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Heuristic Fabrication: An Interactive Robotic Building System for Enhancing Human Participation in Timber Structures

Teruyoshi KANEKO*, Arastoo KHAJEHEE*, Yasushi IKEDA*

*The University of Tokyo
Department of Architecture, Graduate School of Engineering, The University of Tokyo, Building No.11, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan
t.apple.0326teru@gmail.com

Abstract

This research delves into human-robot collaboration in the construction sector, particularly for building complex timber structures. It presents a novel interaction system where humans and robots work in tandem, with humans making timber placement decisions and robots executing the assembly. This synergy is augmented by algorithms that aid human choices. A standout contribution is the development of an incremental timber fabrication system that accommodates real-time design changes. This system uses a computational model to strategically place timber pieces, ensuring proper surface contact and avoiding collisions. Addressing the challenge of scaling such collaborations to large structures, the study introduced an Arduino-controlled rotating table to increase assembly flexibility. Moreover, it developed a visualization algorithm based on the Finite Element Method, aiding humans in making informed decisions about the structure's design and the robot's assembly process's feasibility. In experimental tests, a 1.6-meter timber section of a larger structure, and a complex tree-like structure were constructed, demonstrating the system's effectiveness. The structural analysis confirmed the safety of the design, with a maximum tensile force of 6.5 N/mm² at the joints, below the timber's tensile limit. The robotic assembly's accuracy was within a 1.2 mm tolerance, highlighting the system's precision. This research underscores the potential of combining human intuition with robotic accuracy in constructing large-scale timber structures, with human input crucial for correcting any assembly inaccuracies.

Keywords: Heuristic Design, Interactive Fabrication, Human-Robot Interaction, Modular Assembly, Robotic Building System

1. Introduction

Research on robot arm construction has progressed along two main trends. At first, the pursuit of automation and efficiency became the focus. Between 1950 and 2010, productivity increased in manufacturing, utilities, agriculture, and transport & warehousing, yet construction productivity showed no significant improvement (Willis et al. [1]). The second trend revolves around precision. It is possible to send design information such as CAD to robots without compression and carry out construction. This enables three-dimensional complex assembly and accurate work (Carpo [2]). Robot arms, operating based on coordinate information in software, can precisely capture positions. Research has explored highly complex designs made possible by the precise construction of robot arms. Over the last few decades, researchers have explored robotic fabrication in large-scale 3D printing (Gosselin et al [3]), complex timber construction (Alvarez et al. [4], Wagner et al. [5]), and free-form patterned brick walls (Dörfler et al. [6]). These use cases take advantage of robots' precision and digital programmability. However, to leverage their high precision, they are mostly used in controlled environments such as fabrication cells or on top of even surfaces to reduce unpredictable variants in the fabrication process, limiting the utility of this highly potent tool. For instance, it makes it hard to use robots in construction sites where the environment is relatively uncontrollable (Edsinger and Kemp [7]). Accordingly, the

Robot Building System has enabled more complex geometry and structural design. On the other hand, it requires extremely precise construction by robots, advanced network systems and fast computational processing by digital technology. Therefore, human involvement lacking accuracy has been minimized in the Robot Building System.

The involvement of humans in the robotic fabrication process is another aspect that is under investigation by many researchers. Human-Robot interactions presents a wide range of new ways we can think about architectural design and fabrication. Involving humans allows us to break away from the execution path-based unidirectional fabrication paradigm of using robots (Knight [8]). This is closer to traditional crafting practices that embrace a more adaptable and iterative process, fostering creativity and flexibility (Knight [9]). This discrepancy has been addressed by Knight and Stiny, who developed a computational framework based on making grammars, extending the scope of shape grammars to encapsulate the temporal dynamics of craftsmanship . Their approach underscores the integral role of sensory feedback in the crafting process, permitting ongoing adjustments and innovation [10]. This theoretical foundation paves the way for more *interactive fabrication* workflows, exemplified by advancements in user-controlled fabrication techniques (Willis et al. [1]). Since information transmission can be instantaneous, real-time prototyping is possible by transmitting designs to robot arms in real-time. An action-state-informed, real-time programming model including ActionIssued, ActionReleased and ActionExecuted allows us to further enhance how to collaborate with a robot (Garcia del Castillo Lopez [11]). Real-time digitally-aided design can help humans design structures with much more freedom and flexibility. Wu and Kilian demonstrate how Deep Learning vision systems enables a robotic arm to adaptively assemble wood logs into structures without prior knowledge of the materials, showcasing the potential for more efficient and flexible human-robot collaborative architectural construction [12]. Even in highly automated and sensor-equiped robotic fabrication frameworks, humans can help with material tolerance issues by holding materials or clamping them (Thoma et al. [13]). Mitterberger et al. demonstrate how humans can enhance robotic fabrication by intuitively knoting structure joints with ropes [14].

Among different approaches in human-robot interactive fabrication, this research focuses on the question of scalability. It seeks to integrate human creativity and intuition with robotic fabrication through computational methods. The goal is to synergize human ingenuity with the precision and efficiency of robotics and digital technology in the design and fabrication process of large structures. The complex geometrical system presented in this research signifies the combination of design freedom and structural stability for crafts-like non-linear fabrication.

2. Research Method

This research introduces a human-robot interaction system wherein the design and assembly processes are carried out interactively by a robot arm with real-time human input. To achieve this, a geometrical system was developed that enables humans and robots to incrementally perform design and construction tasks. It also presents algorithms for automatic robot task execution, informed by the current state of the built structure based on the digital model. It explores human-centric design processes, constructing methods for automated collision avoidance, and calculating the feasible fabrication range to improve assembly flexibility. The timber placement decision-making algorithm is based on a geometrical system and encompasses two distinct approaches: One approach involves an algorithm designed to assist human decision-making by providing supplementary support, while the other entails a computer-based exploratory method utilizing optimization techniques for optimal timber placement without direct human involvement.

As case studies, this article presents meter-scale experimental structures made of smaller parts and how we can grow the structure while keeping the intuitiveness of the design process.

2.1. Geometrical System

In this research, the design is conducted without a predetermined target shape, making it desirable to have minimal constraints imposed by joints. Therefore, we utilized a timber fabrication system called the Connected Stick Geometry System (CSGS), which was previously developed in our research lab. It helps with the incremental placement, exploration, and assembly of timber bars based on simple rules.

The system follows the rule that faces of timber touch each other. The timber square bars may slide or rotate freely as long as their faces touch. Therefore, we can simplify the condition for joint connectivity represented by surface alignment. The status of the joint can be defined in a relative manner in terms of four independent parameters: the shift distance between the connection point and the center of the first unit (S1), the shift distance between the connection point and the center of the second unit (S2), the rotation angle of a joint (RA), and the side of the cuboid having connections (JS) (Figure 1). This relative expression can reconstruct any global assembly status mathematically.

CSGS involves three-dimensional combinations of location and vector coordinates, making it suitable for mutli-axis robot arm assembly. These processes are incrementally performed by both humans and a robot arm. One significant point that makes this geometrical system suitable for real-time decision-making and design lies in its small parts. Having smaller parts in the system allows the designers to enhance their design decisions on the go. With large structures made of large pieces, the effect of each component placement can become quite noticeable and may constrain one's exploration down the line.

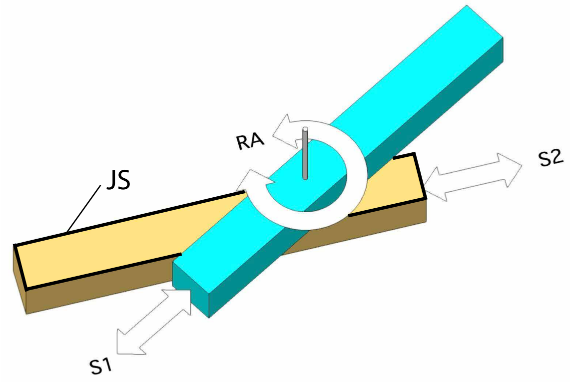


Figure 1. Connected Stick Geometry System

2.2. Assembly Method

This research uses the six-axis robot arm UR10e for assembly. We used RobotExMachina[15] to establish a real-time connection with the robot and to transmit the assembly data to it directly from Grasshopper[16]. We used 18×18×300mm square timber bars as the structure's material. The robot arm applies the adhesive by pressing the gripped part against a syringe containing adhesive (Figure 2), followed by automatic attachment to the structure. Furthermore, to avoid colliding the robot arm's trajectory (Tool Path) with the existing object, the appropriate path is automatically selected from multiple accesible tool paths.

Figure 2. Assembly process by the robot

The Tool Path can be determined by setting intermediate points that can help the robot find the appropriate approach tool path. We identified approach movements along the length of the timber bars to be the most collision-free paths. Thus, the trajectory of the gripper is defined as a collision check box, enabling the calculation of collisions between this box and existing objects. There are two types of tool paths (Figure 3). Based on the calculation results of each path, the non-colliding one is automatically transmitted to the robot arm.

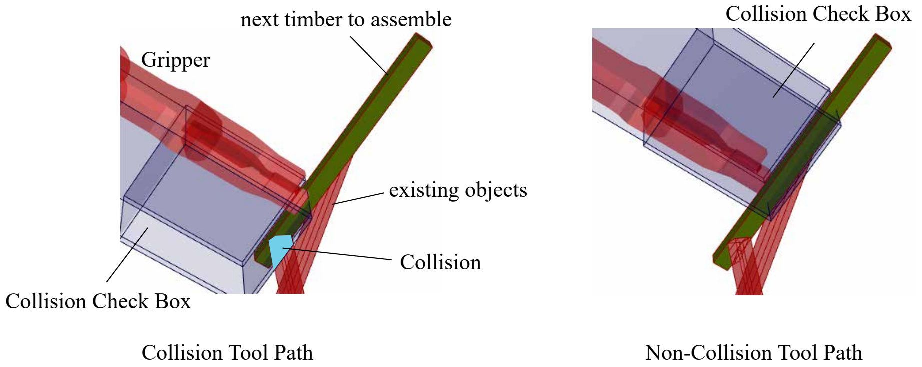


Figure 3. Non-Collision Path Finding algorithm

3.3. Timber Placement Decision-Making Algorithm

Timber placement can be either a branching placement or a linking one. With branching, the human expands the structure and navigates the growth. With linking, two existing timbers are connected by two new placement timbers (Figure 5). In the branching placement, the placement exploration is assisted by a navigation algorithm that visualizes two evaluation values: (1) the possibility of robot arm assembly and (2) the structural recommendations. In (1), the evaluation value is the number of collisions that the robot arm may have with the existing structure during the approach movement. If assembly is possible, the placement timber is colored green; otherwise, it is colored yellow. In (2), the structural recommendations are visualized on the connection surface based on the maximum tensile force applied to all joints. This endeavor aims to prevent joint break and minimize disparities between digital and physical models. Furthermore, conducting analysis and visualizations at each assembly step serves to assist the human design processes. This paper used linear analysis of the finite element method with Karamba3D in Grasshopper to calculate the axial forces on the joint surfaces. The purpose is to ensure that the maximum axial force at the joints does not exceed the adhesive bond strength (15 N/mm^2). The alanysis was visualized for the human user by color-coding the surface of the timber joint (Figure 4). Humans explore and decide the timber placement based on the above navigation algorithm.

The linking placement is an arrangement where two timbers (Blue, Purple) are connected by two new members (Yellow, Orange), and computer-based optimization with genetic algorithms is used for the search (Figure 5). Any 3D normal vector of two different surfaces can be resolved into two specific angles of two orthogonal axes. However, when the theoretical connection point falls beyond the length of these two units, it is impossible to join them. Thus, the joint can be fixed in specific shift distances constraint by the length of the member; impossible shifts and angles require extra members to be added to the structure. We use a genetic algorithm to find a solution in the assumed condition (Figure 5). The linking placement is used to verify the assembly accuracy, as the four timbers must be assembled without errors with the computer model in order to be in contact with each other.

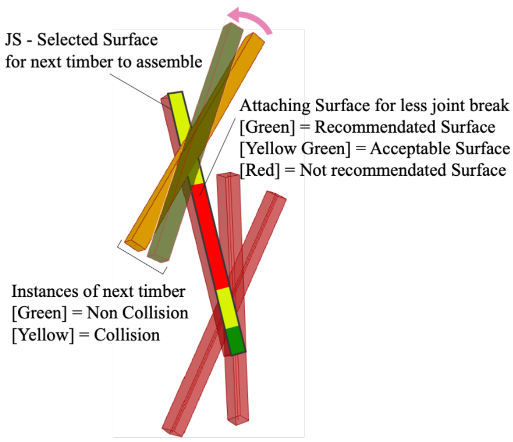


Figure 4. Navigation of the timber placement

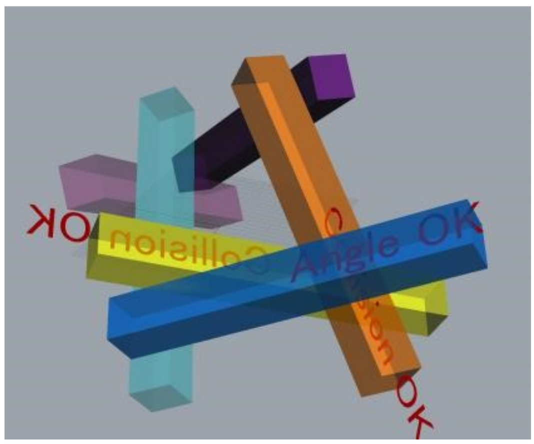


Figure 5. "Linking module"(yellow and orange) connecting target unit (blue and purple)

4. Case Study Experiments

To design and assemble large timber structures with human involvement in robot fabrication, it is effective to divide the structure into units that can be handled by a robot arm or humans (Figure 6). In this research, we produced two types of structures: one requiring meter-scale height and the other requiring complexity. In Experiment 1, we fabricated a column-shaped structure. In Experiment 2, we created a tree-like complex structure with many joints for stability. For each experiment, we developed and analyzed assembly methods such as an Arduino-controlled rotation table and conducted assessments of construction accuracy and verification of structural analysis algorithms.

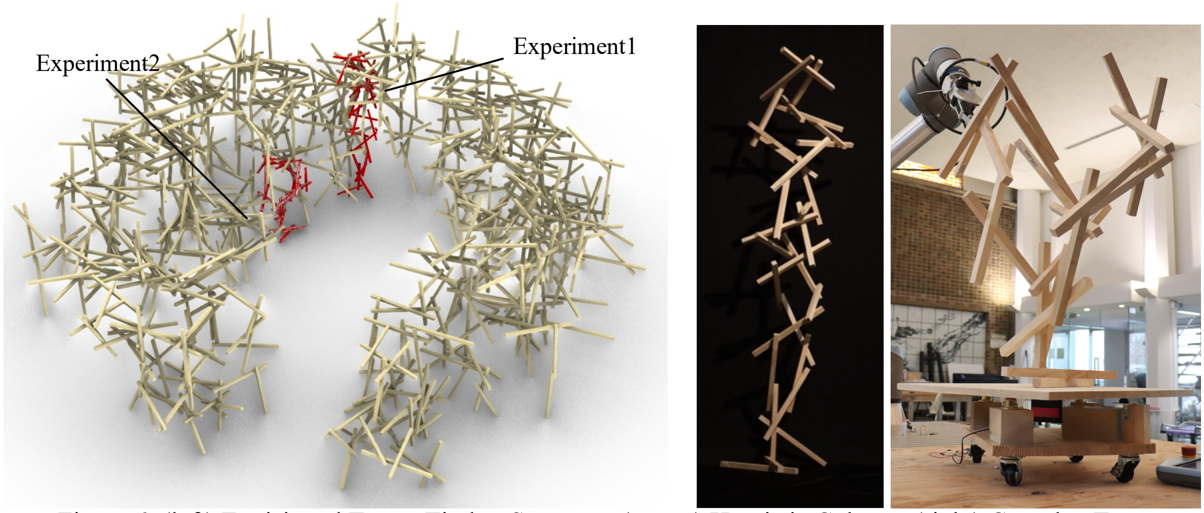


Figure 6: (left) Envisioned Target Timber Structure, (center) Hueristic Column, (right) Complex Tree

4.1. Experiment 1 – Heuristic Column

In Experiment 1, a 1.6-meter-long structure was produced, in the form of a spiral. The two halves of the spiral were connected by two linking placements (Figure 6). The two linking placements were assembled accurately with an average error of 1.2 mm (24th to 28th timbers), demonstrating the precision of the assembly and the predicting computational model.

Due to the limited Motion Range (MR) of the robot arm, assembly was conducted at two heights: on a table with a height of 800mm and on the floor. When changing heights, we calibrated the assembly by moving the robot's gripper to match the vector coordinates that was perpendicular to a specific timber bar's surface on the existing structure (Figure 7).

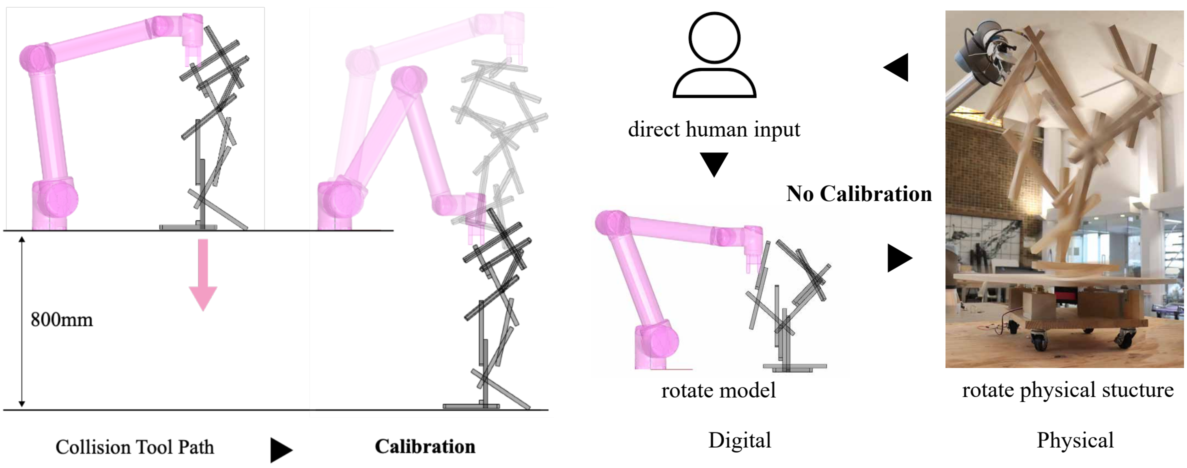
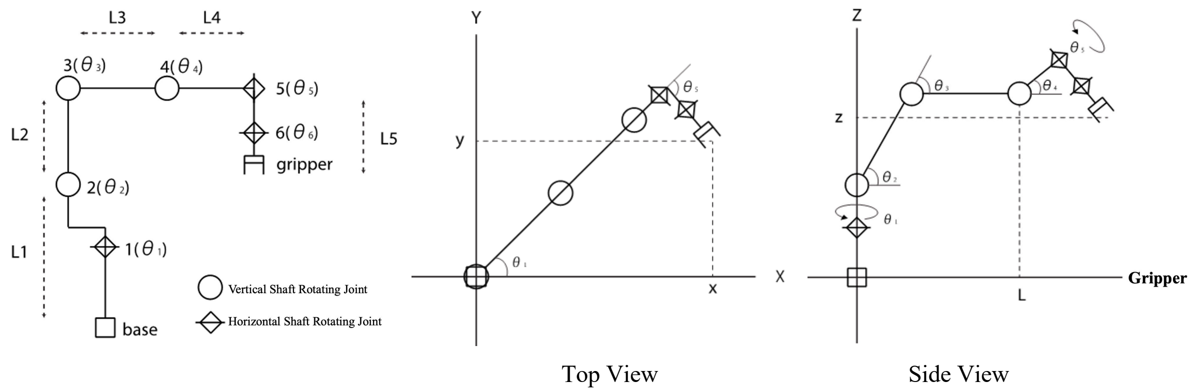


Figure 7. Accounting for the robot's fabrication range by elevating (left) or rotating (right) the structure

On the other hand, there were many areas that could not be assembled within the MR, requiring human intervention to anticipate the fabricable range (FR) considering assembly robot approach motion during the decision-making process. This is because timber assembly requires not only coordinate information but also vector information. The robot arm consists of Vertical shaft rotating joints that rotate on x-y coordinates (Top View) and Horizontal shaft rotating joints that rotate on z-gripper coordinates (Side View), and the TCP plane of the Gripper tip coordinates can be illustrated schematically in the following diagram (Figure 8).



L1 = 181, L2 = 613, L3 = 571, L4 = 120, L5 = 460 (mm) $0 \leqq \theta_1 \leqq 360$, $0 \leqq \theta_2 \leqq 180$, $0 \leqq \theta_3 \leqq 180$, $0 \leqq \theta_4 \leqq 360$, $0 \leqq \theta_5 \leqq 360$

Figure 8. Robot FR calculation mehtod based on arm lengths and angles

From Figure 8, the TCP Plane can be obtained in the following equations.

$$L = L2\cos\theta 2 + L3\cos\theta 3 + L4\cos\theta 4 \tag{1.1}$$

$$z = L1 + L2\sin\theta 2 + L3\sin(\theta 2 - \theta 3) + L4\sin\theta 4 + L5\cos\theta 5\sin(\theta 4 - 90) \tag{1.2}$$

$$x = L\cos\theta 1 + L5\sin\theta 4\cos(-\theta 5 + \theta 1) \tag{1.3}$$

$$y = L\sin\theta 1 + L5\sin\theta 4\sin(-\theta 5 + \theta 1) \tag{1.4}$$

From the above equations, the following MR and FR are obtained. For the FR, substitute θ4 = (θ2 - θ3) - 90 and θ5 = 0, where the gripper is in the opposite direction to arm(L).

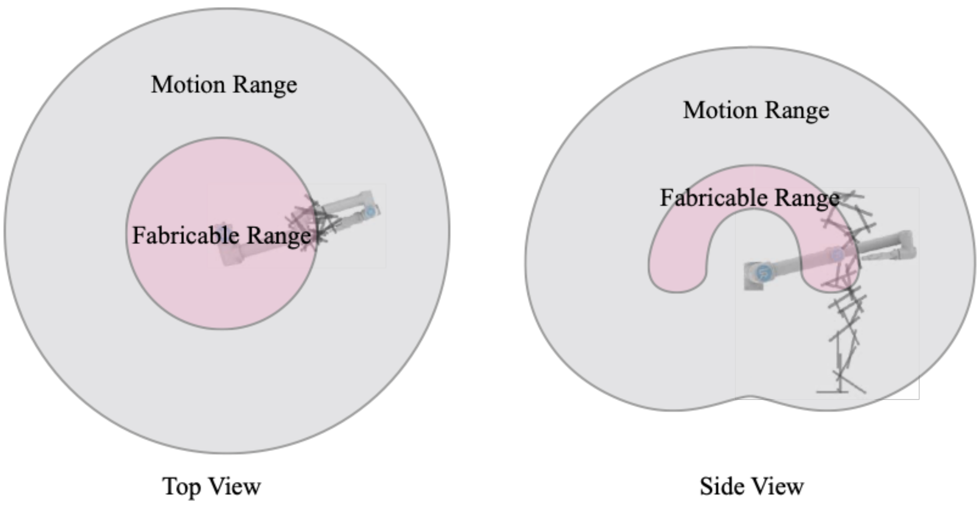


Figure 9. Motion range of robots arm and fabricable range for the structure

We confirmed the validity of the calculations by visualizing the FR, and it is found that the volume of the FR is extremely small, approximately 6% of the volume of the MR. While the equasions are specific to our robot setup and may not be generalizable, they provided valuable information about the robot's movement limitation (Figure 9). Adjusting for this limited FR we managed to build the structure without hitting joint limits. Singularity points, on the other hand, had to be checked by the human user who observes the robot’s motion simulation.

4.2. Experiment 2 – Complex Tree

In Experiment 2, we fabricated a complex structure resembling tree branches(Figure 6). Each branch was connected using linking placements to ensure structural integrity. Furthermore, to improve the FR limitations discovered in Experiment 1, we developed a rotating table to enhance assembly flexibility.

The rotation degree is controlled using Grasshopper, FireFly[17], and an Arduino, eliminating the need for calibration with each rotation (Figure 7). However, direct input of rotation angles is necessary, and the development of automatic angle adjustment methods is anticipated.

While the rotation table facilitated the assembly of a structure where timbers were closely aligned, the precision of the table resulted in a larger average error of 1.4 mm for each timber. This discrepancy can be attributed to the accuracy of the rotation table.

5. Results and Discussion

In this study, we developed a solution for human-centric robotic timber structure assembly for larger structures made of smaller parts. Additionally, we conducted experiments to validate these methodologies and tested two types of assembly methods. In this section, we will evaluate the effectiveness of the robotic assembly based on the experimental results and assess the algorithm's performance through structural analysis.

5.1. Robotic Assembly

In experiments 1 and 2, the accuracy of the assembly was insufficient, necessitating human intervention to support the robotic attachment process. The reasons for this included assembly errors or dimensional discrepancies in the materials, as well as the inability of the existing timbers to withstand the pushing force exerted by the robot arm during attachment, resulting in displacement. To specifically evaluate the load-bearing capacity of individual timbers within the timber structures, we measured the displacement when applying a 1 N tensile force to the outer surface of the joint (Figure 10). The average displacement observed in experiment 1 was 23.6 mm/N, while the average strength recorded in experiment 2 was 4.05 mm/N. Figure 10 shows that in Experiment 1, as the number of timber bars increased, the displacement also increased. This suggests that the effect of the moment due to greater distance from the ground became more pronounced, resulting in a larger average displacement compared to Experiment 2. In the future, clarifying the relationship between these displacement values and attachment accuracy is expected to enhance the precision of automatic assembly by incorporating this information into the structural eecommendation algorithm.

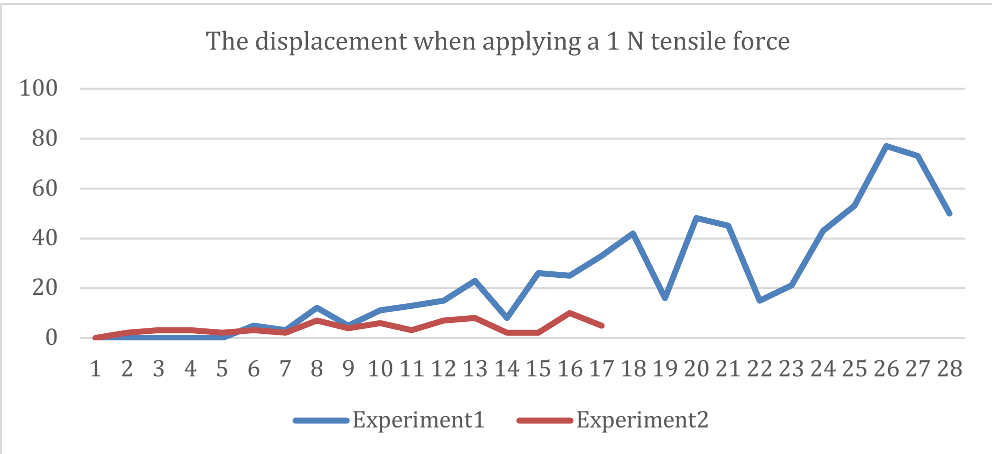


Figure 10: Timber placement deviation (mm/1N) tends to increase per timber bar placement. However, the rleation is not completely linear.

During the robotic timber placement, we measures the distance between the current structure and the timber bar gripped by the robot (Placement Deviation) for each timber placement. Considering 1 millimeter as the acceptable devation, Figure 11 shows whether we had a successful automatic robotic placement (〇) or one that required human intervention (×).

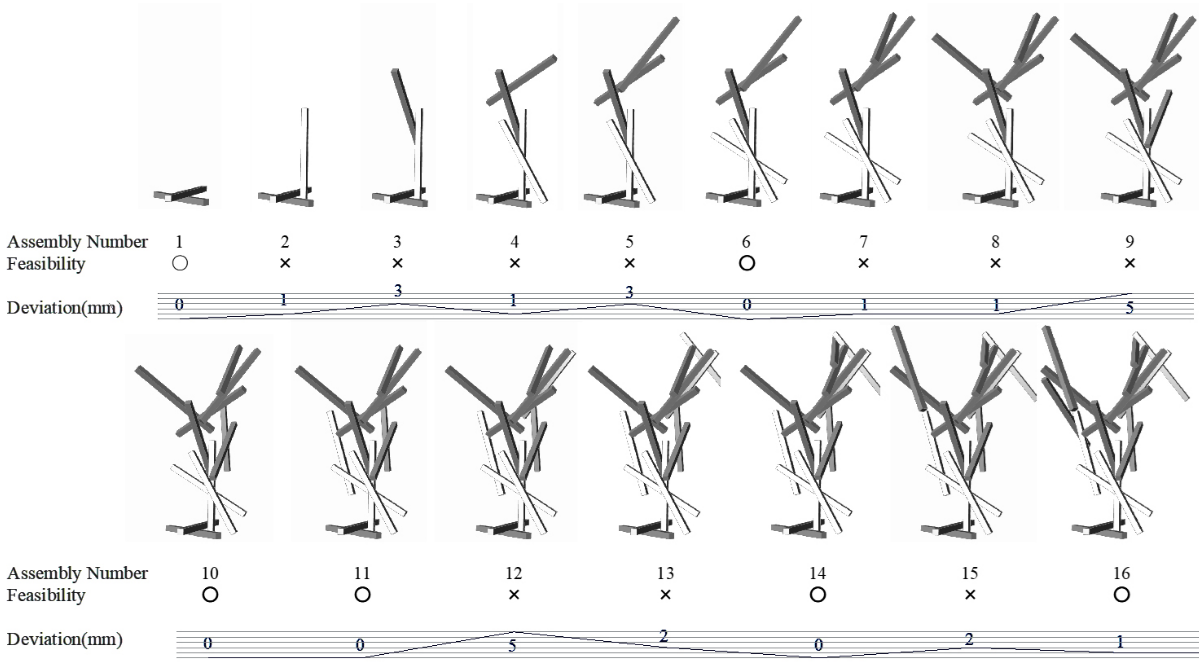


Figure 11: Step-by-step placement deviation measurement and feasibility of automatic assembly

4.4. Validation of the Navigation Algorithm

After the experiments, we conducted structural analysis of the assembled structures to analyze deformation and the tensile forces acting on the joints. Regarding deformation, it was indicated that the maximum deformation was 2.57 mm in Experiment 1 and 0.47 mm in Experiment 2 (Figure 12). Furthermore, concerning the tensile forces on the joints, values of up to 6.5 N/mm^2 in Experiment 1 and 2.5 N/mm^2 in Experiment 2 were obtained (Figure 13). As previously mentioned, the Structural recommendation within the Timber placement decision-making algorithm aims to ensure that the tensile forces on the joints do not exceed 15 N/mm^2. Both Experiment 1 and Experiment 2 meet this structural constraint. The afterwards analysis verified that the structural recommendation navigation algorithm was functioning correctly. The deformation analysis here provides more insight to the structure's behaviour, propmting further explorations on implenting this tool into the design stage as well.

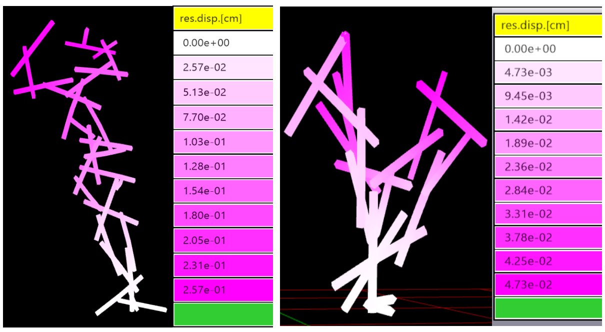


Figure 12. Deformation analysis of entire structure

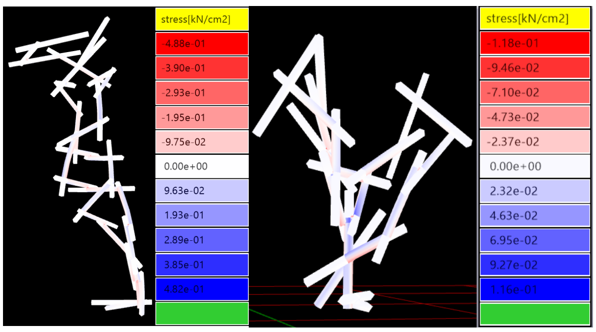


Figure 13. Tensile force analysis of entire structure

6. Conclusion and Future Prospects

In this case study, it became evident that an interactive design and fabrication workflow involving both humans and robots was achievable. The navigation system assisted human involvement in an advanced design process, while the three-dimensional fabrication process was executed by robotic arms. However, designing and assembling incrementally, one by one, without pre-determining the final shape, proved to be a time-consuming process. This inefficiency can largely be attributed to challenges in the automatic assembly process and the imperfect nature of computer-assisted linking placement algorithms.

Initially, the automatic assembly process was envisioned to be fully automated by the robot arm for picking up timber, applying adhesive, and assembling. However, it was discovered that automated assembly, particularly during the assembly process, proved difficult due to errors and structural vulnerabilities. Humans needed to adaptively assist the robot assembly process by observing and intervening as necessary. It became apparent that the distinction between successful (〇) and unsuccessfull (×) automatic timber placement was unrelated to the construction stage (Figure 11). Therefore, it is likely that construction errors are not due to discrepancies between the digital and physical models caused by structural deformation. Rather, these errors are more likely attributed to inaccuracies in the dimensions of the timber materials. Moreover, in the design process, the linking placement finding algorithm, aimed at exploring configurations to join two timbers with new components, did not always find suitable placements, necessitating more time-consuming decision-making by humans regarding timber placement. Additionally, in Experiment 2, the rotation angle of the table was manually determined by human direct input, requiring time to locate assembly-compatible angles. From these observations, it can be concluded that human intervention was necessary to assist the robot arm and compensate for the imperfections in design algorithms and assembly methods, resulting in an inefficient approach.

On the positive side, involving humans in the robotic fabrication process eliminates the need for highly advanced algorithms and fabrication techniques. The effectiveness of the navigation system was confirmed through structural analysis after the experiment, and humans were able to design complex three-dimensional timber structures, validating the accuracy of the robotic arm and fabrication system.

Such fabrication processes will enable the construction of buildings in environments where more adaptive design and construction are required in the future. The addition of human flexibility and intuition to robot fabrication allows for adaptive architectural production. For example, in constrained urban spaces where conventional construction machinery faces difficulties entering and existing buildings surround the area, adaptive and incremental construction while interpreting the existing urban context may be required. In such locations, rather than large-scale "scrap and build" approaches by city block, there may be a new paradigm of architectural production through collaboration between robots and humans, adapting to the environment (Figure 14).

Figure 14: Human-robot collaborativly assembled public communal space

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