ASSEMBLY OF SPACE FRAMES IN HYBRID TEAMS

Adaptive Digital Fabrication Workflows for Human-Robot Collaboration

ELENI SKEVAKI[1], MARIRENA KLADEFTIRA[2], ALEXANDRA NICOLE PITTIGLIO[3], and STEFANA PARASCHO[4]
[1,2,3,4]*Lab for Creative Computation, EPFL*
[1]*eleni.skevaki@epfl.ch, 0000-0003-4820-4048*
[2]*marianthi.kladeftira@epfl.ch, 0000-0002-5416-3601*
[3]*alexandra.pittiglio@epfl.ch, 0000-0002-8932-7450*
[4]*stefana.parascho@epfl.ch, 0000-0001-8929-1825*

Abstract. In spatial timber assemblies, a multitude of factors can lead to errors that hinder the implementation of complete automation including but not limited to inaccuracies of the robotic setup, deformations of the structures during assembly, or the natural dimensional variability of wood. Any unplanned event, construction detail, or material variability that was not embedded ahead of time in the CAD environment can cause failure. To mitigate these challenges, this paper expands this conventional one-directional design-to-fabrication pipeline and proposes interactive digital fabrication workflows where humans and robots work synergistically, blending the adaptability of human craft with the precision of robotic technology. The method is validated with two prototypes comprising linear timber elements and 3d printed connections that showcase adaptability in the fabrication setup and allow for design changes to happen concurrently with fabrication. In this paradigm, human operators are not mere extensions of the robotic system but rather central to dynamic problem-solving and instrumental in making immediate adjustments.

Keywords. Human-Robot Interaction, 3D Printed Connections, Timber Assemblies, Human-In-The-Loop, Multi-Agent Fabrication, Adaptive Digital Fabrication

1. Introduction

Recent advancements in robotic assembly of timber structures have proposed methods to automate the construction of freeform and complex structures. A diverse range of typologies have been explored such as spatial trusses (Apolinarska et al., 2016; Eversmann et al., 2017), timber framing (Helmreich et al., 2022; Leung et al., 2021; Thoma et al., 2018), reciprocal frames (Apolinarska et al., 2021), space frames (Søndergaard et al., 2016), timber plate assemblies (Robeller et al., 2017; Rogeau, 2023), and joined timber cassettes (Alvarez et al., 2019; Claypool et al., 2021). These developments have highlighted key challenges in timber construction, such as the

ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024, Volume 3, 291-300. © 2024 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

deviations through detailed simulations and advanced, carefully designed setups, resisting any discrepancies between what is planned and what is built. While minimising errors is a valid approach, there lies the potential to actively involve humans in the loop, leveraging the quick and adaptive responses that they can offer when faced with such unexpected challenges. This gap in current research presents an opportunity to explore how human insight and adaptability can be integrated into robotic construction processes to complement technological solutions. The presented study aims to investigate how individuals can actively engage with and modify aspects of the design or fabrication process during the collaborative assembly of space frame structures, offering a more dynamic and interactive approach to their construction. The aim of this study is to establish resilient fabrication workflows that integrate the inherent uncertainties of assembly into the digital fabrication process, allowing for real-time decision-making and improvisation.

2. State of the Art

2.1. SPACE FRAME ASSEMBLY

This paper presents methods for the collaborative assembly of space frames in hybrid teams. Automating the assembly of space frames is challenging due to their complex spatial configuration and the convergence of many elements at a single node which leads to complex joint formations in constrained areas, while manual assembly often requires workers to operate at height, which not only escalates labor demands but also introduces safety risks. To address these challenges, recent advancements have been made in utilizing collaborative industrial robots. These robots alternately add new structural elements or support the already assembled part of the structure, allowing human operators to secure them in place, for instance, through welding (Parascho, 2019) or by connecting butt-joints in timber frameworks (Thoma et al., 2019). Additionally, the deployment of robotic actuators can parallelize assembly and joint-fastening tasks (Leder et al., 2019; Leung et al., 2021). However, such processes rely on a top-down design-to-fabrication approach that often leads to incremental build-up of errors due to fabrication tolerances, which results in mis- and retro-fits.

Several researchers have explored the use of 3D printing for manufacturing bespoke connections ensuring the precise positioning and alignment of the connecting struts (Bañón & Raspall, 2021; Dritsas et al., 2017; Kladeftira et al., 2022). However, the assembly of multiple dissimilar parts remains time consuming and expensive. Complex structures with custom angles can be fabricated with adaptive joints thus minimizing the need for struts of different lengths (de Oliveira, Pauletti, and Meneghetti 2020), but the precise positioning of members is challenging while its automation demands a level of dexterity beyond current robotic capabilities. A collaborative human-robot setup is, therefore, better suited to address adaptive fabrication workflows, where not only errors can be spotted and mitigated by humans, but also on-the-fly changes and adaptations of the structure can happen, facilitated by tracking systems and digital twins.

2.2. HUMAN-ROBOT COLLABORATION

In the field of construction robotics, the most common form of human-robot collaboration occurs when humans perform tasks that exceed robotic capabilities. For instance, a robot positions predrilled timber slats, while humans manually hammer in the connecting dowels (Thoma et al., 2019). In such scenarios, humans function in a capacity similar to that of machines. Aligning more closely with Industry 4.0 principles is the introduction of robotic assistants that enhance the capabilities of human workers, as discussed by Haddadin (Haddadin et al., 2011). For example, Lipton et al. (2018) introduced a robotic fabrication system that integrates standard carpentry tools with mobile robots, while Tian & Paulos (2021) suggested using a robot as a virtual jig to constrain the tool's motion. A step toward robotic autonomy is the introduction of control systems designed to adjust planned trajectories based on force sensor data or the collaborating human's intent in assembly tasks (Devadass et al., 2019). Moreover, robots can also learn from humans through demonstration (Billard et al., 2008), which is a process where robots acquire specific skills by observing demonstrations by human experts (Kramberger et al., 2022). Human-robot collaboration further extends into co-design processes, in some cases granting both humans and robots a degree of creative agency. Examples include the collaborative assembly of a complex timber structure (Atanasova et al., 2020), where building actions alternate between two people and a robot, coordinated via a mobile device, and the improvisational construction of a bamboo structure assembled by two industrial robotic arms and several humans using a collective decision-making mechanism (Han & Parascho, 2023). Another intriguing experimental setup delves into paper plane design and evaluation using a robotic launcher (Obayashi et al., 2023). This project aims to explore the non-linear design space of paper plane creation, with the robot taking over the initial design search in this engineering optimization challenge and handing it off to the human to complete the design. To encapsulate these diverse collaborative modes, Figure 1 provides a comprehensive taxonomy of human-robot collaborative teams in construction, illustrating the varying levels of robot autonomy and human effort (Liang et al., 2021).

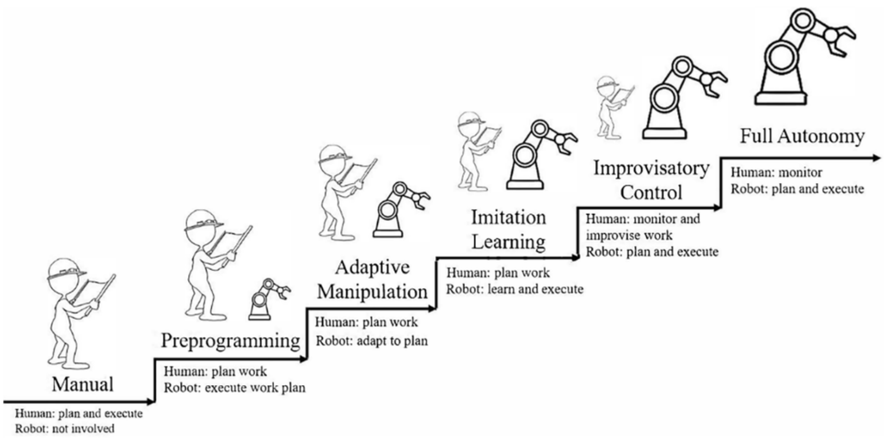


Figure 1. Taxonomy of HRC teams in construction with the level of robot autonomy and human effort. (Liang et al., 2021) With permission from ASCE

3. Materials and Methods

3.1. MATERIAL SYSTEM

To implement and test the interactive fabrication workflows that we propose, we developed a constructive system composed of linear members of the same rectangular profile (23mm x 8mm) with varying lengths connected with 3D-printed joints manufactured using Fused Deposition Modeling (FDM). The assembly process involves the collaborative efforts of two robots and a human who are sharing the task of placing linear members while the human is responsible for adding the joints. A key challenge of the system is managing the tolerances in the multi-robot setup. To address this, we designed the connectors so that they allow significant freedom: they featured ball joints for rotation and an adjustable screw for translation. This design choice greatly enhances the ease of assembly. Each joint's core structure is derived from a platonic solid (tetrahedron, octahedron or dodecahedron), as illustrated in Figure 2b. To add the detailing, volumetric modelling is used, implemented with Axolotl (Bernhard, 2018) in the Rhino/Grasshopper environment, which facilitates a streamlined workflow for executing boolean operations, ensuring the creation of manifold meshes. This is essential for achieving successful 3D printing results.

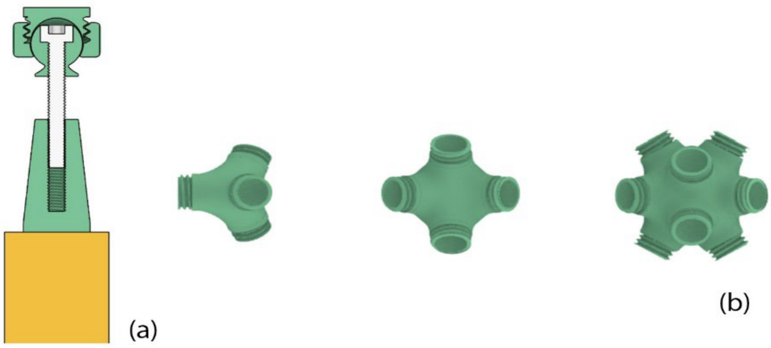


Figure 2. 3D printed connections: (a) Ball joint connection detail, (b) Node Design Exploration Starting from Three Platonic Solids

3.2. FABRICATION SETUP

The fabrication setup features two GoFa™ CRB 15000 collaborative robots equipped with a PGN-plus-P 64-1 pneumatic gripper with 3D-printed fingers and an Azure Kinect sensor attached to their sixth axis. A Dremel 3000 tool is combined with a 3D-printed attachment to serve as a compact mini table saw. The robot is programmed to grasp a rectangular pine timber profile from its center, trim it from both sides using the mini table saw to achieve the required length, and then position it in place. We use compas_fab for path planning (Rust et al., 2018) and compas_rcc (Fleischmann et al., 2020) for robotic communication within the Grasshopper visual programming environment inside Rhinoceros 3D. A separate python script reads and processes the sensor input. This information can be retrieved on-demand via a WebSocket interface which is established with the Bengesht plugin (Tahanzadeh, 2018) in Grasshopper.

3.3. ADAPTIVE FABRICATION

The connectors' design, with rotational freedom in the connecting axis, implies that the structure couldn’t be assembled without robots guiding the assembly, given the numerous potential configurations for the connecting elements. It also leverages human agility to mitigate errors by adjusting the connections and securing them with a nut. Hence, the fabrication setup capitalizes on the robots' precision and strength as well as humans' nuanced dexterity and adaptability. The design uses a tetrahedron as the simplest rigid construction unit. In each step of the assembly process, a new tetrahedron is added to the structure, enabling a collaborative rhythm where robots initiate the placement of elements, followed by humans who add components in positions geometrically determined by the already built structure. Additionally, human operators guide the robot(s) through prescribed gestures, to instruct them to move or rotate the structure to improve reachability for them or another robotic agent to place the next element. Finally, human operators, are allowed to exercise creative improvisation and define or adjust the position of members. This approach embraces emergent design concepts that evolve through the direct interaction of humans with the tools and the material context. Following human intervention, the structure is scanned using an Azure Kinect to update the 3D model and the subsequent fabrication steps.

4. Results

Two structures were collaboratively fabricated. The design and fabrication logic for each is described in the sections below.

4.1. CASE STUDY I: TETRAHELIX

The goal of the first case study is to explore the challenges, potentials, and constraints of 3D structures collaboratively assembled by humans and robots. A space frame consisting of 35 identical linear timber elements and 14 3D-printed connections was designed and assembled utilizing the fabrication setup described in 3.2 and a human operator.

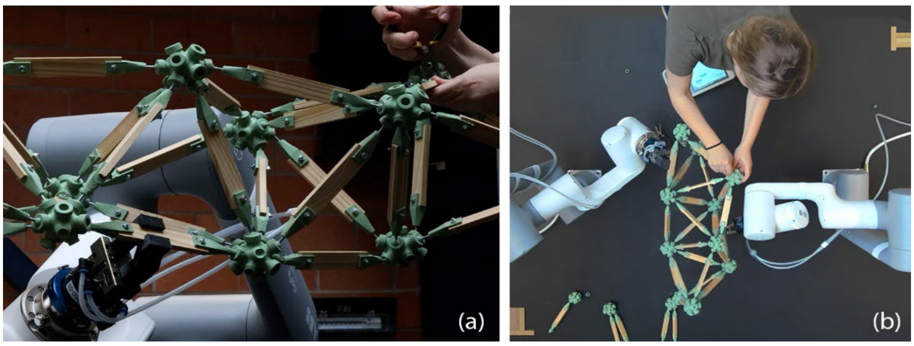
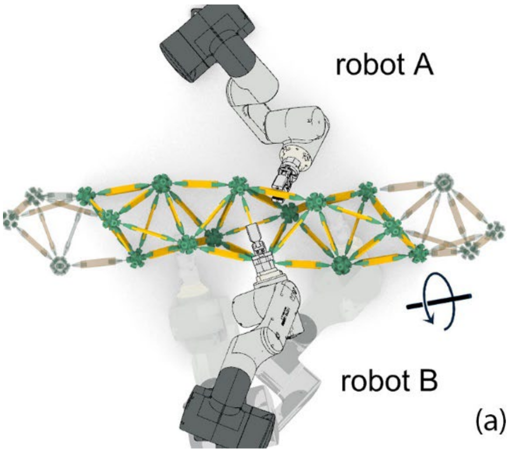


Figure 3. Case Study I: Tetrahelix. Impressions from the Collaborative Fabrication Process

4.1.1. Design

The design is a helical truss formed by the face-to-face aggregation of regular tetrahedra. The vertices of the regular tetrahedra of the tetrahelix with edge length L all lay on the surface of a cylinder of radius r and their coordinates x,y,z can be computed with the following systems of equations, where n is the index of the vertex (Figure 4b).



$$r = \frac{3\sqrt{3}}{10} \times L$$

$$\theta = \arccos\left(-\frac{2}{3}\right)$$

$$h = \frac{1}{\sqrt{10}} \times L$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} r \times \cos(n \times \theta) \\ r \times \sin(n \times \theta) \\ n \times h \end{pmatrix}$$

(b)

Figure 4. (a) Robot B maneuvers the structure to adapt to the reach constraints of Robot A, (b) System of equations to calculate the coordinates of the vertices of a tetrahelix

4.1.2. Fabrication

The fabrication process employed a turn-taking logic, as described in section 3.3 with robots and the human operator alternating placing tasks. Every assembly cycle added a new tetrahedron and started with robot A precisely positioning a timber element in place. The human followed by installing the additional two timber elements and corresponding nodes, their placement being intuitively dictated by the geometry. Robot B primarily provided support for the structure which was held in the air. As the construction progressed, a new challenge arose: calculating viable paths for Robot A's placement tasks. To navigate this, we explored the idea of Robot B reorienting the structure to accommodate the reach limitations of Robot A (Figure 4a). This was triggered by the human signaling to the robot to either rotate or move the structure by coupling four fixed movements of their fingertip coordinates (clockwise, counterclockwise, left, and right) with the corresponding transformations (clockwise and anticlockwise rotation and positive and negative translation along the tetrahelix's principal axis). Those gestures are interpreted through the MediaPipe framework developed by Google (Lugaresi et al., 2019). The assembly was successfully completed in 2 hours, offering valuable insights into the dynamics of human-robot collaboration in assembly tasks.

4.2. CASE STUDY II: OGEE

Building on the collaborative human-robot assembly framework established in the first case study, this second prototype aimed to explore the potential for a non-deterministic emergent assembly, granting humans greater agency in modifying the result based on their intuition. The completed structure consisted of 69 linear elements, 20 standardized connections, and 3 custom base connections.

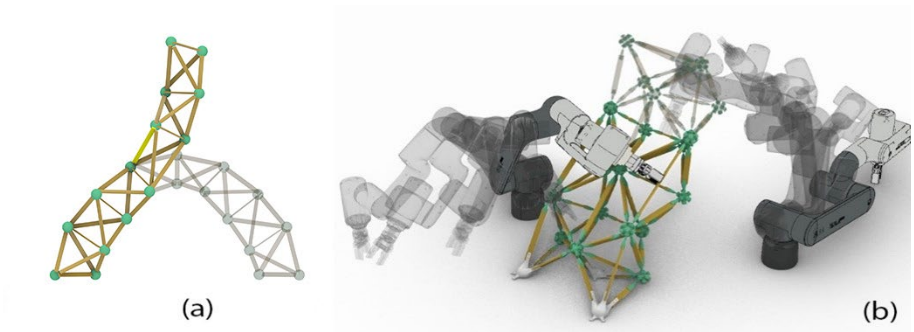


Figure 5. (a) Design is adapting to human altering the angle of a linear element (yellow), (b) One robot always maintains its grip on the structure for support

4.2.1. Design

The design features an arc truss starting from the base with constant curvature, which is rendered with transparency in Figure 5a. The process allows the human operator to adjust the angle at which a linear element is placed, triggering real-time updates in the digital twin model and adapting the subsequent fabrication steps. This resulted in an arched geometry combining two arcs – one convex and one concave, with the human operator determining the inflection point. The space frame's topology comprises two layers (top and bottom) interconnected to form tetrahedral cells.

4.2.2. Fabrication

As in the previous case study, a turn-taking approach was used between the three agents (two robots and a human). To optimize reachability and avoid collisions between the two robots, Robot A was responsible for placing the elements in the bottom layer, while Robot B handled the top layer elements (Figure 5b). Central elements, which required careful manoeuvring around the pre-assembled structure, were placed by the human along with all the 3D-printed connections. Throughout the process, one robot always maintained its grip on the structure for support, while the other robot performed the picking and placing of the next element. When the human operator defined the angle of the linear element, the Azure Kinect, attached to Robot A’s flange (Figure 6b), scanned and digitized the current state of the structure. This allowed the digital model to be updated with the new angle, thereby adjusting the subsequent robotic trajectories to align with the human's input. In total, Robot A placed 14 elements, Robot B placed 6, and the human operator placed 40 elements, excluding the 9 connected to the base nodes that were pre-assembled. This results in the human performing a significantly larger portion of the assembly, with the human-to-robot contribution ratio for the main part of the structure standing at 2:1.

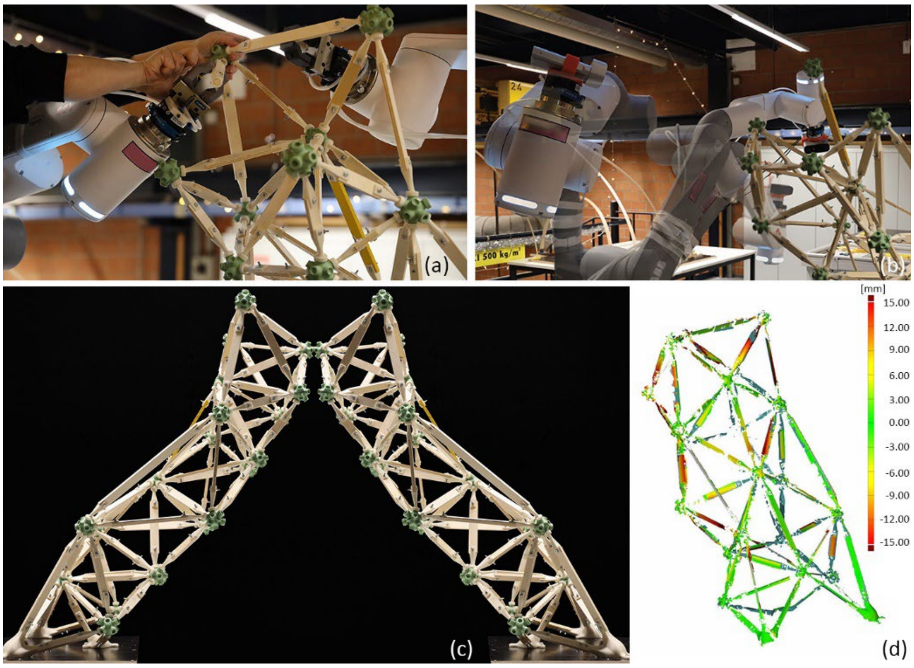


Figure 6. (a) Human adjusts connections, (b) Robot scans the structure after human intervention, (c) Final assembly result (mirrored) (d) Comparison between the as-built and CAD design model

5. Conclusion

By enabling designers and operators to directly intervene in a robotic process, the research aims to improve the adaptivity of robotic assembly of spaceframes so that humans in hybrid teams can effectively mitigate tolerances, or suggest design changes concurrently with the fabrication process. The primary contribution of this paper lies in the proposal of such adaptive fabrication workflows:

- humans mitigate errors by adjusting 3D-printed connections
- humans decide to adjust the position and/or orientation of the structure to make it easier for them or a robot to place the next element
- humans can exercise creative improvisation and modify the position of the linear elements during the fabrication process

A comparison of the as-built structure with the CAD design model (Figure 6d) for the second prototype reveals a mean deviation of 3.5 mm which becomes increasingly pronounced higher up. This highlights the critical role of human involvement; without it the accumulation of tolerances could halt production. However, it must also be acknowledged that human intervention introduces a degree of uncertainty in the digital fabrication process. The key challenge lies in balancing the strengths of both humans and robots to create a cohesive and synergistic collaboration and enable more resilient and adaptable construction processes. Future research will focus on developing more intuitive interfaces and interaction protocols that further empower this collaboration.

Acknowledgements

The research is supported by the NCCR Digital Fabrication, funded by the Swiss National Science Foundation (NCCR Digital Fabrication Agreement #51NF40-205604).

References

Alvarez, M., Wagner, H., Groenewolt, A., Krieg, O., Kyjanek, O., Scheder-Bieschin, L., Bechert, S., Sonntag, D., Menges, A., & Knippers, J. (2019, October). The BUGA Wood Pavilion – *Integrative Interdisciplinary Advancements of Digital Timber Architecture.*

Apolinarska, A. A., Knauss, M., Gramazio, F., & Kohler, M. (2016). The Sequential Roof. In *Advancing Wood Architecture: A Computational Approach* (pp. 45–57). Routledge.

Apolinarska, A. A., Kuhn, M., Gramazio, F., & Kohler, M. (2021). *Performance-Driven Design of a Reciprocal Frame Canopy – Timber structure of the FutureTree*

Atanasova, L., Mitterberger, D., Sandy, T., Gramazio, F., Kohler, M., & Dörfler, K. (2020). Prototype as Artefact: Design Tool for Open-ended Collaborative Assembly Processes. In *Proceedings of the 40th Annual Conference of the Association for Computer Aided Design in Architecture: Distributed Proximities, (ACADIA)* (pp. 350-359)

Bañón, C., & Raspall, F. (2021). *3D Printing Architecture: Workflows, Applications, and Trends*. Springer Singapore. https://doi.org/10.1007/978-981-15-8388-9

Bernhard, M. (2018). Axolotl https://www.food4rhino.com/app/axolotl.

Billard, A., Calinon, S., Dillmann, R., & Schaal, S. (2008). Robot Programming by Demonstration. In B. Siciliano & O. Khatib (Eds.), *Springer Handbook of Robotics* (pp. 1371–1394). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-30301-5_60

Claypool, M., Retsin, G., Garcia, M. J., Jaschke, C., & Saey, K. (2021). Automation and the Discrete: Exploring New Potentials for Streamlining Production in *Architectural Design Research.* Journal of Architectural Education, 75(1), 108–114.

Devadass, P., Stumm, S., & Brell-Cokcan, S. (2019, May 24). Adaptive Haptically Informed Assembly with Mobile Robots in Unstructured Environments. *36th International Symposium on Automation and Robotics in Construction*, Banff, AB, Canada.

Dritsas, S., Chen, L., & Sass, L. (2017). Small 3D Printers / Large Scale Artifacts—Computation for Automated Spatial Lattice Design-to-Fabrication with Low Cost Linear Elements and 3D Printed Nodes. 821–830. https://doi.org/10.52842/conf.caadria.2017.821

Eversmann, P., Gramazio, F., & Kohler, M. (2017). Robotic Prefabrication of Timber Structures: Towards Automated Large-Scale Spatial Assembly. *Construction Robotics*, 1(1–4), 49–60.

Fleischmann, P., Casas, G., & Lyrenmann, M. (2020). COMPAS RRC: Online control for ABB robots over a simple-to-use Python interface.

Haddadin, S., Suppa, M., Fuchs, S., Bodenmüller, T., Albu-Schäffer, A., & Hirzinger, G. (2011). Towards the Robotic Co-Worker. In C. Pradalier, R. Siegwart, & G. Hirzinger (Eds.), *Robotics Research* (Vol. 70, pp. 261–282). Springer Berlin Heidelberg.

Han, I. X., & Parascho, S. (2023). Improv-Structure: Exploring Improvisation in Collective Human-Robot Construction. In A. Gomes Correia, M. Azenha, P. J. S. Cruz, P. Novais, & P. Pereira (Eds.), *Trends on Construction in the Digital Era* (pp. 233–243). Springer International Publishing.

Helmreich, M., Mayer, H., Pacher, M., Nakajima, T., Kuroki, M., Tsubata, S., Gramazio, F., & Kohler, M. (2022). Robotic Assembly of Modular Multi-Storey Timber-Only Frame Structures Using Traditional Wood Joinery. In *Proceedings of the 27th International*

Conference for the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) (pp. 111-120). CAADRIA

Kladeftira, M., Leschok, M., Skevaki, E., Tanadini, D., Ohlbrock, P. O., D'Acunto, P., & Dillenburger, B. (2022). Digital Bamboo: A Study on Bamboo, 3D Printed Joints, and Digitally Fabricated Building Components for Ultralight Architectures. *ACADIA 2022: Hybrids & Haecceities.*

Kramberger, A., Kunic, A., Iturrate, I., Sloth, C., Naboni, R., & Schlette, C. (2022). Robotic Assembly of Timber Structures in a Human-Robot Collaboration Setup. *Frontiers in Robotics and AI*, 8. https://www.frontiersin.org/articles/10.3389/frobt.2021.768038

Leder, S., Weber, R., Bucklin, O., Wood, D., & Menges, A. (2019). Towards Distributed In Situ Robotic Timber Construction. In C. Leopold, C. Robeller, & U. Weber, *Research Culture in Architecture* (pp. 67–76). De Gruyter.

Leung, P. Y., Apolinarska, A. A., Tanadini, D., Gramazio, F., & Kohler, M. (2021). Automatic Assembly of Jointed Timber Structure using Distributed Robotic Clamps in. *CAADRIA 2021: Projections*, Hong Kong, pp. 583–592 https://doi.org/10.3929/ETHZ-B-000481928

Liang, C. J., Wang, X., Kamat, V. R., & Menassa, C. C. (2021). Human–robot collaboration in Construction: Classification and Research Trends. *Journal of Construction Engineering and Management*, 147(10), 03121006.

Lipton, J. I., Schulz, A., Spielberg, A., Trueba, L., Matusik, W., & Rus, D. (2018). Robot Assisted Carpentry for Mass Customization. 2018 *IEEE International Conference on Robotics and Automation* (ICRA), 3540–3547.

Obayashi, N., Junge, K., & Hughes, J. (2023). Exploration of Human-Robot Collaboration Methods for Iterative Design Optimization of Paper Airplanes. *International Workshop on Human-Friendly Robotics*, 131–145.

de Oliveira, I. M., Pauletti, R. M. de O., & Meneghetti, L. C. (2020). Connection System For Gridshell Structures Using Parametric Modeling and Digital Fabrication. *Automation in Construction*, 109, 102996. https://doi.org/10.1016/j.autcon.2019.102996

Parascho, S. (2019). Cooperative Robotic Assembly: Computational Design and Robotic Fabrication of Spatial Metal Structures (p. 235 p.). https://doi.org/10.3929/ETHZ-B-000364322

Robeller, C., Helm, V., Thoma, A., Gramazio, F., Kohler, M., & Weinand, Y. (2017). Robotic Integral Attachment. 92–97. https://doi.org/10.2307/j.ctt1n7qkg7.16

Rogeau, N. H. P. L. (2023). Robotic Assembly of Integrally-Attached Timber Plate Structures: From Computational Design to Automated Construction.

Rust, R., Casas, G., Parascho, S., Jenny, D., Dörfler, K., Helmreich, M., Gandia, A., Ma, Z., Ariza, I., Pacher, M., Lytle, B., & Huang, Y. (2018). COMPAS FAB: Robotic Fabrication Package for the COMPAS Framework. https://doi.org/10.5281/zenodo.3469478

Søndergaard, A., Amir, O., Eversmann, P., Piškorec, L., Stan, F., Gramazio, F., & Kohler, M. (2016). Topology Optimization and Robotic Fabrication of Advanced Timber Space-Frame Structures. In *Robotic Fabrication in Architecture, Art and Design 2016* (pp. 190–203). Springer.

Tahanzadeh, B. (2018). Bengesht (3.3). https://github.com/behrooz-tahanzadeh/Bengesht

Thoma, A., Adel, A., Helmreich, M., Wehrle, T., Gramazio, F., & Kohler, M. (2018). Robotic Fabrication of Bespoke Timber Frame Modules. *Robotic Fabrication in Architecture, Art and Design*, 447–458.

Thoma, A., Jenny, D., Helmreich, M., Gandia, A., Gramazio, F., & Kohler, M. (2019). Cooperative robotic fabrication of timber dowel assemblies. *Research Culture in Architecture*, 77–88.

Tian, R., & Paulos, E. (2021). Adroid: Augmenting Hands-on Making with a Collaborative Robot. *The 34th Annual ACM Symposium on User Interface Software and Technology*, 270–281. https://doi.org/10.1145/3472749.3474749