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Foam2Form: 4D Printing with Programmable Foaming

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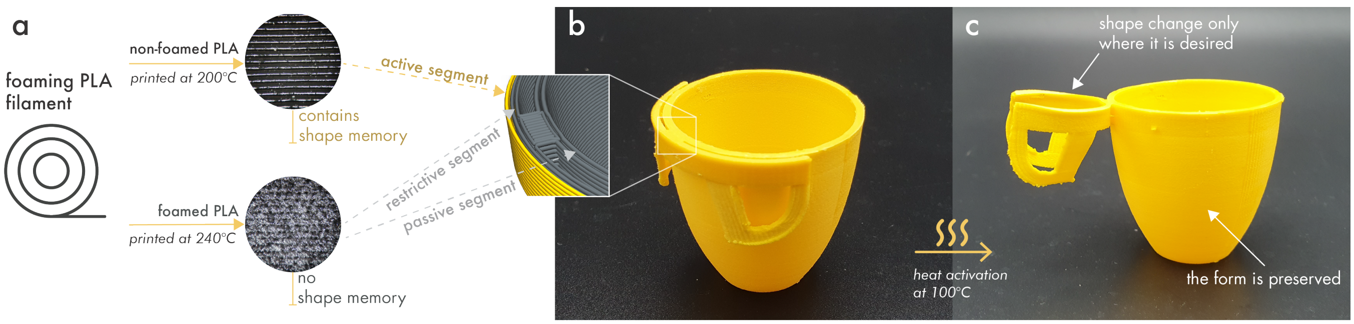

Figure 1: (a) Foam2Form uses a single foaming PLA filament that is printed at a foamed or non-foamed state, depending on the nozzle temperature. The foamed state of the material loses the shape memory property. (b) We design the shape change by selectively printing the object at foamed (for active segments) or non-foamed states (for restrictive and passive segments). (c) Upon heat activation, only the desired parts experience shape change, while the rest of the object preserves its form.

ABSTRACT

For heat-triggered shape-changing 3D prints, active and restrictive segments need to be 3D printed next to each other to obtain the desired morphing of an object. Current single-material methods rely on locally controlling the orientation of the printing lines to adjust the amount and direction of shrinkage. This approach, however, limits design freedom as it restricts the shape and fabrication of the objects. Moreover, it results in undesirable deformations in more complex and larger designs. Addressing these challenges, we introduce Foam2Form, a method that forms active and restrictive segments by programming the shape-memory properties of foaming PLA during the printing process. We propose to use the material in a non-foamed state for active segments and in a foamed state for restrictive and passive segments, which results in more stable 4D designs free from unwanted deformations. We present the first results of this low-cost 4D printing method and demonstrate its capabilities with various application examples.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI).**

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KEYWORDS

4D printing, foaming PLA, shape memory, shape-changing interfaces

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1 INTRODUCTION

4D printing is an emerging fabrication technique that adds programmable shape-changing behavior to 3D-printed objects [9]. Potential benefits include ease of fabrication of complex designs and the creation of interactive and responsive objects capable of transforming at form, function, or property levels [3, 9]. Previous research demonstrated the fabrication of responsive objects that transduce, sense, or actuate in response to different stimuli with various 3D printing techniques using single or multi-material structures [3]. HCI researchers have mainly focused on accessible 4D printing to design and fabricate shape-changing interfaces using low-cost fused deposition modeling (FDM) printers and off-the-shelf shape-memory polymers, such as PLA. Examples include various shape-changing artifacts such as linear morphing structures [17], shape-changing mesh surfaces [18], textured 3D surfaces [13] and shrink-and-fit adaptations on existing objects [14]. The common 4D printing methods use a bi-layer structure of active and restrictive segments. For single-material 4D printing, active segments use the heat-activated shrinking behavior of the PLA, and restrictive segments are created by printing the same PLA in patterns designed to diminish shrinking in the main direction. While using a single material has advantages in printability and cost-effectiveness, this current approach runs into its limits because the PLA in the restrictive segments and regions of the design that are not intended to change shape always exhibits some shrinking. As a result, undesired deformation can occur. In more complex design configurations and at larger scales, these effects become significant, which diminishes the applicability of the existing methods.

We address these limitations by introducing Foam*2*Form, a 4D printing approach that uses one single material that can be applied for the active segment and be de-activated during the 3D printing process to remain stable with limited unintended deformation. In Foam*2*Form, *active* and *restrictive* segments are defined by using a foaming PLA filament. The foaming PLA is a material that is similar to regular PLA at low printing temperatures but expands into a foam structure when printed at elevated temperatures [11]. We identified and leveraged the foamed material's loss of the shape-memory effect, and our method relies on selectively foaming the material to create geometrically stable restrictive and passive regions.

Foam*2*Form expands the 4D printing design space and creates new opportunities for shape-changing interfaces. The offered freedom of *active-restrictive* segment distribution also enables diverse modes and directions of activation and allows more complex shape-morphing designs and larger 3D objects with locally-morphing features.

Our contributions include:

- A 4D printing approach that expands the design flexibility and complexity of single-material shape-changing interfaces
- Demonstrating the ability of foaming PLA to provide dimensional stability in 4D printing
- Presenting application examples that highlight the design capabilities of Foam*2*Form

2 RELATED WORK

2.1 Programming Shape Change Behavior

PLA is the most commonly employed material for 4D printing with FDM, which is a very accessible off-the-shelf SMP with a low T_g that allows activation with various heat sources. Rapid cooling of the stretched polymer chains during 3D printing creates internal stress in the deposited material. When the printed part is heated above T_g (about 60 °C for PLA), the relaxation of the polymer chains causes shrinkage, and the part shifts to a more stable shape. The shrinkage occurs in the direction of the printed lines while the material expands in the other directions [16]. This *shape memory* embedded in the printed part is the basis of actuation in commonly utilized 4D printing mechanisms with PLA [6, 12].

Design of the extruded line pattern and orientation allows programming various shape-changing behaviors [9]. The simplest form of actuation is by using linear or in-plane shrinkage [14]. Another approach is a mono-layer arrangement of segments with different line orientations, where the shrinkage difference between the segments creates an out-of-plane buckling [16]. Hence, this approach is effective for topographical shape changes. The most common way of obtaining out-of-plane actuation is using a bi-layer structure where one is an *active* layer with lines designed for the desired actuation, and the second is a *restrictive* layer constraining the *active* layer on one side to force out-of-plane shape change [16, 20]. Thus, such active/restrictive layer structures allow actuations like bending, curling, or twisting. The main restrictive layer design in the literature is a pattern of printed lines perpendicular to the printed lines of the active layer. Preserving the form of the *passive* elements in the design is also important; the common strategy in this case is alternating line orientations in every other layer. Patterns with smaller line segments or alternating line orientations are demonstrated to provide the least amount of isotropic shrinkage [14, 16]. However, both restrictive and passive layers depend on the printing pattern, which limits the applicability to simple geometries where these patterns can be created. Another limitation is the actuation direction since the patterns can only be created on the x-y plane. While an active layer can be vertical (such as a wall), designing a layer that restricts in the z-direction is challenging.

In this paper, we focused on accessible 4D printing using a single material. Some approaches include a secondary material to build restrictive and passive segments [2, 19]. However, multi-material FDM introduces new printing challenges, such as the bonding between different materials [7].

2.2 Controlling shape change amount and rate

The activation amount and speed can be programmed by the design of the actuator and 3D printing parameters [1]. Decreasing layer height and line width is highly effective in increasing the activation amount [4, 16, 20]. Another important parameter is the nozzle temperature, where higher temperatures decrease the shape memory effect [16, 20]. The printing pattern, infill structure, and ratio affect the amount and direction of shape change [14, 20]. In terms of geometry, the ratio of the active and restrictive layers and the width and thickness of the actuator are influential parameters. The actuation amount increases with a higher active layer ratio and increasing actuator width and thickness [16, 17].

These parameters control the shape change and even allow complex and sequential actuations. Tuning 3D printing parameters to reduce deformation on restrictive and passive segments is also possible to a certain degree. However, their dependency on the printing pattern remains a limiting factor. The shrinkage of a printed line is not proportional to its length, which creates anisotropic deformation (e.g., warping). This also causes significant undesired deformation as the object size increases, making it difficult to design large 4D features.

2.3 Shape-changing interface applications

Researchers employed various strategies to use the shape memory of PLA to obtain different shape change behaviors (for different design purposes) by the design and distribution of active, restrictive, and passive segments. Most of the previous work focuses on shape-changing flat surfaces into non-flat structures due to benefits such as flat packaging or ease of fabrication. These include hinge mechanisms [10, 20], self-rising textured surfaces [13], self-folding objects and kirigami surfaces [16]. An example with more actuation freedom is A-line [17], a method to control the bending angle and direction of rod-like parts to create 3D forms. Using rod-like elements in a mesh form, 4DMesh presented a method to design flat mesh surfaces that morph into non-developable surfaces [18]. The work on shape-shifting non-flat 3D structures is rather limited.

In ShrinCage, researchers used the in-plane shrinkage to create 3D models that fit onto existing objects [14]. To enable actuation in 3D geometries, Van Manen et al. [15] proposed a modified FDM printer to allow printing on curved surfaces. While this method enables novel shape transformations in 3D geometries, it is limited to tubular forms by its nature.

Apart from the ease of fabrication, the focus of previous work on shape-changing flat surfaces or linear forms is also due to the limitations of layer-by-layer printing and dependency on printing patterns. While the printing pattern dependency limits the actuator designs to planar forms, it also creates the challenge of avoiding undesired deformation. The challenges related to dimensional stability also limit the designs to small-scale flat surfaces or line structures. Other researchers also have pointed out the limitations with the dimensional stability of the restrictive segments, where undesired bending and warping occur with the heat-triggering process [14].

3 FOAM*2*FORM

Addressing the outlined challenges, we introduce a method that employs a foaming material that can be used as an effective active segment and turned into a passive and stable segment where needed. Compared to other single-material 4D printing approaches, Foam*2*Form has less dependency on printing patterns, alleviates undesired deformation modes of the restrictive segment and can be used to print large passive segments that remain stable in their form.

In this study, we use a foaming PLA filament, namely *LW-PLA*[1], which exhibits different material properties depending on the 3D printing parameters. This material has a foaming agent that expands with increasing nozzle temperature or decreasing pressure in extrusion, forming a porous structure. The formation of this porous structure and the changes in the degree of crystallinity affect the material properties significantly [5, 8]. One of the property changes we observed is the loss of shape memory. Non-foamed *LW-PLA* has comparable shape memory to regular PLA; however, after achieving a foamed state, the shape deformation is significantly less when subjected to heat activation. Hence, by printing the *LW-PLA* in its non-foamed state, we use the same design principles for the active segments as in the existing literature with regular PLA. But, for the restrictive and passive segments, we print the *LW-PLA* in a foamed state, allowing these segments to be independent of printing orientations and infill patterns, which is not possible with regular PLA. This enables actuation design in different directions (e.g., actuators on vertical or tilted walls) and minimizes undesired deformation. This shape preservation capability also aids the geometry and size limitations. With Foam*2*Form, large 3D forms with locally actuating elements become possible.

We use a straightforward printing method in Foam*2*Form: printing the active segments at 200°C, and the restrictive/passive segments at 240°C (using 50% flow rate due to the expansion of the material). The pattern and line orientation of the active segments and shape change primitives can be designed the same way as in the literature [3, 9]. The restrictive/passive segments do not require a specific pattern, and thus, these can be designed more freely.

[1] *LW-PLA* filament by Colorfabb: https://colorfabb.com/LW-PLA-black

For accurate and consistent heat activation, we used a climate chamber at 100°C for all the samples throughout the paper. All the test samples were activated in the climate chamber for 2 minutes. However, the activation time of the examples in Section 5 had small variations since the activation time depends on the design as well.

In the following section, we demonstrate the shrinking behavior and shape stability of foamed *LW-PLA* compared to a regular PLA filament to explain its advantages in creating restrictive and passive segments. In Section 5, we elaborate on the design space of Foam*2*Form, explaining the unique capabilities in terms of actuation directions and form freedom and showcasing our preliminary examples.

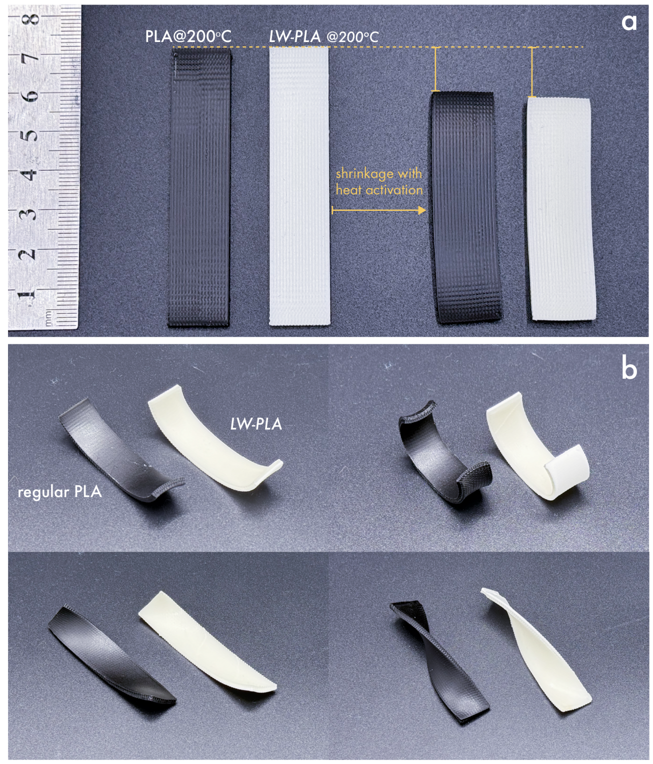
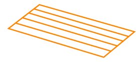
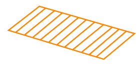
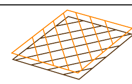
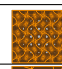
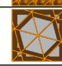
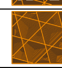
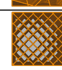


Figure 2: (a) Linear shrinking behavior comparison of regular PLA with non-foamed *LW-PLA*. Both samples were printed with a nozzle temperature of 200°C. (b) Bilayer basic shape change primitives printed with regular PLA (black) and *LW-PLA* (white).

4 SHAPE MEMORY OF *LW-PLA*

The shrinking behavior of non-foamed *LW-PLA* is nearly identical to regular PLA. Figure 2a compares the shape change of *LW-PLA* and regular PLA samples upon heat activation. All the samples were printed with a nozzle temperature of 200°C, at which *LW-PLA* remains non-foamed. Figure 2b compares bilayer basic shape change primitives printed with regular PLA (black) and *LW-PLA* (white). The desired activation of the samples is similar; however, regular PLA samples also show undesired deformation in other directions. We also provide a bending characterization of a bi-layer

Table 1: regular PLA (@200°C and @240°C) and the *LW-PLA* samples compared for shape deformation and the percentile changes in dimensions upon heat activation.

Tested sample				**Deformation (%)**		
dimensions (mm)	pattern		material	length	width	height
70*x*15*x*2	longitudinal		PLA@200°C	-19	5.7	17
			PLA@240°C	-5	0.6	7.8
			LW-PLA	-1.8	0	6.8
70*x*15*x*2	transverse		PLA@200°C	-1	-4.9	6.4
			PLA@240°C	-1.5	-0.4	5.6
			LW-PLA	-0.8	-0.7	0
70*x*70*x*2	alternating		PLA@200°C	-2	-2	5
			PLA@240°C	-2	-2	7
			LW-PLA	-0.7	-0.6	0
20*x*20*x*20	gyroid		PLA@240°C	-2.8	-2.5	1.9
			LW-PLA	-0.5	-0.5	6.7
	triangles		PLA@240°C	-3.9	-3	2.2
			LW-PLA	-0.8	-0.8	7.1
	cubic		PLA@240°C	-3.5	-4	3
			LW-PLA	-1.1	-1.1	8.1
	lines		PLA@240°C	-2.7	-2.8	0.7
			LW-PLA	-0.7	-0.7	6.1

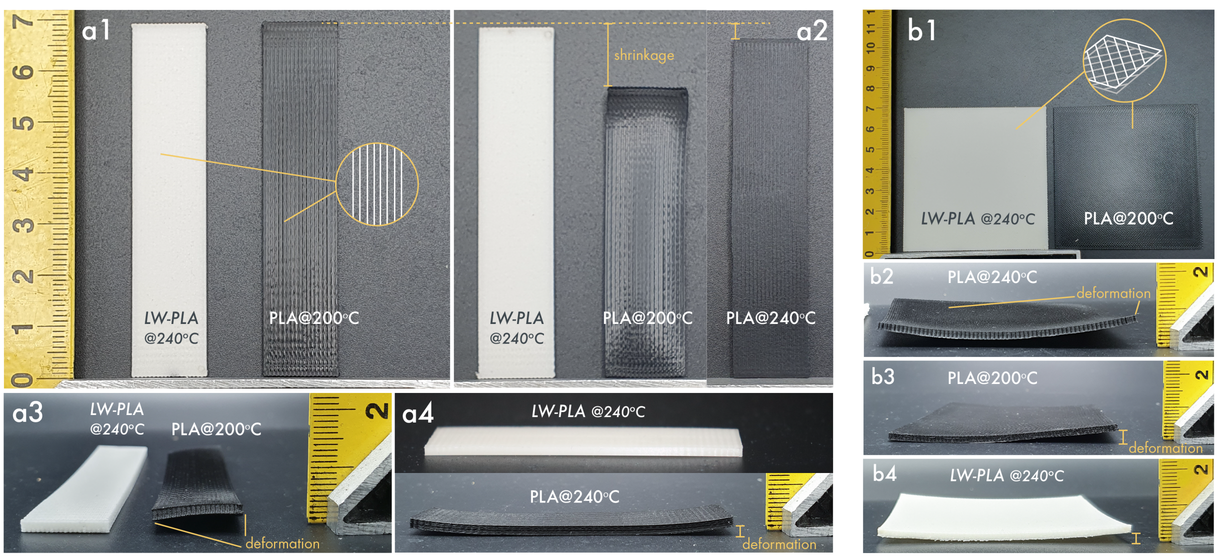


Figure 3: Comparing shape stability of *LW-PLA* (white) with common strategies for passive and restrictive segments for regular PLA (black). (a1) Test samples printed with longitudinal print lines. (a2) Comparison of *LW-PLA* and regular PLA (@200°C and @240°C) after being exposed to 100°C for 2 min. (a3) Out-of-plane deformation of the PLA (@200°C) sample. (a4) Deformation of the PLA (@240°C) sample in comparison to the *LW-PLA* one. (b1) Tested samples with alternating diagonal lines. (b2) Large out-of-plane deformation with regular PLA (@240°C). (b3) Deformation on the edges with PLA@200°C. (b4) Deformation on the edges with *LW-PLA*.

non-foamed/foamed *LW-PLA* sample and the effects of various parameters on the bending performance in Appendix A.Since the focus of the paper is the particular ability of foamed *LW-PLA*, the comparisons in the rest of this section do not include non-foamed *LW-PLA*.

We compared the shape deformation upon heat activation of foamed *LW-PLA* to regular PLA to demonstrate its potential for creating restrictive and passive segments that are more stable (have less undesired shape deformation). Three main comparison criteria are shrinkage behavior along the print lines, shape preservation with alternating line directions, and 3D structures with infill patterns.

The compared test samples and their shape deformation upon heat activation are listed in Table 1. All samples were printed with 0.1 mm layer height and 60 mm/s print speed. The *LW-PLA* sample was printed with a 50% flow rate to compensate for the volume expansion of the material. The nozzle temperature was 240°C for *LW-PLA*, and the two regular PLA samples were printed at 200°C and 240°C. We tested regular PLA samples printed at a common nozzle temperature and also at the same temperature as *LW-PLA* to account for the effect of nozzle temperature, which was found to be highly influential on shape memory [16]. Finally, the samples were activated in a climate chamber at 100°C for 2 min.

To compare the shrinkage along the print lines, we printed test samples (70*x*15*x*2 mm) with longitudinal print lines (Figure 3a1). Upon activation, the largest shape change was observed with the PLA sample printed at 200°C (Figure 3a2). The longitudinal shrinkage of the PLA@200°C was 19% while expanding 5.7% in width and 17% in height. Besides the dimensional changes, PLA@200°C showed out-of-plane deformation (Figure 3a4). As expected, the PLA@240°C sample experienced less shape deformation with 5% longitudinal shrinkage, 0.6% shrinkage in width, and 7.8% expansion in height. Moreover, some warping occurred near the short edges of the sample (Figure 3a5). The *LW-PLA* sample demonstrated the least deformation in all directions with 1.8% longitudinal shrinkage, no difference in width, and 6.8% expansion in height. No out-of-plane deformation was observed with the *LW-PLA* sample. Among the samples with transverse line direction, PLA@200°C sample showed the most shrinkage along the lines (in width) and expansion in height. PLA@240°C also showed a similar expansion in height. *LW-PLA* sample did not experience any significant change in this case, with less than 1% deformation in all directions. The insignificant deformation of foamed *LW-PLA* implies that it can be used to create restrictive segments regardless of the printing pattern. In addition, comparing the shrinkage ratio of the longitudinal and transverse-line samples of regular PLA, we can see that shrinkage is not proportional to the line lengths. This causes anisotropic deformation and makes larger and 3D geometries more challenging. The results of *LW-PLA* samples are promising to create passive segments overcoming these challenges.

Comparing the shape preservation ability for passive segments, we tested square samples (70*x*70*x*2 mm) with diagonal lines alternating directions in every layer (Figure 3b1), which is the common approach in literature. In this case, PLA@200°C and PLA@240°C showed similar shrinkage in length and width, while PLA@240°C expanded slightly more in height. The shrinkage of the *LW-PLA* sample was the least in this case, with no change in height. Apart from the dimensional changes, PLA@200°C demonstrated large out-of-plane deformation (Figure 3b2). PLA@240°C and *LW-PLA* samples showed some warping on the edges (Figure 3b3 and b4).

Finally, we compared cubic samples (20*x*20*x*20 mm) with four different infill patterns (Figure 4a). All patterns were printed with 15% infill and a single outer wall. PLA@200°C samples experienced large anisotropic deformation in all directions, as seen in Figure 4b. Due to the difficulty in measuring the dimensions with the anisotropic deformation, the dimensional deformation data of these samples are not included in Table 1. While PLA@240°C samples also

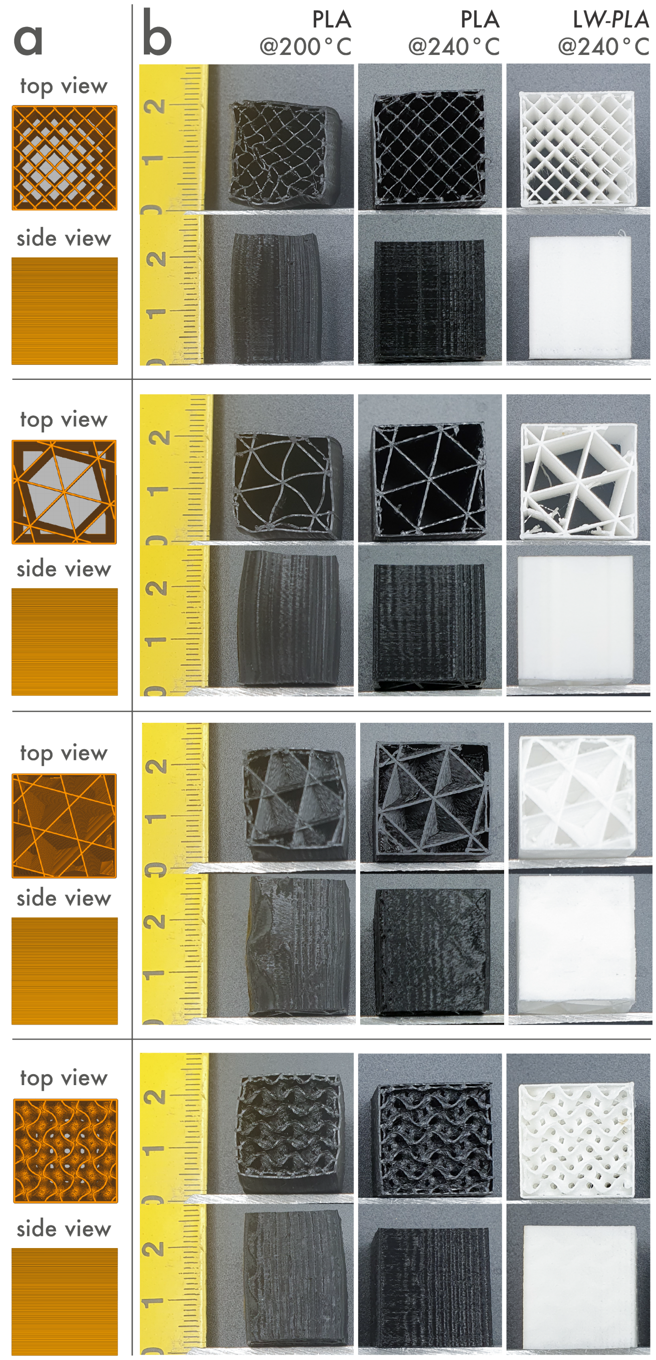


Figure 4: Shape deformation comparison of regular PLA (black) and *LW-PLA* (white) samples with different infill patterns, showing that the foamed LW-PLA is more stable as a passive segment. (a) Tested infill patterns. (b) Comparison of regular PLA (@200°C and @240°C) and *LW-PLA* after being exposed to 100°C for 2 min.

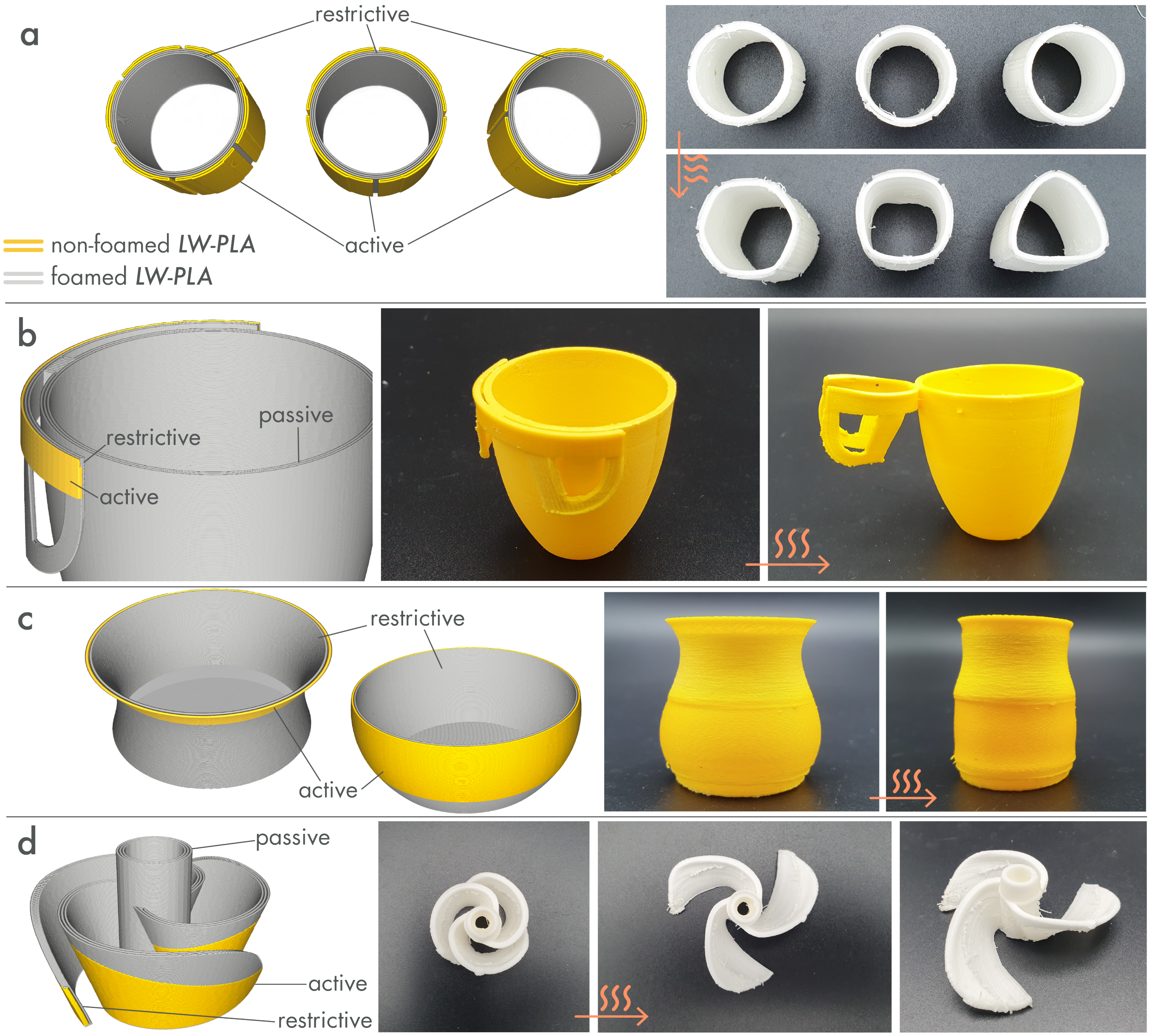


Figure 5: 3D-to-3D shape morphing examples with Foam2Form. All examples are printed by a single *LW-PLA* filament using its foamed and non-foamed states. Active segments are non-foamed, and the passive and restrictive segments are foamed.

demonstrated some anisotropic deformation, it is significantly less in comparison to PLA@200°C (Figure 4c). On the other hand, *LW-PLA* samples largely preserved their forms. The shape deformation of the *LW-PLA* samples is significantly low and isotropic in the horizontal plane and also very similar for all tested infill patterns. This indicates the capability of foamed *LW-PLA* to avoid undesired deformation in the passive segments of the design. However, we still observed vertical expansion, which has to be accounted for in the design.

5 DESIGN SPACE

The common primitives of basic shape-change behaviors were previously demonstrated by various 4D printing techniques [3, 9]. These primitives explain the modes of 2D-to-3D shape transformations. In the Foam2Form design space, we present additional ways for users to embed shape-change to printed objects, afforded by the shape preservation performance of restrictive and passive segments printed with *LW-PLA*.

This also gives a directional freedom to place active segments. Having restrictive segments independent of printing patterns enables actuators in 3D space, which allows shape morphing on geometries such as thin walls (Figure 5). As an example of this, Figure 5a shows thin-walled cylinders with changing cross-sectional shapes. Figure 5c demonstrates the curvature change on a 3D shape. Both examples contain 3D bi-layer structures on thin walls. While the first example has a circular distribution of active segments, the latter has a vertical arrangement.

Another possibility of Foam*2*Form is having different bending directions in 3D. Figure 5d shows a propeller with shape-changing blades upon activation. In this case, the bi-layer structure is positioned on a more complex surface, tilted in one direction and curved in the other. Upon activation, the blades unfurl in one direction and bend in the other. Such structure allows the design of self-deploying 3D objects. The restrictive segments are printed parallel to the active ones in all three examples.

The shape-preservation ability also enables new designs in terms of passive segments. In addition to significant shape preservation, there is also more freedom with using different infill structures since there is virtually no influence of these in the horizontal plane. A use case of this is integrating active elements on large passive geometries. Figure 5b shows a cup grip unfolding upon activation. In this case, only the grip part has an active segment. Such designs can be employed for nesting 3D objects. Large-scale objects are also more viable with the proposed method. While normally longer print paths augment the effect of shape deformation, in Foam*2*Form this is negligible for passive segments.

6 DISCUSSION

With Foam*2*Form, we aim to contribute accessible 4D printing with more freedom in actuation and geometry compared to existing single-material 4D printing methods. This enables diversity in the geometries of shape-changing interfaces. Our preliminary examples show the applicability to 3D geometries and actuation freedom in different directions, such as on thin walls or inclined surfaces. We also demonstrated the shape preservation potential of foamed *LW-PLA*, compared to a regular PLA filament. Foamed *LW-PLA* showed minor isotropic shrinkage (between 0.5% and 1.1%) in the x-y direction and, more importantly, preserved the form in all the test samples. However, one limitation is the expansion in the z-axis, which is larger than the regular PLA. This expansion could be compensated in the design by applying a z-scale correction factor. The foamed material in the restrictive and passive segments has slightly different properties when printed, such as density and surface roughness. This may need to be taken into account when designing some applications. Furthermore, 3D-printing foaming filaments introduce some oozing issues that need to be addressed in the slicing settings and 3D printer configuration.

We used a dual nozzle setup for the examples, printing the same material at two different temperatures. It is possible to use Foam*2*Form on a single nozzle printer as well by switching the nozzle temperature between active, restrictive, and passive segments. However, depending on the slicer, this may require manual G-code editing.

7 CONCLUSION

We have introduced the 4D printing method Foam*2*Form, which uses the programmable nature of foaming PLA filament to obtain new design freedom for 4D printing with a single material. The non-foamed PLA's shape-memory effect and the foamed PLA's stable nature give rise to a design space where shape change can be more freely defined. In our proposed method, 3D printing process parameters are varied to control the amount of foaming, allowing for to local assignment of active, restrictive, and passive segments. We share our initial findings on the 4D printing capabilities of the method and show the increased stability of the restrictive and passive segments compared to common single-material 4D printing strategies. Demonstrating the capabilities of the approach, we highlight application examples where the shape change is applied to non-planar designs and designs with significant passive regions.

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