Robotic Fabrication of Kinetic Finger Joints for Modular Timber Systems

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Abstract. Finger joints are interlocking woodworking joints commonly used to connect two pieces of wood in multiple configurations, including right-angle, end-to-end, or side-to-end connections. Historically, they have been handcrafted with saws and other handheld tools, as well as table routers with various cutting profiles that maximize surface area for strength and stability. This research explores how robotic fabrication techniques can be applied to design and be used to construct scalable wooden finger joints that enable rotation around one axis. By digitally modeling and fabricating joint prototypes, we aim to evaluate how automation can enhance both efficiency and adaptability in wooden assemblies. This work is part of a final wood blocks project that applies robotic finger joint systems to create modular wooden components capable of controlled and functional movement.

Keywords: finger joint, robotic fabrication, timber joinery, 6-axis robotic arms.

1 Introduction

Finger joints, also known as box joints, are built into wood pieces that attach in multiple ways. Its name comes from its unique appearance, as it has alternate "fingers" of material fit together like two clasped hands (Kristin Lia 2024). Compared to more basic butt joints, such as the simple and mitered joints, finger joints increase the strength by creating a larger surface area in the connection of the pieces of wood that helps distribute loads evenly over the entire joint. These joints are usually bonded with adhesive, which spreads across the increased contact area between the interlocking fingers and enforces the connection. As a result, finger joints are highly regarded in both joinery and carpentry because they can effectively use material and have mechanical stability.

Historically, finger joints have been made by hand. Tools such as saws, chisels, and layout guides played a big role in the creation of the finger features in wood. Because even the smallest mistakes in finger depth or spacing could fatally jeopardize the joint's structural integrity and fit, the procedure needed an impeccable amount of precision. The demand for accuracy and scalability was one of the many reasons for choosing to start machine-cut and CNC-milled finger joints. These methods allow for more customizability, which allows for more precisely controlled joint dimensions and profiles to suit different desired requirements.

After the expansion of engineered wood manufacturing in Europe, North America, and Asia throughout the 1970s, finger-jointed timber started to become more widely used. Europe is still the top producer despite an increase in contributions to the industry from both South Korea and Japan (Hducc 2020). Since it has incredible load-bearing capacity and effectively uses small wood offcuts, industrial finger-jointed panels have grown in popularity. In today's age, you can find these finger jointed panels in anything from architectural elements to furniture and cabinets to tables to drawers to chairs. They are also commonly used to join pieces of dimensional lumber into larger lamellas for glued laminated timber fabrications. leading to the production of reliable members from the shorter wood segments. However, they are not without their own disadvantages, some being aesthetic constraints as the joint patterns are often still visually apparent in the design.

Before examining the broader possibilities of finger joint design, it is important to clarify their relationship to box joints. Finger joints and box joints are based on the same interlocking joinery principle and differ primarily in usage rather than structure. A box joint typically refers to the application of a finger joint at a right-angle corner condition, commonly seen in boxes, drawers, and cabinets, where evenly spaced rectangular fingers interlock to form a corner. In figure 1, the joint on the upper right is a box joint and a finger joint, and all the other joints are finger joints only. The term finger joint is more broad and references the same interlocking geometry used in many configurations, including end-to-end, side-to-end, and linear extensions of wood members. In relation, all box joints are finger joints, but not all finger joints function as box joints.

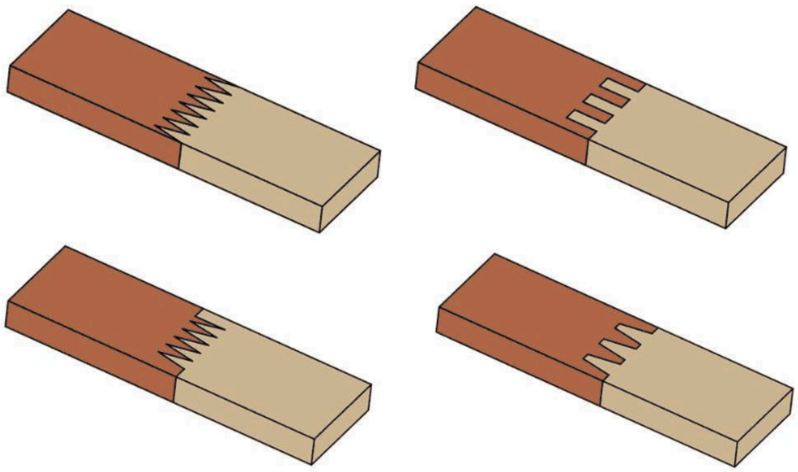

Fig. 1. Variations of finger joint patterns illustrating different finger geometries and configurations. Source: Homemade Furniture, n.d.

Joinery design and execution have changed as a result of recent advancements in robots and digital fabrication. Designers can now make wooden joints with a sense of geometric accuracy and flexibility that is better to traditional machining thanks to multi-axis robotic systems. This versatility makes it possible to design finger joints with more controlled motion and flexibility (Robeller et al. 2014). Moreover, with the ability to complete repetitive assembly jobs, with collision-free toolpaths, robotic fabrication proves to make it easier to reduce material waste and be more sustainable and efficient (Stehling et al. 2020).

This study aims to explore the design and construction of scalable wooden finger joints that allow for both fluid and useful motion using robotic fabrication techniques. While finger joints are traditionally designed as static connections and are known to be rigid, as seen in our precedent from Fig. 2a and 2b, this research reimagines the joint as a kinetic system that can achieve limited but articulated movement. The goal of the research is to create a joint system that permits controlled movement between joined wooden pieces while preserving structural strength. This study is a component of the block project, which uses modular wooden units which are intended for controlled mechanical motion. This paper investigates the relationship between traditional joinery knowledge in the finger joint field and more robust robotic operations using research, precedents, modeling, and physical prototypes derived from robotic techniques. There will be discourse of two case studies which both highlight the value of precise carpentry and the potential for robots to push the boundaries of both functionality and aesthetics.

Fig. 2a. Finger joint structure and connection detail. Source: "Everything You Need to Know About Finger Joint Construction," Knapp Connectors (2025). © KNAPP USA INC.

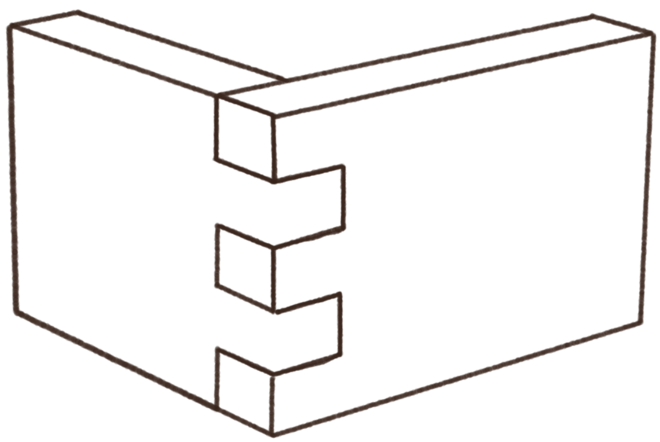

Fig. 2b. Box Finger Joint Precedent

2 State of the Art

It is essential to look into previous examples where robotic manufacturing has been used in tangent with conventional joinery principles to understand how it can be applied in hardwood finger joints. The two case examples that follow demonstrate how creative fabrication methods can lead to accuracy, material efficiency, and scalability. Guitar neck finger joints exemplify small-scale craftsmanship and finds a balance between sustainability and structural integrity, while the BUGA Wood Pavilion depicts large-scale robotic timber building inspired by biological structures.

2.1 Case Study 1

In guitar manufacturing, finger joints are commonly used to join shorter sections of wood into a longer, dimensionally stable neck blank, allowing makers to conserve high quality tonewood while reducing material waste. Rather than relying on a single long piece of lumber, neck blanks can be fabricated by machining together precisely interlocking fingers that are bonded with strong adhesives. This interlocking geometry significantly increases the glue surface area, resulting in a joint that is often stronger than the surrounding wood itself. Once bonded together, the neck blank behaves as a single structural part that is capable of holding the forces generated by string tension, which can exceed 70 to 80 kg on steel string guitars (Maltby, 2025).

From a fabrication standpoint, finger jointed guitar necks are typically produced using CNC milling or specialized finger joint cutters that can create consistent finger lengths, spacings, and alignments. This precision is uber important, since even minor inaccuracies can introduce stress concentrations or long term deformation. After gluing, the jointed blank is planed, shaped, and reinforced with a truss rod, which further enhances resistance to warping, twisting, and environmental changes such as humidity and temperature changes. The resulting necks demonstrate long-term dimensional stability, making finger joints particularly suitable for large scale production (Maltby, 2025).

Visually, the finger joint is sometimes exposed near the headstock or heel, appearing as a zigzag or angled seam in natural wood finishes Other times, it is typically concealed under finishes. Although one-piece necks are often preferred for their uninterrupted grain and traditional aesthetic appeal, a large number acoustic and electric guitar manufacturers rely on finger-jointed necks without compromising performance. Acoustically, studies and industry practice indicate that a properly executed finger joint has little to no impact on tone, as the thin adhesive layer does not significantly impact the vibration transfer along the neck (Maltby, 2025). As a result, finger-jointed guitar necks represent a balance between structural performance, material efficiency, and manufacturability, showing how precision joinery can meet functional and economic demands in instrument fabrication.

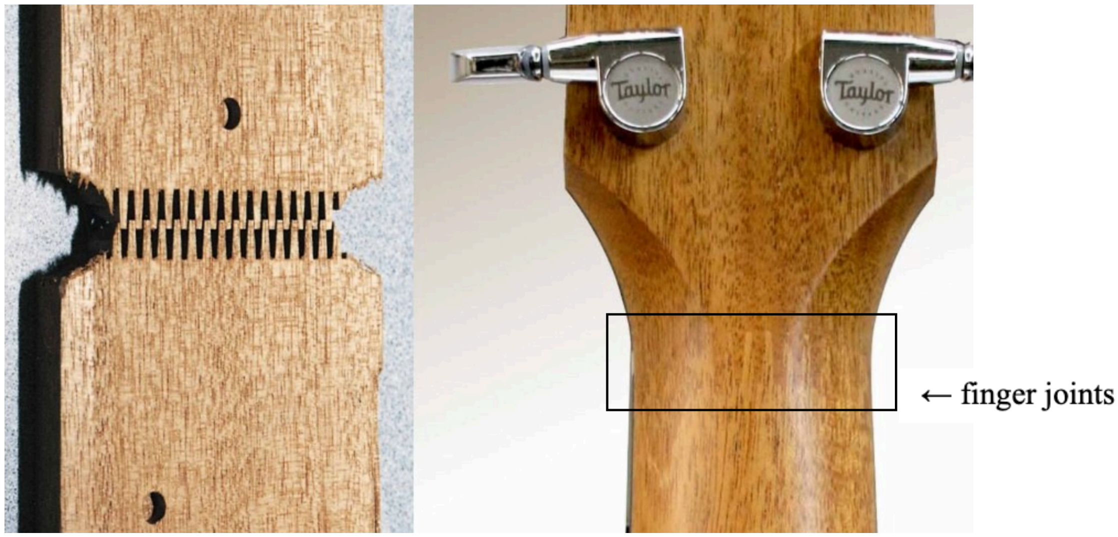

Fig. 3. Finger-jointed guitar neck showing interlocking joint geometry near the headstock. Source: Guitar Anatomy Basics: Scarfed Joints, ProjectGuitar.com; photograph by Carl Maltby, 2025.

2.2 **Case Study 2**

The BUGA Wood Pavilion represents a new approach to digital timber construction through the close integration of computational design and robotic fabrication. Its segmented wood shell is inspired from biological principles observed in the plate skeletons of sand dollars, a line of research developed by the Institute for Computational Design and Construction (ICD) and the Institute for Building Structures and Structural Design (ITKE) at the University of Stuttgart for over nearly a decade. Biomimetic research indicates that sand dollars employ a plate structure with interlocking connections in its individual plates, (Fig. 4.b.), which influenced the design of the hollow cassettes in the pavilion. To fabricate this complex geometry at full scale, a transportable robotic timber construction platform (referred to as TIM) was developed, combining multi-axis robotic milling with automated assembly processes (Wagner et al., 2020).

Each of the pavilion’s 376 bespoke hollow timber segments was produced through a compound fabrication workflow that integrated additive assembly and subtractive machining. They were fabricated from thin spruce plywood sheets CNC-milled using KUKA robotic arms and subsequently laminated into two-layer plates. Each cassette consisted of paired LVL plates with integrated edge beams, forming a stiffened perimeter system. After robotic assembly and adhesive bonding of the cassette components, the elements were mounted on a rotary workpiece positioner, enabling continuous multi-face access during milling without manual repositioning (Alvarez et al., 2019). Subtractive milling routines included initial planning and roughing passes, followed by precision profiling to create the curved interior void and finishing passes to mill finger-jointed edge connections and drilling operations with sub-millimeter accuracy (Fig. 4.b.) . The coordinated use of a six-axis robotic arm and a two-axis rotary positioner ensured consistent tool orientation, minimized collision risks, and enabled the precise fabrication of thousands of custom joint interfaces. The cassette assemblies were assembled with large interior voids, reducing overall material usage while maintaining structural depth and stiffness.

Each element was tagged with a unique ID for input that allowed for full automation and assembly (Alvarez et al., 2019). Through this controlled robotic workflow, the pavilion's segments were fabricated with exceptional geometric accuracy and assembled like a three-dimensional puzzle, resulting in a lightweight yet structurally efficient timber roof spanning 30 meters while minimizing material usage (Wagner et al., 2020).

Fig. 4.a. BUGA Wood Pavilion in Heilbronn, Germany, illustrating the segmented timber shell structure. Source: ICD/ITKE, University of Stuttgart; photograph by Roland Halbe, 2019.

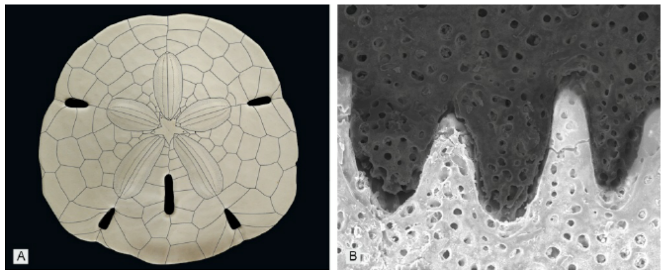

Fig. 4.b. Sand dollar inspiration for the BUGA Wood Pavilion. Source: Gerber & Nebelsick / Nebelsick & Grun, University of Tübingen.

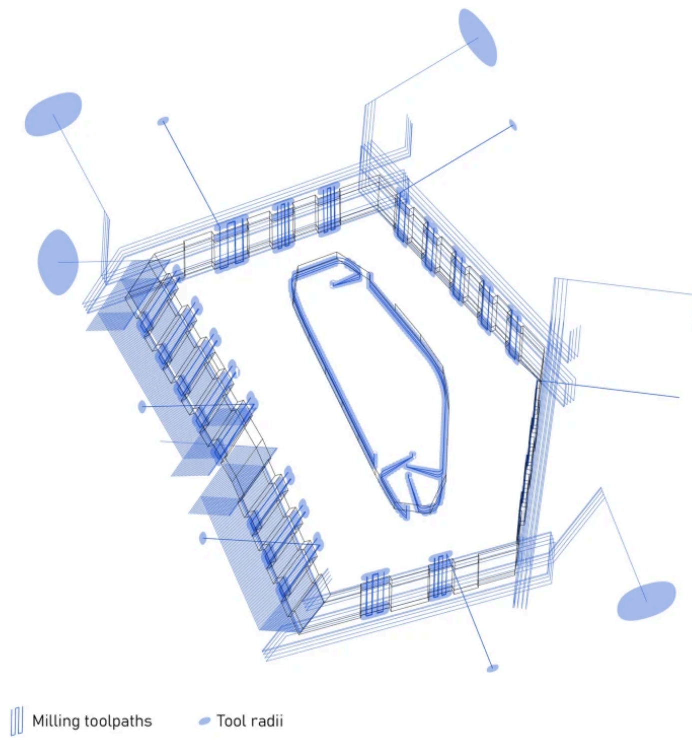

Fig. 4.c. Cassette milling toolpaths. Source: Wagner, H.J., Alvarez, M., Groenewolt, A. et al. Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and co-design of the BUGA Wood Pavilion. Constr Robot 4, 187–204 (2020). https://doi.org/10.1007/s41693-020-00038-5

3 Methodology

1) Cut 2 x 6 wood with circular saw into approximately 3’ lengths
2) Place both panels into the robot setup, make sure one has an overhang of 250mm and the other 200mm, drill in to secure
3) Jog robot to confirm mounting position alignment, warm up the spindle, send script to robot via Grasshopper or RobotStudio.
    a) Grasshopper script featuring dogbone profiling + swarfing with a ½” end mill and a ¼” end mill to help profile ½” holes, exported as RAPID code for execution
4) Cut wood to final size and clean up wood with sanding blocks, sand paper, circular rasps, powered hand sander, and oscillating multi-tool
5) Mark hole position on each finger and drill a ½” hole following the drill profile
6) Glue and clamp each panel securely to one another (24 hrs wait time)
7) Cut dowel down to right length with pull saw, insert through each finger hole
8) Final touches with multiple sanding techniques

The box finger joint is unique in its capability to provide a rigid interlocking mechanism in one direction while still allowing movement along a different axis. This helps the possibility of kinetic movement about the axis of the joint, provided there is ample space for the joint to move. This dual characteristic makes the box finger joint particularly suitable for applications where both structural integrity and controlled motion are desired.

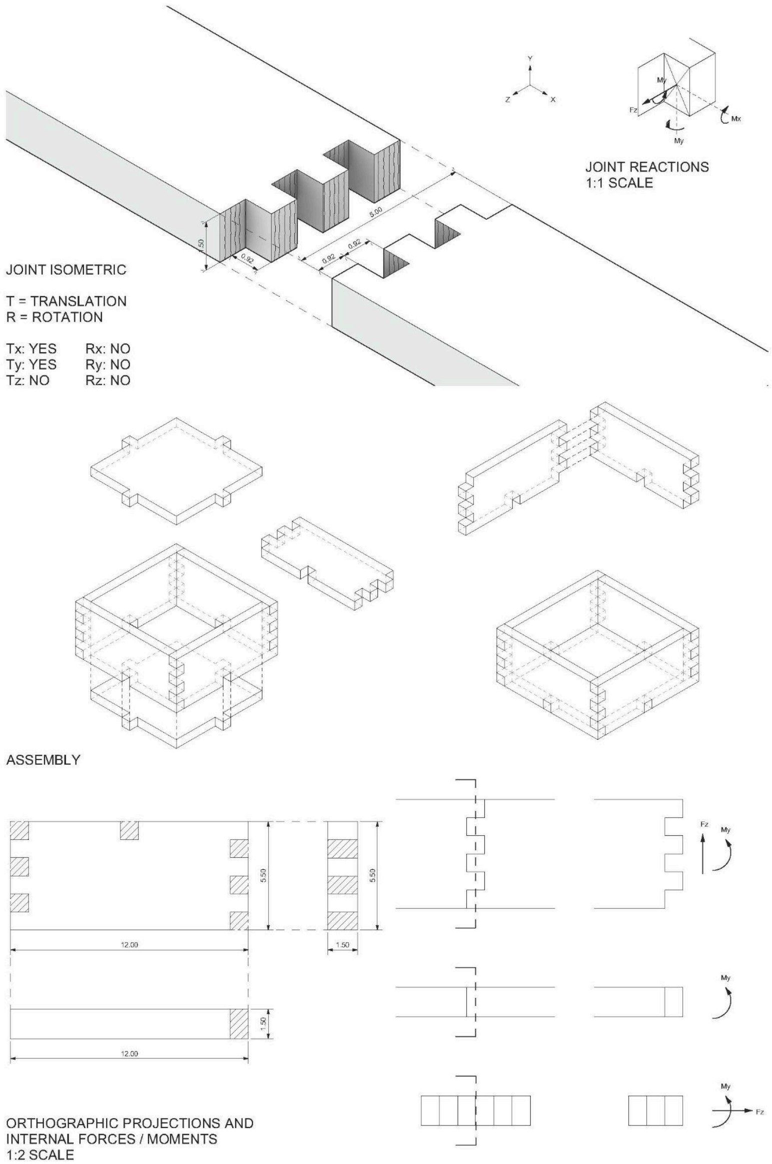

Fig. 5. Initial design of box finger joint, which allows for translation in the y-direction and can rotate when the gap is extended into the joint, allowing for the possibility of a kinetic joint.

Each iteration of our joint explores the kinetics of a typical box joint. Working from the first joint in Iteration A and B with the simplest end to end connection, we observed and analyzed the joint at various angles until we understood that an increase in the finger length parameter could allow for rotation. Additionally, we optimized the design in Iteration D through G by creating a semicircular profile at the end of the joint and exploring multiple boundary conditions, including stoppers and a full-rotation hinge. We further tested out the rotational capabilities of the joint on a multiple sides in Iterative H and I on a cube combined from multiple pieces of dimensional lumber, which could be expanded across multiple axes and allow for a cross-lamination, where the last piece adhered is a finger joint, allowing for maximal stability across the piece.

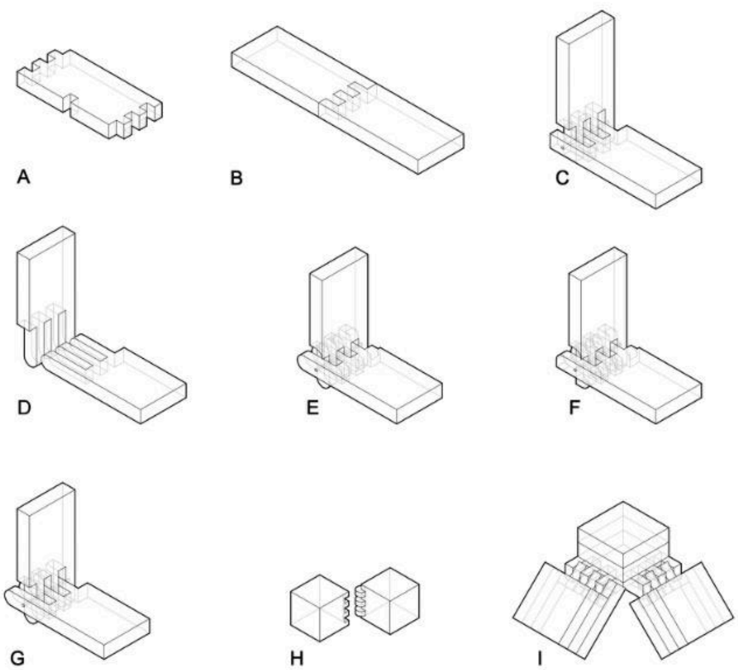

Fig. 6. Joint iterations of the finger joint, moving towards a more kinetic yet stiff joint.

3.1 Digital Modeling

The digital modeling workflow begins with the creation of simplified geometric forms representing the final milled component. The primary objects used for the toolpath generation are boxes and planar surfaces, designed to be cut from the top downward to the referenced surface (Fig. 7.b.). These geometries define the material boundaries and provide the basis for generating both profiling and surface-milling toolpaths.

Two key machining strategies are employed:

a) The first strategy is dog bone profiling. To ensure precise interlocking between each finger, dog bone profiles are incorporated at the interior corners of the joint geometry. This feature compensates for the tool's circular cutter radius, enabling tight-fitting, right-angle joints after milling. The dog bone toolpaths follow the outer contour of each piece, cutting from top to bottom (green to red) as seen in Fig. 8.b.

b) The second strategy is swarfing. For parts that include non-planar or curved, sculpted features, swarfing toolpaths are generated. This method maintains the tool's side in contact with the wood surface, allowing for efficient multi-axis machining and smoother finishes. See Fig. 8.c.

A third machining strategy known as hole profiling, although not employed to its full capacity, was used to mark the 1/2″ diameter hole for the dowel using an end mill. Because the end mill could not reach the full 5.5″ depth of the wood, only a shallow pilot hole was produced, and the milling operation was separated from the remainder of the procedure. The tool entered the material in a spiral motion, as seen in Fig. 8.d.

Overall, the workflow integrates simple parametric solids with targeted toolpath operations, profiling for joint accuracy and swarfing for surface quality, resulting in efficient and precise fabrication.

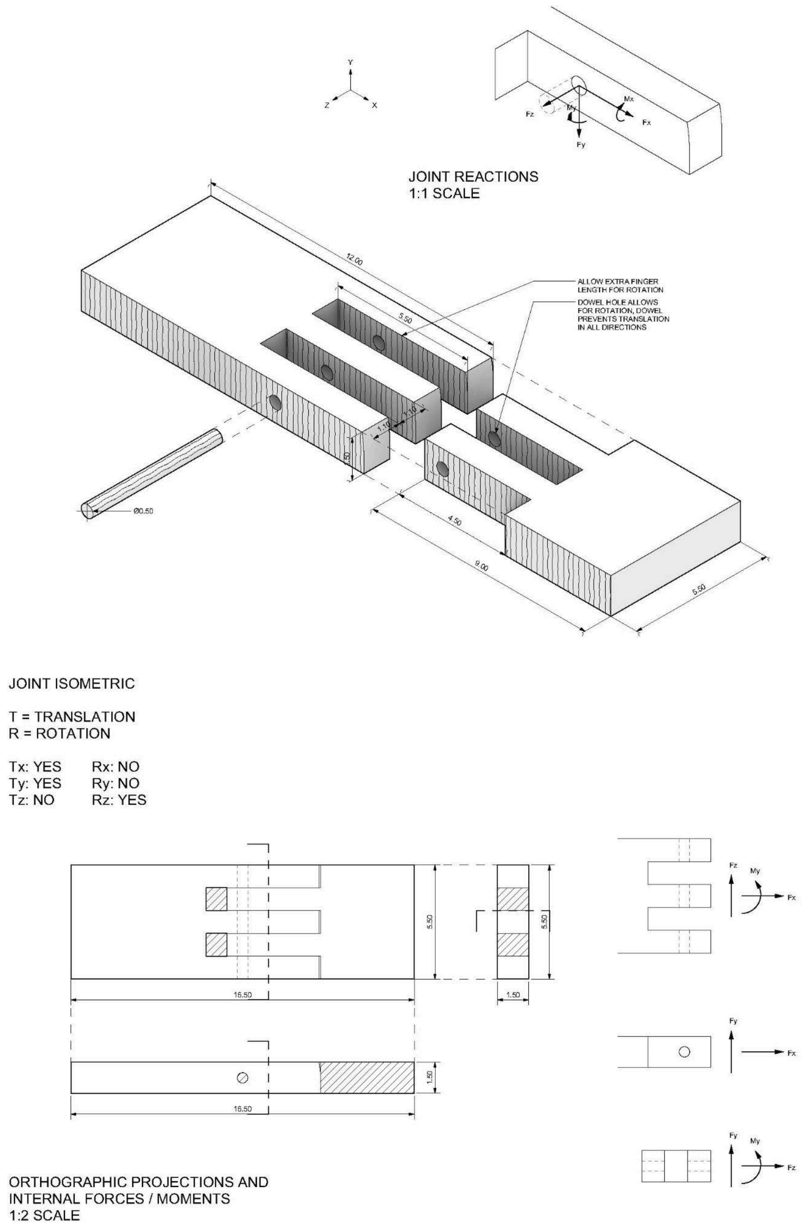

Fig. 7.a. Primary geometry of the final finger joint.

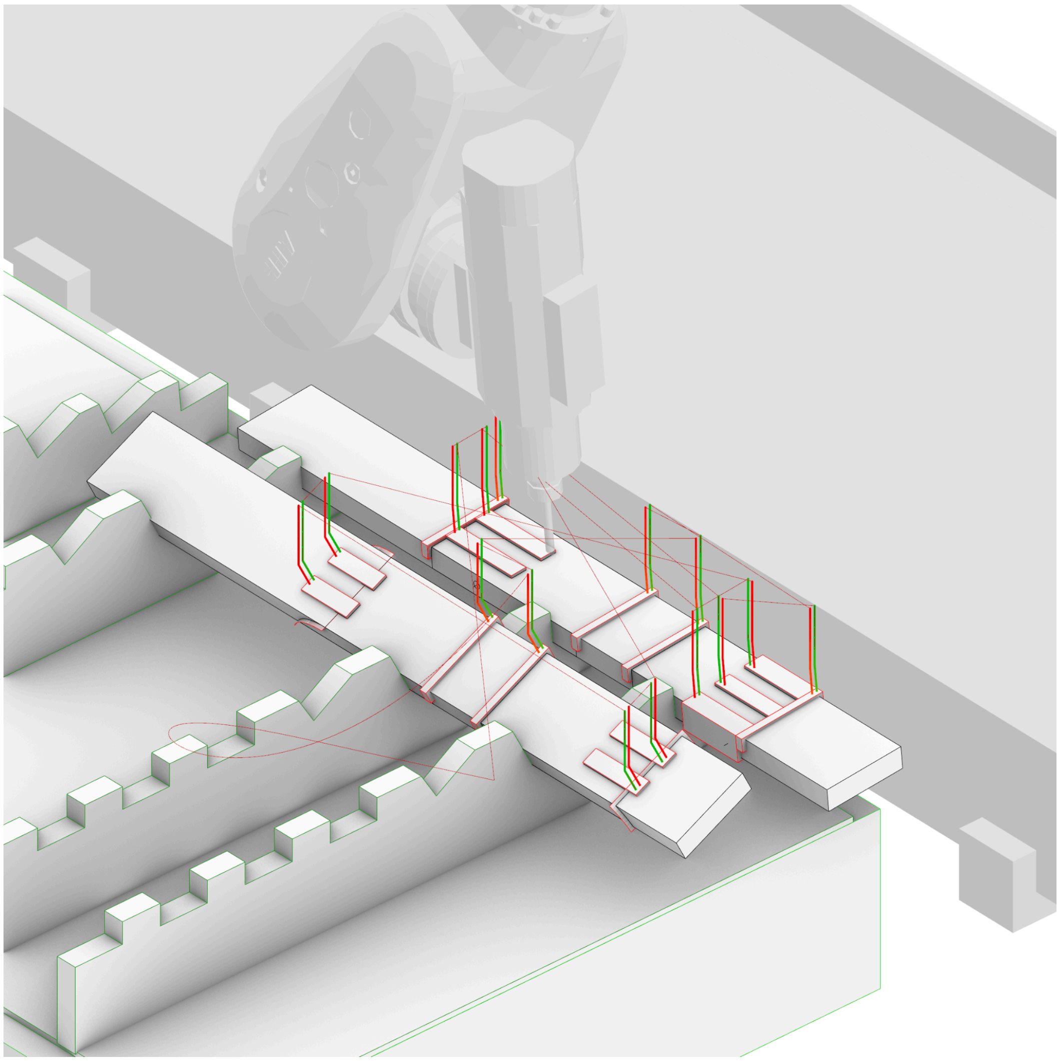

Fig. 7.b. Main geometries for roughing, profiling, and swarfing the finger joint, mounted on base.

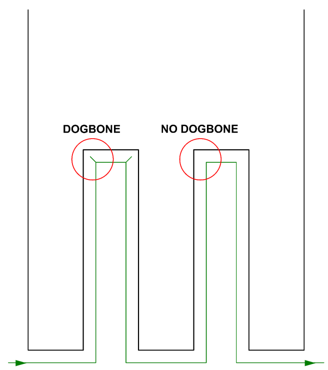

Fig. 8.a. Comparison between tolpath with and without dogbone profiling.

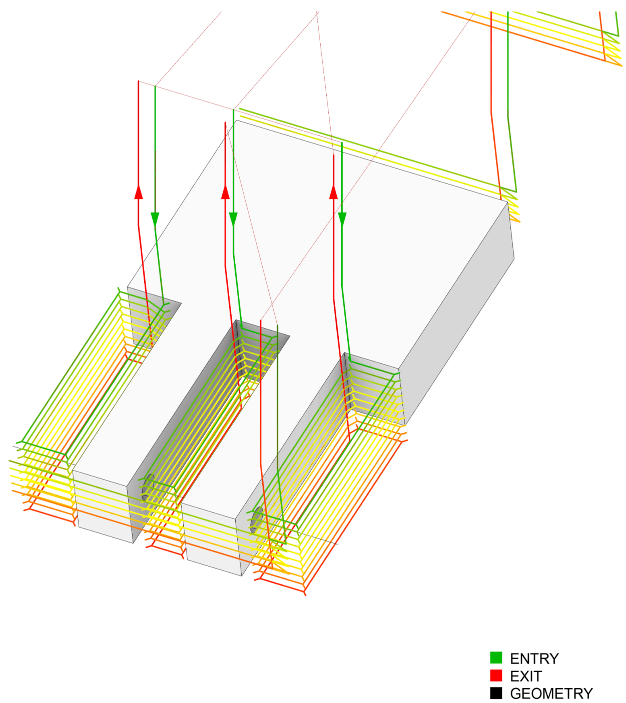

Fig. 8.b. Dogbone profiling toolpath.

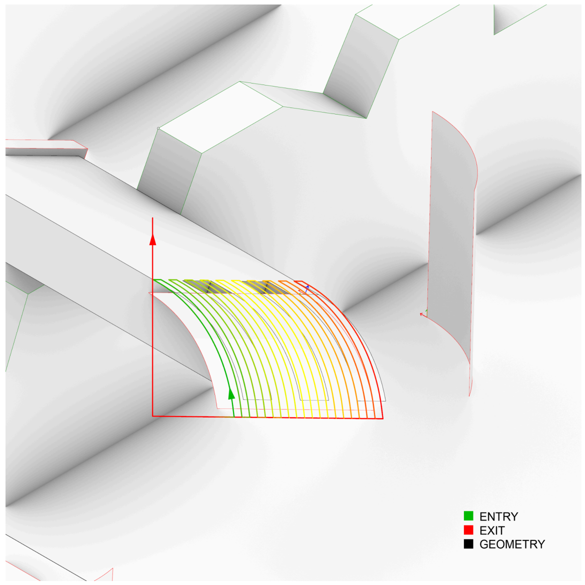

Fig. 8.c. Swarfing toolpath.

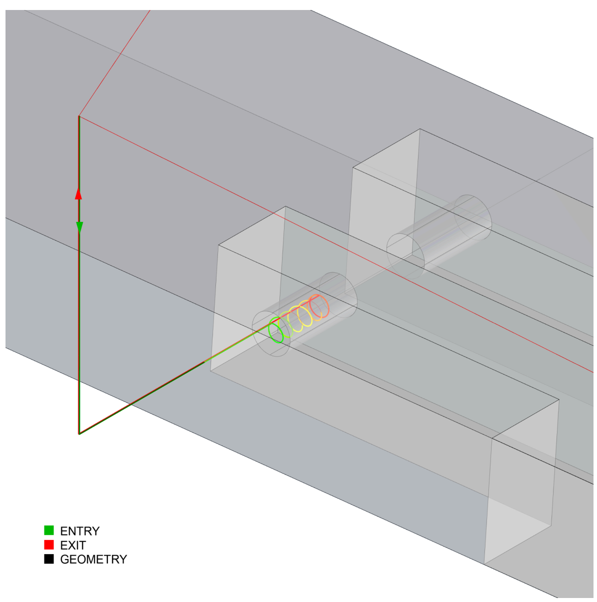

Fig. 8.c. Hole profiling

3.2 Robotic Fabrication

Our stock material was mounted in front of the robotic arm at two slight angles. The angled panels were securely fastened with screws (Fig. 9) to minimize vibration and prevent movement during milling. The operation was carried out using an ABB IRB 6700-150/3.2 robotic arm equipped with a 10 HP HSD spindle end effector, mounted on a 6.4 m ABB IRBT 6004 linear external track. For this setup, the robot maintained a fixed tool orientation, with motion constrained primarily to the x and y axes (Fig. 7.b and Fig. 9). The milling process used a half-inch end mill following a rectangular toolpath along the x-axis, incrementally stepping down in the y-axis to reach the target depth. The total runtime for the milling sequence was approximately 20 minutes, excluding setup and tool changes.

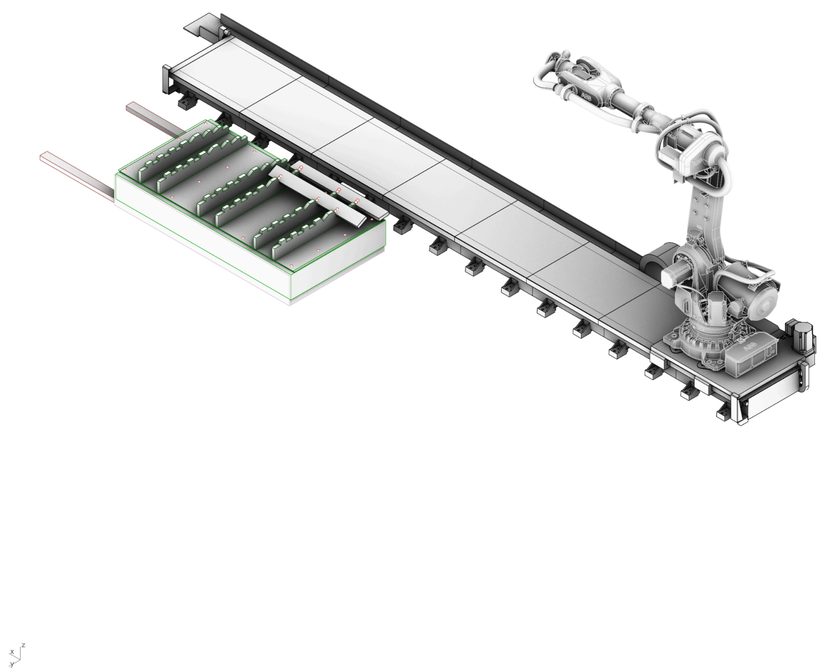

Fig. 9. Stock material mounted at a slight angle for robotic milling. Screws are notated as red points.

4 Results

Our work explored how robotic fabrication can redefine the traditional wooden finger joint by introducing controlled movement while maintaining structural integrity (Fig. 10.a.). Most finger joints we studied were static, designed solely for rigidity, but our goal was to create a system that could balance strength with dynamic motion. By increasing the surface area available for gluing, we aimed to reinforce the joint without sacrificing flexibility. This study, part of the larger Block Project (Fig. 10.b.), sought to merge historical joinery knowledge with advanced robotic workflows, showing how digital precision can expand the design possibilities of modular wooden systems capable of mechanical motion. The process allowed us to appreciate how robotics can not only replicate traditional artisanship but also enhance it through scalability, accuracy, and experimentation with movement.

To achieve this, the joint was developed through multiple fabrication iterations, each revealing key constraints related to tolerance, orientation, and robotic control.

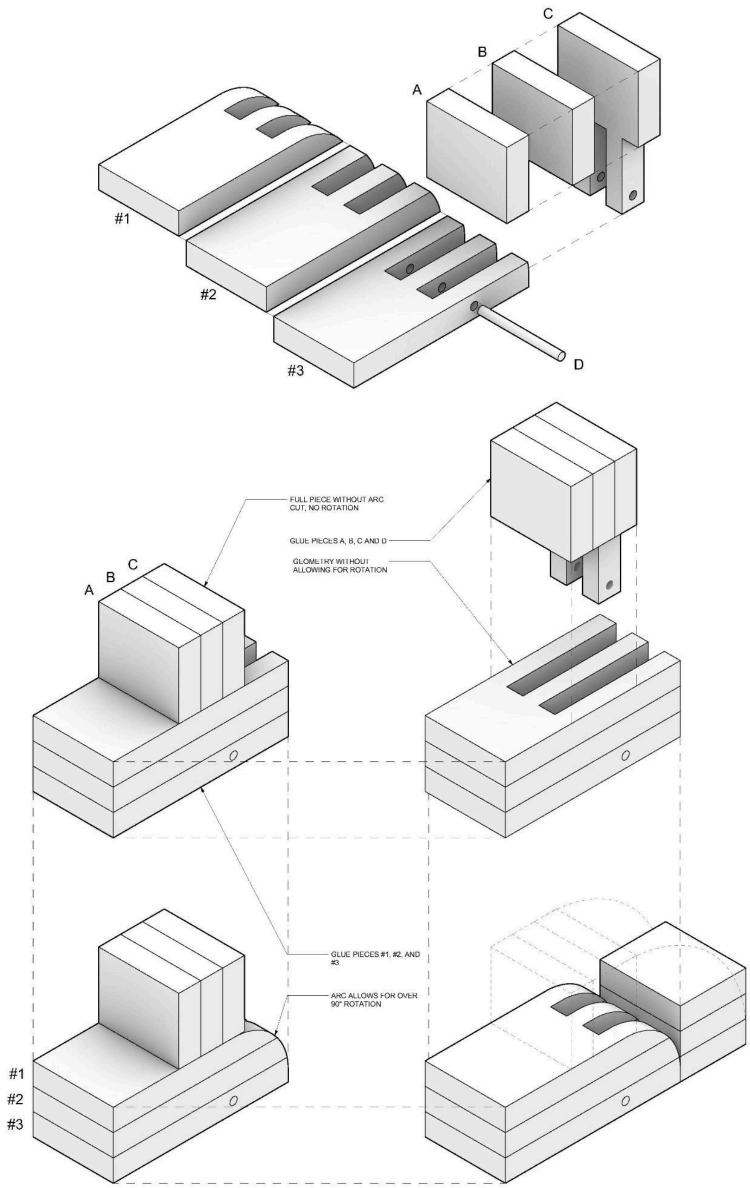

Fig. 10.a. Assemblage diagram of final joint.

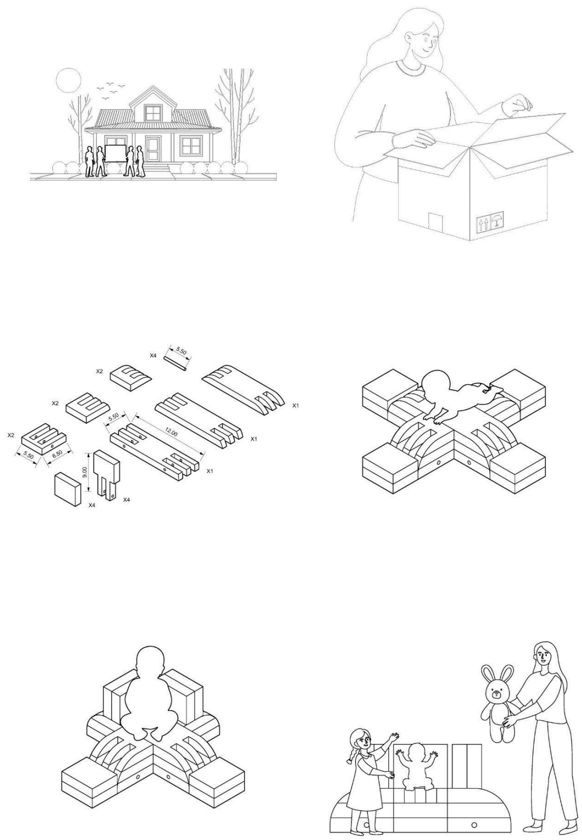

Fig. 10.b. Larger application of joint in the Block Project.

4.1 **First Mill Iteration**

The first iteration, as seen in Fig. 11, established a baseline finger joint geometry fabricated through robotic milling. A major challenge arose from a tolerance issue in our robotic script, which resulted in excessive looseness between the fingers, preventing the joint from behaving structurally as intended while compromising the effectiveness of the dog-bone feature. Despite this issue, the iteration was successful in validating the overall fabrication workflow, including toolpath generation, dogbone profiling, and fixturing. (Fig. 12.a. and 12.b.). This initial prototype was therefore critical as a learning tool, confirming machining logic while exposing the sensitivity of finger joints to tolerance calibration, as the joinery did not achieve full edge-to-edge contact. Thus, the initial end-mill offset of 5 mm in the script needed to be adjusted during further iterations.

Fig. 11. Finger-joint prototype

Fig. 12.a. Finger-joint: first mill operation

Fig. 12.b. Unscrewing milled finger-joint

4.2 Second Mill Iteration

Building on this baseline, the second iteration extended the length of the fingers to begin exploring rotational behavior around the joint axis. The longer fingers introduced the possibility of hinge-like motion; however, the tolerances remained oversized due to the end-mill offset of 5 mm being too small, leading to instability and uncontrolled movement. Instead of enabling intentional rotation, the looseness reduced structural clarity and compromised load transfer. This iteration clarified that kinetic performance must be achieved through precise geometry rather than relaxed tolerances and that longer fingers amplify tolerance errors rather than compensate for them. Additionally, parts of the geometry were not cut all the way through, so the profiling geometry was enlarged in the further iterations to account for misalignment.

Fig. 13. and 14. Finger-joint: second mill operation

4.3 Third Mill Iteration

The third iteration introduced a diagonal cut intended to create internal clearance for rotation. While the robotic milling executed the geometry accurately, with the tolerance being changed from a 5 mm end-mill offset to a 6.35 mm one, a miscalculation in the diagonal profile caused the fingers to mechanically interfere with one another. As a result, the joint could not rotate as expected because the fingers collided and locked the system. Although the intended motion was not achieved, this iteration marked an important conceptual shift by revealing that kinetic joints require careful anticipation of three-dimensional interference conditions, not just planar alignment. This failure emphasized that motion must be explicitly designed through controlled clearance paths rather than implied through form alone.

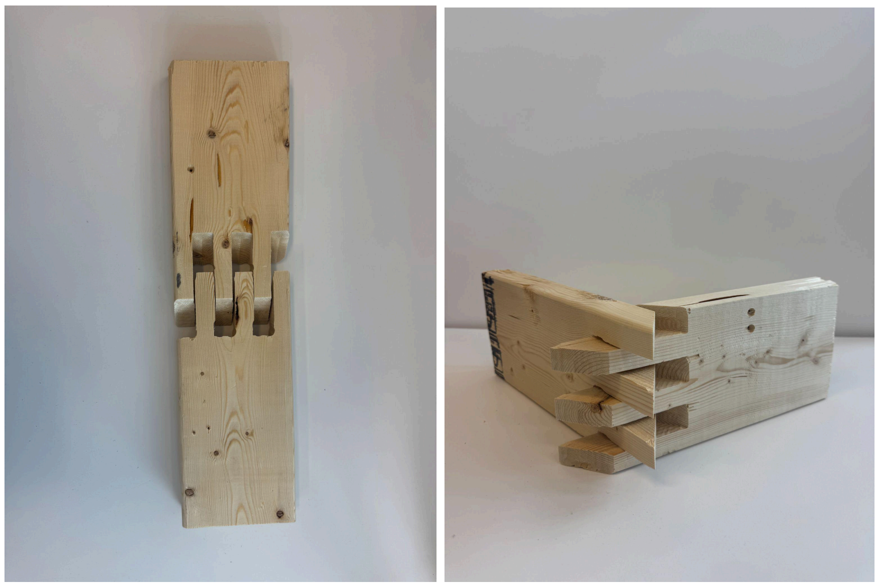

Fig. 15. and 16. Finger-joint: third mill operation

4.4 Fourth Mill Iteration

In the fourth iteration, the joint was scaled and integrated into the Block Project chair prototype (Fig. 17). For the first time, the joint successfully exhibited controlled motion; however, a scripting error during the hole profiling operation caused the robot to exceed its allowable depth, generating excessive friction and heat between the chuck and the wood. This damaged the robotic tool and nearly burned the wood component. While this iteration failed operationally, it confirmed that the joint geometry itself was capable of kinetic behavior. The failure exposed the risks of robotic fabrication.

4.5 Fifth Mill Iteration

The final iteration refined tolerance values, corrected rotational clearances, and optimized the robotic sequencing. Furthermore, the fingers were reconfigured so one side would have three fingers and the other would have two fingers to ensure joint stability and reduce rotational play. These adjustments resulted in a functional kinetic finger joint that could rotate predictably while maintaining stiffness along the load-bearing axis. The final joint was assembled into the chair, demonstrating controlled movement without structural failure or fabrication damage. This iteration represents the culmination of material testing, geometric refinement, and robotic control developed throughout the semester.

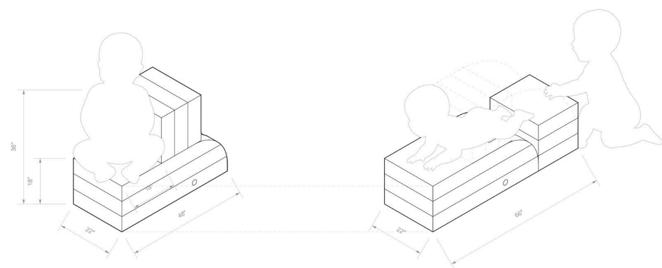

Fig. 17. Digital Design for the Final Block Chair

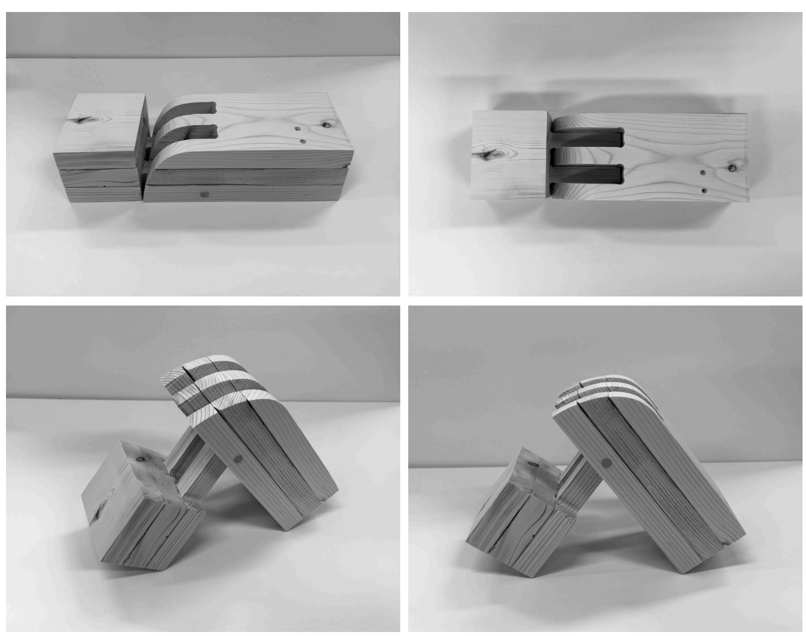

Fig. 18. Physical Finished Product

Overall, the iterative process transformed a traditionally static woodworking joint into a robotically fabricated kinetic system. Each failure directly informed subsequent design decisions, illustrating how physical prototyping and robotic experimentation are essential when extending historical joinery techniques into dynamic, digitally fabricated assemblies.

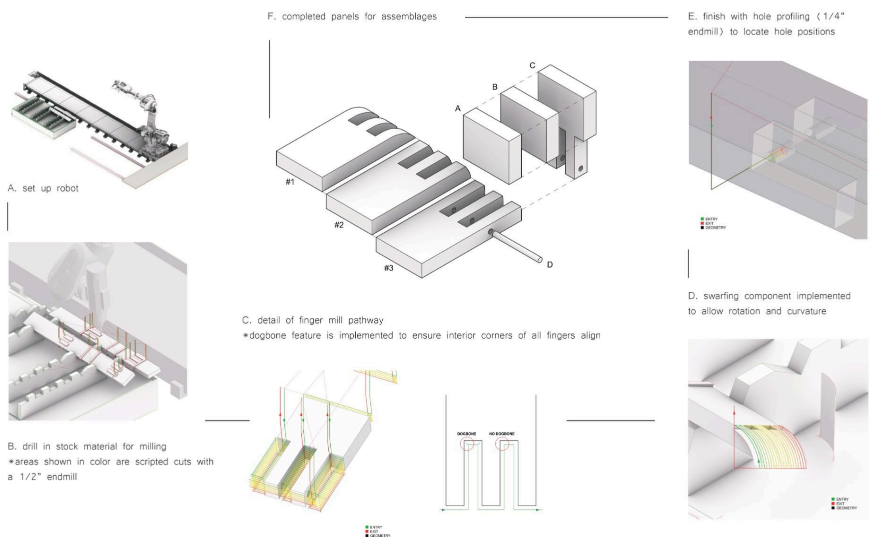

Fig. 19. Milling Workflow Diagram

5 Conclusions

This work contributes to the ongoing dialogue between traditional woodworking techniques and contemporary robotic fabrication by demonstrating how digital precision can enhance the adaptability and performance of wooden finger joints. By developing a scalable joint system that balances structural integrity with controlled motion, the research offers a framework for integrating dynamic joinery into modular wooden assemblies. More broadly, these findings can inform applications in architectural systems, kinetic structures, and adaptive furniture design, where movement and flexibility are essential. One potential application lies in timber framing systems, where such joints could facilitate the controlled rotation and deployment of horizontal elements into vertical positions, enabling efficient assembly, reconfiguration, or erection through reduced friction and precise, repeatable motion. Future investigations will focus on refining the robotic workflow, optimizing material efficiency, and exploring how sensor integration or responsive actuation could further expand the functional potential of these robotic finger joints.

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