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Robotic Fabrication of Bespoke Timber Frame Modules

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Abstract. This paper presents methods and techniques to robotically prefabricate timber frame modules. The key challenge of this research lies in enabling the digitally informed and fabricated spatial assembly of timber beams into prefabricated timber frame modules. The project combines the fabrication and the spatial assembly of timber beams into one fully integrated robotic fabrication process. A cooperative robotic construction procedure that minimises the need for scaffolding and allows for the informed assembly of spatial structures with non-planar geometries was developed. This required the examination of suitable timber joining methods, assembly sequencing, as well developing appropriate and novel strategies to register and handle material deviations and construction tolerances. The physical implementation of the research in multiple experiments and finally, a full-scale building project validates the approach.

Keywords: Cooperative robotic assembly · Computational design
Timber bar structures · Prefabrication · Building scale · Additive construction
In place milling · Timber frame modules

1 Introduction

The implementation of digital fabrication technology in timber construction dates back to the 1980s. Inventions of specialised digital joinery machines and CNC milling machines (Schindler 2009) enabled the digital production of complex timber parts and are well established in the construction industry. However, the actual assembly of these parts predominantly is still done manually (Willmann et al. 2016), requiring extensive logistics. Timber modules, typically being assembled flat on the ground in various steps and comprising of standardised planar geometry are mostly assembled by hand however, there are a handful of machines which can automatically assemble simple standardised timber frames: exceptions such as window or door frames are still added manually.

The implementation of industrial robots into the fabrication loop, performing a variety of programmed tasks, allows not only the production of individual parts but also the digital assembly of them. The Sequential Roof project (Apolinarska et al. 2016), developed by Gramazio Kohler Research at the ETH Zurich and robotically

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constructed by ERNE AG Holzbau, marked the first step into the digital fabrication of a non-standard timber assembly at a building-scale.

By shifting the fabrication scenario from The Sequential Roof's layer-based assembly method to a method of spatial assembly, this research expands the possible timber architecture repertoires and applies it at a building-scale to the typology of the timber module: a prefabricated volumetric unit of timber framing which is subsequently assembled on-site. The spatial assembly method builds upon previous work demonstrating the construction of stable spatial structures without the need for any scaffolding by means of a cooperative robotic sequencing (Mirjan 2016; Parascho et al. 2017) by shifting from an assembly logic that constantly requires the robotic support of parts during assembly to one where parts only require support at specific steps of the assembly process.

The DFAB HOUSE (NCCR Digital Fabrication 2018), a three-story building project initiated by the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication, allows for the transfer of this research to its building-scale application. The timber modules have to reach outside the research setting and are subjected to multiple real building challenges such as fire code, engineering code, acoustics, transport logistics, interfaces with neighbouring building components and finally the test of time while being used and exposed to the elements.

2 Techniques

2.1 Timber Frame Construction System

In this section, we present the constructive system for the research. The constructive system is a modification of the well-established timber frame construction that includes vertical timber beams in combination with structural plates (i.e. balloon frame or platform frame construction). This constructive system is informed by the robotic fabrication constraints and the required assembly sequence of the structure. The structure consists of generic timber beams with rectangular profiles that have only one simple cut (at varying angles) at each end. The connection between two timber beams consists of either one or two pairs of screws allowing for tension, compression and shear. The connection can be reinforced where needed by introducing a steel rod. The cutting planes for the beams at each end are generated algorithmically, and processed automatically by the robot in cooperation with the CNC saw. Concurrently, the algorithm generates the milling and drilling vectors for the screws or the tension rod. This approach ensures the possibility of assembling complex structures from generic timber beams without the need for complicated CNC joinery.

This constructive system has several advantages. First, structural plates are not necessary since the arrangement of the timber beams can provide lateral stiffness through triangulation. Therefore, this constructive system provides the opportunity to introduce suitable surfaces based on architectural requirements such as glass, translucent membranes, and openings without compromising the structural stability. Second, since the structure is assembled spatially, it is not necessary to have two corner beams as is the case with prefabricated plate components[1]. Therefore, the spatially assembled corner only requires one beam which is also free to rotate in plan, thus allowing for non-orthogonal configurations without the need for CNC manipulation along the length of the beam.

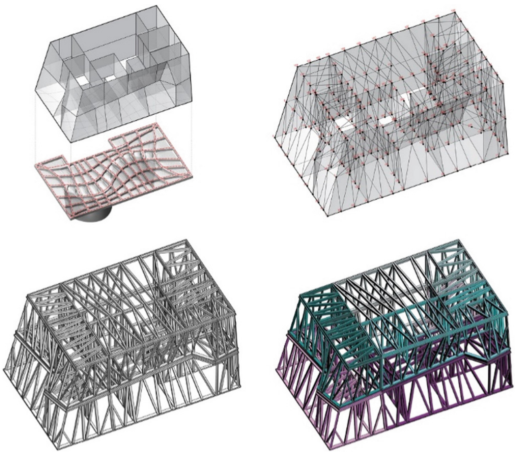

Fig. 1. Illustration of the computational design process/feedback. Diagrams: a. Architectural Inputs: the loadbearing ribs of the lower floor, programmatic organisation, and the exterior envelope b. Structure topology generation (Network graph) c. Generation of Beam class instances d. Modules.

2.2 Computational Design

A bespoke computational design and robotic fabrication workflow is developed for this research project (see Fig. 1). The computational design starts with a set of inputs including support condition (in the case of DFAB HOUSE, the loadbearing ribs of the lower floor), programmatic organisation, and the exterior envelope (see Fig. 2a). This workflow is organised around two main classes: "Building" and "Beam". The Building class is a non-manifold graph[2], which includes methods and attributes to generate and store the topological information of the building structure. The Beam class includes methods and attributes to generate and store all necessary geometrical, structural, and fabrication information for an individual beam.

The timber frame structure is generated in two sequential steps. Based on the inputs previously mentioned, an instance of the "Building" class is initialized. Successively, the methods of this class generate and store topological information of the timber

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[1] These components each require an edge beam which, when fully assembled result in a double corner beam.

[2] The Building class is built on top of the "Network" class from "COMPAS". For more information about the Network class please see: http://block.arch.ethz.ch/docs/compas/core/pages/core/compas.datastructures.network.html.

structure in the attributes of the graph: vertices and edges. The topology of each beam in the Building class is represented as an attribute of the class "bar" with an identifier of the two end vertices. In the Building class, each bar has all the necessary information in relation to other beams and the overall structure such as neighbours, parents, and assembly order. After the generation of the building structure topology a "Beam" object for each bar is instantiated. Each generated timber beam (an instance of the Beam class) has the necessary information for fabrication such as the gripping plane, end cut planes, milling and drilling vectors and diameters, connections typology, cross-section etc. Implementation.

2.3 Experimental Setup

One requirement of the fabrication setup (see Fig. 2) is the ability to produce prefabricated timber modules at a building-scale. The setup in general and the engineered tools are designed with a dynamic planning process in mind e.g. changing material dimensions and assembly strategies throughout the course of the project due to changes in the planning process and findings made along the way. Certain timber beam constellations require cooperative robotic manipulation, meaning, two robots work together on the same task during assembly. The same robots also prefabricate (cut, mill and drill, the timber) beams.

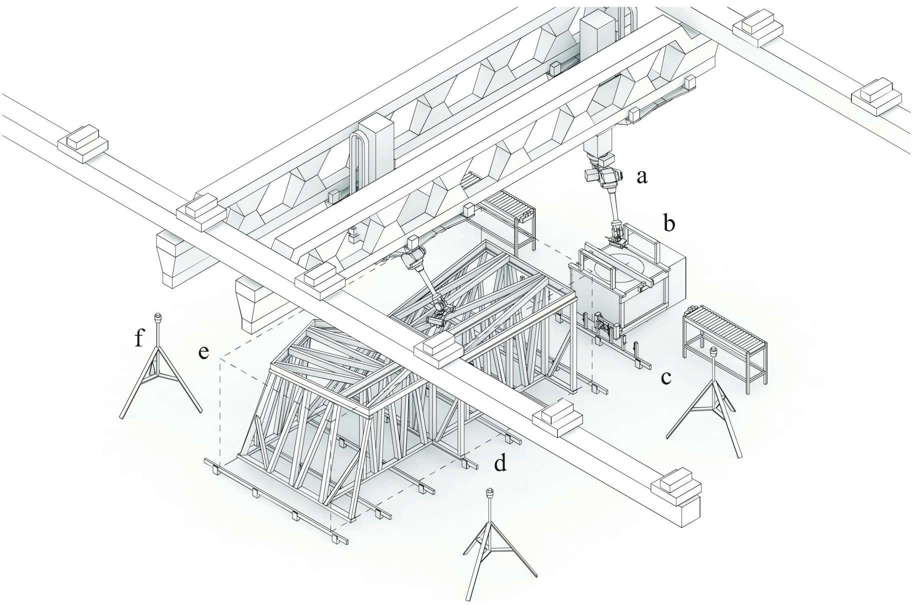

Fig. 2. Multi-Robotic Prefabrication Setup: a. Industrial robotic arm attached to a gantry system. b. CNC saw and fixing station. c. Robot end-effector storage. d. Assembly stand. e. Maximum cooperative building envelope of 3.75 m × 3.50 m × 8.20 m. f. Tracking system.

Multi-Robotic Prefabrication Setup. All of the tests and experiments are fabricated using ETH Zurich's Robotic Fabrication Laboratory (RFL). The setup has a total work space of 45 m × 17 m × 6 m. The robotic setup consists of two six-axis industrial robotic arms, each attached to a base with three axis of movement, x, y and z.

A three-axis CNC saw[3] is implemented for cutting the timber beams and serves simultaneously as a fixing station for the further processing of beams. The robots are equipped with automatic tool changers allowing them to switch easily between multiple tools during a fabrication sequence without the need of human interference. A custom gripper comprising of mostly off-the-shelf components was designed to pneumatically grip timber beams ranging from 60 mm to 220 mm in width and depth, thus enabling the robots to grip all of the timber beams on either their short or long side. This flexibility in gripping allows beams to cut in one orientation and placed in another. In other words beams can firstly be oriented so that cuts shallower than the saw's minimum pitch can be made, secondly the beam can be gripped from a different orientation to avoid collisions with neighbouring beams or cooperating robots during placement. The screw connection detailing required the design of a double-spindle tool. One spindle being equipped with a mill bit while the other houses a long drill for drilling holes at shallow angles.

Path Planner. The robotic fabrication and assembly of bespoke spatial structures leads to the requirement of bespoke robot path planning in order to manoeuvre a part from a start position to its final position in the structure without colliding with the already built structure or the other robot (Gandia et al. 2018). Sampling-based path planning algorithms (Kavraki Lab 2012) are used to generate collision-free trajectories. The path planner takes multiple criteria into account such as: what is already built, the timber currently being held by the robot and the position of the other robot as to avoid collisions.

RFL Correction System. The tracking system iGPS (Nikon Metrology) is implemented to firstly, bring the facility to sub-millimetre accuracy and secondly, to enable an absolute referencing system for accurately setting up additional machinery as well as allowing for the quality control of assembled parts for example using the handheld probe. In order to harness the accuracy provided by the tracking system in any robotic process, two iGPS i5 sensors are mounted to each robot's end-effector on the robot flange side.

2.4 Experiments

Throughout the course of the project new tools and techniques were tested on a series of empirical experiments leading up to the final experiment, the full-scale fabrication of the DFAB HOUSE timber modules. Four experiments, respectively Experiment 1, 2, 3 and 4 were undertaken to validate the cooperative robotic assembly of a corner, beam

[3] The saw has a 650 mm blade and three axis of movement: 0°–360° of rotation, 90°–25° of pitch and −10 mm–230 mm of linear movement.

processing and robotic pose correction, in place milling and finally the integration and realisation of a complete module.

Fig. 3. Cooperative assembly sequence

Experiment 1: Cooperative Robotic Assembly of a Corner. The first experiment aims to verify the assembly sequencing and fabrication strategy. By cooperatively assembling the timber beams with multiple robots, a building-scale timber frame module can be assembled in space without the need for additional scaffolding.

As the fabrication setup was still being developed, the beams were ordered pre-cut by a joinery machine. Despite the robots being accurately measured in and parts being fabricated to an accuracy of plus-minus 1 mm, the assembly proved to have gaps of up to 5 mm, especially in cooperative scenarios where both robot coordinate systems would need to align. Assembly is split into two distinct scenarios, singular, requiring one robot or cooperative, requiring two (see Fig. 3). First the base is assembled using a single robot on which corners are cooperatively assembled. Each is corner is constructed of three beams where the first robot brings the initial beam and supports it while the cooperating robot places the second and subsequent third beam. Once all three beams are connected, the robots can release the corner.

The assembly sequencing was adjusted as it became apparent that it was necessary to leave a “corridor” parallel to the gantry’s y-axis free during assembly to allow both robots to avoid collisions with the structure when moving the robots from one side of the assembly stand to the other. The fixed base-to-wrist path planning approach proves to work in most cases but can lead to collisions and situation specific adjustments. There were collisions between the robot and the already assembled structure as well as self-collisions between the robot and the beam it was carrying due to the beams length of up to 3.3 m. The fixed base-to-wrist ratio also requires situation specific tweaking for different beam types e.g. the lower beams require the robot’s base to be located above the wrist whereas the ceiling joists require the base to be approximately at the same height, as the z-axis of the robot’s base was close to its limit. This shows that the implementation of bespoke path planning would be of assistance during the assembly.

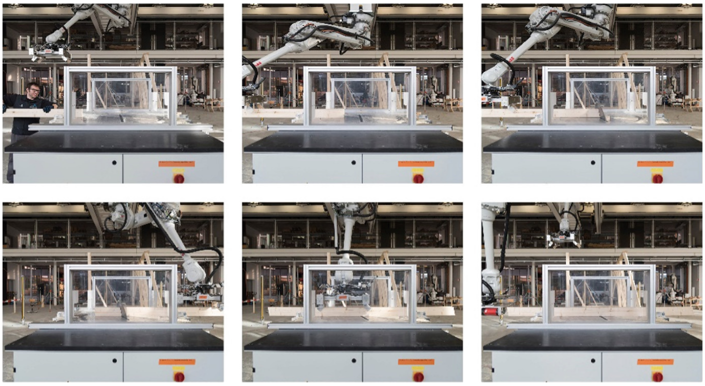

Fig. 4. Beam Cutting and Detailing Sequence: 1. The robot positions the beam and saw executes the first cut. 2. The robot positions the beam and the saw executes the second cut. 3. The beam is repositioned and the robot proceeds to mill and drill the required detailing.

Experiment 2: Beam Processing and Robotic Pose Correction. This experiment aims to implement and test the robotic fabrication of timber beams based on the computational design and reduce tolerances encountered in Experiment 1 via the introduction of the RFL correction system to the robot's end-effector.

In contrast to Experiment 1 the timber beams in this experiment are cut by the robots based on the embedded fabrication information supplied by the computational design model's "Beam" class. The fabrication process (see Fig. 4) consists of multiple tasks carried out by either one or two robots depending on the assembly sequence of the beam. Firstly, a stock timber beam is placed by hand on the saw's conveyor belt. From there on the saw's grippers centre the beam and the robot proceeds to pick up the beam. In collaboration with the saw, the robot places the beam for both end cuts. After cutting has been completed, the beam is placed on the saw and supported again by the saw's grippers allowing the robot to automatically change tool from the gripper to the double-spindle tool and proceed with the milling and drilling of the required connection detailing. The beam is then picked up again by the robot and manoeuvred to its final place in the assembled structure with the aid of the path planning algorithms. Finally, double-threaded SFS structural screws are screwed manually into the predrilled connection detailing to fix the beam. Depending on the beam's assembly, the robot can now either release the beam and continue fabricating the next beam or continue supporting the beam while the other robot prepares subsequent beams. The RFL correction system is also implemented for the first time in conjunction with the robot's end-effector to reduce tolerances during fabrication and assembly. This requires the robot to pause and measure its position for approximately 2 s at every position requiring accuracy[4].

[4] A typical fabrication cycle requires accuracy at the following positions: initial pick-up, placement for the first cut, placement for the second cut, placement of the beam on the fixing station, milling approach, drilling approach, subsequent pick-up and final placement.

Experiment 2 shows if each tracking system sensor has visual contact to 4 or more transmitters, an end-effector accuracy of below 1 mm can be achieved. It also needs to be noted that despite the end-effector being positioned under 1 mm accurately in space and the beam cuts being accurate to 1 mm of one another while in the fixing station, some beam connections were up to 5 mm away from their target geometry. This deviation is due to timber tolerance in beams longer than 2.5 m and the robot gripping the centre of the beam, the point farthest from the connection. The insertion of joists into the perimeter of rim joists proved to be difficult due to tight material tolerances.

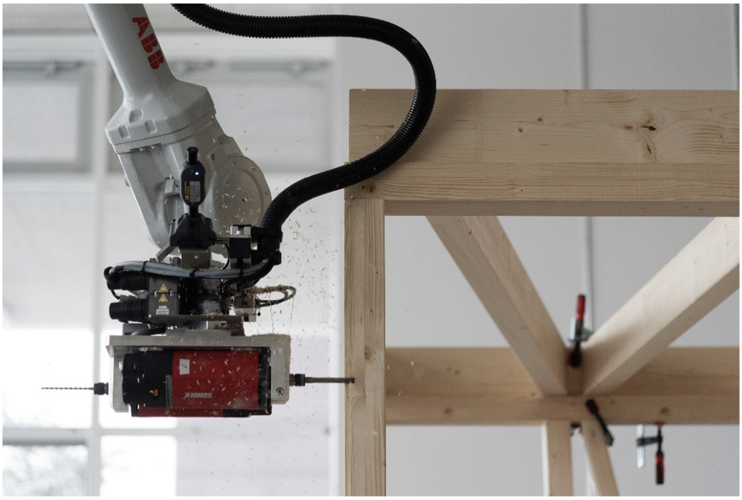

Fig. 5. In Place Milling: The robot mills the required façade detailing into the already assembled structure.

Experiment 3: In Place Milling. The aim of Experiment 3 is applying the findings of the previous experiments to a full-scale mock-up module from the DFAB HOUSE. The experiment also aims to integrate all of the necessary facade detailing that is required for final production.

The façade's geometry required certain lower and upper chords to be milled to a ruled surface. This requirement made way for the development of a novel method of fabrication "In Place Milling" (see Fig. 5). In place milling has several advantages over prefabricated milling. If the required ruled surface were to span multiple beams and were to be prefabricated, then a high level of accuracy would be required to ensure that the parts line up again smoothly once assembled. On the other hand in place milling allows for the fabrication of a continuous smooth surface across multiple beams without the need for high accuracy during placement of the beams. It allows for the decoupling of assembly and detailing tolerances. To tackle the tolerances occurring when inserting the joists into the perimeter of rim joists a feedback loop was integrated. Using the handheld probe, strategic points are measured on the rim joists and are fed back into the fabrication loop. This allows for the exact positioning of the rim joists to be updated thus updating the joists and their respective fabrication data.

In place milling greatly increased the accessibility for fabrication as obstructions such as grippers for fixing the part were not required. The ability to mill in place also delivers an absolute level of accuracy as it buffers out additive tolerances. The milled surface is within 1 mm accuracy of the target geometry. The feedback loop proved to be necessary when dealing with material tolerances and tight-fit insertion paths.

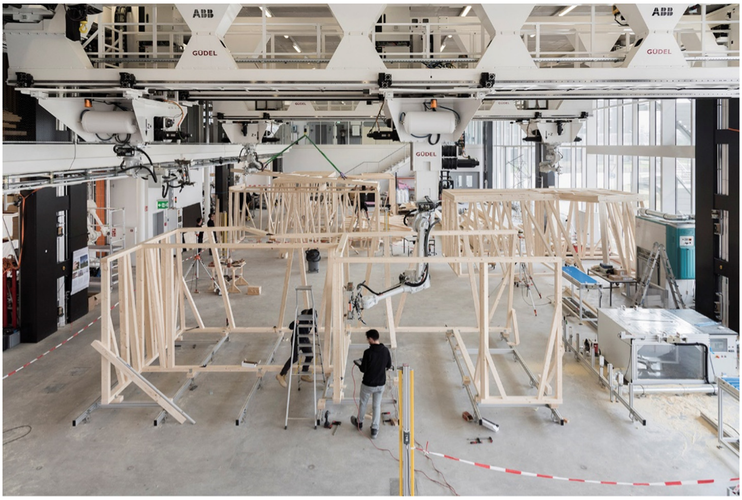

Fig. 6. Photo of the RFL during the production of DFAB HOUSE timber modules.

Experiment 4: Integration and Realisation of a Complete Module. The DFAB HOUSE timber modules aim to integrate all of the findings from the previous experiments and reach outside the research setting by taking real building challenges into account. The DFAB HOUSE includes 487 beams with unique geometries. The timber frame structure is divided into six modules (volumetric) and three flat panels.

The transfer of the research to a real world application led to multiple adaptations of the required detailing and subsequent fabrication. The precise positioning of the double threaded screws in the timber frame butt-connections lead to revision of their insertion approach. The screws are no longer inserted from above but rather from below. Based on the engineer's calculations, some of the connections would be exposed to tension forces above 14 kN[5] leading to the introduction of a rod and steel-plate connection.

The fabrication of the DFAB HOUSE timber modules (see Fig. 6) proves that the developed tools and techniques can successfully fabricate timber frame modules consisting of up to 99 beams and measuring 8.1 m × 3.6 m × 2.8 m (length × width × height) as well as flat elements such as the roof and the back walls. The robots are able to fabricate and manoeuvre beams weighing up to 55 kg and measuring

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[5] 14 kN was calculated to be the highest tension force for two pairs of double threaded SFS screws.

8.1 m × 0.16 m × 0.08 m (length × width × height). This being said, beams of this size incur large material tolerances and require manual intervention when fixing.

3 Conclusion

The experiments throughout this project have shown that the robotic fabrication of spatial timber frame modules allows for the fabrication and assembly of geometrically complex and bespoke timber structures. The flexibility of the setup allowed for a seamless integration of a wide range of fabrication processes such as sawing, milling, drilling, in place milling and in place drilling. This in turn permitted the introduction of new details at late stages of the project without delaying fabrication, showcasing the advantage of the continuous digital chain. The setup allowed for the fabrication of timber modules at full-scale, thus expanding the range of prefabricated timber architecture.

The developed assembly logic worked in principle but still required adjustments as this proved to be more complex than anticipated. The parts require high tracking system transmitter visibility when being placed, cannot be occluded by previously assembled parts and need to be sequenced so that the robots can reach them. The positioning of the robot and the robotic fabrication of the parts themselves was highly accurate. However, the assembly of the parts proved to be challenging due to material tolerances, the robot's mechanical stiffness and the force-inducing nature of the screw connection. These tolerances were taken care of through human intervention by supporting the part by hand or with clamps and controlling accuracy visually or with the handheld probe.

Strategies to tackle these tolerances such as follows could be developed in the future, making the robust, swift and accurate assembly of spatial timber structures possible. A focus could be set on local accuracy of joining rather than global accuracy. In other words, the detail where two parts come together would be where accuracy is needed rather than the overall position of the part. This could be achieved by the robot gripping close to the connection rather than the centre of the part. The accuracy of the detail would be increased and more stiffness would be provided during assembly as less force would be applied to the robot. Force and/or proximity sensors could be implemented to allow the robot to feel or see its surroundings and place the part accordingly. In place detailing rather than prefabricated detailing could improve connection accuracy and make way for robot-driven methods of detailing such as nailing or doweling.

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