Design and motion analysis of axisymmetric 3D origami with generic six-crease bases

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ABSTRACT

Origami, also known as paper folding, has shown its potential to construct 3D structures from designed crease patterns on a flat sheet. This paper proposes a method to design axisymmetric 3D origami with generic six-crease bases. Inspired by the conventional six-crease bases, i.e., waterbomb base or Yoshimura base, where six regular crease lines meet at an interior vertex, we generalize the generic base so that the lengths of the crease lines can be regular or irregular. This method is based on designing the crease patterns. First, we interactively generate a crease pattern consisting of such generic bases. Then, our method analytically calculates the 3D origami shape with an axisymmetric structure. We demonstrate various configurations, i.e., sets of input parameters, to explore the variations of the calculated 3D origami. The 3D origami can have multiple degrees of freedom, but by continually changing one parameter we present a motion that can axisymmetrically deploy or flatten the shape. The method for designing 3D origami has potential applications ranging from self-folding tessellations to deployable architectures.

1. Introduction

Origami, also known as paper folding, has received much attention in geometry, mathematics, and engineering. An origami (e.g., Fig. 1 (b)) can be defined by its crease pattern (e.g., Fig. 1 (a)), which contains a set of mountain folded lines (shown in red) and valley folded lines (shown in blue) appearing on a sheet of paper when the origami is opened flat (Mitani, 2011a).

Among the crease patterns, a waterbomb pattern (Fig. 1 (a)) and Yoshimura pattern (Fig. 1 (c)) with interior vertices having six-crease lines are widely used and have been widely researched. For a waterbomb pattern, Tachi et al. (2012) worked on the rigidity of a six-crease origami tessellation to achieve an adaptive freeform surface. Kuribayashi et al. (2006) made the first origami stent to achieve a large deployable ratio. Based on such pattern, a worm robot (Onal et al., 2013) and a deformable wheel robot (Lee et al., 2013) were also proposed. Chen et al. (2016) proposed a comprehensive kinematic analysis on a waterbomb origami with one degree of freedom (DOF) motion under symmetric folding.

A Yoshimura pattern, also known as the diamond pattern (Yoshimura, 1951; Hunt et al., 2003; Thompson et al., 1985) is another crease pattern with interior vertices having six-crease lines. For this pattern, Foster and Krishnakumar (1987) proposed a family of foldable structures. De Temmerman et al. (2007) proposed a concept for a mobile shelter.

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Thrall and Quaglia (2014) gave a historical review of origami-like deployable shelters developed by the US military. Cai et al. (2016) investigated the motion of the foldable barrel vault structure based on the regular and irregular Yoshimura pattern.

In this paper, inspired by the six-crease base, which we can be seen from the waterbomb pattern and Yoshimura pattern where six regular crease lines meet at a vertex, we present our generalization of the base, enabling the lengths of the crease lines to be regular or irregular. This method is based on designing the crease patterns. First, we interactively generate a crease pattern consisting of such generic bases (Fig. 2 (a)). Then, our method analytically calculates the 3D origami shape with an axisymmetric structure (Fig. 2 (b)). Finally, while referring to the shape of the 3D origami, the user can fabricate the 3D origami piece (Fig. 2 (d)).

Rigidly foldable origami allows for motion where all facets remain rigid, and deflection only occurs at the crease lines. A rigidly foldable origami can be made of thick materials other than paper. 3D origami consisting of triangular facets has multiple DOFs (Tachi, 2010a), but by continually changing one parameter we present a motion that can axisymmetrically deploy or flatten the shape around the z axis (Fig. 2 (c)). The designed 3D origami has potential applications ranging from self-folding tessellations to deployable architectures.

2. Related work

Origami has advanced significantly based on the development of mathematical theories and more computational resources (Wang-Iverson et al., 2016; Demaine and O’Rourke, 2007). TreeMaker is software used to design flat-foldable origami (Lang, 2016). Its basic concept was first introduced by Meguro (1991) and fully described by Lang (1996). This software generates the crease pattern from a graph tree that represents the base structure of the object by using a circle/river packing technique. Tess is another computer program that makes crease patterns for origami tessellations involving twist folds in a repeating pattern (Bateman, 2016). These approaches focus on flat-foldable origami, but we are aiming at making 3D origami.

The Origamizer algorithm by Tachi (2010b) is a very general approach that generates a crease pattern for an arbitrary 3D triangle mesh model with a topological disc condition. The approach is based on the tucking technique, which hides the unnecessary areas of a sheet of paper inside the shape. Although the Origamizer can handle axisymmetric origami, the generated crease pattern might be over complicated for a simple model.

Mitani proposed a method for designing 3D origami based on a rotational sweep (Mitani, 2009, 2011b), which generates a simpler crease pattern for an axisymmetric structure by adding flaps outside of the target shape. Although the flaps might be considered obtrusive, his method succeeds in generating 3D curved origami. His other method (Mitani, 2012), which combines the advantages of the rotational sweep and mirror reflection approaches, has been used to build geometrically attractive origami pieces. Even though these methods can handle the axisymmetric structure of origami, they cannot adequately handle axisymmetric 3D origami consisting of triangular facets.
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