3D Printed Shape Memory Polymer Composite for Fabric Actuation

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Abstract— **In this work, we propose to study an intersection between robotics and art: actuating fabrics by rapidly manufacturing shape memory polymer (SMP) composites via 3D printing. We present preliminary designs for SMP composites that can induce undulatory motions in fabric, and characterize their behavior by varying geometric parameters of the 3D printed composite and controlling the shape using electrical heating.**

I. INTRODUCTION AND BACKGROUND

One interesting interface between science and art involves actuating fabrics. Fabrics are used in the arts for fashion and costume design. The development of smart and adaptable fabrics increases the application possibilities for morphing clothing. However, one of the challenges when it comes to integrating interdisciplinary areas and communities (e.g makers, roboticists, and artists) is the different language and tools used to express ideas generated by this interdisciplinary research.

Smart materials development in shape memory polymers (SMPs) allows an alternative to be explored for smart fabric. Shape memory polymers (SMPs) are smart materials capable of changing their shape upon external stimuli [1]. Improvements such as tuning temperature and mechanical properties and creating a shape memory effect (SME) can be achieved by fabricating SMP composites [2]. SME also allows smart actuation for other areas of application such as laminate manufacturing, soft robotics, morphing structures, and as aforementioned in smart fabrics.

Recent work by Wu et al. [3] demonstrated a manufacturing method for producing a SMP composite capable of reversibly changing its shape by varying the composite temperature from 0 ^{o}C to 70 ^{o}C. Multiple groups of SMP fibers are 3D printed with different glass transition temperatures in a rubber matrix and heat-treated using a water bath. An advantage of this method of 3D printing SMPs is the ability to customize the actuation pattern. This manufacturing process also offers some advantages compared to other shape memory materials such as liquid crystal elastomers (LCEs) and shape memory alloys (SMAs). Specifically, fabrication by 3D printing is faster, more adaptable, and more repeatable compared to the preparation of LCEs [4], and the molding [5] or threading of SMAs [6] into structures.

3D printing SMP composites can enhance the communication between makers, roboticists, and the arts community by enabling a customizable, rapid, and user-friendly approach to manufacturing actuatable structures. For example, artists might focus on selecting a fabric for their clothing design and makers and roboticists may be drawn to the actuation performance and control of fabrics.

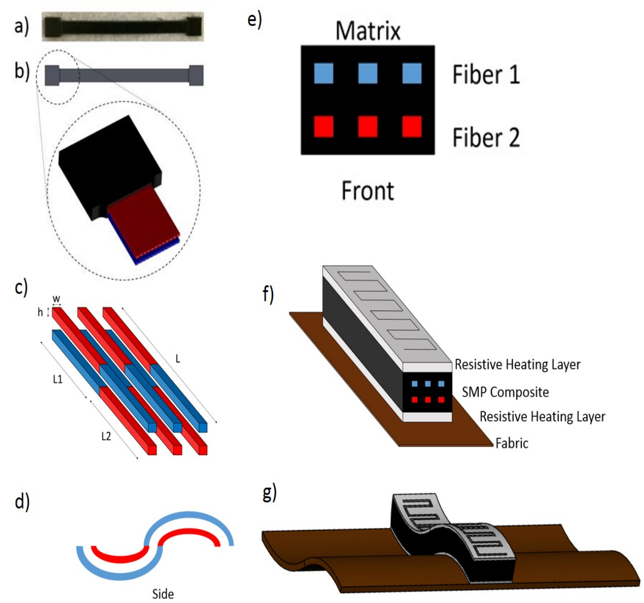

Fig. 1: SMP design. a) 3D printed SMP. b) SMP CAD model with an enlarged section for viewing internal fibers. c) Internal fibers of the SMP composite with parameters of interest labeled (L = total length, L1 and L2 = fiber lengths, w = width, and h = height). d) Undulating behavior of the fibers when heated due to different material characteristics. e) Cross-section view of unactuated fibers, contained within a matrix of material. f) SMP between resistive heating layers for actuation, attached to a textile. g) Undulatory motion of the fabric once heated by the resistive pattern.

Even though SMPs can exhibit continuous movements that are more biomimetic compared to the discrete motions produce by more rigid mechanisms, creating an actuator that can move fabrics presents its own challenges. One of the challenges is designing a self-contained, lightweight actuation system that can achieve specific shapes. In previous work [3], the stimulus used to change the 3D printed composite was hot water, which is not easily transportable or wearable, and the motion orientation was achieved by changing the the position of the fibers.

In this work, we explore the use of 3D printed SMP composites as actuators for fabrics by actuating the SMP composite using resistive heating. To demonstrate the shape

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Fig. 2: Initial results of SMP actuated with resistive heating layer at room temperature (top and bottom left) and heated to 79 ^{o}C (bottom right).

Layer	Material
Matrix	TangoBlack+
Fiber 1	FLX9095-DM
Fiber 2	FLX9060-DM

TABLE I: Materials used in the Stratasys Objet350 Connex3 3D printer.

variations of the composite on the fabric, we vary the geometry dimensions of the fibers so that its dimensions generate undulatory motions (Fig. 1g).

II. FABRICATION OF SMP COMPOSITE

Our initial SMP composite and the layers of the prototype are shown in Fig. 1c. The fabrication methodology and material selection are based on previous work by Wu et al. [3].

The materials we used for initial tests (Fig. 2) are shown in Table I. Temperature control was achieved using resistive heating (flexible printed circuit board) layers above and below the SMP as shown in Fig. 1f. This actuator laminate is then attached to the fabric to be actuated. By varying the current passing through the resistive layer, we expect to describe the shape variation and thermal response of the SMP composite and develop a characterization for undulating fabrics.

The 3D printer used to produce the SMP composite is a Stratasys Objet350 Connex3. After printing the part, it is necessary to mechanically program the SMP composite. The programming is achieved by stretching the structure (initial strain) at a temperature higher than the T_g of both internal fibers used [3]. Then, the device is cooled to a temperature lower than the T_gs of both fibers while maintaining the initial prescribed strain. The first temporary shape is obtained by releasing the applied strain. Subsequently, we can obtain a secondary temporary shape by heating the SMP composite to a temperature higher than the T_g of the matrix layer but lower than the temperature of the fiber with the lowest T_g. Other temporary shapes can be obtained by varying the temperature between the T_gs of the fibers. To return to the original flat shape, we can heat the sample to a temperature higher than the T_g of both fibers.

The heating layer is obtained by printing a resistive serpentine pattern as an etch mask with a solid ink printer (ColorQube 8570, Xerox) onto a copper-clad polyimide sheet. The exposed copper is then etched with ferric chloride and the remaining ink is removed with isopropyl alcohol. Electrodes can then be attached to the resistive layer and connected to a power supply. Then, the SMP composite, resistive layer, and fabric can be attached using an adhesive (e.g. silicone tape).

III. RESULTS AND DISCUSSION

Our initial results for this electrically heated actuator are shown in Fig. 2. The SMP actuator was suspended by its wire leads and held at room temperature prior to the experiment. A power supply (DIGI-35A, Electro Industries) was used to apply current in constant voltage mode while a temperature probe connected to a digital multimeter (Fluke 87V) was affixed to the center of the actuator to measure the temperature. We ramped the voltage up to a maximum of 2.5 V (resulting in a maximum current of 2.47 A) over the course of one minute until the temperature approached 80 ^{o}C and the actuator completed bending. The power was then ramped down to 0 ^{o}C and the sample was allowed to cool back to room temperature. A small curvature was induced as the sample heated, as can be seen in Fig. 2.Though we have work to do to further optimize the geometry and design of the actuator, we do notice some small deflections with our initial design. We believe the small deflection might be due to the Tg of the materials used during our experiments which, even though they had similar mechanical properties, the Tg might differ and thus impact the shape change of the SMP composite.

IV. CONCLUSION

We present initial steps towards characterizing the undulating behavior of SMPs as a function of its internal geometry. This work is significant because it enables researchers and makers who are interested in SMP actuation to easily customize and prototype an SMP esign corresponding to their desired motion. These motions are continuous along the body of the actuator, and provide makers with more lifelike behaviors. The information obtained from this design, fabrication technique, and characterization could be useful to the robotics and maker community because it is expected to provide a lookup table of design parameters for obtaining specific SMP actuation trajectories.

In future work, we plan to characterize the behavior of the SMPs by varying the geometric parameters of each fiber such as width, thickness, length (both overall length, as well as the ratio of L1 to L2 in Fig. 1a), temperature, Tg of the materials and to examine the resulting motion of the SMP actuators. Using computer vision techniques to track the body of the SMP as it moves, we can map and compare the workspace available for each set of parameters. This data can inform makers who are seeking to achieve a desired motion on how to design their printed SMPs. This data can also enable development of mathematical models that can be used to characterize how the SMP geometry affects its actuation.

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