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Doctoral Research Plan

Robotically assembled timber structures with integral timber joints

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Abstract

This research investigates the robotic assembly of architectural-scale timber structures that are jointed with integral timber-to-timber connections, such as lap joints and tenon joints.

Previous researches in robotic timber assembly have investigated many different methods of jointing timber elements (such as screws, nails and glue) where the joint geometry is often a simple straight cut. This research will investigate the use of integral timber joints, which contains intricate geometries that are better customized for load transfer in robotically fabricated structures. In particular, I propose a novel robotic assembly process based on distributed high-force actuators that aim to address assembly challenges unique to integral timber joints, such as high assembly force, precise alignment and simultaneous joint closure. This process will enable the assembly of structures that contains an arbitrary amount of tight-fitting joints, which were previously not achievable by robotic processes.

A set of parametrically defined joint types (parametrically and topologically variable) are used to demonstrate the potential of the process in creating customized structures, As a set of design grammar, these joints provide large freedom for a combinatorial design space. Design studies (digital) and large scale experiments (physical) will be used to demonstrate and validate the hypothesis that many different structures can be designed and constructed using this process. Three evaluation cycles will be performed between process development and design studies as an evaluation of the versatility and applicability of the for both design and construction process. This research will be performed in collaboration with PhD student Davide Tanadini from the Chair of Structural Design, whose research will provide methods for integral joint design and structural analysis.

This research builds on the hypothesis that the integration of digital design, robotic fabrication and automatic assembly can offer unique opportunities for creating structures that would otherwise be prohibitive to construct. As such, the thesis aims to advance digital fabrication processes by neutralizing the impact of complexity in custom designs.

Keywords:
Timber structures, Robotic timber assembly, Integral timber joints, Remote controlled tools

Contents

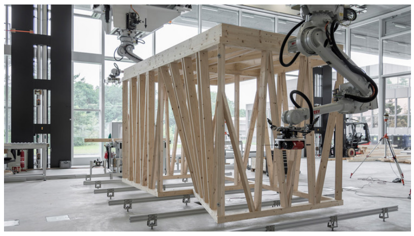
1 Rationale

Robotic timber construction concerns the use of programmable robots for cutting, sorting, placing and jointing timber elements. It is a rapidly advancing field in academia and industry that aims to address automatic production and assembly of timber components into architectural structures. It aims towards neutralizing the impact of non-standard design using programmable robotics and automated processes.

1.1 Introduction

(a) Robotic Pavilion 2014, Zurich

(b) Sequential Roof 2016, Zurich



(c) DFAB house Timber Module 2018, Zurich

Figure 1 Precedence robotic timber assembly projects

Research in the past such as the **Sequential Wall** project investigated the use of robotics arms to pick and place timber elements to construct geometrically complex design. (Gramazio, Kohler, and Willmann 2014) The **Robotic Pavilion** project (Fig.1a) extended the concept to create prefabricated units that was assembled into a two story structure. In this case, human performed the installation of screws to create structural joints. (Eversmann et al. 2016) The **Sequential Roof** project (Fig.1b) is the first fully automated fabrication process of its kind. The entire process of sorting timber sizes, cutting, placing and nailing was fully automated and has demonstrated the complexity-agnostic benefit of robotic fabrication. The high level of prefabrication resulted in large modules that are quick to install on site, only constrained by transportation and lifting limitation. (Apolinarska, Bärtschi, et al. 2016) The **DFAB HOUSE Spatial Timber Assemblies** project (Fig.1c) tackled the problem of non-layer-based assembly for creating bespoke residential timber modules. A robot was used to position all the horizontal, vertical and tilted timber elements directly in their 3D position while human performed the installation of fasteners. The flexibility of the robot provided the freedom to position structural elements that were designed according to force flow and created architecturally expressive curvy walls. (Adel et al. 2018)

These precedence projects have used nails, screws and glue (Helm et al. 2017) to join timber elements that were essentially butt jointed, i.e. no notches were cut into the wood. This new research builds upon the robotic techniques developed in the precedence and investigate the use of integral timber-to-timber joints. **The motivations for this research** are the following:

- The structural capacity of integral joints can be much higher than simple butt joints in certain load cases.
- As an alternative to metal plates and fasteners, integral jointed structures have substantially lower part count and thus simplifies part handling for robots.

- A matured industrial process already exists for cutting customized joints on timber elements.

1.2 Background

1.2.1 Integral Timber Joints

(a) Roof of Westminster Hall **(b)** Pagoda of Fogong Temple **(c)** Bridge by Grubenmann Brothers

Figure 2 Examples of timber structures constructed with integral timber joints.

Integral timber joints were used extensively in pre-industrial timber structures [1] and are still used today in large scale timber structures and prefabricated timber constructions. Many stunning architectural examples (Fig.2) such as timber frame houses, large span roof trusses and bridges were created purely with timber to timber connections.

In the past few decades, industrial automatic joinery machines (Fig.3a) had substantially lowered the cost of the otherwise the labour intensive process of cutting intricate timber joints. These machines are designed to accept milled timber with a uniform profile as input and can be digitally programmed to cut different joint geometries at a variable location (Fig.3b and Fig.3c).

(a) Hundegger K2i **(b)** Joint cutting process **(c)** Different joints produced by the K2i

Figure 3 Example of an Automatic Joinery Machine and its capability

State of the art timber-specific CAD software can create digital information [2] that can be interfaced with an automatic joinery machine, allowing a seamless transfer of building data from design to prefabrication. They are able to cut different joints types of different angles at different locations along an element. However, despite of this flexibility, most of their current use is for constructing timber structures that are

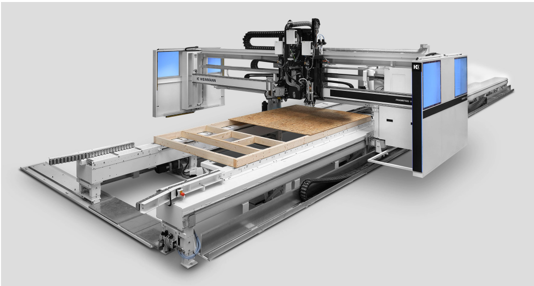
[1] Examples include log frame construction, timber frame construction and post-and-beam houses from European heritage (Zwerger 2015) (Jack A. Sobon 2002), and many post and beam structure from Chinese heritage (Seike, Yobuko, and Davis 1977) (Sato Hideo and Nakahara Yasua 1995)

[2] Building Transfer Language (BTL) is a commonly adopted language for describing geometrical information of timber elements and their joinery details between CAD and CAM software. This language contains a set of standard joinery details (such as mortise and tenon joints) and allow parametric angular and size variations of each joint type. (*BTL interface description 10.6* 2018)

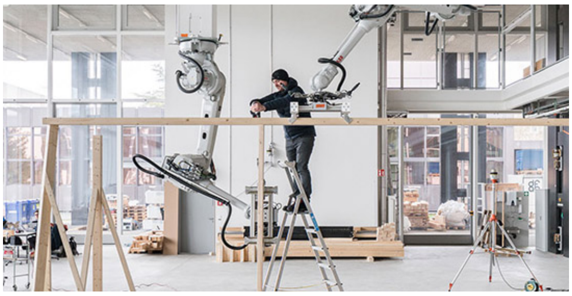
repetitive. While these machines possess the capability of producing highly complex timber parts, this thesis identified the bottleneck being the complexly in the assembly process.

Despite some machines can process and cut joints on curved timber elements, the focus of this research is on linear timber elements because of their economical production process.

1.2.2 Robotic Assembly



(a) HOMAG Combi Wall System capable of fully automatic production of flat wall assembly. However, spatial assembly is not possible.



(b) Robotic spatial assembly during the construction of DFAB House. However, manual work was needed for the screwed joints.

Figure 4 State of the art in robotic timber assembly.

Until now, prefabricated timber elements with integral timber joints were assembled manually [3]. Although automatic machines and production lines were developed for assembling flat walls and floors (Weinmann 2019), they cannot assemble carpentry joints, or any non-planar (a.k.a. spatial) assemblies. In order to facilitate the construction of more complex timber structures, where (1) the assembly location and orientation cannot be performed on a flat assembly table (2) the assembly sequence are nonrepetitive for a manual worker and (3) the number of timber elements are large [4], this thesis identified the need for a flexible automatic assembly process to be the crucial component for constructing bespoke and unique timber structures.

2 Problem Statement

Precedence projects in the past have addressed technical challenges required for robotic timber assemblies, such as collision-free robotic control (Stadelmann et al. 2019) (Gandia et al. 2019) and computational design workflow (Apolinarska, Ralph Bärtschi, et al. 2016). However, the introduction of intricate timber joinery creates unique challenges that will be addressed in this research.

[3] State of the art timber frame manual assembly are often assisted by mechanical cranes. However, manual tools such as hammers and ratcheting straps were used to overcome friction of the tight fitting joinery. The collaboration of a team of craftsmen are necessary to align and install some of the elements which spans between multiple pieces.

[4] Apolinarska, Bärtschi, et al. had used more than forty thousand pieces of uniquely cut timber for creating the Sequential Roof. This is only possible when the logistic between prefabrication (cutting) and assembly is automated.

2.1 Large assembly force to overcome joint friction

Timber joints are often designed to be tight fitting in order to ensure structural rigidity. However, this requires large assembly forces to overcome the friction during joint closure. Robeller et al. [5] have characterized the source of friction in tenon joints to be related to the fit. Moreover, when multiple joints are assembled in the same movement, small imprecision will causing mating faces to rub against each other and induce large friction.

2.2 Precise alignment between members

Previous projects which employed industrial robots for assembly (Fig.5b) [6] had pointed to the need for a better strategy to handle construction tolerances. These tolerance can originate from the inaccuracy of the milled timber raw material, the prefabrication process by the automatic joinery machine, expansion or shrinkage caused by moisture change in the timber after prefabrication, inaccuracy of the assembly robot and the gripper and the deformation of the timber member during pick and place handling

While some of the inaccuracy can be accommodated by detail design that includes chamfered edges, the assembly process needs to react and correct for larger misalignment before joint closure.

2.3 Simultaneous assembly of multiple joints

In a timber structure, it is common for each timber element to be jointed with multiple other elements. It is also common that the integral joints are designed such that only one assembly trajectory is possible. In order to avoid jamming, it is necessary for multiple joints to close at the same speed [7].

2.4 Temporary support of timber elements

The design of complex timber structures often involve non-planar assemblies that cannot be built on a flat table. Very often, the individual timber elements are not stable until the structure is at least partially completed. In the past, researchers have used robots to temporarily support an unstable element (Fig.5a). However, this solution is hard to scale up for structures with multiple unstable elements [8].

[5] The Robotic Integral Attachment research (Robeller et al. 2017) is the only literature that have attempted joint insertion using a robotic arm.

[6] For example the DFAB HOUSE Spatial Timber Assembly project which employed overhead robots mounted on gantry.

[7] Jamming occurs between two tight fitting components when a small misalignment creates a positive feedback that worsen the misalignment. This is often observed when the assembly motion is highly constrained and the fit is tight. This problem manifest also in manual assembly where multiple carpenters had to each attend to one joint and meticulously synchronize their hammering actions Therefore, it is often a rule of thumb when designing a manually assembled structure, to restrict the total maximum of joints per element, and to avoid designing joints that are too close to each other.

[8] During the DFAB HOUSE Spatial Timber Assembly project, two robotic arms were used. One arm would temporarily support a horizontal beam while another arm place vertical supports. (Fig.5a) Using two robotic arms, the method is limited to support only one unstable element.

(a) One robotic arm can be seen temporarily supporting a beam.

(b) Misalignment during test assembly.

Figure 5 DFAB HOUSE Spatial Timber Assembly process

3 Research Question

Question 1: How can robots assemble timber structures with integral timber-to-timber joints?

This research aim towards finding a generalizable robotic solution that is applicable for structures that includes integral timber joints. This enables an automatic assembly process for designs that are previously not possible. A novel assembly process is hypothesised (details in Chapter 4 - Hypothesis) to address the technical challenges specific to assembling timber structures with integral joints. This process introduces the concept of distributed robotic tools that have not been explored in the past.

The research question asks, from the perspective of process design, is this process efficient? Is this process robust and flexible? Which are the joint types that can be reliably assembled by a robot? What are the design features in the joints that make it compatible with robotic assembly? What are the practical limits of this process in terms of element sizes, weight, joint types, number of parts? Can this process overcome the stated challenges as hypothesised? Are there new challenges that were not discovered before?

Question 2: What type of timber structures can be built by the robotic assembly?

The proposed assembly process can be applied to many different types of joints. However, to limit the scope, a selected set of three parametric timber joints will be used to demonstrate the automated assembly process. Despite limiting to only three joint families and linear elements, this thesis hypothesis that numerous design possibilities exists through the parametric and combinatorial use of these joints (details in chapter 4 Hypothesis).

This research question studies what meaningful combinations can result from this set of joints. From the perspective of architectural and structural design, what type of timber structures can be designed with such grammar? What are the design limitations imposed by process constraint?

4 Hypothesis

4.1 Hypothesis 1: Distributed Robotic Tools

This research hypothesis that a **distributed assembly tool strategy** can solve all the assembly challenges mentioned in the problem statement. The proposed assembly process will use an agile pick-and-place robot (the **"robot"**) such as a robotic arm, and a set of custom developed end effectors that resemble carpentry clamps (the **"clamps"**). These clamps contain high force actuators to overcome any contact forces that may appear at a single joint. The process will start with a few timber elements fixed to a temporary foundation and progress by sequentially adding more elements. The robot will attach one clamp for each joint that needs to be assembled and position a timber element into the clamps.

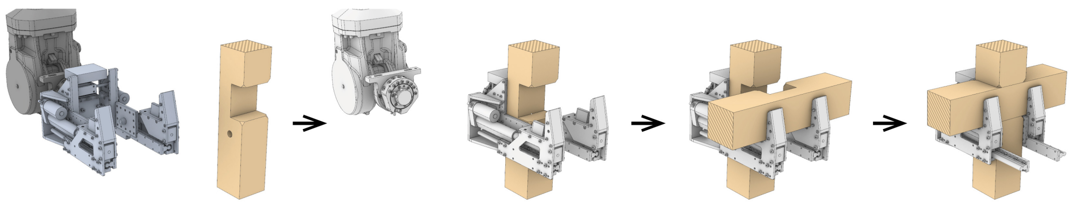


Figure 6 Assembly process of one timber joint using a clamp: (from left to right) A clamp being moved by a robotic arm; Clamp attached to one side of the joint; New timber element placed in clamp; Joint closure by clamp actuators.

The clamps will then be activated simultaneously to assemble all the joints. The clamps can be repositioned afterwards by the robotic arms, or left in place to act as temporary support for the incomplete structure. Additionally, the geometry of the clamps will provide passive guidance features to correct for misalignment between mating members.

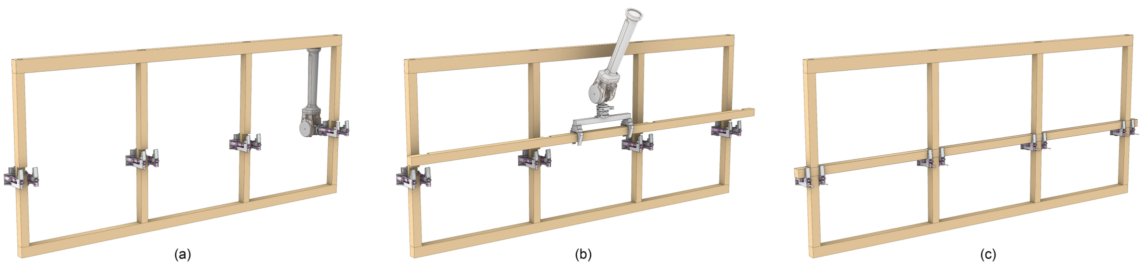
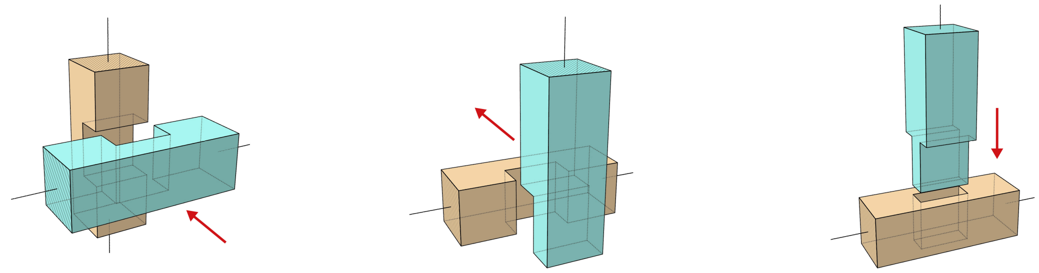


Figure 7 Illustration of multiple joints requiring simultaneous closure. (a) Robotic arm sequentially attaches multiple clamps on a structure. (b) Robotic arm with gripper places new timber element. (c) Clamps operate simultaneously to close all joints.

Because different types of joints (such as lap joints and tenon joints) have very different assembly direction in relation to their geometry, different types of clamps will be necessary for each type. To minimize the number of distinct clamp types, yet remain flexible for different joint angles and joint geometries, joints types that share the same assembly directions and external geometry are grouped into a joint family that can share the same clamp. Three joint families (Fig.8) have been identified to be fundamental for timber construction, and will be included in this research. Each of them is flexible to include different detail design that are relevant for structural performance, and a wide range of jointing angle.



(a) Cross Lap Joint **(b)** Tee Lap Joint **(c)** Mortise Tenon Joint

Figure 8 Three joint families included in this research. They are illustrated in their 90 degrees configuration. The red arrows indicate the assembly directions of the blue parts in relation to the brown parts.

4.2 Hypothesis 2: Different timber structures assembled by robots

This research focuses on three of the most common joint types used in timber construction. Despite being a small set, their parametric definitions (Fig.9b) allow them to be used in different combinations to create various designs for different architectural and structural requirements. Each joint family contains numerous typological possibilities (Fig.9c) that can be chosen or designed based on structural analysis.

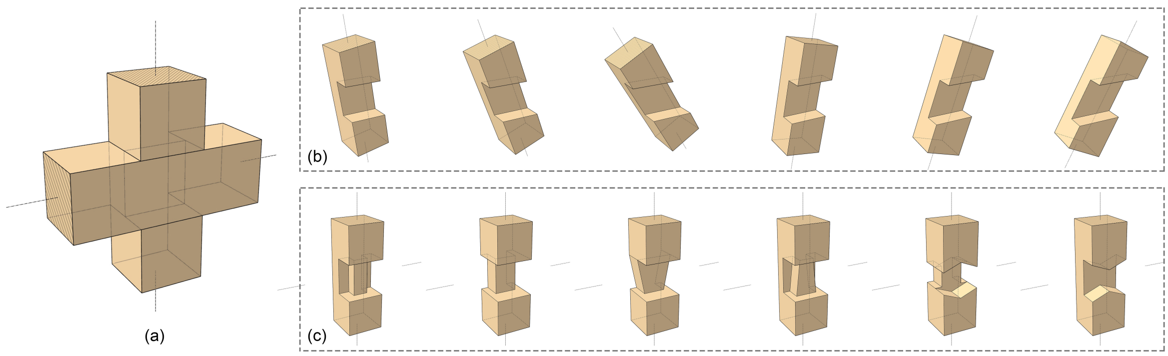
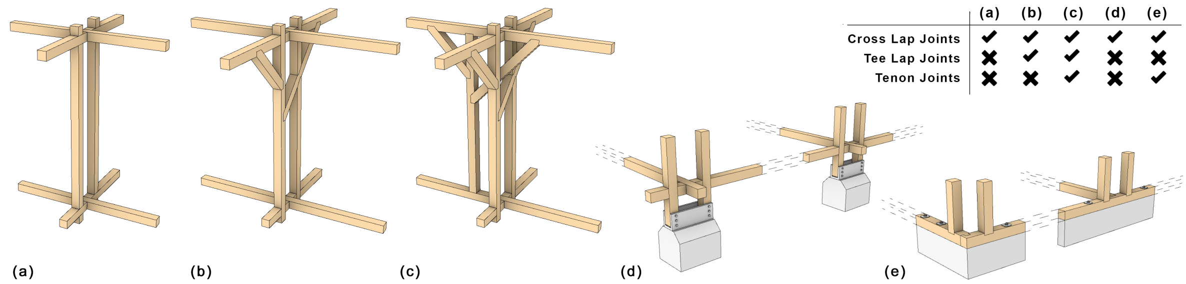


Figure 9 Cross lap joints family and its various configurations. (a) Typical cross lap joint in 90 degree configuration (b) Different angular configurations. (c) Different joint typology configurations. (Only one element is drawn in b,c for clarity.)

Despite all three chosen joint families are two-way joints (jointing between only two elements), many commonly used timber construction details can be recreated by arranging the elements in different ways and by combining different types of joints. (Fig.10) This research hypothesis that different structural systems and architectural typology can be created with these three families of joints alone.



	(a)	(b)	(c)	(d)	(e)
Cross Lap Joints	✔	✔	✔	✔	✔
Tee Lap Joints	✖	✔	✔	✖	✖
Tenon Joints	✖	✖	✔	✖	✔

Figure 10 Various framing details and the types of joints used. Post and beam arrangements with (a) no stiffening brace (b) one pair of braces (c) two pair of braces. Post and plate arrangement, connected to (d) isolated foundation and (e) perimeter foundation.

5 Research Plan

5.1 Methodology

Because of the interdisciplinary nature of the research, two different research trajectories will occur in parallel. The first is process design: Robotic clamps and control software will be developed, and trial constructions will be used to study and validate the proposed robotic assembly process. This includes mechatronics and software development performed by the author to develop custom clamps and remote motion control. Collision free robotic path planning, assembly action sequencing [9] and motion control software shall be adapted from existing work by other researchers.

The second is design studies: Digital drawings and models of different timber structures will be designed and validated through computer simulation and physical experiments. Attempts will be made to design modular houses, roof structures and tower structures with regard to the fabrication constraints that are discovered. Special attention will be made to create valid structural systems. The resulting catalog of designs will show the available design space of the proposed process.

Spatial and formal customization will be explored by the author while structural level topological customization and joint level geometry customization will be investigated in collaboration with PhD candidate Davide Tanadini from the Chair of Structural Design. His proposed PhD research in modeling force flow within timber joints provides a novel method for structural analysis and design.

Phase 1: Assembly process In the first development phase, a proof of concept clamp for a 90 degrees lap joint (may include tenon joint) will be designed. [10] Validation experiments will be conducted to better understand the limits of this assembly process and how future clamp design can be improved.

Case studies will be created based on the constraints, and a simple structure with orthogonal joints will be designed and constructed with the proof of concept clamp.

[9] Assembly actions include robot movement to pick up and install clamp, pick up timber gripper, pick up and position timber elements, clamp jaw opening and closing movements. The sequence of a complex structure often requires careful planning to avoid deadlock.

[10] The proof of concept clamp and preliminary studies was successfully completed as part of the pilot study in 2019.

Phase 2: Bespoke Structure Case studies will be used to identify the angular flexibility needed in each joint family for customized design. A balance is important between the flexibility and the complexity of clamp design. Based on these findings, angle-flexible clamps will be designed, constructed and the assembly process will be validated again. Remote control and synchronization systems will also be developed.

Design studies will be performed by digital modeling and validated by robotic simulation. Physical assembly experiments will be performed to ensure accuracy of simulation, in particular, multiple joint closure and non-orthogonal element arrangement.

Phase 3: Integration with Structural Design Phase 3 will focus on developing a design process that is integrated with structural analysis software developed by Davide Tanadini. The mode of collaboration will largely be based on automatic design checks that can be implemented at joint, member and structure level. The checks that will be implemented by the author includes assembly sequence deadlock, robotic collision, clamp movement collision and automatic joinery machine limitations. Structural capacity checks for joint detailing and member sizing will be implemented by Davide Tanadini. [11]

Finally, a 1:1 scale demonstrator will be created to demonstrate the benefit of an automatic assembly process for both architectural and structural proprieties. A design and structural concept will be outlined collaboratively, and an interactive design process (based on the design-checks) will be used to design the structure. [12] Comparative study will be conducted to study the implication of cost and labour.

5.2 Experimental Setup and Infrastructure

Hardware The robotic development, verification experiments and the construction of three 1:1 scale demonstrators will be performed in the Robotic Fabrication Lab (RFL) of the Institute of Technology in Architecture (ITA). Existing robotic infrastructure of 6-DOF robotic arms on 3-DOF gantry can be adapted with minimal change to perform the robotic manipulations required. The proposed clamps will be developed and constructed by the author in the machine shop of RFL, assisted by technicians. An external fabricator that operates automatic joinery machines will provide the machining capability to create the timber elements used in the experiments.

Software Most of the case studies will be conducted digitally using Rhinoceros 6.0 as the primary modelling and visualization environment. Software for creating assembly information [13], RFL robot control software, and robotic path planning will be adapted from the robotic fabrication package of the COMPAS Framework (Van Mele et al. 2017). Wireless communication, clamp synchronization, motion control, design check algorithms and data migration algorithms (from design environment to automatic joinery machines via BTL Language) will be developed by the author.

[11] The structural assessment and optimization work will be performed by Davide Tanadini as part of his PhD research.

[12] Such computer-aided design approach will allow a designer to evaluate design decisions and find feasible designs that satisfy both fabrication and structural constrains.

[13] Assembly information are semantic data in a design that describes the connection, assembly trajectory and clamping strategy between individual members.

This research operates under the Swiss National Centres of Competence in Research (NCCR) Digital Fabrication (DFAB) research stream 2B; Spatial Timber Assembles.

5.3 Progress to date

The research was started in 2019 and is currently between phase 1 and 2. Two different clamp prototypes have been designed and produced by the author. The first clamp (Fig.11) was created for 90-degree cross lap joints with the purpose to validate the mechanical system.

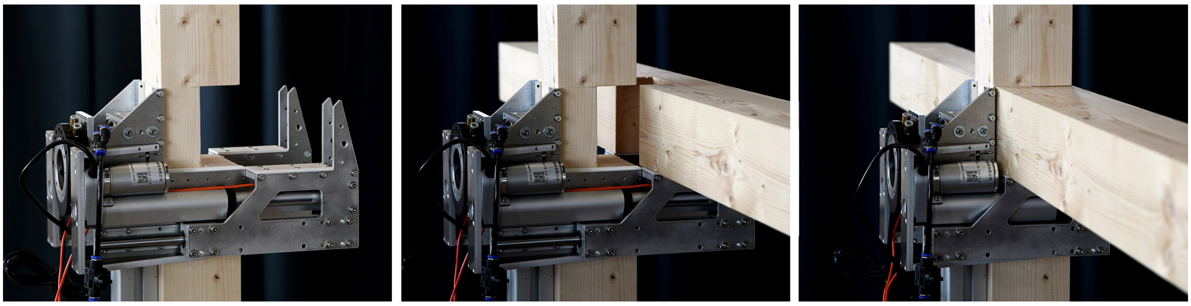


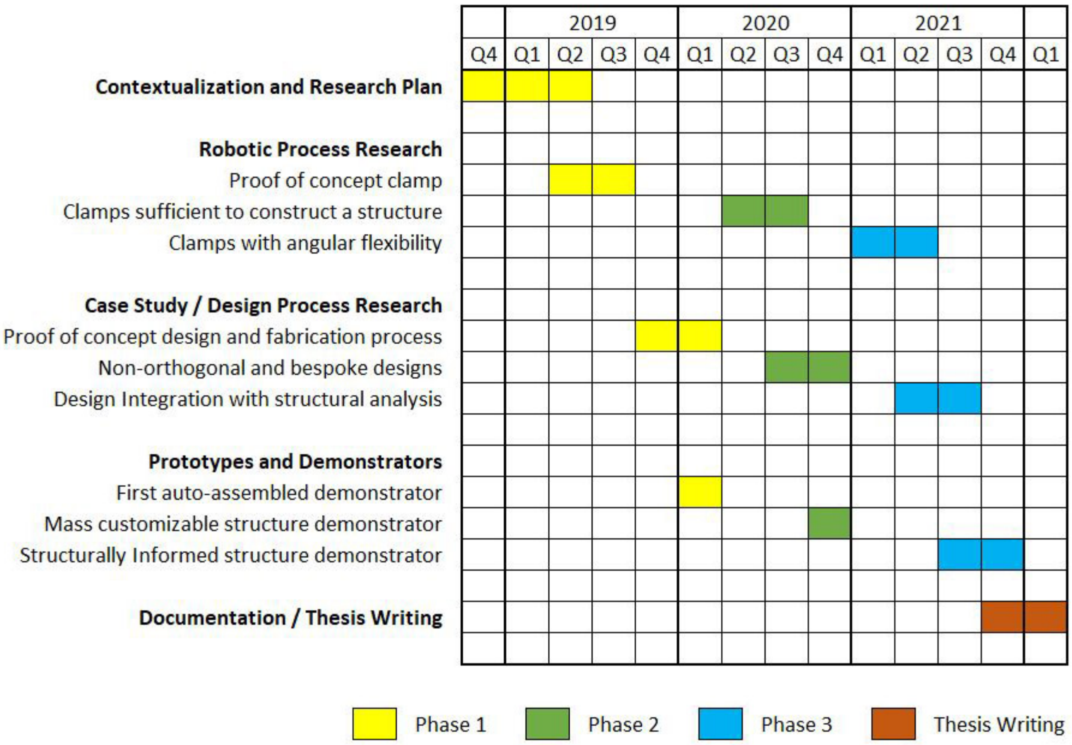
Figure 11 Sequence of operations by the first clamp prototype confirming its ability to attach to an existing column, and the high force actuator assembling the joint.

The second clamp prototype was designed for variable-angle planar tee-lap joints. Two identical clamps were created to test remote control and synchronization with robotic arms in RFL. Results have shown that both systems are feasible but further development is needed to improve robustness. Multi-joint assemblies with different element length, orientation, joint cutting tolerances and joint details will also be tested shortly.

Fig.12 shows a modular timber pavilion designed by other researchers in the research group. The two clamps were used for the assembly of a diagonal element and result shows that they can remove the need for manual intervention.

Figure 12 A modular structure where one of the elements is assembled with the help of two clamps designed by the author. (a) Overview of the structure, arrows indicate the locations of the clamps. (b) This experiment is carried out by manual placement of the element, future experiment will automate this step. (c) (d) Clamps at the top and bottom chord during assembly, respectively.

5.4 Timeline



6 Outlook

The outlook of this research is an automated construction process that can significantly lower the effort to construct bespoke timber construction. We believe the substantial reduction in manual labour offers new design opportunity in itself.

Similar to the now ubiquitous 3D printing process, the freedom (in both form and complexity) that is available to designers are only possible because the entire fabrication process (from creating machine data to material deposition) is automated. The larger context of this research is to arrive towards similar design freedom in the context of timber design and construction, where spatial differentiation, repetition and topological optimization can be applied to create various architectural effects or improve structural efficiency, or both. With the increasing availability of robots and automation in production, lights-out production can soon be achievable in the context of prefabricated timber construction. The automatic nature of such assembly process avoids the cost for laborious logistics and complex assembly procedures, where the savings will be apparent for structures with many pieces or complex arrangements.

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