Morphlour: Personalized Flour-based Morphing Food Induced by Dehydration or Hydration Method

Ye Tao[†*], Youngwook Do[‡*], Humphrey Yang[*], Yi-Chin Lee[*], Guanyun Wang[*], Catherine Mondoa[*], Jianxun Cui[§*], Wen Wang[*], Lining Yao[*]
[*]Carnegie Mellon University, [†]Zhejiang University, [‡]Georgia Institute of Technology, [§]University of Wisconsin
[*]{ytao2, hanliny, yichinle, guanyunw, cmondoa, wenwang2, liningy}@andrew.cmu.edu,
[†]taoye@zju.edu.cn, [‡]youngwookdo@gatech.edu, [§]jcui23@wisc.edu

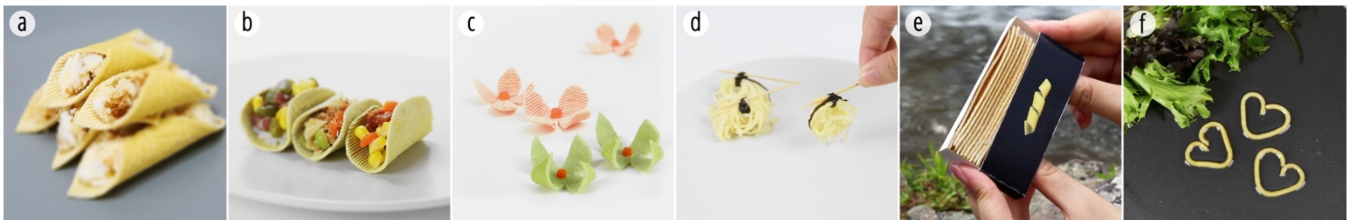

Figure 1. Applications of Morphlour. Dehydration-based examples through baking, including (a) Self-wrapping cannoli, (b) Self-wrapping tacos, and (c) Self-folding multi-flavored cookies. Hydration-based examples through boiling, including (d) Self-assembling noodles for accessibility, (e) Flat-pack hiking food, and (f) Shape customization for special events - morphing heart shape.

ABSTRACT
In this paper, we explore personalized morphing food that enhances traditional food with new HCI capabilities, rather than replacing the chef and authentic ingredients (e.g. flour) with an autonomous machine and heterogeneous mixtures (e.g. gel). Thus, we contribute a unique transformation mechanism of kneaded and sheeted flour-based dough, with an integrated design strategy for morphing food during two general cooking methods: dehydration (e.g. baking) or hydration (e.g. water boiling). We also enrich the design space of morphing food by demonstrating several applications. We end by discussing hybrid cooking between human and a design tool that we developed to ensure accuracy while preserving customizability for morphing food.

Author Keywords
Morphing food; programmable material; interactive food; design tool; dehydration; hydration; hybrid cooking.

CSS Concepts
• **Human-centered computing~User interface toolkits;**
• Human-centered computing~Scenario-based design;
• Applied computing~Computer-aided manufacturing

ACM 978-1-4503-6816-2/19/10 $15.00
https://doi.org/10.1145/3332165.3347949

INTRODUCTION
From Chinese dumplings, Japanese ramen, Italian pasta, to Mexican tortillas or French bread, flour plays an important role in our civilization and supplies us energy as a staple food across culture and history. Here, we demonstrate how material driven design with advanced digital technology transforms the way we customize and interact with flour-based food through shape-changing techniques.

Previously, shape-changing food has been introduced to the HCI community as a design concept [17, 42]. In particular, the pasta shape-changing property has been demonstrated with a gelatin/cellulose mixture by [42] and chitosan by [17]. However, these edible proteins, or polysaccharides-based materials are not conventionally used to make authentic pasta for our daily consumption and energy supply. It is necessary to re-engineer the material components of pasta with the advanced digital design and fabrication tools to add utility to democratize the shape-changing food concept.

Inspired by the design vision of prior work, here we introduce a new type of stimulus (dehydration via baking) to trigger food shape-change during cooking upon a new edible material: flour-based food. Besides this, we also propose a new shape-changing mechanism through hydration (via boiling) for flour-based authentic pasta to obtain shape-changing behavior. Both dehydration and hydration methodologies were able to be accomplished through digital design by having the understanding of the material compositions and the mechanical behaviors. In this paper, we will go through the details of how to make morphing flour-based food from the aspects of understanding its design space, material behavior, design and fabrication tools.

This paper presents the following contributions:

- Design strategy and mechanisms for authentic flour-based morphing food during dehydration (e.g. baking) or hydration (e.g. boiling) processes with natural, staple and edible ingredients for energy supply.
- A tailored computational design tool and hybrid fabrication methods.
- Exploration of the design space for morphing food via several novel applications.

RELATED WORK

Shape-changing Food

Recently, shape-changing materials have been used in a variety of HCI contexts, leveraging the morphing materials' characteristics to create novel interactive affordances. Isabel et al. [30] reviewed a set of novel shape-changing interfaces with variable material properties, such as foldable interactive objects [16, 27, 31, 37-39, 45], stretchable interactive sensors [21, 43], and inflatable interactive interfaces [28, 29, 44]. In their papers, they describe transformative materials that respond to one stimulus type. Our work contributes to this study by introducing one food material mechanism triggered by two different stimuli types, broadening this approach to more applications of food.

Previously, shape-changing food has been explored with different materials and triggering mechanisms, including pneumatic-driven inflatable bread [35], water swelling induced shape-changing gelatin-cellulose-based pasta [42], and pH responsive chitosan-based shape-changing noodles [17]. Our work focuses on flour-based food. Compared to the previous work on shape-changing food [17, 42], the differences are manifold. Firstly, the transformation mechanisms are different. While literature introduces bi-layer composition, we use grooving patterns as the major transformation mechanism. Secondly, we focus on both dehydration and hydration processes with a unified design and fabrication process. Lastly, we use natural ingredients that are functional for energy supply purposes, i.e., all the shape-changing flour-based food examples are mainly pasta composed of semolina flour. Consequently, our shape-changing food can produce authentic flavor, nutrition and mouthfeel, and be considered as common food with various functionalities.

Human-Food Interaction in HCI

Within the HCI community, recent research on human-food interaction plays an important role in validating the importance of food in our daily lives [4, 15]. More edible user interfaces are created as a playful interaction modality [22, 24, 26]. For instance, EdiPulse [19], an interactive Chocolate Machine, creates activity treats which support physical activity by offering playful reflections, to facilitate self-control and to deter undesirable behaviors [18]. Moreover, food related products and interfaces offer a new channel to explore how people interact with food, such as food journals and food photographs [5, 6, 25]. In addition, there has been increasing interests in the ecological value of food such as post-harvest processing, by-product processing as well as food waste [8-10].

In the digital fabrication area, recent products and research projects have enabled digital technology to customize the "shape, color, flavor, texture and even nutrition" [33] of food. For instance, Digital Gastronomy integrated existing digital fabrication instruments into traditional kitchens, allowing chefs to personalize dishes [23], Digital Konditorei merged a modular mold and a genetic mold-arrangement algorithm to control the taste structures of a dish [48], and there are an increasing number of projects which provide diverse engineering solutions for digitalized food design [3, 11, 12, 36] and nutrition control [7, 20, 34, 47]. Moreover, robotics-based food manufacturing technologies are emerging to automate conventional manual cooking processes [2, 32].

With the advent of digital technology enabled by computer-controlled machines [13, 46], an increased number of food properties can be prompted to be explored in production and cooking procedures. We continue to think about how to integrate the shape-changing food in this domain of research. Also, we propose a design strategy and mechanism of designing, making, cooking and interacting with morphing food with the hope that these findings will serve as a valuable reference for the HCI community.

DESIGN SPACE OF MORPHING FOOD

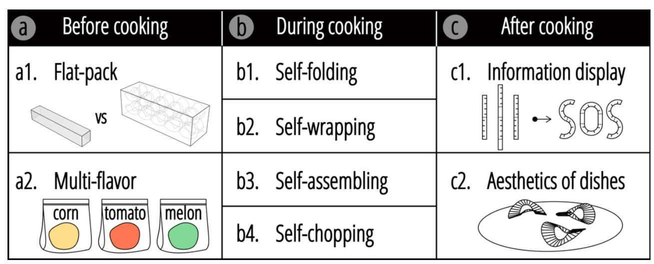

Figure 2: Design space of morphing food: (a) before cooking (e.g. flat-pack function, multi-flavor nutrition), (b) during cooking (e.g. self-folding for fine dining [27], self-wrapping for baked food, self-assembling or self-chopping noodles [27] for accessibility, etc.), and (c) after cooking (e.g. information display, aesthetics of dishes, etc.).

We hope that the temporal transformation of morphing food can open up new design space about the interaction with shape-changing food such as the usage of morphing food in daily life and even self-morphing robot in a human body for future medical purpose. Here, we introduce morphing food's unique utility in the temporal order (Figure 2): (1) before cooking, the compact flat-pack function and multi-flavor nutrition can be achieved by applying the Morphlour technique; (2) during cooking, various transformation behaviors can be explored for different usages. The Morphlour dough's transformation can be an effective visual cue to communicate the cooking progress of food to users, identical to the progress bar of software installations. For instance, if the Morphlour pasta is not yet fully transformed, users can tell if the cooking is not yet finished; (3) after cooking, the Morphlour food can be used to encode information into food, in which the cooking process can be considered as the decoding process. For example, a diner can receive a message that a cook hides (encode) in the Morphlour food. Also chef can explore unique aesthetic of dishes.

The temporal properties of Morphlour can inspire applications in personalized food contexts. We will talk about it in the Application section.

MORPHLOUR DESIGN STRATEGY

Morphlour (a portmanteau of "morph" and "flour") introduces an integrated design strategy, which contains stimuli, composition and property, for flour-based morphing food during either dehydration (e.g. baking) or hydration (e.g. water boiling) cooking processes (Figure 3).

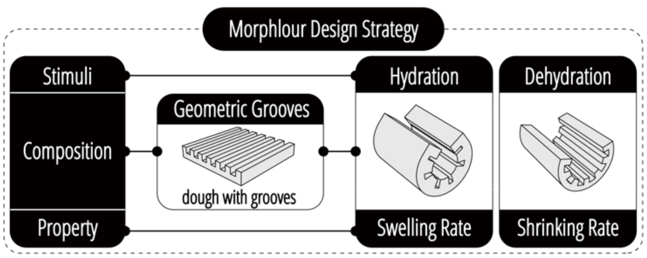

Figure 3: Illustration of Morphlour design strategy for creating flour-based morphing food induced by dehydration or hydration stimuli.

Challenges in Flour-based Morphing Mechanisms

In material science, constructing a bi-layer structure with two materials that possess different expansion or contraction rates under specific stimuli (e.g. water diffusion) is one of the most commonly used methods to achieve a shape-changing effect for a sheet-shaped material [1, 41, 42, 45]. We initially hypothesized that we could achieve a shape-changing property with authentic flour-based ingredients by replicating the same mechanism, creating a bi-layer structure with two different flour types. However, in the initial experiments, we were not able to gain the satisfying results from the flour-based bi-layer structure samples. As Figure 4 shows, oat fiber bi-layer samples that consist of flour and flour-oat fiber showed bending angle smaller than 5 degrees.

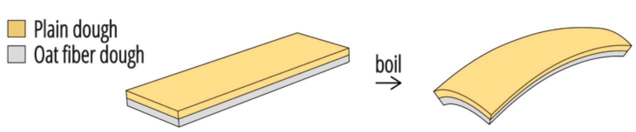

Figure 4: A plain flour/oat fiber bi-layer film does not show dramatic bending effect. (All the ingredients can be found in the following Material Performance Section.)

In addition, flour brings newer challenges to the manufacturing process. Standard pasta dough has much higher viscosity than gelatin (the base material for Transformative Appetite [42]) or chitosan (the base material for Organic Primitives [17]). Additionally, the gluten network within the dough makes it impossible to use either the same film making procedures reported previously [17, 42], or other alternative manufacturing methods reported for hydration-based shape changing materials beyond food applications [14]. Instead of dissolving the raw ingredients in water or organic solvents, we adapted the classic method of sheets production in cooking - kneading the dough with a dough mixer and sheeting it with a pasta sheeter. Multi-layer composite sheets can be produced, which will be detailed in the production section.

Groove-induced Morphing Mechanisms

To tackle the aforementioned challenges, we discovered a novel mechanism that enables a flour-based sheet to achieve a shape-changing property - groove-induced differential swelling or shrinking. By grooving geometrical features on the surface of the sheeted dough, we can control the swelling rate (Figure 5a) or dehydration rate (Figure 5b) of the material, which causes the pasta shape to morph.

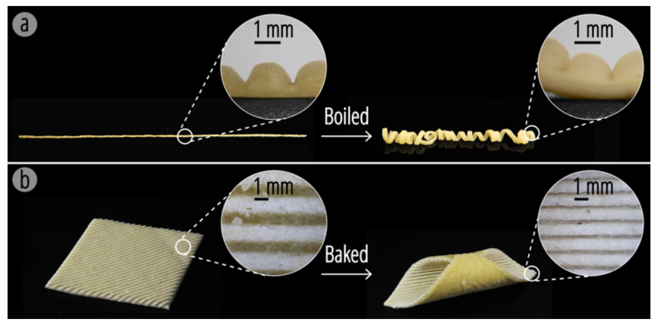

Figure 5: The groove-induced morphing mechanism examples: (a) a thin hair pasta noodle transforming into a dense coil when it is boiled; (b) a sheeted square piece of dough turning into a dried cannoli wrap when it is baked.

Hydration Stimulus. We validated the grooves' geometrical features by observing the microstructure of the dough (Figure 5a). We found that the grooves caused the difference in the swelling rate and the side with grooves contributes to slower rate of swelling. Grooves also provide the space that each peak can expand both directions vertical to grooves, while the side without grooves can expand much larger without any interruption. When the peaks on both sides of each groove are close enough during the swelling process, the two peaks tend to stick together under the gelatinization of dough, which serves to maintain the transformed shape.

Dehydration Stimulus. We observed that the drying process enables the pasta sheet to achieve the same bending orientation as the swelling process (Figure 5b). However, we found that the dehydration process required a longer duration (45 to 90 minutes) to achieve the sheet's deformation than the swelling process. Due to this long process, we presumed that heat is applied inside and outside the pasta sample uniformly. This allowed us to infer that the difference in the shrinkage rate between the side with and without grooves caused by the rate of thermal diffusion propagation may not be a main reason of the dehydration-based deformation. We hypothesized that the side with grooves has a larger surface area which can cause a higher shrinkage rate, while the surface without grooves has a smaller surface area which means a lower shrinkage rate. We found that higher temperatures can enhance the deformation effect, which prompted us to achieve a baking method for self-wrapping food.

COMPUTATIONAL DESIGN AND FABRICATION

Parameterized Material Performances

In order to integrate the mechanism into our computational design tool, we calculated and validated transformation behaviors systematically with parameters that include the geometry parameters for grooves, geometry parameter for dough and the ingredient composition.

For all the experiments, we used three different types of dough - plain dough, egg white dough, and oat fiber dough, which are commonly used for the ingredients of pasta dough and recommended by professional pasta producers. The plain dough was made with 112g semolina flour and 43g water; the egg white dough contained 112g flour, 9g egg white, and 43g water; and the oat fiber dough contained 112g flour, 42g oat fiber, and 125g water. The pasta sample size was 50mm in length, 15mm in width, and 2mm in thickness. The mold we used to groove had a pitch distance of 1.5 mm. For angle measurements, we took a side-view photo of the pasta samples and traced their outlines in CAD software (i.e., Rhinoceros 3D) using Bézier curves. We then measured the angle between the tangential vectors at both ends of the pasta outlines. The measured maximum bending angle deviation was less than 10% in our repeatability tests.

Groove Depth. The groove depth is proved to be an effective control parameter to determine the maximum bending angle of the sheeted dough. Figure 6 shows that for the three chosen groove depths, the deeper the groove depth is, the bigger the maximum bending angle is. For the same sample, the average maximum bending angle is bigger during the hydration process than the dehydration process. We used plain dough for this experiment.

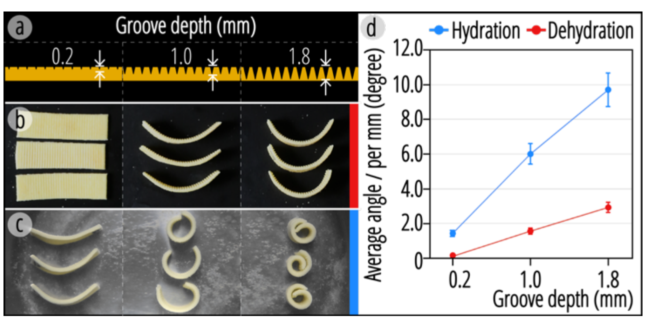

Figure 6: Groove depth affects the bending angle. (a) The groove depth of different samples with the same mold. Maximum bending angles of samples during (b) dehydration or (c) hydration process. (d) The groove depth to the average maximum bending angles per unit length.

Groove Direction. The groove direction determines the bending orientations. As Figure 7 shows, during both dehydration and hydration processes, the samples bend perpendicular to the directions of the parallel grooves. For this experiment, the groove depth was 1.8 mm and plain dough was used.

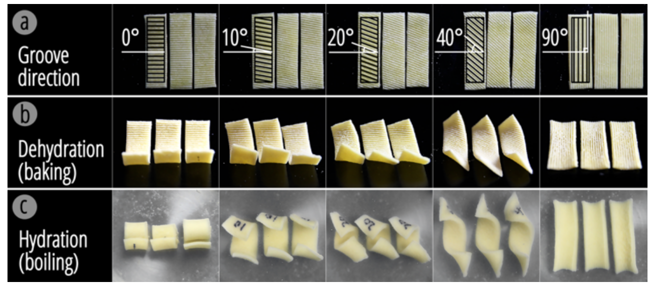

Figure 7: (a) A group of parallel grooves with varied angles to the edge of the rectangle samples. During (b) dehydration or (c) hydration process, the samples bend along the direction of the grooves.

Ingredients. The purpose of this test is to optimize the maximum bending angle by introducing a bi-layer material composition in conjunction with the groove effect. Figure 8 shows that by forming either a flour and flour-egg white bi-layer (egg white dough), or a flour and flour-oat fiber bi-layer (oat fiber dough), the maximum bending angle can be further increased. For this experiment, the groove depth was 1.8 mm.

In this experiment, egg white was chosen for its ability to harden when cooked due to the denaturation of its proteins at high temperature.

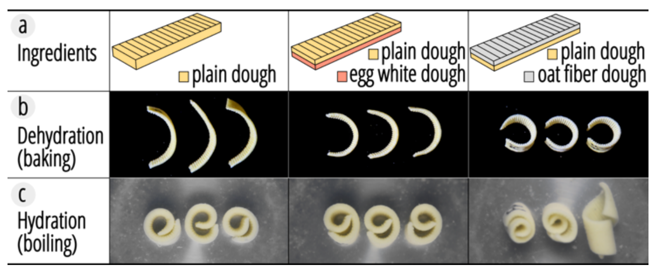

Figure 8: The maximum bending curvature can be increased by introducing bi-layer composite structure into the grooved dough.

Computational Design Tool

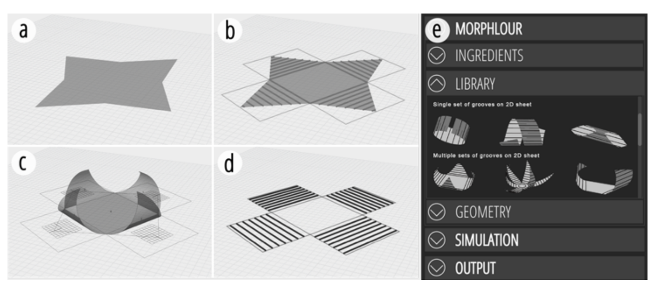

Figure 9: The design flow. (a) Defining the dough shape; (b) Setting the area of grooves and grooving parameters; (c) Simulating the 3D shape; (d) Generating molding guidance and the G-code to control machine. (e) User interface for control parameters and example shape selection.

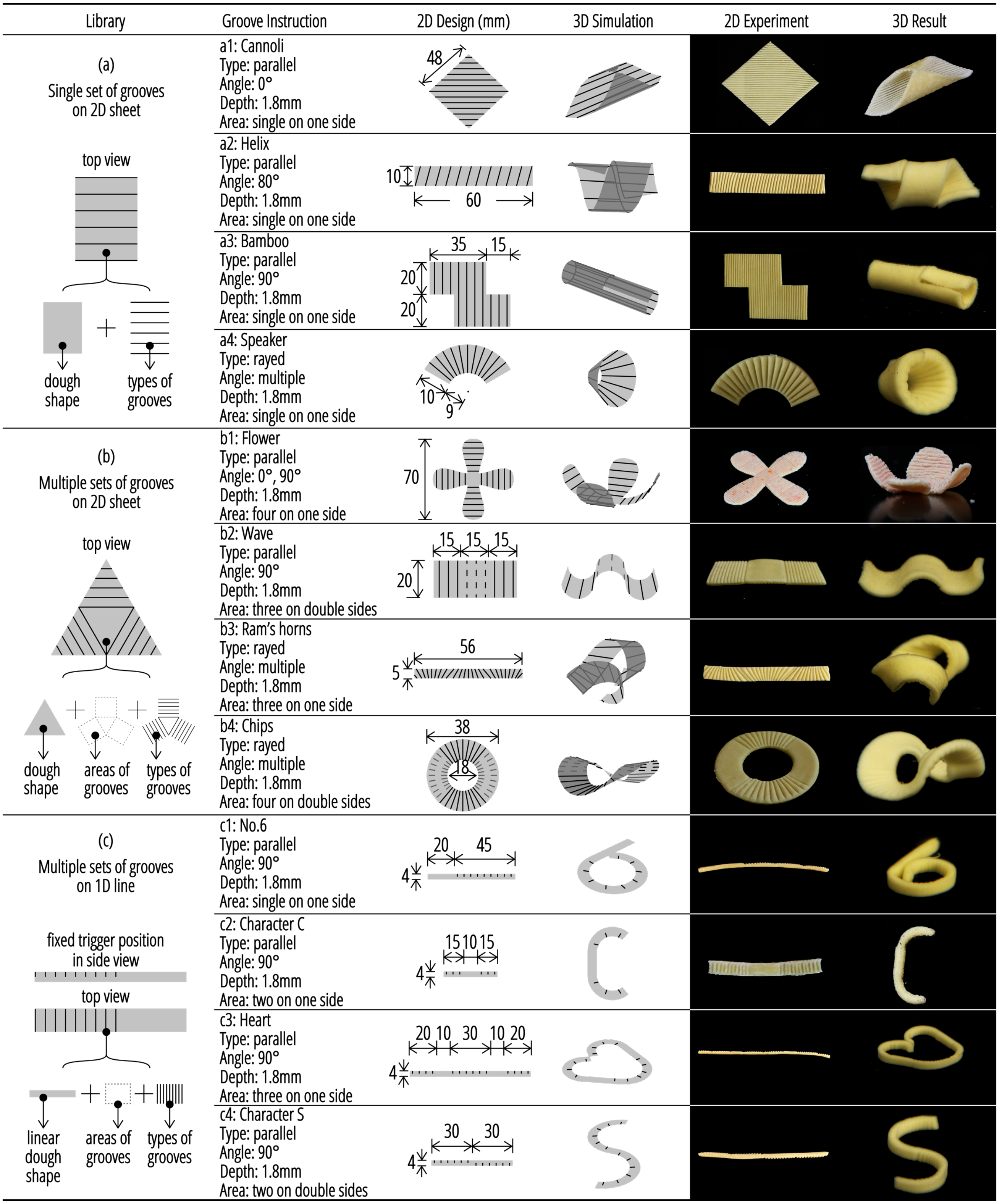

Figure 10: Design library and experimental examples. (a) A single set of grooves on a 2D sheet through (a1) dehydration and (a2-4) hydration process. (b) Multiple sets of grooves on a 2D sheet through (b1) dehydration and (b2-4) hydration process. (c) Multiple sets of grooves on a 1D line through hydration process. All the samples were made of semolina flour except for the b1 sample which is made of oat fiber with tomato.

We developed a computational design tool to integrate design parameters and cooking guides to help users easily design and simulate morphing food (Figure 9). The tool will compile G-code for mold fabrication and future machine operation.

Shape Library. Based on our tests of the dehydration and hydration cases, we recommend multiple shape designs, including a single set or multiple sets of grooves on a 2D sheet or 1D line (Figure 10).

Grooving Mold Design. To quickly iterate and test the design parameters of the molds, our experiments utilized 3D printed molds with an Objet 24 Stratasys 3D Printer with a 16μm printing resolution setting. We used a food grade mold release (CRC 03311) to make our fabricated molds food safe.

Based on our experimental results, the small pitch distances and the sharp tips of the mold are essential to achieve high-quality - fine and sharp - grooves on the dough, and the quality of the grooves will consequentially affect the quality of the transformation performance. The optimal groove pitch distance was identified to be 1.5 mm (the pitch distance less than 1mm was challenging to fabricate due to the stickiness and elasticity of dough), and the groove depth was chosen due to the thickness of sheeted doughs. Since the groove depth tends to vary depending on the applied pressure, we added stoppers to both sides of the mold to keep the consistency of the groove depth during the manual grooving process (Figure 11a). In the digital fabrication process, we adopted a part modularization method [40] to easily switch customized molds with magnets.

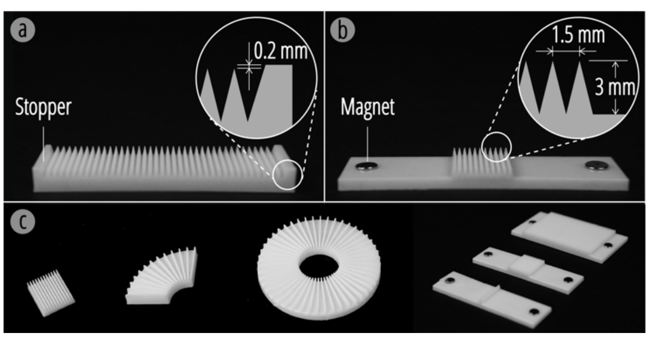

Figure 11: 3D printed customized molds: (a) Grooving mold with stoppers for the manual process; (b) Grooving mold with magnetic connections for the digital fabrication process; (c) Variable molds for shape customizability.

Hybrid Fabrication Process

Dough Preparation. This is a semi-manual process that is commonly used in kitchen. It includes three steps - mixing, sheeting, and cutting. In a dough mixer (Cuisinart SM-50 5.5 - Quart Stand Mixer), we add all the ingredients at once and mix it for 15 to 20 minutes. The dough can be stored in a zipper bag to retain the dough's moisture until the sheeting process begins. For the sheeting process, a roller sheeter (Marcato Atlas 150 Pasta Machine) can be used to sheet the dough up to 150 mm wide with 10 optional thicknesses from 0.6 mm to 4.8 mm (defined by roller No. 0 to 9). Most of our experimental samples are 2 mm in thickness, which can be sheeted sequentially at thickness setting No. 0 for one time, No. 2 for one time, and No. 3 for three times. For our bi-layer structures, two separately sheeted doughs can be prepared, stacked, sheeted, using the same previously mentioned process. Finally, the dough can be cut into a proper size and shape.

Grooving. Unlike a traditional pasta dough preparation process, grooving is a unique step tailored to our method. On one side, we can manually press our customized mold with stoppers on its both ends (Figure 11a) into the sheeted dough to produce grooves, such that the dough exhibits shape-changing behavior. On the other side, the manual method has limited shape complexity, accuracy and repeatability. Therefore, fabricating the groove patterns with corresponding shape-changing motions with digital fabrication methods is recommended.

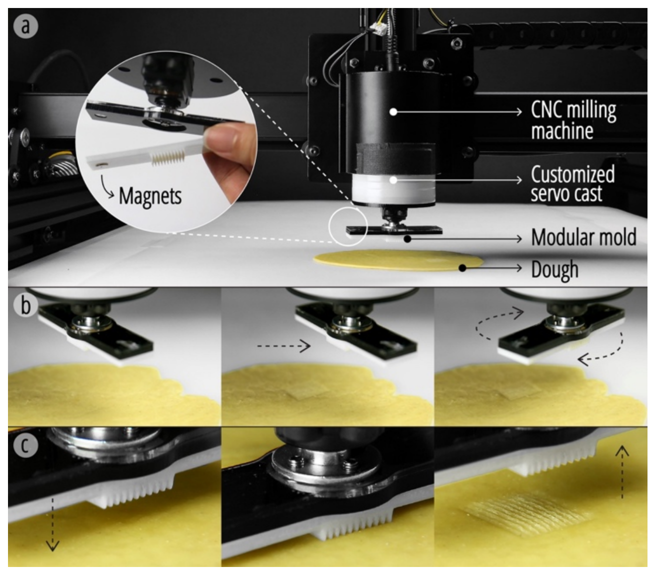

Figure 12: Digital fabrication for the grooving process. (a) A CNC machine was equipped with a rotational tool head with a replaceable grooving mold. (b) The tool head goes through a cycle of rotating and grooving according to the design. (c) The result of the automatic grooving.

We developed a four degree of freedom grooving platform by modifying a 3-axis CNC milling machine (Inventables X-carve 750mm x 750mm) which is controlled by an X-controller and a 3D carving motion controller kit distributed by Inventables. The machine is compatible with our design software. It can take the G-code toolpath compiled by the design tool and execute the grooving task. We replaced the spindle of the original milling machine with our customized servo cast that mounts a 55g Metal Gear Servo connected vertically with our customized grooving mold. A user can switch the mold to another one with a different size or shape according to the target transformation (Figure 12a). The customized tool head can groove the pasta dough in various directions with 180-degree rotation range.

Drying. This step is necessary only for dried flat food that is designed to exhibit the hydration-based transformation. For example, commercial pasta is often dried to prolong the shelf life. The aforementioned morphing mechanisms introduced previously indeed work for both fresh and dried dough. We shared our drying method in Figure 13. This process takes 12 - 24h. The cover and the base plate with mesh holes are aimed to accelerate the process by allowing large airflow to contact with the sheeted dough. All the samples were dried at room temperature (25 °C).

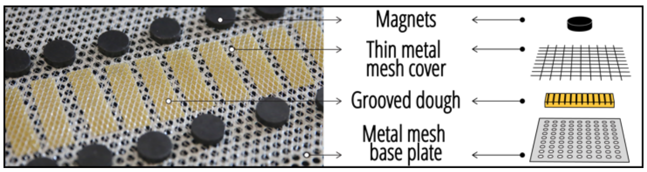

Figure 13: Drying process optional to the hydration-based shape-changing food.

Cooking Conditions

Dehydration Cooking. We employed a convection oven (Oster) as our dehydration cooking (i.e. baking) environment. We found that a low-speed and convection-based dehydration process will enhances the bending performance. Thus, we set the oven to 200 °F with turbo convection function under bake mode and kept the oven open with a fan to accelerate air movement. Over a period of 90 minutes, we observed that the deformation started in around 4 min, and the maximum deformation behavior occurred in about 45 min.

Hydration Cooking. we employed an induction cooker (Rosewill RHAI-13001) as our hydration cooking (i.e. boiling) environment. Using the conventional method for cooking pasta, we boiled water, put pasta into the pot, and cooked it for 12 to 15 min. The transformation begins shortly after the pasta enters the boiled water, reaching its maximum bending angle in about 12 min, and retaining the angle within 20 min. Hence, users can decide when to stop the cooking depending on the preferred mouthfeel.

PRELIMINARY USER STUDY

To investigate how people would perceive shape-changing food regarding both its taste and function, we ran a tasting and individual interview session with 6 diners (Figure 14).

Session Structure

The study session consisted of two parts, a 30-minute session of cooking demonstration and tasting of our pasta and a 30-minute private survey. 6 people (Average age: 28.3; STD age: 3.3; Gender: 4 Male / 2 Female) participated in the session. All participants had experiences about cooking and eating pasta and none of them had professional career experience in the culinary field. We prepared three different types of shape-changing pasta and one normal flat pasta made of egg white dough: (1) Cylindrical shape pasta (2) helix shape pasta (3) cannoli shape pasta (4) normal flat pasta (Figure 14a). Once finishing our demonstration of cooking, we asked them to try the pasta in the aforementioned order.

Figure 14: Collecting user feedbacks on the mouthfeel and experiences.

Taste and Feedback

Shapes and Textures. Participants pointed out the fact that shape-changing pasta holds tomato sauce better than the normal pasta. As a result, Morphlour pasta tastes more savory. Moreover, some participants mentioned that they enjoyed the elastic and volumetric texture when they bit the Morphlour pasta samples. Lastly, one participant indicated that it was easier to hold the Morphlour pasta with their utensils because of their resilient texture and curve shape. On the other hand, some participants complained that Morphlour pasta had not been cooked as well as the normal pasta, even though we cooked all the samples for the same amount of time. From their feedback, we learned that Morphlour pasta with the same thickness must cook for one or two minutes longer than normal pasta to achieve an al dente consistency. This is due to the groove structure on the surface of the pasta.

Shape Variations. One participant argued that the textures of the pasta differed by shape of the pasta. Another participant felt that the cylindrical shape and the helix shape are more visually appealing than the others.

Playful Experiences. Generally, all participants gave positive feedbacks about the cooking process. One participant suggested that the customizable shape change would make it more fun to cook and to observe the cooking process. Three participants mentioned that it was an amazing experience to watch pasta transform its shape in the boiling water and commented that they would love to showcase the cooking process at house parties as a performance.

APPLICATIONS

To envision how Morphlour pasta can shape daily experiences and interactions with people, we developed four application scenarios as followed.

Personalized Pasta Shapes from Flat-pack

We developed four transformation types for flatly packed hiking food. In previous work, Transformative Appetite [42] introduces the vision that shape-changing food can enable a flat-packaging technique to achieve high space efficiency of food packaging. Morphlour brought this vision into reality. We developed four examples of semolina flour-based pasta that can save packing spaces ranging from 41% to 76% (Figure 15). Figure 16 shows that the food was cooked and consumed in an outdoor environment with a backpacking stove.

Figure 15: Four flat-pack hiking food, before and after cooking.

Figure 16: A field cooking experience for outdoor hikers.

Customized Edible Information Display

Pasta noodles can be transformed on the dining table while it is being served, potentially providing a rich platform for diners to experience interactive information delivery. This interaction can provide different types of information by heating a metal plate that is responsive to various kinds of stimuli, like music.

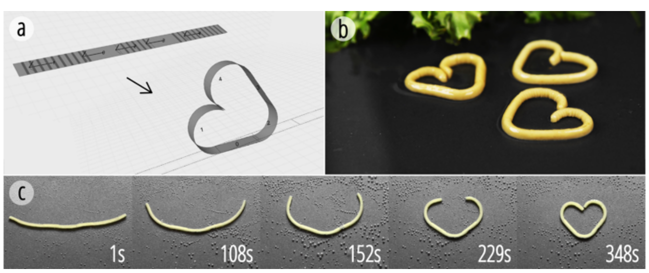

Figure 17: Food as an information display. (a) The design tool to customize and simulate the transformation for a special event; (b) Thin lines transform into hearts; (c) the actual transformation behaviors.

With this platform, people can send messages served on dishes. We imagine and demonstrate the following scenarios: a metal plate containing uncooked angel hair noodles is served to a diner's table. A violinist comes to the table and plays a song, 'Salut d'amour'. Upon recognizing the song, the heating table begins heating the plate. The pasta starts being cooked on the heated plate and changes into a heart shape within 4-6 minutes (Figure 17c), conveying a message of love from the diner's partner (Figure 17b).

Multiple Flavors and Dishes

Multi-flavored cookies. We explored composite dough with different flavors and nutrition components. Figure 18 shows that different types of dough can work as raw materials for self-folding baked food.

Self-wrapping tacos and cannoli. We replicated the classic food with a relative smaller size, which allows us to envision that our method can be easily adopted in our daily life to provide new experience with our traditional food. Figure 19 shows the preparation process and the final shape of baking-induced self-wrapping covers made of flour dough. This method starts with flat shape dough and enables the dough to transform into a target shape without a human intervention, which reduces a cook's work during cooking.

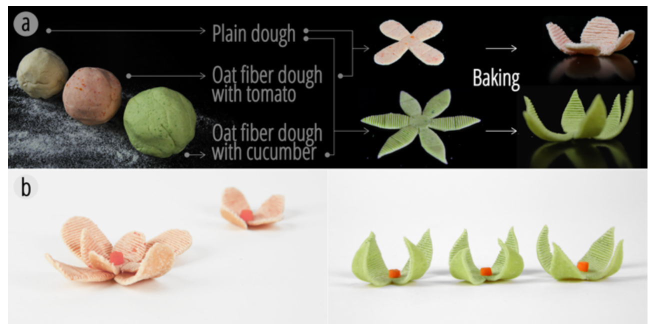

Figure 18: (a) The preparation process of self-folding cookies with different flavors and nutrition contents. (b) The final shape of the cookies after baking process.

Figure 19: The preparation process of (a) self-wrapping tacos and (b) self-wrapping cannoli.

Self-assembling Noodle Balls for Accessibility

The shape-changing property of noodles can be used to introduce a new type of eating experience for those who have difficulty using common utensils including forks and chopsticks. For example, a pile of thin noodles with a wood stick can be transformed into a lollipop-shaped noodle ball so that children who have not learned how to use forks can handle eating long noodles. With this method, they can easily hold the stick and feed themselves (Figure 20). We expect that this approach will leverage the advantages of shorter cooking time and flat-packing capabilities, in addition to the post-assembled shape to improve accessibility for the young, handicapped and the elderly.

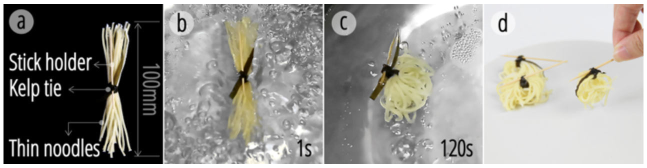

Figure 20: Self-assembling noodle balls for accessibility. (a) The design parameters. (b) A pile of thin-hair noodles before cooking. (c) Self-assembled noodle ball after cooking; (d) The self-assembled shapes afford easy accessibility.

LIMITATION, DISCUSSION AND FUTURE WORKS

Geometry and Accuracy

Sheet-based and Line-based Geometry. Morphlour exhibits folding-based transformation from a flat sheet or a line shape. This means that we can make developable shapes, but not a completely arbitrary one. In addition, for dehydration method, double-side folding geometry is limited by gravity and friction in the air.

Repeatability. Morphlour has good repeatability as long as grooving and the cooking condition stay consistent. Figure 21 shows the same geometry cooked by dehydration and hydration method three times. This result shows that the dehydration method has lower repeatability compared to the hydration method mainly because gravity affects the sample's transformation less in water than in air due to buoyance, and the heat can be applied more uniformly in water than in air.

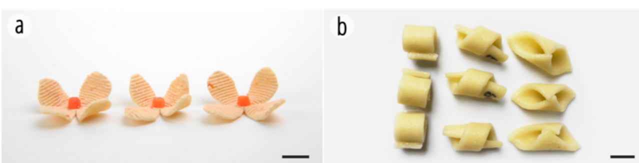

Figure 21: Morphlour examples through (a) dehydration method and (b) hydration method. Scale bar: 10mm.

Digital Technique Improvement

Software. Compared to a general design software tool, Morphlour provides a forward design tool with simulation function which generated by the experimental bending data. An inverse design tool and an ingredient library that can support personalized capability are not included but desired.

Fabrication machine. Morphlour demonstrates how a customized fabrication machine improves the way for grooving sheeted dough. The fabrication machine can help enhance the standard groove quality and save manual efforts for multi-area grooving demand. Based on the feedback of our industrial partner, grooving can be incorporated as an additional step following the standard manufacturing pipeline of sheet-based flat pasta. However, several processes are not automated yet. For example, the steps of placing dough, shifting molds or cutters, and cutting outline are not included in the automatic process but desired to be included.

Envisioning Food Customizability for HCI

What if food can sense, respond, and even compute? How can programmable materials and material-driven interface development inspire the way to design the cooking and eating experiences? Through Morphlour, we built on top of existing work, and tried to explore, a few of these design aspects. Dynamic food can be leveraged as an information display to reveal a hidden message that says that it is tasty; food can be a cooking progress indicator; food can be a responsive packaging - self-wrapping covers; food can transform in ways to make eating experiences more accessible and convenient. In the future, we can also leverage the rich literature on food and senses in order to explore how transformative food can bring unique sensational experience.

CONCLUSION

In this paper, we discussed a novel and simple mechanism that utilizes either the dehydration or hydration cooking process for flour-based dough to achieve its shape-changing property. We presented detailed experimental results, a customized design software and hybrid fabrication process that includes a user's intervention. Applications are developed to indicate the potential design space for flour-based morphing food. Both baked and boiled Morphlour examples are designed to achieve the Morphlour's shape-changing property. Besides the flat packaging functionality of authentic pasta, we also proposed novel use-case scenarios including food as an information display, food that improves accessibility, and food that self-wraps and is suitable for multiple favors. On a higher level, we hope that this work can expand the design vision, space, and interface design of a shape-changing property. Food can become media that transforms and interacts with cooks and diners. By pushing the utilization of authentic and common food ingredients, we also hope that this technology can be adapted further for real-world use and commercialization in the near future.

ACKNOWLEDGMENTS

The authors would also like to thank Tingyu Cheng and Zeyu Yan for assisting the molds printing; Danli Luo and Haolin Liu for the material mechanism suggestion.

REFERENCES

[1] B. An, Y. Tao, J. Gu, T. Cheng, X.A. Chen, X. Zhang, W. Zhao, Y. Do, S. Takahashi, H.-Y. Wu 2018. Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces. In *Proceedings of the Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 260.

[2] M. Bollini, S. Tellex, T. Thompson, N. Roy, D. Rus 2013. Interpreting and executing recipes with a cooking robot. In *Proceedings of the Experimental Robotics*, 481-495.

[3] M. Chang, L.V. Guillain, H. Jung, V.M. Hare, J. Kim, M. Agrawala 2018. Recipescape: An

interactive tool for analyzing cooking instructions at scale. In *Proceedings of the Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 451.

[4] R. Comber, J.H.-J. Choi, J. Hoonhout, K. O'hara 2014. Designing for human–food interaction: an introduction to the special issue on 'food and interaction design'. *International Journal of Human-Computer Studies 72*, 181-184.

[5] F. Cordeiro, E. Bales, E. Cherry, J. Fogarty 2015. Rethinking the mobile food journal: Exploring opportunities for lightweight photo-based capture. In *Proceedings of the Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, 3207-3216.

[6] F. Cordeiro, D.A. Epstein, E. Thomaz, E. Bales, A.K. Jagannathan, G.D. Abowd, J. Fogarty 2015. Barriers and negative nudges: Exploring challenges in food journaling. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, 1159-1162.

[7] K. Fukuchi, K. Jo, A. Tomiyama, S. Takao 2012. Laser cooking: a novel culinary technique for dry heating using a laser cutter and vision technology. In *Proceedings of the ACM multimedia 2012 workshop on Multimedia for cooking and eating activities*, 55-58.

[8] E. Ganglbauer, G. Fitzpatrick, R. Comber 2013. Negotiating food waste: Using a practice lens to inform design. *ACM Transactions on Computer-Human Interaction (TOCHI) 20*, 11.

[9] E. Ganglbauer, G. Fitzpatrick, F. Güldenpfennig 2015. Why and what did we throw out?: Probing on Reflection through the Food Waste Diary. In *Proceedings of the Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, 1105-1114.

[10] E. Ganglbauer, G. Fitzpatrick, G. Molzer 2012. Creating visibility: understanding the design space for food waste. In *Proceedings of the Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia*, 1.

[11] T. Gayler 2017. Towards edible interfaces: designing interactions with food. In *Proceedings of the Proceedings of the 19th ACM International Conference on Multimodal Interaction*, 623-627.

[12] T.D. Gayler, C. Sas, V. Kalnikaitē 2018. User Perceptions of 3D Food Printing Technologies. In *Proceedings of the Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, LBW621.

[13] N. Gershenfeld 2008. *Fab: the coming revolution on your desktop--from personal computers to personal fabrication*. Basic Books.

[14] A.S. Gladman, E.A. Matsumoto, R.G. Nuzzo, L. Mahadevan, J.A. Lewis 2016. Biomimetic 4D printing. *Nature materials 15*, 413.

[15] A. Grimes, R. Harper 2008. Celebratory technology: new directions for food research in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 467-476.

[16] J. Gu, D.E. Breen, J. Hu, L. Zhu, Y. Tao, T. Van de Zande, G. Wang, Y.J. Zhang, L. Yao 2019. Geodesy: Self-rising 2.5 D Tiles by Printing along 2D Geodesic Closed Path. In *Proceedings of the Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 37.

[17] V. Kan, E. Vargo, N. Machover, H. Ishii, S. Pan, W. Chen, Y. Kakehi 2017. Organic Primitives: Synthesis and Design of pH-Reactive Materials using Molecular I/O for Sensing, Actuation, and Interaction. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 989-1000.

[18] F. Kehr, M. Hassenzahl, M. Laschke, S. Diefenbach 2012. A transformational product to improve self-control strength: the chocolate machine. In *Proceedings of the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 689-694.

[19] R.A. Khot, D. Aggarwal, R. Pennings, L. Hjorth, F.F. Mueller 2017. Edipulse: investigating a playful approach to self-monitoring through 3D printed chocolate treats. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 6593-6607.

[20] B. Lee, J. Hong, J. Surh, D. Saakes 2017. Ori-mandu: Korean Dumpling into Whatever Shape You Want. In *Proceedings of the Proceedings of the 2017 Conference on Designing Interactive Systems*, 929-941.

[21] E. Markvicka, G. Wang, Y.-C. Lee, G. Laput, C. Majidi, L. Yao 2019. ElectroDermis: Fully Untethered, Stretchable, and Highly-Customizable Electronic Bandages. In *Proceedings of the Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 632.

[22] D. Maynes-Aminzade 2005. Edible bits: Seamless interfaces between people, data and food. In *Proceedings of the Conference on Human Factors in Computing Systems (CHI'05)-Extended Abstracts*, 2207-2210.

[23] M. Mizrahi, A. Golan, A.B. Mizrahi, R. Gruber, A.Z. Lachnise, A. Zoran 2016. Digital gastronomy:

Methods & recipes for hybrid cooking. In *Proceedings of the Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, 541-552.

[24] M. Murer, I. Aslan, M. Tscheligi 2013. LOLL io: exploring taste as playful modality. In *Proceedings of the Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, 299-302.

[25] J. Noronha, E. Hysen, H. Zhang, K.Z. Gajos 2011. Platemate: crowdsourcing nutritional analysis from food photographs. In *Proceedings of the Proceedings of the 24th annual ACM symposium on User interface software and technology*, 1-12.

[26] M. Obrist, C. Velasco, C.T. Vi, N. Ranasinghe, A. Israr, A.D. Cheok, C. Spence, P. Gopalakrishnakone 2016. Touch, taste, & smell user interfaces: The future of multisensory HCI. In *Proceedings of the Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, 3285-3292.

[27] S. Olberding, S. Soto Ortega, K. Hildebrandt, J. Steimle 2015. Foldio: Digital fabrication of interactive and shape-changing objects with foldable printed electronics. In *Proceedings of the UIST 2015*, 223-232.

[28] J. Ou, M. Skouras, N. Vlavianos, F. Heibeck, C.-Y. Cheng, J. Peters, H. Ishii 2016. aeroMorph-Heat-sealing Inflatable Shape-change Materials for Interaction Design. In *Proceedings of the UIST 2016*, 121-132.

[29] J. Ou, L. Yao, D. Tauber, J. Steimle, R. Niiyama, H. Ishii 2014. jamSheets: thin interfaces with tunable stiffness enabled by layer jamming. In *Proceedings of the TEI 2014*, 65-72.

[30] I.P. Qamar, R. Groh, D. Holman, A. Roudaut 2018. HCI meets Material Science: A Literature Review of Morphing Materials for the Design of Shape-Changing Interfaces. In *Proceedings of the Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 374.

[31] A. Roudaut, A. Karnik, M. Löchtefeld, S. Subramanian 2013. Morphees: toward high shape resolution in self-actuated flexible mobile devices. In *Proceedings of the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 593-602.

[32] Y. Sugiura, D. Sakamoto, A. Withana, M. Inami, T. Igarashi 2010. Cooking with robots: designing a household system working in open environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2427-2430.

[33] J. Sun, Z. Peng, W. Zhou, J.Y. Fuh, G.S. Hong, A. Chiu 2015. A review on 3D printing for customized food fabrication. *Procedia Manufacturing 1*, 308-319.

[34] J. Sun, W. Zhou, L. Yan, D. Huang, L.-y. Lin 2018. Extrusion-based food printing for digitalized food design and nutrition control. *Journal of Food Engineering 220*, 1-11.

[35] M.M.L. The Tangible Media Group, *Inflated Appetite*, in *Food Futures: Sensory Explorations in Food Design*. 2017, Promopress. p. 203-207.

[36] C.T. Vi, A. Marzo, D. Ablart, G. Memoli, S. Subramanian, B. Drinkwater, M. Obrist 2017. Tastyfloats: A contactless food delivery system. In *Proceedings of the Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*, 161-170.

[37] G. Wang, T. Cheng, Y. Do, H. Yang, Y. Tao, J. Gu, B. An, L. Yao 2018. Printed Paper Actuator: A Low-cost Reversible Actuation and Sensing Method for Shape Changing Interfaces. In *Proceedings of the Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 569.

[38] G. Wang, Y. Humphrey, Z. Yan, N.G. Ulu, Y. Tao, J. Gu, L.B. Kara, L. Yao 2018. 4DMesh: 4D Printing Self-Folding Non-Developable Mesh Surfaces. In *Proceedings of the 2018 ACM Symposium on User Interface Software and Technology (UIST'18)*.

[39] G. Wang, Y. Tao, O.B. Capunaman, H. Yang, L. Yao 2019. A-line: 4D Printing Morphing Linear Composite Structures. In *Proceedings of the Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 426.

[40] G. Wang, L. Yao, W. Wang, J. Ou, C.-Y. Cheng, H. Ishii 2016. xPrint: A Modularized Liquid Printer for Smart Materials Deposition. In *Proceedings of the CHI 2016*, 5743-5752.

[41] W. Wang, L. Yao, C.-Y. Cheng, T. Zhang, H. Atsumi, L. Wang, G. Wang, O. Anilionyte, H. Steiner, J.J.S.a. Ou 2017. Harnessing the hygroscopic and biofluorescent behaviors of genetically tractable microbial cells to design biohybrid wearables *3*, e1601984.

[42] W. Wang, L. Yao, T. Zhang, C.-Y. Cheng, D. Levine, H. Ishii 2017. Transformative Appetite: Shape-Changing Food Transforms from 2D to 3D by Water Interaction through Cooking. In *Proceedings of the CHI 2017*, 6123-6132.

[43] M. Weigel, T. Lu, G. Bailly, A. Oulasvirta, C. Majidi, J. Steimle 2015. Iskin: flexible, stretchable and visually customizable on-body touch sensors for mobile computing. In *Proceedings of the*

Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, 2991-3000.

[44] L. Yao, R. Niiyama, J. Ou, S. Follmer, C. Della Silva, H. Ishii 2013. PneUI: pneumatically actuated soft composite materials for shape changing interfaces. In *Proceedings of the UIST 2013*, 13-22.

[45] L. Yao, J. Ou, C.-Y. Cheng, H. Steiner, W. Wang, G. Wang, H. Ishii 2015. bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces. In *Proceedings of the CHI 2015*, 1-10.

[46] L. Yao, J. Ou, G. Wang, C.-Y. Cheng, W. Wang, H. Steiner, H. Ishii 2015. bioPrint: A Liquid Deposition Printing System for Natural Actuators. *3D Printing and Additive Manufacturing 2*, 168-179.

[47] H. Zhao, J. Wang, X. Ren, J. Li, Y.-L. Yang, X. Jin 2018. Personalized food printing for portrait images. *Computers & Graphics 70*, 188-197.

[48] A. Zoran, D. Cohen 2018. Digital Konditorei: Programmable Taste Structures using a Modular Mold. In *Proceedings of the Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 400.