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REVIEW

Robotic timber assembly

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Abstract
This paper presents an efficient workflow for the established digital fabrication and robotic assembly of a discrete timber structure. Here, the complexity and aesthetic value of the structure are derived from the aggregation and assembly of similar parts. In limiting the architectural building blocks to a few similar pieces, specific assembly is freed, and infinite structures can be constructed through iteration with the same sequential logic. Fabrication of the individual pieces is simplified, reducing material and energy use through standardization of component parts. The research further examines the potential of how three-dimensional wooden joinery can be incorporated to work with the robotic assembly, not only by analyzing the use of industrial robotic arms with an intent to leverage their capabilities, but also by exploring their limitations. In establishing a workflow around a joint which requires no adhesives or fasteners, the ability to robotically disassemble and reassemble the structures infinitely in different ways maximizes structural potential and material reuse. The assembly and aggregation of these joineries demonstrate a prototype that can be adopted for future timber constructions.

Keywords Timber · Topological interlocking joineries · Robotic assembly · Discrete design · Automation in practice

1 Introduction

This exploration utilizes the principle of Topological Interlocking Joineries (TIJs) in which elements of a structural system are held together by the kinematic constraints provided by their shape and surface interaction rather than the use of a binder which, for the most part, requires the application of mechanical fasteners by hand (Estrin et al. 2011). The Chidori Japanese woodworking joint is utilized for the interlocking assembly because of a unique rotational operation required to fix the constituent timber elements into place. Though the joint originates from a tradition of handcraft, the ability to support precise, continuous rotation is physiologically a non-human function (Müller-Sievers 2012).

Using industrial robotic arms to assemble the interlocking joint allows for integration of larger timber elements such as 4″ × 4″ (10 × 10 cm): a widely available profile of dimensional lumber used in building construction. These timber elements are typically used as post and beams or framing components in building construction.

In the United States, timber construction is a highly relevant subject matter, often considered a means to address the crisis of affordable housing and construction. Its efficiency and cost-effectiveness, though, depend largely on a high degree of standardization in terms of code regulations, lumber sizing, hardware availability and structural connections. Furthermore, current timber construction methods are geared towards and optimized for analog, manual labor, as has been the case for decades. In recent years, there has been an interest in developing traditional timber construction methods further with digital fabrication techniques in the manufacturing of engineered wood products such as cross-laminated timber (CLT).

The advent of digital automation tools combined with discrete, modular design methodologies represents an opportunity for innovation in this sector. For example, digitally controlled tools can rapidly execute carpentry tasks with such

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high precision that conventional tectonic joinery (which, in most cases, would be covered by a “finish” material like gypsum wall-board) could be left exposed as an architectural element.

The research objectives consist of two parts: (A) develop a design methodology that exploits the advantages of both chosen structural unit (Chidori joint) and the digital logic of its fabrication and assembly, (B) design and execute the assembly of a small structure in the robotics lab using a scalable process that could be translated to other sites, a process that preferences re-configurability of standardized components over customized parts.

The research methods to achieve these objectives are outlined in four phases: (a) the design optimization of the Chidori joint for digital fabrication and robotic assembly, (b) the development of toolpath scripts for the coordinated assembly of a single joint by two Kuka KR-150 industrial robotic arms, (c) the design methodology of a small building-scale, grid-based structure optimized for robotic assembly, and (d) the structure’s physical construction as an installation design.

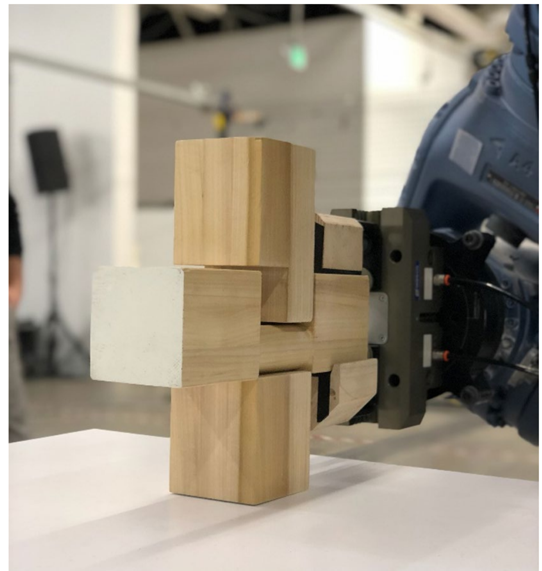


Fig. 1 Interlocking assembly (Chidori joint)

2 Research methods: joint optimization for digital fabrication

2.1 The Chidori joint

The Chidori joint, which was popularized as a children’s toy puzzle in Japanese culture, is an intersection of three uniquely shaped parts that slide, twist and lock together around a central point. The joint requires no fasteners and relies on tight tolerances and a precise order of operation to assemble and deconstruct the members (Fig. 1).

Traditionally, due to the accuracy required for assembly, the joint’s fabrication was left for only the most highly skilled craftsmen. Its toy-like nature inherently required the joint to be small—limited to a single instance—and was only ever assembled by hand. The joint became revitalized through various works by Kengo Kuma, who began to explore the joint’s ability to change size and aggregation of parts.

This joint has multiple qualities which make it ideal for digital fabrication. As previously stated, it has no fasteners or extra parts. The interlocking joinery can be achieved exclusively through material subtraction, which means that the individual members can be digitally fabricated in mass with a CNC machine. Structures can be unassembled as fluidly as it was assembled, and the timbers can be reused in a completely different assembly. Additionally, the intersection of the three individual members occurs at a single, central locus, making motion paths for translational and rotational assembly significantly easier. The joint gets its tightest locking from members with a square profile, which means that the end tool can grip each timber from many angles, giving lots of versatility to the robotic assembly process.

2.2 Novel application for ancient craftsmanship

While the craftsmanship behind the joint is quite ancient, there are various advantages to its production and assembly using digital methods. Milling each joint with the CNC grants both higher accuracy and faster speed for the fabrication of the individual parts. Total CNC tool path cycle time for a single joint was 9 min, 4 min 30 s per side, including a rough and finish pass with a 4-flute, 0.5″ diameter end mill. Additionally, only two tools are used—the milling bit on the CNC for fabrication and the grippers on the robots for placing each timber.

Additionally, the joint can be broken down into a logical sequence of steps, which is perfect for the parameterization of its assembly. The exact movements of a single joint can be scripted, then that logic can be applied to every single subsequent joint. This alleviates pressure for otherwise complex robotic coding and reduces the likelihood of human error in the programming stage. In any design, the logic remains the same, so the designer has the ability to produce complex designs without the additional trouble coordination would likely cause. Kengo Kuma’s GC Prostho Museum (see Fig. 2) is a great example of the Chidori joint’s use in architecture, but its assembly appears relatively repetitive. With spatial solving and coordination at the robotic level, designs like this can become much more varied and customized (Bucklin et al. 2019).

Fig. 2 GC Prostho Museum exterior view (**a**) and interior view (**b**) by Kengo Kuma (Mucciola 2010)

This proposed design methodology allows the production of asymmetrical modules, building on a repetitive system that typically requires uniform parts. With this workflow, roadmaps for variable assembly are embedded into the robotic code during the design phase of the project, so communication errors between designer and construction team are eliminated. If the rigid logic of the joint assembly begins to shift, or certain members are purposefully omitted, those design decisions get automatically coded into the assembly sequence and picked up by the robot during the project construction. Therefore, more complex changes can be introduced, such as an asymmetrical module that gives the assembly the appearance of motion or flow.

2.3 Optimizations of the Chidori joint for robotic assembly

Though the rotational precision of the industrial robot arms is an advantage for the assembly of the Chidori joint, its lack of dexterity can be a hindrance. Tolerances must be built into the joints and careful analysis of the robot's motion must be maintained to ensure the success of the joint assembly.

Mild modification of the original Chidori joint helped alleviate some of these dexterity issues. While the robots require very little tolerance in perfectly repetitive tasks, the natural imperfections in wood cause problems in joints that are supposed to be very tight. CNC milling granted the individual members relatively low deviation in fabrication, but friction and fit were constantly preventing the joints from locking properly into place. Slight chamfering on all contact edges of the joint proved to solve that problem (see Fig. 3). Any small misalignment would be corrected, and the chamfered edges helped to guide each piece into place without sacrificing the snugness of the fit.

3 Research methods: procedures and fabrication methodologies for a single joint

3.1 Assembly logic for a single joint

The sequence for assembly of a single Chidori joint is both complex and strict. Components must slide into place

Fig. 3 Details of the chamfered edges for tolerance (**a**) and the assembled joint with the tolerances (**b**)

with both proper orientation and sequence. Usually, the components need to be held together until all three pieces are in place for the joint to work, and only then can the twisting of the final piece occur that locks everything into place (Fig. 4).

There is only one orientation which allows each piece to be placed individually. If the twisting member is placed vertically and secured to the ground translationally, but allowed to rotate, the other pieces can rest on it during assembly. Then the vertical piece can be twisted in place and the whole part locked together. This takes much of the complexity out of the design of the end tool for the robot. The sequence can occur one piece at a time, without the need for robotic collaboration on each individual component (see Fig. 5).

Given the sequence of assembly, it is important to consider where and how the robot will grip each of the components that will allow it to lift, place, and twist each piece as needed. To lift each component, grabbing the piece along the middle of its length is ideal, as its weight can be balanced and there is less deflection. However, from the robot's perspective, it's better for twisting to grasp the piece from the end, so that the rotation of the robot's sixth axis does all of the work, instead of risking large pose shifts which would come with a perpendicular approach to gripping the timber.

3.2 Optimizing the end-tool

The modularity of the joint requires an equally robust end tool for manipulation. A two-finger grabber suffices to properly grip for both lifting and rotating timbers. In order to meet the needs of the high rotational moment produced by a cantilevering 4″ × 4″ (10 × 10 cm) timber, the Schunk PGN + 200/1 gripper was outfitted with custom steel fingers capable of managing the load. The grips were milled solid wood, designed to reduce any issues in tolerance by slipping any deviating timbers exactly to the desired location (see Fig. 6). Importantly, the Schunk gripper is pneumatically actuated, so it can be opened and closed through the I/O outputs in the Kukalprc (Braumann 2019) software. This greatly reduces stress on the programmer, as the actuation of the end tool can be parametrically linked to the assembly sequence.

3.3 Anticipation of multi-joint components

Whereas traditional Chidori joints are assembled independently of one another, an aggregation complicates the

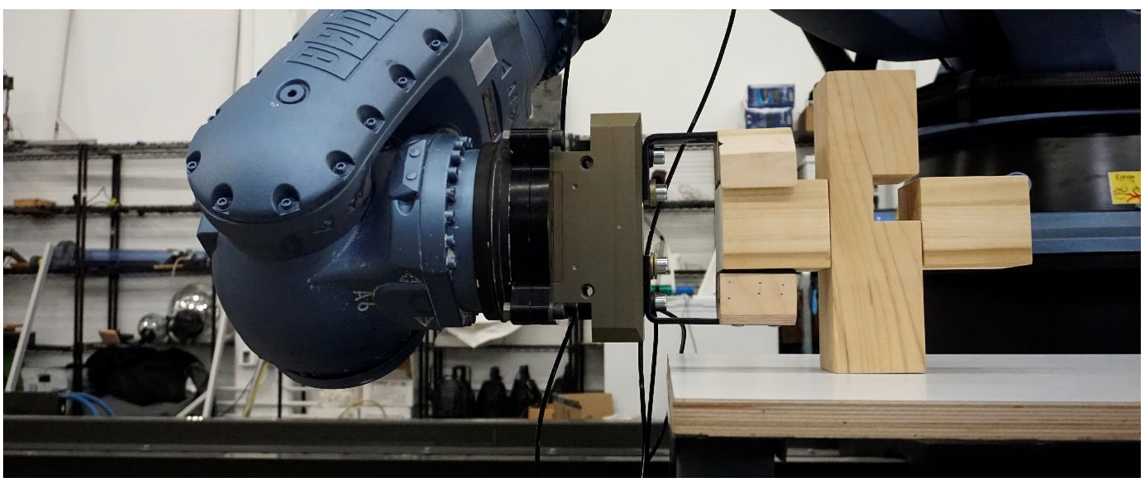


Fig. 4 Interlocking assembly process (Chidori joint)

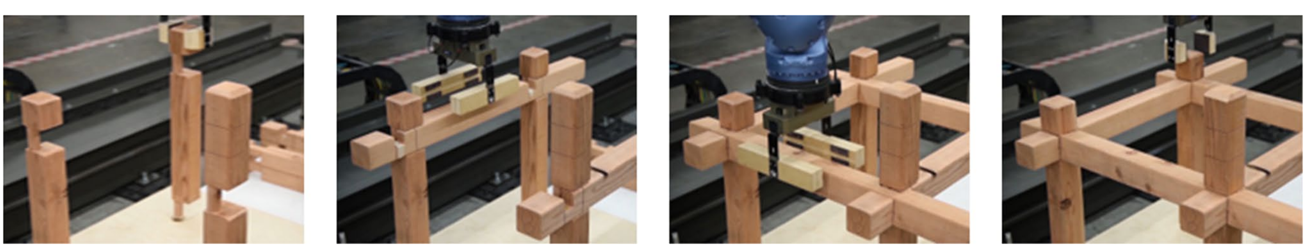


Fig. 5 Sequence of joint assembly: part A (**a**), part B (**b**), part C (**c**), the final twist to lock everything in place (**d**)

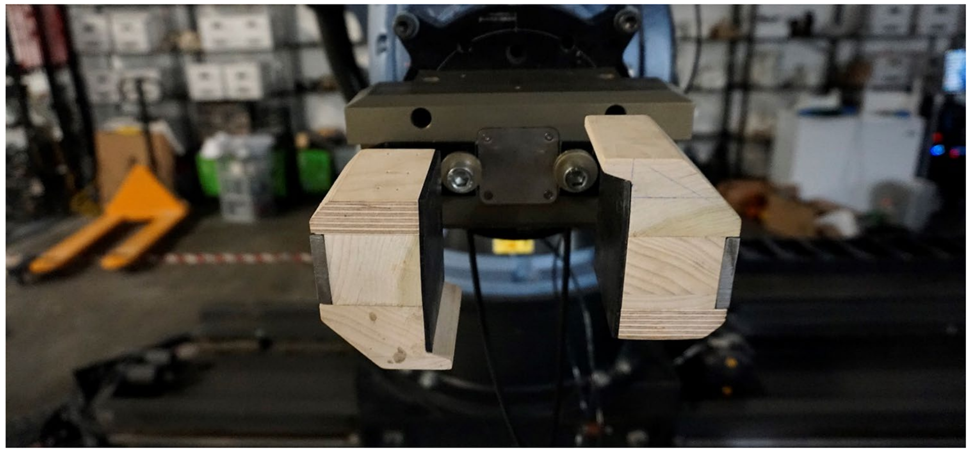


Fig. 6 Milled wood grips with the Schunk PGN + 200/1 gripper

joint's assembly logic across an entire structure. With the design assembly sequence described above, it is possible to carve multiple joints into a single timber and have them all lock into place at the same time (see Fig. 7). They are then assembled by a specific placement order, where part A would be placed first, then part B, then part C. If all joints were independent, this would require a constant shifting of pose. However, as the joints can be modularly arrayed over the length of a timber, the placement order can be modified. The robots can place all pieces of part A first, then go back and place all parts B, and finally the corresponding parts C. This provides an enormous increase to the efficiency of the system, as the robots can maintain their poses for each part, only having to shift twice throughout the whole assembly (see Fig. 5).

Longer members, however, intensify the problem of gripping. The longer pieces have greater weight and deflection, so lifting them properly by the middle is necessary. The end tools for lifting and rotating must be dedicated to their specific task—it is not feasible to have a catch-all gripper. Therefore, either a tool change must be made or multiple robots must be utilized, each devoted to a different task in the task list.

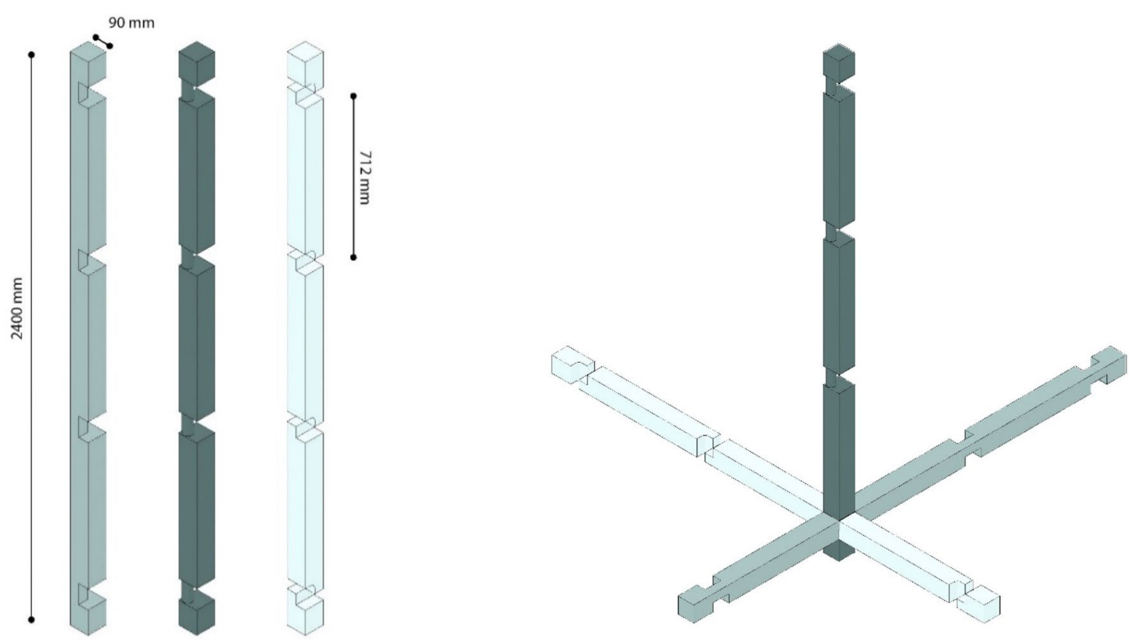


Fig. 7 Multiple joints carved along the length of the 4″×4″ 96″ (10 × 10 × 243 cm) members (**a**) and assembled module **(b)**

4 Research methods: aggregation assembly

4.1 Discrete module design

In 'discrete' design, complexity and aesthetic value are derived from aggregation and assembly while the individual part stays the same (Sanchez 2019). Unlike in parametric design, where structures are often complex and assembly of many unique parts is labor intensive, discrete design celebrates the modularity of the individual parts, emphasizing serial repetition and differentiation through patterns.

To modularize the timbers in the discrete fashion the distance between the joints had to be standardized, so that regardless of where the joints fall in space, it will always line up with the joints of the intersecting members. Each module holds to the superior logic of the overall grid, so that the structure can be extended indefinitely in any direction without the need to customize any single member.

A readily-available 4″ × 4″ × 96″ (10 × 10 × 243 cm) piece of lumber was selected as the unit stock for the individual members. Considering lumber's standard module of 48″ (122 cm) commonly used in the framing of mass timber construction, joints were then cut every 24″ (61 cm) on-center so that members added end-to-end would maintain the same strong joint pattern. Each of the three individual members of the Chidori joint requires a different CNC milling pattern, so in all, there are only three different pieces of lumber required to produce an infinite range of possible designs. As an example, an aggregation of 4 vertical, 4 horizontal, and 4 lateral timbers were selected to represent a module in the overall design assembly. Just those 12 members were able to produce constructions with vastly different functional and aesthetic utility (see Fig. 8).

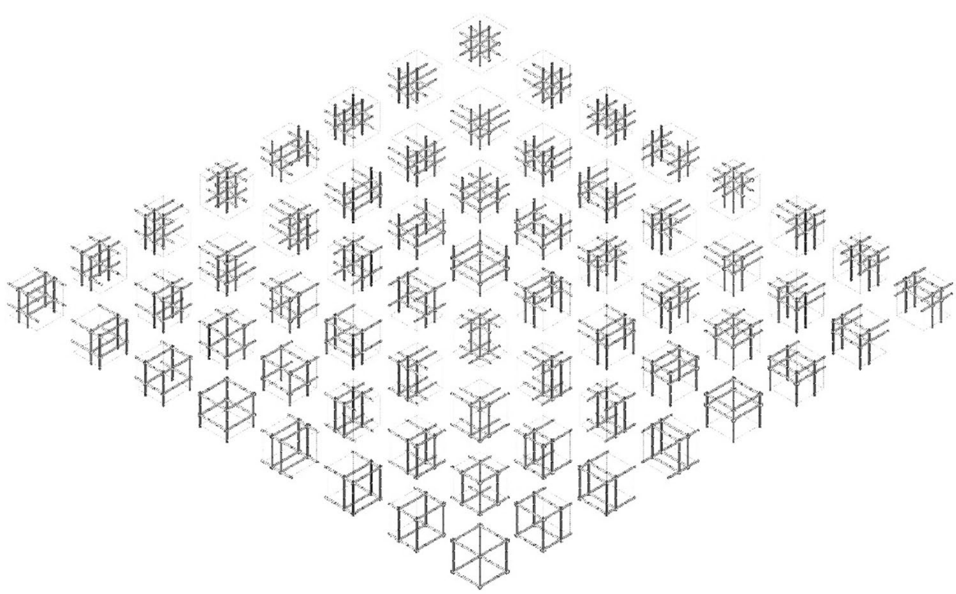
4.2 Application for modular aggregation

Modular aggregation made from discrete elements has incredible potential at the architectural scale. Placing the joints at two-foot increments fits well within codes and standards for rooms and interior partitions. This construction method also offers one benefit that current structural systems do not have—it can be disassembled in the same fashion as its assembly. The members of the joints are 100% reusable and can quickly be repurposed in another application. Once an assembly logic has been applied to a structure, it simply requires the reverse logic to return it to its individual members. This reduces waste and cost in highly flexible spaces. Such savings promote spatial fluidity in designs, giving users impetus to regularly modify their surroundings.

4.3 Robotically logical sequencing

A hierarchical logic tree is required for the assembly of multiple joints. This "superlogic" covers both the motions of the robot and the order in which the joints are assembled across the entire production. Through the motion analysis tools granted by Kukalprc, understanding of the spatial requirements of each joint and the entire procedural assembly through the constraints of the industrial robot arm are gained. This informs certain key parameters of the overall logic, such as: how far apart the joints needed to be located to allow for the robot's reach restrictions, in what order the joints needed to be completed, and the maximum number of

Fig. 8 Reconfigurable aggregation



joints that could be added to each timber member before the assembly becomes too complicated to sequence.

Restrictions in the industrial robot's reach and impositions of its pose cause significant complications in the three-dimensional assembly process. The Chidori joint is a very spatial assembly in that it extends its appendages along all axes and requires at least three of those appendages to be accessible for placement and manipulation. As the timbers and joints grow to an architectural scale, so must the robot's reach increase to properly assemble the parts. This complexity can be significantly reduced if multiple robots work together—one on each side of the assembly. With this layout, the likelihood of a self-collision due to the industrial robot's reach diminishes (see Fig. 9a).

It stands to reason that as more joints and modules are added to the overall assembly, it becomes harder for the robot to navigate through the spatial complexity. It is crucial, then, to consider exactly what impact the joint sequence has on reducing that entropy in the system. Through Grasshopper, this spatial logic was packaged as a series of poses relative to the joint itself. When that series is merged with I/O signals for the gripper, it can be interwoven with similar packages produced for other joints and then processed and analyzed with Kukalprc. The entire assembly process can be parametrically linked to each joint's position and converted into the robot's motion path, so various assemblies can be constructed with little manipulation necessary from the designer or operator (see Fig. 9b).

5 Digital to physical robotic fabrication

5.1 Prototype design

The prototype module represents a multitude of joint types and adjacencies. It is both scalable and repeatable, and its successful assembly can insinuate the successful assembly of similarly complex modules (a wide range of options for similar modules is possible, as is shown earlier in the paper). This module contains four Chidori joints, arranged in an interlocking square, and four floor joints (see Fig. 10). The base contains four holes to receive the pegs from the vertical

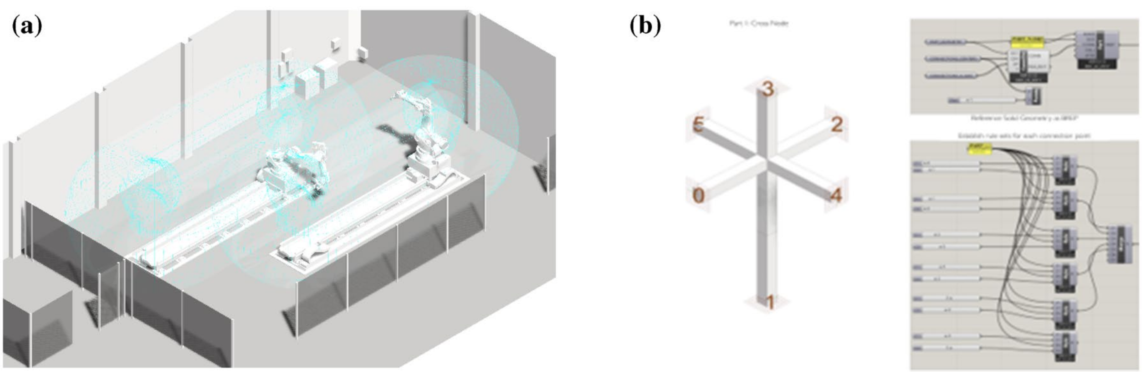


Fig. 9 Work envelope for dual robots on linear tracks (**a**) and pose sequence for the fabrication of a single joint (**b**)

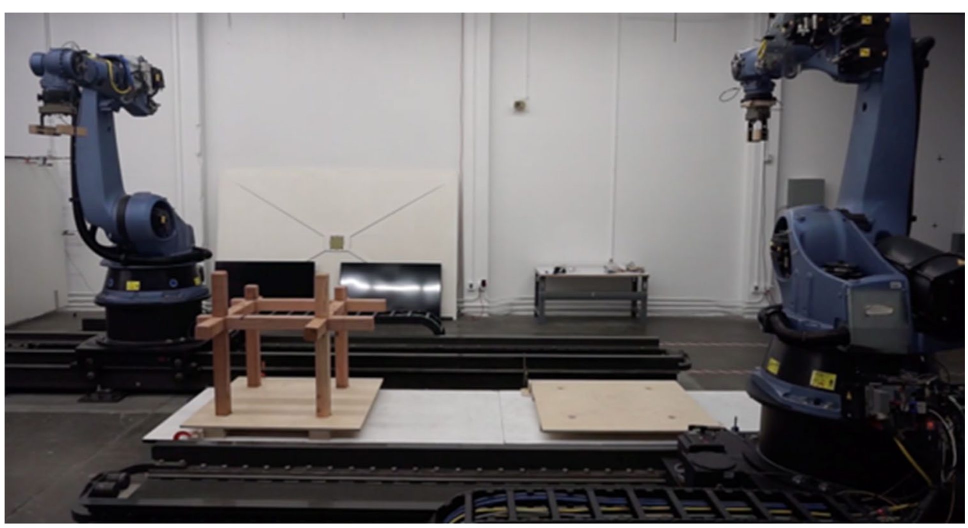


Fig. 10 Robotically assembled prototype module

members, allowing them to freely rotate while being translationally locked.

This prototype is assembled in the UCLA AUD IDEAS robotics laboratory, in a space dedicated to two Kuka KR150-2 robots on 6 m tracks. This setup uniquely allows for the robots to work collaboratively on tasks. The staggered tracks create a large overlapping work envelope, and the linear mobility of the tracks grants more control over pose during the assembly process. However, for future development, we envision the setup to be an off-site prefabricated system with the potential for an on-site aggregative robotic assembly. This would be an efficient combination of both on-site and off-site construction (see Figs. 9a and 13).

5.2 An entirely digitized process

Constant iteration throughout this exploration has proven that every design change has an impact on the overall project—from assembly to fabrication. Therefore, this project greatly benefits from the digitization of the entire process. Standardization (discretization) of the individual components means that any changes made to the assembly process will also result in changes to the CNC files for fabrication and vice versa. The project is held in tension by the relationships established between each component of the design. Wherein the development of these relationships can be quite complex, their establishment is critical to the customization and flexibility of the proposed applications.

Digitization of the entire fabrication process doubles as a tool in simulation and analysis of any proposed designs. Rapid iteration for testing and production is possible once these relationships are in place, which saves both time and reduces costs in the prototyping stages of this proposal.

5.3 Mass customization through procedural methods

With the process digitized, it is opened to use procedural methods to generate more complex modules, structures, and forms. Any method used to strategically organize points in space can be used to produce a Chidori structure which follows that same logic.

Gramazio Kohler Research and the Institute for Computational Design (ICD) have both built 'Complex Timber Structures' that have predrilled components. The focus of this robotic assembly was to adapt the stiffness of the triangular arrangement of the node (Krieg et al. 2017). Learning from this intricate stiff assembly and autonomous angled connections, the Chidori joineries were incorporated for the purity of the timber wood connections and the need for a locking joinery which enables the robot arm to twist and lock the joints to achieve full automation.

The Grasshopper plugin Wasp (Rossi 2017) (by Andrea Rossi) reveals how discrete elements might be logically organized within the work envelope of the robots. The module (see Fig. 9b) contains points of connection at the end of each member which must be aligned adjacently with faces on neighboring modules. Each module is free to rotate and aggregate in any way within the constraints of the robot's work envelope, but many other constraints could be employed.

5.4 Wood construction and automation in practice

Mass timber construction has been around for generations. More recently, manufactured wood columns, beams, and panels have been developed and tested in architectural projects. Cross laminated timber (CLT) and Mass Plywood Panels (MPP) are commonly used due to their lightweight and quick fabrication process. Assembling is rapid, with minimum labor and little need for construction storage space. Due to standardizations and overall weight improvements, panels can be brought in constantly during the construction process (Elbein 2020).

Designing a new assembly typology and joint system to assemble timber construction with industrial robotic arms strengthens construction methodology. Collaboratively, industrial robotic arms can assist one another and communicate through sensors and machine vision to more efficiently conduct fluid operations and regularly calibrate (Andraos et al. 2016). The aggregative assembly, and even the Chidori joint itself, take into consideration this collaborative mechanism.

From a fabrication standpoint, the automation of wood construction has many valuable qualities. (1) It allows for greater formal complexity. With different geometries and highly articulated surfaces, automation allows connections and joints that cannot easily be done with the limits of human strength and motion. (2) It thrives through highly repetitive motions. This includes linear movements, rotation with different axes, and twisting. (3) It benefits from quantitative value and standardization of parts. This couples well with much of the research that is being conducted on discrete modular design. A structure composed of self-similar modules, such as the Diamonds House in Gilles Retsin's "Discrete Assembly and Digital Materials in Architecture," lends itself to this type of automated assembly through its serial repetition and combinatorial tectonic (Retsin 2016). (4) The automated process is inherently scalable. The six-axis arm robots could have an increased payload and more advanced gripper system to handle larger timber members for greater spans. Likewise, the number of robots could be increased and new workflows developed which allow robots to collaborate to create larger constructions. While larger modules and more complex assemblies would require

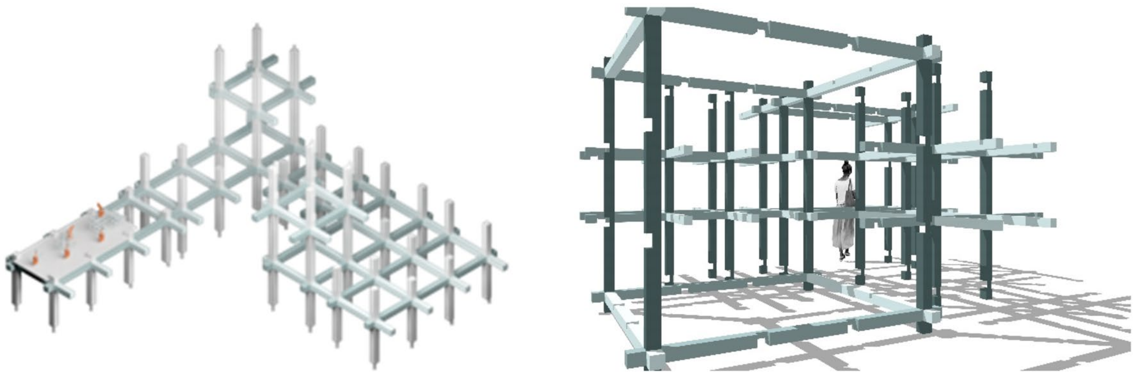


Fig. 11 Proposals for aggregation in exhibition space (**a**) and full-scale installation (**b**)

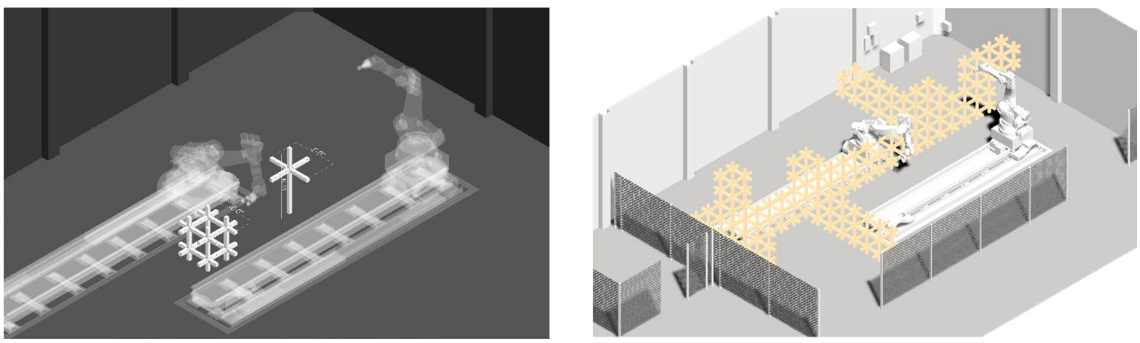


Fig. 12 Examples of single module assembly (**a**) and modular aggregation (**b**)

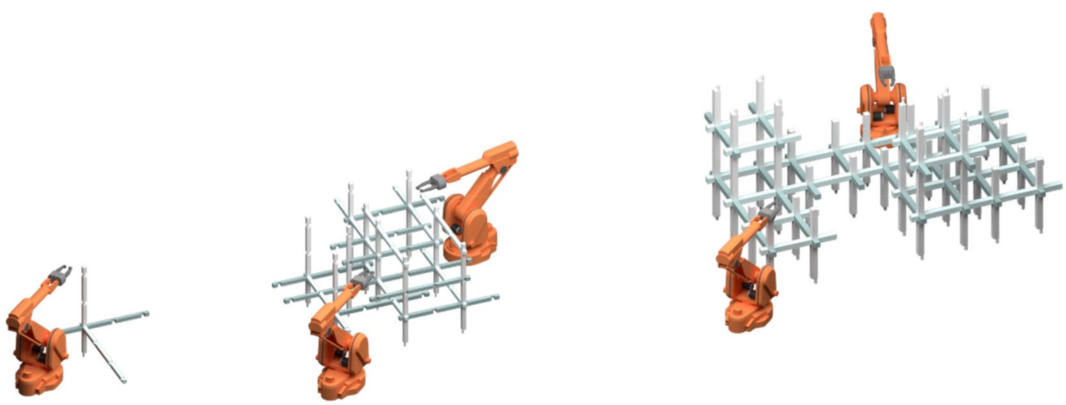


Fig. 13 Scalability of the module. Could be constructed either on or off-site

alterations to our sequence, the fully digitized process (from timber milling to assembly) provides the perfect platform on which these futures studies could take place (Figs. 11, 12).

Naturally, there are also limitations to using robotics in wood construction. Humans possess a high level of dexterity through responsive motor functions. Any discrepancy in the wood or any environmental change can be recognized and adjustments can be quickly made to alleviate the issue. In other words, humans have a greater tolerance for imperfections, which are generally inherent in wood construction. However, with improved sensor technology, these imperfections can be reduced and imperfections can be mitigated. As smart sensors and 3D scanning devices continue to improve in accuracy and affordability, tolerances for robotic assembly of discrete elements will improve.

6 Conclusion

The methodology established by the research in this paper links the three phases of design, fabrication, and assembly into a coherent workflow. The consistent, digital language of each phase eschews the need for translation into the language of construction as materials, modules, and aggregations flow between digital and physical space. This closed system establishes the experimental conditions under which an existing, time-tested construction method (in this case, wood joinery) can be tested under the new parameters of an emerging, digital technology.

Digital and robotic automation have already proven to be impactful within the highly controlled environments of industrial mass production (Menges and Schwinn 2012). However, the viable application of such technology to custom, architectural-scale assembly remains to be seen. While the experiments outlined in this paper took place in a laboratory environment, the results are intended to contribute to the burgeoning field of applied robotics within the building design and construction sectors by demonstrating a fully digital work-flow that spans design, fabrication and assembly.

While similar research focuses predominantly on the assembly of highly custom modules, this research focuses both on repetitive elements and the highly-specific robotic kinematics to connect the individual parts. As such, it blends principles of prefabrication, discrete modularity, reconfigurability and aggregational logic in an effort to calibrate the architectural proposal to the digital tools being used to carry it out. The result is a proto-architectural approach that can easily shift in scale and complexity, since it's rooted in repetition and modularity. However, further research is required to demonstrate this hypothetical ease of scalability and complexity, since the physical robotic assembly of a much larger structure was beyond the scope of this project.

In the United States, over 90% of homes are constructed using conventional wood framing (Deitz 2015), and innovations in heavy timber manufacturing demonstrate the ability for engineered wood products to serve as primary structural members in large-scale commercial construction. Therefore, a body of research that begins the process of adaptation and optimization of wood-frame construction to emerging digital and robotic technology is critical. Engineered wood framing products like cross laminated timber (CLT), laminated veneer lumber (LVL) and parallel strand lumber (PSL) are likely to be much more conducive to both CNC milling and robotic assembly since they greatly minimize the natural variability and inconsistencies that characterize solid wood framing products (Roberts 2020).

Advances in spatial calibration technology like machine vision and 3D scanning can serve to bridge the gap between digital and physical space, making it possible for algorithmic aggregation and assembly programs to adapt in real-time to site conditions, measurement errors, and material discrepancies. While a fully automated construction site may be a distant ambition, the application of these technologies to augment and assist in today's construction processes is on the horizon with the potential to improve safety, efficiency, and precision (Fig. 13).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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