Design and Simulation Tool for Sequentially and Conditionally Programmable Waxpaper Morphing Interfaces

Emily Guan
eguan12@pratt.edu
Pratt Institute
Brooklyn, NY, USA
Carnegie Mellon University
Pittsburgh, PA, USA

Di Wu
di.wu@northwestern.edu
Northwestern University
Evanston, IL, USA
Carnegie Mellon University
Pittsburgh, PA, USA

Qiuyu Lu*
qiuyulu@berkeley.edu
University of California, Berkeley
Berkeley, CA, USA
Carnegie Mellon University
Pittsburgh, PA, USA

Lining Yao*
liningy@berkeley.edu
University of California, Berkeley
Berkeley, CA, USA
Carnegie Mellon University
Pittsburgh, PA, USA

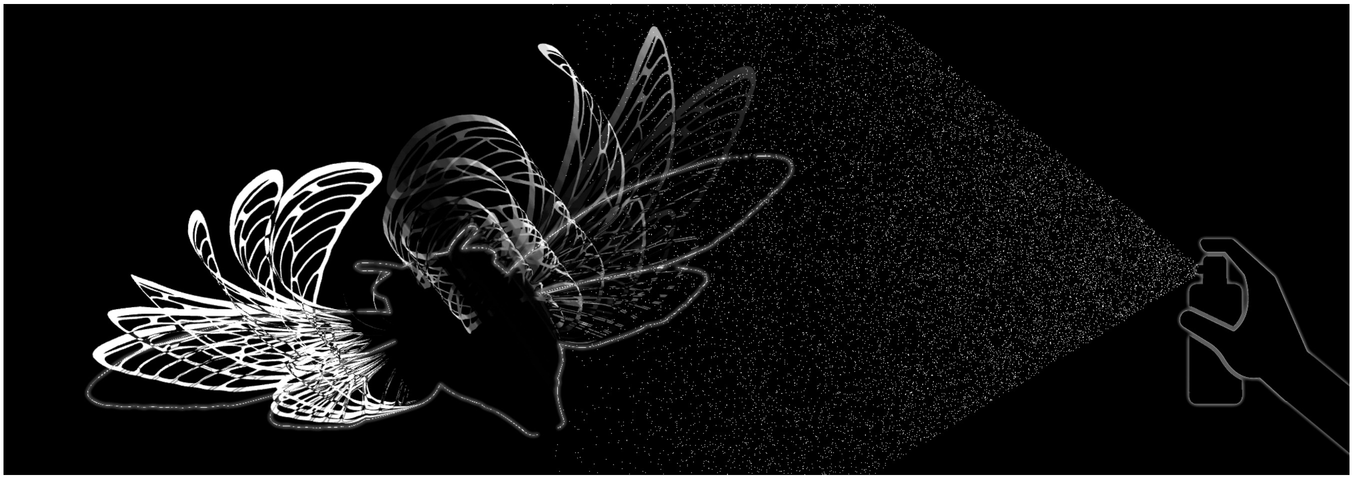


Figure 1: The waxpaper actuator morphs in shape when triggered by moisture.

ABSTRACT

This Interactivity demonstrates a design tool that aids the design and simulation of waxpaper actuators. The waxpaper actuator is a sequentially-controllable, moisture-triggered, rapidly-fabricated, and low-cost shape-changing interface. We introduce a design tool that integrates the characteristic data of the waxpaper actuator to aid users in the customization of swift personal actuators. It uses gray levels to control the wax interface's deformations, bending degrees and response times. Users can design their own actuators or import samples we provide, customize variables to best fit their needs, and create simulations to preview the performance. This gives higher precision to the effectiveness of the waxpaper actuator before it is fabricated. This makes the technique more accurate and accessible to future HCI projects.

CCS CONCEPTS

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

KEYWORDS

sequential control method; shape-changing interfaces; programmable material; morphing materials; rapid fabrication.

ACM Reference Format:
Emily Guan, Di Wu, Qiuyu Lu, and Lining Yao. 2024. Design and Simulation Tool for Sequentially and Conditionally Programmable Waxpaper Morphing Interfaces. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24), May 11–16, 2024, Honolulu, HI, USA.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3613905.3648661

---

*Corresponding authors.

Permission to make digital or hard copies of part or all of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for third-party components of this work must be honored. For all other uses, contact the owner/author(s).
CHI EA '24, May 11–16, 2024, Honolulu, HI, USA
© 2024 Copyright held by the owner/author(s).
ACM ISBN 979-8-4007-0331-7/24/05
https://doi.org/10.1145/3613905.3648661

1 INTRODUCTION AND RELATED WORKS

Customized computational design tools have significantly streamlined the design and prototyping process [4, 6, 14], much like their impact on paper-based interfaces. This material, known for being both economical and biodegradable, benefits from the enhanced precision and innovative possibilities brought about by these specialized tools. These tools visualize the characteristics of how paper materials react to different scenarios and aid users with predicting and designing their behaviors, such as the simulation of origami crafts [11] and foldable models [1]. Paper actuators have also been explored in many possibilities, such as interaction design toolkits [8], actuating artifacts [7], soft robotics [2, 9, 10], rapid prototyping [8], sensors [5], and artistic expression [3]. These tools and explorations, however, are not catered towards the specific material characteristics of the waxpaper, which can bend into various curvatures based on different parameters.

The waxpaper actuator [12, 13] is a technique that relies on a sequential control method that harnesses gray levels. By integrating this variable within a bilayer structure, composed of a paper substrate and wax layer, we produce a diverse wax pattern using a solid inkjet printer. The technique allows for a flexible variation of forms, with control over sequential deformations, bending degrees, and response times. Within the design tool, users can customize their personal paper actuator in four steps: draw or import actuator design, indicate gray levels, simulate the actuation, and export for fabrication. The simulation integrates the characteristics of the material, including the waxpaper's thermal properties, absorbency, density, and fiber orientation, which all may influence how it responds when moisture-triggered.

In this interactivity, we demonstrate a design and simulation tool that makes the waxpaper actuator more accessible and customizable to HCI researchers, DIY enthusiasts, and anyone interested in this technique. We also explain the underlying physics, the implementation, and a walkthrough of this tool.

2 WAX PAPER ACTUATOR

2.1 Mechanism

The waxpaper actuator is triggered by moisture to create a bending deformation. A bilayer structure is constructed by printing wax on one side of the paper. The side of paper without wax can absorb water and expand in proportion to the moisture content due to its porous structure and hydrophilic cellulose fiber. Water molecules that penetrate the paper weaken the bond between adjacent cellulose fibers and increase the gaps between the cellulose fibers, enabling hygro-expansion. On the other side with wax printed, the hydrophobic nature of wax clogs pores and keeps moisture out. The disparity in layer expansion causes a localized bending of the paper. The speed and shape of this bending can be controlled through altering the influencing variable: gray levels. We record these characteristics and integrate them into the design tool.

2.2 Fabrication and Applications

Once a desired actuator has been created using our design tool, it can be fabricated in three steps: printing, baking, and laser cutting. First, we use an inkjet solid wax printer (Xerox Colorqube 8580 or 8570) to print the design pattern on a letter (or A4) size paper. This creates a bi-layer sample with a paper substrate and a wax layer. Secondly, we bake the sample in the oven with the temperature of 300-degree Fahrenheit for 5 seconds. The wax gradually melts into the paper layer and partially fills the space between fibers, which ensures no wax pieces being produced in the next step. Thirdly, we laser cut the sample into designated shapes, and spray it with water to trigger the bending mechanism.

This creates the potential for a variety of customizable applications, ranging from sequential seed dispenser, morphing toys, home decoration, to electrical switch. The seed dispenser leverages the bending property of the actuator to create a dispenser that is triggered by natural moisture. It also utilizes the different response time of actuators with varying gray levels to create a sequential order for dispensing seeds before dispensing the soil. Origami and other paper toys made of waxpaper become more dynamic because they can move when triggered by moisture, such as a paper cicada that can flap its wings in sequence. Home decorations such as responsive lampshades can provide different levels of shading based on the amount of light revealed by varying bending curvature. The actuator can be used as a switch in an electrical circuit as the paper morphs to connect and disconnect.

3 DESIGN TOOL

3.1 Physical Mechanism

Gray levels serve as an independent variable influencing the responsive behavior of waxpaper, specifically impacting two dependent variables: bending degree and bending speed (Figure 2). "Gray levels" refers to the opacity of the printed wax, ranging from 0 to 100%. A higher gray level results in a higher density of wax, therefore, a higher resistance to moisture, and vice versa. Wax can be printed on both sides of the paper or solely on one side. The ratio of gray levels on each side determines the degree of bending in our paper actuator. The maximum bending occurs when one side is printed with a full 100% wax coating, while the other side is wax-free.

We test the relationship between gray levels and their bending curvature as well as how much time it takes (Figure 2) to generate data for the design tool, facilitating the simulation of more accurate curvature at the appropriate moment. The performance of our tested sample consistently reveals a clear correlation: a rise in the ratio of gray levels correlates with heightened bending curvature, a reduced time to reach maximum curvature, and a prolonged duration of deformation.

This tool is designed to replicate the sequential morphing process of the double-sided printed waxpaper actuator (with the back side printed at 100% gray level and the front side from 10% to 50%) triggered by a single water spray from 100mm distance in the time period from 0 second to the time it reaches the maximum curvature value. Consequently, the tool exclusively incorporates data from experiments involving various gray levels. It also considers the paper fiber direction that affects the orientation of the bending curvature.

The tool consists of three primary sessions: pattern selection, assignment of gray levels to each part of the pattern, and simulation to observe the sequential morphing of different sections (Figure 4).

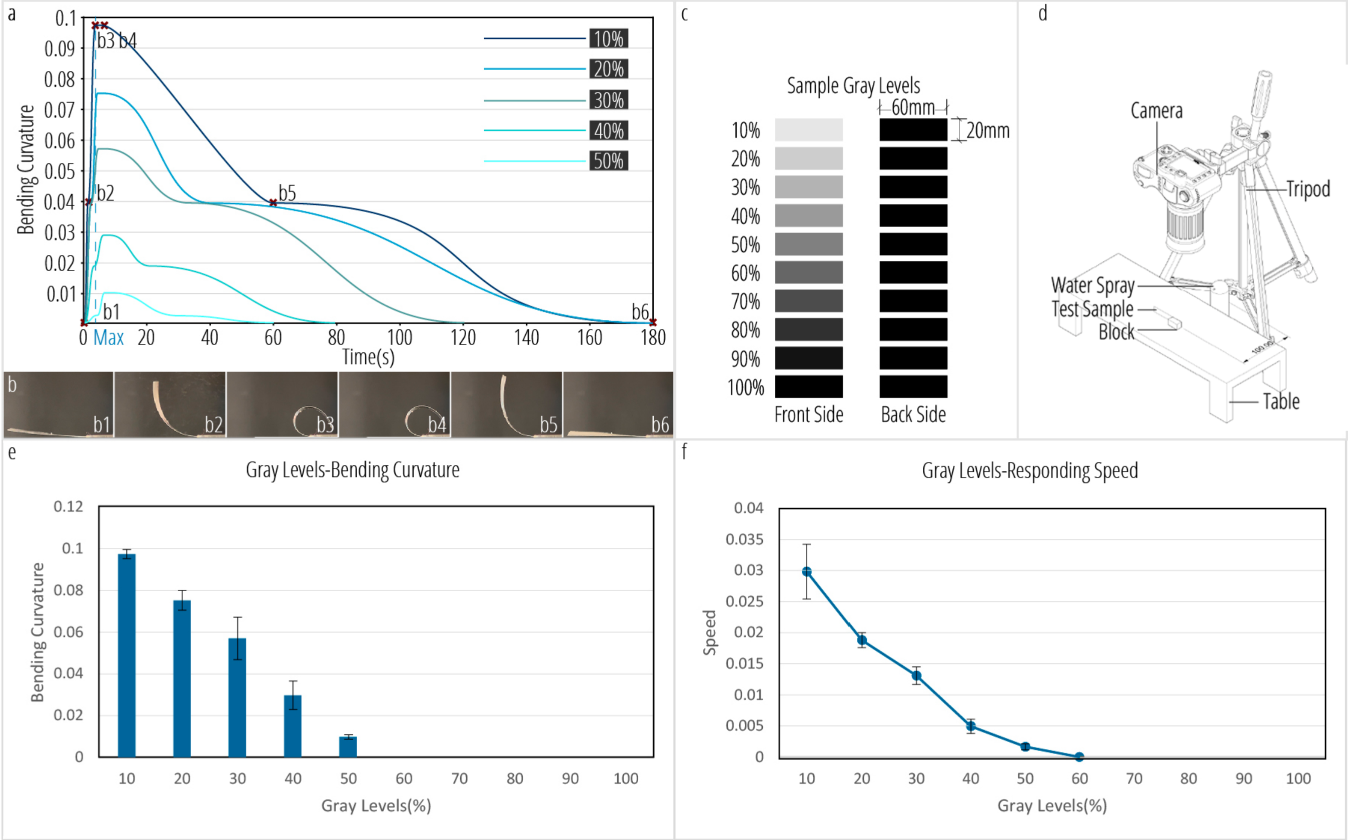


Figure 2: (a) Relationship between bending curvature and responding time for waxpaper samples with front side gray levels from 10% to 50% with one time spray; (b) Morphing process for waxpaper samples with front gray level of 10%. Sample size for each curve: n=1. (c) Testing samples in different gray levels; (d) Experiment setups; (e) Relationship between gray levels and bending curvature. Sample size for each gray level: n=3; (f) Relationship between gray levels and responding speed. Sample size for each gray level: n=3.

In the gray level experiment, we examine the relationship between gray levels and bending curvature, and the correlation between gray levels and speed. The waxpaper exhibits distinct bending curvature at specific times (Figure 3). Therefore, we computed for each gray levels and found that the relationship between time and curvature conforms to the following equation:

$$b = y \times t$$

where y is the bending constant, b is the bending curvature, t is the reaction time (in seconds) and the domain of t is the time period from 0 second to the time it reaches the maximum curvature value (0 to $T_{\max}$). The relationship between gray levels and the bending constant is governed by the following functional equation:

$$y = 0.0484e^{-0.0503g}$$

Where g is the gray levels from 10% to 50% (since our experiments show that the paper wouldn't bend after 50%). It's important to note that this relationship is contingent on the specific materials and methods used in our experiments. Variations such as different brands of paper could necessitate adjustments to the constant in the equation. Such changes might arise from differences in thermal properties, structural integrity, or the paper's absorbency, which could all influence the actuator's response to moisture.

Subsequently, we input this functional relationship into the curvature control module in Grasshopper. Ultimately, after users complete the pattern and gray levels selections, they can observe the sequential bending process of the chosen pattern by adjusting the time slider.

Since paper's fiber runs in one direction, the bending curvature curves perpendicularly to the fiber direction. This means the orientation of how the actuator is drawn and cut out makes a difference in its morphing form. This aspect has also been integrated into the tool.

3.2 Implementation

We developed the design tool (Figure 4) in Rhino with Grasshopper plugin for parametric design and simulation, and Human UI Plugin for graphic user interface. The tool can be then distributed as a new plugin package for Rhino.

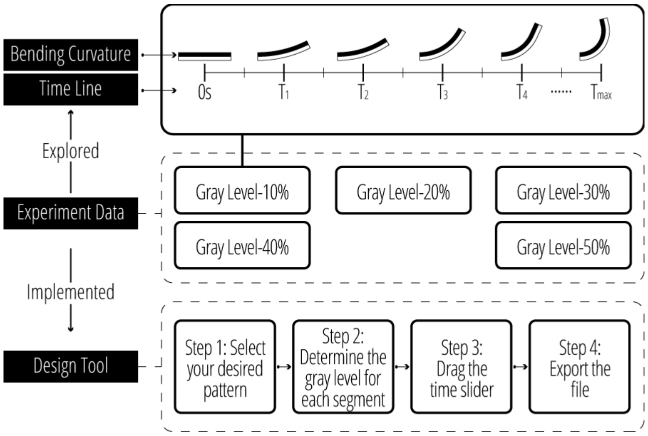
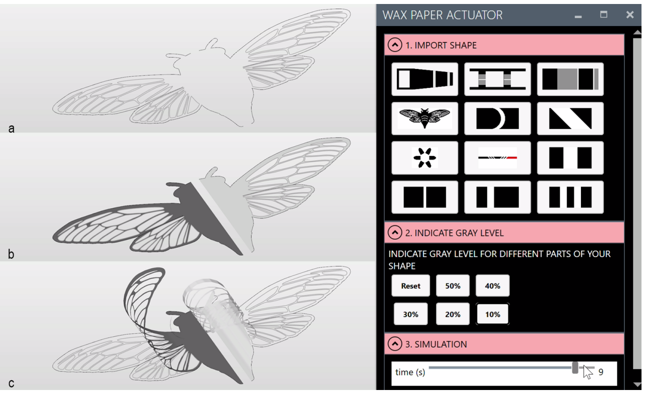


Figure 3: Mechanism of the design tool.



INDICATE GRAY LEVEL FOR DIFFERENT PARTS OF YOUR SHAPE

Figure 4: The interface of design tool.

Once the actuator's line drawing has been imported, the open curves are identified as the parameters of the actuator's shape while closed curves are parts within the parameter that need to be excluded. The two endpoints of an open curve connect in a line to make a close curve that identifies the shape of the actuator; this curve is also the hinge, where the bending of the actuator starts. Next, the lines of paper fiber are identified on the shape, which run parallel to the short edge of the 8.5 x 11 paper. When the actuator is triggered by moisture, these fiber lines fold inward and the angle of the fold is determined by the variables (gray level and time since triggered) the user inputs; when zoomed out to the size of the actuator, the folding fibers create a bending curvature that morphs the actuator into a curved form.

3.3 Walk-through

The user opens the design tool in Rhino and follows these steps to create an actuator. Step 1: Select your desired pattern (Figure 4-a). The shape of the actuator is drawn as polylines. Users have the option of choosing patterns from the pattern library or creating their own line file by drawing or importing lines into rhino.

Step 2: Determine the gray levels for each segment of the pattern, ranging from 10% to 50% (Figure 4-b). The back side has a gray level of 100% and users can adjust the gray levels of the front side to control wax ratio and bending. Given that the experiment has demonstrated the lack of moisture response in the double-sided printed wax paper actuator when the gray levels exceeds 60%, we limit the gray levels to the range of 10% to 50%.

Step 3: Drag the time slider and check the morphing process (Figure 4-c). As time progresses, regions with different gray levels will sequentially undergo bending. Simultaneously, users can make adjustments to the lines and gray levels to create relatively more precise designs that reach the bending forms they desire at the given time.

Step 4: Export line file. Users can export the line file in PDF format from Rhino for printing and laser cutting.

4 CONCLUSION

The design tool has limitations on its simulation accuracy for very specific environmental factors. In the future, we aim to enhance the tool by conducting more experiments and integrating the data into the tool for more customization characteristics, such as humidity, temperature, paper quality, etc.

In conclusion, this interactivity demonstrates a novel design tool that enhances the utilization of waxpaper actuators in HCI projects. These actuators, known for their cost-effectiveness, rapid fabrication, moisture-responsiveness, and shape-changing capabilities, can be customized extensively through our tool. By manipulating key variables, users can control the actuator's deformation, bending degree, and reaction time with more precision. The tool's integration of characteristic data allows for the creation of personal actuators, either from scratch or the provided samples, and includes a simulation feature for performance preview. This not only increases the accuracy and efficiency of the waxpaper actuator prior to fabrication but also makes this innovative technology more accessible and precise for future HCI endeavors.

ACKNOWLEDGMENTS

The authors acknowledge the support from the National Science Foundation Career Grant IIS-2047912 (LY) and the Pratt Institute School of Architecture. We express our gratitude to Dr. Dinesh K. Patel from the Morphing Matter Lab at Carnegie Mellon University for offering valuable feedback on wax-related printers. Furthermore, we express our gratitude to Michael Vinciguerra, Humphrey Yang, and Lea Albaugh from Carnegie Mellon University, Tianyu Ma from Tsinghua University, and Dr. Haresh Lalvani from Pratt Institute for their valuable ideas and feedback to the development of the paper.

REFERENCES

[1] Emily Guan and Yibo Fu. 2023. Fold It: Creating Foldable 3D Volumes From Planar 2D Surfaces. In *Proceedings of the 8th ACM Symposium on Computational Fabrication* (New York City, NY, USA) *(SCF '23)*. Association for Computing Machinery, New York, NY, USA, Article 16, 2 pages. https://doi.org/10.1145/3623263.3629153

[2] Mahiar M. Hamedi, Victoria E. Campbell, Philipp Rothemund, Firat Güder, Dionysios C. Christodouleas, Jean-Francis Bloch, and George M. Whitesides. 2016. Electrically Activated Paper Actuators. *Advanced Functional Materials* 26, 15 (2016), 2446–2453. https://doi.org/10.1002/adfm.201505123 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/adfm.201505123

[3] Robert J. Lang. 2009. Computational Origami: From Flapping Birds to Space Telescopes. In *Proceedings of the Twenty-Fifth Annual Symposium on Computational Geometry* (Aarhus, Denmark) *(SCG '09)*. Association for Computing Machinery, New York, NY, USA, 159–162. https://doi.org/10.1145/1542362.1542363

[4] Qiuyu Lu, Yejun Liu, and Haipeng Mi. 2020. MotionFlow: Time-axis-based Multiple Robots Expressive Motion Programming. In *Proceedings of the 3rd International Conference on Computer Science and Software Engineering* (Beijing, China) *(CSSE '20)*. Association for Computing Machinery, New York, NY, USA, 145–149. https://doi.org/10.1145/3403746.3403919

[5] Qiuyu Lu, Lydia Yang, Aditi Maheshwari, Hengrong Ni, Tianyu Yu, Jianzhe Gu, Advait Wadhwani, Haiqing Xu, Andreea Danielescu, and Lining Yao. 2024. Guttation Sensor: Wearable Microfluidic Chip for Plant Condition Monitoring and Diagnosis. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '24)*. Association for Computing Machinery, New York, NY, USA, 9 pages. https://doi.org/10.1145/3613905.3651087

[6] Qiuyu Lu, Tianyu Yu, Semina Yi, Yuran Ding, Haipeng Mi, and Lining Yao. 2023. Sustainflatable: Harvesting, Storing and Utilizing Ambient Energy for Pneumatic Morphing Interfaces. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 32, 20 pages. https://doi.org/10.1145/3586183.3606721

[7] H Okuzaki, T Saido, H Suzuki, Y Hara, and H Yan. 2008. A biomorphic origami actuator fabricated by folding a conducting paper. *Journal of Physics: Conference Series* 127, 1 (aug 2008), 012001. https://doi.org/10.1088/1742-6596/127/1/012001

[8] Jie Qi and Leah Buechley. 2012. Animating paper using shape memory alloys. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 749–752. https://doi.org/10.1145/2207676.2207783

[9] Jihyun Ryu, Maedeh Mohammadifar, Mehdi Tahernia, Ha-ill Chun, Yang Gao, and Seokheun Choi. 2020. Paper Robotics: Self-Folding, Gripping, and Locomotion. *Advanced Materials Technologies* 5, 4 (2020), 1901054. https://doi.org/10.1002/admt.201901054 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/admt.201901054

[10] Jihyun Ryu, Mehdi Tahernia, Maedeh Mohammadifar, Yang Gao, and Seokheun Choi. 2020. Moisture-Responsive Paper Robotics. *Journal of Microelectromechanical Systems* 29, 5 (Oct 2020), 1049–1053. https://doi.org/10.1109/JMEMS.2020.2997070

[11] Kai Suto, Yuta Noma, Kotaro Tanimichi, Koya Narumi, and Tomohiro Tachi. 2023. Crane: An Integrated Computational Design Platform for Functional, Foldable, and Fabricable Origami Products. *ACM Trans. Comput.-Hum. Interact.* 30, 4, Article 52 (sep 2023), 29 pages. https://doi.org/10.1145/3576856

[12] Di Wu, Emily Guan, Yunjia Zhang, Hsuanju Lai, Qiuyu Lu, and Lining Yao. 2024. Waxpaper Actuator: Sequentially and Conditionally Programmable Wax Paper for Morphing Interfaces. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, 16 pages. https://doi.org/10.1145/3613904.3642373

[13] Di Wu, Qiuyu Lu, Hsuanju Lai, Yunjia Zhang, and Lining Yao. 2023. Demonstrating Waxpaper Plus: Sequentially and Conditionally Programmable Morphing Wax Fabrics. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI EA '23)*. Association for Computing Machinery, New York, NY, USA, Article 442, 5 pages. https://doi.org/10.1145/3544549.3583924

[14] Tianyu Yu, Mengjia Niu, Haipeng Mi, and Qiuyu Lu. 2024. MilliWare: Parametric Modeling and Simulation of Millifluidic Shape-changing Interface. In *Proceedings of the Eleventh International Symposium of Chinese CHI* (Denpasar, Bali, Indonesia) *(CHCHI '23)*. Association for Computing Machinery, New York, NY, USA, 461–467. https://doi.org/10.1145/3629606.3629654