The Application of Robotic Fabrication in Reinterpreting Traditional Chinese Joinery: The Dougong Capital

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The Application of Robotic Fabrication in Reinterpreting Traditional Chinese Joinery

The Dougong capital

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The Dougong (bracket set), consisting of wooden blocks (Dou) and bow-shaped brackets (Gong), is a typical structural element in traditional Chinese timber buildings. Its primary function is to transfer roof loadings to pillars. Applying the Dougong in contemporary design offers significant advantages, including cultural continuity, sustainability, and seismic performance. However, its complex geometries, installation methods, and connections make their use in contemporary timber architecture challenging. Robotics have been increasingly adopted in timber architecture in recent decades, opening new possibilities for reinterpreting the Dougong. This paper presents a file-to-fabrication framework for applying the Dougong in contemporary design. A column was used to test the feasibility of the workflow. The paper also emphasises the crucial role of human-robot cooperation in minimising collisions caused by differences between the positions of components in the real lab and Rhinoceo3D. It also proves that a workable gap between the tenon and mortise could maximise the success rate of its robotic fabrication and ensure the stability of the column.

Keywords: *Dougong, Timber Structures, Parametric Design, Robotic Assembly, Topology Optimization.*

INTRODUCTION

A Dougong is an independent class within the traditional Chinese timber frame construction systems. The main function of a Dougong is to transfer roof loads to a pillar. While there were various types of Dougong in different regions in China, this paper will focus on the intermediate set of an official Dougong in the Qing Dynasty recorded in *Qing Dynasty Architectural Methods* published by the Ministry of Construction of the Qing Dynasty in 1734. There are official Dougong and folk Dougong in China. The former has three main kinds of dougong—intermediate Dougong, corner Dougong, and column Dougong—classified based on their location within traditional timber structures, as shown in Figure 1. As for the folk dougong, various types were developed by carpenters based on local culture. The folk dougong does not have standard design codes to follow, which causes challenges in studying its design rules. In contrast, the official Dougong has two historic rule books which record its design and assembly rules, such as the *Treatise on Architectural Methods* (*Yinzhao Fashi 营造法式*) and *Qing Dynasty Architecture Construction Methods* (*Qing Gongcheng Zuofa Zeli*

清工程做法则例). The abundance of extant buildings constructed during the Qing Dynasty provided precise data for analysing the underlying principles of the Dougong.

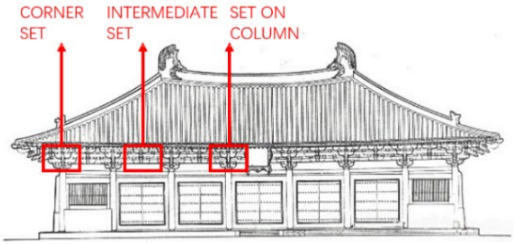


Figure 1
The locations of the Dougong in ancient Chinese buildings.

Due to the complex technology of Dougong production, specialised carpenters are often required to produce and assemble them on construction sites of timber framework buildings (Ma, 2003). Nowadays, some researchers have started exploring the possibility of reinterpreting a Dougong in contemporary design with digital design tools and robotic fabrication technologies. The aim is to find a way to revitalise the traditional knowledge of Chinese timber structures.

As the existing digital research on the Dougong demonstrates, 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. Moreover, Takabayashi and Kado (2019) explored the feasibility of using robotics to produce traditional Japanese wooden buildings, including the Dougong joint and the pillar and roof beams, referring to original crafting skills. Further, Chai et al (2019) robotically produced and manually assembled a timber tower consisting of various wooden beams designed based on the connection method of the Dougong joint. All these projects investigated how to reproduce building components or parts by employing robotic technology based on the z

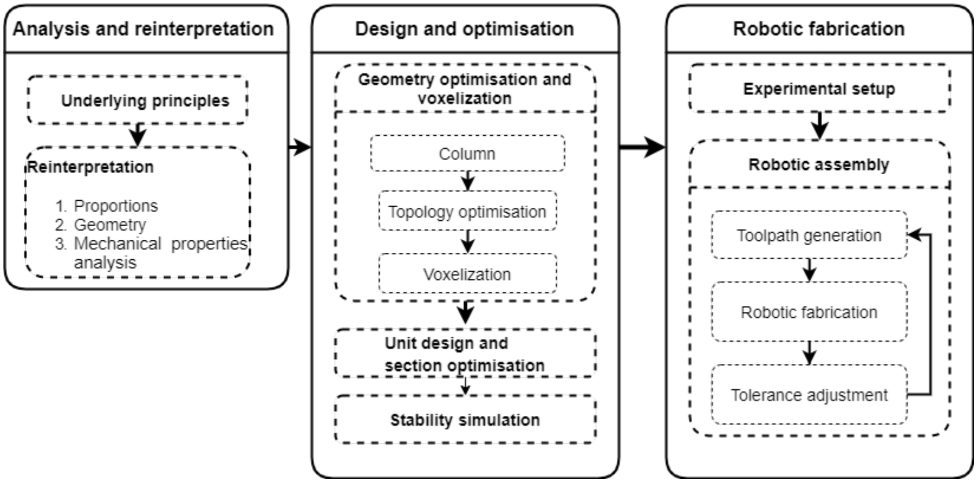


Figure 2
Research methodology frame.

proportions or connections of the original structure. Even so, they did not focus on how to reinterpret the Dougong joint and, thus, apply it to contemporary design solutions. Additionally, the methodology used in these projects provided valuable insight into the reinterpretation of traditional timber tectonics. The wood components were produced with the support of robotic arms but assembled manually, and they did not examine the underlying principles of the Dougong, such as assembling logic, in sufficient depth; however, they did apply the connections of the Dougong in their design.

Based on this existing research, we can see that parametric design and robotic fabrication have significantly advanced the development of complex timber structures, which provide new light to reinterpret the Dougong. This paper continues our previous research, which explored the reinterpretation methods and mechanical properties of the Dougong components and introduced general methodology, related technologies of applying the Dougong in contemporary designs (Zhao et al., 2022)and a prototype assemble (Zhao et al., 2023). Furthermore, a file-to-fabrication workflow (Figure 2) integrating topology optimisation, voxelization, multi-objective optimisation and robotic fabrication for reinterpreting the Dougong joint in contemporary design. Partially, our paper aims to answer the following questions:

1. How can we create a digital design-to-fabrication framework for Dougong design, optimisation, and robotic fabrication?
2. How does the human-robot collaboration improve the performance of the robotic assembly?

METHODOLOGY

To answer these questions, we developed a new computational framework using Rhinoceros/Grasshopper and its plugins Millipede, Robots and Wallacei (Makki et al., 2019). The framework followed three steps 1) analysis and reinterpretation of the original Dougong geometry, 2) design and optimisation, and 3) robotic fabrication. This research examined the reliability of the workflow by designing and fabricating a timber column consisting of these reinterpreted Dougong. The column was designed based on a supporting system of a traditional Chinese timber structure.

Phase one: analysis and reinterpretation of Dougong set

Underlying principles. Phase *one* analysed the underlying principles of the Dougong set according to the book *Qing Dynasty Architectural Methods*. It reviewed the assembly rules, generation grammar, proportions, and connection methods of components within the Dougong. These components are assembled following a consistent rule: the Gong sits atop the Dou, which in turn sits atop the Gong in successive layers, and the pieces are fixed together using tenon and mortise joints, as shown in Figure 3. Within the Dougong set, four distinct types of joints were employed to connect the components, namely, the straight joint, the Dado joint, the castle joint, and the cross-lap joint (Figure 4).

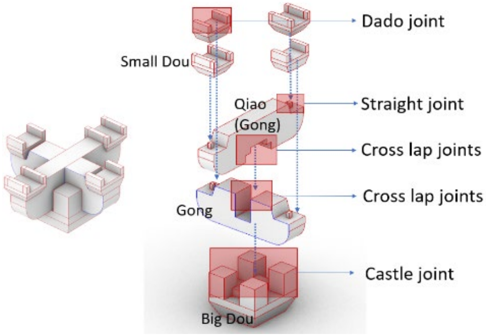


Figure 3
The assembly method of a typical Dougong.

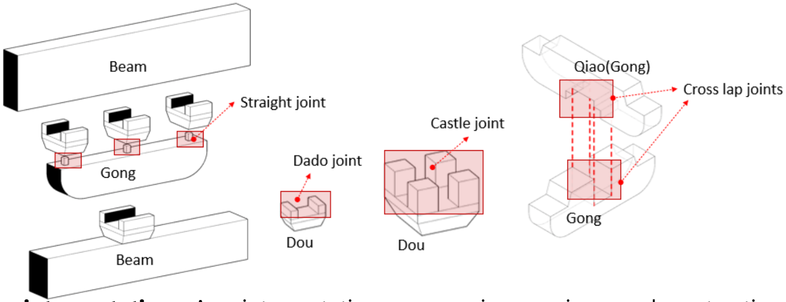


Figure 4
The kinds of tenons and mortises (straight joint, dado joint, castle joint and cross lap joint) used in the Dougong.

Dougong reinterpretation. A reinterpretation was done on the geometries and proportions of the Dougong set. The aims were to meet the requirements of automatic and robotic fabrication, where simplified and standard shapes could be produced effectively, and with the goal of minimising collisions in the robotic fabrication process. The decorative elements and complex curve lines were removed and replaced with simple straight lines.

The proportions of the Dougong were adjusted to match the modern metric system. The original components were designed based on the traditional Chinese unit, *cun* （寸）, which differs from the modern metric system. The *doukou* was a unit that described the proportions of components in timber structures in China, as shown in Table 1. In this research, the proportions of the components were adjusted slightly to multiples of 0.5, which could match the modern metric system. For example, two selected Gong were initially 6.2 *doukou* and 9.2 *doukou* in length, with a section size of 1.24 *doukou* in width and 2 *doukou* in height. The proportions were adjusted to 6 and 9 *doukou* in length, with a section of 1 *doukou* in width and 2 *doukou* in height.

Regarding reinterpreting the geometry, the researcher aimed to match the production requirements of a 3-axis CNC router that was available in our lab. The reinterpretation method involved removing complex decorations and slightly adjusting the Gong and Dou geometry by removing carvings and contraction curves and replacing them with regular straight elements (see Figure 5). At the same time, tenons and mortises were also adjusted to meet the one-side production requirement of the CNC router.

To analyse the mechanical properties of both reinterpreted and original Gong, the displacement in the z-axis direction was compared at four points that had similar coordinates within both types of Gong. According to our previous research (Zhao et al, 2022), the difference between the displacement of these points was light, which meant the mechanical properties were similar before and after reinterpretation. Additionally, this finding confirmed the feasibility of the reinterpretation methods.

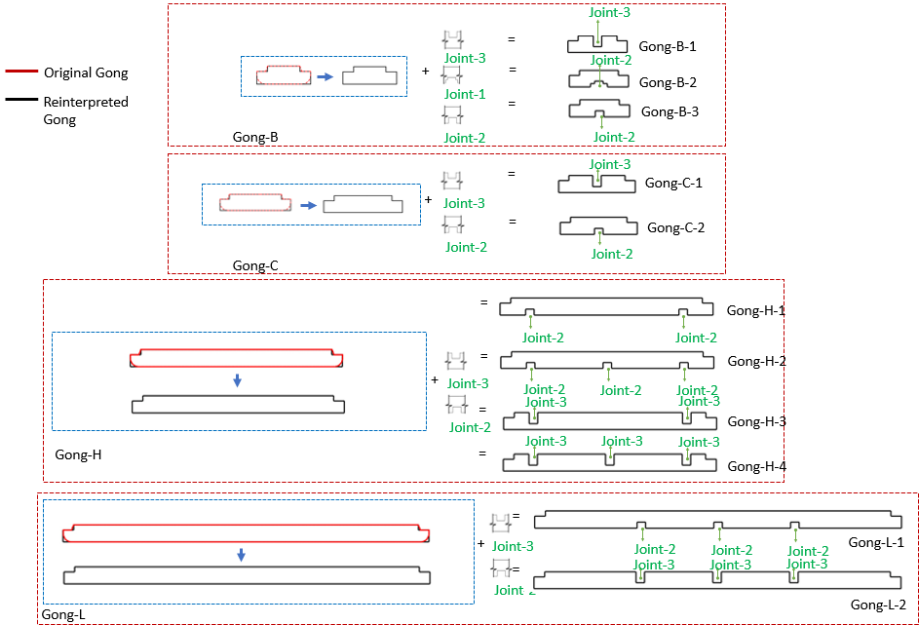
Phase two: design and optimisation

This paper used a column designed based on a traditional Chinese timber building support system to test the feasibility of the workflow. The column was subjected to a vertical uniform load of 0.7 kN/m^2.

Table 1
Comparison of the original and reinterpreted proportions of the selected Gong and Dou; The unit is doukou, and the values used in this experiment are 20mm.

Name of elements			Name of elements in the experiment	Length (doukou)	Width(doukou)	Height(doukou)
Original Proportion	Dou(block)	Big Dou	Dou-A	3	3	2
		Small Dou	Dou-B	1.8	1.5	1
				1.3	1.74	1
				1.3	1.5	1
	Gong(bracket arm)		Gong-C	9.2	1.24	2
			Gong-B	6.2	1.24	2
			Gong-H	23	1	2
			Gong-L	45	1	2
Reinterpreted proportion	Dou(block)	Big Dou	Dou-A	3	3	2
		Small Dou	Dou-B	1.8	1.5	1
				1.3	1.5	1
				1.3	1.5	1
	Gong(bracket arm)		Gong-C	9	1	2
			Gong-B	6	1	2
			Gong-H	23	1	2
			Gong-L	45	1	2

Figure 5
A process of reinterpreting Gong in 6 *doukou* and 9 doukou.



Geometry Optimisation and Voxelization. Topology optimisation was applied to optimise the geometry of the column. Topology optimisation is a method used to determine the best material layout within a given design space. Its goal is to maximise the performance of a structure while minimising its weight or material usage. In this research, the Millipede, a topology optimisation plugin, was utilised to optimise the material layout of the initial column. As shown in Figure 6, after 25 optimisation iterations, the initial geometry stopped changing, indicating that the case study had reached the optimal solution. Once the geometry of the column was decided, it was voxelised.

After voxelization, a workable size of voxel should be considered in post-processing. The voxel's function was to control the Dougong components within the optimal geometry. A smaller voxel means smaller-sized Dougong components. On the other hand, larger or smaller voxel sizes could cause failed voxelization and be challenging to process in production and fabrication to match the constraints of related lab conditions, as shown in Figure 6. In this research, the workable size of a voxel was set to 180mm.

and Dou formed multiple groups of components for voxels. Four reinterpreted Gong in 6 *doukou* and 9 *doukou*, twelve reinterpreted small Gou and a big Gou were selected as components within a voxel(180mm). One *doukou* was equivalent to 20mm, according to the proportion relationship between the voxel size and the selected reinterpreted Gong. Therefore, the dimensions of Gong in 6 *doukou* and 9 *doukou* lengths were 120mm and 180mm in length, with a cross-section of 20mm in width and 40mm in height.

The cross-section of the components was optimised by maximising the structure stability and minimising the weight of a group of components within a voxel using multiple-objective optimisation (MOO). According to Hooke's law, maximising stability (stiffness) means minimising the displacement when the

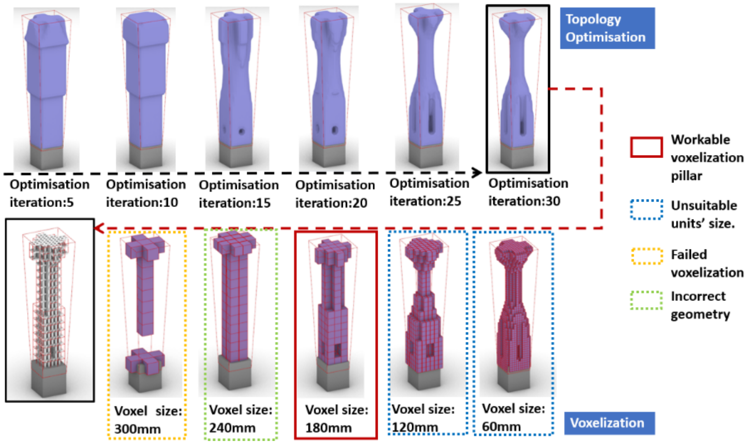


Figure 6
The topology optimisation and voxelization process of the selected column.

Unit design and section optimisation. Following the assembly rules, reinterpreted Dougong components (a Gong-C, a Gong-B, a big Dou and a small Dou) were chosen to generate the unit within voxels, while a Gong-H and a Gong-L were used to connect adjacent units within the column. The rule was that the Gong was placed atop the Dou, the Dou atop the Gong, and the pieces were connected using tenon and mortise joints. The combination of various Gong

external force is fixed. Optimisation objectives were to maximise the stiffness of the reinterpreted components by minimising mass displacement based on Hooke's law and to minimise material usage by reducing the mass of the unit. To achieve these objectives, the maximum displacement and mass of the unit outputted from the Karamba3D (Preisinger, 2013) were used as input objectives in the Wallace to optimise the section size of components within

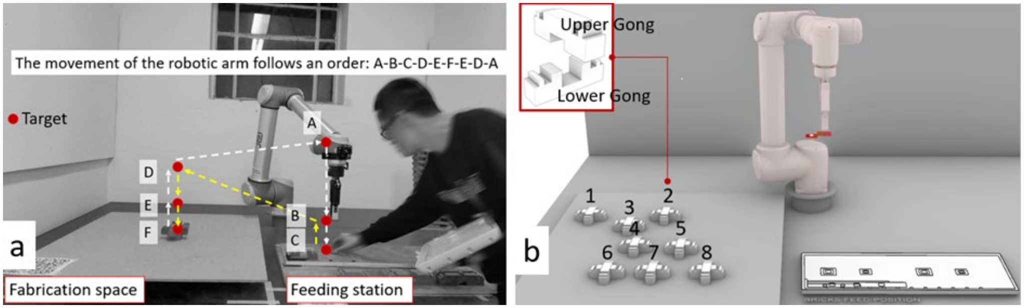


Figure 7
a) a standard robotic fabrication workflow; b) eight tests were fabricated with the cooperation between the human and the robot. The video link to the assembly process can be found at https://youtu.be/PTHnxMj0i14?si=PEJyTLJR2-ncVdYD.

the reinterpreted Dougong unit. The optimal section size of the reinterpreted Gong was 30mm in width and 40mm in height.

Stability simulation. The stability simulation was conducted to analyse the load-bearing capacity of axially compressed members and the shear load capacity of bending and axially compressed members within the column and wall. Using Karamba3D, the components' maximum bending moment and maximum stress values within the column and wall were determined. The values were then input into the expressions of stability calculation recorded in the Standard for Design in Timber Structures (2017 Edition). The Ministry of Housing and Urban-Rural Development of the People's Republic of China published the book in 2017. It became the official standard for timber structure design. The book recorded various expressions and design values of strength, which were utilised to analyse the capability of the timber structure. The timber column was workable according to the calculation results, which met the limitation of maximum bend moment and stress recorded in the code.

Phase Three: robotic fabrication

Experimental setup. We utilised a robotic arm (UR10e) with a gripper (Robotiq 2f-140 gripper), an assembly space, and a block feeding station in this research. Due to the limitations of the lab workspace, a layer of the column was assembled in the fabrication space and the block-feeding station was utilised to position Dougong components. The robotic arm collected the components from the feeding station and assembled them in the assembly space. An AXYZ ATC 4004 CNC router produced these components.

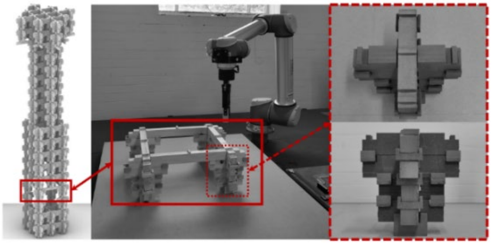


Figure 8
A layer of the column was assembled to test the feasibility of the workflow. The video link to the assembly process can be found at: https://youtu.be/9J0__1I8VoY.

Robotic assembly. The robotic assembly phase included toolpath generation, assembly simulation, and adjustment of tolerances. In this paper, a layer of the column was fabricated, which includes three kinds of Gong and two kinds of Dou. During the robotic assembly phase, Grasshopper 3D was utilised to generate toolpaths based on the central mass points of the Gong and Dou. First, they were manually divided into groups based on their geometry in Rhinoceros3D to construct targets of various components. Then, the group components were put in order according to the Z-coordinates of central mass points. The robotic arm tracked these targets to move between points and adjusted the gripper's opening and closing commands based on assembly requirements. The

Table 2
The coordinates of the original and adjustment positions of the upper Gongs.

Positions of upper components		Coordinates (mm)		
		x	y	z
Test-1	Original position	-925.8	-383.65	-3.59
	Adjusted position	-925.66	-383.95	-8.28
Test-2	Original position	-612.8	-383.65	-3.59
	Adjusted position	-612.37	-384.28	-7.37
Test-3	Original position	-744.8	-488.65	-3.59
	Adjusted position	-744.23	-488.73	-6.91
Test-4	Original position	-681.80	-680.65	-3.59
	Adjusted position	-681.82	-680.65	-5.49
Test-5	Original position	-505.8	-693.65	-3.59
	Adjusted position	-505.82	-693.64	-6.58
Test-6	Original position	-744.8	-892.65	-3.59
	Adjusted position	-744.81	-892.64	-8.44
Test-7	Original position	-580.8	-892.65	-3.59
	Adjusted position	-580.81	-892.64	-7.25
Test-8	Original position	-385.8	-892.65	-3.59
	Adjusted position	-385.79	-892.65	-8.55

process was seamless and efficient. The speed and type of robotic movement could be adjusted according to the fabrication needs. Assembly simulation results helped to optimise toolpath generation by identifying errors in the assembly orders. The Grasshopper plugin ‘Robots’ was used to simulate and generate the robotic code for the robotic arm's teaching pedants. Before mass fabrication, we conducted a prototype test, a layer of the timber column, to minimise collisions and adjust tolerances.

A standard assembly toolpath was developed in the research. The components of the reinterpreted Dougong set and the column were ordered based on their robotic fabrication sequence. They were assembled layer by layer using the original assembly rule, which stated that the Gong should be placed on top of the Dou and joined with tenon and mortise joints. The targets of these components followed a basic workflow of robotic fabrication, as depicted in Figure 7a. The robotic arm began and ended fabrication at point A, while point D was used to prevent any collisions between the arm and the assembly objective. To prevent collisions, after picking up a component at point C, the robotic arm moved back to point B first and then to point D, instead of moving directly from point C to point F, where it could collide with the other components. The heights of points B and E were appropriately adjusted according to the height of the components being erected. A safe height avoided collisions between the robot and the components. Points B and E acted as waiting points to slow down the robotic arm's high-speed movement, which could cause the deflection of timber components due to inertia. The deflection could result in larger tolerances in the fabrication process. Therefore, a slow speed was set between point E and point F, as well as point B and point C. Moreover, a faster speed was set for the robotic arm's movement from point B to point D relative to the former, considering the efficiency of the robotic fabrication process.

In the fabrication process, the unreasonable gap could cause collisions of reinterpreted components or shaking of the column. According to the Technical Code for Maintenance and Strengthening of Ancient Timber Buildings, the gap between two components within Dougong should not exceed 1mm. In this paper, the gap between two reinterpreted components was set as 1mm; one side had a 0.5mm gap.

The two components were robotically assembled at eight positions in the assembly space. First, the bottom components were fabricated automatically and then the upper components (Figure 7b). The results showed that a 1mm gap was feasible for robotic fabrication. However, variations between the positions of the reinterpreted Gong in Rhinoceo3D and the actual lab caused collisions in test-1, test-2, and test-3. These discrepancies were partly caused by our working conditions, which were not perfectly levelled. The rough surface of the timber components could also have contributed to these discrepancies. The timber components within the reinterpreted Dougong, produced by the CNC router, had irregularities on the top surface. Before fabrication, this roughness should be manually polished, but manual polishing could not ensure perfectly even surfaces. The uneven surface could cause slight deflection of the components within the reinterpreted Dougong.

To resolve the issue, the human operator used the teaching pendant, a robot controller, to adjust the coordinates of the upper components to match the position of the bottom component in the real lab. Table 2 displays the differences between the original and adjusted coordinates of the upper components. The coordinates were adjusted manually around 0.3mm on the X and Y-axis, and 4mm on the Z-axis for test-1, test-2, and test-3. Other tests only required adjustments in the Z-axis, ranging from 2mm to 5mm. These adjusted coordinates were inputted into the Grasshopper to minimise the tolerance during robotic fabrication.

Based on the results of eight tests, the human-robot collaboration method has been proven to be workable in assembling Dougong components connected with tenons and mortises. Therefore, it should also be feasible to assemble the column consisting of discrete Dougong components. Given the workspace size of our robotic lab, the human-robot collaboration was applied to assemble a layer of the column to test the feasibility of the proposed file-to-fabrication workflow (Figure 8). Concerning the assembly of the column's layer, the coordinates of its Dou component were modified between 1mm and 2mm. The coordinates of the Gongs located in three corners were fine-tuned on the Z-axis, with adjustments of approximately 1mm, 2mm, and 3mm, respectively. The coordinates of eleven Dous were fine-tuned, with adjustments ranging from 1 mm to 2 mm on the X and Y axes. The assembly process of the layer (at a 1 to1 scale) takes approximately 30 minutes, an individual feeds these elements and controls a robotic arm to complete the fabrication. The Gongs' length are 120mm, 180mm, 460mm and 900mm, and its width and height are 30mm and 40mm, respectively.

CONCLUSIONS

Regarding our first question, the paper introduced a file-to-fabrication workflow for applying the Dougong in contemporary design, integrating topology optimisation, the successful design, fabrication and assembly of a selected layer of a column proved that our workflow is feasible. The simplified Dougong component could be efficiently assembled during the assembly process and produced using a CNC router.

In regard to our second question, the paper highlights the benefits of human-robot collaboration in assembling complex timber elements like a Dougong. Both tests indicated that human-robot collaboration is an efficient method for assembling the complex timber elements (like a Dougong) connected with tenons and mortises. The experiment shows that there are slight differences between the virtual and physical positions of elements, which was caused by the uneven assembling space and rough edge of timber Dougong. This slight tolerance could cause unpredictable collisions, even if the accuracy of a robotic arm is around 0.1mm. The eight tests of the two selected components prove that the human-robot collaboration performs well in reducing collisions. According to the assembly results, the coordinates of the physical components of the three tests were adjusted around 0.3mm on the X and Y axes and 4mm on the Z axes, while other tests only adjusted coordinates on the Z axes, ranging from 2mm to 5mm. These adjustments were conducted by a human operator based on a realistic fabrication process. The changes in coordinates of these physical components were feedback to Rhinoceo3D to correct virtual positions to ensure the repeatability of the assembly. Similarly, for the column components, the human-robot cooperation also corrected the coordinate difference, which ensured the successful assembly of the elements.

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