ShrinCage: 4D Printing Accessories that Self-Adapt

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Figure 1: The ShrinCage workflow. User can (a) measure an existing object roughly, (b) design an adaptation in the software, (c) attach the printed part onto the object, (d) trigger them to be fixed in hot water, and (e) get a new functional object.

ABSTRACT

3D printing technology makes Do-It-Yourself and reforming everyday objects a reality. However, designing and fabricating attachments that can seamlessly adapt existing objects to extended functionality is a laborious process, which requires accurate measuring, modeling, manufacturing, and assembly. This paper presents ShrinCage, a 4D printing system that allows novices to easily create shrinkable adaptations to fit and fasten existing objects. Specifically, the design tool presented in this work aid in the design of attachment that adapts to irregular morphologies, which accommodates the variations in measurements and fabrication, subsequently simplifying the modeling and assembly processes. We further conduct mechanical tests and user studies to evaluate the availability and feasibility of this method. Numerous application examples created by ShrinCage prove that it can be adopted by aesthetic modification, assistive technology, repair, upcycling, and augmented 3D printing.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interactive systems and tools.

KEYWORDS

Self-adaptation, 3D printing, 4D printing, Design tool, Do-It-Yourself, Shape-changing interfaces

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1 INTRODUCTION

The recent development of fused deposition modeling (FDM) as a 3D printing technology has made personal fabrication accessible, where it has been used for fast prototyping [28, 29], customizing interactive objects [21, 49], as well as reforming existing objects with printed tactile textures [32, 43] and adaptations [5, 6] which improves accessibility or implements customized features for specific scenarios. However, when designing and fabricating a 3D printed part, especially as an adaptation for an existing object, the conversion (existing object - digital model - physical artifact) inevitably suffers from errors during measuring, modeling, and fabricating, which lead to variations and iterations [18, 23]. Prior works focused on improving accuracy in measurement [20] and modeling [6], as well as broadening adaptable shape space in the assembly process [23], such as using soft material as a connection and splitting the model or adding clamps and screws. All these processes, however, require extra fasteners and additional skills to model and assemble the 3D prints (Figure 2).

We propose to address this problem by printing shrinkable attachments to fit and fasten the existing objects with high tolerance in measurements and printing errors, which lowers the barrier for

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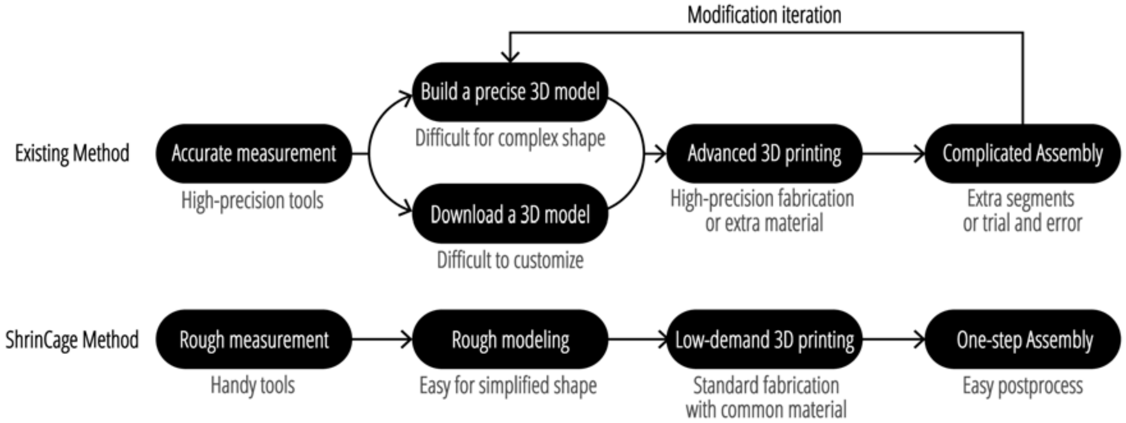

Figure 2: Comparison of existing adaptation method with ShrinCage.

users to engage in personal fabrication. We believe that the features embedded in the end-to-end ShrinCage system could benefit different stages of the process for the following reasons:

- Rough measurements with handy tools: without requiring a dedicated precision measuring tool or 3D scanner, ShrinCage can allow novice makers or DIY hobbyists to measure objects with a ruler or tape measure.
- Abstract input shapes: replicating an existing object into a digital model renders the adaptation process challenging for users with limited experience in digital modeling. Our design tool simplifies the modeling process by abstracting the existing object into a low-fidelity model.
- High tolerance for machine errors: for hobbyist rapid prototyping tools such as FDM printers, fabrication errors are inevitable. Our method can ensure a relatively tight fit between the print and the existing object while tolerating printing errors.
- One-step assembly: a trial-and-error process caused by size mismatch is usually experienced in DIY post-processing, which can be avoided in our method without extra procedures.

Using our method, users can change the appearance of an existing object, repair or repurpose unwanted household items, make assistance to people with disabilities, and extend the functionality of a 3D print.

Our contributions in this paper are as follows:

1. Exploring a material-driven method that constitutes the shrinking ability of 3D printed thermoplastic objects.
2. Proposing an end-to-end workflow including a design tool that allows novice users to design attachments that can self-adapt to existing objects. It allows users to securely connect 3D printed adaptations with existing objects while reducing the difficulty of measuring, modeling, and assembling.
3. Validating the practicality of this workflow by a series of mechanical tests and an informal user study.
4. Showcasing a number of adaptation examples reformed by ShrinCage to expand the design space in daily usage scenarios.

2 RELATED WORK

This work intersects with several areas in HCI, including personal fabrication, assistive technology, and shape-changing interfaces, which we will discuss below.

2.1 Personalized 3D Printing

The increasing popularity of consumer-grade 3D printing technology opens up a new opportunity for people to practice and elevate craftsmanship. To democratize 3D printing, researchers have developed platforms and tools to streamline the process of design and fabrication. From a functional point of view, some projects functionalized 3D printed artifacts with mechanical actuation [21, 22], embedding electronics [9, 38, 40, 41, 50], and tactile feedback [52]. A set of works merged 3D printing with traditional craftsmanship to form hybrid crafting [27, 53]. For example, Takahashi et al [41] combined a 3D pen and a 3D printer for rapid creative making. Some researchers focused on developing methods that combine 3D printing with fabrics [10, 19, 34, 37]; other researchers enabled conventional 3D printing with interactive techniques [33, 35]. Furthermore, augmenting 3D printed objects with rich material properties have been introduced [5, 25, 36]. On the other hand, improving assistive technology with 3D printing has drawn more attention to researchers in HCI. For instance, Hofmann et al. investigated the potential advantages of 3D printing in clinical assistive technology and recommended integrating software solutions into client care [17]; Reprise [6] developed a design tool to specify, generate, customize, and fit adaptations on everyday objects. Facade [15] introduced a 3D printing pipeline to make tactile-button interfaces for blind users. On top of these works, ShrinCage expands the boundaries of personalized 3D printing by proposing a method to seamlessly combine 3D printed artifacts and everyday objects with a shrinking mechanism inspired by shrink fitting.

2.2 Bonding 3D Printed Adaptions to Existing Objects

Although 3D printing has infiltrated personal fabrication as a way of small-quantity customization and adaptation, the intrinsic variation in this technology complicates the bonding between the print and an existing object. Jeeeun et al [23] has pointed out the inevitable uncertainty in measurement and printing, which consequently affects the assembly of a 3D printed part. The successful assembly also relies on the precise measurement of the object to be adapted, yet Nathaniel et al [18] has revealed the difficulty in modeling by surveying novice 3D printing users. Many newcomers rely on online sources for 3D models, but often they are made for specific uses and cannot be recycled by other users [11]. In terms of 3D printed adaptations to daily objects, the original 3D models (e.g. OpenSCAD and Blender files) are shared and the parameters can be adjusted to fit different sizes.

In the field of HCI, previous works have focused on computational design and fabrication pipelines of adaptation and discussed possible combining mechanisms. In terms of capturing existing objects for further adaptations, SPATA [8] adapted traditional measuring tools (such as calipers and protractors) to reproduce and present real-world objects in virtual design environments. Fitter [1] installed a touch panel display in the build plate system of a 3D printer to capture the bottom of physical objects. MixFab [48] built a mixed-reality modeling environment to integrate object capturing with digital modeling.

In terms of modeling the adaptations, Reprise [6] and AutoConnect [24] both automated the model generation for the connector part based on an accurate input model. [23] proposed the idea of modeling replaceable joints to accommodate measurement errors. PARTs [16] discussed integrating, modifying, and reusing existing 3D models through the graphically specific design intent. In terms of assembling a 3D printed adaptation to an existing object, previous works have used extra soft materials to tolerate size mismatch [23] and applied glue [5] or zip tie [8] to reassure a firm bonding. On a system level, Encore [8] incorporated a pause function so that the user can embed the existing object before resuming the print job. It is also possible to manually adjust the shape of the final product for better fitting [13]. Yet, all these methods solved either the modeling accuracy problem or the fabrication and assembly challenge, but not both. Comparing with these existing methods, the fabrication pipeline of ShrinCage has the benefits of both lowering the accuracy requirement for the input model and simplifying the design and assembly processes.

2.3 3D Printing of Shape-Changing Interfaces

In recent years, researchers have proposed a series of 3D printed shape-changing interfaces with a range of materials. bioLogic [51] printed biological materials to encode transformation triggered by humidity change. Transformative Appetite [47] and Morphlour [42] applied edible materials in shape-changing interfaces using food as the medium. Sequential Support [30] used 3D printed dissolvable material to create time-dependent mechanisms. ShrinkyCircuits [26] used pre-stressed plastic film, which is widely used in engineering, to enable partial self-assembly of the miniature circuit and components. PLA is among all materials the most ubiquitous in consumer-grade 3D printing, with which many researchers have developed shape-changing interfaces with the shape-memory effect associated with the 3D printing process. Printed Paper Actuator [44] and Foldio [31] bonded PLA to another substrate to create interactive objects. A-line [46], Thermorph [2], and 4DMesh [45] explored various 3D geometries which were transformed from 1D lines, 2D sheets, and 2D meshes.

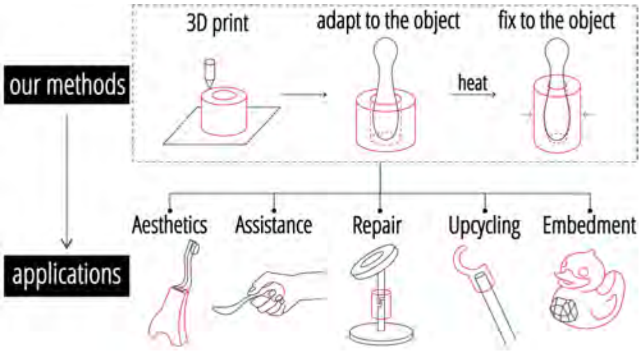

Figure 3: Design space of ShrinCage.

3 DESIGN SPACE

Based on these relevant projects and our preliminary work [39], ShrinCage aims to democratize the design and fabrication methods for creating shrinkable adaptions for everyday objects, which can further extend the functionality of 3D printed shape-changing interfaces.

Utilizing the shrinking effect of 3D printed thermoplastics, ShrinCage is a 4D printing system that can accommodate measurement and printing deviation, create adaptations to the shape of existing objects, and simplify 3D modeling and assembly. The design pipeline of ShrinCage allows even novices to easily create shrinkable adaptations to fit and fasten existing objects (Figure 3). Our method is suitable for reforming most common daily necessities made of metal, plastic, glass, etc. that can withstand a temperature of 90°C. We believe our method can help users to change the appearance of an existing object, repair or reuse everyday junk, make assistance to people with disabilities, and extend the functionalities of 3D prints. More cases will be described in the Design Example section.

4 MATERIAL AND MECHANISM

In this study, we choose a thermoplastic material PLA, a low-cost, accessible, and bio-derived material with shape memory property, in our designs and experiments. As Figure 4 shows, as the thermoplastic filament is extruded through a tiny nozzle at a printing temperature around 200°C, internal stress is encoded as the printed trace cools down rapidly. An elevated temperature, which is usually above 60°C, triggers the stretched polymer chains to relax, releasing the build-up stress and allowing the polymer to shrink to their stable state [3, 12]. This shape-memory effect of thermoplastics has been utilized for 4D printing repeatedly and detailed in previous works [45, 46].

Printing parameters such as printing direction and layer height determine the shrinkage direction and the shrinkage ratio of the printed structure. To parameterize the shrinking mechanism in the ShrinCage design tool, we quantify the shrinking behavior systematically with a series of parameters based on previous studies

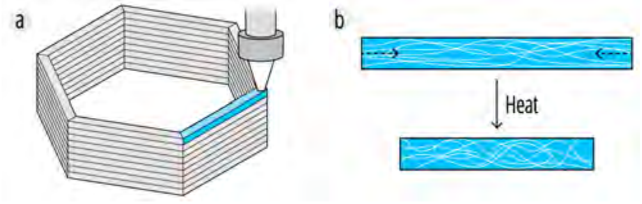

Figure 4: Material mechanism of ShrinCage. The polymer releases stress and shrinks along the printing path upon heating.

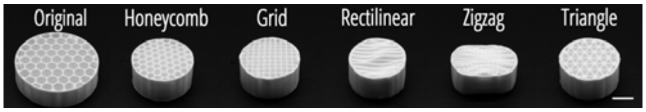

Figure 5: The shrinking test results of five different infill structures. (Scale bar: 1 cm)

[2, 14, 39, 45, 46], including the geometry for infill and outer shell as well as printing parameters.

4.1 Ensuring Omnidirectional Shrinking

We observe that both the outer shell and the infill structure contribute to shrinkage during the triggering process. The infill structure stabilizes the outer shell and helps preserve the shape of the designed structure. Our experiments in Figure 5 demonstrate the shrinking results of different infill structures. Among the five infill patterns tested, the honeycomb performs the best for retaining shapes after triggering, while other infill structures are prone to buckling during deformation. Comparing with the rectilinear or zigzag infill, the honeycomb infill structure ensures the isotropicity of the shrinkage and maintains the shape of the entire structure. Therefore, we conclude that the honeycomb infill outperforms other structures and is chosen for further implementations.

4.2 Efficient Layout of Shrinking Structure

To effectively distribute the shrinking mechanism, we conduct a series of experiments with a disc shape of 40 mm in diameter and 20 mm in height before triggering.

Infill rate: Figure 6a shows that a smaller infill rate gives a greater shrinkage ratio. However, the strength of the prints with a small infill density is insufficient to perform some daily functions. Considering the trade-off between strength and shrinkage ratio, we employ the 20% infill rate to achieve a 25% shrinkage ratio on average. The following layer height and printing temperature experiments also use a 20% infill rate.

Layer height: we test three different layer heights with otherwise consistent 3D printing settings. The result (Figure 6b) shows that the 0.1mm layer height gives the largest shrinkage ratio.

Printing temperature: printing temperature also affects shrinkage. We test a range of temperatures recommended for PLA filament. The result (Figure 6c) shows that the lowest printing temperature (190°C) results in a larger shrinkage.

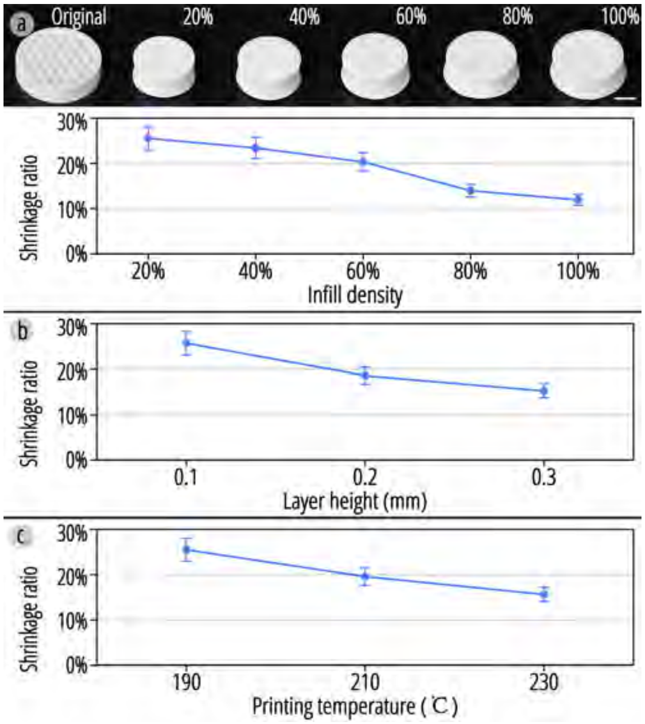

Figure 6: The effect of infill density, layer height, and printing temperature on shrinkage ratio. (Scale bar: 1 cm)

4.3 Preserving the Shape Before and After Shrinkage

To validate whether the print preserves the appearance after heat triggering, we tested the shrinking behavior of prints with different shapes and inner channel diameters, using the above-mentioned infill and printing parameters. As shown in Figure 7a, regularly shaped (such as the star, triangle, and hexagon) prints can maintain the original outline after heating and shrinking. Figure 7b shows the results printed with different infill areas have a similar shrinkage after heat triggering, which means that trimming the infill structure will not severely impact the shrinkage of the entire structure. Lastly, two samples with different outer shell thickness (Figure 7c) are tested to conclude that when combined with irregular objects, a thicker outer shell allows the prints to maintain their outline shape better after shrinking.

5 FABRICATION

5.1 3D Printing Setting

Considering the irreversibility of heat-triggered shrinkage, we integrated a function in our design platform that allows users to assign shrinkable and non-shrinkable parts to one print model. Based on the results shown in the previous section, we decide on two pairs of printing settings to achieve 25% and 5% shrinkage ratios respectively, as shown in Table 1.

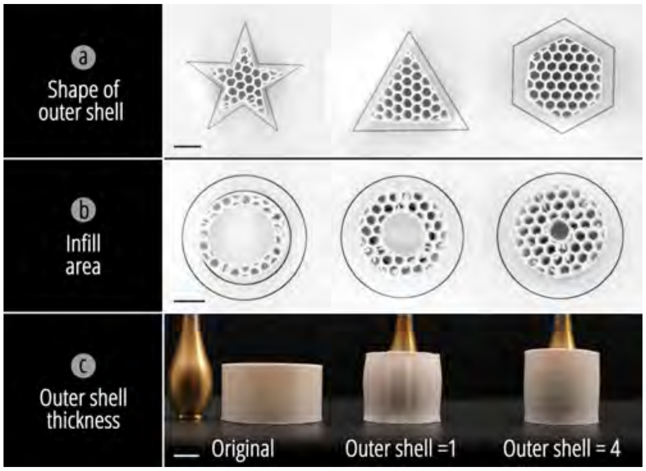

Figure 7: Shape preservation of (a) different shapes, (b) infill area, and (c) outer shell thickness. (Scale bar: 1 cm)

Table 1: Infill and print settings for shrinkable and non-shrinkable parts.

	Shrinkable Part	Non-shrinkable Part
Infill Density	20%	100%
Layer Thickness	0.1 mm	0.3 mm
Infill Structure	Honeycomb	Rectilinear (different direction per layer)
Shrinkage Ratio	25%	5%

Based on the experiments we conducted, a rectilinear infill structure, which is printed by 100% infill every layer in a parallel direction and every four layers alternate in the direction of 0, 90, 45, 135 degrees, is adopted as a non-shrinkable pattern with minimum shrinkage ratio (lower than 5%). The release direction of the residual stress of each layer is different from that of the adjacent layers, so they restrain each other and minimize the overall shrinkage.

We use commercially available PLA filaments (polymaker PolyMax PLA) and an FDM 3D printer (FlashForge Creator Pro) with a 0.4 mm extrusion nozzle that works within a 225 x 145 x 150 mm^3 space. We set the printing speed at 4800 mm/minute in all experiments.

5.2 Heat Triggering with Two Methods

We use a hot water bath or a heat gun to trigger the prints. The printing test samples and mechanical test samples are tested in a 90°C water bath. It takes 2-3 minutes for the shrinking to complete, but we wait until the water cools to 65°C before retrieving the samples as they harden. The time of triggering and retrieval also depends on the size of the prints. We adjust the time accordingly in the later implementation and user study.

The heat gun is suitable for transforming part of a print connected with a larger or fixed object. We adjust the heat gun to 120°C and move close to the parts that need to be shrunk. The accuracy of this triggering method is yet to be quantified, hence we recommend using this method only for scenarios with lower accuracy requirements.

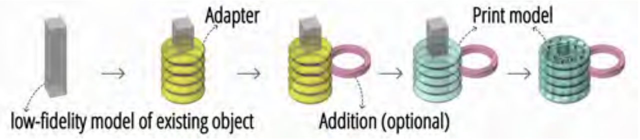

Figure 8: The design workflow of the ShrinCage software.

6 USER INTERFACE

We implement our software using Rhinoceros, Grasshopper (a visual programming language and environment that runs in the Rhinoceros), and Human UI (a plug-in for Grasshopper), which is available in the supplemental document.

Our software provides a simple and user-friendly interface to help novices design custom shrinkable adaptations. The software workflow is shown in Figure 8. In general, firstly, the user roughly models their object in a simple and fast way. Next, the user chooses a functional adapter from our library and visually attach it to the model. Selecting non-shrinkable one addition to enrich the adaptation is an optional step. Finally, the interface generates and previews the printing model for fabrication.

Step 1: Roughly model the existing object

Instead of acquiring the precise model or accurately measuring dimensions of the existing object, ShrinCage software allows users to roughly measure the object. As shown in Figure 9, in most situations, the specific attachment site on a daily object can be simplified as a cylinder or cuboid (Figure 9a), and users only need to input the maximum length, width, and height of this particular part (Figure 9b).

Step 2: Design the Adapter for Attachment

The adapter, which shrinks after heat triggering, is the part that is directly attached to the existing object. Notably, we take into account the size change caused by the shrinking and only present the final adapter size for users to perceive the final product. After perusing numerous cases on the 3D printing model platform Thingiverse[1], our tool supplies a practical model library including 9 models (as shown in Figure 10a), which can resemble common functional parts such as a base, a lever, a handle, and decoration. Users can also build or import other adapter models in Rhinoceros. After confirming the adapter type, users can adjust the position and scale of the adapter and receive a real-time visualization. The dimensions of the adapter including length, width, and height are displayed at the bottom of this tab for users who want precise modification. The software automates the removal of the union part between the rough existing object and adapter, allowing users to focus on designing the adapter shape.

Step 3 (Optional): Model the Addition (Non-Shrinkable Part)

An addition can be understood as a supplement to an adaption, although the latter can shrink and the former cannot shrink. If

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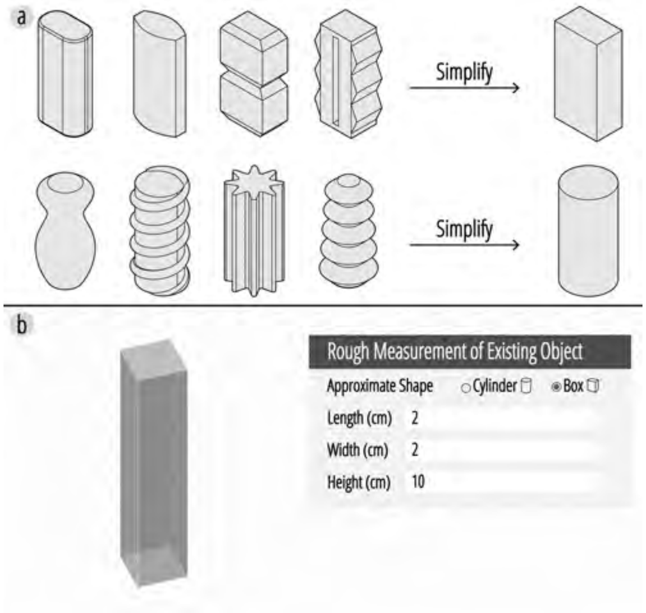
[1] https://www.thingiverse.com



Rough Measurement of Existing Object

Approximate Shape ○ Cylinder ● Box

Length (cm) 2

Width (cm) 2

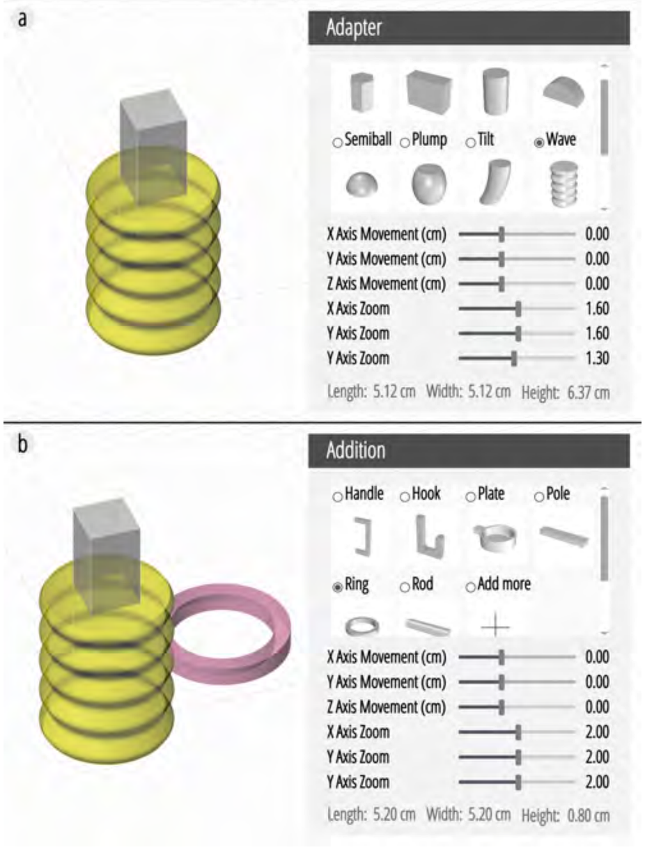
Height (cm) 10

Figure 9: Rough model of the existing object. Users only need to input an abstraction of the existing object by (a) choosing from the software interface and (b) inputting the approximate dimensions.

users plan to add a functional part that is not shrinkable, a library of additions is available to choose from. Similar to the adapter part, our addition library (Figure 10b) contains some useful common models, including handle, ring, hook, plate, pole, and so on. Adjustment for the spatial position and scale is also available for addition. Users modify the position of an addition freely without considering the alignment and overlap as our software can remove the union part between the adapter and addition automatically. Eventually, a single print file will be generated to 3D print the addition with the adapter as one print.

Step 4: Reversely Generate the Print Model

After finishing the steps above, users can toggle the switch to preview the printing model (Figure 11). The implementation is achieved as follows: trim the adapter (from step two) according to the rough model of the existing object (from step one), leaving a hole shaped as the existing object on the original adapter Next, the tool reversely stretches the remaining adapter by 1 / (1 - 10%) - 1 = 11.1% horizontally, 1 - 1 / (1 + 15%) = 13.1% vertically, and cut the union between the remaining adapter and the addition. The infill structure of the adapter will be set as honeycomb before exporting the print model.



○ Semiball ○ Plump ○ Tilt ● Wave

X Axis Movement (cm) 0.00

Y Axis Movement (cm) 0.00

Z Axis Movement (cm) 0.00

X Axis Zoom 1.60

Y Axis Zoom 1.60

Y Axis Zoom 1.30

Length: 5.12 cm Width: 5.12 cm Height: 6.37 cm

○ Handle ○ Hook ○ Plate ○ Pole

● Ring ○ Rod ○ Add more

X Axis Movement (cm) 0.00

Y Axis Movement (cm) 0.00

Z Axis Movement (cm) 0.00

X Axis Zoom 2.00

Y Axis Zoom 2.00

Y Axis Zoom 2.00

Length: 5.20 cm Width: 5.20 cm Height: 0.80 cm

Figure 10: The interface of (a) adapter and (b) addition libraries.

On Preview Printing Model

On Preview Infill Structure

Figure 11: The interface of step4. The software allows the user to roughly combine the attachment to the existing object, automatically stretching the adapter and generating the infill structure.

7 DESIGN EXAMPLES

To demonstrate our method, we showcase a series of design cases navigating our design space.

7.1 Aesthetic Appearance

ShrinCage can change the appearance of existing objects to obtain stylish or interesting shapes. As shown in Figure 12, the butterfly wings are added to the heel of a high-heeled shoe. After the attachment shrinks around the heel, the wings are stably suspended on the high-heeled shoe.

7.2 Personal Assistance

ShrinCage can interest assistive technology (AT) for certain populations such as the elderly, children, and patients with arthritis or hand disabilities, catering to their special needs. As shown in

Figure 12: Example of using ShrinCage to create high-heeled shoe decoration. (a) The existing object and the print (b) are combined and shrink-fit by a heat gun. (c) The final result of the accessorized object.

Figure 13: Design examples of ShrinCage for assistive technology. (a1) A zipper attachment, triggered by a heat gun (a2) for easier grasp (a3); (b1) a key is tightly bounded by the attachment (b2) for easier grasp (b3); (c) an attachment added to a spoon, triggered in a hot water bath (c3), can change the grasping gesture (c5-6).

Figure 13, we delivered several AT examples including wrapping a zipper with an easy-to-grip knob, adding a large handle to a key for gripping and turning, and transforming an ordinary spoon for people who need to manipulate with a different gesture.

Figure 14: Attaching a ShrinCage adapter to repair a broken curtain rope.

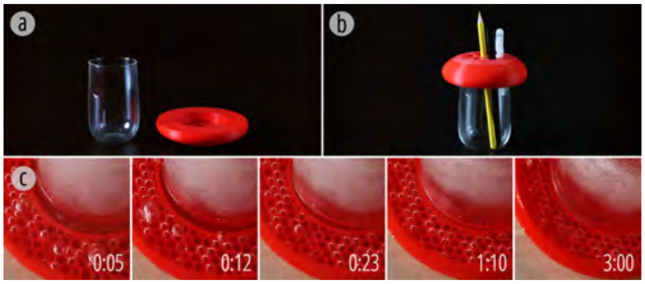


Figure 15: A cup-transformed pen holder. (a) The original unwanted cup and print; (b) mushroom-shaped pen holder after triggering; (c) sequential shrinking transformation over time.

The original zipper case and spoon modification case[2] need to be printed with soft materials to be assembled and fixed, and the original key case[3] requires that the key and the print have holes and are secured with additional screws and bolts. Compared with existing methods, ShrinCage does not require soft materials and additional parts to assemble, and the print can be adapted to objects with different widths by widening the insertion slot according to the maximum width. As shown in Figure 13b, a key handle with a square slot can be adapted to fit an irregular shape.

7.3 Repair

For daily objects and products that are incomplete, broken, or missing parts, the ShrinCage method can be used to repair the object to extend its longevity. As shown in Figure 14, the two ends on a broken curtain cord can be connected using ShrinCage, and the ball chain is embedded in the print after thermal triggering. The connection is strong enough to withstand the force of pulling the curtain so that the curtain can return to normal use. Also, the attachment makes the grasping and pulling easier.

7.4 Reusing / Upcycling

ShrinCage can transform unwanted objects into a completely new shape with new functionalities, which mitigates the problem of accumulating wastes and junks. As shown in Figure 15, a discarded glass food container combined with a perforated lid can be upcycled as a mushroom-shaped pen holder.

Using the ShrinCage method to transform old objects is in line with the principle of circular economy [4] - the modified parts can

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[2] https://www.thingiverse.com/thing:2960070

[3] https://www.thingiverse.com/thing:1852950

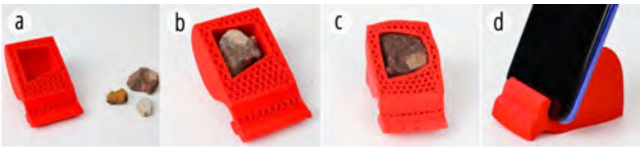

Figure 16: (a) 3D printed mobile phone holder. (b) Extra weight can be added for stability. (c) ShrinCage print securely surrounds the weight. (d) A stable mobile phone case is made.

Figure 17: Setup for testing grip strength. We measure the minimum pulling force (a) and torque (b) that are required to move the ShrinCage print from a metal rod by pulling in two directions.

be cleanly separated from the existing objects by reheating and softening. Without using a bonding agent or adhesive, ShrinCage is convenient for separate recycling of the existing object (such as the glass container in the case) and the PLA print.

7.5 Embed and Augment 3D Print

ShrinCage can enhance the performance of 3D printed parts by embedding daily items with rich material properties. We used ShrinCage to print a mobile phone holder[4] and embedded some stones at the bottom, using the weight of the stones to stabilize the phone holder (Figure 16). For objects with a completely irregular shape like stones, ShrinCage can envelop the complex shape tightly.

8 MECHANICAL EVALUATION

In normal usage scenarios, the adaption prints are expected to remain rigidly attached without any loosening. We evaluate the firmness of the fastening between the printed part with the existing object after heat-triggering and shrinking. Similar to the grip strength test in [24], we measure the minimum force required to detach the prints and the minimum torque required to rotate the prints by slowly pulling on the prints. As shown in Figure 17, we firmly fix ShrinCage adaptations on a cylinder, and we use the dynamometer to pull it along the major axis of the print and at 90°C to the side relative to the major axis of the print.

Considering the different surface roughness of objects in daily life, we select a polished metal rod as an experimental example, which represents the lowest friction. We also attach prints with different wrap widths (5mm, 10mm) to test its influence on grip strength, which demonstrates a trade-off between the volume (material consumption) and the functionality (grip strength) as a design consideration. In our experiments, the cylinders are 20 mm in diameter, and the printed parts have an inner diameter of 21.2 mm and a wall thickness of 10 mm before heat-triggering and shrinking.

The results show that ShrinCage with wrap widths of 5 mm can withstand 77.4 N of pulling and 0.78 N·m of rotation. For the possible use cases, this is considered enough to resist detachment. The print with larger wrap width (10 mm) measures similar in the pulling force (82.3 N), but it is more prone to rotation (0.41 N·m). If the existing items have rougher surfaces or irregular shapes (especially with uneven bumps), the prints will bond more firmly with the existing objects.

9 USER STUDY

We recruit participants to design and fabricate adaptation through the ShrinCage approach and analyze their reactions and feedbacks. The objective of the study is to assess the usability of our system.

9.1 Participants

We recruited eight participants from our university (No. female students = 3, age mean = 24.6, SD = 6.48). two majored in industrial design, one in architecture, one in mechanical design and automation, one in electrical engineering, and three in computer science. Most participants reported having little 3D modeling experience using CAD tools. Only one participant was experienced with 3D printing (P6).

9.2 Apparatus

The design and fabrication session took place in a professional laboratory with standard fab shop supplies. We have no restrictions on choosing the existing objects, thus participants can bring their personal items, or design with the provided items, including pins, pens, water bottles, spray paint cans, umbrellas, bicycles, tables, chairs, and so on. We also provided them with commonly used measurement tools, such as transparent plastic rulers, tape measures, and cutting pad, following the survey in [23]. We prepared a consumer-grade FDM 3D printer and optional heat triggering tool (heating rod, hot air gun, tweezers, water tank, and cup). Cameras and audio recording devices in the lab environment recorded the behaviors and utterances of participants.

9.3 Procedure

The task of the design and fabrication session for the participants is to repurpose the existing objects. Considering the contents and duration of a single session, we divided the session into two days consisting of practicing, designing, modeling on day 1 and heat triggering on day 2.

a) Introduction and practice: After a demographic survey, we played an introduction video about the method and application and another video demonstrating the basic operation of the software tool by modeling a cup holder for chair. We also gave a brief description of other models available in the library. Participants practiced the operation of the software for about 20 minutes.
b) Design and measurement: Participants picked the items to be repurposed, curated their ideas of adaption, and drew sketches. The participants discussed the feasibility of their

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[4] https://www.thingiverse.com/thing:2646344

Figure 18: Outputs from the user study session: a handle for a water bottle (P1), a spinning top modified from a pen cap (P2), a pill bottle pendant (P3), a handle for a ladle that can change the direction of picking and prevent scalding (P4), a handle of a cooking spoon (P5), a key tray on the studio pole (P6), an Allen Wrench attachment for easier rotation (P7), a decorative zipper pendant (P8).

plans with the host to make sure it can be 3D printed and assembled. Participants could use any measuring tool they chose to measure existing objects and recorded the size on a piece of paper.

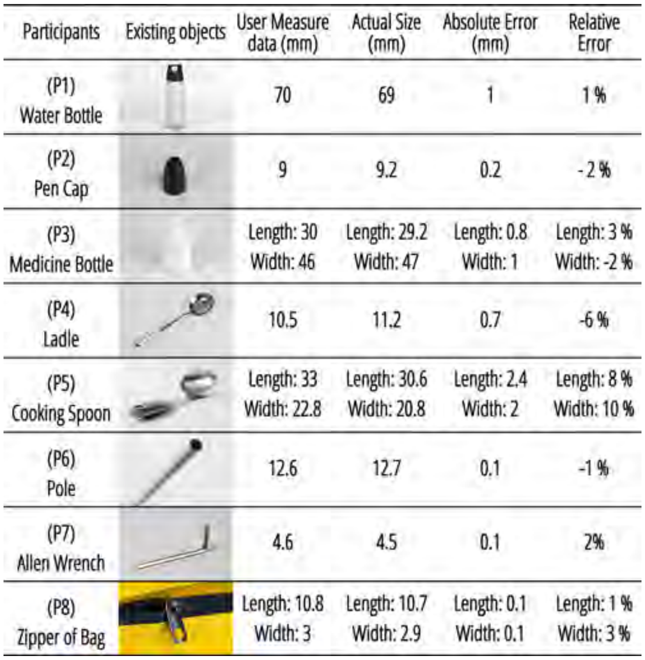
c) Think-aloud modeling: Participants used ShrinCage software tools to model the adaption. We observed the process and sometimes asked questions to promote the think-aloud practice. If they were confused and wanted to know how to use our software, we gave instructions. After modeling, the participants attended a semi-structured interview about the usability of the tool. The time of the modeling session depended on the participants (10-30 min).
d) 3D Printing and triggering (Day 2): After exporting files to the 3D printer, participants retrieved the 3D printed items the next day. The host demonstrated different heat triggering methods. Participants heat-triggered the print with either hot water or heat gun, thus completing the integration of the print with the existing objects. They then described their experience with ShrinCage, such as what they liked about the tool and the method, what problems they encountered, and what they would like to have in the future.
e) We conducted a discourse analysis by transcribing recorded videos using a method akin to the Affinity Diagram approach [7].

9.4 Summary of User Study

Overall, most participants are positive about the design and fabrication pipeline of ShrinCage. They were able to grasp the technical implication of the software, the design process, and the streamlined fabrication. All participants successfully produced adaptations to an existing object, and the triggered samples are shown in Figure 18.

Measurement Error Accommodation

Figure 19: Measuring techniques and tools employed by participants.



Participants	Existing objects	User Measure data (mm)	Actual Size (mm)	Absolute Error (mm)	Relative Error
(P1) Water Bottle		70	69	1	1 %
(P2) Pen Cap		9	9.2	0.2	- 2 %
(P3) Medicine Bottle		Length: 30 Width: 46	Length: 29.2 Width: 47	Length: 0.8 Width: 1	Length: 3 % Width: -2 %
(P4) Ladle		10.5	11.2	0.7	-6 %
(P5) Cooking Spoon		Length: 33 Width: 22.8	Length: 30.6 Width: 20.8	Length: 2.4 Width: 2	Length: 8 % Width: 10 %
(P6) Pole		12.6	12.7	0.1	-1 %
(P7) Allen Wrench		4.6	4.5	0.1	2%
(P8) Zipper of Bag		Length: 10.8 Width: 3	Length: 10.7 Width: 2.9	Length: 0.1 Width: 0.1	Length: 1 % Width: 3 %

Figure 20: Participants' measurement deviation.

Errors commonly exist in the participants' measuring process. Figure 19 shows the way they used the measuring tools and Figure 20 tabulates the errors in user measurement. The measurement errors mostly fell below 5%, but measuring irregular shapes and diameter (P5) was subjected to larger errors at 10%.

Several users with prototyping experience mentioned their previous unsatisfactory experience of measurement and adaptation: P3 mentioned that he had experienced size mismatches between 3D printed parts and existing objects many times. P4 used a drill and a knife to manually change the aperture of the 3D printed part to make a button cap. "It was very time-consuming and frustrating."

Software Function

Generally, participants including those who had little experience in modeling found it easy to get started with ShrinCage. P5, P6, P8 mentioned that the three modules of the software were very self-explanatory and easy to follow. "This method allows me to prototype a functional component very conveniently." (P4)

P3 and P5 were particularly fond of the feature that ShrinCage software takes a rough shape of exiting objects for the design process without the need for precise modeling. P3 chose to design an adaptation for a pill bottle that had an irregular shape and filleted corners. "It is much easier to build an adaptation on top of a cuboid."

Four participants mentioned that they appreciated the model library. "The model library saves a lot of time." (P8) "This allows someone with little modeling experience to invent and fabricate with advanced technology." (P2) "The library gives me a lot of inspiration. It has included shapes which I didn't think of before but are interesting for me to apply to a real-world use case." (P4) "The model library is useful. I do not need to adjust the handle I designed because its default size just fits." (P1)

P4 liked the feature where the software integrates Boolean operation to automatically drill holes and combine models of the adapter and addition. "I do not need to worry about how and where to leave a hole. With ShrinCage I simply drag the addition model to the adapter without worrying about their overlapping region and I do not need to attach them precisely."

Heat Triggering

All participants were intrigued by the triggering process as they first saw it. P1, P3, and P4 mentioned the shrinking and minimizing of the honeycomb structure were amazing. "I couldn't imagine that this hard plastic part could actually shrink by itself. I could see it shrink and tighten in a very short time." (P5)

Matching and Bonding

All participants agreed that the prints after shrinking fitted the existing objects. "The pill bottle I chose to adapt is completely irregularly shaped. I had not expected the filleted corners to be surrounded as the gaps before shrinking were large. Yet the print shrank to fit on the bottle perfectly which actually surprised me." (P3)

All the prints were attached firmly to the existing objects. "The cooking spoon I picked has a fusiform handle. Although there are small gaps at the ends of the handle after shrinking, the print was attached to the belly of the handle firmly and the function is promised." (P5) "My water bottle has a curved surface. I had been worried that the attachment cannot be secured, but actually, it was unexpectedly firm. I imagine it would not budge at all." (P1) "If I were to model this attachment from scratch without ShrinCage, I may have built a more complex plug but it would not be as firm as this attachment." (P6)

Method Application Space

All participants found this method practical. "Hot water is accessible for triggering at home." (P5) "If I buy something for daily use and it was not handy, I can modify its function. If it is handy but looks poorly designed, I can change the appearance too" (P3). P5 mentioned that the ShrinCage method would be greatly helpful if his household item broke. P1 mentioned, "I want to customize a drawer pull to my liking and embed a screw through ShrinCage so that it will fit into the drawer with a hole."

Existing Problems and Suggested Features

Participants also pointed out some existing problems and suggested new features in this method and the design tool. P1, P3, and P6 mentioned that they would like to add multiple adapters and additions at the same time. P2 and P6 would like to have more usable models directly from the model library. P2 and P5 suggested that it would be helpful to have more model parameters, such as the fillet size, adjustable. P3 and P4 looked forward to an open-sourced platform utilizing ShrinCage as the fabrication technique. They believed that a platform where everyone can share easily usable adaptations of daily objects would be meaningful. P5 suggested the software could prompt the duration of heat triggering and shrinking. All these suggestions fertilize opportunities for future work.

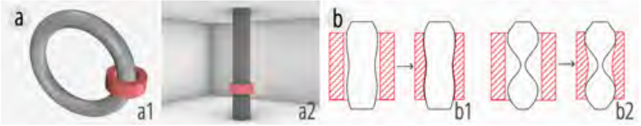


Figure 21: limitation on compatible existing object shapes. (a) The adaptation cannot cut through a closed shape during assembly. (b) Objects with curvy surfaces can be fitted but may not be completely wrapped.

The overall process of design and fabrication using ShrinCage was enjoyable and all participants were satisfied with their achievement. Two of the participants (P1, P8) modified their items. They indicated their willingness to continue to use the modified items after the workshop.

10 DISCUSSION, LIMITATION, AND FUTURE WORK

Heat Trigger Process

The triggering method requires that the existing object tolerate at least 90°C heat. When triggering inside a hot water bath, it is difficult to fix the relative positions of the existing object and the adaptation and manipulate inside hot water, especially when the buoyancy of the combined object overcomes its weight. Furthermore, when the adaptation is designed for a much larger object, it is impossible to use a hot water bath for triggering. The heat gun triggering method will mitigate this problem with compromised uniformity.

Deformation Control

The non-shrinkable part, while it is supposed to maintain dimensional stability, also softens in the hot water bath, which causes the part to slightly bend and warp. The visualization in the software has not taken the random warping into consideration yet. There is also internal friction between the print and the existing object during the shrinking process, which distorts the cross-sections of the print. We hope, in the future, to address these issues with a detailed simulation and generate a case-specific infill structure.

Shape Compatibility

In terms of limitation on compatible existing object shapes, 3D printed parts cannot be installed and fitted on objects with a closed surface such as rings or rods connecting the ceiling and the floor (as Figure 21a shows). Besides, we reserve cylindrical and cuboid holes in the 3D print to fit and fasten the existing objects. For objects with a curvy surface (the curvature along the cross-section of the axial direction varies beyond the shrinkage limit of the 3D print, as Figure 21b2 shows), the 3D printed part can achieve a tight but compromised fit after shrinkage that does not conform to the surface (especially on an extra-thin neck) of the target object.

11 CONCLUSION

In this work, we present ShrinCage, a 4D printing design and fabrication pipeline that allows everyone to easily create shrinkable adaptations to modify daily objects. ShrinCage introduces a unique method to offload the design complexity for novice users. It simplifies measuring, modeling, fabrication, and assembly. Our design and fabrication pipeline allows a streamlined integration of the ShrinCage technology with daily use cases. Through this work, we have shown that our method can enrich the design space of 3D printed objects that adapt to existing daily objects, repurpose unwanted wastes, repair broken items, and assist people with disabilities. The feasibility is validated by a set of mechanical tests, an informal user study, and various real-world applications. We hope that our work can greatly benefit the end-users for their personal creation and fabrication.

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