Design and Control of Nanostructured Origami™

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Two-dimensional (2D) nanofabrication processes such as lithography are the primary tools for building functional nanostructures, since features on the order of 20 nm can be patterned with nanometer alignment precision [1]. The third spatial dimension enables completely new devices to be realized, such as photonic crystals with arbitrary defect structures and materials with negative index of refraction [2]. Presently, available methods for three-dimensional (3D) nanopatterning tend to be either cost inefficient or limited to periodic structures. The Nanostructured Origami method [3] fabricates 3D devices by first patterning nanostructures (electronic, optical, mechanical, etc) onto a 2D substrate and subsequently folding segments along predefined creases until the final design is obtained. This approach allows almost arbitrary 3D nanostructured systems to be fabricated using exclusively 2D nanopatterning tools.

In this paper, we present two approaches to the kinematic and dynamic modeling of folding origami structures. The first approach deals with the kinematics of unfolding single-vertex origamis. First, a unit positive “charge” is assigned to the creases of the structure in its folded state. Thus, each configuration of the structure as it unfolds can be assigned a value of electrostatic (Coulomb) energy [4]. Because of repulsion between the positive charges, the structure will unfold if allowed to decrease its energy. We obtain the desired unfolding trajectory by numerical minimization using the steepest descent algorithm (Fig. 1). If the energy minimization can be carried out all the way to the completely unfolded state, we are simultaneously guaranteed of the absence of collisions for the determined path.

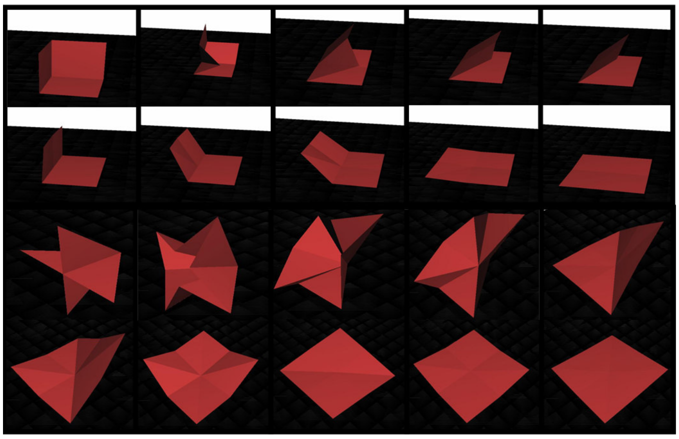

Fig. 1 Energy unfolding of corner cube and water bomb base

The second method deals with dynamic modeling of folding multi-segment (accordion style) origamis. The actuation method for folding the segments uses a thin, stressed metal layer that is deposited as a hinge on a relatively stress free structural layer. Through the use of robotics routines, the hinges are modeled as revolute joints, and the system dynamics are calculated for the accordion origami. Figures 2 and 3 illustrate the trajectory and response plot of a 3-flap accordion to a step input, respectively. The dynamics of the corner cube are also being calculated due to its potential use as a reflective optical device.

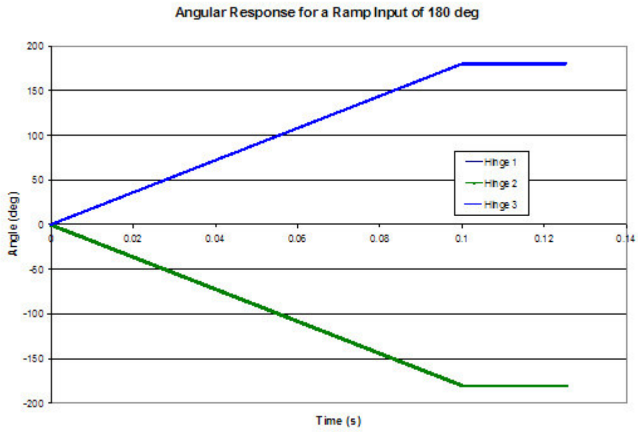

Fig. 2 Response of accordion origami to a step input of +/- 180 deg

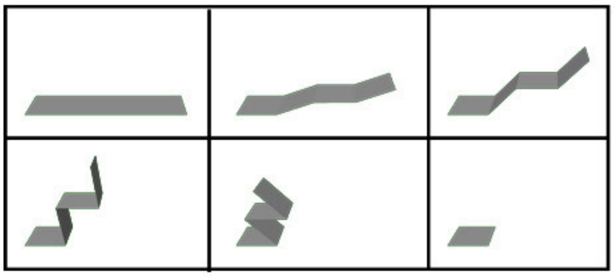

Fig. 3 Trajectory of 3-flap origami to ramp input

References

[1] J. T. Hastings, F. Zhang, and H. I. Smith, "Nanometer-level stitching in raster-scanning electron-beam lithography using spatial-phase locking," *Journal of Vacuum Science & Technology B*, vol. 21, pp. 2650-2656, 2003.

[2] M. Qi, S. Johnson, J. D. Joannopoulos, and H. I. Smith, "Fabrication of three dimensional photonic crystals with mid-gap wavelength at 1.55 microns," presented at Conference on Lasers and Electro Optics (CLEO), Baltimore, MD, 2003.

[3] S. M. Jurga, "3D micro and nanomanufacturing via folding of 2D membranes," in *Dept. of Mechanical Engineering*. Cambridge: Massachusetts Institute of Technology, 2003, pp. 130.

[4] Cantarella, J.H., Demaine, E.D., Iben, H.N., and O'Brien, J.F. “An energy-driven approach to linkage unfolding.” In *Proceedings of the 20th Annual ACM Symposium on Computational Geometry,* Brooklyn, NY, June 2004.