Designing Reconfigurable Joints

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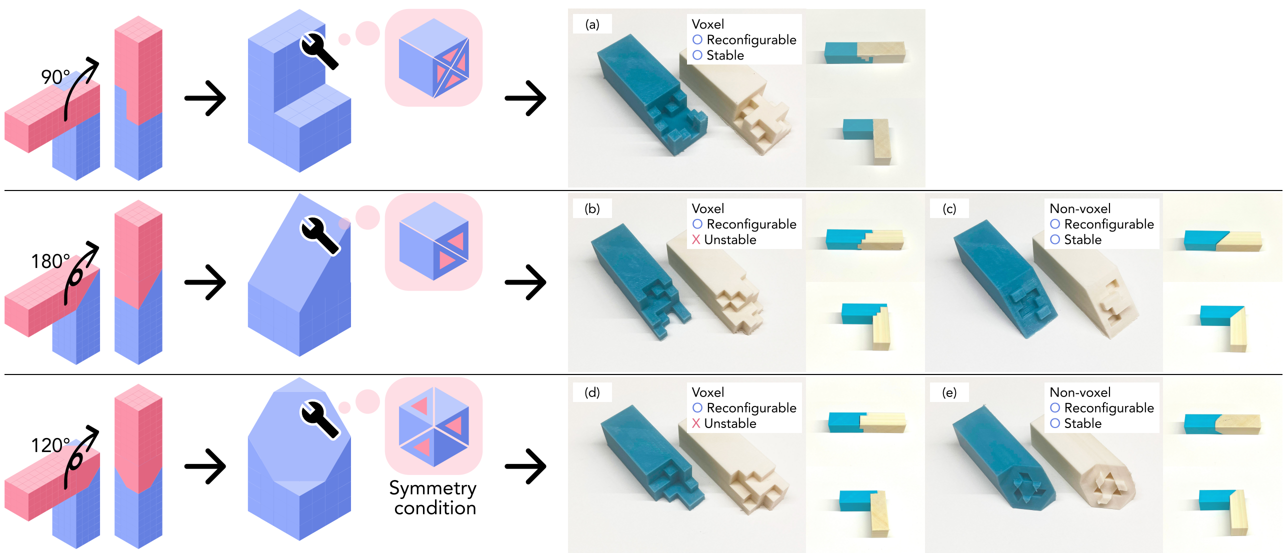

Figure 1: The proposed method creates reconfigurable joints by selecting a re-orientation plane and angle (left) and then constructing a geometry that fulfills symmetrical conditions (middle). Based on this method, we designed and fabricated reconfigurable joints with stable voxel- and non-voxel-based geometries (right).

ABSTRACT

We propose a method to create reconfigurable joints, where reconfigurability entails that a set of components can be connected in multiple ways. The advantage of this type of joint is the possibility of efficiently reusing limited components for multiple purposes. In established carpentry practices, a popular reconfigurable joint geometry called *Kawai Tsugite* has two components that can be reconfigured in different orthogonal angles. However, the general geometric requirements for the design of reconfigurable joints have not been defined previously. We clarify the conditions for reconfigurable joints from the perspective of symmetry-based geometry repetition and provide guidelines for constructing multi-component joints and for ensuring stability. Moreover, we present a system that assists in the design of voxel-based reconfigurable joints and use it to fabricate several stable reconfigurable joints.

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1 INTRODUCTION

Joints represent an established technique to connect components without nails or screws. There are sub-categories of joints with distinctive properties, such as interlocking and reconfigurable, the latter of which entails that the same set of components can be combined in multiple ways, such as in different angles. A well-known example of a reconfigurable joint is the *Kawai-Tsugite* joint (Fig. 2) [Kawai 2019], which consists of two geometrically identical components that can be connected in three different orthogonal directions: an I-configuration (i.e., in a straight line like the letter "I") and two L-configurations (i.e., at a right angle like the letter "L"). However, the geometric condition for reconfigurability has not been formulated before. Although some previous studies examined the reconfigurability of structures, few works have focused on local joint geometries. Song et al. proposed a system for reconfigurable structures such as tables that can be reassembled into chairs [Song et al. 2017]. Liy et al. focused on local joints, examining replaceable rather than reconfigurable components, which do not require all parts to be reused during reassembly [Liu et al. 2015]. In contrast, the present study focuses on the reconfigurability of individual joints. We defined geometric conditions for reconfigurability, and applied those guidelines to create novel reconfigurable joint geometries.

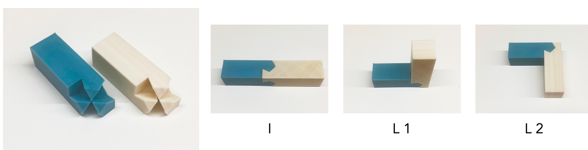

Figure 2: *Kawai-Tsugite* is a popular reconfigurable joint.

Our guidelines for designing a reconfigurable joint comprise of three steps: 1) determine the number of intersecting components and pair of joint shapes to be reconfigured; 2) determine how to change the orientation of a component; 3) construct the geometry with symmetry-based repetition. Based on these guidelines, we made three findings. First, the problem of two-component reconfiguration in orthogonal joints can only be defined between I- and L-configurations. Second, the reconfigurability of a joint with three or more components can be attributed to the problem of two-component reconfigurations. Third, there is a specific coordinate system to consider for guaranteeing stability. Moreover, we demonstrated that the proposed method can be used to effectively through experiments in computer programs and 3D printer fabrication. We designed a program that assists in creating reconfigurable joints in voxel space, enumerating reconfigurable voxel-based joints. We further designed and 3D-printed voxel- and non-voxel based geometries, demonstrating that reconfigurable and stable joints can be created by applying our guidelines.

In summary, our contributions are:

- Design guidelines for creating reconfigurable joints
- A method for ensuring that reconfigurable joints are stable

2 RELATED WORK

Joint Design and Fabrication. Jochen Gross introduced a database joint geometries compatible with 3-axis computer-numerical control (CNC) milling [Gros 2020]. Kanasaki et al. adapted traditional joints for CNC milling fabrication [Kanasaki and Tanaka 2013], whereas other studies proposed design interfaces for joint modeling [Larsson et al. 2020; Magrisso et al. 2018]. Several studies have been conducted on interlocking joints and structures, wherein the parts are fixed into place once the last component is added [Fu et al. 2015; Song et al. 2012; Xin et al. 2011]. Although the aforementioned works consider several properties of joints, including fabricability and interlocking, they do not consider reconfigurability of individual joints.

Reconfigurable Structures. Several previous studies have been conducted on the replacement of components [Kalojanov et al. 2012, 2016; Liu et al. 2015]. Kalojanov et al. [Kalojanov et al. 2012] proposed a system called *Microtiles* based upon the partial symmetries or self-correspondences of substructures. Liu et al. [Liu et al. 2015] tackled this problem from the perspective of matching the subgraph of the assembly. However, these techniques do not require all parts to be reused during reassembly. Other studies focused on the recombination of substructures during assembly [Guan et al. 2022; Jain et al. 2012; Xu et al. 2023]. Moreover, Song et al. [Song et al. 2017] showed the computational design of reconfigurable assemblies. They proposed a method to assist the design of reconfigurable furniture by maximizing the reuse of the components and making compatible joint connections. However, their method focuses on the reconfigurability of entire assemblies, whereas our study focused specifically on joint geometries.

3 METHOD

3.1 Two-component configurations

The first step for creating reconfigurable joints is to determine the number of components and their configurations. For two-component orthogonal joints, there are four combinations: I-, L-, T-, and X-configurations (Fig. 3). The T- and X-configurations involve joints that are positioned in the middle of a component, as opposed to on the edge. Consequently, these components cannot be re-configured into other compositions if both parts are to be reused. We therefore conclude that the reconfigurability of two-component orthogonal joints can be achieved only between I- and L-configurations.

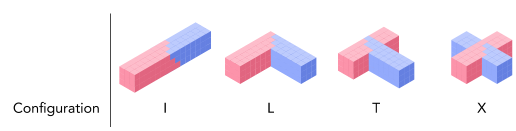

Figure 3: Four configurations of two-component orthogonal joints.

3.2 Multi-component configurations

We extended the above logic of judging the possible reconfigurability of two-component orthogonal joints to joints with three or more components. There are six joint configurations with three-component orthogonal joints and four configurations with four-component orthogonal joints (Fig. 4). For two-component joints, we verified the reusability of components based on the positions where they connect to other components, and found that there are two possible reconfigurations for three-component joints (Fig. 4, 3C-A to/from 3C-B and 3C-C to/from 3C-D). For joints with four components, there is one possible reconfiguration (Fig. 4, 4C-A to/from 4C-B).

When considering the reconfigurability of joints within these patterns, only one component, denoted in green in Fig. 5, changes

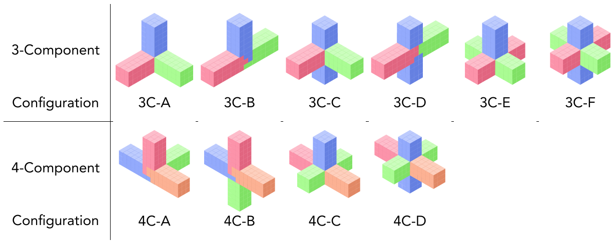

Figure 4: Joint configurations three and four components.

its orientation to a different axis while all other components remain fixed. Therefore, when considering the structure without the other components, the problem of reconfigurability can be reduced to that between the I- and L configurations of two components (Fig. 5). It is therefore relevant to investigate the conditions for reconfigurability between the I- and the L-configurations not only for the two-component case, but also for multi-component reconfigurations.

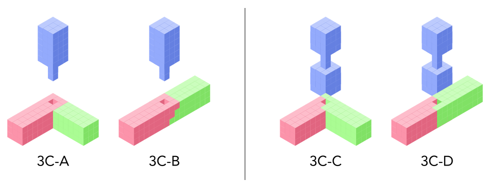

Figure 5: Decomposition of three-component joints to two-component joints.

3.3 Changing the orientations of components

There are three possible rotations that can change a joint from an I- to an L-configuration (Fig. 6b-d). A rectangular box has 24 possible positions: 6 choices for the front face, and 4 orientations for the front face, giving 6 × 4 = 24. The relationship between two parts can also be defined in 24 ways. Each position can be represented by applying one of three types of rotations from the top-left in Fig. 6a. The three rotations can be understood intuitively by using cross-sections. With a square cross-section (Fig. 6b), the shape changes from I to L through a 90-degree rotation, referred to as α-rot. With a rectangular cross-section (Fig. 6c), the shape changes through a 180-degree rotation, referred to as β-rot. With a hexagonal cross-section (Fig. 6d), the shape changes through a 120-degree rotation, referred to as γ-rot. The *Kawai Tsugite* joint belongs to this last type. These cross-sections define the plane and rotation that represent our base units for constructing reconfigurable joints.

3.4 Geometric rotational symmetry

We define the symmetry condition of the joint geometry by considering the geometric correspondence between the states before and after rotation. As an example illustrating this condition, the voxel-based joint in Fig. 7a is reconfigurable by α-rot. In the I-configuration, parts A and B interlock, whereas in the L-configuration, parts A and C interlock. Therefore, parts B and C should both connect to part A. In other words, part B and C should have the same

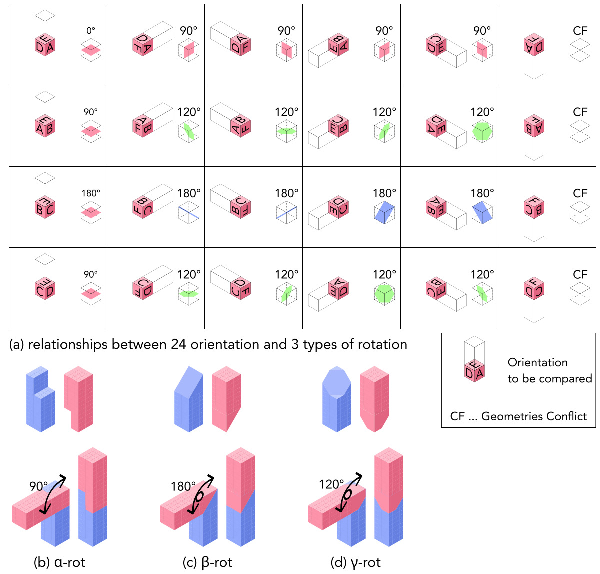

Figure 6: Three possible rotations to change from an I- to an L-configuration. See also supplement material.

geometry but different orientations. For each of the three rotations (refer to Section 3.3), the conditions for reconfigurability are defined by geometric repetitions. In the case of α-rot (Fig. 7b), the geometry is divided into four substructures, each identical in shape and repeated uniformly. For β-rot (Fig. 7c), the geometry splits into two substructures, which are mirrored and replicated. Lastly, for γ-rot (Fig. 7d), the geometry is divided into three substructures. These symmetric substructures ensure that the overall structure maintains its integrity and coherence after reconfiguration.

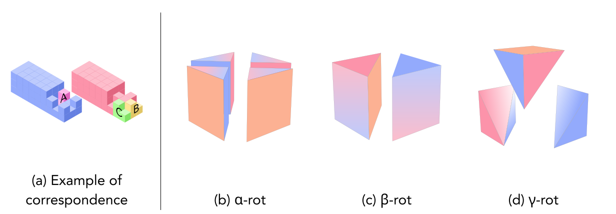

Figure 7: a) Example of correspondence. b-d) Geometric symmetry for each of the three rotations.

3.5 Joint stability

One challenge in designing reconfigurable joints is to ensure that the joints are stable in all configurations. An existing method to guarantee stability of voxel-based joints is to verify that each component slides in only one of six orthogonal directions, considering the positive and negative directions of the X, Y, and Z axes [Larsson et al. 2020]. This method can be used for arbitrary geometries if the axes along which slidability is checked are determined appropriately. Using the cross-sections described in 3.3, the following proposition can be made:

Proposition 3.1. *For I-to-L reconfiguration, if, when one component is fixed, the other component can slide in only one direction ($\vec{d}$) while all other directions are blocked, then $\vec{d}$ is equal to the normal direction ($\vec{n}$) of the cross-section plane of the base unit.*

Two conditions prove this proposition: 1) the symmetry described in Section 3.4, and 2) any direction $\vec{d'}$ other than $\vec{n}$ will change orientation in the global coordinate system forming the I- or L-configuration even if $\vec{d'}$ is not changed in the local coordinate system of the moving component. Therefore, joint stability can be evaluated in terms of the slidability of components by defining a coordinate system where $\vec{n}$ corresponds to the z-axis of the orthogonal coordinate system and considering geometry such that extrusion occurs in the positive or negative direction with respect to the z-axis.

4 EXPERIMENTS

First, we implemented a system that assists in the design of reconfigurable joints in voxel space, demonstrating the effectiveness of the proposed guidelines (Section 4.1). Subsequently, we designed and fabricated reconfigurable joints via 3D printing (Section 4.2).

4.1 Generation of reconfigurable joints

Based on our guidelines, we implemented a program that converts non-reconfigurable voxel-based joints into reconfigurable joints. The input is a set of components, a desired reconfiguration, and an initial joint geometry that might be reconfigurable. The output is a reconfigurable joint geometry that preserves the input geometry as much as possible, i.e., the total number of added and removed voxels is minimized. We tested the program by inputting all joint patterns with a voxel resolution of $3\times3\times3$, and found that, without considering stability, more reconfigurable joints satisfied the β-rot condition than the other conditions. Specifically, we found 1,004 unique reconfigurable β-rot joints, and 56 each for α-rot and γ-rot joints.

4.2 Fabrication

We fabricated reconfigurable joints using AnkerMake M5 fused deposition modeling (FDM) 3D printer and polylactic acid (PLA) material. First, we fabricated examples of reconfigurable joints in voxel geometry for all three rotation conditions (Fig. 1a, b, and d). These joints were designed based only on conditions relating to symmetry (refer to Section 3.4). In both the I- and the L-configurations, the structures of the two components were matched, but only the joints based on α-rot (Fig. 1a) were stable. Next, we manually designed and fabricated non-voxel joint geometries following our guidelines (Fig. 1c and e). These joints were designed to ensure both reconfigurability and stability (refer to Section 3.5), and all pairs of components were stable in both configurations.

5 CONCLUSION

In this paper, we proposed a method to design reconfigurable joints and found that rotational symmetry is essential for reconfigurability. We also proposed a way to guarantee the stability of reconfigurable joints. The fabricated results show that the proposed method is instrumental in the design of reconfigurable joints. However, a current limitation of our system is the lack of support for automatic design in non-voxel space. Moreover, the angle at which components intersect is limited to the orthogonal directions. As a future direction of research, we aim to explore reconfigurable joints with three or more components, as well as the expressive potential of these joint structures and their applications in furniture and building construction.

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REFERENCES

Chi-Wing Fu, Peng Song, Xiaoqi Yan, Lee Wei Yang, Pradeep Kumar Jayaraman, and Daniel Cohen-Or. 2015. Computational Interlocking Furniture Assembly. *ACM Trans. Graph.* 34, 4, Article 91 (jul 2015), 11 pages. https://doi.org/10.1145/2766892

Jochen Gros. 2020. 50 Digital Wood Joints by Jochen Gros. http://winterdienst.info/50-digital-wood-joints-by-jochen-gros/.

Yanran Guan, Han Liu, Kun Liu, Kangxue Yin, Ruizhen Hu, Oliver van Kaick, Yan Zhang, Ersin Yumer, Nathan Carr, Radomir Mech, and Hao Zhang. 2022. FAME: 3D Shape Generation via Functionality-Aware Model Evolution. *IEEE Transactions on Visualization and Computer Graphics* 28, 4 (2022), 1758–1772. https://doi.org/10.1109/TVCG.2020.3029759

Arjun Jain, Thorsten Thormählen, Tobias Ritschel, and Hans-Peter Seidel. 2012. Exploring Shape Variations by 3D-Model Decomposition and Part-based Recombination. *Comp. Graph. Forum (Proc. Eurographics 2012)* 31, 2 (2012).

Javor Kalojanov, Martin Bokeloh, Michael Wand, Leonidas Guibas, Hans-Peter Seidel, and Philipp Slusallek. 2012. Microtiles: Extracting Building Blocks from Correspondences. *Computer Graphics Forum* 31, 5 (2012), 1597–1606. https://doi.org/10.1111/j.1467-8659.2012.03165.x

Javor Kalojanov, Michael Wand, and Philipp Slusallek. 2016. Building Construction Sets by Tiling Grammar Simplification. *Computer Graphics Forum* 35, 2 (2016), 13–25. https://doi.org/10.1111/cgf.12807

Kazuharu Kanasaki and Hiroya Tanaka. 2013. Traditional Wood Joint System in Digital Fabrication. *eCAADe proceedings* (2013). https://api.semanticscholar.org/CorpusID:107831918

Naoto Kawai. 2019. Kenchiku No Kenkyu (Volume 248) 2019/04. https://ndlsearch.ndl.go.jp/books/R100000002-I000000065683-i9082620.

Maria Larsson, Hironori Yoshida, Nobuyuki Umetani, and Takeo Igarashi. 2020. Tsugite: Interactive Design and Fabrication of Wood Joints. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST '20)*. Association for Computing Machinery, 317–327. https://doi.org/10.1145/3379337.3415899

Han Liu, Ulysse Vimont, Michael Wand, Marie-Paule Cani, Stefanie Hahmann, Damien Rohmer, and Niloy J. Mitra. 2015. Replaceable Substructures for Efficient Part-Based Modeling. *Computer Graphics Forum* 34, 2 (2015), 503–513. https://doi.org/10.1111/cgf.12579

Shiran Magrisso, Moran Mizrahi, and Amit Zoran. 2018. Digital Joinery For Hybrid Carpentry. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, 1–11. https://doi.org/10.1145/3173574.3173741

Peng Song, Chi-Wing Fu, and Daniel Cohen-Or. 2012. Recursive Interlocking Puzzles. *ACM Trans. Graph.* 31, 6, Article 128 (nov 2012), 10 pages. https://doi.org/10.1145/2366145.2366147

Peng Song, Chi-Wing Fu, Yueming Jin, Hongfei Xu, Ligang Liu, Pheng-Ann Heng, and Daniel Cohen-Or. 2017. Reconfigurable Interlocking Furniture. *ACM Trans. Graph.* 36, 6, Article 174 (nov 2017), 14 pages. https://doi.org/10.1145/3130800.3130803

Shiqing Xin, Chi-Fu Lai, Chi-Wing Fu, Tien-Tsin Wong, Ying He, and Daniel Cohen-Or. 2011. Making Burr Puzzles from 3D Models. *ACM Trans. Graph.* 30, 4, Article 97 (jul 2011), 8 pages. https://doi.org/10.1145/2010324.1964992

Xianghao Xu, Paul Guerrero, Matthew Fisher, Siddhartha Chaudhuri, and Daniel Ritchie. 2023. Unsupervised 3D Shape Reconstruction by Part Retrieval and Assembly. In *2023 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*. 8559–8567. https://doi.org/10.1109/CVPR52729.2023.00827