

# Multi-Crease Self-Folding by Uniform Heating

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## Abstract

This paper presents a self-folding method for multi-crease structures. The proposed method utilizes the symmetric breaking of a 3-layered two-dimensional sheet, where an inner contraction sheet induces shear force when heated, which directs the inclined folding direction. The fabrication technique developed enables distant placements of tiling patterns of the surfaces. The experimental result shows that by applying uniform heat, a feature with 62 folds can be simultaneously folded, an advantage over manual folding. The method presented is a new instant fabrication technique for making semi-rigid structures.

## Introduction

Biological entities achieve their fertile morphogenetic processes based on protein self-assembly and self-folding. Inspired by such processes, various attempts at the automated structuring of robot bodies have been made in the field of robotics. Hawkes et al. (2010) demonstrated self-folded ship and plane origami structures employing shape-memory alloy (SMA) actuators. Cheung et al. (2011) showed arbitrary 3D shapes that could theoretically be folded from a single strand. The underlying principle behind these approaches is assigning an individual actuator (i.e., shape memory alloy, or an electric motor) to each folding site. Thus, scalability of the system remains an open challenge. Recently, Onal et al. (2011) showed that the body of an insect-shaped, legged robot could be folded from a single laser-cut polyester sheet. MEMS technology employing a pop-up technique was proposed by Whitney et al. (2011). Felton et al. (2013) advanced Onal's model and incorporated the self-folding of a robot's body by assigning conductors around the hinges for localized heating by current application.

## Self-Folding Method

In this study, we use uniform heating to attain self-folding. We utilize thermal deformation of a contraction sheet (polyvinyl chloride, PVC) sandwiched by rigid structural layers with different gap widths, such that the shear force of a contraction layer induces a bending motion of the surface. We show the basic principle of the folding method in Fig. 1. Schematics of the fold are shown in side views on the left side in the figures, with corresponding snapshots on the right. The method is capable of (1) simultaneous mountain and valley

folds, (2) simultaneous multiple folds, and (3) coarse angle control by varying gap widths.

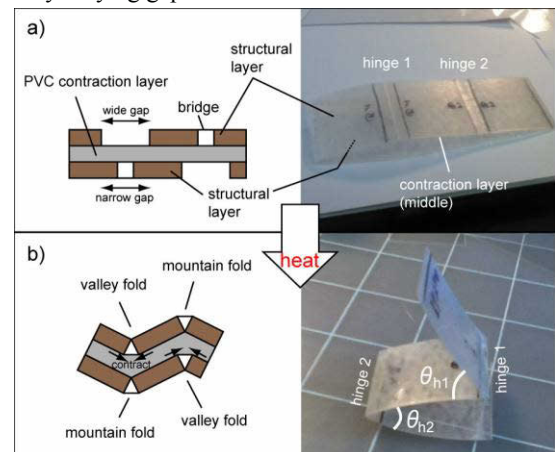


Fig. 1. Self-folding process by uniform heating.

## Accurate Folding Angle by Angle Fold

Attaining an arbitrary folding angle of a sheet structure is difficult at any scale, for it is dependent on the folding torque generated by the material. In order to attain accurate arbitrary folding angles, we focus on the kinematics of angle folds, specifically, the V-fold, in which one of the angles (termed output angle  $\theta_{out}$ ) can be precisely controlled by being kinematically coupled with another actuable angle (termed input angle  $\theta_{in}$ ). Since the derivative of  $\theta_{out}$  is small when  $\theta_{in}$  is small, in spite of the absolute change, the idea here is to “crudely” actuate  $\theta_{in}$  to exercise precise angle control over  $\theta_{out}$ . The concept for V-folds is illustrated in Fig. 2.

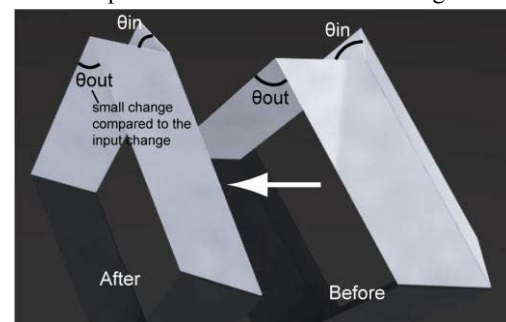


Fig. 2. Input angle and output angle in V-fold.

## Fabrication

Since the pattern of a structural layer involves multiple discrete tiles (islands), structural layers are cut out and placed on a semi-rigid backing layer. Once a laser makes the pattern, parts that position at gaps are manually peeled off. A contraction layer is then inserted and sandwiched by the backing-laminated structural layers, by folding it in half. Finally, the backing layer is removed from the structure, and the desired self-folding sheet is obtained.

## Result

The temperature control for the self-folding process is managed in an oven. To realize ideal uniform heating for the body, the sheet is hung from the ceiling. To demonstrate the advantage of self-folds, we chose an origami pattern that could only be folded if all the creases were folded simultaneously. This structure, which is shown in Fig. 4, consists of 62 mountain and valley folds.

Fig. 3 shows the self-folding process by uniform heating. Starting at room temperature and ramped up to 65 degrees, the process is complete in about 5 minutes.

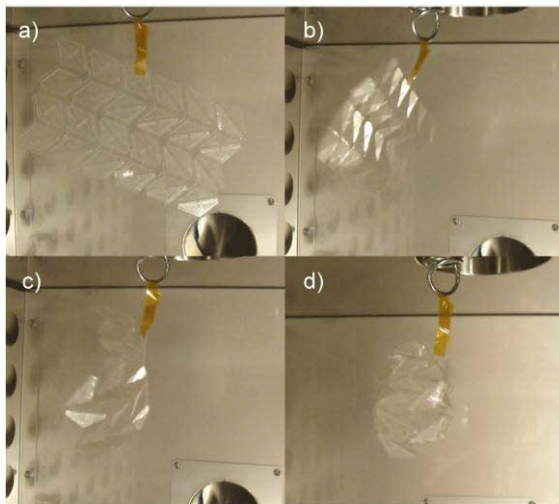


Fig. 3. Self-folding process by “baking.”

The fabricated structure is shown in Fig. 4. The process, although applicable one time only, is reliable and fast. The method is suitable for types of fold that consist of many pleat patterns, because heat is applied to the entirety of the targeted material.

## Conclusion

This work presents the self-folding of a multi-crease structure by uniform heating. We first developed a technique that, by having different gap widths between a contraction layer, achieved the simultaneous folding of mountain and valley folds by heating the middle contraction layer. We further developed a fabrication technique, designing the island

features and placing them onto the contraction sheet. The self-folding process achieved is fast and reliable, and is promising for the fabrication of more complex structures.



Fig. 4. Self-folded structure, which consists of 62 mountain and valley folds.

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