Co-Robotic Assembly of Nonstandard Timber Structures

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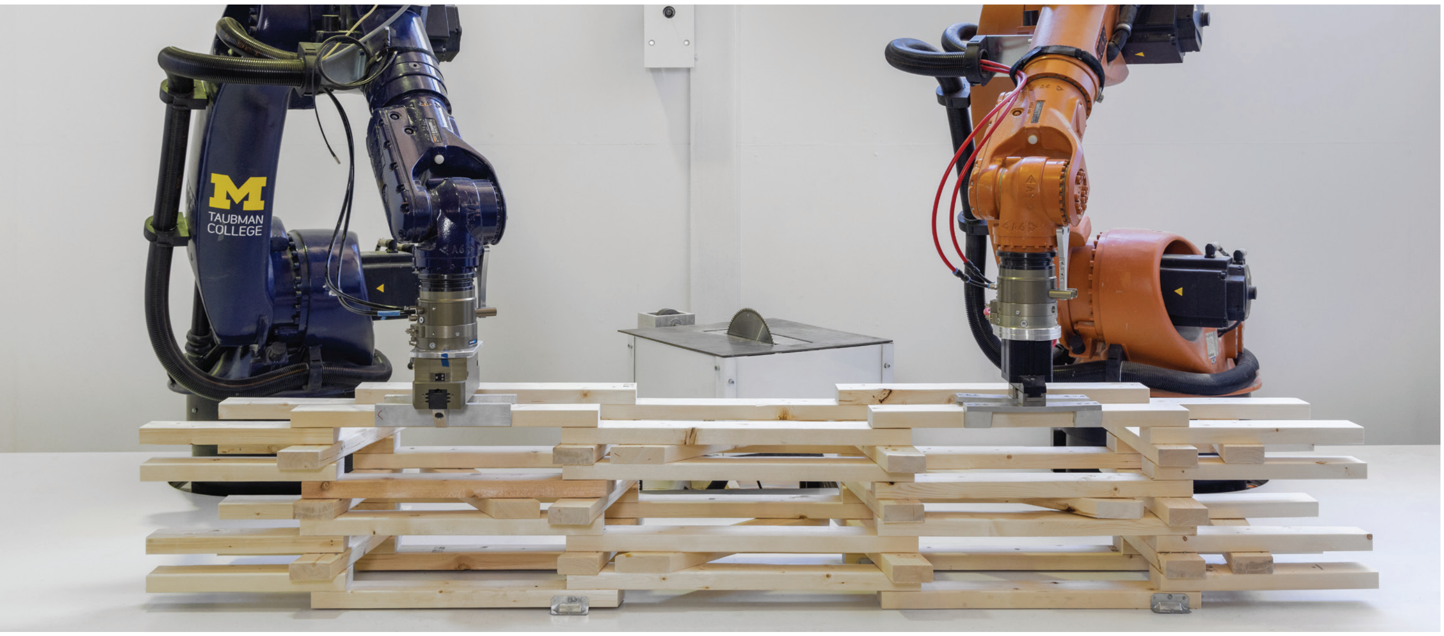

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1 Co-robotic timber assembly

ABSTRACT

This paper presents a novel approach for the construction of nonstandard timber structures made from regionally sourced short dimensional lumber, which is enabled through human-robot collaborative assembly (HRCA). This approach is an attempt to address several challenges that exist in dominant timber frame construction practices, in particular: 1) Construction and manufacturing off-cuts that may not be used in the construction of full-height or full-span structural components, and 2) Short reclaimed lumber elements resulting from the deconstruction of buildings, which are limited (when not completely disposed) in their use for the construction of new structures. Therefore, to address these challenges, we ask the following research question: how can robotic assembly be integrated into a comprehensive design, planning, and construction process to facilitate the realization of building-scale structures made from short timber elements?

To address the research question, three main research objectives are identified and experimentally explored: 1) Characterization of a comprehensive construction process, which consists of off-site HRCA of bespoke timber sub-assemblies, 2) Development of a suitable constructive system for robotic assembly, making feasible the realization of articulated structures out of short timber elements, and 3) Incorporation of these techniques and their constraints into an integrative digital design and fabrication method and implementation of a continuous digital design-to-fabrication workflow. These objectives are developed through simulation and physical experimentation (e.g., prototyping) and validated in a real-world case study, Robotically Fabricated Structure (RFS).

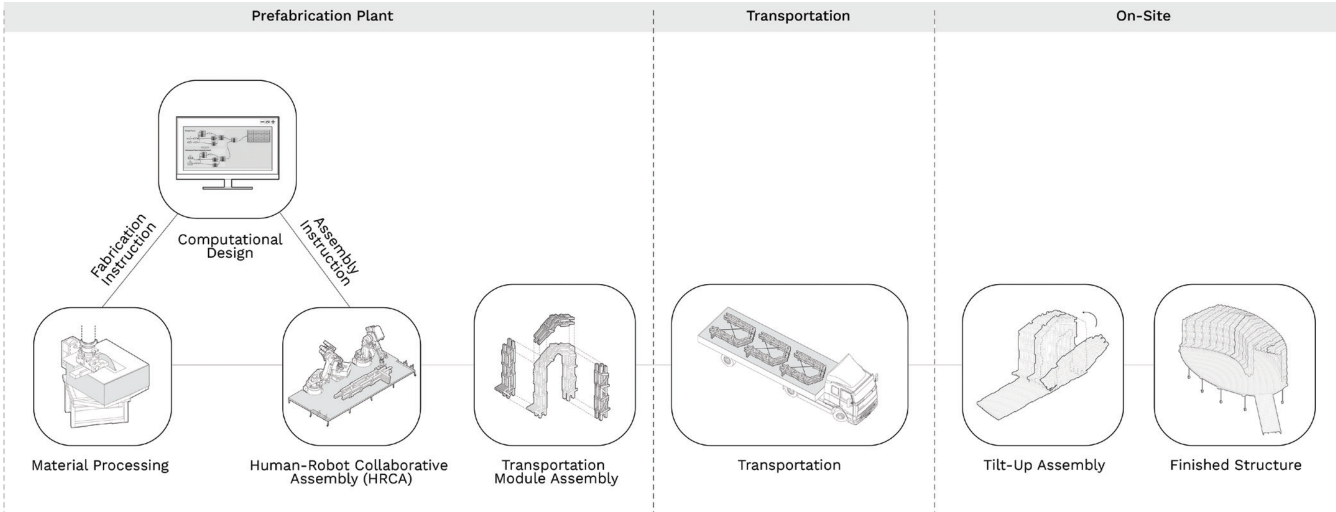
INTRODUCTION

Addressing climate change requires significant innovations to reduce the carbon footprints of buildings and structures since the building industry contributes to one-third of global CO2 emissions (Green 2012). Timber is a renewable material with a long history of use in creating structures and buildings and has the lowest embodied energy compared to other structural materials such as concrete and steel (Slavid 2006). However, several challenges exist in dominant timber frame construction practices, in particular: 1) Construction and manufacturing off-cuts that may not be used in the construction of full-height or full-span structural components, and 2) Short reclaimed lumber elements resulting from the deconstruction of buildings, which are limited (when not completely disposed) in their use for the construction of new structures. Therefore, to address these challenges, we ask the following research question: how can robotic assembly be integrated into a comprehensive design, planning, and construction process to facilitate the realization of building-scale structures made from short timber elements?

Robotic timber construction has been of interest in several research projects in recent years. For instance, Willmann et al. (2015), Helm et al. (2017), Adel et al. (2018), and Adel (2020) investigated the use of industrial robotic arms and other automated technologies (e.g., portal robots) for the fabrication and assembly of nonstandard timber structures. More specifically, the *Sequential Wall* (Oesterle 2009) and the *Sequential Roof* (Apolinarska et al. 2016) demonstrated the use of such technologies for assembling short timber slats into building-scale structural components. Their constructive system consists of layers of short timber slats connected by nails in a side-grain to side-grain configuration to form full-height wall modules in the case of the *Sequential Wall* and full-span beams in the case of the *Sequential Roof*.

The constructive system and the fabrication process of these two projects are highly interconnected. In the case of the *Sequential Wall*, a six-axis industrial robotic arm grips a raw timber element, moves it along the main axis of the element based on the predefined length of the structural element, and holds it until a human fabricator cuts it with a circular saw. The robotic arm then moves the processed element to its final position, where the human fabricator attaches it to the elements of the previous layer. This process repeats until the wall sub-assembly (or a portion of it) is fully fabricated. The fabrication process of the *Sequential Roof* is very similar, with some minor differences. A four-axis portal robot is attached to a telescopic base mounted on a two-axis gantry system. The robot grips a raw timber element and moves it along the main axis of the element based on the predefined length of the structural element, where a computer numerical controlled (CNC) saw cuts it. Subsequently, the portal robot moves the processed element into its final position and attaches it to the elements of the previous layer by shooting nails. This

2 The case-study project of this research, Robotically Fabricated Structure (RFS)



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process repeats until the beam sub-assembly is fully fabricated. While these two projects are successful in developing a manufacturing process coupled with a constructive system for specific building components (i.e., wall sub-assemblies in the case of the *Sequential Wall* and ceiling beam sub-assemblies in the case of the *Sequential Roof*), further investigations are required to develop a complete building system consisting of floor, wall, and ceiling components.

More recently, Adel (2020) presented a comprehensive process to facilitate the design, planning, and construction of robotically assembled nonstandard modular timber frame buildings. The construction process includes cooperative robotic spatial assembly of bespoke timber frame modules, transportation of the prefabricated modules to the construction site, and mounting them on-site to realize nonstandard buildings. This process was tested and validated through a real-world case study, *DFAB HOUSE* (Adel et al. 2018; Adel 2020; Graser et al. 2021), which demonstrated the feasibility and potential of this process for fabricating nonstandard timber frame buildings.

Building on these projects, we present a novel approach for the construction of nonstandard timber structures made from regionally sourced short dimensional lumber, which is enabled through human-robot collaborative assembly (HRCA). More specifically, to address the main research question, three research objectives are identified and experimentally explored: 1) Characterization of a comprehensive construction process, which consists of off-site HRCA of bespoke timber sub-assemblies, 2) Development of a suitable constructive system for robotic assembly, making feasible the realization of articulated structures out of short timber elements, and 3) Incorporation of these techniques and their constraints into an integrative digital design and fabrication method and implementation of a continuous digital design-to-fabrication workflow.

These objectives are developed through simulation and physical experimentation (e.g., prototyping) and validated in a real-world case study, Robotically Fabricated Structure (RFS, Figure 2), which must satisfy strict building code requirements and constraints such as structural integrity. RFS is a timber pavilion located in the Matthaei Botanical Gardens in Ann Arbor, Michigan. It includes a raised platform that creates an opportunity for small public events and performances, an exterior seating area, and a semi-enclosed walkway that can be utilized for exhibitions and intimate conversations.

METHODS

Construction Process

We propose a comprehensive construction process, which facilitates the realization of building-scale structures made from short timber elements. Figure 3 illustrates the proposed construction process for the case-study structure of this research. This process includes the HRCA of bespoke timber sub-assemblies. We call these sub-assemblies fabrication modules. We will discuss the HRCA in detail in the following section. After the fabrication modules are completed, they are pre-assembled into an intermediate scale, which we call transportation modules. Subsequently, these transportation modules are braced for structural stability and transported to the construction site, where they are mounted together to form the whole structure. We designed this process to avoid crane usage on the construction site. The transportation modules can be carried by four to five people and put in place using a tilt-up action (Figure 3).

As illustrated in Figure 3, the construction process includes a prototypical just-in-time HRCA of bespoke timber sub-assemblies made from short timber elements.[1] The HRCA process (illustrated in Figure 4) consists of the following main steps. A robotic arm picks up a raw timber element positioned at the picking station, carries it to the CNC saw, and moves the timber element based on a computationally calculated path alongside the saw blade to cut it. When the robot reaches the end of the cutting path, the CNC saw turns off, and the robot carries the element and places it in its relative final position within the module on the assembly platform.[2] At this point, the robotic arm goes into HALT mode, and the human fabricator enters the workcell to shoot nails at the top face of the element to connect it with the previous timber layer and perform quality control. Elements are stacked to form a fabrication module, and therefore, the connection between two elements has a side-grain to side-grain configuration. We chose nails for connecting elements during this step due to the faster speed of using a nail gun for shooting nails compared to inserting screws with a compact driver. After connecting the timber element to the previous layer, the human fabricator exits the workcell, the robotic process resumes, and this process repeats until the module is fully assembled. A key consequence of this process is the elimination of error-prone and labor-intensive logistical steps such as labeling non-identical timber elements since the raw timber element is picked, cut, and placed in a single continuous process without any breaks (Adel et al. 2018; Adel 2020; Craney and Adel 2020).

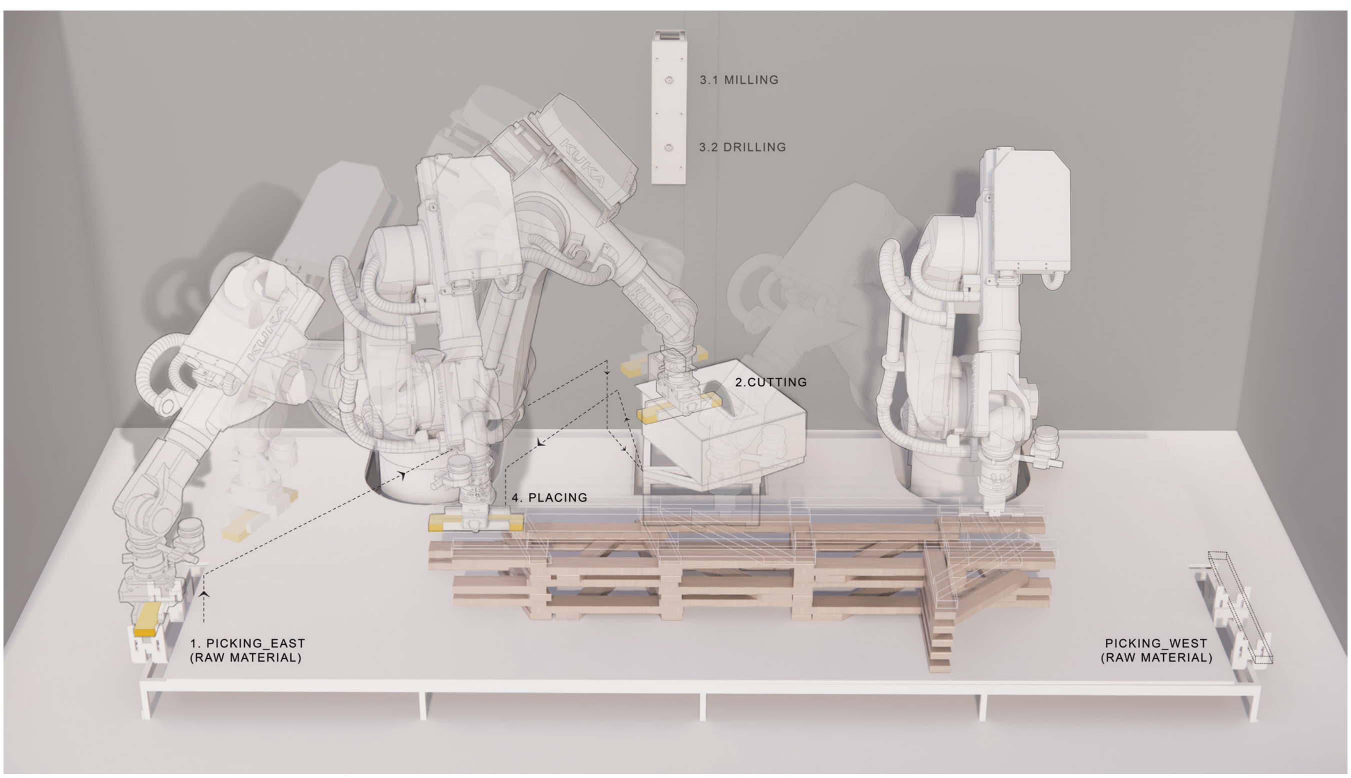
Constructive System

We propose a constructive system made from short timber elements suitable for the discussed construction process. The proposed construction process and the HRCA procedure necessitate the development of strategies for dividing the structure into sub-assemblies at various scales (e.g., wall, floor, ceiling, and transportation modules). Each step of the construction process requires an in-depth analysis to define manufacturing constraints associated with that step and devise suitable joining techniques for that specific step. Our analysis reveals that this process includes several scales illustrated in Figure 5, which inform the development of the constructive system and characterization of its rules and constraints, as well as the implementation of the necessary data structure required for the digital design-to-fabrication workflow (discussed in the following sections).

In our proposed constructive system, short timber elements are stacked to form a fabrication module. These fabrication modules are then connected to each other to form a transportation module, and these transportation modules are connected to each other on the construction site to form the whole structure. We conducted simulation studies and performed physical prototyping experiments to identify the fabrication constraints of our prototypical fabrication setup, such as the minimum

3 The proposed construction process

4 Steps of the HRCA process (for clarity, the joining process by the human fabricator is not included in the diagram)



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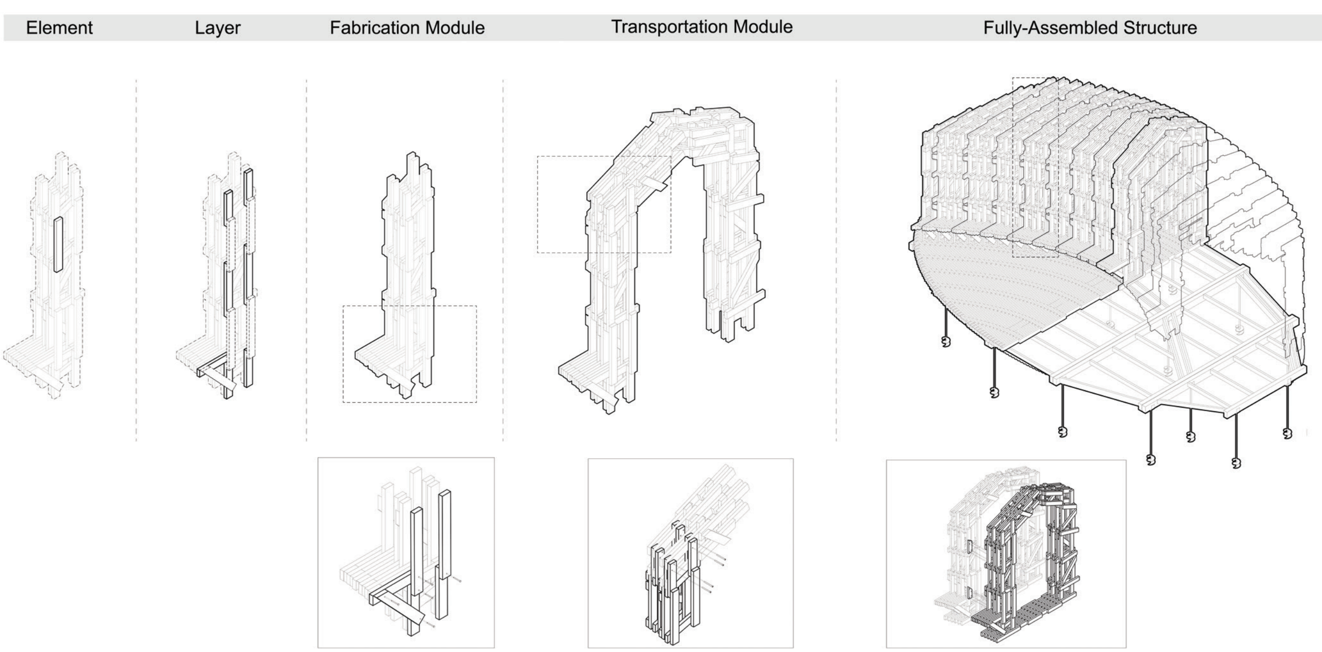
and maximum dimensions of the individual timber elements, directly impacting the manufacturability of sub-assemblies. These constraints must be integrated into the design-to-fabrication process and satisfied to guarantee manufacturability. We discuss a few key constraints here.

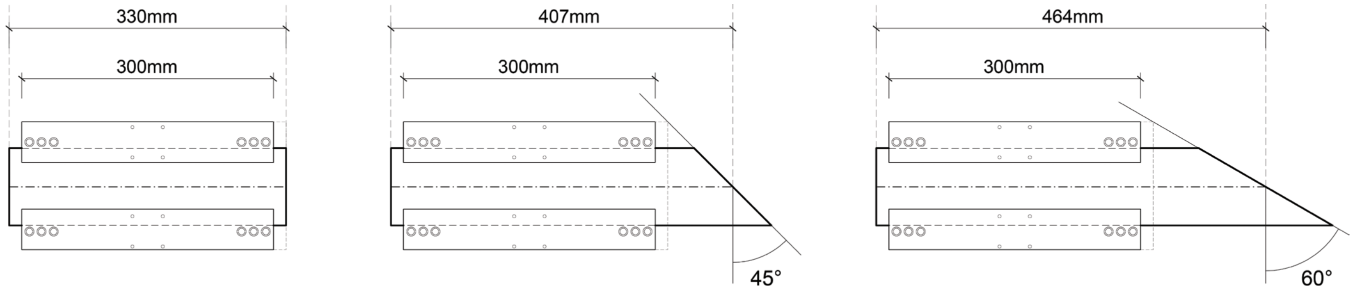
One of the main constraints is the minimum and maximum dimensions of the timber elements. Our constructive system consists of regionally sourced dimensional lumber, and for the case-study structure, we limit the elements to 2x4 lumber. The length of an element is measured as the distance along the element's central axis between each cut plane. Several key parameters were identified to precisely define the lower and upper length bounds of the 2x4s. The first is the length of the gripper, which, combined with the angle of the miter cut, defines the minimum length of the element. An element with a length smaller than the minimum length will result in the collision of the gripper with the saw blade during the cutting process. Figure 6 illustrates this constraint. A key observation is that the minimum length of an element can change depending on the angle of the miter cut; for instance, the minimum length of an element with perpendicular cuts is 330 mm, and the minimum length of an element with 45-degree miter cuts is 407 mm (including a safety margin). The maximum length of each element is defined such that the timber element does not collide with the body of the robot during the fabrication process. The moment of closest contact occurs during the cutting process due to the proximity of the saw to the robot, which limits the maximum length to 880 mm. The integrative computational design process performs this check and indicates the elements that do not satisfy the length constraint.[3] The design is then iteratively refined until all the elements satisfy this constraint.

Another key constraint is the maximum dimensions of a sub-assembly that can be fabricated in the workcell. Based on the results of simulation studies and physical experiments, we identified the overall working envelope of our workcell, which has maximum dimensions of 1.6 m wide by 4.6 m long by 2.0 m high. A key observation made during these studies indicates that this working envelope may shrink based on the desired angle of the sixth axis of the robot and the orientation of the tool center point (TCP) of the gripper for placing the elements. Since the modules of the case-study structure are assembled horizontally on the assembly stand, the orientation of the sixth axis needs to be parallel to the world *z*-axis, which reduces the maximum dimensions of sub-assemblies to be 1.0 m wide by 4.6 m long by 0.8 m high. These dimensions are much smaller than the transportation volume constraints; therefore, we devised an intermediate scale consisting of three to four fabrication modules joined together to form a transportation module (Figure 5). This approach reduces the time spent during the on-site assembly process since fewer modules need to be assembled on site.

For the pre-assembly of the transportation modules, we devised a suitable joining technique using alternating fingers coupled with screws, which enables the same side-grain to side-grain connection typology between timber elements of the two connecting modules (Figure 5). Here, we use screws since longer screws can easily penetrate several timber layers (fingers) to form a robust structural connection between two



5 Constructive system and multiple scales of the structure



6 Calculation of the minimum length of the timber elements based on the length of the gripper fingers and the angle of the miter cut

modules. Furthermore, screws can be easily removed when disassembling the structure and relocating it or completely dismantling the structure and reclaiming its lumber for future use. On the construction site, transportation modules are connected to each other using module-connecting blocks coupled with screws (Figure 5).

Design-to-Fabrication Workflow and Process

The successful execution of this research requires the implementation of dynamic task and motion planning as well as a seamless digital design-to-fabrication workflow to automate the fabrication and assembly of non-identical timber elements. This workflow should enable the automatic generation of manufacturing instructions to control the robotic arms and the CNC saw (as well as the mill and the drill) based on the geometric attributes of each element. We implemented the necessary data structure and workflow to enable this process, which are discussed in detail in the rest of this section.

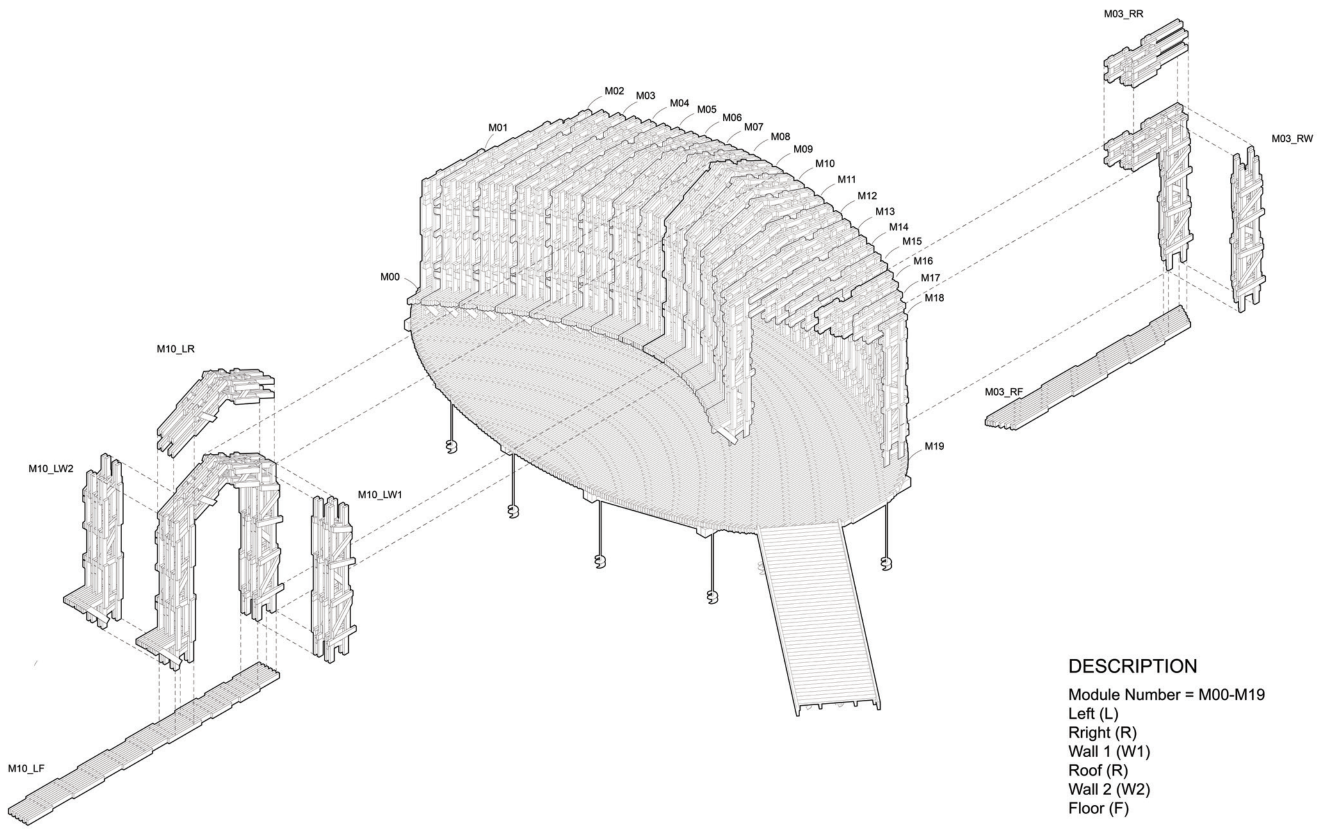
As previously discussed, the fabrication modules are assembled layer by layer horizontally (Figure 4). For each module, the human operator assigns a frame to that module (usually located at one of its corners) and defines its transformed counterpart on the assembly platform. Accordingly, a four-by-four transformation matrix is calculated and applied to the elements of that module to transform them onto the assembly platform. This approach simplifies the transformation of the selected module and the preparation of the manufacturing instructions for its timber elements. Each timber element is computationally represented as an instance of a custom object (Class), titled Element, which is implemented in Python (Python Software Foundation 2001-2018) and includes the necessary attributes (e.g., gripping frame, cut planes, etc.) to derive manufacturing instructions specific to that element. Based on these attributes, picking, cutting, and placing paths are calculated, and subsequently, manufacturing instructions are generated. For instance, the path for cutting each element is generated such that the gripping frame of the element has a specific distance to the frame of the saw blade, and the *x*-axis of the gripping plane forms a specific angle with the *x*-axis of the saw blade, both of which are derived from the desired length of the element and the angle of the miter cut.

RESULTS

We employed the discussed methods in the design, planning, and construction of RFS. The HRCA process proved effective in fabricating the bespoke sub-assemblies of this nonstandard structure. The primary structure of RFS is divided into 76 fabrication modules, which form 19 transportation modules (illustrated in Figure 7, not counting the floor sub-assemblies).[4] The transportation modules are connected to each other on site using 56 module-connecting blocks coupled with screws.

The primary structure consists of 4,045 timber elements connected by 17,336 nails. Out of these, 3,787 timber elements (93.62% of the total number of elements) are robotically cut and placed. The lengths of these elements vary from 345.20 mm to 861.80 mm, with a mean value of 615.70 mm and a median value of 600.20 mm. Besides these, there are 258 short elements (6.38% of the total number of elements), which are cut and placed by the human fabricator since these elements are too short to be cut and placed by our robotic setup. Most of these elements are fillers to fill the gap between the timber elements of the floor boundary and have a length of 110 mm.

Figure 8 includes a series of photos corresponding to the construction process illustrated in Figure 3. While the developed HRCA process proved effective, we observed several challenges during this process. One observation regards human intervention while nailing the elements. In our system, each connection requires two nails arranged on the diagonal of the overlap between the two timber elements. From one layer to the next, the arrangement of the nails alternates to the other diagonal of the overlap to avoid collisions between the nails of the two adjacent layers. While this simple system is effective for human interventions without any guides, bespoke nailing and screwing layouts will require additional guiding mechanisms and further research. Another observation regards the role of the human fabricator while handling exceptions, e.g., placing short timber elements that could not



7 RFS and its modules

be cut and placed robotically. It can be argued that exceptions occur in most architectural projects beyond the constraints of the manufacturing process due to the specificities and requirements of each project. Fabricating RFS illustrated that human interventions could effectively complement robotic processes for handling exceptions. However, developing suitable digital communication channels for human interventions also requires further research.

A third observation regards the on-site tilt-up assembly of the transportation modules. Although this process is straightforward, the overall length of the RFS ended up being 212 mm longer than the digital model. This increase in length is due to the average thickness of the elements used (of which are not exactly consistent) being slightly larger than the modeled element thickness. Since the whole structure consists of 234 layers, the accumulative build-up of this tolerance resulted in a noticeable increase in the length of the structure. To avoid having this tolerance showing up only on one side of the finished structure, we assembled the transportation modules starting from the middle of the structure (module 10 in Figure 7) and built it outwards. This approach distributed the accumulative tolerance to both sides of the structure. Handling accumulative tolerance requires further research as well.

The proposed construction process, coupled with the developed constructive system, enables the construction of full-height wall and full-span floor and ceiling sub-assemblies using short timber elements, which respond to various programming requirements integrated into RFS such as a seating area, a raised platform, and an enclosed space. RFS also exemplifies the expressive qualities resulting from this approach (Figures 2 and 9) and its potential for creating novel architecture.

CONCLUSION

In this paper, we presented a comprehensive construction process coupled with a suitable constructive system and digital design-to-fabrication workflow to facilitate the design, planning, and construction of nonstandard timber structures made from short dimensional lumber. Furthermore, we demonstrated the application of developed methods in the realization of a case-study structure, RFS, which tested and validated the methods in a real-world setting beyond the laboratory environment. RFS illustrated the potential of the developed processes for the design and manufacture of highly articulated timber architecture. This research paves the way for further investigations utilizing short reclaimed lumber elements in the construction of new structures.

8 The HRCA and construction process photos

9 RFS at night

Future Work

Several challenges were identified throughout the research, which could not be addressed within the scope of this project. We see a potential for integrating augmented reality (AR) to assist and guide human interventions for nailing and inserting screws, as well as providing a digital communication channel beyond conventional methods (e.g., two-dimensional drawings and measurement techniques) for handling exceptions. Moreover, we observed that the on-site assembly of the modules relied solely on drawings and manual measurements for placing the transportation modules in their correct position within the whole structure. We see an opportunity for integrating AR to assist with the on-site assembly process. Furthermore, the accumulative tolerance built-up (discussed in the previous section) could have been quantified during the prefabrication process using laser scanning or other digitization methods to develop a bidirectional digital twin of the built structure and could have been accounted for by employing adaptive fabrication methods. These approaches can be integrated into the future development of the research. Additionally, RFS demonstrated the application of the research in a single-story structure; future research could investigate the design and construction of multistory structures.

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NOTES

1. We designed and built an HRCA workcell, which includes two industrial robotic arms (Figure 4). However, the discussion of this workcell is beyond the scope of this paper.
2. After cutting the element, if necessary, milling and drilling procedure are performed on the element. However, milling and drilling procedures were not employed for the case-study structure.
3. The discussion of the computational design process is beyond the scope of this paper.
4. As illustrated in Figure 7, we used earth screws acting as the foundation of the structure. There is a conventional structure, that sits on these earth screws below the floor of the RFS.

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IMAGE CREDITS

Figures 1, 9: Daniel Ruan, 2022

Figure 2: Bob Berg, 2021

Figures 3-7: Yunyan Li/Arash Adel, 2022

Figure 8: Mehdi Shirvani, Jacob Cofer, Bob Berg, 2021

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