

FLOUR-BASED SHAPE-CHANGING FOOD AND RELATED METHODS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is a PCT International Application claiming priority to U.S. Provisional Application Serial No. 62/864,547, filed on June 21, 2019 and U.S. Provisional Application Serial No. 62/869,753, filed on July 2, 2019, both applications are incorporated by reference herein in their entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] From Chinese dumplings, Japanese ramen, and Italian pasta, to Mexican tortillas and French breads, flour plays an important role in our civilization and supplies energy as a staple food across cultures and history. The present invention demonstrates how advanced digital fabrication with material driven design transforms the way flour-based food is prepared and consumed through shape-changing techniques.

Description of Related Art

[0003] Previously, shape-changing food has been introduced to the human-computer interaction (“HCI”) community as a design concept. In particular, the pasta shape-changing property has been demonstrated with a gelatin/cellulose mixture and chitosan. 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 advanced digital fabrication tools to add utility to the design.

[0004] The present invention introduces a new stimulus (dehydration via baking) to trigger food shape-change during cooking upon a new edible material - flour-based food. Besides this, the present invention also encompasses a new shape-changing mechanism through hydration (via boiling) for flour-based authentic pasta to obtain shape-changing behavior. Both dehydration and hydration methodologies are accomplished through digital fabrication by understanding the material compositions and the mechanical behaviors. The present invention encompasses the details of how to make shape-changing flour-based foods from the aspects of understanding its material behavior, design and fabrication tools.

[0005] ***Shape-Changing Food:*** Previously, shape-changing food has been explored with different materials and triggering mechanisms, including pneumatic-driven inflatable bread, water swelling induced shape-changing gelatin-cellulose-based pasta, and pH responsive chitosan-based shape-changing noodles.

[0006] The present invention focuses on flour-based food. Compared to the previous work on shape-changing food, the differences are manifold. First, the transformation mechanisms are different. While literature introduces bi-layer composition, the present invention uses grooving patterns (surface texture modification) as the major transformation mechanism. Second, the present invention focuses on both dehydration and hydration processes with a unified design and fabrication process. Third, the present invention uses natural ingredients that are functional for energy supply purposes, (*i.e.*, in some embodiments of the present invention the shape-changing flour-based food examples are majorly composed of semolina.) In Italy, egg whites and oat fiber (as additives) are commonly used in pasta and recommended by professional pasta producers. Consequently, shape-changing foods according to the present invention can produce authentic flavor, nutrition and mouthfeel, and be considered to be a natural food with utility.

[0007] ***Digital Fabrication in Food:*** Recent products and research projects have enabled digital technology to customize the shape, color, flavor, texture and even nutrition of food. For instance, Digital Gastronomy integrated existing digital fabrication instruments into traditional kitchens, allowing chefs to personalize dishes. Digital Konditorei merged a modular mold and a genetic mold-arrangement algorithm to control the taste structures in the dish. Additionally, there are an increasing number of projects which provide diverse engineering solutions for digitalized food design and nutrition control. Moreover, robotics-based food manufacturing technologies are emerging to automate traditional manual processes. With the advent of digital fabrication technology enabled by computer controlled machines, increased food properties can be prompted to be explored in production and cooking procedures, and the present invention's shape changing food opens a promising new territory for the future of digital food technologies.

[0008] ***User Experience with Food in HCI:*** Within the HCI community, recent research papers on human-food interaction play an important role in understanding the importance of food in our daily lives. More edible user interfaces have been created as a playful interaction modality. For instance, EdiPulse, an interactive Chocolate Machine, creates activity treats which support physical activity by offering playful reflections to facilitate self-control and to deter undesirable behaviors. See F. Kehr, M. Hassenzahl, M. Laschke, S. Diefenbach 2012. A Transformational Product To Improve Self-Control Strength: The Chocolate Machine (*Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 689-694). Moreover, food related products and interfaces offer a new channel to explore how people interact with food, such as food journals and food photographs. In addition, research continues to explore the ecological value of food, especially as it relates to food waste.

[0009] ***Shape-Changing Materials in HCI:*** Recently, shape-changing materials have been used in a variety of HCI contexts, leveraging the morphing material's characteristics to

create novel interactive affordances. To the extent that researchers in this field have reviewed novel shape-changing interfaces with variable material properties, their research has focused on transformative materials that respond to one stimuli type. The present invention expands upon prior research in a novel manner by introducing one food material mechanism triggered by two different stimuli types; thereby, broadening this approach to more food applications.

[0010] *Challenges in Flour-based Shape-Changing Mechanisms:* In material science, one of the most common methods for generating a shape-changing effect for a sheet involves constructing a bi-layer structure with different expansion or contraction rates under specific stimuli (*e.g.* water diffusion). However, the bilayer structure alone is *not* effective for flour-based dough samples.

[0011] In previous research it has been explained that edible materials can swell differently: agar, gelatin, starch and cellulose have different swelling rates and by composing these raw ingredients into bi-layer or tri-layer composites, self-folding can be achieved during the hydration process. *See* 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 (*Proceedings of the CHI 2017*, 6123-6132). Replicating the same mechanism for re-creating a bi-layer structure with authentic flour-based ingredients presents challenges, however, due to the different mechanical properties of flour dough.

[0012] As Figure 2 shows, flour and flour-oat fiber bi-layer dough shows a bending angle smaller than 5 degrees (some effect by the layering of dough but not a dramatic bending effect). In this experiment, the plain dough contained 112g flour and 43g water, and the flour-oat fiber dough contained 112g flour, 42g oat fiber and 125g water. The sample size was 50mm in length, 15mm in width and 2mm in thickness.

[0013] 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) or chitosan (the base material for Organic Primitives), both materials have been the subject of previous research in the field. Additionally, the gluten network within the flour dough makes it impossible to use either the same film making procedures reported previously or other alternative manufacturing methods reported for hydration-based shape changing materials beyond food applications. Instead of dissolving the raw ingredients in water or organic solvents, the present invention includes an adaptation of 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 are detailed herein.

[0014] To tackle the aforementioned challenges, the present invention introduces a novel mechanism that enables a flour-based dough to achieve a shape-changing property, namely, groove-induced differential swelling or shrinking. By grooving geometrical features on the surface of the sheeted dough (thereby modifying the surface texture), the present invention controls the swelling rate or dehydration rate of the material, which causes the pasta/dough to change shape.

[0015] *Traditional Pasta Making:* As context for the present invention, traditional pasta is made via a multistep process that involves the steps of mixing and kneading the dough; the optional addition of flavoring and coloring; rolling the dough into sheets; cutting the dough into specified shapes and sizes; and then, optionally, drying the dough. The technique that is used in the cutting/shaping steps depends upon the type of noodle being produced. In general, this step is accomplished either by cutting the dough with blades or by extruding the dough through dies. Ribbon and string-style pasta (fettucine, linguine, spaghetti, etc.) are cut via blades. Tube or shell-shaped pasta (rigatoni, elbow macaroni, etc.) are extruded through dies. The present invention includes, among other things, a novel method, system and device for creating shape-morphing dough by imprinting or grooving a design into flat dough to change the surface texture of the flat piece of dough.

BRIEF SUMMARY OF THE INVENTION

[0016] The present invention encompasses the following: mechanisms for authentic semolina flour-based shape-changing food during the dehydration (e.g., baking) or hydration (e.g., boiling) processes with natural, staple and edible ingredients for multi-layered doughs; shape-changing semolina flour-based foods based on multi-layered doughs; methods for creating shape-changing semolina flour-based foods from multi-layered doughs; and a method for creating pasta dough having a grooved surface and two or more dough layers with different compositions.

[0017] One embodiment of the present invention comprises a shape-changing food made from a flat piece of semolina flour-based dough, which has a top surface and a bottom surface and two or more dough layers having different compositions. The flat piece of semolina flour-based dough is cut to an initial shape and an initial size. Additionally, the top surface of the dough has at least one set of parallel grooves imprinted onto it, which run perpendicular to a predetermined bending direction of the dough. Finally, the at least one set of parallel grooves has a groove depth and a groove spacing chosen to achieve a predetermined bending angle or a predetermined final shape. In other embodiments, at least one groove or a at one set of non-parallel grooves also can be used.

[0018] Another embodiment of the present invention is a method for creating shape-changing food comprising the following steps: (1) imprinting or grooving at least one set of parallel grooves onto a semolina flour-based dough, the dough having a top surface and a bottom surface and two or more dough layers having different compositions, at an angle perpendicular to a predetermined bending angle and at a groove spacing and groove depth chosen to result in a predetermined final shape and/or a predetermined bending angle; and (2)

exposing the semolina flour-based dough with the at least one set of parallel grooves to a stimuli to cause the flour-based dough to change shape.

[0019] Another embodiment of the present invention is a method for creating pasta dough having a grooved surface. The method of this embodiment comprises imprinting or grooving at least one set of parallel grooves onto the top surface of a flat semolina flour-based dough, wherein the dough has a top surface and a bottom surface and two or more dough layers having different compositions.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0020] For the purpose of facilitating understanding of the invention, the accompanying drawings and descriptions illustrate preferred embodiments thereof, from which the invention, various embodiments of its structures, construction and method of operation and many advantages may be understood and appreciated. The accompanying drawings are hereby incorporated by reference.

[0021] Figures 1A through 1F show various applications of the present invention with different types of food products;

[0022] Figure 2 demonstrates the limited bending effect of plain flour with an oat fiber bi-layer film;

[0023] Figures 3A through 3D show an overview of a manufacturing process according to one embodiment of the present invention;

[0024] Figures 4A through 4D illustrate how groove depth affects the bending angle;

[0025] Figures 5A through 5C illustrate how parallel grooves with varied angles to the edges of the dough samples impact bending;

[0026] Figures 6A through 6C illustrate the impact of a bi-layer composite structure on bending curvature;

- [0027] Figures 7A through 7E illustrate one possible process implemented by one embodiment of a computational design tool according to the present invention;
- [0028] Figures 8A through 8C show a design library comprised of a few select shaped designs according to one embodiment of the present invention;
- [0029] Figure 9 illustrates one possible instruction process for one embodiment of a manufacturing process according to the present invention;
- [0030] Figures 10A through 10D illustrate one possible dough preparation process according to one embodiment of the present invention;
- [0031] Figures 11A through 11C illustrate one possible digital fabrication process for the grooving process of one embodiment of the present invention;
- [0032] Figures 12A and 12B are two possible embodiments of a grooving mold according to the present invention;
- [0033] Figure 13 illustrates an optional drying process according to one embodiment of the hydration-based shape-changing food of the present invention;
- [0034] Figures 14A and 14B illustrate one setup of a dehydration cooking process according to one embodiment of the present invention;
- [0035] Figures 15A and 15B illustrate two embodiments of a preparation process for foods according to the present invention;
- [0036] Figures 16A and 16B illustrate one possible preparation process for self-folding cookies and the final shape of those cookies according to the present invention;
- [0037] Figures 17A and 17B illustrate one embodiment of a set-up for hydration cooking according to the present invention;
- [0038] Figures 18A through 18D show various types of flat-pack hiking foods before and after cooking according to the present invention;

- [0039] Figures 19A through 19G illustrate various field cooking experiences according to the present invention;
- [0040] Figures 20A through 20D show one embodiment of self-assembling noodle balls according to the present invention;
- [0041] Figures 21A and 21B show some examples of food as information displays according to the present invention;
- [0042] Figures 22A through 22C show one embodiment of a design tool and the resulting transformation behaviors of food according to the present invention;
- [0043] Figures 23A and 23B demonstrate a collection of user feedbacks on the present invention;
- [0044] Figures 24A through 24D illustrate how the bending angle changes with groove density according to the present invention;
- [0045] Figures 25A through 25C show samples to optimize thickness in bending performance and shape retentivity according to the present invention;
- [0046] Figures 26A through 26C show some of the design spaces that open up with the present invention;
- [0047] Figure 27 illustrates the present invention's design strategy for creating flour-based morphing food induced by dehydration or hydration stimuli;
- [0048] Figures 28A through 28C are one embodiment of a design library according to the present invention;
- [0049] Figure 29 shows examples of 3D printed customized molds according to one embodiment of the present invention;
- [0050] Figures 30A and 30B illustrate the repeatability of shapes using one method of the present invention;

- [0051] Figures 31A and 31B show one stamping method controlled by an automated machine gantry and the shape transformation of fusilli lunghi pasta (i.e., long spirals);
- [0052] Figures 32A through 32E are examples of different geometries of shape-changing pastas and their possible applications;
- [0053] Figure 33 illustrates the space saving potential of flat-packed pasta;
- [0054] Figures 34A through 34D show the experimental results on geometrical parameters of morphing pasta;
- [0055] Figure 35 is a chart of various morphing pasta samples showing a design schematic and a photograph of the corresponding flat sample;
- [0056] Figure 36 are close-up images of the gaps or grooves over time;
- [0057] Figure 37 is a flowchart of a method of making shape-changing food according to the present invention;
- [0058] Figure 38 is a flowchart of one embodiment of the computation design tool of the present invention;
- [0059] Figure 39 is a flowchart showing the interaction of the digital design process, fabrication process and cooking process for one embodiment of the present invention;
- [0060] Figure 40 is a flowchart of one way in which a computational design tool of the present invention can interact with the digital design process and the fabrication process; and
- [0061] Figure 41 illustrates the digital grooving and cutting steps and the manual grooving and cutting steps in the process of creating shape-changing food according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

- [0062] The present invention will be understood more readily by reference to the following detailed description of the invention and the accompanying figures, which form a

part of this disclosure. This invention is not limited to the specific devices, methods, processes, elements or parameters described and/or shown herein and the terminology used herein is for the purpose of describing particular embodiments and is by way of example only and not intended to be limiting of the claimed invention. Any and all patents and other publications identified in this specification are incorporated by reference as though fully set forth herein.

[0063] Also, as used in the specification including the appended claims, the singular forms "a," "an," and "the" include the plural, and reference to a particular numerical value includes at least that particular value, unless the context clearly dictates otherwise. Ranges may be expressed herein as from "about" or "approximately" one particular value and/or to "about" or "approximately" another particular value. When such a range is expressed, another embodiment includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent "about," it will be understood that the particular value forms another embodiment.

[0064] The present invention's flour-based shape-changing materials, foods **10**, methods **100**, devices, computational design tools **200** and digital fabrication processes **300** introduce an integrated design strategy for making shape-changing flour-based foods **10** during either dehydration **54** (*e.g.* baking, Fig. 30A) or hydration **52** (*e.g.* water boiling, Fig. 30B) cooking processes. Figures 30A and 30B also show the reliability and repeatability of producing food **10** of a desired or predetermined shape and bending angle **42** when utilizing the various embodiments of the present invention. This application includes a novel morphing mechanism – modifying the surface texture of dough **20** and more specifically, groove-induced differential swelling or shrinking; a design tool **200** (as shown in Figure 3); and a digital fabrication platform **300** (also shown in Figure 3) that are tailored to this novel mechanism. Figure 3C shows a thin hair pasta noodle transforming into a dense coil when it is boiled (hydration **52**). Figure 3D shows a sheeted square piece of dough **20** turning into a dried

cannoli wrap when it is baked (dehydration **54**). Figure 1 shows several applications of various embodiments of the present invention including: self-wrapping cannoli (Fig. 1A); self-wrapping tacos (Fig. 1B); self-folding multi-flavored cookies (Fig. 1C); self-assembling noodles (Fig. 1D); flat-pack hiking food **10** (Fig. 1E); and shape customized pasta (Fig. 1F). Figure 32A shows a variety of designs of novel pasta shapes (straight grooves, curved grooves, grooves on both sides) in 2D and actual pasta (from top to bottom: bamboo, container, spring, folded, wave, ring saddle, twisted) before and after cooking and shows the actual results compared with the simulation results (which can be obtained by simulating the 3D shape **230** with a computation design tool **200** according to one embodiment of the present invention). Figure 32C demonstrates the utility of flat shape pasta transforming into fusilli pasta. Finally, 32D and 32E illustrate heart shaped pasta as a medium for communication enhancement.

[0065] The method **100**, design tool **200** and digital fabrication process **300** described offer three possible embodiments of ways to make shape-changing food **10**. The various shape-changing foods **10** are made from a flat piece of flour-based dough **20**, which has a top surface **22** and a bottom surface **24**. The flat piece of flour-based dough **20** is cut to a predetermined initial shape **26** and a predetermined initial size **28**. Additionally, the top surface **22** of the dough **20** has at least one set of parallel grooves **30** running perpendicular to a predetermined bending direction **40** on it. Optionally, the bottom surface **24** of the dough **20** has at least one set of parallel grooves **30** running perpendicular to a predetermined bending direction **40** on it. For any sets of parallel grooves **30** on either the top surface **22** or the bottom surface **24**, the grooves can cover all or part of the top surface **22** and/or bottom surface **24**. Finally, the at least one set of parallel grooves **30** has a groove depth **32** and a groove spacing **34** chosen to achieve a predetermined bending angle **42** or a predetermined final shape **44**. This grooved dough **20** is then exposed to a stimuli **50**, such as hydration **52** or dehydration **54**, which causes the flat piece of flour-based dough **20** to change shape or bend. This dough **20** can be made of

one or more than one layers **29** of different doughs having different compositions and different thicknesses. The optional use of different layers **29** of dough **20** having different thicknesses, compositions, and/or different ratios of thicknesses impacts the bending angle **42** of the dough **20** and these factors can be varied to achieve predetermined bending angle **42** and/or predetermined final shapes **44**. Alternatively, any one of these factors can be varied to achieve a predetermined bending angle **42** and/or predetermined final shapes **44**. For example, the dough **20** can be comprised of layers **29** that have the same composition but different thicknesses or layers **29** that have different compositions but the same thicknesses or be made of only one layer of one composition of dough. The present invention's pastas and other flour-based foods **10** provide a traditional pasta and food taste, mouthfeel and cooking processes (hydration **52** and dehydration **54**) with entirely novel shape-changing properties. These novel foods **10** provide distinct advantages over prior shape-changing food technologies and new applications for shape-changing foods **10**.

[0066] *Overview of Hydration Stimuli and the Impact of Grooving Generally:* The present invention utilizes the impact of grooving **110** geometrical features into the microstructure of at least one surface of flour-based dough **20** (Figures 5A through 5C). Reference is made herein to flat, flour-based dough **20**, which has a "top surface" **22** and a "bottom surface" **24**. Alternatively, the phrases "first surface" and "second surface" are used herein. The use of the phrases "top surface", "bottom surface", "upper surface", "lower surface", "first surface" and "second surface" are relative terms and merely mean that the flat dough **20** has two opposing surfaces, which can be interchangeable, with at least one of the two surfaces having grooves thereon. A "top surface" **22** is generally referring to the surface that is exposed during the grooving process **110**. While the opposing "bottom surface" **24** is the surface that is resting on a support surface during the grooving process **110**. By flipping the dough **20** over, the "top surface" **22** becomes the "bottom surface" **24** and vice versa. The

various embodiments of the present invention encompass grooving **110** either or both surfaces to achieve one or a plurality of predetermined bending angles **42** on a piece of dough **20** and/or to achieve a final shape **44**.

[0067] The grooving **110** of geometrical features on the surface of the sheeted dough **20** (thereby modifying the surface texture) controls and takes advantage of the differences between the swelling rate or dehydration rate of the material of the grooved and ungrooved surfaces, which causes the pasta/dough **20** to change shape. The grooves cause a difference in the speed of water swelling (or contracting) between the upper/top **22** and lower/bottom surfaces **24**, more specifically, the side with grooves has a slower water swelling rate than the side without the grooves. Grooves also provide space into which each peak can expand in both directions, while the side without grooves can expand much larger and/or faster without any interruption. When the peaks on both sides of the groove are close enough during the swelling process, the two peaks tend to stick together under the gelatinization of dough **20**, which serves to maintain the transformed shape. Figure 31B shows the shape transformation of fusilli lunghi pasta (i.e., long spirals) before and after cooking. As the grooves collide, the released amylopectin causes them to adhere to each other. For both hydration **52** and dehydration **54**, the maximum bending angle **42** increases as the groove width decreases.

[0068] For many of the desired final shapes **44** for shape-changing food **10** illustrated in the figures associated with this application, the individual grooves in a set of grooves **30** are parallel to one another. However, the present invention does not require that the individual grooves in a set of grooves **30** be parallel to one another. The bending angle associated with an individual groove will be perpendicular to the longitudinal direction of the groove. The resulting or total bending angle or final shape **44** of a shape-changing food **10** will be the accumulation of the curvatures at each local point that is grooved on the dough **20**. Figure 35 illustrates non-parallel grooves in the “Wing” shape and the “Ring” shape 2D designs. Figure

35 also shows the corresponding photographs of dough **20** imprinted with those two non-parallel sets of grooves **30** designs. Similarly, given that the bending angle associated with an individual groove will be perpendicular to the longitudinal direction of the groove, bending of flour-based doughs or other materials can be achieved by the use of even one groove, instead of a set of grooves **30**.

[0069] For flour dough **20**, the morphing is irreversible. Pasta samples in Figs. 34A through 34D reached their maximum bending curvature between 10 to 20 minutes and remained three dimensional until the samples were overcooked and disintegrated. After 2 hours of continuous hydration **52** in 90°C, the bending curvature only had a 20% decrease. This irreversible shape assembly and shape-locking is due to amylopectin that leaks out of starch from the flour during cooking (Fig. 31B) as a natural glue to partially fuse the colliding grooves (Fig. 31B and Fig. 36) and the irreversible gluten denaturation and starch gelatinization. To maximize the bending curvature, the viscoelasticity of the dough **20** was utilized to produce quadrilateral frustum shaped grooves with a stamping mold **400** that has cuboid shaped extrusions (Figs. 12A, 12B and 31A). Additionally, the design leveraged the irreversible morphing phenomenon of flour dough **20** for shape locking (Fig. 36).

[0070] *Overview of Dehydration Stimuli:* The present invention encompasses a similar process via dehydration **54**. In the drying process, the same bending orientation performance takes place as the swelling process (Figure 5B) occurs. However, in the case of dehydration **54**, which has a longer deformation duration, the difference in the shrinkage rate between the side with and without grooves caused by the rate of thermal diffusion propagation is not the only reason for the change in the dough's shape. The side with grooves has a larger surface area which causes a higher shrinkage rate, while the surface without grooves has a smaller surface area which means a lower shrinkage rate. Additionally, higher temperatures

can enhance the deformation effect, which brings additional value to the creation of a baking method for self-warping food **10**.

[0071] *Computational Design and Fabrication - Parameterized Material*

Performances: The present invention's groove-induced shape-changing method **100** is effective for morphing flour-based food shapes. This is a novel method **100** to induce a shape-changing effect during both the hydration **52** and dehydration **54** processes, which involves modifying **110** the surface texture of the dough **20** and then exposing **120** the dough **20** to a transformational mechanism (such as a stimuli **50**) to induce a shape changing behavior. The method **100** for creating shape-changing food **10**, broadly diagramed in Fig. 37, involves grooving **110** at least one set of parallel grooves **30** onto a flour-based dough **20**, having a top surface **22** and a bottom surface **24**, at an angle perpendicular to a predetermined bending angle **42** and at a groove spacing **34** and groove depth **32** chosen to result in a predetermined final shape **44** or the predetermined bending angle **42** and then exposing **120** the flour-based dough **20** a stimuli **50** to cause the prepared flour-based dough **20** to change shape. As illustrated in Fig. 37, once the dough **20** is prepared it is then cut and/or grooved. The cutting **316** and grooving **110** steps are interchangeable in terms of the order in which they occur. Drying **330** the cut and grooved dough **20** is an optional step for those instances when the dough **20** is not going to be cooked immediately. Then, as shown in Fig. 37, the cut and grooved dough **20** is exposed **120** to a stimuli **50** and then removed from the stimuli **130, 50** when the ultimate bending angle **42** or shape **44** is achieved. When preparing shape-changing food **10** by boiling or baking, the dough **20** is then removed **130** from the stimuli **50** (boiling or baking) when it is finished being cooked and/or when the predetermined final shape **44** or the predetermined bending angle **42** has been achieved. As illustrated in Figure 27, one embodiment of the design strategy implementing this method **100** involves creating flour-based morphing food **10** that is induced by dehydration **54** or hydration stimuli **50**.

[0072] To integrate the method **100** into the present invention's computational design tool **200**, design variables need to be parameterized. In the following discussion of experiments, certain design variables are described that can control the maximum, predetermined or desired bending angle **42** and the bending orientation(s) **40** of the sheeted dough **20**. These variables are integrated into a design tool **200** according to the present invention.

[0073] The experiments used plain dough **20**, egg white dough **20** and oat fiber dough **20**. The plain dough **20** was made with 112g semolina flour and 43g water. The egg white dough **20** contained 112g flour, 9g egg white, and 43g water. The oat fiber dough **20** contained 112g flour, 42g oat fiber, and 125g water. However, it will be obvious to one skilled in the art that the exact composition of the dough **20** used with the present invention can vary by type of flour (wheat, corn, rice, spelt, garbanzo, semolina, white, bread, pizza, pasta, cake, etc.) and type of liquid (water, egg, egg yolk, milk, juice, broth, etc.), the inclusion of other ingredients including but not limited to eggs, egg whites, salt, sugar, colorings, flavorings, etc., and the ratio of dry ingredient(s) to wet ingredient(s).

[0074] For the described experiments, the sample size (or initial shape **26** and initial size **28**) was 50mm in length, 15mm in width, and 2mm in thickness. The mold **400** that was used to groove had a pitch distance of 1.5 mm. It will be obvious to one skilled in the art that other flour-based dough recipes will work with and are included in the present invention. Additionally, as explained more fully herein, it will be obvious to one skilled in the art that molds **400** having different pitch distances and groove depths **32** will accomplish different folding effects and all such variations of pitch distance (or groove spacing **34**) and groove depth **32** are included within the scope of this invention.

[0075] Groove depth **32** is an effective control parameter to determine the maximum bending angle **42** of the sheeted dough **20**. Figures 4A through 4D show that for the three

chosen groove depths **32**, the deeper the groove depth **32** is, the bigger the maximum bending angle **42** is. Figure 4A shows the groove depth **32** of different samples made with the same mold **400**. Figures 4B through 4D illustrate maximum bending angles **42** of the samples during dehydration **54** (Fig. 4B), hydration **52** (Fig. 4C) and the groove depth **32** to average maximum bending angles **42** per unit length (Fig. 4D). For the same samples, the average maximum bending angle **42** is bigger during the hydration process **52** than the dehydration process **54**. The results shown in Figure 4 were achieved using plain dough **20**, made according to the previously-described recipe for the experiment.

[0076] Groove direction **36** determines the bending orientations. As Figure 5 shows, during both dehydration **54** and hydration processes **52**, the samples bend perpendicular to the directions of the parallel grooves **30**. For this experiment, the groove depth **32** was 1.8 mm and plain dough **20** was used. Figure 5A shows parallel grooves **30** with varied angles to the edge of the rectangular sample. Figures 5B and 5C show how the varied angles bend along the direction of the grooves. These experiments showed that, for this particular composition of dough **20**, the preferred parameters are a groove depth **32** of about 1.8 mm, an initial dough thickness of about 2 mm, and a groove spacing **34** of about 1.5 mm. However, it will be obvious to one skilled in the art that the groove depth **32**, the groove direction **36**, the groove spacing **34**, the groove density, the groove direction **36**, the pitch distance, the dough composition and the initial dough thickness, size and shape can be varied to achieve any desired or predetermined bending angle **42**, desired or predetermined bending direction **40** and desired or predetermined final shape **44**, and all such combinations are included within the scope of this application. As demonstrated by the research explained herein, these factors are all interrelated and varying any one of the factors impacts the bending direction **40**, the bending angle **42** and the final shape **44**. Therefore, this application encompasses all variations and

combinations of these factors to achieve any desired or predetermined bending direction **40**, the bending angle **42** and/or the final shape **44**.

[0077] While groove depth **32** is one of the most important factors in determining dough bending, groove density, groove distance and/or pitch distance also are factors that help to determine dough **20** bending and shape. Figures 24A through 24D illustrate the effect of various groove densities on bending. As shown in Fig. 24D, a pitch distance of 1.5mm displays the best bending performance for both hydration **52** and dehydration **54** processes for the dough **20** tested under the conditions described herein. Therefore, most of the research conducted and explained herein utilizes grooves with 1.5mm pitch distance. Figures 24A through 24D also demonstrates how the pitch distance and density can be varied to achieve more or less bending depending upon the desired or predetermined bending outcome for any given application of the present invention. Various manufacturing devices and techniques can be used to achieve greater or lesser pitch distances. Figures 34A through 34D also demonstrate the results of four of these factors on the morphing pasta. Pasta strips have different bending performance with varied groove width (Fig. 34A), groove gap (Fig. 34B), groove depth **32** (Fig. 34C) and base thickness (Fig. 34D).

[0078] Another factor described more fully herein is the impact of using single-sided or double-sided grooving patterns. Both positive and negative gaussian curvatures are achieved with either single sided or double sided grooving patterns (shown in Fig. 35). Figure 35 illustrates various morphing pasta samples as a design schematic and as a flat sample. The thickness of the samples shown in Fig. 35 is 2mm.

[0079] Research on the present invention explored optimization of the maximum bending angle **42** by introducing a bi-layer **29** material composition in conjunction with the groove effect. Figures 6A through 6C show that by forming either flour and flour-egg white bi-layer **29** (egg white dough **20**), or flour and flour-oat fiber bi-layer **29** (oat fiber dough **20**),

the maximum bending angle **42** can be further increased. For this experiment, the groove depth **32** was 1.8 mm.

[0080] In this experiment, egg white was chosen for its ability to harden when cooked due to the denaturation of its proteins at high temperature. As a result, the cooked egg white dough **20** has a smaller swelling rate than plain dough **20**. In contrast, oat fiber dough **20** has a higher swelling rate than the plain dough **20**.

[0081] Layer thickness is another variable. As Figure 25 shows, during the hydration process **52**, the sheet with a layer thickness at around 2mm achieves the best shape retention after the sheet is taken out of water and the most significant or drastic bending angle **42** when the sheet is still in water. For this reason, the experiments conducted and described herein utilize 2mm as the sheet thickness, but other thickness can be used and are included within the scope this application.

[0082] Different bilayer **29** thickness ratios were tested as another variable, whereby it was determined that a 1:1 layer **29** thickness ratio for egg white dough **20** and oat fiber dough **20** behaves the best for the dough composition being used in these experiments. Thus, a 1:1 ratio applies to all bilayer experiments discussed below unless noted otherwise.

[0083] *Computational Design Tool 200:* One embodiment of the present invention is a computational design tool **200** that integrates design parameters and cooking guides to help users easily design and simulate shape-changing food **10** (broadly shown in Figures 7A through 7E and diagramed in Figs. 38, 39 and 40). More specifically, the design tool **200** implements the present invention's method **100** with a multi-step design flow, which steps can be displayed and controlled by an optional user interface. One embodiment of the computational design tool **200** has a 3D shape library **210** comprised of at least one 3D shape for flour-based foods **10**, from which library **210** the dough shape and/or the predetermined final shape **44** is defined or selected (Figs. 7A, 39 and 40). This computational design tool **200**

also has database **212** containing information on grooves and grooving parameters that correlates to each of the at least one 3D shapes for flour-based foods **10** (Figs. 38 and 40). From this database **212** the area of grooves and the grooving **110** parameters are set **220** (Figs. 7B and 40). This embodiment of the computational design tool **200** also has a code generator **214** to produce code for production of the 3D shaped flour-based foods **10**. G-code or other similar code is generated **240** to control the machine(s) (Figs. 7D, 38, 39 and 40).

[0084] Another embodiment of a computation design tool **200** comprises an additional element of a simulator to simulate the 3D shapes (Figs. 7C, 38, 39 and 40). A further element of some embodiments of the computation design tool **200** is a fabricator to groove patterns onto a flour-based dough **20**. Finally, Figure 7E illustrates one possible embodiment of a user interface for selecting control parameters for shape selection. One embodiment of the tool **200** compiles G-code for machine operation. Additionally, the code generator **214** further can generate an ingredient list **242**, dough preparation instructions **244**, and/or cooking instructions **246** and this code is used to control at least one machine in a digital fabrication process **300**. However, the design tool **200** is not limited to a particular code or machine language, and any code appropriate to the machine being used can be generated **240** and are included within the scope of this application.

[0085] One step or element of one embodiment of both the design tool **200** and the method **100** of the present invention involves determining the desired or predetermined final shape **44**. For the computational design tool **200** of the present invention, the first step involves the user choosing the dough shape. The second step is defining the groove parameters **220**. The third step is the design tool **200** simulating the final 3D shape **230** of the dough **20** after grooving **110** and exposure a stimuli **120, 50**. The design tool **200** incorporates a shape library **210**, such as the library **210** illustrated in Figure 28, that correlates these three pieces of information (the initial dough shape, the grooving parameters, and the final dough shape).

Figure 28A shows a single set of grooves on a 2D sheet **215**. Figure 28B shows multiple sets of grooves on a 2D sheet **216**. Figure 28C shows multiple sets of grooves on a 1D line **217**. Based upon tests of the dehydration **54** and hydration **52** cases, it is possible to utilize multiple shape designs, including a single set **215** or multiple sets of grooves on a 2D sheet **216** or 1D line **217**, as shown in Figures 8A through 8C.

[0086] Second, some embodiments of both the computational design tool **200** and the method **100** can involve the utilization of fabrication instructions. Following the convention of a cooking recipe, one embodiment of the tool **200** generates instructions containing material ingredients **242** and illustrated manufacturing processes **244, 246**, as shown in Figure 9. Figure 40 illustrates how these fabrication instructions can be fed into a fabrication process.

[0087] Third, one embodiment of the method **100** and the design tool **200** involves preparing the dough **310**. This embodiment employs a manual or semi-manual process that is commonly used in traditional dough making. For one embodiment of the method **100**, this process **310** includes three steps – mixing **312** (Fig. 10A and 10B), sheeting **314** (Fig. 10C), and cutting **316** (Fig. 10D). For the design tool **200**, the user can set ingredients before shape designing and the design tool **200** will generate the manual process guidance. First, all of the ingredients are placed in the bowl of a mixer at one time and mixed for 15 to 20 minutes. This step can be accomplished in a mixer capable of handling dough **20** or the dough **20** can be prepared by hand. When necessary, the dough **20** can be stored in a zipper bag or appropriate container to retain the dough's moisture until the sheeting process **314** begins. Second, for the sheeting process **314**, a roller sheeter (any capable sheeting machine or hand rolling pin) can be used to sheet the dough **20** up to 150 mm wide with 10 optional thicknesses from 0.6 mm to 4.8 mm (defined by roller No. 0 to 9 on the Marcato Atlas 150 Pasta Machine used for this research). Most of the experimental samples were 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. However, there are numerous known ways of sheeting **314** pasta that vary depending upon whether the sheeting **314** is done by hand, on a kitchen pasta maker or in a commercial-production setting. All such methods are included within the scope of this invention.

[0088] For the bi-layer **29** structures, two separately sheeted doughs **20** can be prepared, stacked and sheeted, using any of the previously mentioned processes. Doughs **20** that utilize more than two layers **29** can be prepared using a similar method. Finally, the dough **20** is cut into to an initial size **28** and initial shape **26**. It will be obvious to one skilled in the art that there are numerous automated and manual processes that can be used to prepare dough **20** for the present invention, and all such methods are included in the present application.

[0089] Grooving **110** is the third step in dough preparation. Different from common and existing dough processing steps, grooving **110** is a unique element of the present invention. Many embodiments of the present invention include pressing a customized mold **400** into the sheeted dough **20** to produce grooves, so that the dough **20** exhibits shape-changing behavior. Some examples of customized molds **400** are shown in Figures 12 and 29. One embodiment of a mold **400** has a base **410** that connects the mold **400** to a grooving machine. Another embodiment of a mold **400** has a base **410** designed for hand-held use. Each of these molds **400** also has a grooving surface **420** designed to impart grooves of a desired groove depth **32** and groove spacing **34** onto the top surface **22** and, optionally, the bottom surface **24** of the dough **20**. For different embodiments the base **410** and the grooving surface **420** can be made from a single piece of material or they can be different pieces of the same or different materials that are connected by any appropriate means known in the art. Figure 12A shows a grooving mold **400** with stoppers **430** for use with a manual process. Figure 12B shows a grooving mold **400** with magnetic connections for use with a digital fabrication process **300** of one embodiment of the present invention. Figure 29 shows variable molds **400** for shape customizability. However, the manual grooving method **110** has limited accuracy and

repeatability. Therefore, another embodiment of the present invention comprises fabricating the groove patterns **250** with corresponding shape-changing motions with digital fabrication methods **300**. For the production of food, the grooving surface **420** should be made of an appropriate food-safe material. Additionally, the quality of the grooves and tips on the mold **400** impact the quality and character of the grooves made on the dough **20**. A mold **400** with sharp inverted V-shaped tips was used for the experiments described herein.

[0090] The present invention also encompasses a digital fabrication process **300** for creating shape-changing flour-based dough **20**. Similar to the method **100** and computational design tool **200**, the digital fabrication process **300** includes the steps of: (i) mixing **312** at least a flour and a liquid together to create a flour-based dough **20**; (ii) sheeting **314** the dough **20** by rolling the dough **20** to a predetermined thickness as measured between a first surface of the dough **20** and a second surface on the dough **20**; (iii) cutting **316** the dough **20** to a predetermined initial shape **26** and a predetermined initial size **28**; and (iv) grooving **110** the dough **20** on at least one of the first surface and the second surface to cause the dough **20** to bend when the dough **20** is exposed to a stimuli **120, 50**. For some food products, the digital fabrication process **300** also can comprise drying **330** the dough **20** after grooving **110** the dough **20**.

[0091] Also, for some food products, the step of mixing **312** at least a flour and a liquid together to create a flour-based dough **20** can be performed more than one time to create more than one dough **20** and the step of sheeting **314** is performed on each dough **20**. These different doughs **20** will be layered on top of each other prior to cutting **316** the dough **20** to the predetermined initial shape **26** and the predetermined initial size **28**. For the digital fabrication process **300**, grooving **110** the dough **20** comprises grooving **110** at least one set of parallel grooves **30** into the dough **20** perpendicular to a predetermined bending angle **42**. One

embodiment of the digital fabrication process **300** can include recording the data associated with the steps of mixing **312**, sheeting **314**, cutting **316** and grooving **110** the dough **20**.

[0092] The flowcharts in Figures 39, 40 and 41 explain how the various embodiments of the present invention can be used together to go from selecting a desired design shape to producing the pasta to cooking the pasta. As illustrated in Fig. 39, the digital design process (as embodied in the computational design tool **200**) involves inputting basic information regarding the desired shape, which is used to determine or select the groove design or grooving parameters. In some embodiments, the computation design tool **200** simulates the 3D shape. The information from this digital design process then can be fed into a digital fabrication process **300**, in which the dough **20** is prepared via the steps of: (i) mixing the raw materials/ingredients **312**, (ii) sheeting **314** the dough **20**, (iii) optionally drying the dough **20** for a brief period of time, (iv) grooving **110** and cutting **316** the dough **20**, and (v) optionally drying the dough **20** more completely to create a dried food product. This prepared dough **20** is then cooked by either boiling or baking.

[0093] The flowchart shown in Figures 40 illustrates one embodiment of the computational design tool **200** in additional detail. Similarly, the flowchart shown in Figure 41 illustrates one embodiment of the digital fabrication process **300** in greater detail. All three flowcharts illustrate how the computational design tool **200** can work with the digital fabrication process **300** to produce dough **20** that is ready to be cooked (and then is cooked). Additionally, all three flowcharts (Figs. 39-41) illustrate and describe, through narrative labels, additional steps, inputs, outputs, substeps and details, which are discussed in greater detail throughout this application and which can be included in some embodiments of the method **100**, computation design tool **200**, and fabrication process **300** of the present invention but are not necessarily required in all embodiments.

[0094] One possible embodiment of each of the method **100**, design tool **200** and digital fabrication process **300** uses a four degree of freedom grooving platform that was created 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. Similar machines are in Figs. 3B and 31A, which show a stamping method controlled by an automated machine gantry to create surface grooves on sheeted pasta dough **20**. It will be obvious to one skilled in the art that any machine with similar properties and abilities can be converted and/or used to accomplish the present invention's goals. This machine is compatible with the present invention's design software (see Figs. 3A and 3B). It can take the G-code toolpath compiled by the design tool **200** and execute the grooving task **110**. The spindle of the original milling machine was replaced with the present invention's novel customized servo cast that mounts a 55g Metal Gear Servo connected vertically with a novel customized grooving mold **400** according to the present invention. A user can switch the mold **400** to another one with a different size or pitch distance according to the target transformation (as shown Figure 11A). Figure 11A illustrates a CNC machine equipped with a rotational tool head with a replaceable grooving mold **400**. The customized tool head can groove the pasta dough **20** in various directions with 180-degree rotation range. Figures 11B and 11C show a grooving sequence with varied grooving angles. Figure 11B shows a tool head moving through a cycle of rotating and grooving **110** according to the design. Figure 11C shows the result of the automatic grooving **110**. In order for a user to adjust the servo rotation angle, one embodiment of the present invention uses the spindle PWM port of the original X-controller setup. Embodiments utilizing this grooving platform and related equipment map the range of the PWM (pulse width modulation) signal to the range of a signal to control the servo rotation angle by using an external microcontroller connected with the X-controller and the servo. The microcontroller is programmed to read the PWM signal and to convert it according to the

mapped range. Then, the converted digital signal is transmitted to the servo motor, which allows a user to control the servo via the X-controller by the command originally designed for setting the spindle speed. One embodiment of this process is illustrated in Figure 41.

[0095] The newly sheeted dough **20** can be sticky, and the mold **400** can stick to the dough **20** once pressed. There are some optional steps that can be incorporated into various embodiments of the method **100**, design tool **200** and digital fabrication process **300** to address this. To minimize this, the sheeted dough **20** is allowed to air dry for five minutes after sheeting **314**, or whatever time is appropriate for the conditions of the dough **20** and the surrounding environment, to minimize sticking (see the “shortly drying” step in Figure 39). Sprinkling flour on the mold **400** before pressing can prevent the dough **20** from sticking to the mold **400** as well. Additionally, cutting **316** the dough **20** with a roller cutter before or after the grooving **110** can be required depending on the target contour. For rectangular shapes, the most effective way is to cut a long strip with calculated width firstly, and then groove it with the mold **400**. However, different shapes can require different cutting process **316**.

[0096] For most embodiments of the present invention, the steps of grooving **110** and cutting **316** are interchangeable with respect to the order in which they are performed. By using high quality cutting blades, there is little impact of the cutting process **316** on the quality of the grooves (generally, cutting does not dull or compact the edges of the grooves). However, in limited circumstances it can be found that cutting **316** the dough **20** before grooving **110** will stretch the dough **20** and, thus, change its target contour. So, in those instances it can be preferable to groove **110** the dough **20** before cutting **316** it.

[0097] To achieve the various goals of the present invention, grooving molds **400** are designed according to the predetermined or desired groove depth **32**, direction and density. Certain types and compositions of dough **20** will require the use of small pitch distances and sharp tips on the mold **400** to achieve high-quality - fine and sharp - grooves on the dough **20**,

and the quality of the grooves will consequentially affect the quality of the transformation performance. To quickly iterate and test the design parameters of the molds **400**, one embodiment of the present invention utilizes 3D printed molds **400** with an Objet printer (Objet 24) with a 16µm printing resolution setting. A food grade mold release (CRC 03311) is used to make the fabricated molds **400** of the present invention food safe. It will be obvious to one skilled in the art that there are other comparable printers, tools and methods **100** for creating molds **400** according to the present invention.

[0098] For one embodiment of the mold **400** and method **100**, the optimized groove of the mold **400** is 3mm deep with a 1.5mm pitch distance. Since the groove depth **32** tends to vary depending on the applied pressure, stoppers **430** can be added to both sides of the mold **400** to maintain consistency of the groove depth **32** during the manual grooving process **110** (shown in Figure 12A). In the digital fabrication process **300**, a part modularization method was adopted to easily switch customized molds **400** with magnets (as shown in Fig. 12B); however, other methods for attaching and switching molds **400** can work and are incorporated into the present application.

[0099] *Drying 330:* This step is necessary only when dried flat food **10** is desired for the hydration-based transformation **52**. For example, commercial pasta is often dried to prolong the shelf life. Depending upon the composition of the dough **20** some hydration can need to be included in the drying **330** process to prevent the grooved dough from cracking. This additional hydration can be accomplished by introducing a mist of water or a bit of steam in the drying process. All of the shape-changing mechanisms of the present invention work for both fresh and dried dough **20**.

[00100] One drying method **330** is shown in Figure 13. This process takes 12 – 24 hours. 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 **20**. Any other acceptable drying method **330** can be used as well and many are known within the art.

[00101] *Dehydration-based Transformation - Setup:* As Figure 14 shows, a convection oven (Oster) is one example of a dehydration **54** cooking (i.e. baking) environment that can be used with the present invention. It will be obvious to one skilled in the art that many different kinds of ovens and heat sources will work with, and are incorporated into, the present application. For example, a low-speed and convection-based dehydration process **54** enhances the bending performance. Thus, the oven can be set to 200 °F with turbo convection function under bake mode, and the oven kept open with a fan to accelerate air movement. Other temperatures and times may need to be used with different ovens, doughs **20**, environments and dehydration methods **54**. Over a period of 90 minutes, the deformation behavior started in around 4 minutes, and the maximum deformation behavior occurred in about 45 minutes. Figure 14A shows wet samples in the oven after 11 seconds of baking. Figure 14B shows samples that have been transformed after 45 minutes of baking.

[00102] *Applications - Self-wrapping tacos and cannoli:* Figure 15 shows the preparation process and the final shape **44** of baking-induced self-wrapping covers made of flour dough **20** according to one embodiment of the method **100**. This method **100** starts with flat shape dough **20** and saves the preparation efforts. Figure 15A illustrates self-wrapping tacos and Figure 15B illustrates self-wrapping cannoli.

[00103] *Multi-Flavored cookies:* Various embodiments of the present invention involve the use of composite dough **20** with different flavors and nutrition components. Figure 16 shows that different types of dough **20** can work as raw materials for self-folding baked food **10**. Figure 16A illustrates the preparation process of self-folding cookies with different flavors and nutrition contents. Figure 16B further illustrates the final shape **44** of the cookies of Fig. 16A after baking.

[00104] *Hydration-based-Transformation - Setup:* As Figure 17 shows, an induction cooker (Rosewill RHAI-13001) can be used as the hydration cooking (i.e. boiling) **52** environment. It will be obvious to one skilled in the art that many different types of cookers, stoves, stovetops, hotplates and heat sources can also be used for the present invention and the cooking times may need to be adjusted for each cooking environment. Using the same method as for pasta, the water is boiled and the pasta is placed into the pot for 12 to 15 min. The transformation begins shortly after the pasta enters the boiling water (Fig. 17A), reaching its maximum bending angle **42** after about 12 min (Fig. 17B), and retaining the angle within 20 min. Hence, users can decide when to stop the cooking depending on the preferred and/or desire mouthfeel.

[00105] *Flat-pack for Mountain Hikers:* Various embodiments of the present invention include at least four transformation types for flat packed hiking food **10**. In previous work, Transformative Appetite envisioned a scenario involving shape changing gelatin-based food flat-packing. The present invention brought this vision into reality. One embodiment of the present invention includes four examples of semolina flour-based pasta that can save packing spaces ranging from 41% to 76% (shown in Figures 18A through 18D). Figures 19A through 19G show that the food **10** was cooked and consumed in an outdoor environment with a compact gas heater.

[00106] *Self-assembling Noodle Balls for Accessibility:* The shape-changing property of noodles made according to the present invention suggests 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 (as shown in Figures 20A through 20D). The present invention leverages 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.

[00107] *Edible Information Display:* Pasta noodles made according to the present invention can be transformed on the dining table while they are being served, potentially providing a rich platform for diners to experience interactive information delivery. This interaction provides different types of information by, among other things, heating a metal plate that is responsive to various kinds of stimuli, like music. With this platform, people can send messages served on dishes. Various embodiments of the present invention incorporate, but are not limited to, 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 cooks on the heated plate within 5-6 minutes and changes into a heart shape, conveying a message of love from the diner's partner (shown in Figure 21A). Figure 21B shows that customized texts can appear as lines are being cooked. Figures 22A through 22C illustrate how the heart shape was designed, simulated, and put in action as it was cooked. Figure 22 and 22B show a design tool **200** to customize **220** and simulate **230** the transformation of food **10** for a special event. Figure 22C illustrates the actual transformation behaviors of the dough **20**.

[00108] These novel foods **10** provide distinct advantages over prior shape-changing food technologies and new applications for shape-changing foods **10**. For example, some embodiments of the present invention hold sauce better than the traditional pasta because of its bent shape. As a result, shape changing pasta **10** tastes more savory and can be created to have more elastic and volumetric texture than traditional pastas or previous shape-changing foods **10**. Additionally, it may be easier to hold the shape-changing pasta with utensils because of its resilient texture and curved shape. The present invention's pastas have a more traditional mouthfeel than previous shape-changing pastas; however, the present invention's pasta with

the same thickness may need to be cooked 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 of the present invention.

[00109] The present invention opens up multiple design spaces for shape changing food **10**, some examples of which are shown in Figures 26A through 26C. As shown in Figure 26A, the present invention provides space-saving advantages because of its flat-packing and multi-flavor options. Additionally, there is the novelty of the morphing processes of self-folding, self-wrapping-self-assembly and self-chopping (Fig. 26B). Finally, the novel shape-changing attributes of the present invention create a new food entertainment experience, as exemplified in Figures 23A and 23B and Fig. 26C. Diners can watch pasta transform its shape in the boiling water and showcase the cooking process at parties as a performance. Additionally, the present invention's shape-changing foods **10** have the ability to deliver visual information. Pastas according to the present invention can be shaped to represent different characteristics including flavor, nutrition, or even cooking time. For example, creating pasta that utilizes letters as visualization cues. A few nonlimiting examples might be an S-shaped pasta that is "sweet", a U-shaped pasta that is "umami", or a G-shaped pasta that is "gluten-free". Additionally, a cook can easily tell if the pasta is ready to eat when the pasta reaches its target shape, which negates the need for tasting the pasta during the cooking process. Alternatively, the pasta can be programmed to transform from the flat shape to an R-shape when it is "ready" to be served. The present invention's pasta can even be customized to a customer's requested shape. Foods **10** prepared according to the present invention also can be designed to reduce the hands-on time or preparation time of certain foods. For example, when preparing dishes that form a container, i.e. wraps or dumplings, traditional preparation methods involve additional time to fill and close the wraps. Wraps and dumplings according to the present invention can be

designed to self-wrap and eliminate this step in the traditional preparation process. Some examples of this aspect of the present invention are shown in Figure 15 and Figure 17.

[00110] As suggested previously, foods **10** prepared according to the present invention enable flat-packed foods **10** to have a wider variety of shapes when cooked. For example, when hiking on long duration trips, the weight, package size, and packaging and product shape become important to efficient packing and to the ability for hikers to get rid of food and make their packs lighter as the trip progresses. At the intersection of these constraints and the available equipment, there lies an opportunity for the implementation of the present invention's shape changing pasta. Packaging for food **10** made according to the present invention can be both flat and efficient because the food **10** starts out with a flat shape. However, the present invention's foods **10** can be designed to cook up into a variety of different shapes using traditional camping and hiking equipment. This provides hikers with food variety previous unattainable in efficiently packed food products.

[00111] In modern society, a large portion of food is produced remotely and shipped to customers, resulting in pollution to the air due to the emissions of greenhouse gases to the environment. The flat-packed food **10** of the present invention helps to alleviate pollution by reducing the amount of air shipped during food transport (Figs. 18A through 18D, 32B and 33). Contributing to sustainable food packaging, the morphing pasta saves 41% to 76% packaging space compared to conventional three dimensional pasta (Figs. 18, 32 and 33). Take a package containing short macaroni pasta as an example (Fig. 32B), the densest packing of tubes (side view of the pasta) in the plane is the hexagonal lattice of the bee's honeycomb. The packing density (θ) can be calculated to establish that 67.3% of volume in the package is air. The present invention takes flat-pack pasta and transforms it into 3D shapes during cooking, therefore, more than half of the space during shipping and storage will be saved. For the helical

shaped pasta packaged as a hiking food **10** (Fig. 19), this flat-pack approach can save up to 72.9% of packaging space.

[00112] The application demo previously described in Figure 19 demonstrates this idea that the present invention is, among other things, a novel and simple mechanism for morphing flour-based dough **20**, during either the dehydration **54** or hydration **52** cooking process. The various embodiments of the present invention include these novel dough **20** and food products **10**, a customized design software and a digital manufacturing platform and novel food molds **400**. Applications are developed to indicate the potential design space for flour-based shape-changing food **10**, as shown in Figure 32B (illustrating a calculation on the space saved from 2D to 3D morphing). Both baked and boiled foods **10** are designed with shape-changing behaviors. Beyond the realization of flat-pack authentic pasta, the present invention also encompasses novel use-case scenarios including food **10** as an information display, food **10** that transforms for accessibility, and food **10** that self-wraps and saves the effort of preparation and cooking. On a higher level, the present invention illustrates how food can become media that transforms and interacts with cooks and diners (Figs. 23A and 23B). By pushing the utilization of authentic and natural food ingredients, the present invention can be adapted further for real-world use and commercialization.

[00113] The previous and following explanation describes example embodiments in which the present invention may be practiced. This invention, however, may be embodied in many different ways, and the description provided herein should not be construed as limiting in any way. Among other things, the following invention may be embodied as methods or devices. The detailed descriptions of the various embodiments of the present invention should not be taken in a limiting sense.