DEVELOPMENT OF AN AFFORDABLE ON-SITE WOOD CRAFT SYSTEM: INTERACTIVE FABRICATION VIA DIGITAL TOOLS

ARASTOO KHAJEHEE1, TAISEI YABE2, XUANYU LU3, JIA LIU4 and YASUSHI IKEDA5
1,2,3,4,5 Keio University, Japan.
1arastookhajehee@keio.jp, 0000-0001-5381-7784
2tai@sfc.keio.ac.jp, 0000-0002-3166-3232
3luxuanyu@keio.jp, 0000-0001-6826-8642
4liujia66@sfc.keio.ac.jp, 0000-0002-0895-1711
5yasushi@sfc.keio.ac.jp, 0000-0002-2016-4083

Abstract. This research aims to develop a craft system that simplifies the transition between design and fabrication. One of the main purposes of this system is to allow non-professionals to engage in craft with the aid of affordable digital fabrication tools. By removing the technical hurdles that prevent beginners from engaging in digital fabrication, the system aims to enable those who are interested in making things as a hobby or DIY projects to enjoy digital craft. The developed craft system provides a comprehensive workflow, starting from the initial shape to the final CNC milling machine G-Code generation. It is developed through Object-Oriented Programming, resulting in an interactive system that provides information about the fabricability of the final shelf structure to user/designer. The real-time design-to-fabrication aspect allows for some degree of simultaneous design changes, making the craft experience more enjoyable. In line with the UN Sustainable Development Goals, this research is an attempt to provide more opportunities for individuals to get into digital fabrication, enabling them to acquire skills within the rapidly growing industry. Furthermore, as demonstrated by other digital fabrication tools like 3D printers, DIY builds can potentially be economically beneficial for the users.

Keywords. Digital Fabrication; Real-Time Design to Fabrication; Affordable On-Site Craft; SDG 8; SDG 9.

1. Introduction

Authors Over the past 2 to 3 decades researchers and designers have been exploring how to build increasingly complex shapes and forms. The Buga Wood Pavilion and the Landesgartenschau Exhibition Hall, designed by the team of Oliver David Krieg and Achim Menges at Stuttgart university, are great example that demonstrates how robotic fabrication tools can build incredibly intricate structures with amazing accuracy (Alvarez et al., 2019; Menges et al., 2015). Similar to Gilles Retsin's timber installation and Gramazio & Kohler's robotic fabrication projects, it is quite evident that these
structures require incredible precision and complicated tools and techniques (Burry et al., 2020). These achievements demonstrate how our ability to build performative enclosures have evolved via digital fabrication. However, this level of complexity requires meticulous preparation, which can become a major hurdle for those who want to get into digital fabrication. It makes it extremely hard for beginners and non-professionals to engage in the production of such structures. By non-professionals, this paper refers to individuals who may not have specific skills in crafts and fabrication but wish to enjoy making things as a hobby or as "Do It Yourself" (DIY) solutions. Rather than exploring how complex of a structure we can build, this paper focuses on developing a system that facilitates enthusiasts to enter the realm of digital fabrication. As digital fabrication tools become more affordable, we see more people getting interested in DIY builds. Such builds are not only engaging for the user, but also economically beneficial. As Emily E. Petersen and Joshua Pearce have calculated, investing in a 3D printer can have a return value of over 100% for low-cost items in 5 years; as for high-cost items, it can produce a 986% return of investment in less than 6 months (Petersen & Pearce, 2017).

While this might be the case with plastic 3D prints, larger scale productions still are quite difficult to manage as they require more expertise and sophisticated tools. With the aid of affordable digital fabrication tools, this research tries to provide a system that produces timber shelf structures that can be assembled by hand and have as much flexibility as possible in terms of shape, scale and size. Having "Decent Work and Economic Growth" and "Industry, Innovation and Infrastructure" as guidelines, this paper attempts to create an innovative system that allows easy entry for individuals to the digital fabrication industry. As mentioned previously, DIY projects and digital fabrication tools can have great economic potentials. By enabling more people to get engaged in such technologies, this research hopes to foster more innovation in the field by enthusiastic individuals. Consequently, it aims to help people gain new skills that would in turn create more opportunities for growth. In fact, this research was established to create an interior design solution for a small art gallery renovation project located in Tokyo, Japan. The developed craft system in this paper provides a comprehensive workflow, starting from the initial shape to the final CNC milling machine G-Code generation. Figure 1 shows a 2m*1m built example of the structure that was fabricated in multiple stages, with two different ShopBot CNC machines. The design of the shelves also was slightly changed during the fabrication stage.

![Figure 1. Fabricated shelf structure](image)
2. Object-Oriented Programming and Agent-Based Design

Invented in the early 1960s, Object-Oriented Programming (OOP) refers to a programming paradigm that relies on the creation of "objects" with properties and capabilities. OOP relies on custom type objects that have a lot of functionalities and properties built in them. These objects can interact with other objects of the same type or other types (Object-Oriented Programming, n.d.). Closely related to OOP, Agent-Based Design (ABD) can be thought of as a paradigm that is suitable for building systems that involve large numbers of geometrically unique elements. ABD can allow internal interactions between a structure's members and external user inputs (Groenewolt et al., 2018). As an example, Achim Menges et. al used ABD to enable designers to move structural timber plates, while the system dealt with all the joint geometries and structural considerations (Menges et al., 2015).

The craft system developed in the paper generates straight members with unique lengths and joint configurations that as a whole would shape the final curved shelf structure. Since these members need to interact with one another to create notch joints, conventional McNeel Rhinoceros 3D (Rhinocer) and Grasshopper (GH) visual programming proved quite limiting. Thus, the system was developed through ABD based on the Microsoft .NET Framework, using the C# language. The aim of the development has been to reduce as much technical hurdles as possible to allow creative individuals enjoy craft with the aid of digital fabrication tools.

The developed program generates linear objects that represent real-life structural members. These members have inherent properties, such as their dimensions, ID number, list of joints and so on. In terms of interactions, they generate notch joints with other members in the system. They also record their joint count with other members. Identifying and removing redundant members is another example of the ADB interactive implementation. Redundant Member removal refers to an algorithm implemented in the system that would remove extra members with too many joints while making sure all members have a minimum number of joints. Figure 2 shows how these functionalities and properties can be retrieved in a scripting environment.

Figure 2. Creating of a shelf member class instance and accessing its properties

While Achim Menges et. al.'s ADB implementation enabled changes up to the fabrication stage starts. This paper, on the other hand, tries to keep the interactive design capability even during the fabrication stage. Once a part of the structure is built, the developed system in this paper still allows for some constrained design changes, including introducing holes in the shelf, or changing the curvature of the structure, as long as the previously built joints are not affected drastically.
3. Material and Joint System

3.1. WOOD AS A MATERIAL

Wood is among the most sustainable construction materials that is available in the building industry. Compared to other available building materials, wood has a very low embodied energy footprints (Alcorn et al., 1996; Gordon, 2003). Rather than having huge carbon footprints like steel and concrete, it is actually considered to be carbon absorbent since it traps large amount of carbon in its growth phase (Gold & Rubik, 2009). In addition to energy considerations, wood can be shaped into different forms with hand tools and digital fabrication tools. Assembly and disassembly as a sustainable solution is another aspect that is being explored by designers. Kengo Kuma’s KODAMA permanent pavilion for Arte Sella Foundation, and Atsushi Kitagawara’s design for Japan’s pavilion at Expo Milano 2015 are great examples of this approach (Kitagawara et al., 2019; Kuma et al., 2019). With the aid of digital fabrication tools, buildings and structures that have disassembly in mind in their design can have much less of an energy footprint. This approach can also decrease landfill waste to a great degree (Shannon Hosey et al., 2015). Particularly, the re-usability of wood can increasingly contribute to this reduced energy footprint. The system described in this paper creates small notch joints as a means of maximizing the material’s re-usability in other builds at the same time as reducing fabrication waste.

One-by-four (1*4) timber bars are the material of choice for this system because of accessibility, affordability, and the fact that they can be easily processed with a ShopBot CNC mill. In addition, by limiting the type of material for the system, it became possible to develop and build additional tools to improve the CNC milling process, resulting in better cost and material efficiency.

3.2. JOINT SYSTEM DESIGN AND FABRICATION TOOL

Interlocking jointing is one of the most commonly used joint systems in timber structures. These joint systems allow structures to be assembled without the need for nails, glue, or other fasteners as much as possible. However, depending on the function of the structure and regulations extra fastening measures need to be implemented. Since notches can be easily milled using CNC mills and other digital fabrication tools, interlocking joints offer great flexibility in terms of shape and size. As the shape of the structure gets more complex the joints also become more complex and irregular Kengo Kuma's KODAMA pavilion's simple 2D joints, Schwinn et. al.'s Landesgartenschau pavilion robotically fabricated finger joints, and Nabei et. al.'s interlocking joints in a reciprocal panel structure are great example of the versatility of interlocking joints in wooden structures (Kuma et al., 2019; Schwinn et al., 2014; Nabaei et al., 2011).

4. Shape and Structure Design

4.1. SYSTEM FRAMEWORK SUMMARY

The shelf structure is generated based on two inputs: 1. A 2D reciprocal pattern, and 2. A curved 3D surface. The initial 2D line pattern can be changed for the desired shape, size, and functions of the final shelf. The 3D surface can be altered to change the overall
curvature and shape of the structure. The system can generate structures form a variety of 2D patterns. However, 2D reciprocal patterns are recommended for this system as they have inherent structural characteristics that contributes to the stability of the structure. Figure 3 Shows the workflow of the system from the input patterns to the final CNC G-Code generation. Each step will be explained in the following sections.

4.2. 2D PATTERN DESIGN

The system uses 2D patterns to generate shelf structures. This 2D pattern does not necessarily need to be completely repeatable. By adding empty spots in the pattern, it's possible to change the shape. Figure 4 showcases the use of empty spots in the structure as a means of creating bigger shelves and change the final shape.

4.3. 3D MEMBER GENERATION

Alignment of the 3d structures is achieved by extruding the first layer's pattern according to the normal vectors of the input surface. These extrusions are then intersected with the other layers to create the subsequent 3D transformed patterns. In earlier iterations of the system, other methods of generating members were explored. However, those methods proved to create structurally unstable results, or joints that did not alight. Figure 5 showcases the previous and the current iteration of the system. In the current system, the diagonal members are shifted by half of their width inside to create the bonding joints between the different layers.
4.4. REDUNDANT MEMBER REMOVAL

Fabrication time presented one of the biggest challenges in the development. When all of the generated members were kept in the final shelf structure, a lot of extra joints were also created. More than half of the members in the structure would have up to 12 joints. These extra joints drastically increased the fabrication time while not contributing so much to the structure's stability. The purpose of the Redundant Member Removal Algorithm (RMRA) is to remove as many extra members as possible up to the points where all members are necessary to keep the structure stable. The criteria for the developed algorithm were to keep removing members until all members have at least 3 joints with other members. It was discovered during the algorithm's development that less than 3 joints per member would result in unstable structures. The RMRA is developed via the core OOP system. It intersects all the members together in a recursive manner until all members become necessary for the structure:

- Removing one member and checking how many joints other members have left
- If the removal of a member would violate the 3-joint criteria, then that member and all connected members would be marked as necessary and be kept
- The recursive algorithm continues until all members are deemed necessary

The redundant member removal algorithm reduced the member count resulting in less material needed for the structure. Table 1 shows the result of the member removal for 3 different shelf structure (The average fabrication time for each joint was 1.5 minute):
4.5. JOINT GEOMETRY AND GENERATION ALGORITHM

Every Joint in the system is generated as a result of intersecting two members. Going through all of the members after the RMRA, the system detects the 3D intersections between two-member sets. It divides each intersection volume into two parts and removes half of the joint from each one. The resulting joint is an angled volume that needs to be milled out. During fabrication experiments, some problems were discovered regarding the volume of the joints. Sometimes the it was not sufficient enough to be divided into two parts. In such cases, the intersection volume is removed only from one of the members. Another issue was that the length was sometimes so small that the joint became ineffective. As a result, an Intersection Length Checker Algorithm (ILCA) was developed to check for these problematic joints and intersections while designing. The ILCA highlights the members and joints that cause issues, prompting the user to change the initial shape to avoid fabrication errors. In other words, the system offers feedback to the designer regarding the fabricability of the structure. Figure 6 shows the joint generation method and a joint problem example detected by the ILCA.

![Figure 6. (1) ILCA joint problem detection, (2) Joint generation method](image)

4.6. CNC FABRICATION AND G-CODE COMPILER

ShopBot CNC machines were selected as the fabrication tool for this research mainly because of their affordability and ease of use. In order to use a ShopBot for CNC milling, a software named VCarve Pro (Vectric Ltd, n.d.) is commonly used to convert CAD models to machine-readable commands "G-Code" (G-Code, n.d.). VCarve is a powerful tool for different methods of milling, including regular XYZ milling, double-sided milling, additional axes such as angle milling tools. However, the learning curve for the software is steep, which can become a hurdle for new users. Regardless of the skill level, the amount of time that is required for CAD to G-Code conversion is another issue that this paper addresses. Since this paper attempts to simplify fabrication, a custom G-Code compiler is developed that automatically generates the machine-readable commands. An example of custom G-Code compilers is the work of Bae et al. that uses custom control of 3D printers to create novel objects that were impossible to make using regular 3D printing software and slicers (Bae et al., 2020). Developing the custom compiler in this paper removes the necessity to use VCarve Pro altogether, resulting in a real-time CAD to G-Code workflow. Table 2 provides a time comparison between VCarve Pro and the custom compiler. The average time spent for preparing files using VCarve was measured around 5 minutes.
As mentioned, the custom compiler reduced the tool path generation time to virtually none, making it real-time. This real-time aspect affords the user to make design changes even during the fabrication stage. In fact, the design of the fabricated example shelf structure was slightly changed during fabrication to test this real-time design/fabrication concept by adding some extra empty spaces in the structure. The real-time aspect actually allows the users to fabricate members based on the assembly sequence that they want to go through. Figure 7 showcases the virtual model that was used during the fabrication.

![Image of virtual model](image)

**Figure 7.** (Black) Not yet fabricated, (Green) Selected member to be fabricated, (Blue) Fabricated but not yet assembled, (Red) Fabricated and assembled

In terms of fabricability, the resulting joints are volumes with an angle. They cannot be milled out with conventional 2D CNC tool paths. Since regular CNC machines can only move in the XYZ axes, they can only remove material from above. As a result, an algorithm was developed to convert the joint geometries into two parts that can be milled in two steps: milling the top part of the joint, and then milling the bottom part after flipping the material. The ShopBot's approach toolpath was also incorporated in the compiler. It was seen that when the milling bit carves material from inside towards the edges of the 1*4 material, in many cases the timber would break. This was in part because of the speed of the ShopBot, but more importantly because of the milling tool path. Accordingly, a tool path system was developed that would first carve the edges of the material from the outside towards the inside. This prevented the timber's edges from breaking and chipping off. The Tool path was also divided into two phases of material removal and surface smoothing. All of these tool path optimizations resulted in a drastic reduction in milling time and much cleaner result. The time required for each joint on average was reduced from 10 minutes to 1.5 minutes in the latest tool path generator script. Cutting each member in length after the joints also reduced material use. Figure 8 displays how the joint milling operation from the geometry to the final milling operation.

<table>
<thead>
<tr>
<th>Structure Size</th>
<th>Member Count</th>
<th>VCarve Geometry Preparation time</th>
<th>Custom Compiler Preparation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>6m<em>2.5m</em>3layers</td>
<td>512</td>
<td>42.6hrs</td>
<td>None</td>
</tr>
<tr>
<td>4m<em>2.5m</em>3layers</td>
<td>368</td>
<td>30.6hrs</td>
<td>None</td>
</tr>
<tr>
<td>2.7m<em>2m</em>3layers</td>
<td>184</td>
<td>15.3hrs</td>
<td>None</td>
</tr>
</tbody>
</table>

*Table 2. Time comparison of G-Code generation between VCarve Pro and the custom Compiler*
DEVELOPMENT OF AN AFFORDABLE ON-SITE WOOD CRAFT SYSTEM: INTERACTIVE FABRICATION VIA DIGITAL TOOLS

Figure 8. (1) Dividing the joint geometry to 2-side s, (2) Cutting the edge from outside, (3) Material Removal, (4) Smoothing one needed surface, (5) Cutting the member in length

5. Discussion and Conclusion

Digital Fabrication, as an industry, has great space to for growth and offers so many economic opportunities that can significantly improve lives. The aim of this paper is to develop a system that enables non-professionals to engage in making things with CNC machines as the easier to use and affordable fabrication tool. It tries to remove some of the hurdles of using digital fabrication tools that prevent those who wish to engage in digital craft as a hobby, or DIY solutions.

Time and material costs are two of most immediate constraints that beginners face in this field. The development of the Real-Time Geometry to G-Code compiler was an attempt to solve this issue and enable individuals to design and build structures without having the need to think about the technical aspects of file and geometry preparation. By reducing the design to machine code preparation time to virtually zero, it facilitates the fabrication experience for beginners and enthusiasts quite well. Of course, further research can explore how this Real-Time design/fabrication aspect can be applied to more complex shapes using CNC machines. The developed craft system here generates curved-shaped shelf structures that are fabricable with the aid of affordable CNC machines. Curve-shaped structures have been addressed here since they offer more flexibility for the user. At the same time, they present fabrication challenges quite vividly, making the fabrication experience more engaging for the user. The system is developed in a way that shows the results of the design, along with information about its fabricability. It also incorporates optimization algorithms. For instance, the Redundant Member Removal Algorithm substantially reduces material and time costs before the fabrication starts. While it may not be as effective during fabrication, further research on similar algorithms that incorporate the produced waste material, resulting from the current fabrication, can improve time and cost efficiency even further.

Digital fabrication tools have enabled architects and designers to build incredibly complex structures that answer to questions of structure, design, aesthetics, and so on simultaneously. As mentioned earlier in this paper, the robotic fabrications of Gramazio & Kohler at ETH Zurich and timber structures by the team of Oliver David Krieg and Achim Menges at Stuttgart University (Alvarez et al., 2019; Burry et al.,...
have demonstrated the amazing possibilities of digital fabrication in Architecture and Design. Inspired by the "Decent Work and Economic Growth" and the "Industry, Innovation and Infrastructure" of the UN Sustainable Development Goals, this research tries to develop a system that democratizes digital fabrication and enable less skilled individuals to benefit from this industry as well. While the aforementioned researches have demonstrated the great possibilities of the field, this research tries to develop a craft system that simplifies the transition from design to fabrication not just for experts but also for beginners in the field.

References


