Tsugite: Interactive Design and Fabrication of Wood Joints

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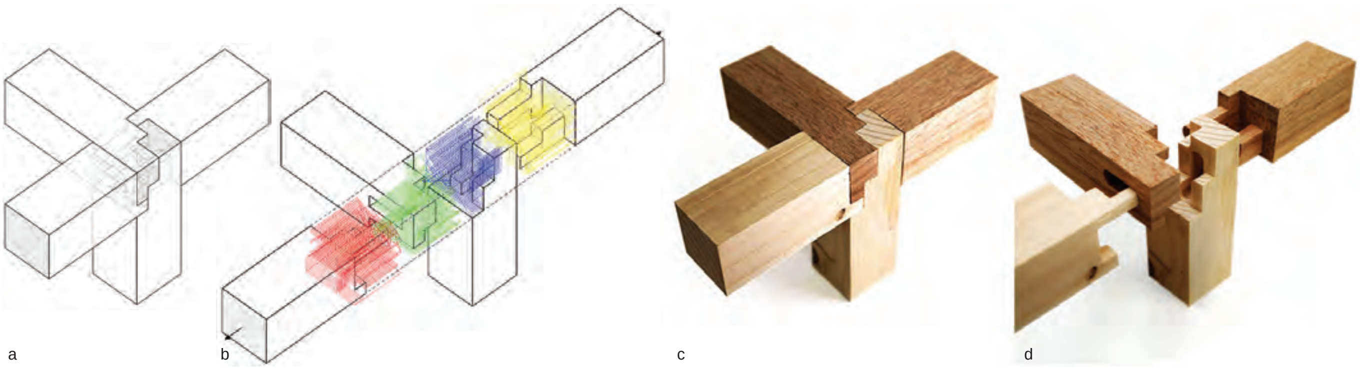

Figure 1. Connecting four timbers designed and CNC-fabricated using the Tsugite system. a) Interface screenshot of closed joint. b) Interface screenshot of open joint with a preview of milling paths. c) Fabricated joint closed. d) Fabricated joint open.

ABSTRACT

We present Tsugite—an interactive system for designing and fabricating wood joints for frame structures. To design and manually craft such joints is difficult and time consuming. Our system facilitates the creation of custom joints by a modeling interface combined with computer numerical control (CNC) fabrication. The design space is a 3D grid of voxels that enables efficient geometrical analysis and combinatorial search. The interface has two modes: manual editing and gallery. In the manual editing mode, the user edits a joint while receiving real-time graphical feedback and suggestions provided based on performance metrics including slidability, fabricability, and durability with regard to the direction of fiber. In the gallery mode, the user views and selects feasible joints that have been pre-calculated. When a joint design is finalized, it can be manufactured with a 3-axis CNC milling machine using a specialized path planning algorithm that ensures joint assemblability by corner rounding. This system was evaluated via a user study and by designing and fabricating joint samples and functional furniture.

Author Keywords

human–computer interaction; joinery; path planning; subtractive manufacturing; computer numerical control; computer-aided design; computer-aided manufacturing

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CCS Concepts

•Applied computing → Computer-aided design; Computer-aided manufacturing; •Computing methodologies → Shape modeling;

INTRODUCTION

Traditional nail-free joinery connecting timber is a traditional craft. The technique is applied in architecture and for making furniture. Wooden joinery is appreciated because of its aesthetic appearance, high quality, and assemblability. There is a large variety of traditional joint geometries including dove tail, cross-lap, and scarf joints. These joint shapes tend to balance aesthetic and functional requirements. Designing and analyzing such joints is challenging because of the geometric complexity and criteria that need to be considered simultaneously. Further, crafting joints with hand tools is a slow and demanding process. Therefore, in this paper, we present an interactive system for creating wood joinery. The system analyzes a number of practical joint properties, and the joints are digitally fabricated by CNC-milling. We call the system Tsugite, from the Japanese word for joinery. The design space is a regularly spaced 3D grid, where each voxel belongs to a unique timber. This setup is suited for efficient computation, which enables real-time feedback, suggestions, and a combinatorial search.

The interface has two modes: manual editing and gallery. In the manual editing mode, the user directly manipulates the joint by pushing and pulling faces. When a block is added, the corresponding block on the mating timber is automatically subtracted, thereby ensuring that there are no overlapping or empty voxels. Further, the user receives real-time suggestions and graphical feedback about joint performance while modeling. The manual editing mode is appropriate for joint types that have many solutions, and high-resolution joints for which a combinatorial search is not feasible because of the exponentially high number of possibilities. In addition, it is suitable for accommodating aesthetic criteria and other user-specified requirements. In the gallery mode, the user can browse and select among valid joints. This mode is convenient for difficult joints with few solutions and for nonexpert users.

The performance of a joint is evaluated based on eight metrics. Some of these metrics check for geometrically isolated parts and blocked sliding directions. These metrics are similar to those in previous works [2, 13, 14, 18]. We introduce new metrics to evaluate fabricability, durability, and friction and contact area. For fabricability, we analyze two properties: first, we test whether the geometry can be fabricated from a single direction, and second, we check for so-called "checkerboard patterns", which are problematic for fabrication and assembly. For durability, we observe that the strength of wood is 10–20 times higher in the fiber direction compared to its strength perpendicular to the fibers [12]. Therefore, protruding parts in nonfiber direction tend to break off. Tsugite analyzes the location of such parts to guide users to create durable joints.

Finally, when a joint design is finished, the system generates the tool path for 3-axis CNC fabrication. Our tool path algorithm identifies the location of the excess material in the inner corners where the cylindrical milling bit cannot reach, and rounds the corresponding outer corners of other timbers. The Tsugite system can be used for building wooden frame structures. This system enables anyone with limited expertise in joinery and with access to basic digital fabrication tools to create assemblies with sophisticated wooden joints. We ran a user study with an earlier version of the system and the result shows that the visual feedback reduces errors in the designs. The system presented in this paper is a refined version based on what we learned from the study. Finally, we show a number of joint samples and furniture designed using our system.

RELATED WORK

Interactive design of joints

Yao et al. propose a tool for designing free-form decorative joints [21]. The tool supports the design of ornamental joints with a high degree of geometrical freedom. However, it does not provide suggestions or feedback in real time. Further, the tool does not consider the fabrication constraints of a CNC machine. Most fabricated results are 3D-printed prototypes. They present a chair made from wood on a 1:1 scale, but it was reportedly handcrafted by a professional woodworker [21], which is time-consuming and costly.

Shape optimization of joints

Several recent works perform topological optimization of joints and 3D puzzles for interlocking and reconfigurable properties [2, 13, 14, 18]. Similar to our study, these works create joints within the design space of a 3D-grid of voxels. However, there is no user interface, and they do not consider practical constraints such as CNC fabricatability and durability with regard to the wood grain direction. The materialized results are mostly 3D-printed scale models or built with LEGO. Graphic results are occasionally rendered in wood, indicating a desire to materialize the designs in wood. Wang et al. built a 1:1 scale chair by gluing wooden cubes together at the end of a wooden bar [18]. They demonstrated that their algorithm for the interlocking property works, but the apparent weakness of the joints does not result in usable furniture.

Interactive design of assemblies

Many other works propose computational systems for designing and fabricating assemblable structures. Some systems mill out joints from wood with a CNC machine [7, 15, 22], while others create bespoke joints using a laser cutter or a 3D printer [1, 4, 6, 10]. Further, some other authors propose methods for creating fabrication plans that can be executed using standard woodworking tools or standard tools in combination with digital fabrication machines [8, 19]. Another related work analyzes the physical validity of furniture and provides user suggestions while modelling [16]. To the extent that these works facilitate the creation of joints, the shapes are typically based on one or multiple standard joint shapes that parametrically adapt to various geometric conditions. For example, the joints adjust to various angles of the intersections and dimensions of the connecting pieces. The user can manipulate the global structure, but they cannot directly control the joint geometries in a meaningful way. Unlike these systems, we focus on designing the joint itself, rather than the global structure.

Digital fabrication of joints

Some works focus on joint geometries specifically adapted for CNC fabrication. Gros designed joint geometries appropriate for a 3-axis CNC machine and uploaded an online library with "50 Digital Wood Joints" for free use [3]. Kanasaki and Yang have similar ambitions to translate traditional Japanese joints into digitally fabricable shapes [5, 20]. However, their results are limited to only one or two joint geometries between no more than two orthogonally intersecting timbers. Note that these joints are designed so that there are no sharp inner corners to avoid the problem that the CNC machine cannot cut such shapes. Moreover, tool path planning for CNC milling has been studied since the 1970s. A tool path optimization problem is generally formulated as maximizing the volume of the removed material without cutting into the intended shape [11]. In our setup, it is necessary to cut into "the intended shape," i.e., to trim off sharp outer corners so that the mating timbers fit together. To the best of our knowledge, the problem of path planning for joinery with unreachable areas has not been considered previously.

Anisotropic materials

There are previous works that leverage the orientation of objects of anisotropic materials, i.e., materials with different properties in different directions. Li and Barbič propose a model for simulating the behavior of anisotropic materials such as wood, plants, and muscles [9]. Umetani and Schmidt [17] observe that for 3D printing with filaments, the layer-to-layer material bond in the z-direction is weaker than the continuous material bound in the xy-plane, and use this to optimize the object orientation accordingly. Unlike a 3D-printed object that has two strong and one weak axis, wood has only one strong axis, i.e., the direction of the fibers.

USER INTERFACE

The proposed system is implemented as a tool for designing a single wood joint for connecting timbers with rectangular sections. Figure 2 shows an overview of the workflow. The user specifies joint type variables including sliding axis, angle of intersection, and number of timbers (Figure 2a). This information comes from the overall design of the structure or furniture, which is beyond the scope of this work. In the manual editing mode, the user manipulates a geometry while receiving graphical feedback and suggestions (Figure 2b). In the gallery mode, the user can look through valid geometries and select one among them (Figure 2c). Finally, the Tsugite system considers the milling bit radius as an input, and exports the tool path to a CNC milling machine (Figure 2d).

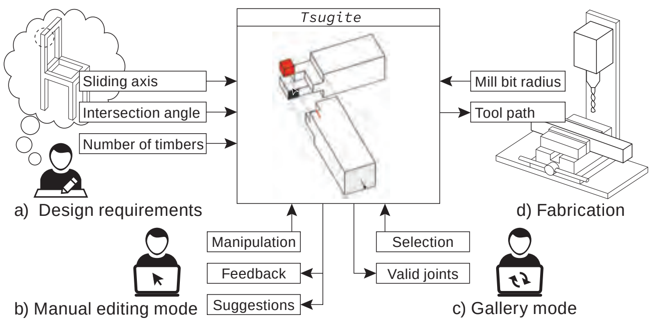

Figure 2. System overview.

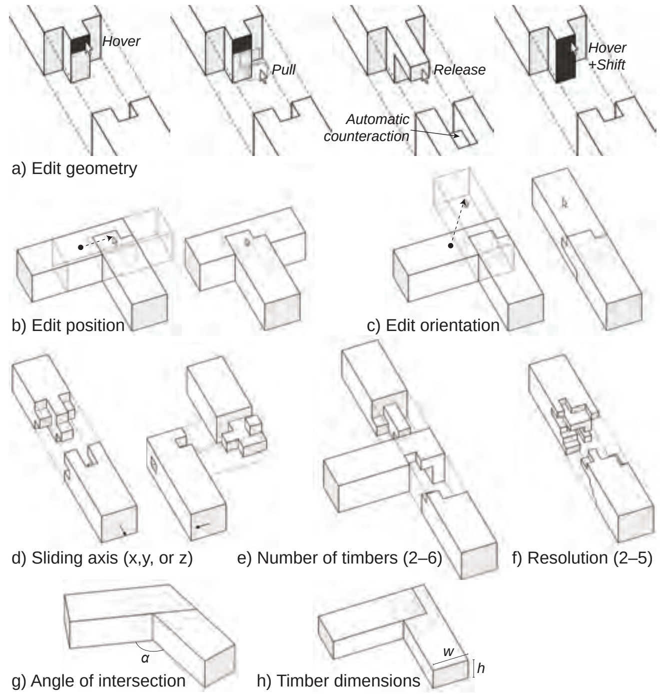

Figure 3. Mouse operations (a–c) and keyboard options (d–h).

Basic Operations

The user edits a joint by pushing and pulling on the faces in the sliding direction (Figure 3a). The user can further change the position and orientation of a timber by clicking and dragging its main body (Figure 3b and 3c). The user chooses an orthogonal sliding axis by pressing the x, y, or z key (Figure 3d). The system supports designs where all timbers slide along a single sliding axis, as in a stack. The number of intersecting timbers can theoretically be increased to six, thereby covering all sides of the cubic intersection (Figure 3e). However, the system is most suited for joints connecting four or fewer timbers because there are few or no solutions for 5–6 timber joints. The default voxel resolution ($3 \times 3 \times 3$) can be changed to one between 2 and 5 (Figure 3f). Finally, the user can set a nonorthogonal angle of intersection (Figure 3g), and the height and width of the cross-section of the timbers (Figure 3h).

Feedback

Tsugite provides visual feedback to the user based on the following eight performance metrics (Figure 4).

a) *Connectivity.* Voxels disconnected from the main body of the timber are shown in red.

b) *Bridging.* If a joint is located along the timber, there are cases where the joint geometry fails to bridge the two sides. If unbridged, separated sides are shown in two contrasting colors.

c) *Milling direction.* If there is no direction from which the joint geometry can be milled out, the body of the timber is shown in orange. This failure mode occurs only for "sandwiched" timbers when there are three or more timbers in a joint.

d) *Checkerboard.* A prohibited checkerboard pattern is marked by a thick red vertical line in the center (see Implementation section for details about why this pattern is prohibited).

e) *Slidability.* Arrows at the end of each timber indicate all slidable directions of the current design. It is usually preferable for each timber to slide along the main sliding axis only. In the presence of undesired sliding directions, the outlines of that timber become red.

f) *Durability.* Nondurable voxels are shown in yellow. These voxels stick out perpendicular to the grain orientation, and therefore they tend to break off easily. Such parts are avoided in traditional joint geometries as well. A group of nondurable voxels is more fragile the further it sticks out and the smaller area of attachment it has. Our metric for durability is designed to provide lightweight feedback quickly; it is not a faithful evaluation of the structural strength of a joint such as that seen in finite element analysis (FEA).

g) *Contact area.* Contact area is the area where materials of different timbers touch each other. Such faces can be optionally previewed with a dotted texture. A larger contact area is preferred for joint intended to be glued.

h) *Friction area.* The friction area is the area that is under friction when the joint slides in and out. Such faces can optionally be previewed with a triangle texture. For joints intended to be held together by friction, a larger friction area is preferred. Note that we measure the *area* of the friction and not the *force*. Analyzing the friction force would require physical testing and careful fine-tuning of parameters which is beyond the scoop of this work.

Metrics *a*-*f* are binary and *g*-*h* are numerical. A joint is valid if it meets the binary criteria. Valid joints can then be ranked according to the numerical criteria.

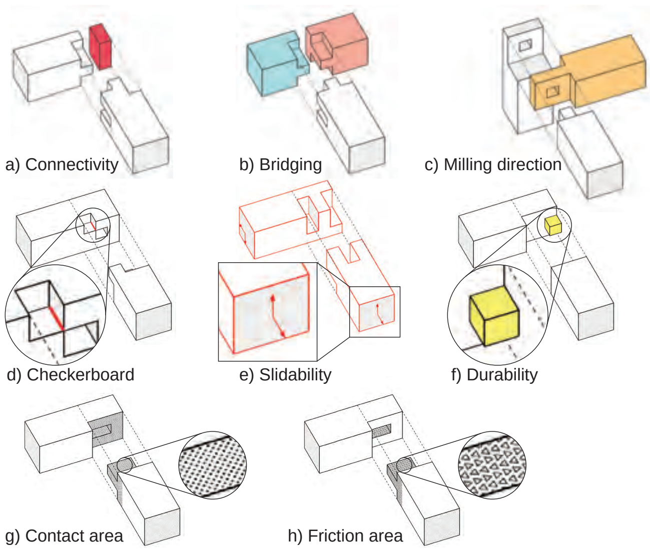

Figure 4. Graphical feedback.

Suggestions

If the current joint design is invalid, i.e., it fails to meet criteria *a*-*f* as formulated in the previous section, the system shows suggestions on the right side (Figure 5a). The suggestions consists of up to four valid joints within one edit distance from the current design, as ranked by a user-specified numerical criterion (friction or contact area). When the user hovers over a suggestion, the difference between the current design and suggestion is displayed on top of the current design. An added or subtracted voxel is shown with dashed outline and white or red filling, respectively. A suggestion is adopted by clicking on it.

Gallery

Sometimes, it is difficult for the user to find a valid joint by manual editing, whether it is because of a lack of experience or that the particular joint type has very few possible solutions. Therefore, the system offers the gallery mode. In this mode, the user can browse among pre-calculated valid geometries, viewing up to 20 geometries at once, and select a desired one (Figure 5b). Similar to the suggestions, the valid joints are optionally ranked according to friction or contact area. The gallery mode is provided for joints with a resolution up to $3 \times 3 \times 3$. For higher resolutions, there are too many combinations to run through all possibilities.

Fabrication

After finalizing a design, the user can preview the milling path (Figure 6) and export it to a CNC machine. To fabricate a joint, the user fixes the material in the bed of the CNC machine, sets the machine origin, and runs the machine.

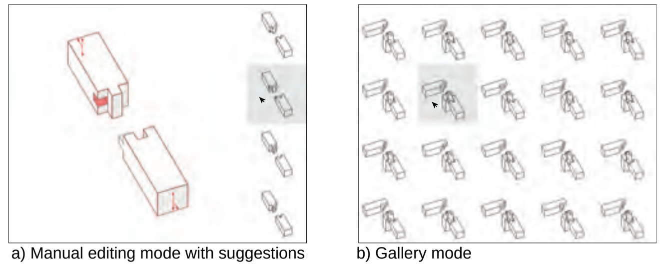

Figure 5. Interface modes.

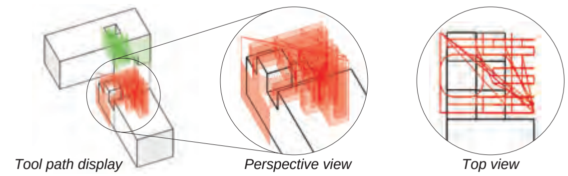

Figure 6. Milling path display.

IMPLEMENTATION

The system defines and enforces geometric constraints for fabrication using a 3-axis CNC machine. We present an efficient data structure and a number of functions for analyzing the geometric performance. Further, we propose a path planning algorithm that ensures joint assemblability by corner rounding. The system was implemented in Python with OpenGL and GLFW as main dependencies.

Fabricability

The geometric criteria for joinery vary based on the fabrication method. We limit ourselves to fabricating joints with a 3-axis CNC machine equipped with a standard milling bit because of its affordability and popularity. This machine setup poses two major constraints. First, it is not possible to cut sharp inner corners parallel to the milling bit (Figure 7a). Such corners have a round fillet with the radius of the milling bit. Second, the machine can approach the material only from above. This means that the machine cannot fabricate a geometry that needs to be cut out where the access from above is blocked (Figure 7b).

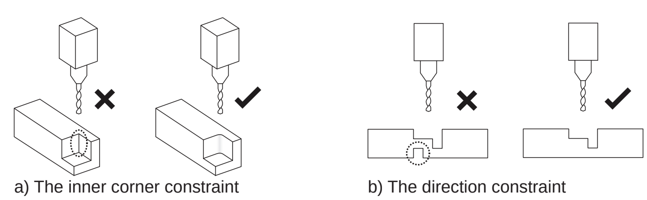

Figure 7. Fabricability constraints for 3-axis CNC milling.

The inner corner constraint (Figure 7a) has two implications for the system. The first problem appears if we attempt to fabricate a voxelized geometry with a conventional path planning tool that considers each timber of the joint individually. In this case, it will not be possible to assemble the pieces because the surplus material of the inner corners of one timber will collide with the corresponding sharp outer corners of another timber (Figure 8a). There are two common solutions to this problem: removing more material from the inner corners (Figure 8b) or rounding the outer corners (Figure 8c). Both these strategies are observed in existing digital joints. We chose the second solution (rounding of outer corners) because it does not have any air pockets, which looks nicer and provides more friction area and strength. Automating corner rounding is the key function of our specialized path planning algorithm (see the section Path Planning for details).

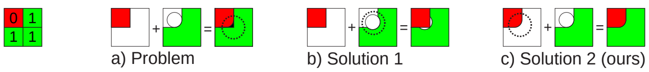

Figure 8. a) Problem of conventional path planning: the joint is unassemblable. b-c) Possible solutions.

The second consequence of the inner corner constraint (Figure 7a) is nonobvious; it makes checkerboard patterns problematic. The reason should become clear by reviewing the alternative rules in Figure 9. If we allow checkerboard patterns without additional rules, the timbers will be impossible to assemble (Figure 9a). An alternative rule would be to round the corners of one timber like outer corners (Figure 9b). However, the gap (d) between the two protruding parts of the second timber will be narrower than the diameter of the milling bit. Therefore, it cannot be fabricated. A third possibility would be to increase this gap until the milling bit can pass through (Figure 9c). In this case, the geometry can be fabricated and assembled. However, it is still not a satisfactory solution because it adds complexity to the system (the user would need to decide which timber to apply which rule to). Moreover, it removes a considerable amount of material on one side compared to the other, which in the case of neighboring checkerboards can result in narrow parts where the milling bit might not reach (Figure 9d). Therefore, we chose to prohibit the checkerboard pattern altogether.

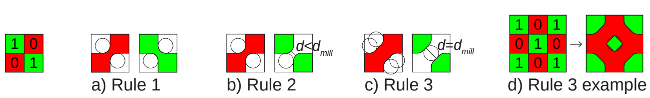

Figure 9. Alternative unsatisfactory rules for checkerboard patterns.

The direction constraint (Figure 7b) introduces the limitation that each timber is milled from a single fabrication direction. This means that fabricable geometries are limited to those that can be expressed as a height field. This observation is the basis for the data structure (refer to the next section).

Furthermore, a joint fabricated using a single fabrication direction is always slidable in that direction (Figure 10a). To simplify the problem by leveraging this property, we impose the limitation that there is only one sliding axis for all timbers of a joint (like in a stack), and that the fabrication and sliding axes are shared. In this situation, it is possible to find fabricable geometries where only two pieces (the first and last) slide out in the assembled state (Figure 10b). The definition of the interlocking property is that only *one* piece should be movable in the assembled state. Therefore, a valid joint in the Tsugite system is never interlocking by itself (it has *two* movable pieces). However, it is possible to arrange the joints in a global assembly with interlocking property, as demonstrated by the interlocking stool in the Results section (refer to Figure 23).

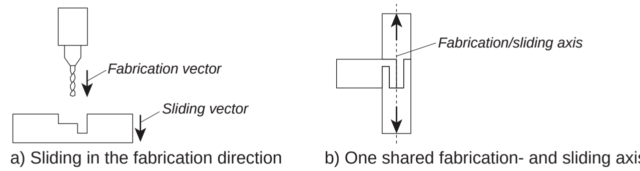

Figure 10. Fabrication direction implications.

Data Structure

Internally, a joint is represented by a 3D matrix of integers, where each integer indicates a unique timber ID. As discussed in the previous section, the design space is limited to geometries that can be expressed as a height field. By initializing the geometry as a 2D height field, the number of possibilities is greatly reduced, compared to the entire design space of a 3D cube of voxels. In the case of a $3 \times 3 \times 3$ resolution joint between two timbers, the number of possible designs are reduced from about 134 million to about 260 000 (Figure 11). For joints with a higher resolution or more intersecting timbers, the number of possibilities increase exponentially.

Figure 11. For a two-timber joint in $3 \times 3 \times 3$ resolution, the number of possibilities for a voxelized cube (left) compared to the height field representation (right).

The first height field is given as a 2D matrix of integers ranging from zero to the maximum height given the resolution. This height field describes the distribution of voxels between two timbers. When there are more than two timbers, additional height fields are added to describe the distribution between each sequential pair. Oblique and nonsquare joints have the same data structure; these variables are accommodated by the deformation of the 3D-grid (Figure 12). Finally, it is necessary to consider which of the six sides of the joint are connected to the main body of the timber. We refer to these as "fixed sides." In our implementation, each timber has either one or two fixed sides. One fixed side indicates that the joint is located at the end of a timber, which is the case for the timbers of an L-joint. Two fixed sides means that the joint is located somewhere in the middle of the timber, as for the timbers of an X-joint.

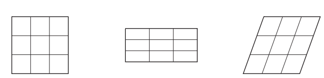

Figure 12. Grid distortion principle to accommodate nonsquare timbers and nonorthogonal angles of intersection.

Joint Performance Analysis

The eight feedback metrics are calculated as follows.

a) *Connectivity.* We run a flood fill algorithm starting from all fixed sides of a timber, and determine whether it covers all voxels belonging to the timber. Covered voxels are connected; and uncovered voxels are unconnected.

b) *Bridging.* Bridging is evaluated for timbers with two fixed sides. We run a flood fill algorithm starting from one fixed