Mechanism and Machine Theory 77 (2014) 13–24

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

A position analysis of coupled spherical mechanisms found in action origami

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ARTICLE INFO

Article history:
Received 6 December 2013
received in revised form 30 January 2014
accepted 8 February 2014
Available online 7 March 2014

Keywords:
Spherical mechanisms
Origami

ABSTRACT

Origami has been previously utilized in design to create deployable systems. Action origami, origami designed to move, has the ability to deploy to a larger state and have motion in the deployed state. The majority of action origami achieves motion through coupled systems of spherical mechanisms. An origami vertex, the point at which folds converge, is shown to be equivalent to a spherical change-point mechanism. A position analysis of an origami vertex is presented, resulting in a relationship between input and output angles as well as the path of the coupler link. A method for analyzing coupled systems of repeated spherical mechanisms is proposed and demonstrated using two examples. A better understanding of the kinematics of action origami increases the ability of designers to create compact, deployable mechanisms for use in packaging, space, and medical industries.

1. Introduction

The ancient Japanese art of origami has intrigued people for centuries with a beautiful complexity arising from the single fabrication process of folding. The quantity and complexity of origami models have been increasing partly due to the introduction of mathematical tools which model and characterize the design parameters found in the art [1,2]. Engineers and designers have looked to origami for inspiration due to its potential in deployable systems. Origami, for example, has been used as a source of inspiration for space applications [3,4] and automobile safety [5,6].

Action origami refers to the subset of origami models designed to move. Simple examples include flapping birds and opening mouths (Fig. 1). Action origami has received relatively little attention in the literature but has great potential to inspire new and useful mechanisms. This is in part due to the ability of many action origami models to deploy from a compact (and even flat) state to a larger state. In addition, these models are designed to exhibit motion in the deployed state. There are several areas of application for such mechanisms, including solar pointing arrays and minimally invasive surgical tools.

Action origami has been shown to achieve motion through the use of spherical mechanisms [8]. Action origami that achieves motion through the use of spherical mechanisms is termed “kinematic origami.” All possible kinematic origami configurations have been classified based on the number and arrangement of spherical mechanisms [9]. Some kinematic origami models contain dozens of coupled spherical mechanisms, but can be fabricated by simple folding in just a few minutes. As kinematic origami often utilizes symmetry for visual appeal, many models consisting of several spherical mechanisms use the same mechanism (equivalent link lengths) repeated throughout the model.

In order to utilize the unique properties of kinematic origami in engineering design, the kinematics of coupled spherical mechanism systems must first be understood. The current literature dealing with coupled spherical systems is sparse, possibly because there has not previously been a motivation to investigate them. Recent studies show that spherical mechanisms (both

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http://dx.doi.org/10.1016/j.mechmachtheory.2014.02.006

(a) (b) (c)

Fig. 1. Shafer's "Monster Mouth" [7] is an example of action origami. This model can be stored in a flat state (a). Once deployed (b), it can then open its mouth (c).

single and coupled) demonstrate several advantages over planar mechanisms including lower values of inertial forces and better pressure angle values [10,11].

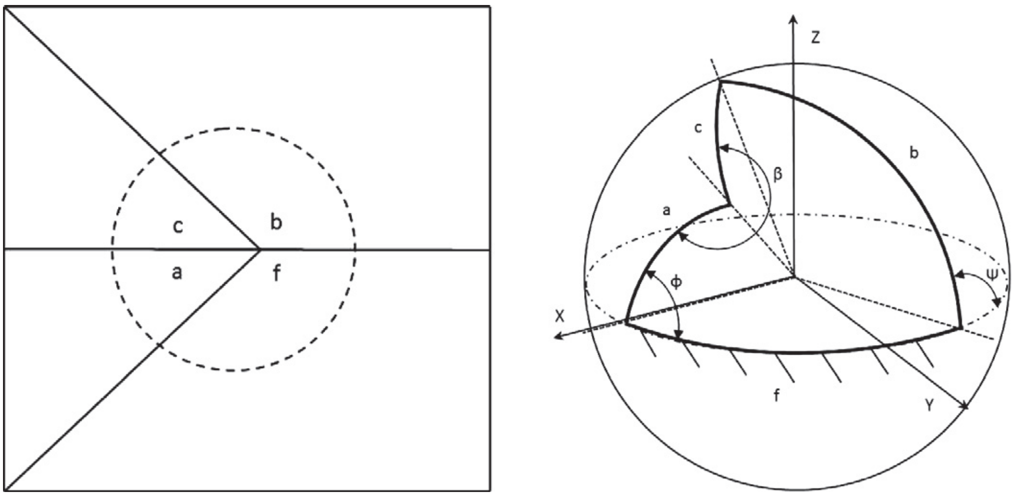
Making explicit the commonality between spherical mechanisms and kinematic origami makes possible mathematical models that can greatly enhance the analysis, optimization, and synthesis of new mechanisms with motion inspired by kinematic origami.

The purpose of this paper is to take a first step toward the advanced analysis and synthesis of kinematic origami-inspired mechanisms by describing and demonstrating a method for the position analysis of coupled systems of repeated spherical mechanisms. Such repeated systems are common in kinematic origami models and tessellations. This method has the potential to make kinematic origami-based design more effective and structured, moving much of the design process to computer-based tools.

2. Literature review

The growing relationship between origami artists and technical designers has resulted in increased literature on the subject of connections between origami and mechanism design. Greenberg et al. [12] point out that origami is a form of compliant mechanisms where the creases act as pin joints to allow movement, and go on to show that graph theory can act as a step between kinematics and origami. Liu and Dai similarly identify carton panels as mechanism links and creases as joints when investigating carton mobility [13].

The origami community has long identified and labeled characteristics of origami models and has particularly noted movement about a single vertex [14], the point at which fold lines converge. It has been noted that an origami vertex (including the surrounding folds and panels) is equivalent to a traditional spherical mechanism [15,8,16].



(a) Single origami vertex. Note that $a + c + b + f = 360^{\circ}$.

(b) Equivalent spherical mechanism with important angles specified.

Fig. 2. Single origami vertex and corresponding spherical mechanism to be analyzed.