Reinterpreting the Dougong joint by using parametric design methods and robotic fabrication technologies: a critical review

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The paper finds its roots in our previous research, which explored the application of robotic technologies for the fabrication of traditional Chinese timber joints and the reinterpretation of the Dougong joint (bucket arch joint) by using parametric tools and robotic fabrication techniques. It investigates which existing robotic technologies are suitable for the automated assembly and production of the Dougong joint through reviewing relevant research. The paper systematically reviews and comparatively analyses ten articles filtered through 1,756 publications searched by using the keywords 'timber', 'digital fabrication', and 'robot' in the databases Scopus, CumlnCAD, ScienceDirect, Engineer village and IEEE (Institute of Electrical and Electronics Engineers). Our findings include a comparative analysis chart evaluating workflows, tools and technologies on their suitability for the robotic reinterpretation of the Dougong as well as the proposal of a novel design to fabrication workflow for that particular purpose.

Keywords: *Dougong joint, timber structures, parametric design, robotic fabrication, optimisation algorithm*

INTRODUCTION

The brief history of Dougong

Timber structures are the primary structural systems in traditional Chinese buildings. The Dougong is a particular component in conventional Chinese timber structural systems due to its mechanical function, modular production method, and elegant form. It is a wooden joint integrated with load-bearing and decoration functions (figure 1). The Dougong transfers the loading from the roof and overhanging structure to the pillar (Dehua, 2011). Its components could be designed and produced modularly and connected by tenon and mortise. It consists of two kinds of bow components (Goug and Qiao), a beam component (Ang), and two square components (Dou and Sheng), (figure 2), which relate to each other with mortise and tenon joints (Ma, 2003). According to its position inside the building, there are two types of Dougong, the external eave and the inner eave Dougong (Ma, 2003). These two types are in the extension and inside the eaves of the traditional Chinese building, respectively.

The Dougong has a long development history, and its earliest images can be found on bronze patterns and murals inside ancient tombs more than 2000 years old. However, the Dougong components' names before the Song Dynasty (960-1279) are challenging to regain due to no related sources being referenced (Liang, 2006).

Two crucial historic rulebooks are the Yin Zhao Fa Shi, competed by Li Jie in the Song Dynasty (960-1279), and the Gongchen Zuofa Zeli, published by the Ministry of Construction of the Qing Dynasty in 1734 (Dehua, 2011), which are the primary sources used for the understanding and reinterpretation of the Dougong joint.

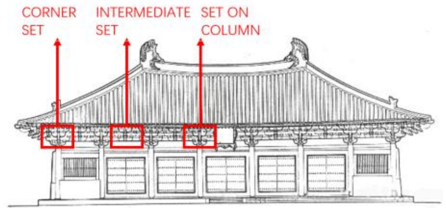

Figure 1
The locations of the Dougong in historic Chinese buildings (Zhao et al. 2021)

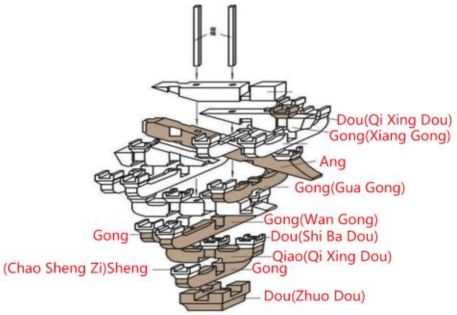

Figure 2
The structure of the Dougong (Zhao et al. 2021)

Current research about digital fabrication in timber frame joints and structures

Some architects and researchers have applied the principles of Dougong in contemporary architectural design. Kengo Kuma introduced the connection method, mechanical property, modular concept, and decorative function of the Dougong system in his designs. Two projects, the Climbable Wooden Pavilion in Paris park and Sun Hill in Japan (2013), applied the tenon and mortise principle, modular production, and the layer assembly method of the Dougong to connect and fabricate the timber beams along the vertical direction. Kengo Kuma designed other four buildings in Japan, the Yusuhara Wooden Bridge Museum (2010), the Prostho Museum Research Centre (2010), the Café Kureon(2011), and the Coeda House (2017), where both mechanical properties and decorative functions of the Dougong were applied. The Chinese pavilion at the Shanghai World Expo 2010 was designed by He Jintang according to Dougong's mechanical characteristics.

Some researchers have applied robotic technology to fabricate Dougong joints. Lange (2017) studied how to automate the design and fabrication of contemporary timber structures based on three traditional Chinese structural systems, namely the Dougong joint, the reciprocal structure in the arch bridges, and the Chidori system. Takabayashi and Kado (2018) explored the feasibility of using robotics to produce traditional Japanese wooden buildings, including the Dougong joint, the pillar and roof beams referring to original crafting skills. Chai et al. (2019) robotically produced and assembled manually a timber tower consisting of various wooden beams designed based on the connection method of the Dougong joint. Finally, in our previous work (Zhao, Lombardi, and Agkathidis 2020; Zhao et al., 2021), We explored the design principles of the Dougong joint based on its dimensions, connection rules and mechanical properties. We presented a digital design workflow, integrating topology optimisation, voxelisation, and multiple optimisations. In continuation, this paper aims to find a useful robotic fabrication workflow, which we can apply to our future research on the reinterpretation of the Dougong joint. Furthermore, the selected research projects demonstrate the application value of the Dougong in contemporary timber constructions and its potential in digital design and robotic fabrication thanks to its modularity, efficient structural performance, and aesthetic value.

Review questions and aims

Although the Dougong joint has been applied to build contemporary architectural projects no scholars have systematically summarised and deeply studied the application of digital design and robotic fabrication techniques to rethink the digital construction of the Dougong joint. In continuation to our previous research, the current paper investigates which existing robotic technologies are suitable for the automated assembly and production of the Dougong joint and its related timber components. In particular, this paper addresses the following research questions:

- Which existing robotic fabrication technologies would be more suitable for the reinterpretation of the Dougong joint and its utilisation in contemporary architecture?
- What are the advantages/disadvantages of utilising robotic technologies for the construction and assembly of timber frame structures?

Review methodology

The systematic review method consists of four phases as can be seen in figure 3, including 1) searching papers through databases (Scopus, IEEE, Engineering Village, CumInCAD, and ScienceDirect), 2) screening the selected papers, 3) comparatively analysing and categorising of the papers and 4) evaluating the research in charts and tables.

In the first phase, our search focused on the databases Scopus (Elsevier's abstract and citation database), IEEE (Institute of Electrical and Electronics Engineers), Engineer village, CumInCAD (Cumulative Index about publications in Computer Aided Architectural Design) and ScienceDirect due to their accuracy, reliability, and completeness. We have searched after the keywords' robot', 'digital fabrication', and 'timber' in titles, abstracts and given keywords of the articles. There are more conference papers than journal papers since the digital design and robotic fabrication of timber structures is a new research field. Most articles occurred in, the database CumInCAD, the database of digital design in architecture supported by the relative associations ACADIA, CAADRIA, eCAADe, SIGraDi, ASCAAD, and CAADfutures, however, Scopus and ScienceDirect comprise the journal articles and book sections related to our research. The IEEE and Engineer village are applied to avoid ignoring any academic practice related to our topic. Subsequently, our research has screened 1,756 academic publications consisting of 1,581 conference papers in CumInCAD, 164 articles in ScienceDirect, and 11 papers in Scopus. There are no relative papers in the databases of IEEE and Engineering village.

In the second phase, the articles were filtered, by removing duplicated papers, review publications, and low-relevance articles. The first filtering took place by using the databases' filtering tools, whereby 72 articles were removed.

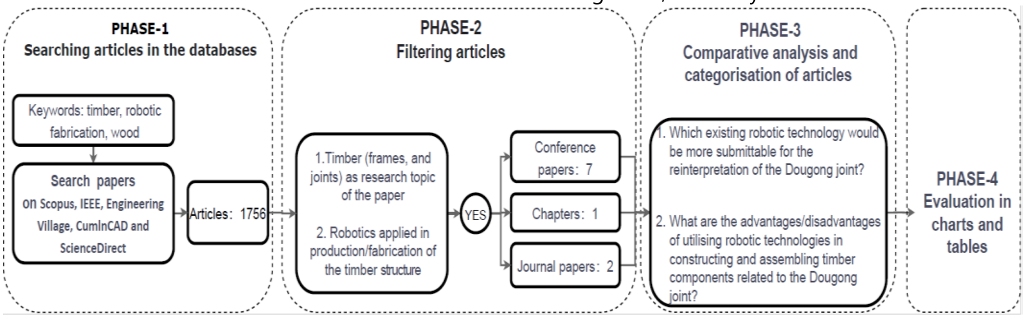

Figure 3
Flowchart of the systematic review process.

The remaining 1,684 articles were reviewed by reading their abstracts. In the second filtering, the papers on news, short messages and reviews were removed. Furthermore, the articles not dealing with robotic fabrication of timber joints or frame structures (e.g. walls, shells, and interior fittings) were also removed. In total there were additional 1,674 articles removed, resulting in the remaining 10 articles which we present here.

In the third phase, the remaining 10 articles were systematically categorised and analysed according to three categories: 1) the workflow of digital design 2) types of robots and their end-effectors, and 3) robotic fabrication method. The final article selection includes one book chapter, two journal articles and seven conference papers. Three articles are using KUKA robots, three articles UR robots, and two ABB robots. Five articles examined the reinterpretation or reproduction of the Dougong joint or similar structures. Five articles explored the application of gripper end-effectors and three explored the use of a robotic arm for the fabrication of timber beams. Finally, in phase four, these categorised articles are analysed and compared to answer our research questions.

ANALYSIS OF THE FILTERED PAPERS

Digital design and optimisation methods

Chai and Yuan (2019) designed various innovative beams according to the analysis of the connection methods between components of the Dougong joint. In the optimisation stage, Karamba3D, a plugin in Grasshopper, was applied to optimise the section size of beams used to assemble a timber tower. In the fabrication stage, the beams were produced with two KUKA robots and assembled layer by layer manually. The layering assembly method is accurate and efficient, suitable for our research on the Dougong joint.

Naboni and Kunic (2019) and Kunic, Naboni, et al. (2021) described a workflow integrating timber unit design, topology optimisation and robotic fabrication. They designed a bridge made of simply shaped units that are easy to be mass-produced by a CNC router and assembled by a robotic arm. The units' positions were arranged along the stress lines of the bridge design, utilising the analysis of Millipede, a Grasshopper plugin for topology optimisation. In their latest paper (Kunic, Kramberger, et al. 2021) presented a robotic assembly and disassembly method for modular timber units. They used two UR robots to pick the components up from a storage space and place them in the right position, then fix them with a screwdriver. After that, the robots unscrewed the screws and moved the components back to the storage space enabling the recycling of the units. The Dougong joint is a similar system, thus the recycling workflow and layering fabrication method could be suitable techniques to use for its reinterpretation.

Koerner-Al-Rawi et al. (2020) introduced a new workflow for the assembly of the Chidori joint, a traditional Japanese interlocking toy with three wooden beams. Their workflow includes three phases: the connection method of the Chidori joint, the physical model's production according to the digital model, and the robotic fabrication process optimisation by designing the gripper's device. Their timber unit was composed of two beams, which were designed based on the discrete theory and assembled by a robotic arm to test the flexibility of the workflow. The feedback loops played a significant role in optimising the robotic fabrication process. The feedback data collected during the fabrication process helped them to redesign the gripper's fingers, making them suitable to catch the beams accurately and firmly. The introduction of similar feedback loops can be useful to our research process as well, e.g. for adjusting the assembly sequence and editing the robotic workflow, making the process more accurate and efficient.

Lange (2017) presented a workflow of rethinking three traditional wooden structural systems, the Dougong joint, a reciprocal system and the Chidori system. The workflow includes three phases, 1) the study of the connection method of three systems, 2) the design of wooden frameworks based on the study of phase one, and 3) the design of a bespoke end-effector of the robotic arm. The researchers produced the design components with an ABB robot mounted with the bespoke gripper, and a router fixed on the table. It appears that the CNC router is still more efficient than the method used in Lange's research to mass produce wooden structural components. Therefore, the CNC router could be a reasonable choice in the mass production of Dougong components.

Kontovourkis (2017) described a workflow integrating digital design, multi-objective optimisation, and robotic fabrication. Their timber frame pavilion was optimised during the design phase by minimising material usage and maximising the usable interior space using the Octopus plugin for Grasshopper. Their fabrication phase includes the assembly of a foam beam pavilion to collect the data which were used to later optimise the fabrication process of the timber components. Using foam mockups to test the fabrication of the design object before using the wooden material would also be helpful for our own research. That would help us prevent errors in the construction of the costlier timber frame structure.

Finally, in our previous work (Zhao, Lombardi, and Agkathidis 2020; Zhao et al. 2021) we have introduced a design approach that, which integrates topology optimisation, voxelisation and multi-objective optimisation and applied it in order to rethink the Dougong joint in a contemporary architectural context of a footbridge design. We have introduced a modular unit based on the underlying principles of the Dougong, maintaining its proportions, connection methods, and mechanical properties. The arch bridge structure consisting of the new modular unit is designed and optimised with topology and multiple-object optimisation methods using the Millipede and Wallacei plugins, respectively.

In summary, our findings from analysing the design and optimisation methods of the selected papers highlight that their workflows generally consist of three phases: 1) the digital design of the object, 2) the optimisation of design, and 3) the automated assembly of the design. One of the papers is about reproducing the corner part of a

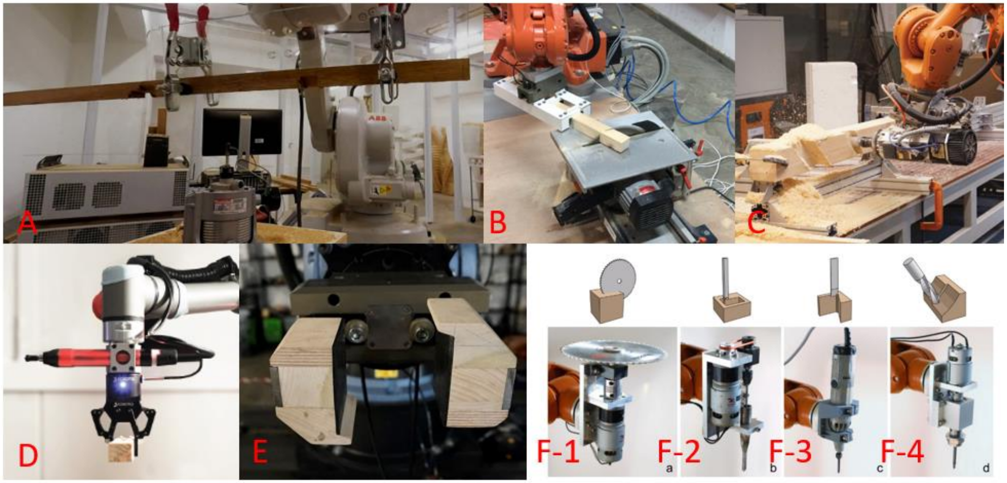

Figure 4
The end-effectors of the robotic arm in the selected papers: A: a tool designed for holding beams (Lange 2017); B: a custom-made end-effector gripper for material handling; C: the spindle for milling beams (Chai et al. 2019); D: a multi-function tool (a gripper, a Camera, a screwdriver and a switch for interaction between human and robot) (Kunic, Kramberger, et al. 2021); E: a custom-made gripper for holding the beam in the fabrication process (Koerner-Al-Rawi et al. 2020); F: (F-1) circular saw, (F-2) square chisel, (F-3) vibration chisel, and (F-4) router (Takabayashi and Kado 2018)

Table 1
The ten articles are analysed on the side of digital design and optimisation, and robotic fabrication.

The digital design	The type of optimization	Fabrication methods	Robotic types	Robotic end-effectors	The number of robotic arms used in research	The type of articles	The research object includes Dougong joint	Reference
Three timber arch structure designed based on Dougong joint, the reciprocal system and the Chidori system		layer fabrication method with the robotic arm	ABB	Tools designed by researchers for holding beams	1	CONFERENCE	YES	Lange, 2017
Freeform timber frame pavilion	Multi-objective optimization	layer fabrication method with the robotic arm	ABB robot, model IRB2600-20/1.65.	A custom-made end-effector gripper tool mounted on the edge of the robotic arm is used for material handling.	1	CONFERENCE	NO	Kontovourkis, 2017
A timber tower consisted of beam designed based on the connection methods of Dougong joint	Topology optimization	The robot produces the components assembled munally	KUKA KR60, KUKA KR120	Milling: two spindles (each robot arm equips a same spindle).	2	CONFERENCE	YES	Chai et al., 2019
A wooden bridge consisted of vaouris components.	Topology optimization	layer fabrication method with the robotic arm	UR10e, UR5e	Two end-effector with an electric gripper	2	CONFERENCE	NO	Naboni and Kunic, 2019
A unit designed based on the properties of the Dougong joint.	Topology optimization and multi-objective optimization					CONFERENCE	YES	Zhao, Lombardi and Agkathidis, 2020
A wooden construction element could be re-assembled		layer fabrication method with the robotic arm	UR10e, UR10e	The two Ur10e robots are equipped with a multi-function collaborative assembly tool (an electric 2F85 Robotiq gripper, a Robotiq Camera, an electric Dessouter screwdriver and a bespoke wrist switch for interaction between human and robot).	2	CONFERENCE	NO	Kunic, Kramberger, et al., 2021
An arch bridge consisted of modular units designed based on the Dougong joint	Topology optimization and multi-objective optimization					CONFERENCE	YES	Zhao et al., 2021
An interlock timber system designed based on the Chidori joint.		layer fabrication method with the robotic arm	KUKA KR-150	The Schunk PGN + 200/1 gripper	2	JOURNAL	NO	Koerner-Al-Rawi et al., 2020
A wooden bridge consisted of vaouris components.	Topology optimization	layer fabrication method with the robotic arm	UR10e UR5e	Two end-effector with an electric gripper and an industrial screwdriver	2	JOURNAL	NO	Kunic, Naboni, et al., 2021
		The robot produces the components assembled munally	KUKA KR 6 R 700	Developed tools and processing examples: (a) circular saw, (b) square chisel, (c) vibration chisel, and (d) router	1	CHAPTER	YES	Takabayashi and Kado, 2018

traditional timber tower in Japan. Five papers designed timber objects based on traditional structural systems such as the Dougong joint, the Chidori system and the reciprocal system. Four papers developed new structural systems such as the timber bridge consisting of various units and the freeform timber frame pavilion. Two articles applied topology and multi-objective optimisation in their design; two only explored the possibility of using topology optimisation. Only one paper utilised the multi-objective method in a freeform timber pavilion. The other article utilised Karamba3D to optimise the structure layout, mainly the section size and length of beams. Finally, six papers introduced the layer fabrication method using robotic arms.

Robotic technologies and fabrication techniques

Takabayashi and Kado (2018) explored how to apply a KUKA (KR6 R700) robotic arm set up with a circular saw, square chisel, vibration chisel and router to reproduce the components, including the Dougong joint of a corner part of a traditional Japanese building. Their method is valuable for heritage conservation. Chai and Yuan (2019) utilised two robots equipped with the spindle, a fixed KUKA KR60 and a KUKA KR120 on a linear rail, to produce the new unit design based on the connection methods of the Dougong joint. However, their production efficiency is not higher than the one produced by a CNC router. Thus, using a CNC router to produce the modular components in our research would be equally efficient as using a robotic arm for the same purpose.

Lange (2017) explained how to utilise an ABB robot with three bespoke end-effectors to hold the beam and mill the tenon and mortise with the assistance of a fixed spindle (figure 4). Although the robotic fabrication technology could produce wooden joints, the CNC router still plays a vital role in mass production due to its high work efficiency. Therefore, CNC routers could be more

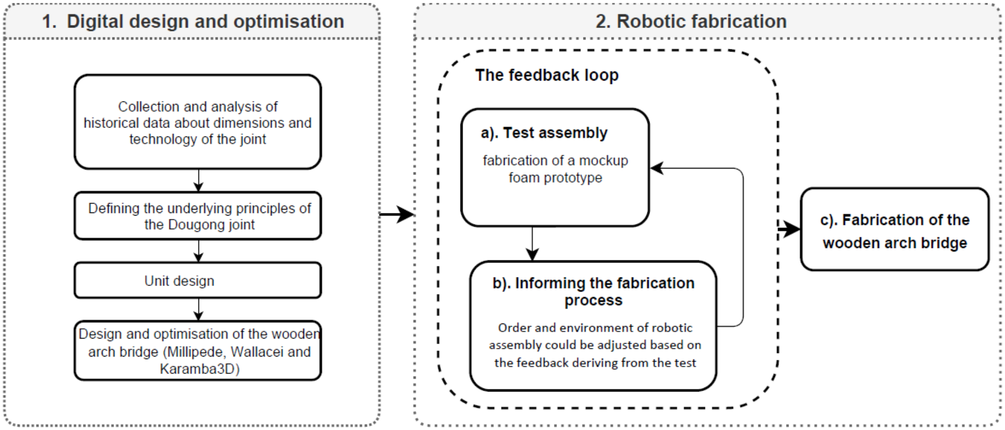

Figure 5
The new workflow for rethinking the Dougong joint based on the review.

helpful to mass-produce the modular Dougong joint in contemporary constructions.

The remaining five articles introduced the robotic gripper as the main assembly tool for timber joints and beams. Kontovourkis (2017) used an ABB IRB2600-20/1.65 robotic arm with a bespoke gripper to hold and cut the wooden beam with the assistance of a fixed circle saw. The beam is placed in the position in the wooden beam pavilion by the robot and fixed manually. Koerner-Al-Rawi et al. (2020) presented a workflow using two KUKA KR-150 robots with bespoke grippers to assemble a traditional interlocking joint (Chidori joint) produced by a CNC router. Naboni and Kunic (2020) put forward an automated fabrication workflow by using two UR10e robots to fabricate a timber bridge composed of various modular units produced by the CNC router. Additionally, they have improved the assembly efficiency by applying a UR10e robot with a gripper and a UR5e robot with a gripper and an industry screwdriver (Kunic, Naboni, et al. 2021). Similarly, they used the same robot to research reassembling and disassembling timber structures (Kunic, Kramberger, et al. 2021). Dougong's modular components are based on the tenon and mortise principle, thus the automated assembly process primarily consists of picking and placing. Consequently, a robotic arm equipped with a gripper would play an essential role in rethinking the Dougong in our research methodology.

CONCLUSIONS

According to table-1, we have identified three primary phases in all the design to fabrication pathways presented: 1) the digital design of the object, 2) the design optimisation, and 3) the automated fabrication and assembly. Two design and optimisation methods were presented. One is about designing the wooden components based on the primary analysis of the connection method, their dimension and the mechanical properties of the traditional timber structural system. The second one is focusing on designing novel components, adjusted to the needs of robotic fabrication and automated assembly techniques. Optimisation tools, such as the Millipede, Wallacei and Octopus plugins for Grasshopper have been used for topology optimisation and multi-objective optimisation accordingly.

Regarding the fabrication phase, we have identified the use of KUKA, ABB, UR robots, whereby UR robots were the most commonly used. We have observed two digital fabrication methods. The first one includes robotic arms (KUKA and ABB) equipped with a custom-made spindle and gripper end-effector, or a circle saw end-effector for cutting, milling and assembling timber components. The second one is based on the production of timber components by a CNC router. The layer-by-layer automated fabrication method appears to be the most popular and effective assembly method.

The review also provides new insights regarding our research methodology aiming to reinvent the Dougong joint. Consequently, we are proposing a new workflow (figure 5) based on the literature review findings. We will start with a design and optimisation phase, based on the collection and analysis of historical data about the dimensions and technology of the Dougong joint. Once we identify its underlying principles, we will design a new unit suitable for mass production and robotic fabrication and test it on the design and fabrication of an arch timber. We will firstly optimise the bridge structurally and fabrication wise then proceed with its fabrication and verification of the entire process and performance.

Our software tools include Rhino3D and the Grasshopper plugins Millipede, Wallacei, Karamba3D, whereby Millipede will be used for topology optimisation, Wallacei multi-objective optimisation and Karamba3D for structural optimisation.

Our hardware includes an AXYZ ATC 4004 CNC router, a UR10e robotic arm and the Robotique 140 gripper. We will adopt the layer-by-layer fabrication technique as described in the reviewed papers. Our workflow will include a feedback loop, whereby the data collected during the assembly of a foam mockup model will prevent errors and inform the assembly process of the final timber bridge structure.

Our future work will include the verification of the proposed design to fabrication workflow by constructing a scale prototype of the arched bridge, whereby the process, as well as the prototype, will be tested on their efficiency and performance.

Finally, the review also highlights the advantages and disadvantages of using robotics in timber construction. According to five papers (Chai et al. 2019; Naboni and Kunic 2019; Xian, Hoban, and Peters, 2020; Mostafavi et al., 2020; Kunic, Kramberger, et al., 2021), robotic arms cannot efficiently assemble from closure connections such as tenon and mortise, thus they recommend manual assembly. Robotic assembly is exposed to tolerances, thus the tenon should be smaller than the mortise, which could increase the instability of the timber structure without using adhesives, nails or screws. Therefore, the researchers tend to avoid using tenon and mortise joints and prefer nails as their primary connection method unless the assembly takes place manually. On the other hand, robotic arms are capable to assemble complex geometry structures faster and with higher efficiency. We believe there are ways to decrease tolerances in tenor-mortice robotic assemblies which is going to be another focal point of our future work.

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