Fabricating Multi-Material Soft Pneumatic Actuators by Integrated 3D-Printing and Casting

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Abstract— **This work proposes a new method to fabricate multi-material soft actuators through 3D-printing rigid material and casting silicone in an integrated way. We locally control the bonding between the rigid material and chemically inert silicones by adding (or leaving out) a well-designed and 3D printed structure. Airtight bonding with strong mechanical properties can be achieved. With the help of this technique, we are able to fabricate zero-thickness chambers. Two compact soft actuator designs are shown to demonstrate the potential of our method.**

I. Introduction

The combined usage of rigid and soft materials is a promising direction to control the behavior of soft robots through design. At present, the fabrication of such multi-material soft actuators is often realized through material jetting or manual casting. Differently, we propose a method that integrates *Fused Deposition Modeling* (FDM) of a rigid material with the casting of silicones to fabricate compact multi-material soft pneumatic actuators.

Bartlett et al. presented a method in [1], demonstrating how the performance of a soft jumping robot can be improved by implementing rigid-soft gradients in the robot's body. Their robot is fabricated by material jetting of different photo-polymers. Alternatively, Sun et al. [2] demonstrated how the stiffness of casted silicone pneumatic actuators can be controlled by integrating fiber patches in a mould. Ma et al. [3] demonstrated a hybrid manufacturing method that combines FDM with casting to fabricate multi-material mechanisms. However, their method relies on a chemical bonding between the soft and rigid material. Their bonding is difficult to be controlled locally and adaptively as what we can. Moreover, they use thermoplastic polyurethanes (TPU) instead of non-reactive silicones.

Figure 1 shows an example actuator fabricated by our method. In its rest state (see Fig. 1(A)), the casted silicone and 3D-printed rigid part are touching without any gap. Upon pressurization, the area in-between the silicone and the rigid part inflates (see Fig. 1(B)) and the deformation is then used in grasping (see Fig. 1(C)). Our method combines the use of durable materials with a digital manufacturing method and enables the fabrication of compact multi-material actuators. This development makes a step further towards the end-use applications of multi-material soft actuators. In this extended abstract, we present the fabrication and preliminary results of two different designs of soft actuators.

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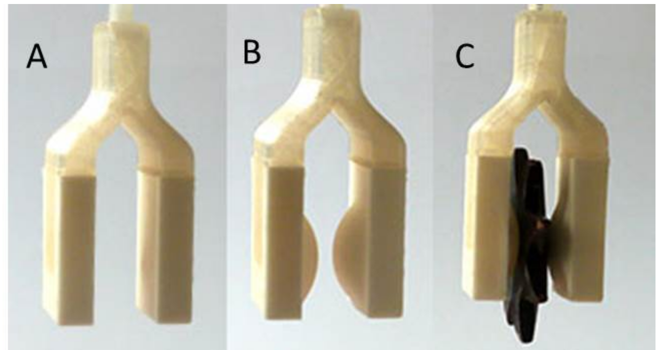

Fig. 1: Multi-material soft pneumatic gripper having a rigid 3D-printed body connected with two silicone parts through a mechanical bonding. Upon pressurization, the zero-thickness chamber between the silicone and rigid body expands. From left to right: the gripper in rest shape (A), the inflated gripper (B), and the status of grasping a chocolate (C).

II. Method

A. Materials & Fabrication

The fabrication process of integrated 3D printing and casting is illustrated in Fig. 2. The steps of fabrication are elaborated as follows.

- **Step 1: Slicing**
  CAD-files are separated into rigid material components, resolvable material components, and the components where the silicone and rigid material should bond. We use CURA as the slicing software to generate the g-code. The rigid structure for the mechanical bonding is realized by printing the bonding bodies as a porous infill structure, as shown in Fig. 2(A) & 2(B). The structure is built from parallel lines that change directions in steps of 36 degrees per layer.
- **Step 2: 3D Printing**
  We use an Ultimaker 3 FDM-machine with dual extrusion to fabricate the mold including the rigid components. The structure and the rigid bodies are printed in *Polylactide* (PLA). The mold is printed in water soluble *Polyvinyl Alcohol* (PVA).
- **Step 3: Casting**
  Silicone is casted in the mold while it is still on the heated printbed. Then, silicone can permeate the structure to create a strong mechanical bonding. The

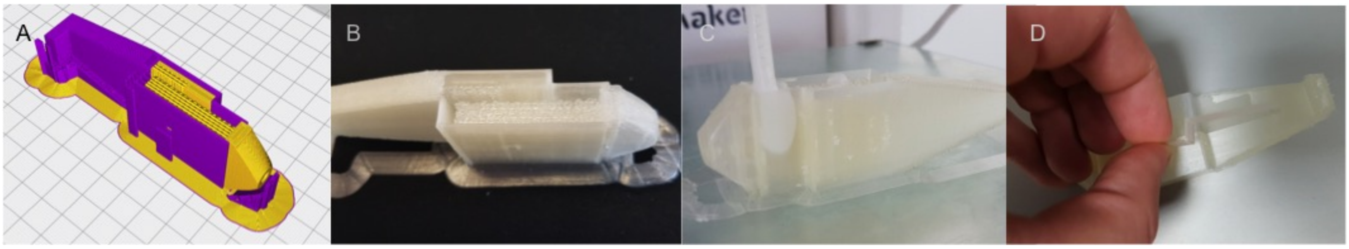

Fig. 2: Fabrication process of a soft actuator. (A) Slicer settings with build-material in yellow and resolvable material in purple. (B) Finished print of the shell, the rigid components and the structure for mechanical bonding. (C) Casting the two silicone components. (D) Removing or dissolving the resolvable material.

silicone does not bond with the rigid bodies without such a bonding structure. Two-component silicones with varying shore values have been used in our experiments. The gripper shown in Fig. 1 is fabricated using Shore A40 silicone, whereas the gripper finger shown in Fig. 3 is fabricated using Shore A10 silicone.

- **Step 4: Post-processing**
  After the silicone has cured, the mold can be removed by breaking manually or dissolving in water.

B. Design of Soft Actuators

Our fabrication method can be used to fabricate compact multi-material soft pneumatic actuators, the geometry of which is not dominated by the shape of the air chambers. This can be realized by selectively adding bonding structures around a rigid component (as described in section II-A). When a layer of silicone is casted on top of such a component, the silicone only creates a mechanical bonding in those regions with bonding structures. Bonding will not occur in those regions without bonding structures. As a result, air chambers with zero-thickness are constructed. These air chambers can be interconnected to create pneumatic networks that are actuated through a single channel (as shown on the gripper in Fig. 1). Small PVA plugs can be printed at the interfaces between the air channels and the silicone so that it can prevent the silicone from filling the air channels during casting. These plugs can be dissolved in water after the silicone has cured. We use structured bodies with a minimum thickness of $2.5\,\mathrm{mm}$ to ensure an airtight connection between the regions of PLA and silicone.

III. Results & Discussion

Preliminary results that are fabricated using our method are shown in Fig. 1 and Fig. 3. Fig. 1 shows a gripper with two zero-thickness chambers that are actuated through a single channel on top of the actuator. Fig. 3 shows a single gripper finger mechanism with an air chamber that can push a rigid element outwards to create a grasping motion. Our extended work will focus on additional soft actuator designs that can make optimal use of the possibility to fabricate zero-thickness chambers. Besides more advanced soft grippers, we will demonstrate a flat silicone 'display' that shows different configurations upon pressurization of different networks of air chambers that lie underneath.

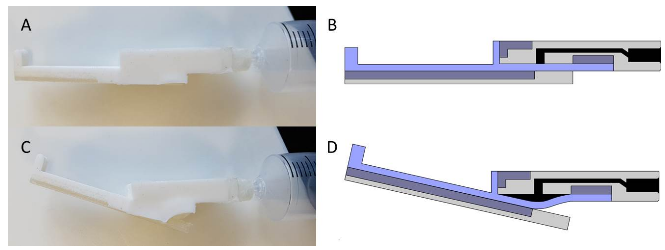

Fig. 3: A single gripper finger mechanism before (A) and after (C) pressurization. The zero-thickness chamber is inflated through the internal air channels and pushes the rigid element outwards to realize a grasping function. Cross-sectional views of the gripper's mechanism for both states are given in (B) and (D). Rigid bodies are indicated in gray, air channels in black, silicone parts in blue and bonding parts in purple.

References

[1] N. W. Bartlett, M. T. Tolley, J. T. B. Overvelde, J. C. Weaver, B. Mosadegh, K. Bertoldi, G. M. Whitesides, and R. J. Wood, "Robot Powered By Combustion," *Science*, vol. 349, no. July, pp. 161–165, 2015.

[2] Y. Sun, H. K. Yap, X. Liang, J. Guo, P. Qi, M. H. Ang, and C.-H. Yeow, "Stiffness Customization and Patterning for Property Modulation of Silicone-Based Soft Pneumatic Actuators," *Soft Robotics*, vol. 4, no. 3, p. soro.2016.0047, 2017.

[3] R. R. Ma, J. T. Belter, and A. M. Dollar, "Hybrid Deposition Manufacturing: Design Strategies for Multimaterial Mechanisms Via Three-Dimensional Printing and Material Deposition," *Journal of Mechanisms and Robotics*, no. 2, p. 021002.