4DCurve: A Shape-Changing Fabrication Method Based on Curved Paths with a 3D Printing Pen

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ABSTRACT

In recent years, 4D printing is of continuous interest and attention in the field of Human-Computer Interaction. However, the advanced settings and complex g-code controls are still raising barriers for newcomers. 3D printing pen, in contrast, provides maximum versatility and accessibility for novices and even children. In this paper, we propose 4DCurve as a low-cost and easy-accessible 4D printing method to create curves with 3D printing pens. Compared with the strictly flat and layer-by-layer printing strategy of machines, the manual use of 3D printing pens enables freely curved and non-planar printing paths for spatial creativity and constant combination with daily objects. In addition, a guidance system has been built up for proposing curve path guidance based on the users' deformation needs, we also demonstrate various application cases on explosive design space for fashion designers, craft enthusiasts and designers in the field of personal fabrication.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**;

KEYWORDS

4D printing, personal fabrication, 3D pen, shape-changing interface

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1 INTRODUCTION

With digital fabrication booming rapidly, the lower threshold of Human-Computer Interaction enables design work in more fields involved. From laser cutting [15] to hybrid carpentry [14], from small body sensors [16] to underwater control [17], machine participation brings designers precise digital implementation for multiple areas of designers. As developing personalized fabrication approach, 4D printing technology comes into view for low-cost and efficient fabrication of curved shapes. Multiple forms of strategies have been developed to advance this technology, from lines [2] to mesh surfaces [8], from novel materials [18] to multi-material [10], from colored [3] to textured [9]. Overall, 4D printing approaches are continuously becoming complicated at an accelerated speed, which constantly raise the threshold for newcomers, both as users and researchers.

Our work presents easy-accessible handheld printing methods on 4DCurve, focusing on curve-structured thermal deformation, along with mechanism study of key influencing factors. Rather than linear-structure printing on plat surfaces, we aim at freely curved and non-planar printing paths with a 3D printing pen. To help novices get familiar with 4DCurve, we have also developed a guidance system, which instructs to fabricate specific printing paths using workflow interfaces. For wider application areas, we demonstrate several 4DCurve results through our approach, focusing on scenarios of children-education, life aesthetics, and fashion design. Overall, we propose 4DCurve as an accessible method for design practice in plentiful fields, which engages a broader range of users, from children to craftsmen in 4D printing.

In this paper, we will first introduce the library of basic deformation test, followed by a description of our design interface. Our main contributions include:

1. Introducing a new deformation mode on curve-printing path and organizing a holistic design and fabrication method for broader use.

2. Providing users with an innovative design method that has lower technical barriers and costs.

3. Demonstrating several 4DCurve works created through our approach, which fully exhibit the easy-accessible, creativity-inspiring and aesthetically pleasing features.

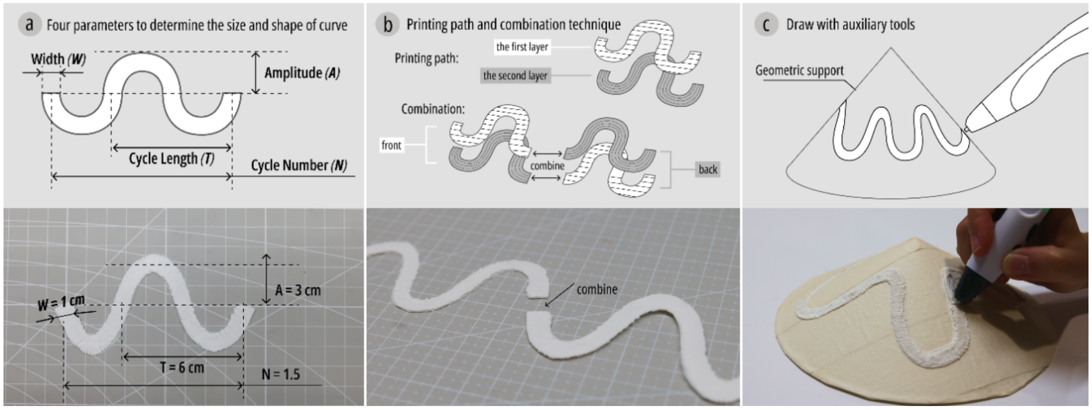

Figure 1: Summarize three ways to control the deformation effect: (a) Change the shape of the printing curve; (b) Choose different printing paths and combination technique; (c) Draw with auxiliary tools.

2 RELATED WORK

The popularity of 3D printers has led to unprecedented development in personal fabrication [6]. Various design systems were developed to help adapt 3D printing to everyday objects [5, 11, 12]. With the use of deformable materials, 4D printing is gaining more attention in the field of Human-Computer Interaction because of its ability to significantly reduce printing time [7] as well as its great scope for exploration [2, 8, 9, 13]. However, most 4D printing researches rely on 3D printers, which brings a high barrier for newcomers and limits the popularity of 4D printing. By using a 3D printing pen instead of a 3D printer, 4D Doodling [4] summarizes the deformation library for manual printing and develops an MR-assisted system to lower the threshold of use while stimulating more creative participation of users. But current 4D printing is mostly based on straight-line printing paths, using whether a 3D printer or a 3D printing pen. To expand the design space for 4D printing, we propose an easy-accessible 4D printing method of curve printing with a 3D printing pen while Printed Paper Actuator [19] presented some methods on curve-printing. The curves after heating can be directly deformed into complex structures, which is more efficient and make it possible to form some three-dimensional structures that 3D printers cannot print.

3 BASIC DEFORMATION TEST

Our work used the thermoplastic materials PLA with a 3D printing pen to conduct the basic deformation test. Rather than other previous studies on 4D printing deformation technique, our work focused on curve printing path on diverse surfaces. We printed and tested the effect of size and shape, printing path, combination technique and auxiliary tools on deformation results(Figure 1). After printing, the cooled and fixed model is put in 75 °C water to trigger the deformation. After testing multiple samples of different parameters, we summarized the deformation mechanism and organized the following tables a library to provide more detailed guidance for users.

For convenience of use, we mark some variables that are mentioned repeatedly in this paper:

1. Amplitude $\boldsymbol{A}$: the maximum distance between the curve path and its central axis.
2. Cycle Length $\boldsymbol{T}$: the lateral length of a total curve, where it ends at the place similar to its start.
3. Width $\boldsymbol{W}$: the width of the printing curve piece.
4. Cycle Number $\boldsymbol{N}$: the number of cycles for a printing curve, which can be complete like 3 cycles or half-taken like 1.5 cycles.

3.1 Size and shape of the curve

Above our deformation tests, the curve's amplitude $\boldsymbol{A}$ and cycle length $\boldsymbol{T}$, which change the curve shape jointly, show a mutual effect on the overall contraction (Figure 2a). When $\boldsymbol{A}$ is much shorter than $\boldsymbol{T}$, there comes the overlap of unitary parts because of the force of lateral contraction, which tends to be more powerful. And when $\boldsymbol{A}$ and $\boldsymbol{T}$ are equal approximately, it turns to a relatively neat long strip, the lateral force and the vertical one meeting a relative balance.

Given a fixed shape that $\boldsymbol{A} = 2$ cm and $\boldsymbol{T} = 6$ cm, we have also explored the deformation effect of width and cycle number (Figure 2b). We found that the bending effect diminishes as width $\boldsymbol{W}$ increases. And in fixed width, when the cycle number $\boldsymbol{N}$ increases, the rotation of the long strip is prone to multiply.

3.2 Printing path and combination technique

The different printing paths of the first and second layer bring about obvious diversity in deformation shape, which means the extent of deformation largely depends on the printing paths (Figure 3a). Besides, the combination methods affect the bending direction and trend as well. Limited by the base plate's size, the cycle number N can't reach a large number at once, so we take the combining methods. In this process, we staggered the frontside and backside of the modular components (Figure 4a). In the test, the direction of the curve varies significantly with different combination methods (Figure 3a). On the basis of 2D assembly, we also perform 2.5D assembly across flat dimensions (Figure 4b). The strategies provide users with rich references to deformation effects, thus expanding the design space.

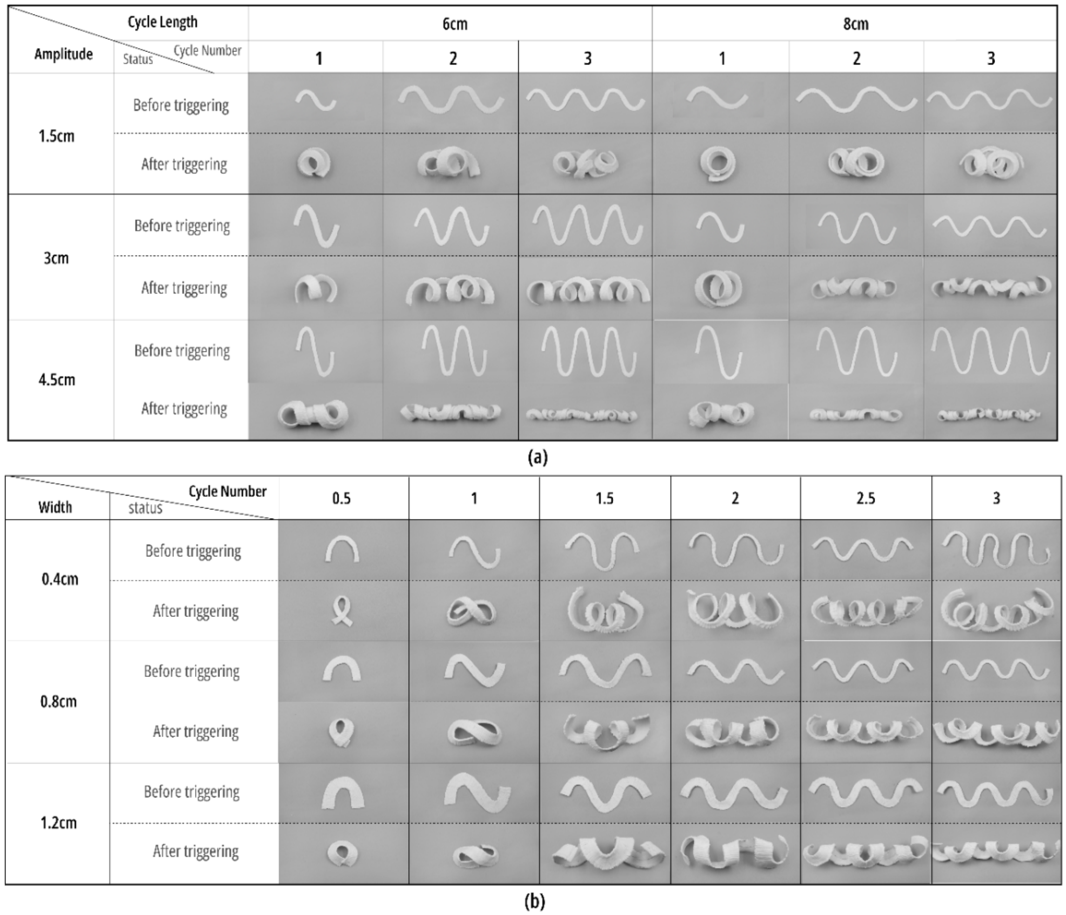

Figure 2: The effect of size and shape on deformation shape: (a) Deformation tests about amplitude *A* and cycle length *T*; (b) Deformation tests about width *W* and cycle number *N*.

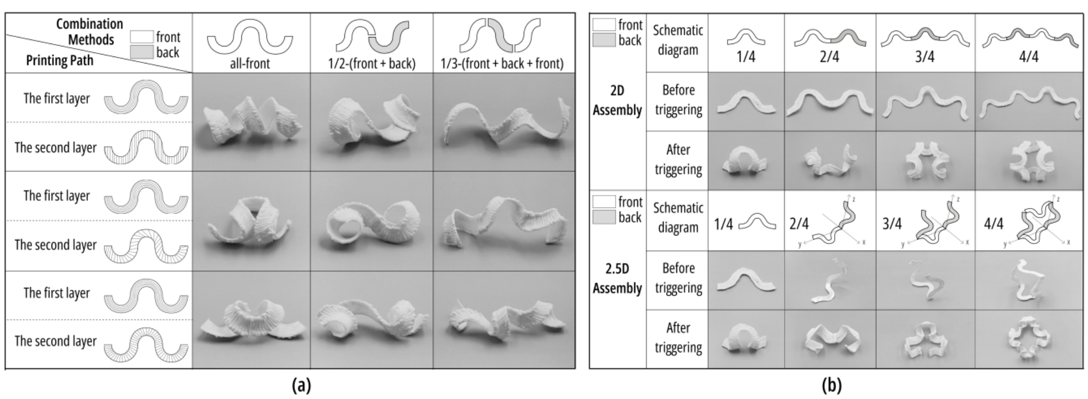

Figure 3: The effect of combination method and printing path on deformation shape: (a) Deformation tests about printing paths and combination methods; (b) Deformation tests about assembly methods.

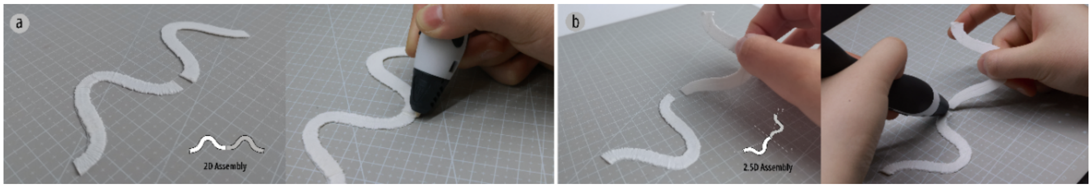

Figure 4: Schematic diagram of (a) 2D and (b) 2.5D front and back assembly of two unit components.

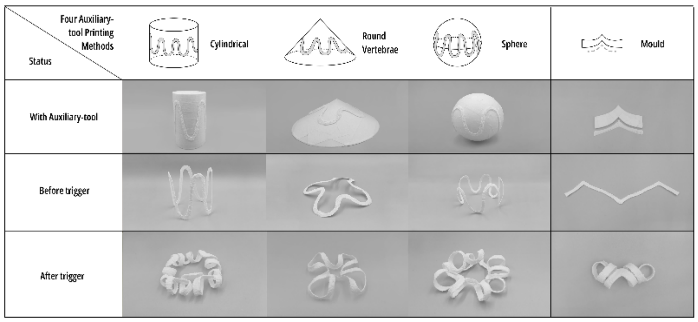

Figure 5: Summary of auxiliary tools: Deformation test about cylinders, cones, spheres and moulds.

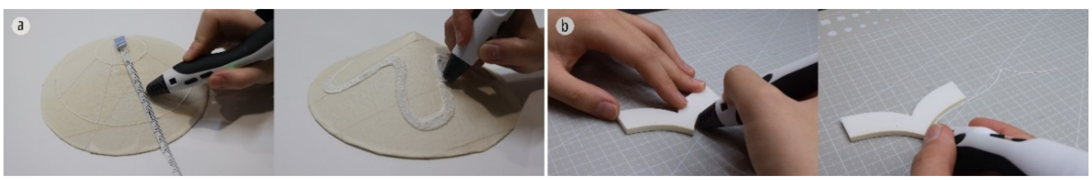

Figure 6: Summary of auxiliary tools: Deformation test about (a) cylinders, cones, spheres and (b) moulds.

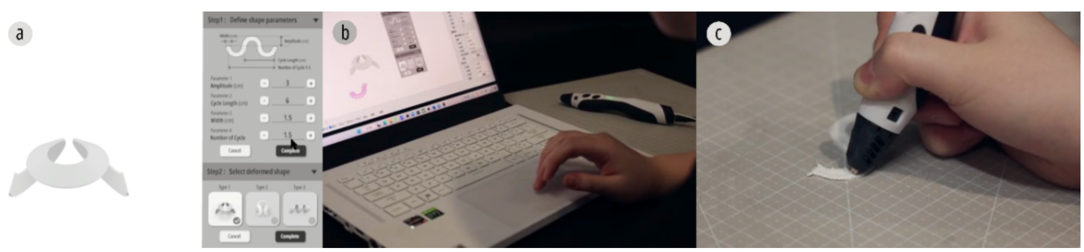

Figure 7: Interface description: (a) The user interface and the animation of the second layer; (b) The user watched the track guidance animation; (c) The user successfully printed the curve.

3.3 Auxiliary-tool printing methods

The convenience of 3D pens lies in direct printing on three-dimensional space, which enables complex non-planner structures that are challenging for conventional 3D printer. The transformation library (Figure 5) lists four types of auxiliary tools (cylinders, cones, spheres and moulds), which performs as bases for further curve printing. As for the former three ones, we printed on some geometric bodies and achieved closed curves (Figure 6a). With the moulds, it gets easier to accurately draw the outer contours of given curves. We found that with the aid of a mould, the outer line can be drawn easier to achieve more precise printing paths.

4 DESIGN INTERFACE

Our goal is to provide our users with an easily accessible approach to creating curves with specific paths, which are difficult to master for novices. The guidance system constructs the corresponding relationship between the printing paths and the expected deformed shape, and can guide the users to draw by displaying animation.

To implement the function, our guidance system is built on Rhino with Grasshopper [1], consisting of several adjustable parameters. The procedure includes:

1. Define shape parameters (Figure 7a). Users can adjust the amplitude, cycle length, width, and cycle number of the printing path,

Figure 8: Children-education design: (a) Drawing of frame curve(A=3cm, T=6cm, W=0.8cm, N=4); (b) Frame before deformation; (c) Frame after triggering; (d) The final product; (e) Continued creating by the child; (f) The usage scenario.

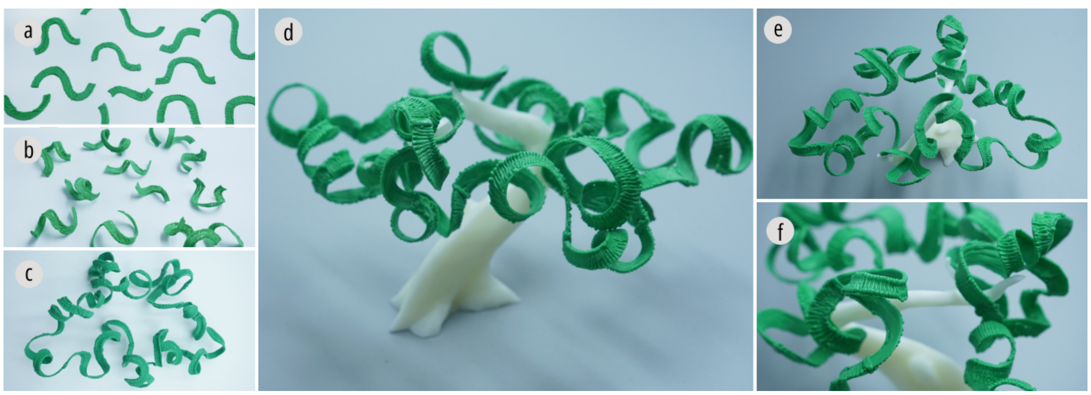

Figure 9: Spiral pin tree: (a) Curves of various shapes; (b) Curves after triggering; (c) Joint-curves; (d, e, f) The decorative scenario.

which are closely connected to the deformed shape of the model. The specific numeric values of these parameters can be modified by simply clicking on the plus and minus signs in the interface. After defining the shape parameters, users can click complete to go to the next step or click cancel to restore the settings.

2. Select a deformed shape (Figure 7a). We provide three deformation types and their corresponding printing paths are linked in the system. Users can choose their expected deformed shape in the interface and the animation will be played after they click the complete bottom.

3. Play animation (Figure 7b). After getting the curve shape data and deformation methods determined, the animation explaining specific paths will be played in rhino to assist users in understanding.

4. Print curve (Figure 7c). Users can refer to the virtual path trajectory played on the screen to draw in reality with a 3D printing pen.

5 APPLICATIONS

To demonstrate our methods, we present several applications which introduce several production methods and display the design space in terms of edutainment and aesthetics.

5.1 Children-education design

Using the 4DCurve methods, users can quickly build a three-dimensional frame and then continue various creation on the basis of it. In this scenario, the designer and the child worked together to create a hat for a plush toy (Figure 8f). The production steps include frame construction (Figure 8a,b) and deformation(Figure 8c), hollow filling(Figure 8d), and finally doodling(Figure 8e).

5.2 Aesthetic design

The spiral structure formed by the deformation of the curves contains a wealth of aesthetic properties. By printing curves of random shapes (Figure 9a) and combining the spiral structures after

Figure 10: Fashion design: (a) Deformation of the unit component (A=8cm, T=22cm, W=1.5cm); (b) Clothing-based design simulation; (c ,d) Using scenario after assembling.

high-temperature deformation (Figure 9b). We designed a closed structure (Figure 9c) with an irregular shape, which has dynamic beauty and artistic tension. The 3D-printed tree trunk serves as the base, resembling a pine tree and full of vitality.

5.3 Fashion design

Inspired by the creative deformation of the large-amplitude unit component (Figure 10a), we tried to apply them to assistance in the formation of design ideas (Figure 10b). By partial outfit assembling, we wrap a large 4DCurve loop in fixed monochrome garments as a unique accessory (Figure 10c, d), as if the original patterns on the clothes come to life. While displaying the distinctive stereoscopic beauty, the combination with clothing tends to be more compelling and expressive for fashion design. As costume accessories, 4DCurve presents an innovative clothing style, expanding expressional forms for fashion designers.

6 CONCLUSION

In this paper, we propose a method to deform curves based on 4D printing technology and present the summarized deformation library to the user through the animation teaching of the design interface, which can enable people to easily fabricate 3D objects with complex structures through a low-cost 3D printing pen. We also emphasized our distinctive effect in edutainment and aesthetics through several applications, to inspire more creative design based on our work. In the future, we plan to enrich the functions of the guidance system with its usability improvement, and verify it through user experiments. We also found that the use of auxiliary tools can greatly extend the design space of curve deformation, which needs further investigation.

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