Demonstrating Waxpaper Plus: Sequentially and Conditionally Programmable Morphing Wax Fabrics

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Figure 1: Application demonstrations. (a) Morphing strip - a strip that can sequentially fold with 45 degrees folding angles; (b) Self-locking structure - a structure with gray levels on different regions that can self lock and unlock itself; (c) Morphing flower - a flower with different gray levels petals that can boom in sequences; (d) Triggered length primitive; (e) Triggered width primitive.

ABSTRACT

We print wax on paper and turn the composite into a sequentially-controllable, rapidly-fabricated, low-cost, and biodegradable shape-changing material. This is a novel, versatile yet highly accessible enabling technology that expands the library of morphing materials in HCI. By integrating three physical phenomena (including the bilayer bending actuation, the hygroscopic nature of the paper, and the hydrophobicity property of the wax) and rapidly printing various wax patterns on paper with an off-the-shelf solid ink printer, we develop wax paper actuators that have highly controllable sequential deformation with a wide range of intervals (from seconds to hours). This paper describes the design factor, fabrication process, sequential control, and transformation primitives, and envisions example applications.

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CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

morphing materials; rapid fabrication; programmable interface

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1 INTRODUCTION

Paper is an affordable, biodegradable and widely used natural material in people's daily life. In human-computer interaction (HCI), paper has been used to design functional interfaces for sensing[5], actuation [3] [10] and energy harvesting [4]. Among many techniques introduced for actuating papers, one of the simplest is to leverage the inherent responsiveness of paper to water. Such a water-triggered response is due to the physics that natural fibers in the paper readily absorb water and swell. Although this actuation phenomenon has been explored by hobbyists and demonstrated in K-12 STEM activities commonly in the form of a blooming flower

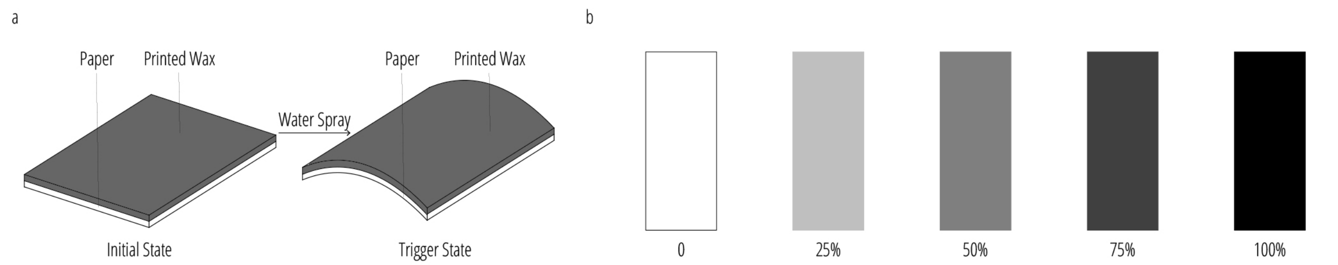

Figure 2: (a)Diagrams of the basic paper deformation with printed wax after water spraying. (b) Gray levels.

on water surface [1], it is not until very recently that the design and engineering community started to take it as a serious enabling material for controllable and programmable morphing. In particular, we have seen that paper-plastic bi-layer was used to mimic hygromorphic pinecones [8], inkjet-printed water pattern was used to program self-folding paper origami[2], and solid ink printer used to selectively coat wax pattern on paper to design paper robots [8]. In these past works, paper actuator techniques were promoted because of its design versatility and accessibility. However, the controllability of water-triggered actuators is still rather limited, hindering its potential use in more sophisticated interfaces. For example, the sequential control aspects have not been explored. The other well-known physical or fabrication affordances of paper, such as the potential for layer-stacking, the integration with kirigami, the fluidic transport and ionic conduction, etc, have not been fully explored in conjunction with its actuation capability. As a result, we believe there is an opportunity to deepen the actuation technique thus broaden the functional design space of paper actuators, without sacrificing paper's charm of accessibility and rapid fabrication affordances for the maker community.

Building on top of existing wax-paper actuator technique [9] that only explored shape changes due to different print patterns with a single layer made of one type of paper, we came up with a set of techniques to achieve versatile sequential shape changing controls of paper actuators, and further integrated the sequential techniques with various structure designs, assembly strategies and multi-functionality such as ionic conduction.

In particular, in order to control the sequential morphing we explored the functions of wax coating on paper in two ways: 1) By varying gray levels in the printed wax pattern, we can control the morphing sequence under a uniform water spray. Here, the wax coating functions as a controllable water barrier that can hinder water transport. 2) By leveraging the hydrophobicity of wax and printing two parallel lines out of it, we could form a fluidic transport channel in between the wax line. Here the geometrical parameters of the channel including the channel length or width could control the morphing sequence of the paper actuator.

In addition and aiming at the same achievement of multi-functional and controllable paper actuators, we showed how different types of off-the-shelf papers including printing paper, tracing paper and Japanese paper could have complimentary performances in morphing responses, water conduction, and reversibility in actuation. We also explored the feasibility of integrating electronics into our paper actuators, e.g., leveraging ionic conduction of salt water to both trigger the morphing and conduct electricity to light up a morphing water lantern. In the past, although both paper diagnostic microfluidics [6] [7] and ionic conductors have been discussed, these techniques have not been leveraged for paper morphing.

2 OVERVIEW

2.1 Fabrication

In brief, the procedure entails printing the designed designs on various papers using the wax printer (a solid ink printer Xerox Colorqube 8580) and then baking them. It can be categorized as either single-side or double-side printing. Single side printing: select several varieties of paper (printing paper, tracing paper, Japanese paper, etc.), place them in the oven, set the temperature to 250 degrees Fahrenheit, and bake them for 30 seconds. However, the wax paper is readily overbaked at a high temperature, resulting in patterns that are disorganized. Therefore, during the baking process, we remove the wax paper every 10 seconds to allow it to cool for 10 seconds. Three times will be spent repeating the same procedure. Double side printing. We repeat the single-side printing on each side of the paper.

2.2 Material - Wax

The wax ink, once baked, is very water resistant and can be printed onto various types of papers by a solid ink printer It is currently available in black, blue, brown, and yellow. The principle is that the wax itself will fill and block the pores of the paper fibers. Right off the printer, the wax only enhances the water resistance of the paper and does not completely isolate water. However, it can penetrate more deeply into the paper after baking and thus achieve the purpose of isolating water.

3 SEQUENTIAL CONTROL METHODS

3.1 Gray Levels

3.1.1 Mechanism - Sequentially Controlling Paper Hygroscopic Swelling with Wax Coating. Due to its porous structure and hydrophilic cellulose fibers, paper may absorb water and inflate in proportion to its moisture level. When water molecules permeate into paper, they weaken the link between adjacent cellulosic fibers, allowing hygroexpansion to occur. The paper does not swell when impregnated with hydrophobic wax because the hydrophobicity plugs the pores and repels the moisture. Nevertheless, if a hydrophilic channel is

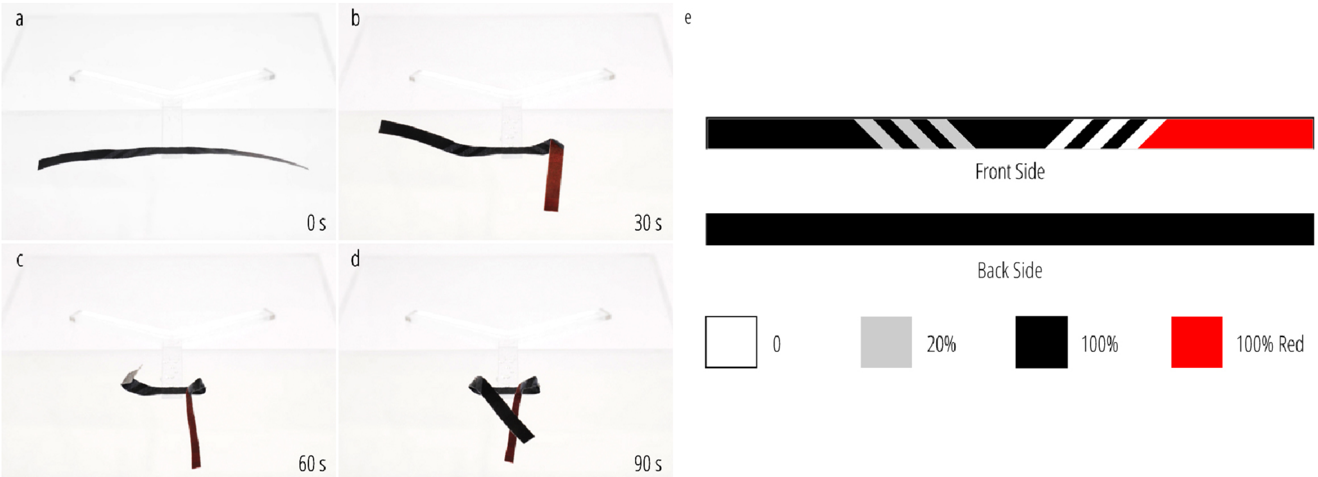

Figure 3: Sequential folding with two 45 degrees folding angles (a, b, c, d) and the printing pattern for the sample (e). The percentage values indicate gray levels of wax.

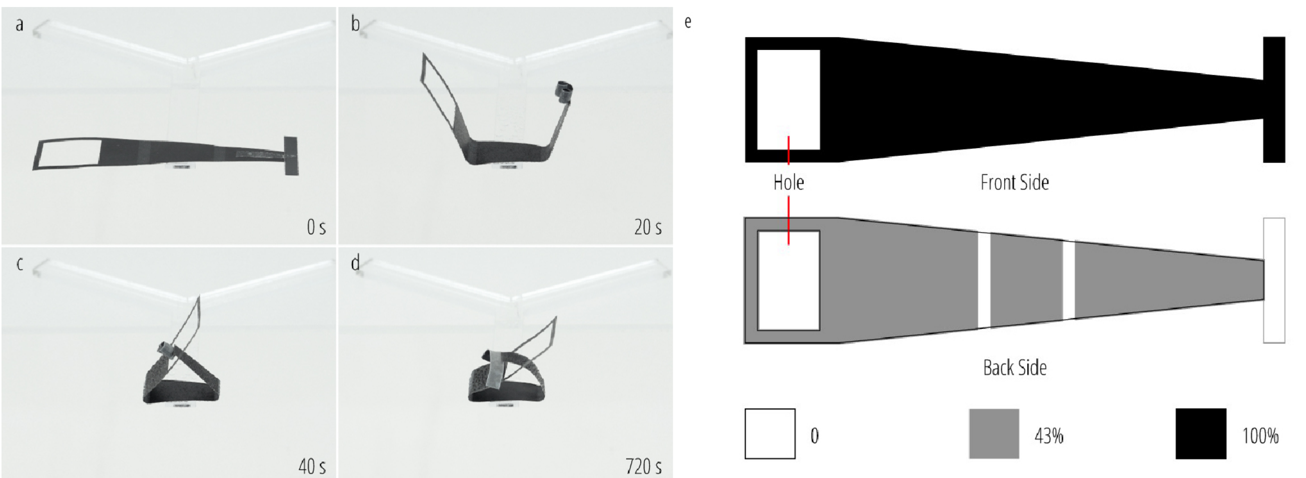

Figure 4: Sequential folding of a self-locking structure (a, b, c, d) and the printing pattern for the sample (e). The percentage values indicate gray levels of wax.

produced by manipulating the positioning of the hydrophobic wax, a bilayered single sheet of paper will fold in response to sprayed water because the hydrophilic channel expands while the wax layer does not. This disparity in layer expansion causes a localized bending of the paper (Figure 2. a), and altering the gray value (Figure 2. b) of the hydrophobic wax affects the temporal order in which this difference occurs, allowing for sequential deformation of the wax-printed paper.

3.1.2 Sequential assembly of structure. This primitive shows how to assemble a body into a specific structure with a specific sequence of approaches. Strips of different gray levels leaning 45 degrees 135 degrees are printed on the right and left side respectively (Figure 3). Spraying water from the front triggers sequential folding– the right side will fold first and the left side ends up over the right side (Figure 3). Note we printed the right end with red wax for visual identification purposes.

3.1.3 Self-Locking. This primitive shows how to realize the lock between structures by combining different gray level structures. We wax the pattern with 43% gray scale excluding the hinge and the thin strip at the right end. Spraying water from the reverse side triggers sequential deformation. Since the lower the gray level is, the faster the reaction speed is, and the faster the end is. The thin blank strip first curls into a small ball and then opens first after entering the frame with the overall folding, thus locking the whole before it is bent and flattened (Figure 4).

3.1.4 Morphing Toy. This flower toy allows us to watch the petals blooming in three different orders by spraying water. Tracing paper with internal gray level of 0, 15, 30% and external gray level of 100

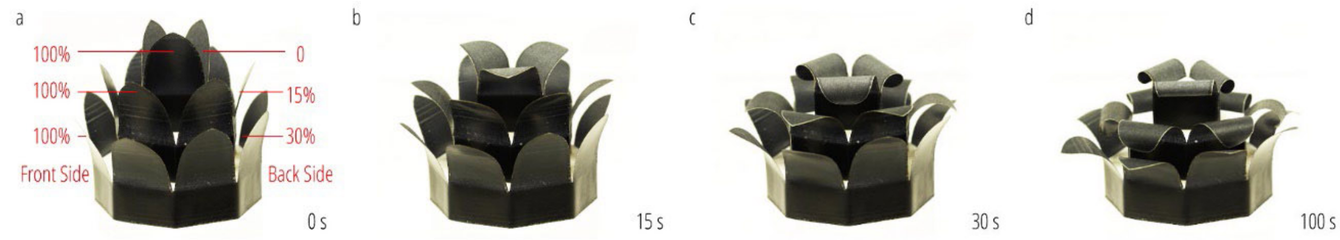

Figure 5: Layered sequential blooming of a rose flower.

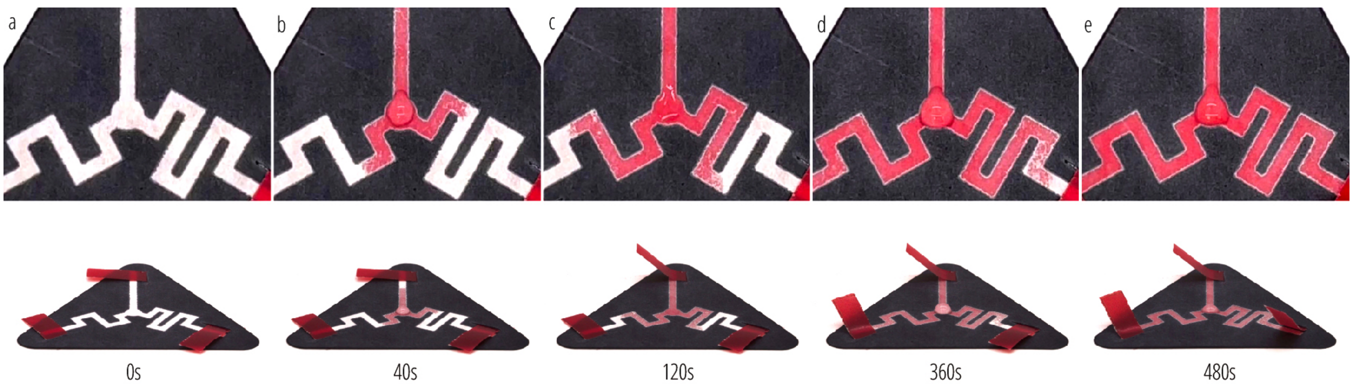

Figure 6: Illustration of triggered length primitive with time tag.

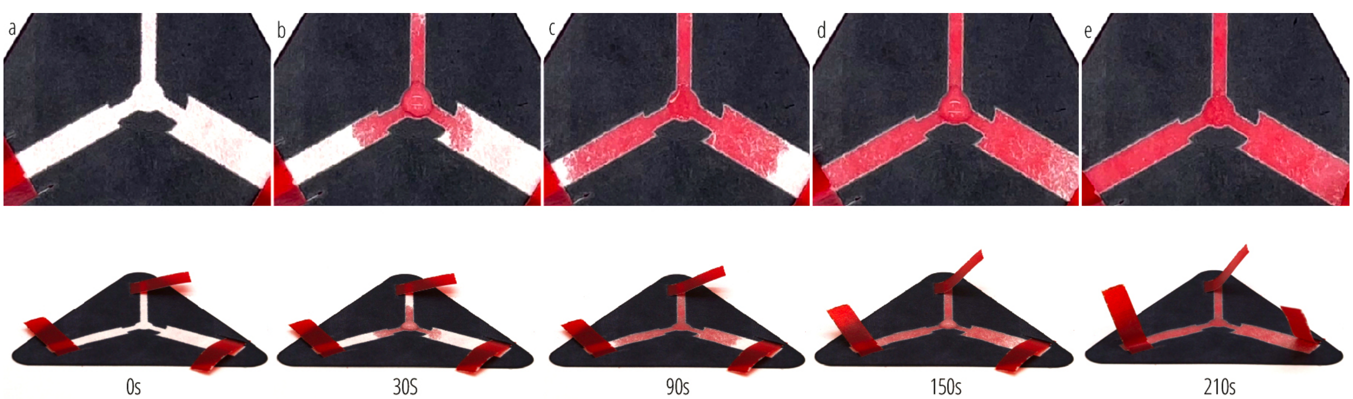

Figure 7: Illustration of triggered width primitive with time tag.

% (Figure 5) was used from top to bottom. Due to different reaction speeds of different gray levels after water spraying, petals with top gray level of 0 bloomed first, followed by the second and third layers.

3.2 Fluidic Channels

3.2.1 Mechanism. As mention on 3.1.1, by manipulating the position of the hydrophobic wax on the unwaxed portions of the paper, hydrophilic channels in which water flows in the shape of the channels are generated. Length and width are two fundamental features of a channel that determine the rate of water flow. In the situation of typical indoor temperature and humidity, the time required for water to reach the end of a channel is inversely related to its length and breadth, i.e., the longer the length, the longer the time; the broader the width, the longer the time.

3.2.2 Channel Length. This primitive is to show the influence of length on deformation order. We made 3 channels with different lengths (25mm 40mm and 55mm) by printing and baking on Japanese paper and placed 3 petals at the terminal. The petals on 25mm-long channels will bloom first after dripping water, followed by 40mm and 55mm (Figure 6).

3.2.3 Channel Width. This primitive is to show the influence of width on deformation order. We made 3 channels with different widths (2.5mm 3.5mm and 4.5mm) by printing and baking on Japanese paper and placed 3 petals at the terminal. The petals on 2.5mm wide channels will bloom first after dripping water, followed by 3.5mm and 4.5mm (Figure 7).

4 DISCUSSION

Wax paper-actuated form change is easy yet limited. 1) Materials have limited reversibility. Though baking increases reversibility, tracing paper loses reversibility after 5 triggers. Wet fibers alter irreversibly. Unprocessed natural fiber (e.g.,thin wood sheet) may make the actuator more reversible. 2) Although waxpaper is biodegradable and environmentally safe, the colored dyes in the wax ink may be dangerous. No-color wax may solve this. 3) Tracing paper is soft, making intricate 3D constructions and enormous forces difficult. Consider this when creating shape-changing structures and applications.

5 SUMMARY

We believe the paper morphing techniques introduced in this paper is very accessible to the maker and designer community. Considering that a solid ink printer and the standard ink cartridge can be purchased off platforms such as eBay with affordable price range, and papers are widely accessible. In addition, we also believe that achieving sequential morphing effects in both 2D and vertical dimensions with a digital fabrication process hence decent accuracy and controllability is non-trivial. For example, to our knowledge, there is no prior work demonstrating complex sequential controls of paper morphing with purely passive triggers like water and mist. Therefore, our methods will contribute to the science and engineering of programmable morphing and shaping changing materials in large.

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