Conference Paper

3D Printing of a Photo-thermal Self-folding Actuator

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Abstract

The demand for rapid and accurate fabrication of light-weight, biocompatible, and soft actuators in soft robotics has perused researchers to design and fabricate such products by rapid manufacturing techniques. The self-folding origami structure is a type of soft actuator that has applications in micro electro mechanical systems, soft electronics, and biomedical devices. 3-dimentional (3D) printing is a current manufacturing process that can be used for fabrication of involute soft self-folding products by means of shape memory polymer materials. This paper presents, for the first time, a method for developing a photo thermal self-folding soft actuator using a 3D bioplotter. Easily accessible and inexpensive pre-strained polystyrene is opted for the backbone of actuator. The polystyrene film (PS) is then structured in a hand shape gripper. Chitosan hydrogel and carbon black ink were combined for printing active hinges on the hand gripper. Various active hinges with different widths and thicknesses were printed on the hand gripper using the 3D bioplotter. An infra-red (IR) heating lamp was placed at a reasonable distance to emit IR light uniformly on the hand gripper. The temperature distribution on the hand gripper was observed using a thermographic camera and the bending angles of the samples were recorded by a video camera. It was observed that the bending angles of the hand fingers depend on factors such as the intensity of the heat flux generated by the IR light intensity, distance, onset temperature, geometry of the fingers such as width and thickness, and area of the hinges.

Keywords: 3D printing, origami, polymer, photo thermal actuator

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1 Introduction

3D origami transformations is defined as self-folding of structures from planar objects into spatial assemblies when stimulated. Soft actuators made on the basis of 3D origami structures have many applications in soft robotics (Onal *et al.*, 2015), packaging (Peraza-Hernandez *et al.*, 2014), adjustable solar antenna (Kimionis *et al.*, 2015b), and agricultural seed culturing (Shin *et al.*, 2014). 3D origami transformations can be realized by several means. One approach is the use of active materials such as shape memory alloys (SMAs) (Koh *et al.*, 2014) or shape memory polymers (SMP) as the structure (Mu *et al.*, 2015). Developing 3D origami soft actuators by incorporating passive materi-

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als like polymers with active hinges is another method. SMPs are capable of responding to a variety of stimuli (Liu *et al.*, 2012) (Mao *et al.*, 2016).

Among environmental-stimuli responsive soft actuators, heat activated 3D origami soft actuators are easy to use in circumstances where waste heat is available such as structure phase transition and joule heating. Laser heating is another choice that was applied for spatial folding of a polymer film (Zhang *et al.*, 2014). Yet, it may result in undesirable interference in the actuator's controller circuitry (Lantada *et al.*, 2016). The control of laser pattern on a specific section of the film as active joints was the bottleneck for using patterned laser light (Liu *et al.*, 2014).

However, photo-thermal responsiveness materials enable soft actuators to be controlled remotely. Emitting light from a distance leads to folding without human intervention, which is appealing for applications such as assembly, packaging, and drug release. The appeal of this approach is its simplicity in converting 2D patterning of inexpensive materials into 3D objects using only light. An example of light activated 3D origami soft actuators in nature is sunflowers demonstrating multiple functions of photo sensing, actuation (tracking the sun), and photosynthesis. Several light responsive actuators have been reported in the literature thus far (Kim *et al.*, 2016) (Lee *et al.*, 2015) (Iwaso *et al.*, 2016).

Making 3D structures out of 2D planar designs required several fabrication and post processing steps (i.e., etching, masking, lithography and etc.). (Deng and Chen, 2015) proposed an origami actuator printed by the mask image projection based stereolithography. Shrinkable PS film was also patterned using etching and physical mask which lacked the flexibility of design geometries (Zhao *et al.*, 1998). A laser cutter was utilised to fabricate origami structures from metal and paper (Piqué *et al.*, 2011) (Silverberg *et al.*, 2015). These actuators require burdensome manufacturing and vigorous chemical processing steps. Subsequently, inkjet printers were utilised to fabricate 3D origami actuators (Lee *et al.*, 2015). A 3D origami radio frequency (RF) sensor was developed by inkjet printer, though silver nanoparticle ink could not be printed directly on its backbone due to the properties of polymer matrix (Kimionis *et al.*, 2015a). Also, inkjet printing affected electrical conductivity because of the discrete droplet formation (Kimionis *et al.*, 2015b). Moreover, a mixture of graphene and iron oxide namely vor-ink was used as a hinge with high microwave absorption capability (Davis *et al.*, 2015). An irregular folding performance with different sample orientations was reported, indicating a drawback of microwave thermal stimulation compared to easy and convenient use of photo thermal stimuli.

In this paper, an inexpensive commercial Shrinky Dink, chitosan hydrogel, printer ink, 3D printer, and infrared lamp are employed to produce a soft actuator. Integration of shape memory polymers and 3D printing is a novel approach for developing soft actuators. The novelty of this study is the use of a 3D printer that gives more flexibility for fabricating complex and geometrically diverse soft actuators (Zolfagharian *et al.*, 2016). Using an extrusion-based 3D printer allows for the easy placement of the substrate between the printing bed and the printing head that is not possible using inkjet printers. Most inkjet printers are limited on the maximum height of the print head since they are mainly designed to accommodate thin substrates and not in height 3D structures.

2 Methodology

2.1 Folding mechanism

Pre-strained PS polymer with the commercial name of Shrinky Dink is selected as the main scaffold in this study because of its availability, sufficient stiffness, high transparency, inexpensiveness, and environmentally friendly features. A pre-strained Shrinky Dink sheet is defined as a PS sheet that has undergone some annealing by stretching above their glass transition temperature (T_g) and then cooling below the T_g. Such materials release their internal stress once heated above the T_g. Shrinky Dink sheets used in this study were reported to shrink up to 60% in both the x and y dimensions while their T_g is approximately 102°C (Liu *et al.*, 2012). The main scaffold is made of transparent PS polymer, which is partially absorbent of IR. Therefore, an appropriate material with high rate of light absorption and conversion of light into heat is needed. A simple method of absorbing heat, using dark-coloured patterns, can be employed to form an actuator hinge. The different thermal rate of backbone polymer and thermally responsive hinge lead to 3D origami actuation. Folding behaviour of the PS sheet occurs due to contraction in response to thermal absorption upon reacting the glass transition temperature.

The polymeric black ink absorbs a wide range of light from ultra violet (UV) to near-infrared (NIR) wavelengths while chitosan is a biodegradable polymer that adds adhesiveness to ink. The black ink functions as a heat source to absorb the NIR light and then converts light energy to thermal energy and causes the underlying printed area to heat up faster than the uncovered section. Increasing the local temperature above the glass transition temperature in the printed area of backbone polymer leads to gradual folding of fingers. The sequential folding of PS sheet is controlled by the degree of transparency of the printed hinges. Hinges with different widths and thicknesses are designed for sequential folding of origami soft actuator exposed to a uniform light intensity.

2.2 Material preparation, printing, and experiments

A CAD model of a small robotic hand including hinges was drawn in Solidworks. Then, the generated file was imported to an EnvisionTEC GmbH Bioplotter (EnvisionTEC, Gladbeck, Germany). Black chitosan mixture made of dispersed chitosan and carbon black ink was loaded into the printer. Various active hinges with different widths and thick-

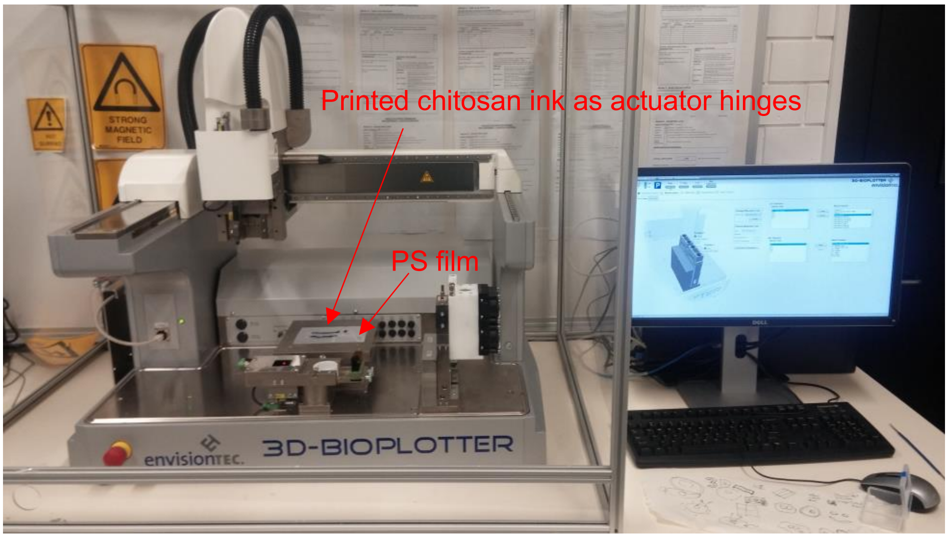

Figure 1: Printing the hand actuator.

nesses were printed on a PS film. The dimensions of active hinges were within the ranges of 6 mm × 2 mm × 0.2 mm up to 8 mm × 4 mm × 0.6 mm.

Medium molecular weight chitosan (with 75–85% deacetylation degree) and acetic acid used in this work were purchased from sigma Aldrich, Australia. A mixture of 5 g chitosan in 100 ml acetic (1 v/v%) was prepared under vigorous stirring and 50°C, for 2 h. After 1 h of mixing, 250 mg carbon black particles was introduced to make the final polymer black. The prepared ink was sonicated in order to remove the bubbles since existence of them deteriorates the quality of the print.

Onset of folding is defined as the exposure time of the PS film to the IR source required to initiate macromolecular folding (Liu *et al.*, 2012). Since heat is required for folding, it is obvious that the onset of folding occurs faster at a higher support temperature (T_S) (Liu *et al.*, 2012). T_S was provided by a hot plate lab on which the actuator is placed. The actuator was separated from the hotplate using two 3D printed polydimethylsiloxane (PDMS) bars to allow uniform onset temperature on the bottom and top of the Shrinky Dink. An IR lamp was located at a reasonable distance (20 cm) to emit IR light uniformly on the actuator plane with the maximum power of 250 W and intensity radiation of 320 mW/cm^2 along the axis of lamp. The temperature distribution of each actuator was observed using a FLIR E60 Thermal Imaging Camera and the bending angles of the samples were recorded by video camera.

3 Results

A 3-finger hand with two printed hinges on each finger was prepared for evaluation. The hand was placed on the PDMS bars above the hot plate with T_S = 70°C. The IR lamp was fixed at a distance of 20 cm perpendicular to the surface of the hand. Upon turning

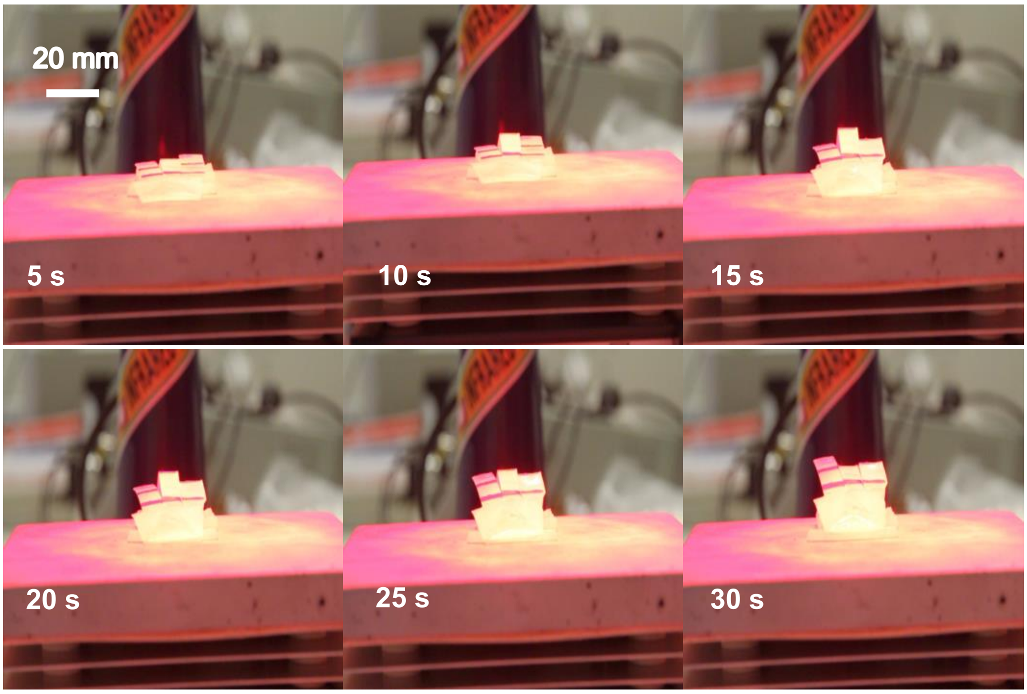

Figure 2: The 3-finger hand actuating in response to IR light.

on the IR lamp, the fingers were observed to move. The thermal gradient throughout the thickness of the fingers below the printed hinge induced a gradient in strain relaxation. The top surface of the fingers, which were hotter, relieved the strain faster than the bottom surface, which in turn led to the folding of fingers. It was observed that a shorter exposure time results in less folding while over exposure often results in heterogeneous deformation and burning of the actuator. As it can be seen in Figure 1, bending occurred earlier in the middle finger than the two other fingers. This is attributed to the larger area (8 mm × 4 mm) of the printed hinge on the middle finger compared to that of the two other fingers, and thus the active hinge absorbed more heat than the backbone and consequently actuated faster. Further, it was observed that the left finger in Figure 1 folded less compared to the other fingers at the end. This is due to the larger width (8 mm) of that finger.

The thermographic photos of the 3-finger hand shown in Figure 2 signifies that the temperature of the hand increased up to 89.7°C after 16 seconds of exposing to IR light while the temperature at the active hinges reached 120°C at middle finger.

It was also observed that less time required to initiate the folding of the finger with applying onset temperature. Besides, it was found that the larger width of hinge provides more heat absorption and faster actuation, and thus greater bending. Also, the proportion of the black ink should be high enough to convert light emission into heat but at the same time low enough for fluent extrusion out of the 3D printer nozzle. This requires a compromise between the ratios of materials.

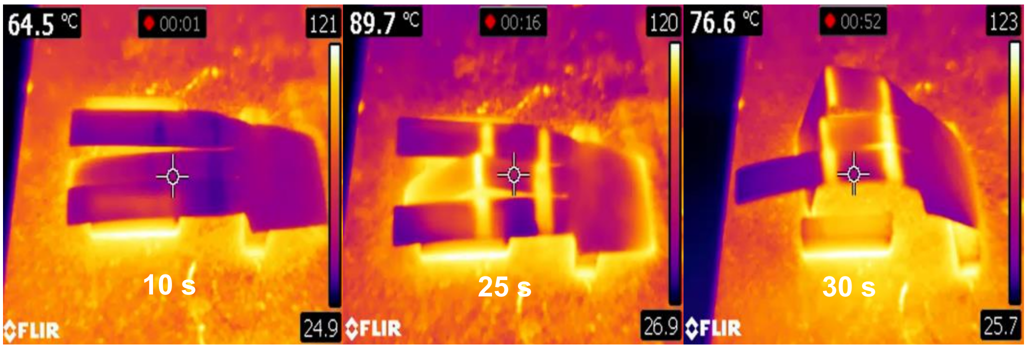

Figure 3: Thermographic illustration of the 3-finger hand during exposure to IR light.

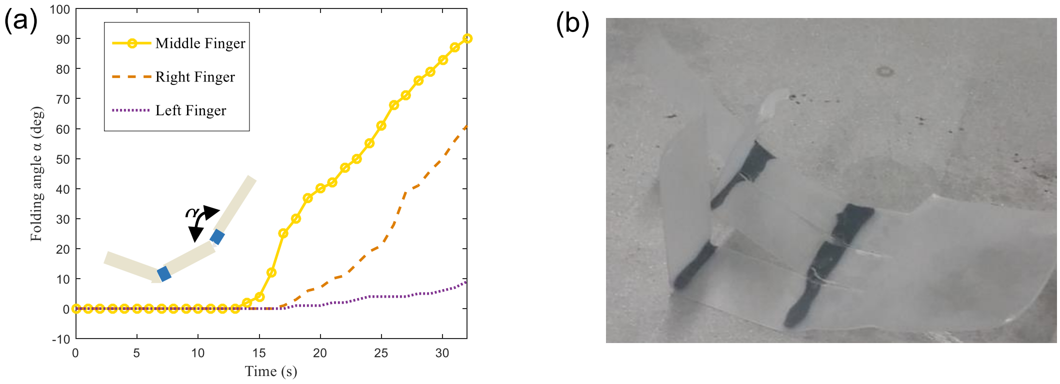

Figure 4: (a) Folding angle of the 3-finger hand in time; (b) Final state of the hand.

The folding of actuator was observed to depend on factors such as the intensity of the heat flux generated via IR light intensity, distance, onset temperature, geometry of the actuator such as width and thickness, surface area of the hinge, orientation and number of printed layers and mechanical properties of the polymer such as the amount of pre-straining. The blackness of the ink, its particle size, dispersity and thermal conductivity are also decisive factors affecting the actuation of the PS film.

The incorporation of the 3D printing is significant because different patterns, widths, and height of active hinges influence the bending angle.

4 Conclusion

A self-folding mechanism that can quickly respond to photo-thermal conditions has been presented. A 3D-printing-based fabrication approach for building the origami actuator has been developed. Various factors such as different hinge widths and onset temperature have been observed to influence the folding angle and the speed of folding. The experimental results verified the effectiveness of the presented design and fabrication method for building self-folding structures with controlled folding behavior. Using a 3D printer to fabricate a self-folding structure paves the way for further investigation into the biomedical applications of self-folding actuators such as drug delivery. Additionally, using biodegradable ink, numerical and mathematical modellings, and various complex geometries can be prospect research directions.

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