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Technical Section

Planar structures with automatically generated bevel joints☆

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ABSTRACT

A generative method based on computer algorithms is proposed to automatically produce parts of planar structures ready for fabrication. The parts resemble surface patches of the digital model of a structure. Each part is generated with bevel joints on the edges so that part-to-part connection is enabled by friction of the joints. The shape of a bevel joint is determined by the interior angle between two parts, and is modelled by a number of parameters, including the thickness of a planar material in use. The bevel joints consist of slanted planes, and in principle when they are assembled, no gap exists on the surface of the physical structure. Due to the slanted planes, the joints cannot be fabricated by a laser cutter that can only produce vertical cuts. We experimented the fabrication with a three-axis CNC router and a 3D printer; both produced accurate and robust parts; however, there is limitation in using a CNC cutter, which is discussed in details.

1. Introduction

Creative design is inevitably influenced by the capability of production. Many years of research has led designers to recognize that physical artefacts, either in the form of low-fidelity prototypes or high-quality products, give valuable feedback on a conceptual idea and are critical to the success of an iterative design process [1]. Methods of rapid physical production are therefore valuable to designers of various industries. Automobile, marine and air plane designers make mockups to study the aesthetics, dynamics, and mechanics of their products [2–4]. Architects make scaled models to understand the interaction between a building and an environment [5]. From a designer's point of view, physical prototypes are best to be created with low cost, in a short time, while having good fidelity and strength because they are supposed to be used for just-in-time evaluation [6]. The two-sided expectation on prototypes has motivated research in rapid prototyping across multi-disciplines. 3D printing as a highly automated rapid prototyping method has been widely used [7]. A printed artefact obtains a solid surface that closely resembles the original digital model. However, 3D printing has limitations, such as low speed and limited build volume. In areas where these limitations are unacceptable, other methods are applied instead.

For large-scale prototyping [8], i.e. practically any dimension that is beyond one meter, planar structures are one of the most adopted approaches [9]. They have long been used in architecture, construction, and ship building. A typical work process starts from a digital 3D model; create a representation of the model by 2D planes in Computer-Aided Design (CAD) software; materialize the planes by assigning a thickness; generate slots and joints for connecting the planar parts; fabricate and assemble the parts to produce a physical artefact. Although the process involves a lot of manual work such as drafting in CAD software, it offers a designer great flexibility in materialize his design. Designers also see opportunities to automate part of the process and come up with creative solutions. Sass [10,11] proposed a shape grammar to streamline the generation of interlocking planar parts to produce house models. He used computer-numerically controlled (CNC) machines to fabricate the parts. This work demonstrated preliminary idea on automation of planar structures, while a shape grammar is not a computer program but rule sets to guide manual drafting.

Researchers in computer graphics started to look into direct physical production in 2006 [12], where direct means that the parts of a physical artefact are directly generated from a digital model with little human intervention in modeling (drafting). This approach also relies on CNC machining but its impact is substantial: Computer algorithms can independently extract relevant shape information to produce the drawings of parts, which are later fabricated using CNC machines. As a result, human error is largely eliminated from modeling and fabrication. Since then, new ideas in automating the production of planar structures have been

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flourished. They address various questions such as improving slots and joints for complex models [13], differentiating importance of planar parts [14,15], chair-design system [16], parametric design system [17], unequally spaced slots [18], non-perpendicular parts [19], and bendable parts [20].

2. Related work

This paper is concerned with a type of planar structures that is a watertight representation of a digital model. Methods aforementioned produce openly sliced models that are not suitable for certain applications; for instance, be used as mold for casting. Watertight planar structures are physical models as a complete volume, as opposed to sets of overlapping slices. There is sparse exploration of this method of model production. Chen et al. [21] developed a multiplanar modeler that subdivided a digital model into several planar surfaces. Interior connectors were used to join the planar parts. Due to the connectors, fabrication of a model requires two separate processes, one for the planar parts and the other for the connectors. Song et al. [22] described a coarse-to-fine prototyping system, where the interior of a model is made of low-fidelity planar structures and the exterior is made of high-fidelity 3D printed parts. The complete model is an assembly of 3D printed parts onto the planar structures.

While the above ideas from the computer graphics field have accomplished watertight representation of a model, explorations in architecture have found real-world applications of these structures. Robeller et al. [23] created interlocking planar structures with dovetail joints. The structures were strong and could be used as pavilion in an architecture scale. Dovetail joints are widely used in conventional woodwork, the intellectual contribution of [23] lies in a computational method to calculate the angle of a dovetail joint from the geometry of adjacent planar parts. The authors also applied robotic machining to fabricate the parts using bevel cutting to accurately produce the joints along the edges. This process greatly simplifies the production of self-interlocking planar structures, in which no additional connectors are needed; all parts are held together by an interlocking mechanism and friction.

Howe [24] applied watertight structures made of finger joints on concrete casting. He showed feasibility of casting large-scale concrete structures that have curves, and demonstrated that formwork (mold) production can be a potential industry application of watertight structures. This work was focused on architecture design but technical details on how finger joints were created were not described. It is clear that to rapidly generate formwork of a customized shape, it is important to have a fully automatic algorithm. Only then, variations in design can be quickly prototyped and evaluated. The algorithm must generate a watertight structure that has an interior volume equal to a digital model, which makes methods that focus on exterior representation unsuitable [21,22] because the interior of an object made by these methods is either occupied by connectors or by supporting structures.

Chen and Sass [25] developed an intelligent modeling system that is able to process a 2-manifold triangle mesh model and generate a corresponding watertight structure made of finger joints. They described the work flow of finger joint generation and showed that the principle is applicable not only to edge-to-edge finger joints but also to a vertex shared by several faces. If an input model has all planar faces perpendicular to each other, the generated physical model will not have gaps on the exterior and interior surfaces. Through many experiments, they demonstrated the work steps of the system and produced a solid spiral staircase by casting it from plywood mold. The original digital model of the spiral staircase did not have all faces perpendicular to each other; hence, the interior volume has gaps between parts, which subject the cast model to undesired surface artefacts.

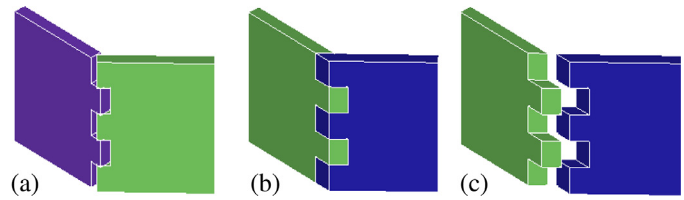

Fig. 1. (a) Finger joints of a watertight structured achieved in [25]. (b) Bevel joints of a planar structure. (c) An exploded view of the bevel joints in (b).

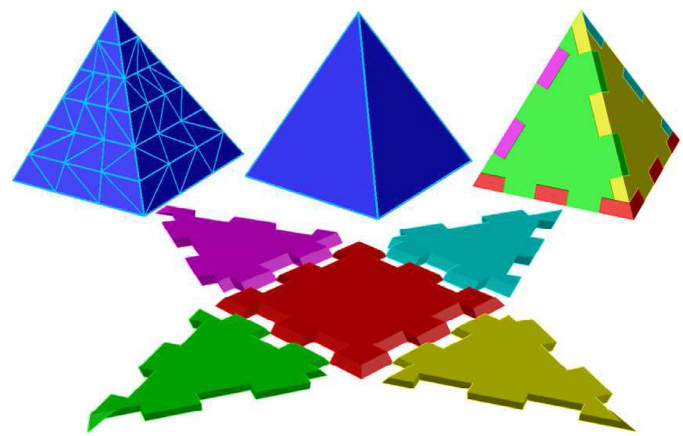

Fig. 2. Overview of the production system for planar structures bevel joints.

We have made an interesting observation based on the work in [25]: Adding one more constraint to a watertight structure, we would get a planar structure without surface gaps. Fig. 1 shows the difference in finger joints between the former achieved in [25] and a type of the latter. Clearly, the latter is more elegant and structurally robust. Note that the dovetail joints in [23] are different from those in Fig. 1(b), which hold an object by friction, just like those in Fig. 1(a). Dovetail joints require much more complicated fabrication, assembly, and disassembly processes because they rely more on intricate shape for interlocking than friction between joints.

This paper extends the algorithms developed in [25] to a new production system that generates structures without surface gaps ready for fabrication. The system not only deals with bevel joints along the edges of adjacent planar faces but creates accurate shape around a vertex shared by multiple faces.

3. Principle

An overview of the proposed production system for planar structures based on bevel joints is illustrated in Fig. 2. The system accepts a triangle mesh model as input, converts it to a polygon mesh, assigns a thickness to each surface patch, and generates bevel joints on all edges.

The data-processing pipeline consists of four steps: (1) conversion from a triangle to a polygon mesh, (2) interior angle determination, (3) bevel joint generation, and (4) vertex formation. The first step has been described in detail in [25]. Steps 2 to 4 are described in the following subsections.

3.1. Interior angle determination

The interior angle between any two adjacent faces should be determined for accurate bevel joint generation. This angle is indicated as α in Fig. 3, where two faces are shown in thickened solid lines. Generally, the angle between two faces is often represented by $\beta \in [0, \pi]$, which does not contain information about