4D PRINTING AND UNIVERSAL TRANSFORMATION

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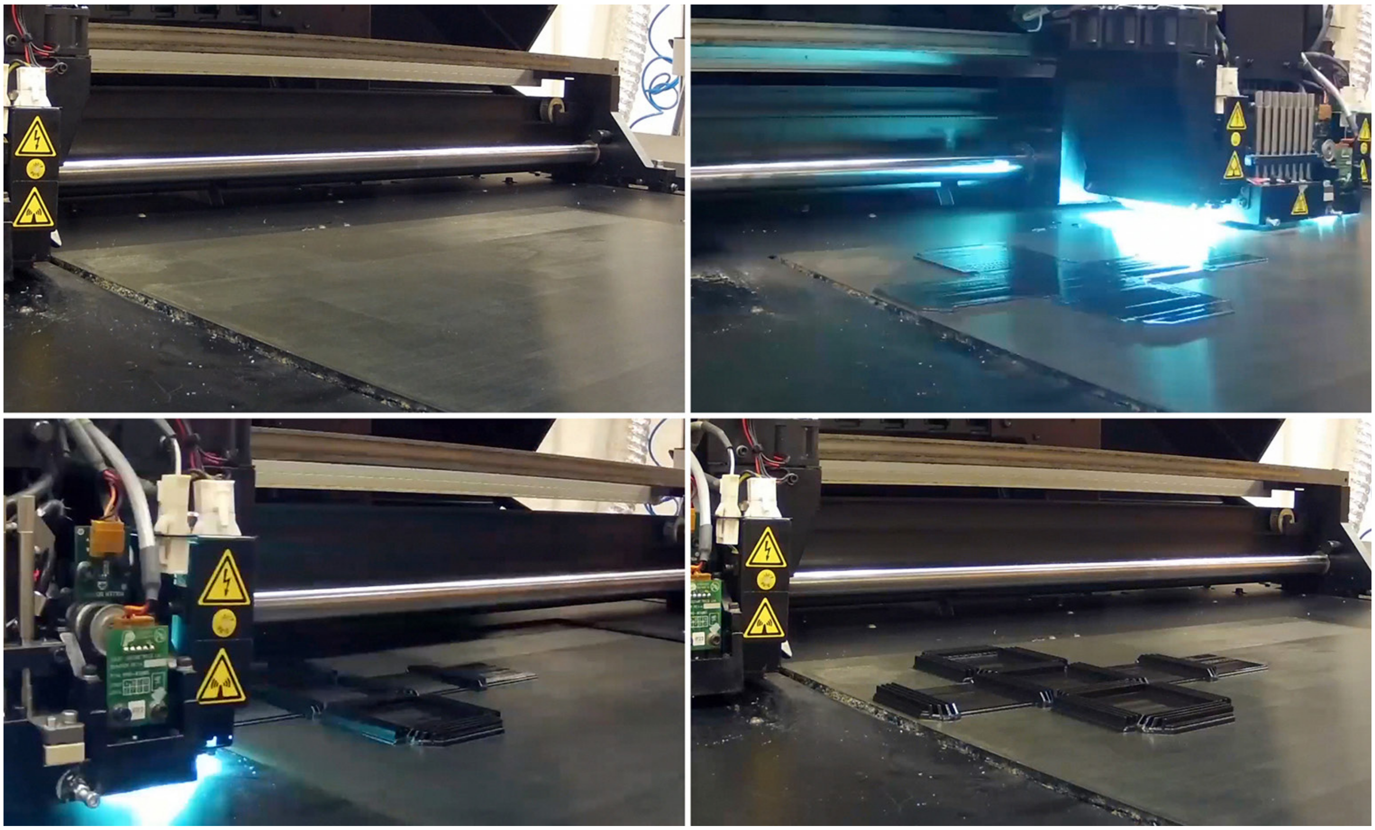


1 Stratasys' Connex Multi-Material Printer Depositing UV Curable Polymers (Dikovsky, Hirsch, Tibbits 2013)

ABSTRACT

3D printing has captured the imagination of everyone from industry experts to at-home hobbyists. However, there are significant challenges that need to be addressed in order for 3D printing to have widespread adoption in construction and manufacturing. A new category of printing has recently been introduced, called 4D printing, which describes the ability for a material system or object to change form and/or function after printing. 4D printing offers a number of unique advantages over 3D printing that may prove to be the critical capability needed to catalyze widespread implementation. This paper attempts to go beyond existing capabilities in 4D printing to create precise and universal folding techniques that approach a wider range of applications through a series of radically new physical models. A number of physical and digital prototypes demonstrate major advances in 4D printing, including: custom angle-structures that can transform from any one shape into another rigid 3D structure, curved-crease origami for doubly curved surfaces and dynamic fields utilizing surface curling and gradient material distribution.

INTRODUCTION

3D printing has captured the imagination of everyone from industry experts to at-home hobbyists. Media attention has helped to promote this technology beyond all expectations. The major arguments in favor of 3D printing and Additive Manufacturing are often cited as free complexity, mass-customization and minimizing weight/volume while maximizing strength in components (Lipson 2012). However, there are significant challenges that need to be addressed in order for 3D printing to have widespread adoption in production and manufacturing, including; print speed/time, build volume, material quality and new software capabilities (Hayes 2013). These hurdles have relegated printing to a space of tentative implementation but not yet unanimous adoption across industries.

A new category of printing has recently been introduced, called 4D printing, which describes the ability for a material system or object to change form and/or function after printing (Tibbits 2013). This technique expands current processes to include the fourth dimension, time, whereby parts can transform themselves in shape or property. 4D printing offers a number of unique advantages over 3D printing that may prove to be the critical capability needed to catalyze widespread implementation. More specifically, 4D printing offers actuation, sensing and programmability embedded directly into a material, without the reliance on external devices and electromechanical systems. This has a number of unprecedented advantages:

a) minimizing the number of components in a product or system

b) minimizing assembly time as compared to traditional processes where motors, sensors and electronics are assembled post-fabrication

c) minimizing cost as compared to expensive components

d) minimizing failure-prone devices that have become common in electronics and robotics

In order to create “smart” products, materials and architectural systems once previously required additional components that were expensive, failure-prone and difficult to assemble. However, 4D printing now allows smart materials to be programmed with linear actuators, folding mechanisms, curling/bending surfaces and material sensors. In essence, printing can now become a Materials Science chamber where the designer is able to customize the deposition of materials, anisotropic behaviors and active sensing based on the surrounding environment.

EXISTING METHODS AND MAIN CONTRIBUTIONS

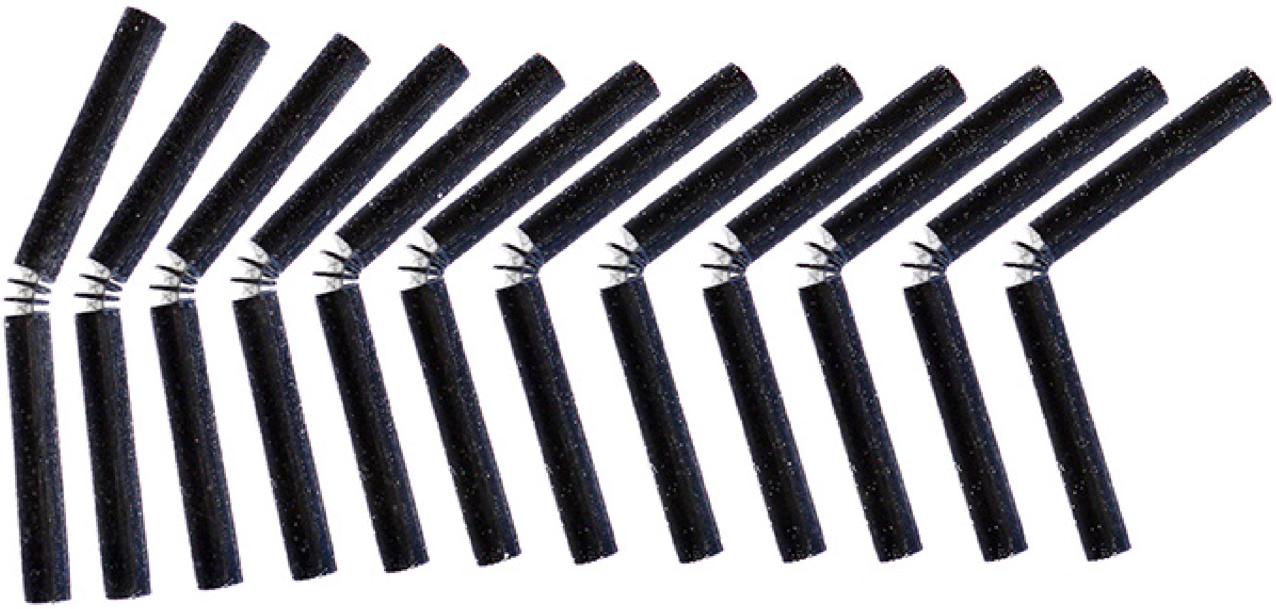
Initially, 4D printing was demonstrated with only ninety-degree folds and simple transformations that were activated when a printed structure was dipped in water (Tibbits 2013). Other researchers have recently shown composite printed materials that can be stretched then heated to activate transformation as well as light-activated materials and electrically-activated materials (Ahn 2009; Liu 2012; Qi 2013). These examples, while expanding the field, still lack universality in folding from any one shape to any other, as shown previously by Cheung et. al. in reconfigurable robotic systems (Cheung 2011; Hawkes 2010). Further, there is need for improved control over autonomous transformation, rather than human or robotic-guided energy. This paper attempts to go beyond existing capabilities to create precise and universal folding techniques that approach a wider range of applications through a series of radically new physical models.

A major challenge in any 4D printed system is how to design structures that can transform from one arbitrary shape into any another. On the hardware side, this requires complex material programmability, precise multi-material printing and a variety of highly specific joint designs for folding, curling, twisting, linear expansion/shrinkage etc. On the software front, the challenge is even greater, requiring sophisticated simulation and topology transformation to include the fabrication and material constraints and in the near future, material optimization for efficient structures.

Universal transformation is the ultimate goal and the following examples provide systematic advances for a wide variety of applications across products, architecture, infrastructure, biomedical and other industry scenarios. The first example demonstrates structures that can fold into another structure in which every joint-angle is unique. A second example demonstrates a two-dimensional structure that can transform into another two-dimensional structure with custom angles precise folding. A third example demonstrates a flat surface that can self-transform into a rigid three-dimensional surface with double curvature and curved-creases. Finally a series of models were produced to demonstrate surface curling and bending rather than folding and creasing, which allow for a dynamic field and surface patterning.

FABRICATION: MULTI-MATERIAL PRINTING

Stratasys' Connex Multi-Material printer is utilized to precisely deposit both active and static materials (Figure 1). The Connex printer deposits a UV curable polymer using inkjet heads and cures layer by layer using UV light to create the complete 3D structure.



2 4D Printed Joints Showing Custom Angles (Tibbits 2014)

The printer can print multiple materials with different properties (such as color, hardness, transparency, etc.) simultaneously, which allows the creation of complex, composite parts in a single process. Moreover, it can be used to generate Digital Materials (*DM*s) that represent distinct combinations of both components in different proportions and spatial arrangements. A *DM* inherits its properties from the parent materials and its structure can be digitally adjusted to have any set of properties in the available range. Since the mixing occurs on the tray, the spatial arrangement of the components plays a significant role in the generated *DM* characteristics and it provides additional flexibility in the *DM* engineering process. 4D printed parts are composed of a rigid plastic base and a material that expands upon exposure to water. The expanding material is a very hydrophilic UV curable polymer that when exposed to water, absorbs and creates a hydrogel with up to 150 per cent of the original volume. This expansion creates a force that drives the shape transformation. When using the expandable material by itself, its immersion in water induces only linear expansion, but when combined with the second material that has negligible expansion in water, it can induce complex geometrical transformations. The direction and the amplitude of such transformation depend on the geometrical arrangement of the expandable and the static regions. In addition, the transformations can be adjusted by replacing the pure expandable material with a *DM*, whose expansion in water can be precisely tuned by mixing the expandable and the static components to fit the required transformation amplitude.

JOINT DETAILS

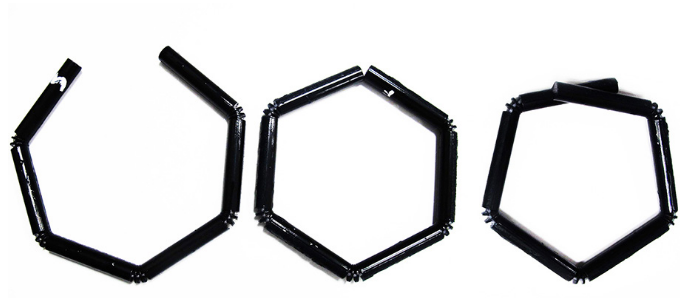
The preferred joint for 4D printing includes two layers of material. The expanding material is placed above or below a layer of rigid material. The orientation of the rigid and expanding material dictates the folding direction. For example, if the expanding material is placed above the rigid material, the two surfaces will fold downward due to the downward force applied to the rigid material and vice versa. The rotational placement of the rigid and expanding material around the long axis of a one-dimensional line dictates the second folding angle in 3D space. If less expanding material is used, the folding force will be less but the folding time will be faster. If more expanding material is used, the force will be greater and the time for folding will increase.

Rigid discs are printed at each vertex to control the angle of folding. The spacing between discs and the diameter of the discs dictate the precise angle (Figure 2). The discs rotate towards one another when the expanding material is activated, which causes them to physically hit one another and stop folding at the precise angle. If the discs are spaced further away from one another, the angle of folding will increase and vice versa. If the diameter of the discs increases, the angle of folding will decrease. However, in our models, the diameter of the discs was kept constant to lineup with the diameter of the linear members, thus the spacing between discs was utilized for custom angles.

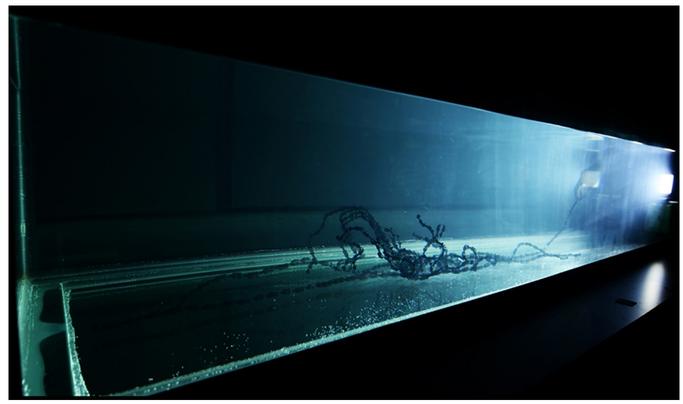
A series of tests, printed and repeated many times, were used to optimize the quantity and placement of materials to achieve precise and arbitrary angles (Figure 3). These empiric tests allowed for the calibration of digital model, simulation, fabrication tolerance and transformation dynamics. Further, the orientation of the part during the printing process created a unique grain direction and appeared to influence the final folded angle. Thus, data was gathered from each test and orientation from the printed structure to update a code that propagated custom angles into the digital model with adjusted tolerances for accurate real-world folding.

UNIVERSAL FOLDING CUSTOM-ANGLE STRANDS

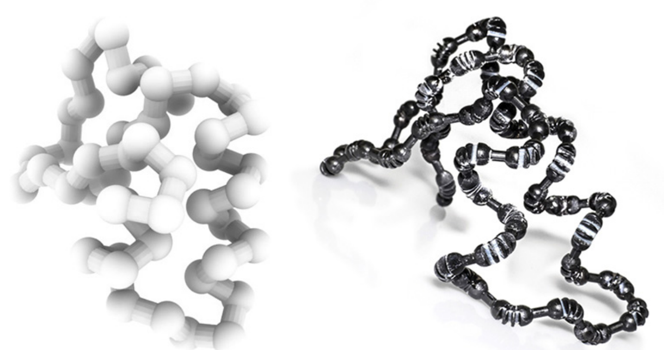
In order to demonstrate the full capabilities of custom angle 4D printing, a first prototype was developed based on a three-dimensional protein structure having arbitrary geometry and a series of complex angles (Figure 4). A model of the Crambin protein was initially downloaded from the Protein Data Bank (Figure 5). Then, a custom angle code was applied to the 3D structure to unroll the shape into a one-dimensional strand. The strand was then analyzed at each node to determine the desired angle and a custom joint was produced to accommodate the angle. This joint takes into account the calibration data encompassing fabrication tolerances and print direction to ensure the real-world transformation accurately forms the desired angle (Figure 5).



3 Three Printed Strands Showing Calibration Tests and the Precision of Custom Angles after Self-transformation (Tibbits 2014)



4 Time-lapse Images Showing the Self-transformation of a 4D Printed Protein Strand (Tibbits 2013)



5 Figure 5. Rendering (left) and photograph (right) of a 4D printed protein strand (Tibbits 2013)

The one-dimensional strand is composed of rigid segments and custom nodes that accommodate the various angles. The rigid segments provide structure and rigidity for the object after folding while the joints provide precision and encoded fold-angles. The sequence of joints embodies a geometric program, much like braille, where information is encoded into geometry. The geometry of the joints and quantity of the material enable the precise folding at each node. The property of the expanding material enables the printed part to sense its environment and thus, information and energy is functionally embedded in the part.

After the model is fully designed, the strand is sent to print on the Multi-Material Connex. The physical object is then dipped in a large 200-gallon tank of water. The temperature of the water helps increase the speed of transformation. Warmer water allows faster folding while colder water tends to take longer. On average with hot tap water, 4D printed prints take roughly fifteen to twenty minutes for full transformation. The printed protein structure ultimately took longer due to the difficulty in heating large volumes of water. Ultimately, the strand transformed itself moving in all three dimensions effortlessly to culminate in the precise final

6 A Series of Photographs Showing the Transformation from a Flat 4D Printed Structure to a Precise Truncated Octahedron (Top to Bottom) (Tibbits 2013)

7 A Series of Photographs Showing the Transformation from a Flat 4D Printed Structure to a Curve-Crease Origami Structure Approximating a Hyperbolic Paraboloid (Left to Right) (Tibbits 2013)

8 4D Printed Strip with Alternating Top and Bottom Expanding Material to Create a Sinusoidal Strip (Dikovsky, Hirsch, Tibbits 2013)

structure of the Crambin protein. The final object is pulled out of the water and encompasses every unique joint across the forty-five segment structure.

As the desired structures scale-up, future work in this direction will be needed to ensure that structure will not tangle during the folding process. Currently, the strand folds uniformly where every joint is activated at the same time. One scenario to ensure folding of complex one -dimensional structure is to control the folding sequence, for example, either folding from one end to the other or other arbitrary patterns. A third material could also be printed in this case to dissolve and then choreograph the activation of each node.

CUSTOM ANGLE SURFACES

To further demonstrate custom angle transformations, a series of flat structures were generated that utilize precise and arbitrary angles to fold from two-dimensional to three-dimensional objects. A truncated octahedron was created with hexagon faces and edge-joints (Figure 6). Similar to the protein strand, the spacing and placement of materials at each joint specified the desired fold angles. A code was generated to produce the custom angle joints and accommodate the data from calibration tests to ensure accuracy when folding.

After the file was generated and sent to the printer, the physical model was dipped in water and filmed to record the transformation process. Due to the manageable size of the model, hot water was utilized and the structure transformed within twenty minutes of activation. The calibration of the custom angles allowed for an extremely precise final structure where every edge aligned perfectly with neighboring edges. The truncated octahedron was removed from water and dried in-place to ensure the shape remains permanent. Given this technique, every known polyhedral that is able to be unfolded can now be 4D printed and self-transformed into a precise three-dimensional shape.

Two-dimensional printed structures emphasize the efficiencies of printing flat shapes, given its extremely quick print time and minimal material used. If the final truncated octahedron shape were printed, it would have taken far longer to print as compared to the flat surface even including the time for transformation, not to mention the amount of support material required. This technique points towards a future of shipping where flat-packed materials can be created, shipped flat then self-transform on-site for precise and volumetric products.

CURVED-CREASE FOLDING

A third prototypical structure was generated to challenge the possibilities of flat sheet transformations. This example attempted to transform a two-dimensional flat sheet into a three-dimensional

doubly curved surface by utilizing a technique called, curved-crease origami. Curved-crease origami is a process whereby curvilinear patterns with mountain and valley folds can approximate a doubly curved surface (Demaine, 2007). Curve-crease structures offer a promising model for 4D printing since they can be printed flat to maximize efficiency while also precisely defining a transformation into complex surfaces with extremely rigid final structures.

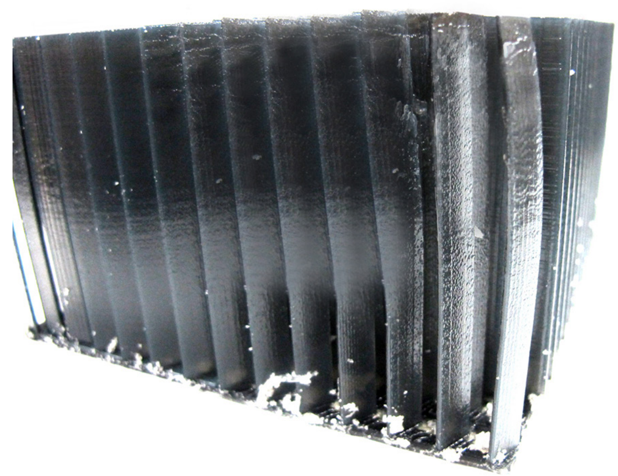
In this example, concentric circles were generated with expanding material separated by rigid material (Figure 7). The rings oscillated between placing expanding material above or below the rigid surface, thereby creating mountain and valley folds. The volume in depth and width of expanding material were empirically tested to account for the force needed for transformation. Too much material ripped the surface apart and too little material did not provide enough force to go from the initial state to the final state. The final dimensions included 1/16" wide rings of expanding material with a depth of 1/64" emphasizing the extremely thin surface structure and great strength for folding.

The printed curve-crease structure was placed in hot water and took roughly twice the amount of time to fold as compared to the truncated octahedron. The model remained static at the bottom of the tank for a long time before quickly popping into place. This strange behavior can likely be accounted to the forces accumulating in the surface until it reached a threshold that allowed the surface to jump into the mountain and valley positions. The surface then continued to fold until reaching the final, doubly curved state (Figure 7). The saddle-like structure remained extremely rigid and stable due to the conflicting forces of the curved surface. Due to this rigidity, unlike the previous models, the curved-crease surface did not unfold when taken out of water and dried.

SURFACE CURLING

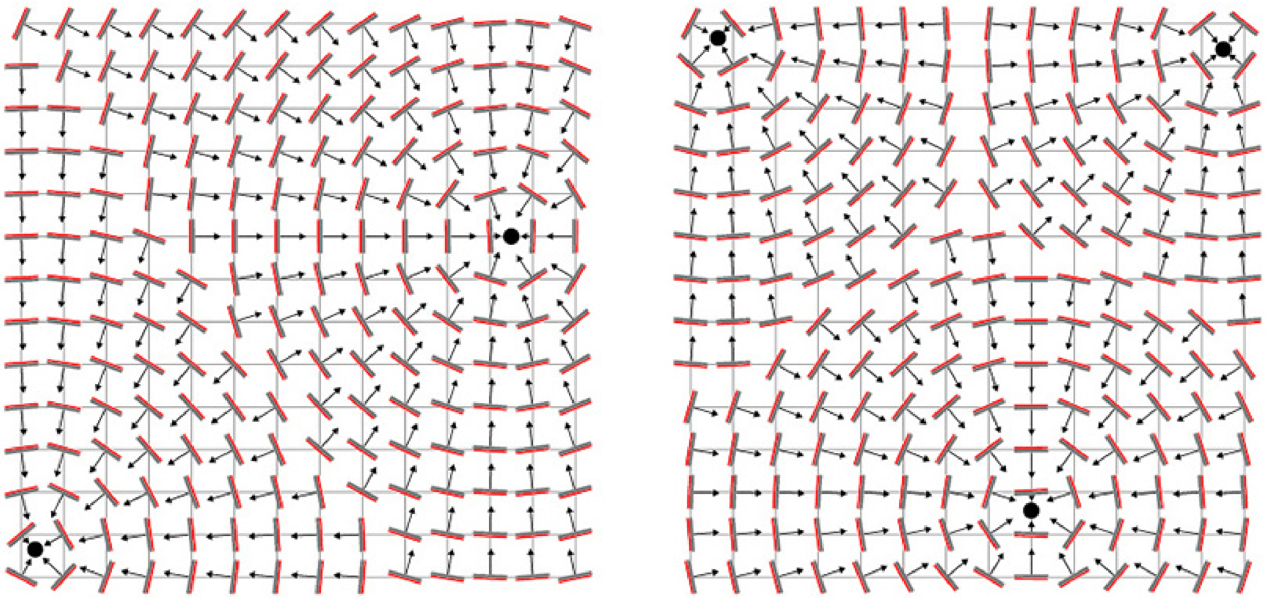
A final set of prototypes were developed showing surface curling and a gradient of material deposition to get continuous surfaces rather than point, edge or curve-crease folding. In this series of prototypes, larger areas of expanded material were deposited without the physical limits or constraints that were previously used for angular folds. The large surfaces of expanding material remained thin in order to have even expansion force across the surface but their length and width increased to create curling. Discrete or continuous amounts of material can be deposited to transition between one direction and another. If the expanding material is placed on top of the rigid material the resulting curved surface will have a smaller radius towards the rigid material and vice versa.

9 4D Printed Grid with Alternating Top and Bottom Expanding Material to Create a Sinusoidal Surface (Dikovsky, Hirsch, Tibbits 2013)



10 A Vertical Field of Straight Strips in the Printed-State with Varying Amounts of Rigid and Expanding Material (Dikovsky, Hirsch, Tibbits 2014)

11 The Resultant Dynamically Curved and Parted Field after Being Subject to Water (Dikovsky, Hirsch, Tibbits 2014)



12 Two Vector Fields with a Number of Attractor Points Dictating the Direction, Height and Placement of Material in the 4D Printed Fields (McKnelly, Tibbits 2014)

A linear strip was generated with alternating top and bottom sections of expanding material to create a precise one-dimensional sinusoidal strip (Figure 8). Similarly, a two by two surface grid was created with alternating sections of top and bottom and resulted in a mathematical sinusoidal surface (Figure 9). These simple demonstrates were used as proof-of concept tests for control and empiric study over behavior, quantities of material and resultant forced-based surfaces. Control and analysis is extremely important in surface curling given that there are not mechanical joints or physical stops, and thus, the quantity and placement of material is critical for precision.

To further demonstrate surface curling, a series of dynamic fields were generated to explore surface patterning and hair-like qualities. Fields of vertical linear strips were created with expanding material deposited on a specific side of the strip, depending on the desired curling direction (Figure 10). A number of attractor points were designed across a field that influenced the placement of expanding material as well as the rotation of the strip in X and Y directions in order to dictate the focal point of transformation. The length of the vertical strips also determined the amount of curling, since longer strips would create more curvature and wrap around neighboring smaller strips with less curvature. Tests were conducted to emphasize grain-direction and splits or ridges within the field (Figure 11). Another set of field tests was created with two and three attractor points to demonstrate more control over the field transformation (Figure 12 and Figure 13). Future tests will explore more recognizable geometric patterns that emerge only after the field is activated. The dynamic fields point towards future applications in sportswear, fashion or construction materials where surface texture and fur-like properties can mediate an external environment, control thickness, shape, and porosity or shock-absorption characteristics.

GRADIENT DISTRIBUTION OF MATERIAL

Finally, physical experiments and simulations were produced using thin surface disk and a gradient distribution of rigid material from the center point (shown in red in (Figure 14)) to a circumference with full expanding material (shown in purple in (Figure 14)). In the experiment, different mathematical surfaces could be produced based on the time of submersion in water from zero

minutes to thirty minutes and twenty-four hours (Figure 15). In the simulation, a gradient material distribution as well as the transition state and the final state were demonstrated. The initial deformation was uniform and flat. However, after increasing the force upon the surface, symmetry was broken and the sinusoidal circumference shape was reached (Figure 14). This example points towards a model of 4D printing where the material is embedded with a patterned distribution and the length and complexities of its environmental exposure may dictate the final structure rather than a pre-designed and deterministic result, as in previous examples.

13 The Resultant Curved Fields Showing Control of Curling and Attraction to Various Attractor Points across a Field. (Dikovsky, Hirsch, Tibbits 2014)

FUTURE DEVELOPMENT & APPLICATIONS

Future development will be focused on a variety of capabilities. Currently, if a 4D printed structure is allowed to dry unconstrained after transformation, it tends to unfold and open towards the original shape. When dipped back in water, it will again self-transform to the precise three-dimensional structure. However, this process is not infinitely repeatable as the material degrades overtime. Continued research will investigate material composition and mechanical means to control directionality and reversibility. For example, certain applications may demand a material to transform once and never return to the original state, while other applications may require continued reversibility, back and forth. Further studies and material development will also be conducted to increase the pallet of activation energies outside of water. Preliminary studies have been conducted with heat and light activated materials that offer promising trajectories.

4D printing points towards a future of education and scientific discovery where physical and tangibly dynamic structures can be used to understand existing mathematically, biological, chemical, physics-based and other dynamic phenomena. Similarly, researchers can utilize self-evolving structures and dynamic models as a test bed for experimenting and discovering new material properties and functional behaviors. The recent discovery of Graphene demonstrates a radical new composition of existing components and an example of what could become far more common through macro-scale models that transform themselves based on internal and external stimulus.

Exciting applications of self-transforming structures can be seen across industries such as; medical devices, sportswear/equipment, aerospace, automotive, marine, defense, construction materials and infrastructure sectors. At extremely large-scales and complex environments, these technologies can be utilized as a manufacturing and construction technique whereby raw materials are printed on small-volume machines then self-transform into extremely large functional structures like space antennae, solar arrays or other non-human constructed space architecture. Further, building materials may soon be able to adapt to fluctuating environments and dynamically mediate moisture control, sound and temperature with varying thicknesses and active surface treatments. 4D printing, much like the ribosome, encodes instructions, actuation, sensing, and assembly capabilities directly into the material themselves for smart and adaptive constructs of the future.

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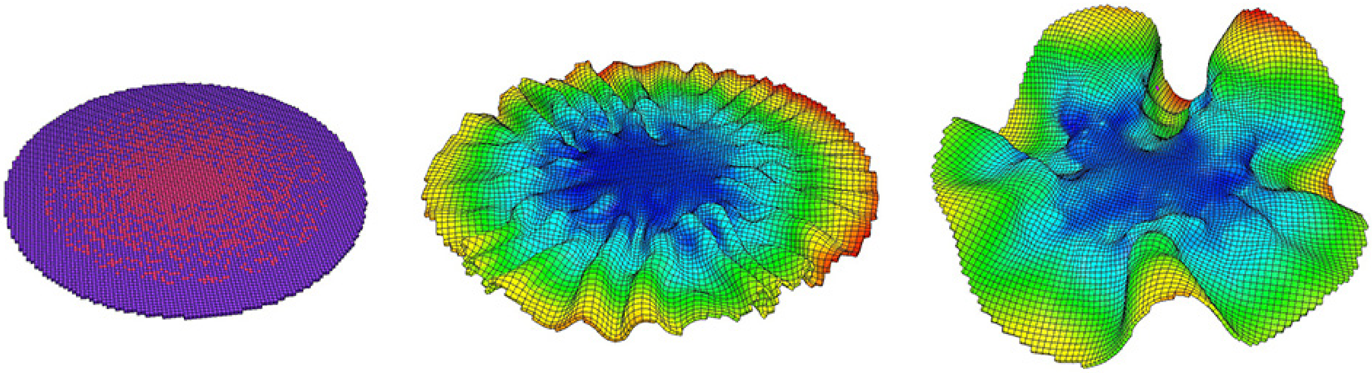

14 Simulation Studies Showing a Gradient Distribution of Material (Red and Purple) and the Simulated Surfaces after Submersion in Water for Thirty Minutes and Twenty-four Hours (Left to Right) (Dikovsky, Hirsch, Tibbits 2013)

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IMAGE CREDITS

Figure 1. Dikovsky, Hirsch, Tibbits (2013) Stratasys' Connex Multi-Material printer depositing UV curable polymers.

Figure 2. Tibbits (2014) 4D printed joints showing custom angles.

Figure 3. Tibbits (2014) Three printed strands showing calibration tests and the precision of custom angles after self-transformation.

Figure 4. Tibbits (2013) Time-lapse images showing the self-transformation of a 4D printed protein strand.

Figure 5. Tibbits (2013) Rendering and photograph of a 4D printed protein strand.

Figure 6. Tibbits (2013) A series of photographs showing the transformation from a flat 4D printed structure to a precise truncated octahedron.

Figure 7. Tibbits (2013) A series of photographs showing the transformation from a flat 4D printed structure to a curve-crease origami structure approximating a hyperbolic paraboloid.

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Figure 11. Dikovsky, Hirsch, Tibbits (2014) The resultant dynamically curved and parted field after being subject to water.

Figure 12. McKnelly, Tibbits (2014) Two vector fields with a number of attractor points dictating the direction, height and placement of material in the 4D printed fields.

Figure 13. Dikovsky, Hirsch, Tibbits (2014) The resultant curved fields showing control of curling and attraction to various attractor points across a field.

Figure 14. Dikovsky, Hirsch, Tibbits (2013) Simulation studies showing a gradient distribution of material and the simulated surfaces after submersion in water for 30 minutes and 24 hours.

Figure 15. Dikovsky, Hirsch, Tibbits (2013) Three 4D printed models showing a gradient distribution of materials with 0 minutes, 30 minutes and 24 hours of water submersion.

15 Three 4D Printed Models Showing a Gradient Distribution of Materials with Zero Minutes, Thirty Minutes and Twenty-four Hours of Water Submersion (from Left to Right) (Dikovsky, Hirsch, Tibbits 2013).

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