ETH zürich

/ ITA
Institute of Technology in Architecture
Faculty of Architecture / ETH Zurich

Pok Yin Victor Leung
BA (AS)/SM(Arch.S)
Email: leung@arch.ethz.ch
Phone: +41 44 633 01 75

Doctoral Research Plan

Robotically assembled timber structures with integral timber joints

Principal Advisor: Prof. Fabio Gramazio, Prof. Matthias Kohler

Prof. Fabio Gramazio, Prof. Matthias Kohler

Pok Yin Victor Leung

Date

Date

Chair of Architecture and Digital Fabrication
Prof. Fabio Gramazio, Prof. Matthias Kohler
ETH Zurich / Building HIB / Floor E / Room 43
Stefano-Franscini-Platz 1 / CH-8093 Zurich
www.gramaziokohler.arch.ethz.ch

GRAMAZIO KOHLER RESEARCH

Abstract

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

Previous research 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. Integral timber joints, however, which contains intricate geometry that is better customized for load transfer in different structures, have yet to be explored. In particular, this research aims to explore the benefits towards timber structure design if the assembly process is robotically automated. This research proposes a novel robotic assembly process based on remote-controlled high-force actuators that aims to address assembly challenges unique to integral timber joints, such as high assembly force, precise alignment and simultaneous joint closure. In order to assemble customized structures, the process will be able to assemble different joint types, jointing angles and an arbitrary amount of joints on a single element.

Design studies (digital) and large scale experiments (physical) will be used to demonstrate and validate the hypothesis that many different structures can be constructed using this process. Three design evaluation cycles will be performed between process development and design studies as evaluation of the versatility and applicability of the entire design to 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 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)

This research builds upon the techniques developed in these precedence projects and investigate in a different timber jointing method. Previous research have used as nails, screws (Robeller, Helm, et al. 2017) and glue (Helm et al. 2017) to join timber elements that were essentially butt joint, i.e. no notches were cut into the wood. Integral timber-to-timber joints, as used in many traditional timber structures, have the following advantages that justifies this research investigation:

- Structural capacity can be used in large structures.
- The absence of fasteners or glue makes setting time quick for robotic automation. [1]
- Digitally controlled automatic joinery machines are available for cutting customized timber joints.

Therefore, this research investigates the design potential of timber structures, where integral timber-to-timber joints are assembled by robotic process.

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 to connect elements into a complete structure [2]. Many stunning architectural examples such as timber frame houses, large span roof trusses (Fig.2b) and bridges (Fig.2c) were created purely with timber to timber connections. Although traditional carpenters did not have analytical engineering tools, they have successfully developed many joints [3] from generations of empirical knowledge [4]. The resulting joint geometries are highly specific to their location in a structure because they correspond to specific load conditions.

Despite newer jointing methods such as nails, screws and metal plates were developed [5], integral

[1]In comparison to glued and screwed connection: Structural glue application often require manual sealing and demands a long setting time. Screwed timber connections often consist of many long screws, and is therefor time consuming to install

[2]Examples include log frame construction, timber frame construction and post-and-beam houses from European heritage, and many post and beam structure from Chinese heritage

[3]Many different joint classification and naming systems exist, for example according to geometrical features (Zwerger 2015), according to their location in the building (Sato Hideo and Nakahara Yasua 1995) , according to the position of the jointed members (Coaldrake et al. 2006) etc. Some of the commonly identifiable features includes lap, tenon, mortise and dovetail. Many complex joinery contains a combinations of these features.

[4]Until recently, rules-of-thumb dominated the timber to timber joint design (RJ, RB, and BL 1996) and scientific knowledge is still rather limited. (Feio, Lourenço, and Machado 2014) (Palma and Cruz 2007) Since empirical approach is not acceptable in modern practice, there has been a growing interest in the engineering field to address this problem by modeling and simulation. (Sandberg, Bulleit, and Reid 2002) (Eva Haviarova 2009)

[5]Metal fasteners has the advantage of which the structural performance can be accurately modeled and predicted for different designs. (Rinke 2010) This avoided the emprical approach when validating a new timber joint design.

timber joints can still be found in new buildings [6], and in some innovative use cases [7]. In fact, a new surge of interest in timber connections are spurred by the improving engineering methods that allowed engineers to more accurately predict the structural behaviour of timber joints [8], enabling their use in unprecedented scales [9].

1.2.2 Jointed Timber Prefabrication

Timber frame construction is a construction system and an architectural style that remained popular in certain cultures until today. In order to overcome the labour intensive process of cutting intricate timber joints, automatic joinery machines (Fig.3a) were developed for this type of construction. These machines are designed to accept milled timber with a uniform profile as input. They can be digitally programmed to cut different joint geometries at variable location and can be easily programmed to produce individually different timber elements (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

Timber-specific CAD software can create digital information [10] that can be interfaced with an automatic joinery machine, allowing a seamless transfer of building data from design to prefabrication. However, despite of this flexibility [11], most of their use is for constructing traditional post and beam timber frame designs that are orthogonal and repetitive. While these machines possess the capability of producing highly complex timber parts, this thesis identified the bottleneck being the complexly in the assembly

[6] Large timber-to-timber joints can be seen in the Headquarters for Swatch and Omega by Shigeru Ban or the Cambridge Central Mosque by Marks Barfield. Despite the connection also contain mechanical fasteners, the geometry of the joint is the main load transferring mechanism.

[7] Recently, mortise and tenon joints were used to connect laminated veneer lumber panels for constructing large scale folded plate structures. (Robeller and Weinand 2016) Dovetail rods were developed to join cross-laminated panels (CLT) for multi story timber constructions. (*X-FIX The timber-to-timber connection system* 2018)

[8] In particular, new methods in non-linear FEM for modeling the post-elastic behaviour of the joints are studied (Parisi and Piazza 2002) which has the potential to better capture the behaviour and allow an increase in structural utilization.

[9] For example the Tamedia office building by Shigeru Ban features large columns and beams that are connected directly via timber-to-timber joints.

[10] 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)

[11] Although automatic joinery machines are very flexible in cutting different joints at different locations, their material handling system is designed for linear timber elements. Free-form timber elements and curved glue laminated beams cannot be processed with these system.

process.

1.2.3 Robotic Assembly

Until now, prefabricated timber elements with integral timber joints were assembled manually [12]. Although automatic machines and production lines were developed for assembling flat walls and floors [13], they are not capable of assembling tight fit 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, orientation and assembly sequence are complex for a manual worker [14], and (2) the number of timber elements are large [15], 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

This thesis uses an interdisciplinary research method that includes structural design, architectural design, computational workflow, process design, robotics and control. Some of the technical challenges such as collision free robotic control and computational design workflow have been addressed in the past by projects mentioned in the introduction. However, challenges unique to the assembly of timber joinery have yet to be addressed. By studying these challenges from various technical perspective, the results from different disciplines can inform future architectural design decisions.

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, Helm, et al. [16] have characterized the source of friction in tenon joints to be related to the fit. Although they have only demonstrated robotic assembly with small joint sizes [17], they have concluded that high force robots or vibration actuators will be necessary for architectural scale joints.

[12] 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.

[13] For example Homag Weinmann Autofloor and Autowall series production lines are used for prefabricated construction. Weinmann 2019

[14] Both problems can be seen in steel construction where individual customization of connection node is already a norm: Logistics and correct assembly becomes highly inefficient like a giant puzzle.

[15] Apolinarska 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.

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

[17] They have successfully assembled a single 40mm x 120mm tenon into a mortise. They were was not able to assemble a joint with multiple tenons using a 200kG payload class robotic arm.

2.2 Precise alignment between members

Previous projects which employed industrial robots for assembly (Fig.4b) [18] 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 [19]; the prefabrication process by the automatic joinery machine, expansion or shrinkage caused by moisture change in the timber after prefabrication [20]; inaccuracy of the assembly robot and the gripper [21]; and the deformation of the timber member during pick and place handling [22]. While some of the inaccuracy can be accommodated by thoughtful detail design, the assembly process needs to react and correct for 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 [23].

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.4a). However, this solution is hard to scale up for structures with multiple unstable elements [24].

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

[19] Construction grade milled timber can deviate $\pm$1mm for $\leq$ 100mm sizes (BS EN 336)

[20] For example an 18% moisture content spruce sample can shrink or expand up to 0.5% in length when moisture content raise or drop by 1%.

[21] The Robotic Fabrication Lab (RFL) in the Institute of Technology in Architecture (ITA) has four 6-DOF robots that is mounted on a overhead 3-DOF gantry system. Their accuracy is $\pm$3mm within its 43 x 16 x 8 meters build volume. Optical tracking and compensation systems developed by Stadelmann et al. can lower this value to within $\pm$0.5mm.

[22] For example, a 6 meter x 100mm x 100mm spruce beam held horizontally by a gripper at the middle of the beam, will have its ends deformed under self weight for 5mm

[23] 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.

[24] 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.4a) 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 4 DFAB HOUSE Spatial Timber Assembly process

3 Research Question

Question 1: What are the robotic means to assemble timber structures with integral timber-to-timber joints?

This address the technical challenges mentioned in the previous chapter and seeks to develop a robotic solution from a process design perspective. A hands-on and experimental approach will be used to find the best technology to assemble timber structures.

Question 2: What type of architecture will arise caused by robotic assembly?

This address the architectural implication of a newly proposed automated process from the perspective of architectural and structural design. A design exploration / case study approach, combined with physical prototypes, will be use to study the structural system and typology that is suitable for the process.

4 Hypothesis

The first hypothesis is that a remote controlled clamping strategy can solve all the assembly challenges mentioned in the previous chapter. The proposed assembly process will use an agile pick-an-place robot (the **"robot"**) such as a robotic arm, and a set of custom developed end effectors that resembles carpentry clamps (the **"clamps"**). These clamps contains high force actuators for closing 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.

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.

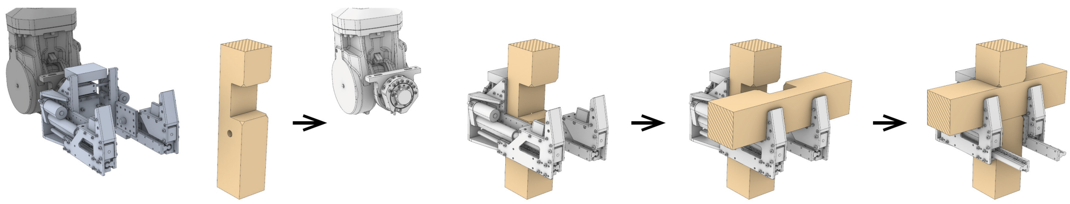
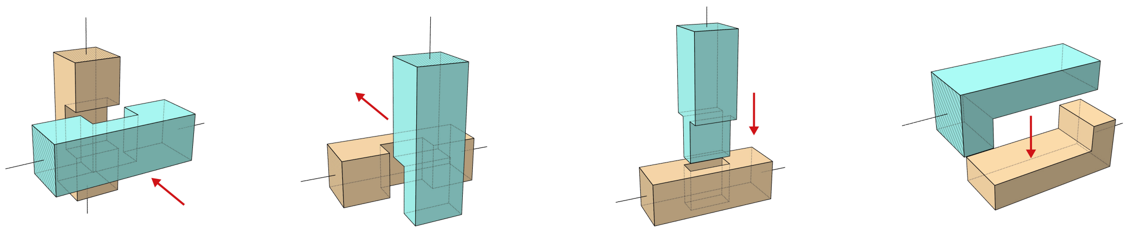


Figure 5 Assembly process of one timber joint using a clamp: (from left to right) A clamp being moved by a robotic arm; Clamp attached to one side of the joint; New timber element placed in clamp; Joint closure by clamp actuators.

Because different type of joints (such as lap joints and tenon joints) have very different assembly direction, different types of clamps will be necessary for each type. In order 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 are grouped into a joint family that can share the same clamp. Three joint families (Fig.6) [25] have been identified to be fundamental for timber construction and will therefore be investigated.



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

Figure 6 Three joint families included in this research. They are illustrated in their 90 degrees configurations, despite their infinite angular possibility. The red arrows indicate the assembly directions of the blue parts in relation to the brown parts.

The second hypothesis is that an automatic assembly system can significantly lower the effort to construct bespoke timber construction and will offer new design opportunity. This research will include most of the joints used in the past for post and beam structures, roof trusses and bridges [26]. They will be broad and generic enough for constructing the same structural typologies with minor modifications and other typologies are speculated to also be compatible. Spatial differentiation, repetition and topological optimization can be applied to create various architectural effects or improve structural efficiency, or

[25] Lap Joint Family, Mortise Tenon Joint Family and Splice Joint family. Each of the family is flexible to include different detail design that are relevant for structural performance, and a range of jointing angle.

[26] In order to investigate the fundamental joints, this reduced set of joints does not include compound types where three elements connect at one node.

both. The automatic nature of the 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.

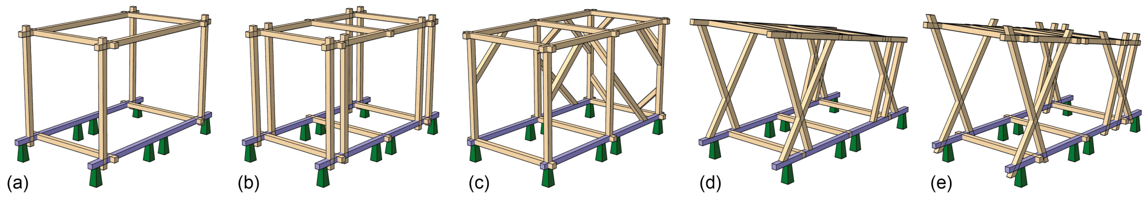


Figure 7 Examples of spatially assembled modular structure that can be assembled by the process. (a) and (b) utilized only orthogonal lap joints, (c) included tenon joints and 45 degrees lap joints, (d) and (e) included lap joints and tenon joints of variable angles.

5 Research Plan

5.1 Methodology

Because of the interdisciplinary nature of the research, [27] two different research trajectory will occur in parallel. Research and development will be used to answer the first question by developing and validating the robotic assembly process, mentioned in the previous chapter. 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 [28] and motion control software shall be adapted from existing work by other researchers.

Case studies and design investigations will be used to answer the second question by creating drawings and models that demonstrate the speculative applications for the process. While the validation experiments provide technical information that describes fabrication constraints, case studies will show the design space relevant to different structural topology and architectural program. For example, large span roof structure, modular construction and bespoke roof add-on structures can benefit from a non-standard design. 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.

To combine both research trajectory, selected case study will be constructed at 1:1 scale to validate

[27] The topic includes mechanical, electrical and control engineering challenges, and investigating the implication to architecture, which is a design challenge.

[28] 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 require careful planning to avoid deadlock.

the process, and comparative study [29] will be conducted to study the implication of cost and labour. Both empirical development and design investigation will happen simultaneously with three major evaluation cycle to provide reality-check and inform the development for both parts.

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. [30] 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.[31] This serves as the first automatic-assembled demonstration using this process.

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 more flexible assembly process will be validated.

Case studies and demonstrations will be performed to demonstrate multiple joint engagements and the clamp's flexibility to adapt to different joint angles. A challenging design will be chosen to illustrate the suitability of the process for bespoke designs.

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. [32]

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

[29] Comparative study will compare the difference between a manual assembly process vs the developed robotic process on selected structures. The goal is to highlight the type of structures that can benefit from a robotic process.

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

[31] One more more clamps have to be created because one clamp alone cannot construct any meaningful structure.

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

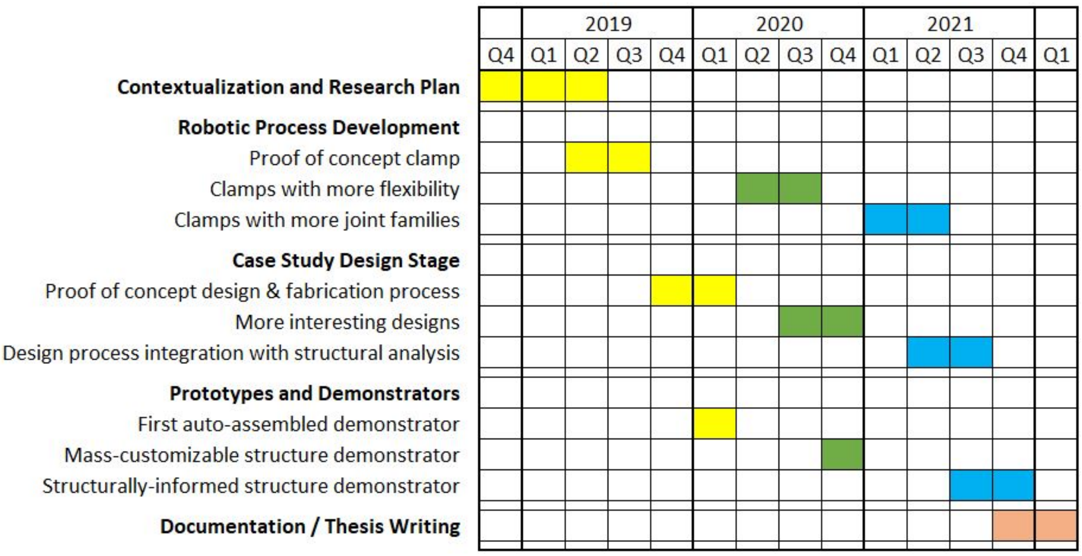
5.2 Experimental Setup and Infrastructure

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 3DOF 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 [33], 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.

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

5.3 Timeline



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

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