Therms-Up!: DIY Inflatables and Interactive Materials by Upcycling Wasted Thermoplastic Bags

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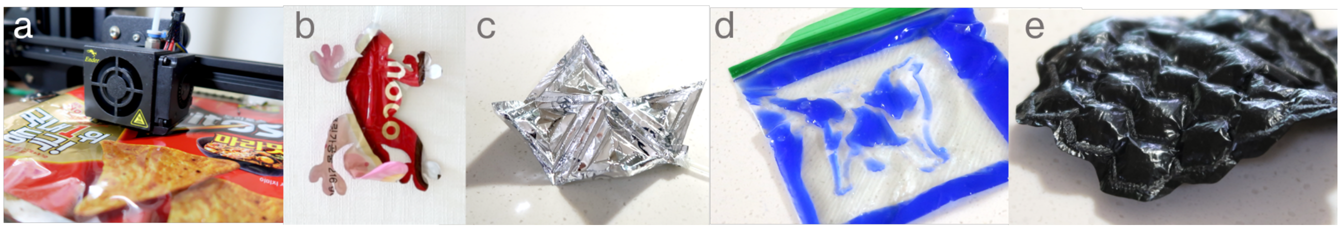

Figure 1: (a) Heat-sealing a plastic bag of chip by controlling the temperature and path of a ready-to-use inexpensive FFF 3D printer's extruder. Examples of using the 3D printer for creating various design and prototyping materials; (b) Gecko that curls its tail made of a cookie bag, (c) multistable origami inflatable made of a cereal bag, (d) interactive fluidic interface that draws a shape of dog on a Ziploc® bag, (e) inflatable shape-changing cushion made of a food delivery plastic bag

ABSTRACT

We introduce a DIY method of creating inflatables and prototyping interactive materials from wasted thermoplastic bags that easily found at home. We used a inexpensive FFF 3D printer, without any customization of the printer, to heat-seal and patterning different types of mono and multilayered thermoplastic bags. We characterized 8 different types of commonly-used product package's plastic film which are mostly made of polypropylene and polyethylene, and provided 3D printer settings for re-purposing each material. In addition to heat-sealing, we explored a new design space of using a 3D printer to create embossing, origami creases, and textures on thermoplastic bags, and demonstrate examples of applying this technique to create various materials for rapid design and prototyping. To validate the durability of the inflatables, we evaluated 9 different thermoplastic air pouches' heat-sealed bonding strength. Lastly, we show use-case scenarios of prototyping products and interface, and creating playful experience at home.

CCS CONCEPTS

• **Human-centered computing** → **Interactive systems and tools**; Accessibility technologies; • **Hardware** → *Sensors and actuators.*

KEYWORDS

Sustainability, Recycle, Upcycle, DIY, Fabrication, Inflatables, Soft Robot, Rapid Prototyping

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1 INTRODUCTION

Since the COVID-19 pandemic lockdown, tangible prototyping and quick idea validation at home environment with limited resources has been challenging. Cardboard has been commonly-used for crafting and quickly validating an idea in a tangible way [22, 28]. Inspired by the cardboard prototyping approach, we were interested in enriching the prototyping process at home where has limited material source and tools, and utilizing wasted materials other than a cardboard box. The growing number of plastic usage in the TEI community [8] and increasing concerns on the huge growth of global plastic consumption [12, 29] motivated us to develop an idea of re-purposing the easily accessible wasted plastic materials. HCI community has put efforts on attaining the environmental sustainability by minimizing the waste of material or re-purpose the wasted material.

However, there is a lack of exploration on DIY method for upcycling [16] wasted plastics to create inflatables and interactive materials, which enables users to realize and validate their ideas quickly with a limited access to tools outside of the laboratory environment. With the increasing number of 3D printer users in their home in U.S [26], we introduce a DIY method of re-purposing wasted thermoplastic bags using an inexpensive fused filament fabrication (FFF) 3D printer without requiring any customization of the printer. We used the 3D printer extruder to heat-seal and create patterns on different types of wasted thermoplastic bags. We

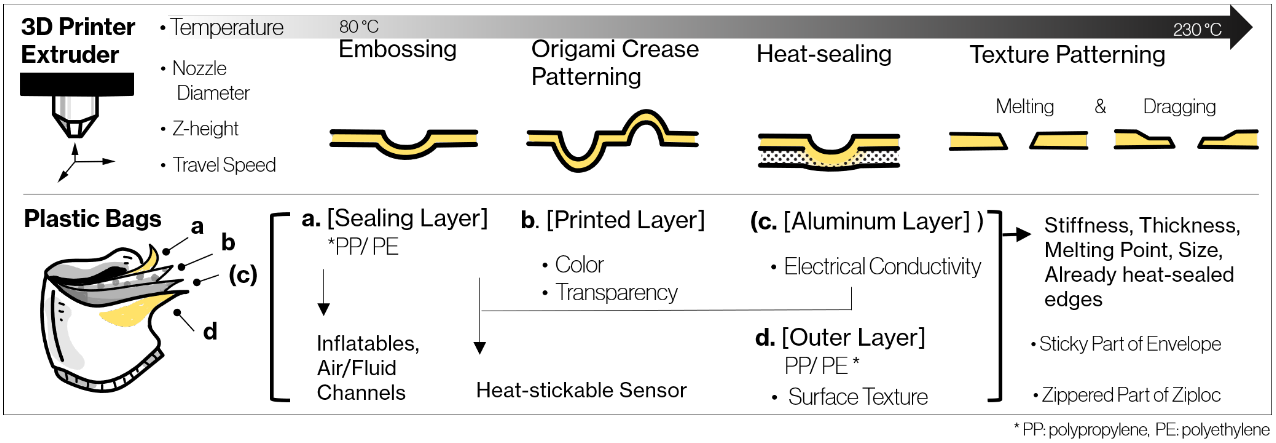

Figure 2: Design space of upcycling plastic bags (materials) with 3D printer extruder (fabrication method). The design parameters for the printer are: temperature, nozzle diameter, z-height, and travel speed of the extruder. Plastic bags that used in this project are consist of either single or multiple layers. Shipping/shopping bags are mostly monolayer made of PE, and Ziploc is made of PP, but food packages like chip bags have (a) sealing layer inside, (b) printed layer that includes any graphic images and labels, (c) aluminum layer that is not necessarily found from all food packages but from retort food package, and (d) outer layer.

characterized 8 different types of commonly-used product package's plastic film, and provide the corresponding 3D printer setting for heat-sealing. Also, we provide detailed instructions for manual heat-sealing process. We explored a new design space of using a 3D printer to create embossing, origami creases, and texture patterning on thermoplastic bags, and demonstrate examples of applying this technique to create various interactive and inflatable materials for rapid design and prototyping. Lastly, we present use-case scenarios of using the introduced method and the design space at home. The contributions of this works are;

(1) Exploration of a new design space of using wasted materials from thermoplastic bags by applying a FFF 3D printer without requiring its modification to create interactive tangible materials and inflatable structures.
(2) Material characterization of 8 different thermoplastic materials wasted from daily household and a 3D printer setup optimized for each material to be upcyled as a functioning material for TUI, and evaluation of its durability in response to pressure.
(3) Demonstrations of design primitives and use-cases that could contribute to playful learning, rapid prototyping and idea validation.

2 RELATED WORKS

HCI community has contributed to attain the environmental sustainability by minimizing the waste of material or re-purpose the wasted material. TrussFab [11] introduced a novel fabrication method using a plastic bottle to create large scale truss structure. Yoshida et al [30] presented a playful way to upcycle tree branches found from nature to create architectural structures. Vasquez et al [27] presented a fabrication method to using a material from the nature, mycelium, to DIY electronics. However, still there is a lack of design exploration for DIY creating inflatables with limited resources and tools. Lots of upcycling craft projects have been shared in online crafting community. Gupta [6] has shared variety of toys crafted from trash. Fashion industries have started to take the environmental issue seriously by developing a product upcycled from trash. BEAMS Coture collaborated with Ziploc® to create a upcycled collection of fashion items [4]. 3D printing industries also have put efforts on reducing the waste of plastics [9]. Recyclebot [3], Filastruder [5], FilaFab [13] provides a machine that converts household plastics into 3D printer filament, and Precious Plastic [7] introduced different plastic recycling machines. Sticky Actuator [20] used a custom-built CNC heat bonding machine to heat-seal a thermoplastic sheet (PE) and create a stickable inflatable pouch. aeroMorph [21] explored various fabrication options for heat-sealing the inflatable materials. They also introduced a robotic sealing method that requires a customized heating head mounting mechanism. milliMorph [15] introduced a fabrication method of fluidic-driven shape-changing materials in micro-scale. Printflatables [25] explored the application of the heat-sealing fabrication in human-scale to create inflatable objects using thermoplastic fabric and a custom fabric folding and sealing machine. However, all of these methods require users to have a special CNC tools or machine. Mitchell et al. [17] introduced a toolkit to create high-performance actuators by using of inexpensive 3D printer to thermally bond a sheet of biaxially oriented polypropylene (BOPP). However, the application of the introduced fabrication method provides only a limited applicable material for creating a specific actuator that requires at least 2 kV.

3 DESIGN SPACE

We explored a new design space (Fig. 2) using of wasted plastic bags combined with FFF 3D printer. Thermoplastic bags are easily

Table 1: Characterization of different thermoplastic packages based on temperature (right), and the corresponding material example photos (left). 3D printer setting shows the required extruder temperature, extruder height from a printing bed, travel speed, usage of cardboard underneath the material and aluminium foil on top of it. Whenever using an iron, we recommend to place a aluminum foil between the plastic bag and the iron to prevent the melting of material and sticking to the iron, and to evenly distribute the heat.

Product Example	Material Inside	Melting Temp. [°C]	Purpose	3D Printer Setting					Clothing Iron Setting
				Z Height*	Travel Speed*	Extruder Temp. [°C]	Cardboard† underneath	AL foil† on top	
a. Ziploc	PP plastic resin	90.6 ~ 100	Sealing	Z0.0	F600	210	X	O	• •
Plastic shopping bag	b. HDPE (Thick)	120 ~ 180	Sealing	Z2.4 ~ 2.6	F400	220	O	O	• • •
			Texture Patterning	Z0.8 ~ 0.9	F400	130		X	
			Origami	Z0.8 ~ 0.9	F2000	100		X	
	c. LDPE (Thin)	105 ~ 115	Sealing	Z0.8 ~ 0.9	F500	120	O	X	• •
Shipping Envelope	d. HDPE	120 ~ 180	Sealing	Z0.5	F600	150	O	X	• •
			Origami	Z0.9 ~ 1	F2000	100			
	e. LDPE	105 ~ 115	Sealing	Z2.4 ~ 2.5	F400	200 ~ 220		O	• •
f. Chip, cereal bag (shiny inside)	LDPE (Multilayer outside)	170 ~ 220	Sealing	Z0.8 ~ 0.9	F400	160 - 170	O	X	• • •
			Origami	Z0.9 ~ 1	F2000	100			
g. Bubble Wrap	LDPE	93 ~ 105	Sealing itself	Z2.0 ~ 2.1	F500	210	O	O	•
			Sealing with HDPE	Z1.5	F600	120	O	X	
h. Retort Food Package	PP (Multilayer outside)	235 ~ 260	Sensor	Z.0.8 ~ 0.9	F100	220	O	X	• • •

* Represented by G-Code command notation. (the Travel speed unit is [mm/min]), † Carboard thickness: 2.5mm , Aluminum foil thickness: 30 μm

found from household product consumption, such as food packaging, shipping, food delivery, and grocery shopping. Using the heat responsive characteristic of the thermoplastic, stiffness, and the plastic package's unique layered-structure, we explored a design space that creates a new function out of the wasted material for a tangible interactive interface such as inflatables, sensor, fluidic interface, and prototyping material. The benefits of using the wasted plastic bags are that we can apply the existing colors and printed images of the plastic bags, and choose various sizes that already include heat-sealed edges which minimize the fabrication time. By controlling the multiple parameters of 3D printer, we were able to create different patterns on the surface of the wasted plastic bag as demonstrated in the following section.

4 IMPLEMENTATION

4.1 Characterizations of Thermoplastic Bags

Table 1 shows 8 different thermoplastic bags that mostly wasted from grocery stores and home and corresponding settings of 3D printer and iron. We have collected thermoplastic bags consumed by a 4-person family over 3 weeks. All the material examples presented in this paper were from this collection. We categorized the thermoplastic bags into 6 types based on its source product's purpose. These were mostly from food and product packaging (Ziploc® (a), retort food container (h)) snack bags like chips and cereal (f)), shipping (package envelopes (d, e), bubble wraps (g)), plastic bags for food take-out, delivery, and grocery shopping (b, c). Then we categorized them depending on its sealing layer material as shown in Table 1. Thermoplastic bags we used here are identified as either high-density polyethylene (HDPE) or low-density polyethylene (LDPE), except for Ziploc® which is made of polypropylene (PP) [31]. Other than the snack bags (f) and retort food package (h) which are consist of multiple layer, all the material shown in the Table 1 are single layer of PP/PE. The material of plastic bags can be identified by the recycle code [24] that is labeled on the product package. Although the listed PP, PE does not contain toxic material like di(2-ethylhexyl)phthalate and are approved by FDA for food packaging [1], we recommend to use our method in a well-ventilated open space/room. For the air channel to the inflatables, we cut a small portion of a corner of the inflatables, inserted a silicone tube or a straw and hot glued it. Creating the examples shown in Fig. 4 can be done either by using a 3D printer or manually with an iron as its temperature setup as described in the Table 1. However, 3D printer is helpful especially when working with a delicate and complicated heat-sealing pattern or a small piece of plastic bags. The printout templates and instructions for the manual heat-sealing process can be found in Appendix.

Figure 3: Embossing examples. Adjusting the Z-height of the extruder controls the depth of embossing pattern. (a) Hatch pattern engraved on a chip bag. (b) a checkered pattern, and (c) writing letters on the sealing layer of a retort food package, and (d) LDPE shopping bag. (e, f) Texture patterning by melting the material (HDPE) and dragging it. (e) By melting the starting point and dragging it to the next point, it can create the knitted-look-like pattern. (f) The same method was demonstrated in combination of X and Y direction.

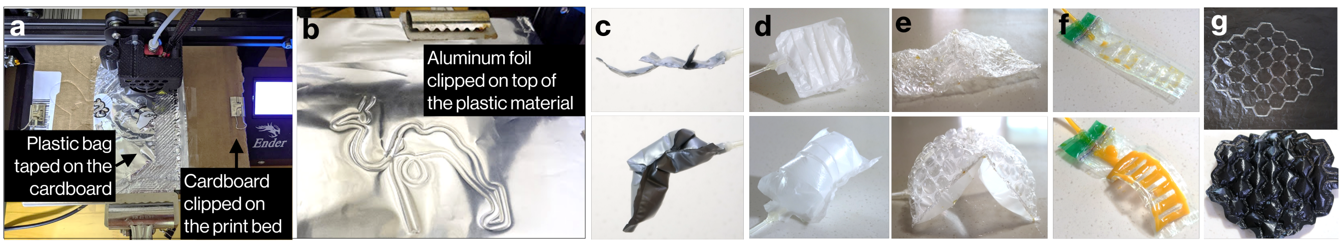

Figure 4: (a) 3D printer setup for heat-sealing ((b) in case of using a aluminum foil). (c) A actuator made of HDPE shipping envelope in bending motion referenced a folding pattern from [25]. (d) HDPE shopping bag inflatable with pre-folded layer to achieve a larger volume change. (e) inflatables having a bending mechanism introduced in [21]; made of a bubble wrap and HDPE shopping bag. (f) Soft actuator made of Ziploc® and actuated by injecting water/air, (g) Cushioning patterns heat-printed on a LDPE shopping bag. All the working motions of the shown examples can be found in the video attached in Appendix

4.2 3D Printer Setup

We used a inexpensive FFF 3D printer (Ender 3, Creality.$167 in 2020) and its maximum extruder temperature is 255°C with the nozzle diameter of 0.4 mm, and the travel precision is ±0.1 mm. Any type of FFF 3D printer could be used for this purpose of the work by adjusting the G-Code setup. To create enough load to make two plastic layers stick together during the extruder's travel along the path, we used a cardboard piece having a 2.5 mm thickness under the plastic layers (Fig. 4(a)). The stiffness of the cardboard produces a enough force to tightly sandwich the heat-sealing plastic with the traveling extruder. We found that adding a aluminium foil (30μm thickness, Fig. 4(b)) on top of the material to be heat-sealed helps the heat-sealing process when working with Ziploc, HDPE shopping bag, LDPE shipping envelope, and bubble wrap itself. Only when using the Ziploc®, putting a cardboard underneath causes defects so that fixing the Ziploc® directly on the printing bed works best. Also, to avoid any slips between the foil and Ziploc® during the heat-sealing, we sprayed a water on the Ziploc® and placed the foil on top of it to make two materials are sticking together via surface tension without leaving any sticking traces on the Ziploc®. Before running the printer, it is important to fix the materials on the printing bed with or without cardboard using a clip or tape and make sure that the plastic film is stretched to have a tension for minimizing wrinkles on it as shown in Fig. 4 (a, b). Table. 1 also includes the dial setting of clothing iron for manually heat-sealing the plastics.

4.2.1 Generating G-codes. We used Inkscape [10] to create traces and patterns (for hand drawing, we used Adobe Illustrator and opened a SVG file from the Inkscape for generating the G-code). We used the 'Gcode tools' in the Inkscape extensions to generate G-code. Using a G-code plug-in like J Tech Photonic Laser Tool [23] is also helpful for generating the code quickly. To create a hatch fill patterns, we used the AxiDraw extension [2]. Before opening the generated G-code in any slicer software, we edited the header of the G-code to have it the temperature of the extruder and printing bed. The detailed G-code setup with examples and instruction can be found in Appendix.

4.3 Embossing and Texture Patterning

Fig. 3 shows the heat-printed examples of embossed and texture patterned plastic bags. By running the extruder temperature lower than the plastic material's melting temperature as summarized in the Table 1, embossed patterns can be created. The melted and dragged texture pattern can be created by increasing the temperature higher than the melting temperature of the material and let the extruder run directly on top of the material without aluminium foil. We found that this texture patterning works best with a mono layered HDPE material like a shopping bag.

4.4 Creating Inflatables

As shown in the Fig. 4.(e), using a bubble wrap creates a interesting design space for creating textures on the surface of soft actuators.

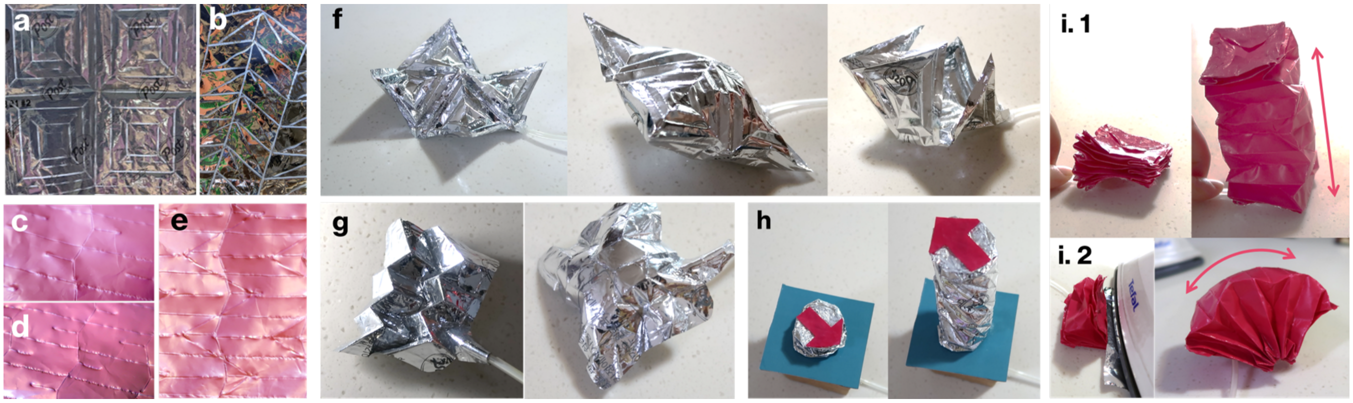

Figure 5: Creating origami crease pattern. (a) Multistable origami pattern created on the cereal bag. (b) Expandable origami cylinder pattern for (h). Mountain (C) and Valley (b) folding line, (e) patterning the both of mountain and valley folding line is completed in a HDPE shipping envelope (used for fabricating (i)) Origami inflatables made of a cereal bag: (f) Multistable origami inflatable inspired by [14]. (g) Miura-fold [18] inflatable, (h) Expandable origami structure while twisting. (i) Quick adjustment of the actuated motion by creating a hinged-constraint with heat

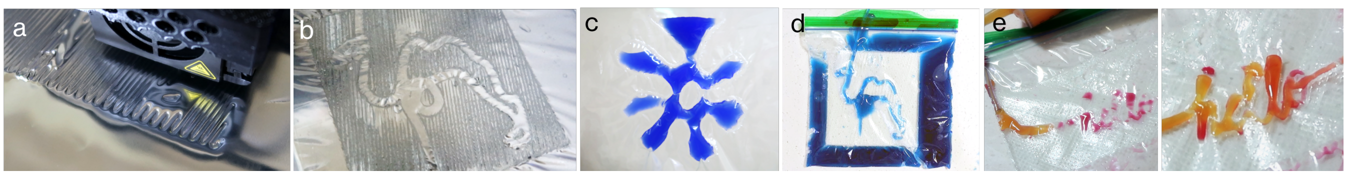

Figure 6: Creating interactive fluid interface by using Ziploc. (a) Hatch-filling the empty space to prevent any fluid leakage. (b) A fluidic channel for drawing a camel. (c) A flower filled with blue watercolor. (d) A drawing of camel from the process (a, b). (e) Writing a word 'hello'.

We poked a little hole on the bottom surface of every bubbles before heat-sealing so that when the air is pumped in, the individual bubble inflates as well as the whole bubble wrap inflatable deforms. Since it is thin and delicate, we recommend to use a aluminum foil on top either when using an iron or 3D printer. For the origami-based inflatables, mountain and valley folding crease (Fig. 5) can be created by flipping the origami material on the 3D printer. The printed crease pattern guides users to fold the plastic bag easily. Primitive examples are shown in Fig. 5 (f-h). Heat-sealing ability of thermoplastics allows users to quickly adjust their design. For example, as shown in Fig. 5(i), when users want to modify the linear motion of the fabricated origami actuator to have a bending motion, they can apply heat to where they want to make the structure constrained all together using an iron (Fig. 5 (i.2)).

4.5 Interactive Fluidic Interface

Mor et al. [19] introduced a interactive fluidic mechanism made of Polydimethylsiloxane engraved with micro fluidic channels. The method we showed in Fig. 6 can be applied to quickly create the interactive fluidic mechanism at an affordable level for general people at home. Also, the zipper of the Ziploc allows users to replace the injecting fluid material whenever they want so that might be applicable to try the fluidic mechanism multiple times with different colors, and viscosity, and to test the design prior to directly producing the final prototype to reduce the waste of expensive materials.

4.6 Sensors

We used a aluminium layer of multilayered plastic bags, such as a retort food package, to fabricate a sensor. We created a capacitive based sensors as shown in Fig. 7. The advantage of using the thermoplastic material is that we can stick the sensor trace to any other plastic materials by applying heat. To demonstrate this idea, we cut a walnut package in two identical square shapes and pasted them on a HDPE shopping bag using a iron (Fig. 7.(a.1)). We created a simple inflatable with the sensor patch on each side, which detects its shape-deformation by capacitive variance due to the distance variance of the HDPE layers (Fig. 7.(a.4)). Also, by using a zipper attached on the walnut package, the pressure sensor's stiffness can be adjusted by adding a sponge inside (Fig. 7.(b)).

5 EVALUATIONS: AIR PRESSURE ENDURANCE

To evaluate the endurance of the heat-sealed bonding of plastic bags, we prepared 9 different inflatables and applied air pressure inside until it leaks air. We measured the yield pressure using a barometric pressure sensor. The detailed evaluation process and the result can be found in Appendix.

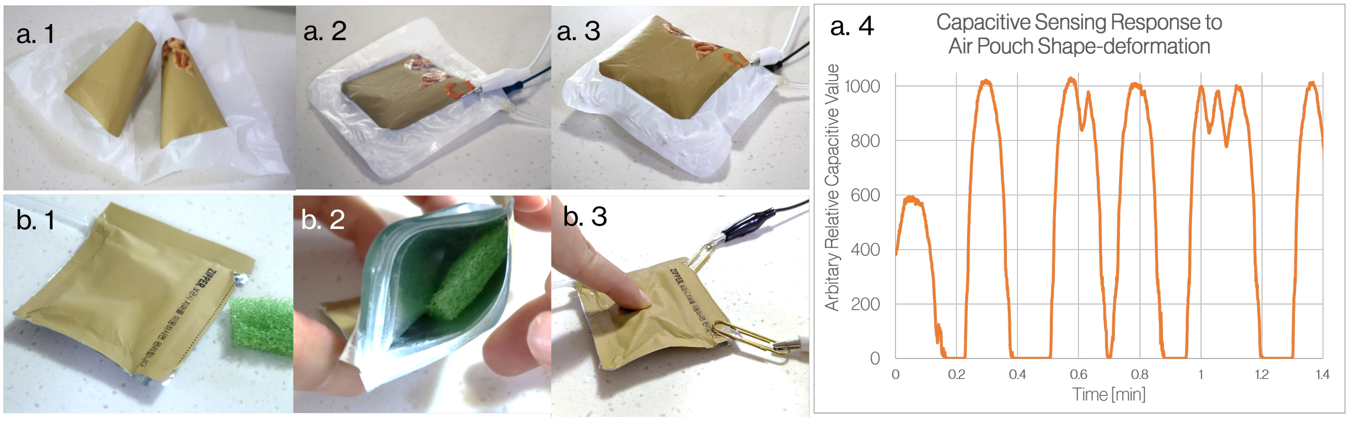

Figure 7: Two use-cases of retort food package (a package of walnuts) for capacitive sensor application: (a) Monitoring of shape-deformation of inflatable pouch, (a.4) Capacitive response to the shape-deformation of the plastic air pouch. (b) Pressure sensitive touch sensor with a adjustable stiffness

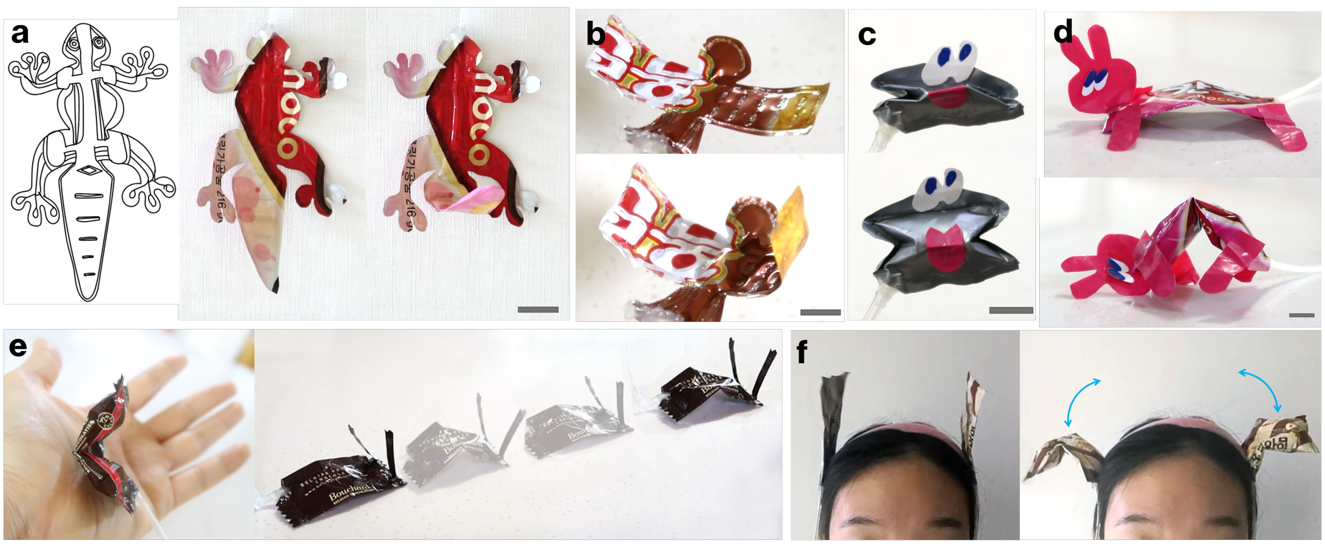

Figure 8: Examples of playful inflatable primitives (the scale bar indicates 10 mm); (a) A gecko bending its tail and its hand-drawn heat-sealing pattern. (b) A bird with flapping wings. These examples are made of a chip bag. (c) Puppet, made of a HDPE shipping envelope, (d) Rabbit made of a cookie bag, (e) Inchworm-like soft robot made of a chocolate package (LDPE sealing layer). (f) Application on a headband for creating a playful accessory

6 APPLICATIONS

The Therms-Up! method could be applied for animating objects [20] with various actuation methods (Fig. 9(a)) for quick validation of ideas, building a playful STEAM program for children. This experience could be enhanced by storytelling using a playful animal-like creatures, toys, and accessories (Fig. 8). Also, it could assist product designers, engineers, makers who want to quickly and physically validate their ideas and concept (Fig. 9 (b-f)).

7 LIMITATIONS AND FUTURE WORKS

We are running a remote workshop with public librarians to develop a playful STEAM program for children and hope to share the outcome in the future. Developing a user interface that allows users to plug in various types of plastics and produces optimized G-codes for each material remains as a future work. The effect of different nozzle diameter of the extruder will be demonstrated and evaluated in the future. The identified types of thermoplastic bags may not be enough to generalize the method due to individual's different plastic consumption behavior. However, we think that our contributions would guide people to understand how to work with thermoplastic bags to create interactive materials with the explored design space.

8 CONCLUSION

We introduced a design space and DIY method to create prototyping materials from re-purposing wasted thermoplastic bags with use of

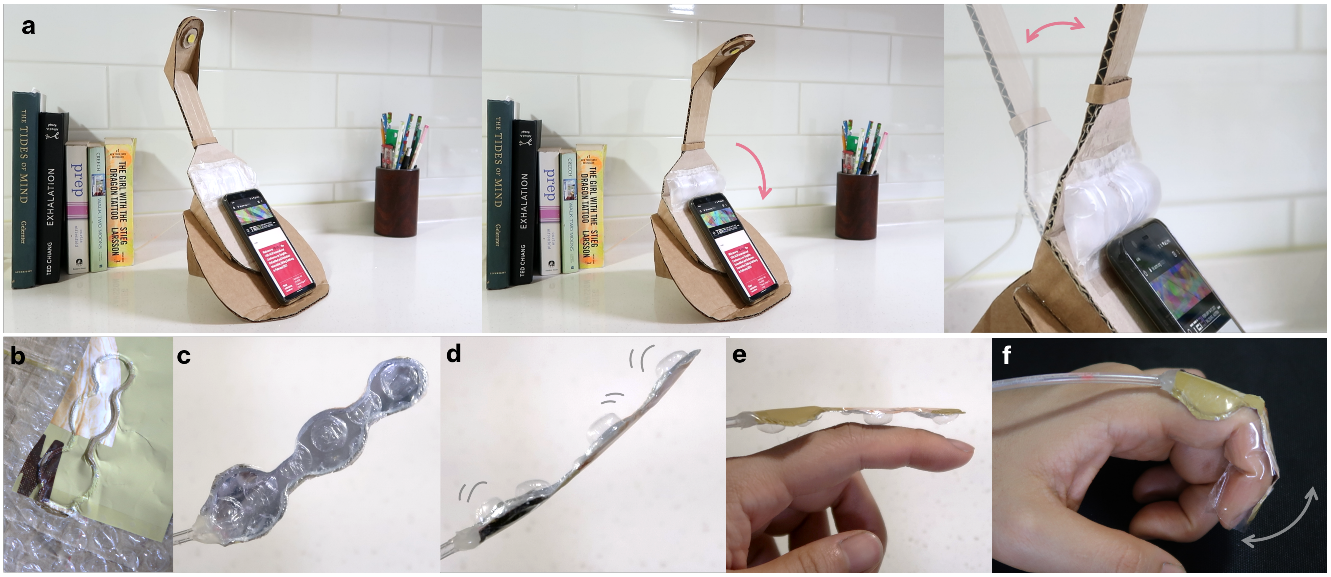

Figure 9: (a) Designing a smartphone lamp stand: Use-case scenario of a designer who needs to quickly prototype and validate his/her idea by actuating cardboard prototype using a HDPE plastic shopping bag. (b-f) Use-case scenario of developing a haptic device: (b) Retort food package and bubble wrap heat-sealed by 3D printer. The retort food package works as a capacitive touch sensor. Bubbles can be used for creating a finer tactile feedback. (c) Prototype with deflated bubbles and (d) inflated bubbles. (e, f) Estimating the location of the prototype and attaching it on a finger to test the bending motion and how the sensor response.

inexpensive FFF 3D printer to print heat-sealing patterns without requiring its hardware modification. We characterized 8 different types of commonly-used thermoplastic bags found from household and provided corresponding heat-sealing settings. We highlighted potential use-case scenarios of playful learning experience with kids, rapid prototyping and concept validation.

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9 APPENDIX

G-Codes, templates, and instructions for shown-examples with video and more are available in the link:
https://github.com/mallcong/Therms-Up