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Designing and programming self-folding sheets

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HIGHLIGHTS

- We propose a new programmable self-folding sheet model and architecture.
- We describe and analyze algorithms for the automatic design of self-folding sheets.
- We describe and analyze algorithms for the synthesis of sticker placement.
- We build and experiment with devices of two different types of self-folding robots.

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ABSTRACT

This paper considers a robot in the form of a self-folding sheet that is capable of origami-style autonomous folding. The sheet is composed of triangular tiles, folding actuators and an integrated electronic substrate, and is formed as an $n \times m$ box-pleated crease pattern. The design of the sheet is generated by an automated sheet design algorithm. We control the sheet with a programming method including a hardware model and supporting algorithms. In this paper we present the programming method. We describe and analyze the algorithms that generate designs and programs for the sheet. We finally demonstrate and analyze experiments with 4×4 and 8×8 self-folding sheet devices.

1. Introduction

A self-folding sheet is a robotic sheet that autonomously transforms its shape by folding into users' desired shapes. Our vision is to develop the hardware and software technology that will allow users to transform a self-folding sheet into desired shapes by adding physical stickers to select and trigger a control sequence. We imagine sheets capable of folding into a variety of objects, such as a table, an airplane or a tent. Applications include digital fabrication, on-demand construction of objects in remote environments, on-demand creation of tools, etc. Our aim is to automate the creation of origami objects.

We developed a novel device called the self-folding sheet (Fig. 1). This device has an $n \times n$ box-pleated pattern (for $n = 4$ and $n = 8$). We associate a SMA (Shape Memory Alloy) actuator with each edge of the sheet and embed supporting electronics. The sheet can be viewed as a modular robot system, where each tile in the system corresponds to a module. The sheet can fold by following planning algorithms, such as those described in [1], to achieve a three-dimensional shape. The planner provides the required sequence of origami folds, which can be executed using the actuators embedded on the sheet.

Making three-dimensional shapes by folding has advantages over achieving shape formation using modular self-reconfiguring robot systems composed of individual independent modules. Since the modules are connected at all times, the self-folding sheet is less prone to the type of connection and disconnection errors that occur in unit-modular systems. The planning system can be computed in a centralized fashion and executed in a highly parallel fashion. The folding operation is relatively easy to control. The challenge, however, is in fabricating a self-folding sheet that is capable of physically delivering self-folding actions, especially with multiple folds on the same edge, and in the planning algorithm that will synthesize the covert folding sequence.

In our prior work, we described the self-folding concept [2] and a centralized planner for multi-origami folding from a single sheet [1]. In this paper, we describe the fabrication process for self-folding sheets (Fig. 1) with embedded electronics and actuation. We also present the design and fabrication of a controller that selects the control for one of the desired shapes associated with the sheet, and the control sequence required to actuate that shape. Our solution is called the *sticker programming*. In the sticker programming, the control sequence is achieved by adding stickers, which are small segments of conductive materials, to key locations on the sheet. The addition of the stickers completes a circuit that

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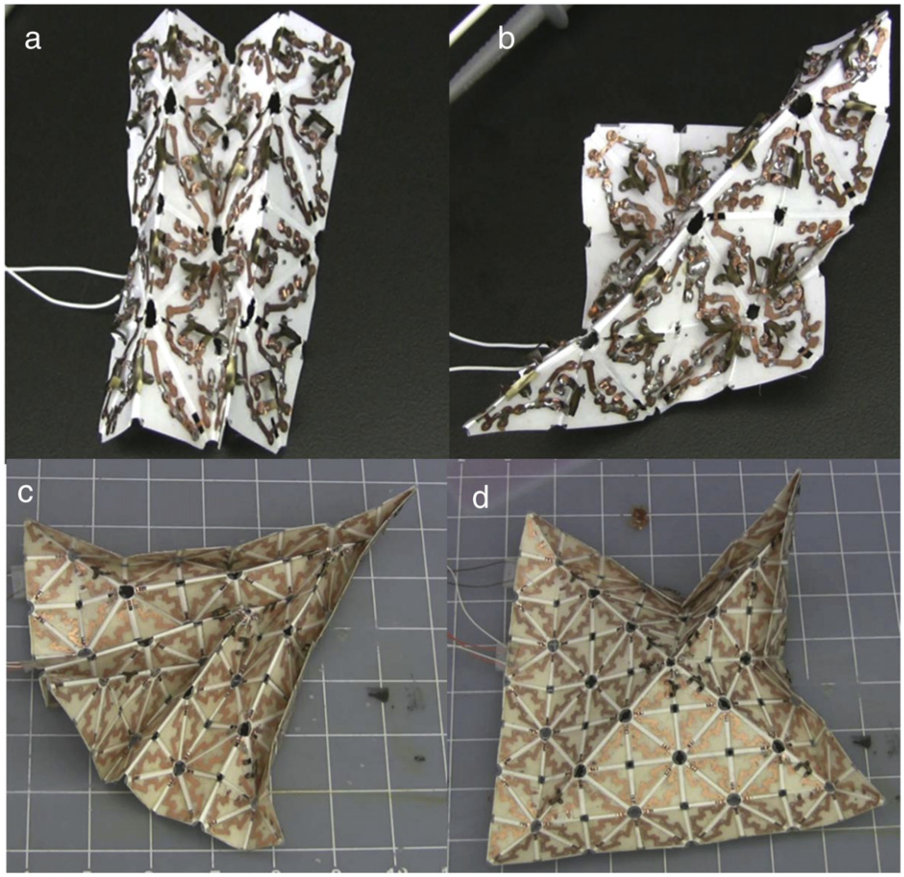

Fig. 1. Two self-folding sheets transform themselves into programmed objects. (a) Vertical folding. (b) Diagonal folding. (c) Space shuttle. (d) Hat.

triggers the function of an actuator. By adding/removing different stickers connecting other locations, we select a control sequence for achieving another described shape. Given the desired shapes, we can automatically compute the number of stickers and their placement on the sheet. Finally, we give experimental results collected from using a 4 × 4 self-folding sheet and an 8 × 8 self-folding sheet (Fig. 1). Our contributions in this paper are (1) a self-folding sheet model and its architecture, (2) algorithms for the design of self-folding sheets, (3) algorithms for the synthesis of sticker placement and (4) experiments with two different self-folding sheet devices.

1.1. Related works

In our previous work [2], we introduced a sheet that folded itself into two origami shapes. The mechanical parts of the sheet were triangular glass-fiber tiles, silicon joints and folding actuators. The sheet was formed as a 4 × 4 box-pleated crease pattern (Fig. 2). Demaine et al. proved that an $n \times n$ box-pleated tiling has, as a folded state, any polyhedral surface made up of $O(n)$ unit cubes on the cubic lattice [3]. They [4] showed that any folded state can be reached by a continuous folding motion without the material penetrating itself.

The multiple origami planner [1] generates a folding plan for this sheet. Given multiple target origami shapes, the origami planner identifies the groups of the actuators that simultaneously fold and the folding sequences of the groups for each target shape. For example, if a shape is achieved by folding two lines sequentially, the actuators on the first line are identified as the first group and the actuators on the second line are the second group. When we input this origami shape, the planner gives these two groups and the folding sequence.

Although the planner automatically generated the folding plan, we controlled the previous sheet [2] with a manually designed circuit. We embedded electronic routes for each actuator group and sent electronic current to the selected routes sequentially. The sheet achieved two 4 × 4 origami shapes with this manually designed circuit. This control method is however intractable for bigger sheets or more complex origami objects. In this paper, we describe a new control method, called the sticker programming, to solve this control challenge. This concept was introduced in [5], but the details of the hardware model and the programming algorithm were not described. The previous paper presented the old design algorithm that only works for $2^n \times 2^n$ sheets. This paper includes the detailed models for the sticker programming, the automated sheet design algorithm for $n \times m$ sheets, and theoretical correctness proofs and analyses of the designing and programming algorithms. The paper also demonstrates and analyzes the experiments with self-folding sheet devices.

Nagpal [6,7] introduced a biologically-inspired control method for a multiagent system, including a programming language that transforms into a language for the multiagents. She applied and simulated this method for a self-folding system. In her simulation, a sheet is composed of many cells (agents); each cell has simple computation and communication ability and the cells on a line can fold the structure. Some simulations ran with several thousand cells. Our programming method, in contrast, is for $n \times m$ box-pleated sheets that are constructed by connecting the triangular tiles with embedded electronic circuits and folding actuators.

The self-folding sheet autonomously transforms its 2D shape into 3D shapes as a new family of self-reconfigurable systems. Our group and other groups built the systems and the algorithms [8–25]. [26] is a good review of this field.