frame = Frame(…)
elem_type = ‘A’
placing_robot = ‘A’
is_held_by_robot = False
robot_A_base_frame = Frame(…)
robot_B_base_frame = Frame(…)
trajectory = […]
is_planned = True
is_built = True
placed_by = ‘human’
```

Figure 4.37: 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

interface [108]. 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 Section 4.4.2.

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. 4.38a). This representation encapsulates both spatial relationships and task dependencies required for assembly. By applying topological sorting [116] 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. 4.38b), 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 stabilisation 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 either humans or robots, providing initial flexibility during the planning phase. Table 4.1 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 [115], affordances represent the possibilities for action based on environmental con-

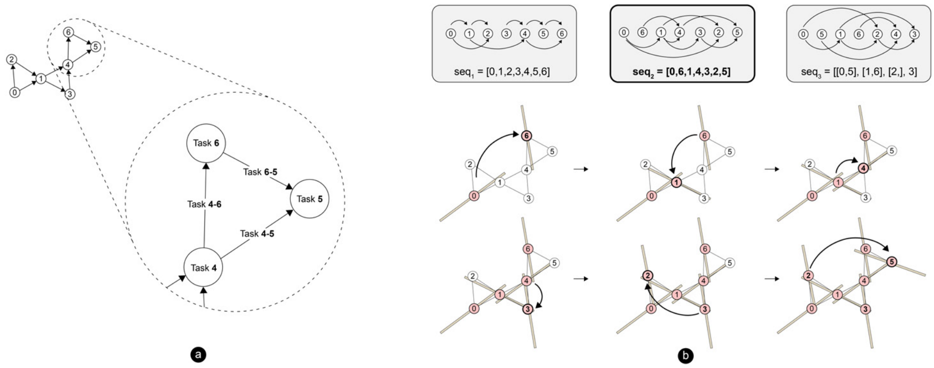


Figure 4.38: Task representation and sequencing: a) The graph represents placement tasks through both nodes and edges, where the edge direction encodes dependencies between tasks. b) The graph's topology enables the generation of multiple valid task sequences

Table **4.1:** List of tasks, their description and assignment based on skills

Task	**Task description**	**Assignment**
Handling	Feeding material to the robot	Human
Positioning	Placement of an element	Robot OR human
Positioning and supporting	Precise placement of an element and temporally supporting	Robot
Joining	Placing connectors	Human
AR operation	User guidance and task verification	Human

ditions 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.

Fabrication-aware design methodology

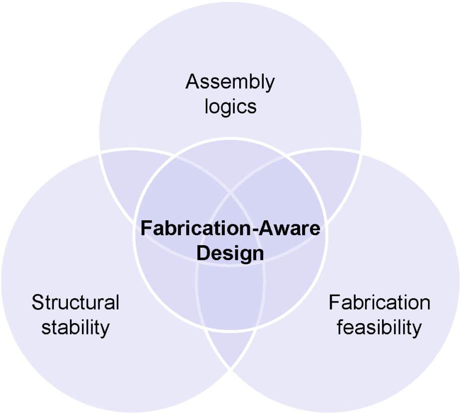


Figure 4.39: The fabrication-aware design methodology integrates assembly logic, structural and fabrication constraints

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. 4.39). 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.

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. 4.40).

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 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.

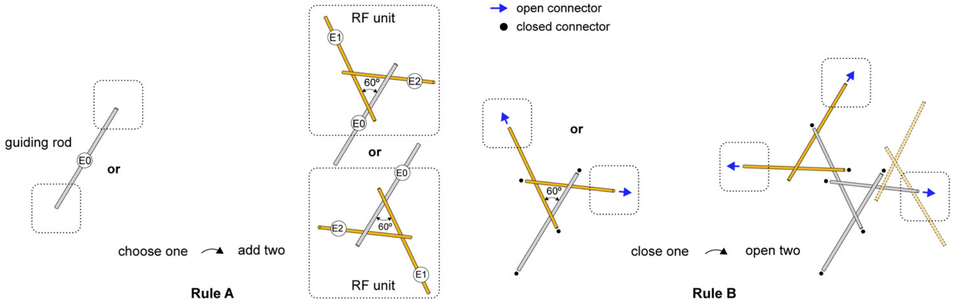


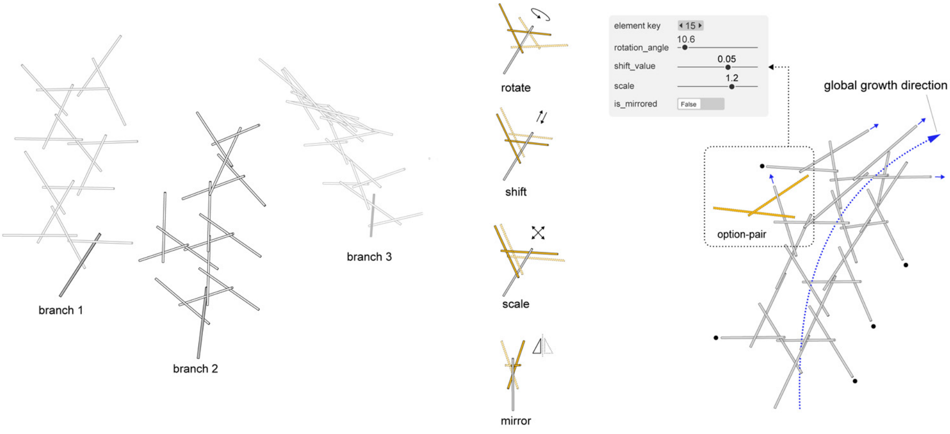
Figure 4.40: The primary rules of the assembly grammar: Rule A - Formation of RF units via overlapping rods by attaching two rods to an existing guiding; Rule B - Structural expansion via open connectors

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 behaviour: 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. 4.41a). The implications of this branching behaviour for design generation, as well as methods for joining branches, are further explored in Sect. Design criteria and constraints.

Directed growth through unit parameters: To achieve greater control over the structure's branching behaviour and growth direction—and to facilitate the joining of branches—a set of unit parameters is introduced (Fig. 4.41b):

- `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.



element key 15
rotation_angle 10.6
shift_value 0.05
scale 1.2
is_mirrored False

(a) random growth **(b) unit parameters** **(c) directed growth**

Figure 4.41: Assembly grammar growth: (a) Random growth and branching behaviour: 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

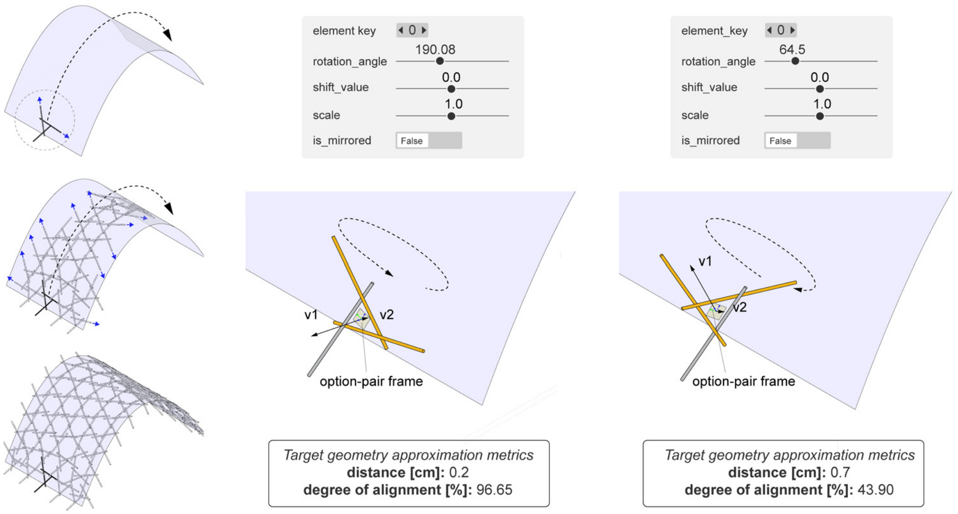
These parameters can be freely adjusted to enable precise positioning and orientation of new rod pairs, referred to as *option-pairs*, relative to the guiding rod. By modifying these parameters, the structure's growth can be directed to achieve specific outcomes. For instance, curvature control can be 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. 4.41c).

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. 4.42).



element key 0
rotation_angle 190.08
shift_value 0.0
scale 1.0
is_mirrored False

Target geometry approximation metrics
distance [cm]: 0.2
degree of alignment [%]: 96.65

element_key 0
rotation_angle 64.5
shift_value 0.0
scale 1.0
is_mirrored False

Target geometry approximation metrics
distance [cm]: 0.7
degree of alignment [%]: 43.90

Figure 4.42: Target geometry constraint: Adjusting unit parameters based on distance and degree of alignment to conform to a predefined geometry

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.

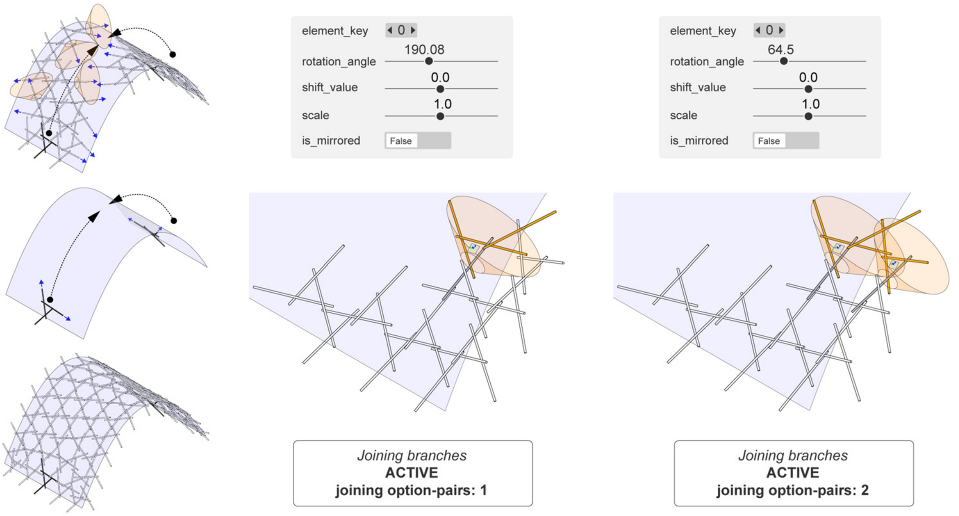
To enable branching or starting from multiple support points—while still treating the entire system as a single, interconnected structure—geometrical methods for closing loops and joining individual branches are explored. These strategies aim to address stability challenges during assembly and minimizing 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. 4.43).

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 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. 4.44a).

The implementation distinguishes between three cases:

- *No additional support required:* The branch-wise center of gravity lies within the support area,



element_key 0
rotation_angle 190.08
shift_value 0.0
scale 1.0
is_mirrored False

element_key 0
rotation_angle 64.5
shift_value 0.0
scale 1.0
is_mirrored False

Joining branches
ACTIVE
joining option-pairs: 1

Joining branches
ACTIVE
joining option-pairs: 2

Figure 4.43: 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

eliminating the need for additional support (Fig. 4.44a).

- *Single temporary support required:* A single temporary support, such as robotic assistance, is required to maintain stability during assembly (Fig. 4.44b).

- *Multiple temporary supports required:* The center of gravity of a branch falls outside the support area, necessitating multiple temporary supports (Fig. 4.44c).

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. 4.44) and are later used in the task assignment (Sect. 4.4.2).

The mobile robot system's reachability is approximated by a sphere with a 1.3m radius, vertically extendable by 0.72m through the vertical linear axis (Fig. 4.45). 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. Human-robot task assignement.

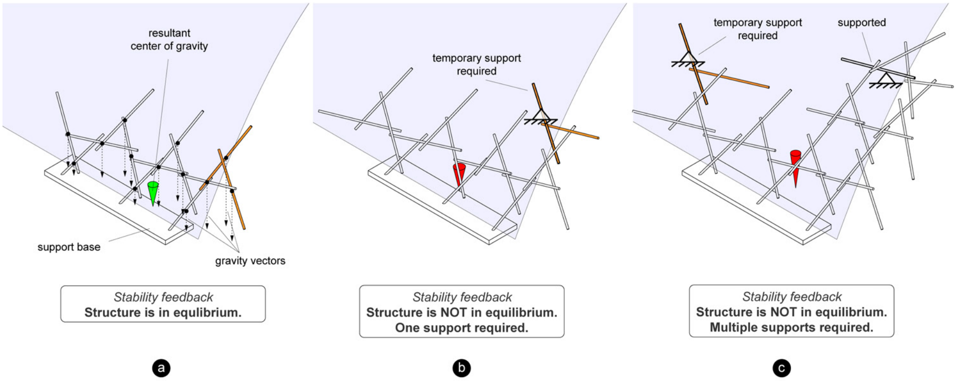


Figure 4.44: Equilibrium condition: Stability is determined by verifying whether the resultant center of gravity, accounting for all elements of the branch in the current fabrication state along with the support base, falls within the support base's footprint

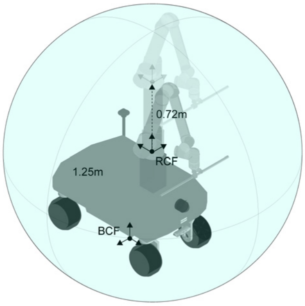


Figure 4.45: Robot reachability approximation: A sphere with a 1.3m radius represents the robot arm's range, combined with a 0.72m vertical extension enabled by the mobile system's linear axis

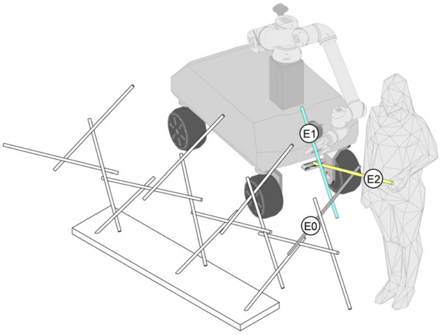


Figure 4.46: Human-robot task assignment: The guiding rod (E0) is pre-assembled first. The robot then places and holds the second rod (E1) steady until the human adds the third rod (E2), completing the RF unit

Human-robot task assignement

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 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. 4.46). 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. 4.47).

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 [62]. The latter interfaces with backend processes, including a robot path planning environment for generating collision-free trajectories.

Built on the assembly grammar rules (Sect. Assembly grammar) and incorporating design criteria and constraints (Sect. Design criteria and constraints), 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. 4.48), and (4) Final AM).

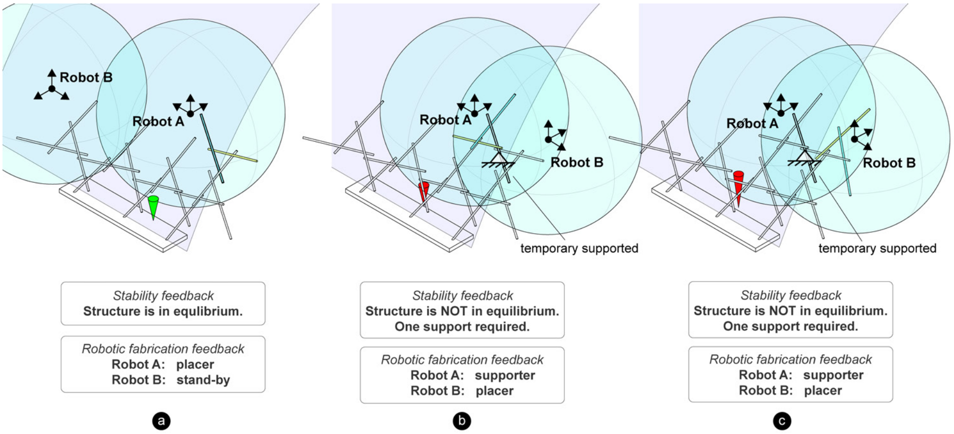


Figure 4.47: Robot task assignment: Tasks are allocated based on availability and reachability, with the robots alternating between placer and supporter roles

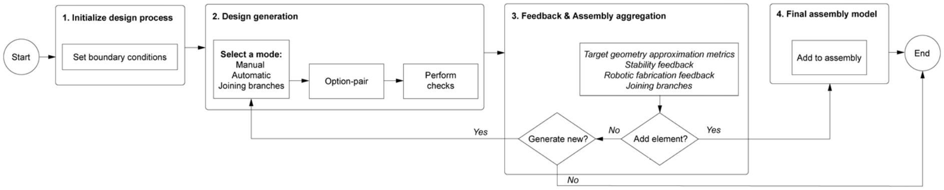


Figure 4.48: Overview of the fabrication-aware computational design workflow, illustrating the key steps: (1) Initialize design process, (2) Design generation, (3) Feedback and assembly aggregation, and (4) Final AM

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. 4.49). 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. 4.50).

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

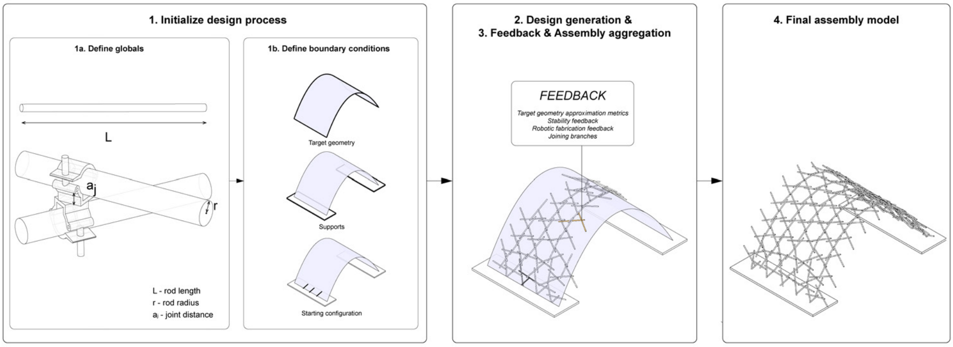
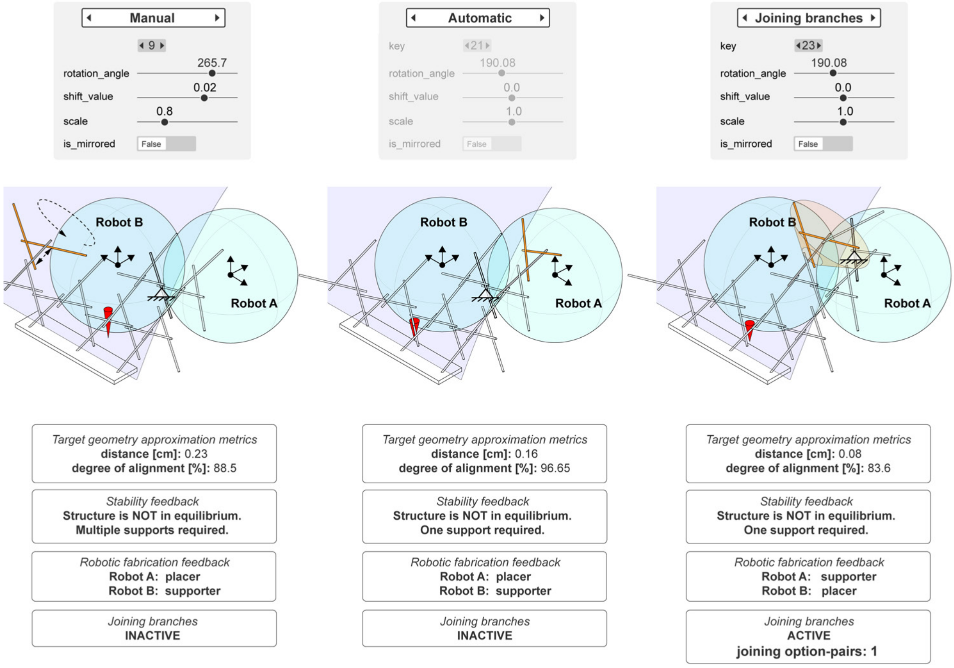


Figure 4.49: The design process starts by defining the (1) boundary conditions of the intended design: these include the (1a) assembly globals and (1b) goal condition represented by the target surface geometry, supports, and the starting configuration, followed by (2) design generation, and (3) feedback and assembly growth, and ends with (4) final AM

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 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.



◂ 9 ▸
rotation_angle 265.7
shift_value 0.02
scale 0.8
is_mirrored False

Target geometry approximation metrics
distance [cm]: 0.23
degree of alignment [%]: 88.5

Stability feedback
Structure is NOT in equilibrium.
Multiple supports required.

Robotic fabrication feedback
Robot A: placer
Robot B: supporter

Joining branches
INACTIVE

key ◂21▸
rotation_angle 190.08
shift_value 0.0
scale 1.0
is_mirrored False

Target geometry approximation metrics
distance [cm]: 0.16
degree of alignment [%]: 96.65

Stability feedback
Structure is NOT in equilibrium.
One support required.

Robotic fabrication feedback
Robot A: placer
Robot B: supporter

Joining branches
INACTIVE

key ◂23▸
rotation_angle 190.08
shift_value 0.0
scale 1.0
is_mirrored False

Target geometry approximation metrics
distance [cm]: 0.08
degree of alignment [%]: 83.6

Stability feedback
Structure is NOT in equilibrium.
One support required.

Robotic fabrication feedback
Robot A: supporter
Robot B: placer

Joining branches
ACTIVE
joining option-pairs: 1

Figure 4.50: Three modes of design generation: Manual, Automatic, and Branch joining

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. 4.51). Sect. Data exchange and visualisation details the data flow between the CAD environment, cloud-hosted database, robotic systems, and the mobile AR device. Section Localisation explains the implemented robot and phone localisation methods, while Sect. Robot motion planning, simulation and control describes the in-process robot motion planning and control.

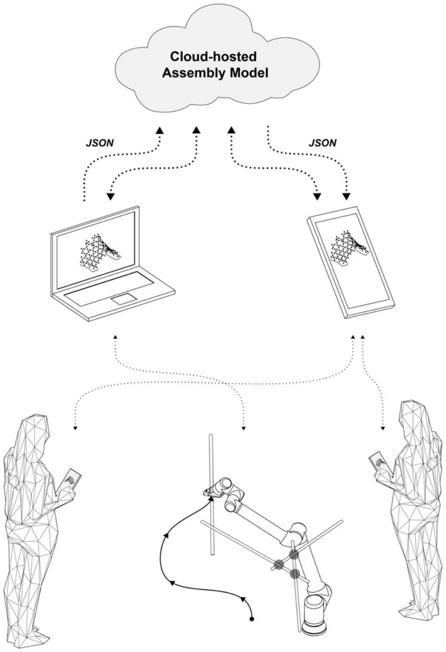


Figure 4.51: Participating entities communicate and coordinate over a cloud-hosted AM

Data exchange and visualisation

Once the design is completed, the AM is serialized to JSON format and uploaded to the *Firebase Realtime Database*[2], 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

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

agents through a custom AR phone-based application that utilizes the COMPAS XR library [117] to integrate the cloud-hosted AM, the CAD environment (interfacing with the motion planner), and the physical construction space (Fig. 4.52).

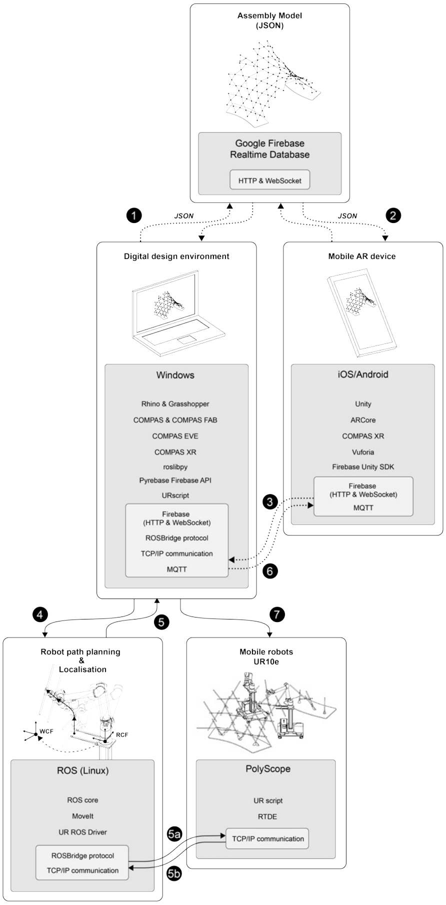

Figure 4.52: System backend architecture illustrating communication and data flow between digital design environment, cloud-hosted AM, robotic planning and simulation environment, and robot controller

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,
- track current task assignments and assembly progress,
- update the central model 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

Figure 4.53: The custom AR phone-based application serves as a communication interface between the cooperating agents - human and robots - in the assembly process

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. 4.53). 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 visualising 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*[3] environment and *MoveIt*[4] to facilitate localization (Sect. 4.4.2) and collision-free trajectory computation for the mobile robots as explained in Sect. 4.4.2. For further details on the mobile AR app implementation, refer to CAA ([108] and COMPAS XR library [118]).

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[3] Robot Operating System (ROS or ros) is a framework for writing robot software

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

Localisation

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 the *Vuforia Engine* library[5]) for localizing the mobile phones and correctly mapping visual objects in the camera feed (Fig. 4.54). 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 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.

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. 4.55). 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* [62], 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

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

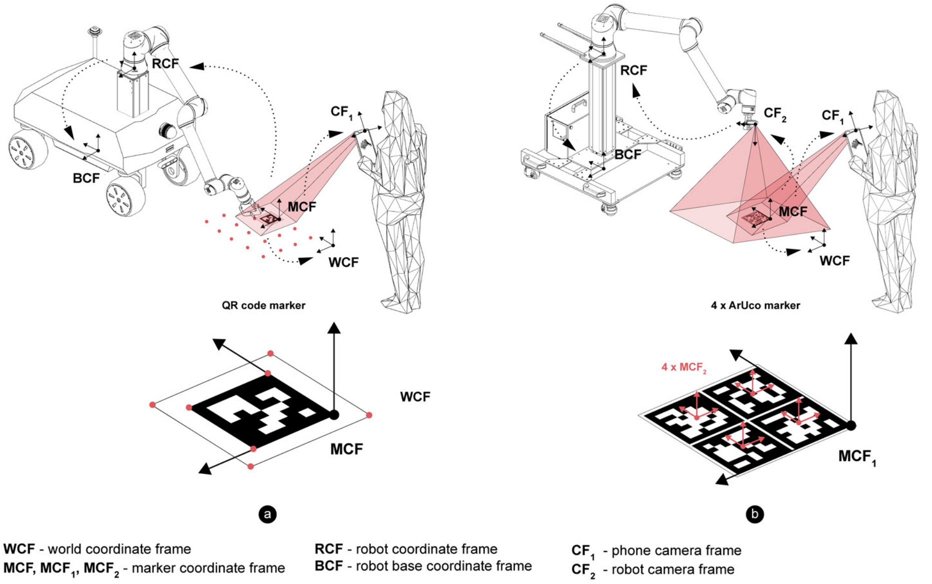

Figure 4.54: Localization methods for synchronized digital-physical workspace: a) Manual point measurement with ICP algorithm for robots, b) Marker-based tracking for robots and mobile devices

custom *Docker*[6] containers. Communication with each robot's UR controller is established over a standard TCP/IP connection. The Real-Time Data Exchange (RTDE)[7] interface is used to transfer planned pick-and-place routines, including target frames, I/O control, and robot parameters.

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. 4.56. 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

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

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

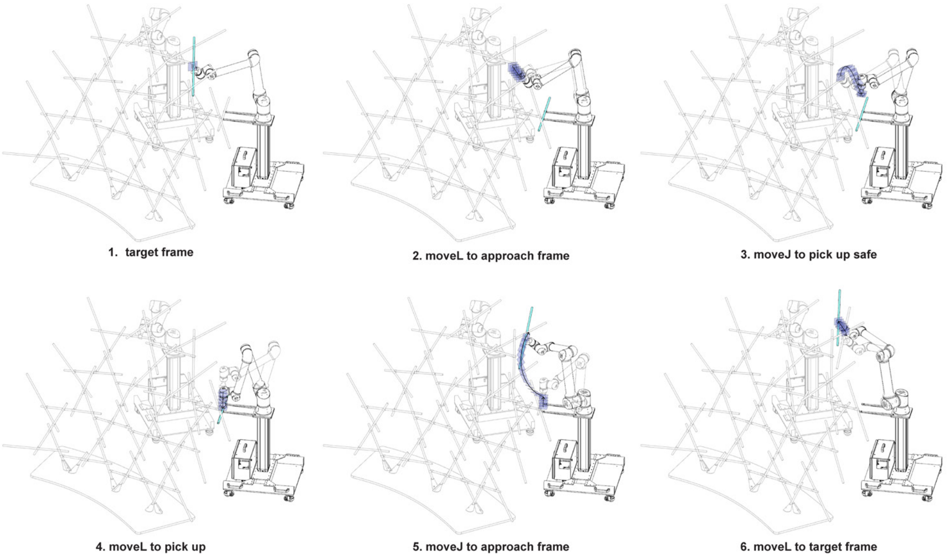

Figure 4.55: Robot motion planning: In-process computation of robot trajectories based on updated positions after mobile robot repositioning

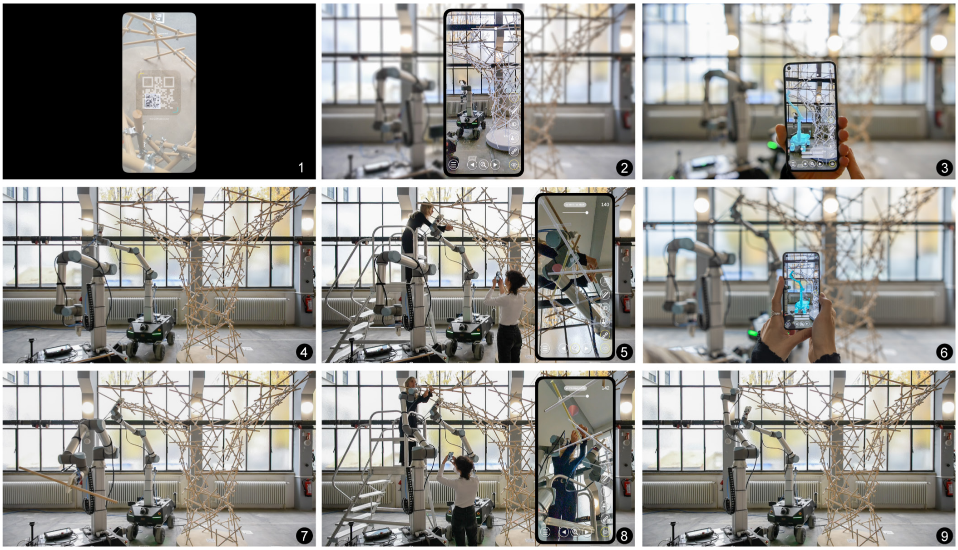

Figure 4.56: Steps of the cooperative assembly workflow involving a human-robot team consisting of two people and two collaborative mobile robots: 1) initialize the app, 2) visualize the geometry with the next element highlighted, 3) request the placement trajectory, 4) execute robotic placement with 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

configuration and a pick-and-place trajectory, which are visualized in the AR interface. The phone

Figure 4.57: Two case studies demonstrating coordinated multi-human-robot cooperative assembly using augmented reality (AR) interfaces. 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

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.

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. 4.57). In this setup, two mobile collaborative robots were employed not only for element placement but also as 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

Table **4.2:** Elements of the conducted case studies

	Case study A	**Case study B**
	2 mobile robots & $\geq$ 2 human builders	2 mobile robots & $\geq$ 2 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, stabilize structure, "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	human perception, marker tracking, 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 a digital design model stored in the design environment, custom mobile AR app	via a digital design model stored on a cloud, custom mobile AR app

study is presented in Table 4.2.

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 screew. 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 4.3). 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.

Case Study 1: Turn-taking task distribution

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

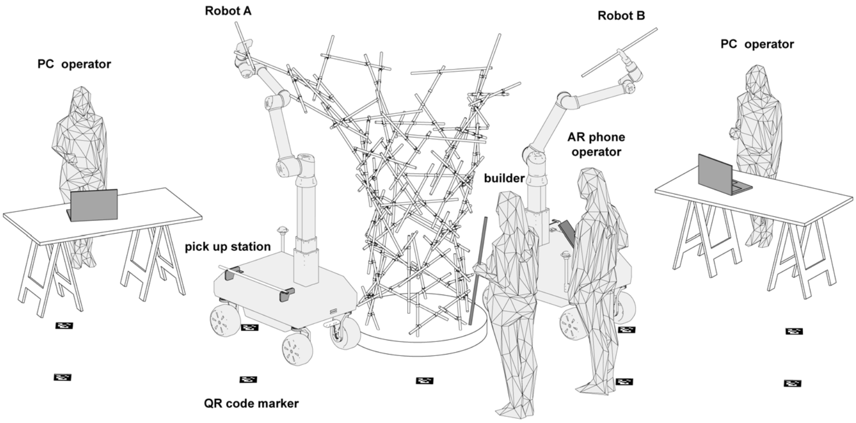

Figure 4.58: Experimental setup of the cooperative assembly workflow for Case Study 1

robotic arms to approximately 3.5 m (Fig. 4.58). 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 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

Table **4.3:** Summarized results of the case studies

	Case study A	**Case study B**
Duration		
Days (approx. 7h)	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	2	12
Accuracy [mm]		
Based on 3D scan	3-60	–
Based on marker tracking	–	20-50

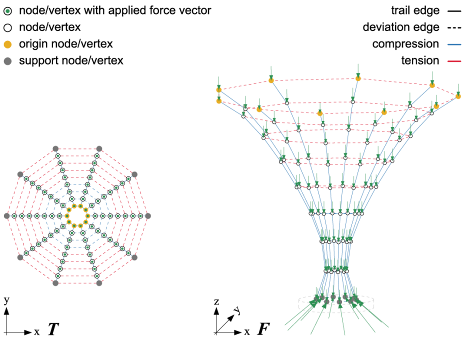

Figure 4.59: Form-finding of the target geometry using CEM: The topology diagram (*T*) defines connectivity, while the form diagram (*F*) represents the equilibrium geometry. Curvature is controlled by adjusting trail lengths and internal forces in deviation edges

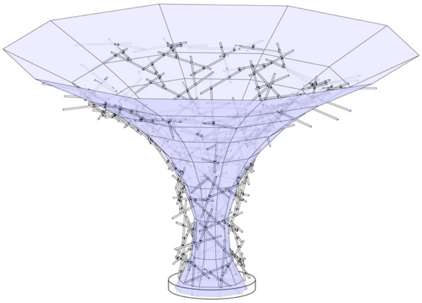

Figure 4.60: Final design of the timber demonstrator, including a visualization of the target funnel-shaped geometry

assembly process.

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) [119] 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) [120] 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. 4.59). 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. 4.60).

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. 4.61). 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.

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 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. 4.62). 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. 4.63).

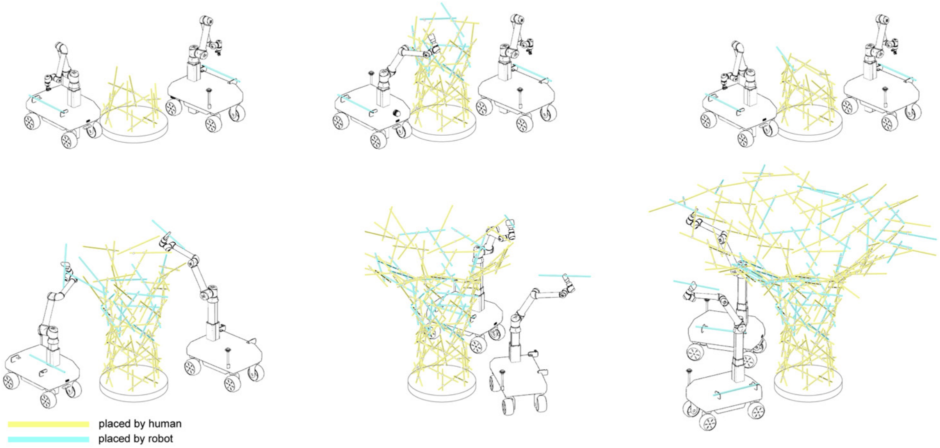

Figure 4.61: Assembly sequence generated during the design phase, illustrating the planned task distribution between two mobile robots and human agents. Color coding indicates which agent is responsible for placing each element

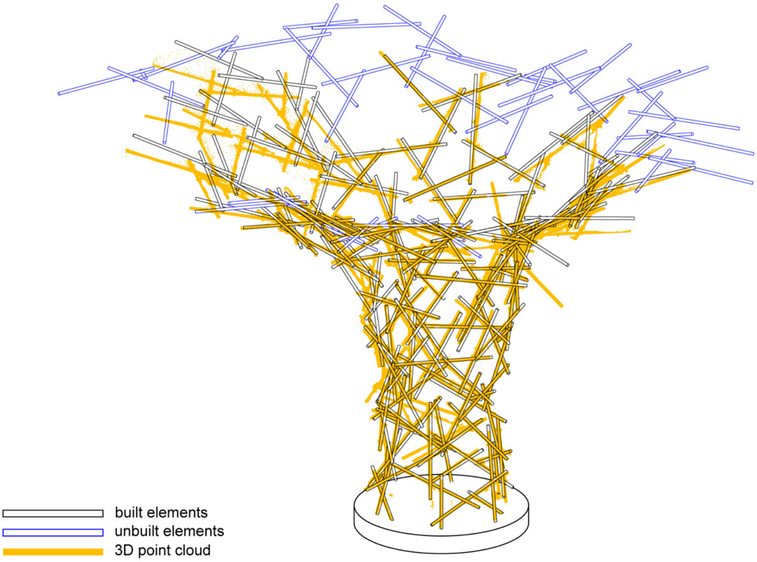

Figure 4.62: 3D laser scan of the partially assembled structure

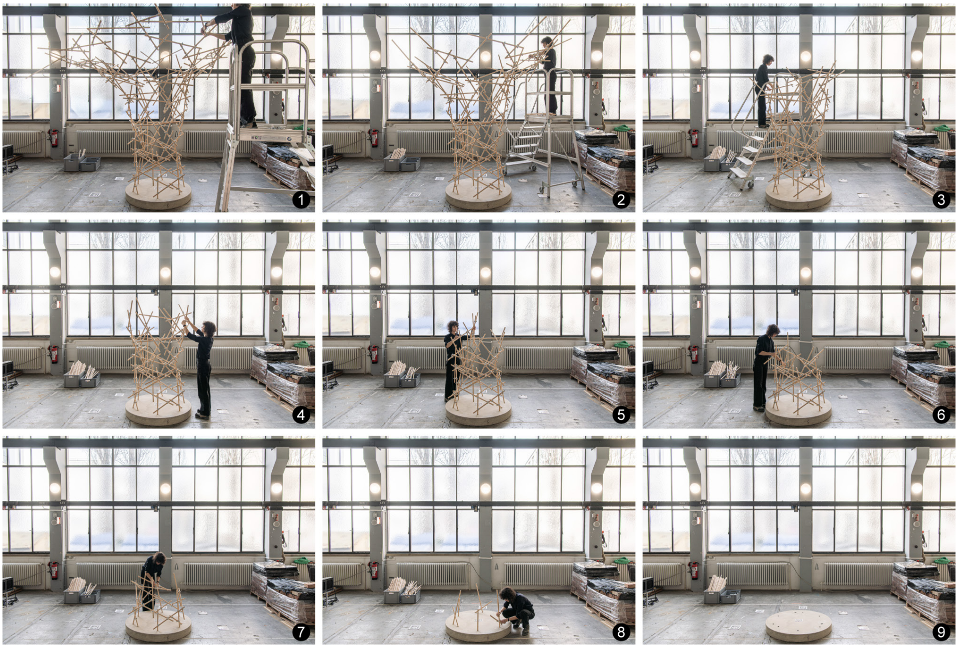

Figure 4.63: Disassembly sequence in Case Study 1 showing the breakdown of the structure into its main components

Case Study 2: Turn-taking with mobile robotic supports

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. 4.64). 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 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.

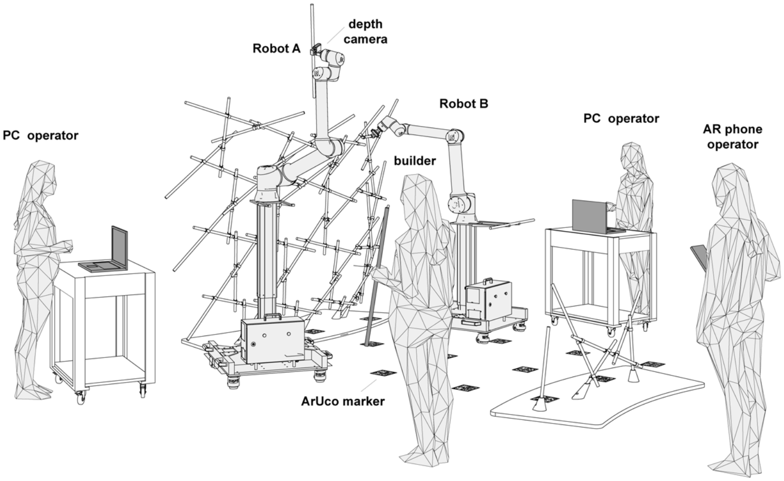

Figure 4.64: Experimental setup of the cooperative assembly workflow for Case Study 2

Design generation

Case Study 2 explores an arc-like shell covering approximately 17 m² with a height of 3.2 m at its highest point (Fig. 4.65).

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)

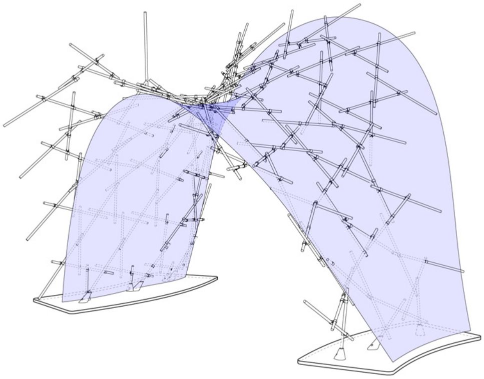

Figure 4.65: Final design of the timber demonstrator, including a visualization of the target geometry

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.

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. 4.66 and 4.67).

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

Discussion

This section discusses and analyzes the outcomes of the case studies presented in Sect. 4.4.2. 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.

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 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

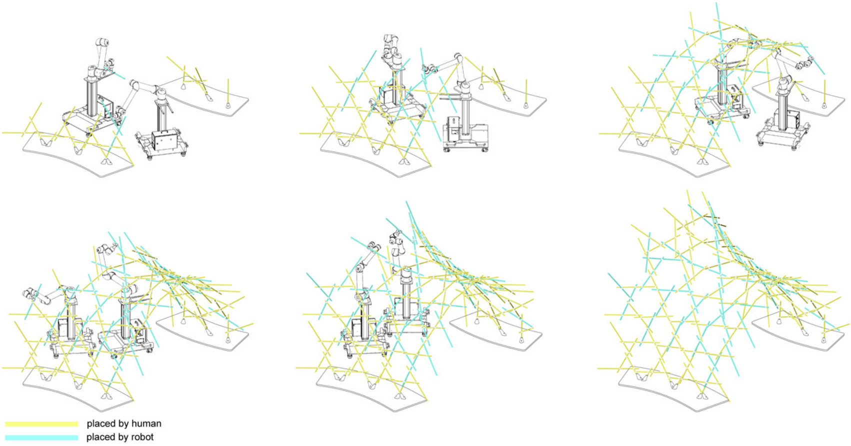

Figure 4.66: Assembly sequence generated during the design phase, illustrating the planned task distribution between two mobile robots and human agents. Color coding indicates which agent is responsible for placing each element

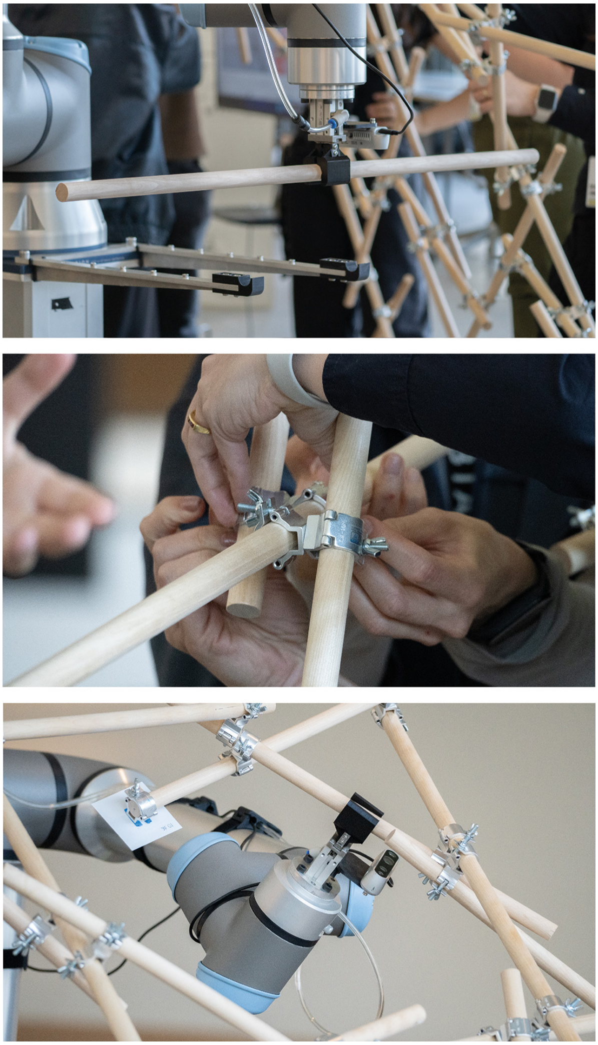

Figure 4.67: Humans and robots share the task of placing rods and supporting each other in their specific roles

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.

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 pre-planned 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.

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.

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.

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.

Acknowledgments

We express our sincere gratitude to our collaborators at TUM Professorship of Structural Design, Prof. Dr. Pierluigi D'Acunto and Paula Loecher, for their support in the equilibrium analysis and the CEM of the target geometry for Case study 1; Dr. Majid Hojjat for co-leading the project, and Tizian Rein for the support in the project coordination and realization of the demonstrator for Case study 1. We thank the students who participated in the seminar "Computational Design and Fabrication" in the summer of 2023 at TUM for their assistance in the design and fabrication of the demonstrator: Raphael Auzinger, Antonia Annica Bader, Anastazja Broniatowska, Julian Egerer, Patrick Fischer, Tamar Eli Friedman, Lelino Gomes de Sousa Junior, Hazhi Rozh Hassan Hassan, Agi Hidri, Tanima Ahmed Hidri, Liubov Kniazeva, Emin Can Özen, Tizian Rein, Mara Starka, Vinzenz Trimborn, Ekaterina Vostokova, Simon-Hauke Wichmann, Ilyas Yilmaz. We also extend our gratitude to Theresa Pfaffinger from the TUM Chair of Engineering Geodesy for measuring the QR code markers used for the localization of the mobile robots and mobile AR devices and for the 3D laser scan of the structure. Case study 2 was conducted with the generous support of the entire ROB | ARCH2024 Conference team, particularly Nicholas Hoban, Zachary Mollica and Jonathon Anderson from John H. Daniels Faculty of Architecture, Landscape, and Design, University of Toronto, Canada. They provided the materials, the mobile robot systems and UR10e robot arms and supported our team in organizing the Workshop "Collaborative Augmented Assembly". Finally, we would like to extend our thanks to the workshop participants: Armando Araiza, Sam Wilcock, Filipe J.S. Brandão, John Nguyen, Julia Hunt, Heinrich Knitt, Martin Schwab, Mohamed Gomaa, Cole Marchant, Moritz Rietschel, Santiago Perez, Selina Almadanat, Soulaf Aburas, Vaanya Paracha for supporting the realization of the pavilion and for their valuable insights and expertise.

4.4.3 Author's contribution

The contributions by the author of this thesis to the realization of this case study can be summarised as follows: The author developed the computational design logic by formulating the *assembly grammar* and extending the AM to encode the full assembly process chain, including geometric, topological, procedural, and agent-specific task assignments. The AM served as the central structure for coordinating task distribution and sequencing within the cooperative workflow. The author developed the design tool and integrated the design environment with the MoveIt robotic simulation platform and the robot control interface, enabling in-process trajectory computation, robot command generation, and execution. In addition, the author led the final architectural design of the demonstrator and contributed to the integration of all system components into a coherent computational workflow required for the construction experiments.


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5 Conclusion

5.1 Summary

This dissertation explored how adaptive human–robot collaboration can be enabled within architectural-scale fabrication through a novel design-to-fabrication methodology. Rooted in a dual algorithmic-computational and empirical-materialist approach, the research reconceptualized multi-agent assembly not as a fixed automation problem, but as a situated, cooperative process grounded in shared human–robot agency and responsive adaptation. Rather than treating fabrication as a downstream phase, the methodology positioned construction as a continuous, feedback-driven process in which design, planning, and execution are tightly interlinked. Across four iterative case studies, the dissertation addressed the research questions by developing, implementing, and validating computational design methods and models, coordination strategies, and shared digital-physical workspaces for cooperative assembly of complex timber structures.

The work contributed an integrated methodology that combines rule-based design methods, task modeling, and multi-agent coordination strategies enabled through the Assembly Model (AM)—a graph-based representation of spatial, temporal, and constructive interdependencies. Human-robot cooperation was examined across varied team configurations, from turn-based to parallel workflows, using AR guidance, vision-based tracking, and robot middleware for real-time communication. Each experiment progressively increased the complexity of team coordination and assembly logic, offering complementary insights into how different levels of task abstraction, material systems behavior, and human agency influence the performance of hybrid teams.

5.2 Summary of experiments

This section synthesizes the key findings from all four case studies, presenting a comprehensive overview of what was discovered through the research.

Case study 1: Human-human cooperative assembly investigated the coordination of multi-user manual construction workflows at a 1:1 architectural scale using mobile augmented reality. The experiment evaluated the potential of digitally supported, human-only assembly processes, in which task distribution and spatial guidance were mediated through a cloud-connected AR interface. A modular construction system composed of geometrically interlocking timber units served as the physical foundation. These 315 discrete modules enabled fastener-free connections, allowing temporary support elements to be repositioned and reused throughout the process. On the computational side, the coordination logic was embedded in a graph-based AM, which formalized geometric layout, modular relationships, and build-state logic. Each module was represented as a node with attributes such as built, buildable, removable, or support, while edges encoded adjacency and dependency relationships. The serialized AM was deployed to a cloud platform and continuously synchronized across connected devices. Mobile AR interfaces—developed in

Unity using marker-based tracking—displayed task-specific views to participants, highlighting modules relevant to their current assignments. Users confirmed completed actions through the interface, triggering real-time updates of the build state. The full-scale pavilion was assembled over two days by eight participants alternating between individual and team-based roles. A network of fiducial markers calibrated with total station measurements ensured stable positional references. The experiment resulted in a non-linear, emergent construction sequence, shaped by decentralized human decisions. A qualitative post-study survey reflected positively on the clarity of the interface, users' perceived autonomy, and their awareness of others' concurrent activities, suggesting the system effectively supported a shared, participatory, and spatially distributed assembly process.

Case study 2A: Human-robot cooperative assembly with one robot illustrated the research's focus on computational modeling and physical prototyping in the context of cooperative human-robot construction. Developed as a demonstrator for interactive, design-to-assembly workflows, *Prototype-as-artefact* explored how architectural structures could be incrementally composed through real-time collaboration between human builders and a robotic agent. Instead of following a fixed construction plan, the process relied on in-situ decisions, with human participants initiating each assembly step and the robot dynamically responding through rule-based behavior. On the computational side, the AM served as the system's central representation, structuring the project through a graph-based framework that encoded spatial relationships, task sequences, and agent roles. This model facilitated context-sensitive robotic behaviors, enabling machine actions to be generated on the fly in response to user input. The assembly grammar embedded in the AM formalized not only geometric constraints but also procedural logic, supporting an open-ended construction process grounded in both algorithmic control and intuitive participation. The physical prototype, comprising 102 timber components, was assembled through alternating contributions: humans selected and placed guiding elements while the robot calculated and executed the remaining placements according to local assembly rules. Augmented reality tools provided contextual overlays to assist human decision-making, while backend systems managed real-time synchronization of progress data, ensuring coordination between digital simulation and physical execution. The workflow demonstrated the feasibility of adaptive, multi-agent construction processes where physical structure and digital model evolved in parallel. The experiment thus provided a concrete platform to examine the interplay of material behavior, human intuition, and computational logic within a shared, responsive fabrication environment.

Case study 2B: Human-robot cooperative assembly with two robots demonstrated the feasibility of a reciprocal, turn-taking assembly workflow involving two human agents and two mobile robotic collaborators. The experiment validated the real-time coordination of a multi-agent system in which design, planning, and execution evolved dynamically through the shared progression of physical construction and computational state updates. Implemented as the full-scale demonstrator *Tie a knot*, the workflow enabled humans and robots to co-construct a reciprocal frame-like timber structure through alternating roles. Each assembly cycle began with a guided interactive design phase and proceeded through robotic placement and stabilization, followed by manual positioning and rope-based joining of structural elements. Unlike *Case study 2A*, humans completed the structural triplet—a task better suited to dexterous, material-aware manipulation—while robots handled the earlier placement steps that demanded high spatial precision. This reversal of the typical agent sequencing aligned with the practical capabilities of each participant and allowed for more efficient cooperation in the construction process. This inversion of agency highlighted the need for mutual dependency in cooperative assembly: the robot's ability to act was conditioned by the human's completion of a prior task, and vice versa. The case study thus advanced the thesis's investigation into adaptive task coordination, real-time system updating, and embodied human–robot interaction, offering a concrete model for distributed authorship and material negotiation in architectural fabrication.

Case study 3: Multi-human-robot cooperative assembly synthesized the technical and methodological insights, such as rule-based design through assembly grammar, turn-taking task distribution, and cloud-based process synchronization, into a centralized, architectural-scale cooperative assembly system involving two cooperative mobile robots and human workers. In contrast to the open-ended design workflows in *Prototype-as-artefact* and *Tie a knot*, this study utilized assembly grammar to generate an assembly plan and encode it in an extended version of the AM. The computational design approach focused on a fabrication-aware design workflow that integrated assembly logic, structural constraints, and task planning into the design phase. Through the rules of assembly grammar, the method enabled the incremental generation of reciprocal frame structures, embedding human and robot task assignments directly into the design process. Task allocation was based on agents' skills and refined during fabrication through affordance-based reassignment, accounting for environmental conditions and real-time feedback. A custom AR interface linked to a cloud-hosted AM supported real-time task visualization, coordination, and data exchange across human and robotic agents. The empirical-materialist component validated the methodology through full-scale experimental case studies. These involved scaffold-free construction of timber assemblies by teams of humans and mobile robots, coordinated through a turn-taking strategy as presented in *Tie a knot*, and guided via the AR interface. The experimental setup allowed for detailed observation of cooperative workflows and collection of performance metrics such as assembly accuracy, timing, and deviation, for potential refinement of the methodology based on practical outcomes. This case study demonstrated the feasibility of tightly integrated, fabrication-aware human–robot construction processes that combine rule-based design, procedural planning, and embodied decision-making within an adaptive digital–physical system.

5.3 Contributions

This chapter outlines the key contributions of the dissertation across five thematic areas. Each contribution is grounded in the development, implementation, and analysis of the four case studies, which together form a cumulative exploration of human–robot cooperative assembly at architectural scale. These contributions include:

- **Adaptive multi-agent assembly processes:** Establishing theoretical foundations for cooperative assembly processes that integrate design, planning, and execution phases
- **Computational design methodology:** Developing integrated design-to-fabrication workflows that embed bottom-up rule-based assembly generation and coordination logic
- **Multi-agent assembly modeling:** Contributing computational methods for representing human-robot participation and interdependencies
- **Multi-agent coordination of assembly processes:** Advancing real-time, multi-agent task planning and coordination strategies that enable scalable hybrid cooperation.

- **Practical validation:** Demonstrating multi-agent coordination approaches through architectural-scale timber structure projects across various construction scenarios

5.3.1 Adaptive multi-agent assembly processes

This research contributed to the theoretical foundations of adaptive, cooperative assembly by integrating design, planning, and execution within a single system. *Case study 1* demonstrated that design and execution could be unified through a graph-based AM, which encoded task interdependencies and enabled asynchronous, distributed human cooperation. The AR interface functioned as a coordination mechanism, allowing users to engage in non-linear construction without centralized task assignment. This enabled decentralized task selection based on local availability and worker capacity, effectively simulating a flexible construction logic responsive to emergent conditions.

Case study 2A extended this model to include robotic participation, introducing an assembly grammar capable of guiding alternation between human and robot tasks. The grammar was implemented as a rule-based growth algorithm that generated iteratively human and robot tasks based on human design decision-making and physical actions. *Case study 2B*, built on this by incorporating two mobile robots that supported two humans in assembling a reciprocal frame-like structure. Here, the role of the robot as assistant in placing building components was extended by the robots assuming temporary structural support roles, allowing humans to connect the parts using rope joints.

Case study 3 synthesized the strategies developed in the previous studies into a full-scale demonstrator involving multiple human and robotic agents. To meet structural requirements, the coordination strategy accounted not only for spatial reach and task dependencies but also for the robots' temporary load-bearing roles. The system implemented a centralized task management approach, linked to a cloud-hosted AM. Unlike earlier cases, execution was coordinated through a preplanned assembly sequence with predefined task assignments, though these assignments could still be dynamically adjusted during execution. This configuration demonstrated how hybrid agent teams can maintain assembly performance under uncertain conditions, showcasing a cooperative fabrication model that combines structured computational logic with adaptive flexibility.

5.3.2 Computational design methodology

The dissertation proposed a rule-based, bottom-up computational design methodology tailored to cooperative assembly contexts. The concept of assembly grammar was introduced in *Case study 2A*, where construction logic was defined not through static global plans but through local interaction rules. These rules governed agents' actions during building and allowed the design to emerge reactively. The grammar described dependent actions based on a predefined design space visualized through an AR interface. It established a method where the structure's physical and procedural logics were co-authored through agent interaction rather than imposed through fixed sequences.

In *Case study 2B*, the rule-based system was extended to encode, besides spatial interdependencies and task assignments, temporary structural logic necessary for reciprocal frame assembly. The grammar handled mutual dependencies between agents and components, dynamically enforcing rules that respected geometric constraints based on human input. *Case study 3* scaled this approach to a large architectural demonstrator. Here, the grammar was embedded with static equilibrium calculations, robot constraints including reachability and availability, and target shape approximation metrics to inform the design of two timber shell structures. Such an assembly process modelling strategy demonstrated the significance of flexible planning where the task distributions could adapt fluidly to in-situ conditions and team configuration

In *Case study 1*, a foundational contribution to the computational design methodology was made through the formalization of state-driven construction logic. Instead of using geometric or procedural rules alone, the design logic operated through dynamically evaluated buildability states—such as "buildable," "support," or "removable"—which were embedded into the AM and recomputed in real-time during construction. This enabled a decentralized, status-aware assembly process where the design evolved according to physical progress and user interaction. While not rule-based in the generative sense, this method laid the groundwork for later grammar-based systems by demonstrating how construction logic could emerge from relational state transitions encoded directly in the model.

5.3.3 Multi-agent assembly modeling

This research introduced a novel modeling approach for representing multi-agent assembly through the iterative development of the AM. *Case study 1* marked the initial deployment, modeling discrete assembly actions as nodes and their interdependencies—geometric, topological, and temporal—as edges. The graph dynamically reflected buildability, task availability, and progress. AR interfaces retrieved and displayed real-time task data, allowing distributed agents to act independently yet coherently.

In *Case study 2A*, the AM was extended to distinguish between human and robotic agents, incorporating role-specific tasks such as placement and holding elements, and placing mechanical connectors. This allowed task allocation to consider both agent capability and the evolving construction state.

Case study 2B introduced a second robot and a turn-taking task distribution logic between the robots, where one functions as a stabilizer while the other is free to perform an accurate placement task. While this supported the dynamic task assignment during execution, it relied on the structural deflection observed during assembly.

To address stability challenges, *Case study 3* implemented a basic equilibrium calculation to generate full assembly structures subject to fabrication-related constraints prior to fabrication. The AM represented a final design including all fabrication parameters. Through the turn-taking task distribution between humans and robots and the flexible task assignment strategy, the assembly execution remained adaptable. By encoding tasks based on equilibrium feedback into the design-to-fabrication pipeline, *Case study 3* utilized the two mobile robots as (1) *placers* of structural elements and (2) *temporary structural support*. These roles were encoded within the AM model but remained adaptable throughout construction, allowing the system to respond to unexpected on-site conditions such as reachability issues or sequencing conflicts. Through these capabilities, the AM became a real-time digital twin of the construction process, capable of synchronizing multiple agents in both sequential and parallel modes. This formalization of hybrid assembly through a flexible graph model represents a key contribution toward enabling systematic, resilient multi-agent construction workflows.

5.3.4 Multi-agent coordination of assembly processes

This dissertation advanced coordination strategies for hybrid teams of human and robotic agents engaged in collaborative assembly. *Case study 1* explored human–human cooperation through a shared AR interface, which distributed tasks based on a dynamic AM representation. The decentralized coordination model enabled agents to self-select tasks, with the system maintaining consistency and avoiding conflicts through element state updates. This scenario tested non-linear workflows and asynchronous execution.

In *Case study 2A*, robot participation was introduced through turn-based coordination mediated by a rule-based design logic. Each task—whether assigned to a human or robot—depended on the successful execution of the previous one. Humans relied on robots to place structural elements and temporarily hold them until connection.

Case study 2B adopted a similar coordination approach but extended the system by introducing a second robot, enabling the robots to alternate between the roles of placers and stabilizers. A key advantage of this approach was the flexibility to dynamically assign robotic support roles based on real-time observations of structural deflection during construction and desired assembly growth direction. This proved especially valuable in open-ended design scenarios, where the final configuration was not entirely predefined, and structural needs emerged during the building process. However, due to the absence of computational methods for tracking structural performance, the placement of robots as temporary supports relied on human intuition, limiting the precision and design space.

In *Case study 3*, agent roles were more clearly defined, but adaptive task reassignment remained necessary due to challenges in executing planned trajectories on-site. Because robots were manually repositioned, their actual location often deviated from the intended positions, sometimes leading to insufficient reachability or infeasible, collision-prone paths. The adaptability of the AM allowed agents to fluidly reassign roles—for example, swapping a robot's placement and support tasks, or having a human take over a misaligned robot's task. This highlighted the advantage of locally adaptable coordination models, even within more tightly scripted task flows. As such, *Case study 3* demonstrated synchronous task allocation, where agents operated in turn-taking cycles informed by spatial conditions and procedural rules. This experiment validated a collaborative logic that combined predefined sequencing with in situ adaptability, leveraging the strengths of both humans and robots to enable more nuanced and responsive coordination systems.

5.3.5 Practical validation

The contributions of this dissertation were validated through a series of full-scale prototyping experiments designed to test system scalability, coordination logic, and adaptability under increasing levels of complexity.

Case study 1 involved the construction of an interlocking timber structure by human agents using AR interfaces and the AM task manager. The experiment validated the feasibility of asynchronous, decentralized execution in which each agent operated semi-autonomously under shared procedural rules. Success metrics included build accuracy, task convergence, and participant feedback.

Case study 2A marked the transition to hybrid human–robot cooperation. A single robotic arm alternated with two human builders to assemble a rectilinear structure based on rule-based design logic. The robot interpreted dynamic task sets in response to human input, while the AR interface provided state-dependent visual guidance. This demonstrated the system's ability to track progress and adapt behaviors in real time.

Case study 2B extended the *Case study 2A* methodology to a dual-robot configuration, involving two mobile robots and two human agents. However, the workflow validated an inverted logic of human–robot cooperation: while robots carried out precise placements and provided temporary structural support, humans not only completed dexterous joining operations but also placed structural elements that were difficult to install robotically. This task assignment emphasized complementary capabilities, combining robotic precision with human adaptability and craft. The team successfully assembled a reciprocal frame-like structure requiring coordinated temporal support, further validating the system's capacity for distributed authorship and responsive collaboration.

Case study 3 served as the final validation of the cooperative assembly methodology, integrating structural constraints into a fabrication-aware design process. The architectural-scale prototype tested the complete design-to-fabrication pipeline under real-world conditions. The system coordinated two to four human participants and two mobile collaborative robots across a large workspace using a centralized, cloud-hosted AM. This model was streamed via an AR interface to enable adaptive task allocation and real-time multi-agent coordination.

5.4 Outlook and future work

This section outlines potential avenues for future research, suggesting how the current study could be extended, improved, or complemented by subsequent investigations.

5.4.1 Fabrication-aware design for cooperative assembly

This research shows that combining fabrication-aware design with human–robot cooperative assembly enables more flexible and adaptive construction workflows. Central to this is a bottom-up design approach, where material behavior, agent capabilities, and assembly constraints directly inform the design logic—rather than being retrofitted during execution. The case studies demonstrated how constraints such as the properties of timber joints, the need for temporary support (*Case study 2B* and *3*), and the robot's workspace limitations (*Case study 2A*, *2B*, *3*) were incorporated into early design decisions. This allowed for task sequences and role distributions that were responsive to both human and robotic agents. Scaling this approach beyond controlled setups requires systems that can accommodate greater variability in team composition and site conditions. In *Case study 3*, differences in human skill levels and slight variations in robotic configurations underscored the need for modular, reconfigurable toolchains—both in software and hardware—that adapt in real time to changing teams and environments. A further direction is to embed learning-based methods into the design-feedback loop. By analyzing data from past assemblies—such as task durations or failure points—the system could begin to anticipate delays, adjust task handoffs, and optimize sequencing dynamically. Although the current implementation focuses on timber, the same logic applies to other materials. For example, the assembly grammar could be expanded to incorporate constraints specific to masonry, steel, or prefabricated components, such as interlocking dependencies or coordination of larger machines.

5.4.2 Assembly modelling

The graph-based structure of the AM provides a flexible foundation for representing both spatial dependencies and assembly logic in construction. The next step would be to evolve the AM from a part-based to a task-oriented representation, where nodes denote discrete fabrication or coordination actions and edges capture process dependencies, sequencing constraints, and shared resource requirements. This shift would allow the model to encode construction intent, enabling it to reason not just about geometry, but about task timing, sequencing logic, and appropriate agent assignment based on skill or reachability. A task-based AM could interface directly with planning, simulation, and optimization tools, supporting dynamic task scheduling, multi-agent coordination, and real-time adaptation to site conditions. Its generality would make it applicable across varying team configurations, workflows, and project scales. Integrating the AM with industry standards such as IFC or 4D BIM would align it with established construction documentation and scheduling practices. Coupled with AR-based interfaces, it could provide a shared, real-time view of task progress—supporting not only builders, but also planners, engineers, site managers, and inspectors throughout the construction process.

5.4.3 Task sequencing and parallel execution

Although the potential for concurrent task execution was demonstrated in *Case study 1*, subsequent scenarios—particularly *Case study 2B* and *Case Studies 3*—presented constraints that limited parallelization. These constraints were due to the requirement for coordinated robotic support, which imposed a sequential flow between interdependent tasks. This serialized logic led to idle time and restricted overall workflow efficiency. Future developments could exploit the directed graph structure of the AM to evaluate and maintain multiple valid construction sequences that still respect stability and support requirements. Such performance checks could be embedded to track deflections in real-time and adapt sequencing accordingly. By dynamically identifying buildable components across the graph and allocating them to available agents, the system could facilitate parallel execution while preserving safety and structural logic. This would enable more flexible division of labor, particularly for human agents, and lead to significant gains in throughput and cooperative performance.

5.4.4 Communication protocols and coordination

The current approach to coordination depends heavily on human intervention for task confirmation and inter-agent communication. Specifically, the AR interface requires users to manually confirm task completion and to verbally convey instructions to team partners. While this setup ensured flexibility and user control, it also introduced latency and potential ambiguity and error. Improvements could include incorporating automated task recognition through vision-based tracking or integrated sensors, enabling the system to autonomously detect or suggest when actions have been performed and to either automatically trigger follow-up steps accordingly or upon human-user confirmation. Additionally, spatially explicit AR instructions could eliminate the need for verbal relaying, offering direct, visual task guidance to all agents in the environment. These enhancements would lead to smoother coordination, faster response times, and fewer opportunities for miscommunication during assembly.

5.4.5 Perception and real-time estimation

The limitations of human visual inspection and manual measurements can be addressed by incorporating advanced sensing and tracking technologies. These systems would facilitate quantitative quality control by enabling real-time monitoring of positional deviations between the planned and actual placement of rods, as well as automated identification of errors in the assembly sequence. Furthermore, structural performance could be continuously evaluated by comparing real-time load-bearing behaviour with predictive models. Integrating automated feedback loops would establish a closed-loop system in which physical changes are instantly reflected in the digital model, ensuring accurate alignment between design and construction. Collectively, these enhancements would optimize the workflow and deliver more consistent and reliable quality assurance throughout the assembly process.

Taken together, the outcomes of this research suggest that cooperative construction is not only a technical challenge but also a design opportunity. By embedding responsiveness, adaptability, and shared agency into both computational tools and physical workflows, this dissertation lays a foundation for new modes of building, where human skill and robotic precision operate not in isolation but in deliberate coordination.

Appendix

A Diversifying construction

Lidia Atanasova, Kathrin Dörfler

Exhibited as part of:
The Great Repair
Exhibition, 14 October 2023 – 14 January 2024
Opening on Friday, 13 October 2023, 7 pm
Akademie der Künste, Hanseatenweg

Concept, design and text: Lidia Atanasova, Kathrin Dörfler
Mason: Julia Ohlmeyer
Video and editing: Moritz Heinrich
Date: 2022–2023

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Since the Renaissance, architecture has been distinguished from craft, privileging intellectual over physical labor, and immaterial over material labor. As architectural theorist Douglas Spencer argues, "Effectively deskilled, those responsible for construction found their labor remotely directed, through newly invented techniques of 'thinking, drawing and model-making,' by a professional class assuming superior status over them."[1] To "repair" the inequalities of architectural practice today, it is crucial to specifically address this division of labor within the sector. A first step in this direction is to appreciate and empower those who possess essential expertise and skills critical for constructing and maintaining our built environment. The diminished status of craftsmanship within the construction industry is reflected in lower pay and a lack of allure for the younger generation, resulting in a shortage of skilled labor and a decline in the transmission and preservation of invaluable craft knowledge. While automation is often promoted as the solution to these issues, industrialized construction has shown that wholly replacing human labor with machines is not only technically infeasible but also risks further deskilling and alienating construction workers. However, we cannot deny technological developments and regress to an idealized artisanal past. Instead, we must use today's technologies to emancipate all those involved in construction. Technological innovation can be used to foster collaboration between humans and machines, improving working conditions and preserving the multifaceted nuances of construction work.

In this context, the research project *Diversifying Construction* explores the integration of robotic technologies into construction sites. Collaborative robots are engineered to operate ergonomically

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[1] Douglas Spencer, "Arbeit, Produktion und der Zweck der Architektur," ARCH+ 251, Unternehmen Architektur (2023): 31

(a) The robot places the bricks

(b) The mason applies the mortar, taps the bricks into place, and cleans the joints

Figure A.1: The human-robot cooperation leverages robotic precision combined with human ingenuity and experience. Stills from *Diversifying Construction*

(a) The human prepares the bricks for the robot to pick up

(b) The mason applies the mortar before the robot places the brick

Figure A.2: The human-robot cooperation leverages robotic precision combined with human ingenuity and experience. Stills from *Diversifying Construction*

and safely alongside humans within the same workspace. They are equipped with sensory mechanisms for measuring and controlling force to ensure a smooth human-machine interaction. The workflow presented in this project involves a mason and a collaborative robot sharing the physical labor required to construct a brick structure. While the robot places bricks based on a digital design model, the mason adds the mortar, taps the bricks into place, cleans the mortar joints, and triggers robot tasks. Together, they form a human-robot partnership leveraging the machine's capacity for repetitive tasks, spatial precision, and large-data processing, combined with the human's ingenuity, dexterity, and skills. A special lime mortar is used to maintain the brick bond and force transmission while enabling the dismantling of the structure and the reuse of the bricks. During disassembly, the mason gently taps the bricks to loosen them and clears residual mortar while the robot retrieves the bricks for future reuse. This project aims to spark a discussion on new modes of collaboration in the fields of skilled and unskilled labor in the construction sector. It asks how human-robot collaboration could help sensibly distribute tasks and provide physical relief for construction workers. It also invites critical reflection on the prospects, limitations, and potential setbacks in this evolving landscape.

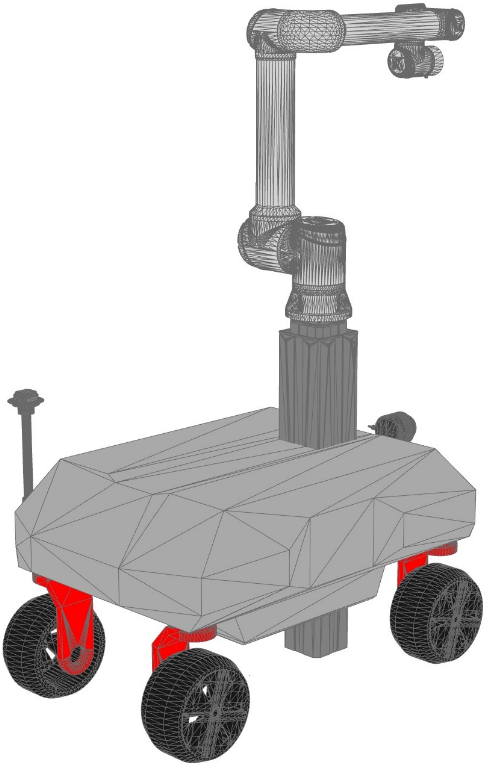
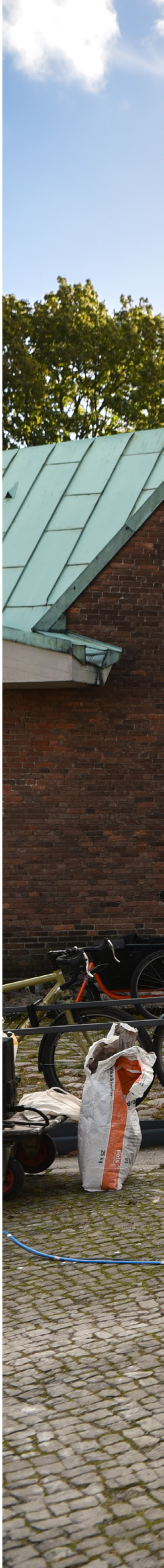


Figure A.3: A collaborative mobile robot.


Robotnik
EMER
STOP




Robotnik

B Cooperative mobile brickwork

Collaborators

TUM Professorship of Digital Fabrication
Lidia Atanasova (project lead)
Begüm Saral
Kathrin Dörfler

Students:
Angie Karolina Guerrero David, Risa Kashiwagi, Cong Liu, Janina Müller

Bauinnung München-Ebersberg
Markus Bruckner (master bricklayer)
Sebastian Posselt (director of the vocational training center and project coordinator)
Laura Lammel (head of the guild and project coordinator)

Bricklaying apprentices:
Felix Haefner, Patrik Goebel, Basti Zopf, Benedikt Altmann, Laurenz Haag

Summer Semester 2022

Cooperative mobile brickwork was a collaboration of the TUM Professorship of Digital Fabrication with Bauinnung München-Ebersberg, a vocational guild that operates a training center for apprentices in the building trades. It explored a cooperative bricklaying workflow between apprentices from the mason's school and a mobile collaborative robot, and was realized as part of the seminar *Fabrication-Aware Digital Design* in summer 2022.

This project was an exploratory experiment designed to introduce bricklaying apprentices to a new kind of assistant—a robot capable of performing precision tasks: placing bricks with high spatial accuracy based on a digital model. The bricklayers, in turn, applied mortar, a task requiring haptic, embodied skill. The focus was on exploring the potential of integrating digital tools into traditional craft in a meaningful, human-centered way. The conclusions are based on observations, informal conversations with practitioners, and reflections on how robots and craftspeople might collaborate.

Bricklaying is a skill-intensive process that requires not only an understanding of how to place bricks accurately, but also a deep knowledge of how materials—bricks and mortar—interact. It demands dexterity and haptic feedback, qualities that are inherently difficult to replicate in a robotic system. Bricklayers typically rely on 2D drawings to infer the spatial geometry of a structure. For complex spatial forms, this translation becomes especially challenging. It often requires interpreting multiple sectional drawings and mentally reconstructing the full 3D geometry in order to plan the construction sequence step by step. A practiced technique—such as tapping on a brick to ensure proper adhesion and positioning—illustrates the embodied knowledge that defines skilled manual work.

To explore a scenario where robotic assistance might be beneficial—without attempting to replace the human craftsperson—a complex vault geometry was designed. Inspired by Nubian vault construction, which avoids the need for scaffolding by relying on the slight inclination of each brick layer, this design aimed to be built without temporary support structures. A rotational pattern was also introduced to create a self-shading surface effect. Representing such a form using conventional 2D drawings would have been extremely difficult.

The robot followed a simple, repeatable pick-and-place routine: it picked up a brick and moved it toward its target position, stopping approximately 20 cm above the final location. This pause allowed the bricklayer to apply mortar manually. Only then did the robot place the brick and return to its home position. The bricklayer would then tap the brick shortly after placement to check for proper adhesion—another embodied practice not easily replicated by machines. The "place" and "return" motions had to be executed swiftly, as bricks absorb moisture rapidly, and if too much time passed between applying the mortar and placing the brick, the bond could be compromised. This workflow required the bricklayers to engage with a different kind of craft—one that slightly deviated from their traditional training. It was not necessarily better, but it was different, and it introduced its own challenges and limitations. The apprentices had the opportunity to experience the constraints and even the "helplessness" of working with a blind robot—one that could place bricks precisely, yet knew nothing about bricklaying.

The experiment highlighted the importance of considering the specificities of craft within robotic fabrication workflows. Only by doing so can we aim to combine the best of both worlds: the physical, skilled practice of the human, and the repeatability and spatial precision of the robot. While the technology still requires significant development, the experiment underscored the need to bring technological advancements and novel tools out of laboratories and universities and into the hands of practitioners, so that they, too, can shape the transformation of their own trades.

(a) The robot places a brick

(b) Bricklayer knocks the brick into the mortar

(c) Bricklayer cleans the mortar

Figure B.1: The *cooperative mobile brickwork workflow*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