Towards Behavior Design of a 3D-Printed Soft Robotic Hand

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Abstract This work presents an approach to integrate actuators, sensors, and structural components into a single product that is 3D printed using Selective Laser Sintering. The behavior of actuators, sensors, and structural components is customized to desired functions within the product. Our approach is demonstrated by the realization of human-like behavior in a 3D-printed soft robotic hand. This work describes the first steps towards creating the desired behavior by means of modeling specific volumes within the product using Additive Manufacturing. Our work shows that it is not necessary to limit the design of a soft robotic product to only integrating off-the-shelf components but instead we deeply embedded the design of the required behavior in the process of designing the actuators, sensors, and structural components.

1 Introduction

Pneumatic actuation is one of the two most used actuation techniques in soft robots [10]. This type of actuation is often realized through the inflation of channels in elastic material. These actuators are promising in soft robotics since (1) they are under-actuated and compliant, (2) they can be free of internal electronics and electric components, and (3) their performance can be tuned through the morphology of the actuated segment [3, 6, 7]. This provides a significant benefit in applications such as soft pneumatic hands [1], orthotics [9] and locomotion [11].

Previous researchers mainly used molding techniques to fabricate silicone soft robots [7, 11, 13]. However, the constraints of the molding processes limit the design freedom. As a result, in existing approaches actuators are usually oriented in the same plane or fabricated separately and later assembled into a functional structure. *Additive Manufacturing* (AM), or 3D printing, is a collection of digital

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fabrication processes that build up objects by adding material layer upon layer. AM has been used to integrate multiple actuators [5, 8] or air pressure sensors [12] with structural components. In literature, an advanced design method was developed to design the deformation elasticity of structures fabricated by AM [5]. Nevertheless, little attention was paid to the methodology of customizing the behavior of each specific actuator and sensor within a soft robotic product.

This work presents a case study in which multiple air pressure actuators, sensors, and structural components are integrated in a single body product using the AM process *Selective Laser Sintering* (SLS). To show the possibility of designing human-like behavior, an interactive setup was made realizing a handshake between a user and the hand. The air pressure-based robotic hand comprises eight actuators and two sensors without any internal electronics. The hand measures the force that is exerted upon it and squeezes back accordingly, adapting itself to the user's grip. For each part of the hand, the behavior was customized based on a given volume and function. The main technical contribution of this work is the integration of air pressure actuators, air pressure sensors and structural components that are designed for the desired behavior of this specific volume within the product.

2 Design of Soft Robotic Hand

We simplified the complexity of the human hand and subdivided it into parts with a specific function as actuator or sensor. The carpometacarpal joint of the thumb is fixed in a position suitable for shaking hands. The design of our soft robotic hand consists of four different parts (see Fig. 1 for an illustration), including (1) bending actuators, (2) a rotational actuator, (3) a bidirectional actuator, and (4) sensing air chambers, all shown and discussed below. They are designed to mimic the behavior of a human's hand.

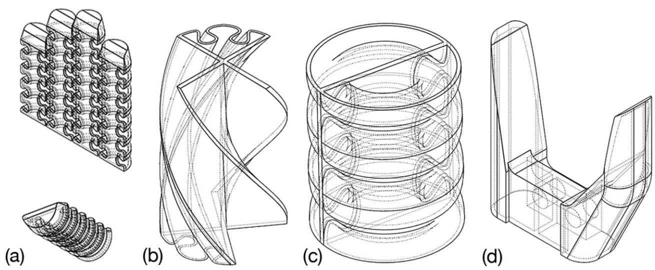

Fig. 1 An illustration of different parts used in our design—from *left* to *right*, **a** bending actuators, **b** rotational actuator, **c** bidirectional actuator and **d** sensing air chambers

2.1 Bending Actuators

The principle of a pneumatic bending actuator is based on pressurizing an air-chamber formed by an inextensible bottom layer and an extensible top layer (see also Fig. 1a). The bending range can be improved by creating a more S-shaped curve of the bellow, whereas the exerted force at a given position can be improved by increasing the bellow's stiffness [3]. This principle was used to create the difference in behavior between the fingers and thumb. Given a designed model and fabrication constraints, the following properties influenced the design process of bending actuators; we need (1) a minimum bending range of 90° of the thumb (the angle measured on tip orientation) at a pressure of less than 400 kPa, (2) a minimum bending range of 180° of the other fingers, to be achieved with the same pressure, (3) to maximize the exerted force of the thumb bellow, and (4) to minimize the radial expansion of the bellows.

2.2 Rotational Actuator

The principle of this rotational actuator was inspired by the elephant's trunk. The elephant has helical muscles in its trunk that, when contracted, cause rotation of the trunk [4]. This principle can be mimicked by sweeping a radially expanding bellow over a helical path (see Fig. 1b). Here, the design process is influenced by the following demands on properties; we need to (1) maximize the radial expansion of the bellow upon inflation, (2) minimize the lateral expansion of the bellow upon inflation, (3) maximize the structure's bending and axial stiffness, (4) minimize its rotational stiffness, (5) at least 45° of pronation to be achieved with at most 400 kPa pressure. Our design consists of a bellow swept over a helical path of 0.4 revolutions over a height of 70 mm. The bellow is encapsulated between two segments of an X-profile, and the actuator has a diameter of 50 mm.

2.3 Bidirectional Actuator

Two bending actuators that share an inextensible layer were used to mimic the antagonistic setup of a bidirectional actuator. Pressurizing one of the two bellows can be used to create palmar or dorsal flexion. Pressurizing both air chambers will inflate the bellows and therefore enhance the palmar and dorsal stiffness of the wrist. The following factors are considered in our design of the bidirectional actuator; we need to (1) minimize the palmar and dorsal bending stiffness, (2) maximize the radial and ulnar bending stiffness, (3) maximize the axial and rotational stiffness, (4) achieve minimal palmar flexion of 45° within 400 kPa pressure, (5) obtain minimal dorsal flexion of 45° with the same pressure, (6) maximize the bending stiffness upon pressurization of both actuators. Our design can be found in Fig. 1c. To increase the radial and ulnar bending stiffness, the inextensible layer of the double bellow is designed rectangular instead of following the curves of the bellows. The shape of the bellows is extensively curved to ensure self-collision to create extra stiffness when inflated. The actuator has a diameter of 50 mm and an effective height of 70 mm.

2.4 Sensing Air Chambers

The principle of our sensor was inspired by the work of [12]. Squeezing an air chamber results in an increase in air pressure, which can be measured externally from the hand. Our design incorporates the following considerations; we need to (1) mimic compliance of a human hand at contact areas, (2) provide a connection structure between fingers, thumb and wrist, and (3) minimize the air volume to maximize the sensitivity. Our design is shown in Fig. 1d. It essentially shows the palm of the hand as base to connect wrist and thumb and two extensions of the palm at which the finger-set is attached. See also Fig. 3. If these extensions are squeezed towards each other they output air pressure that can be measured and electronically processed by our control system.

2.5 Pneumatic Control System

A Freescale MP3V5010 sensor with a range of 0–10 kPa was used to measure the change of air pressure in both air chambers of the hand palm when people shake our soft-robotic hand. The sensed signal is then mapped to a 0–400 kPa pressure using a Festo VPPE-3-1-1/8-6-010-E1 proportional pressure regulator to control the gripping force of the thumb and fingers. The bidirectional and torsional actuator are manually controlled using a 3/2 valve and a pressure of 100 kPa.

3 Design for Manufacturing

The final design was fabricated on an SLS machine by Materialise [www.materialise.com] using the flexible polyurethane-like TPU92A-1 material. It took 12.5 h to print our soft robotic hand. While designing the hand, the following manufacturing factors were considered:

- Wall thicknesses: A minimum wall thickness of 1 mm was used to prevent leakages, whereas the maximum wall thickness was limited to 10 mm to prevent excessive warping.

- Removal of unused material: For each air chamber, an aperture with a diameter of at least 10 mm was required to remove the unused material. The powder was removed by inserting a flexible cable through this aperture. This cable was guided to the end of the air chamber through its internal geometry. Therefore, all sharp edges inside the air chamber were smoothened and branched air chambers were not possible. This means every finger needed to have a separate opening for airflow.
- Fittings: The apertures for the removal of support material were used to insert G1/4 threaded push-in fittings. Therefore, the aperture diameter was determined to be 10.5 mm and the depth at least 10 mm. Because of the flexibility of the material, the apertures were surrounded by a minimum wall thickness of 5 mm to create a secure connection with the fitting.

4 Results

In our design practice, various separate bending actuators of the same length and number of bellows but different shape of bellows were prototyped to find a good design for the thumb and fingers. Figure 2a shows the performance of the designs that were later implemented in the hand. For both bellow designs, the horizontal force was measured in the setup as shown in Fig. 2b. When supplying a pressure with 400 kPa, the exerted force of the thumb bellow was 7.6 N, whereas the finger bellow exerted a force of 1.8 N. The bidirectional actuator shows a bending angle of 45° when a pressure of 90 kPa is applied to one of the bellows (angle measured

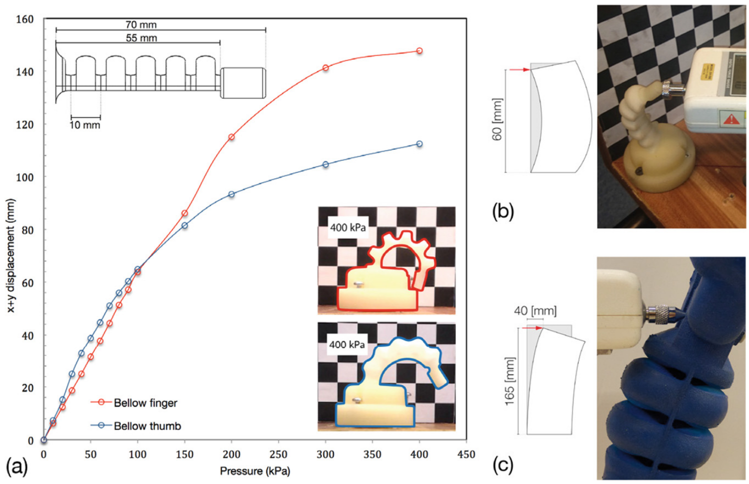

Fig. 2 **a** Displacement of thumb design (*blue*) and finger design (*red*), **b** setup for measuring the force of the bending actuators and **c** setup for measuring the stiffness of the wrist

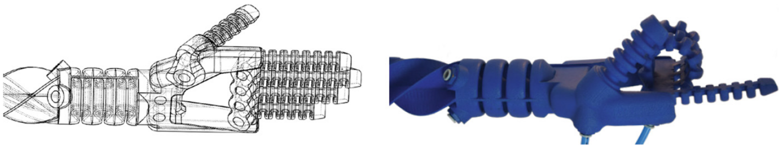

Fig. 3 The final integrated design of our soft robotic hand, the performance of which can be found in video: https://youtu.be/AdMhkIM4hwA

at top orientation). The stiffness of the wrist was measured using the setup as shown in Fig. 2c. A 0.8 N force was needed for a 40 mm displacement of the passive wrist, whereas a 2.9 N force was needed for the same displacement upon pressurization of the bellows at 400 kPa. The rotational actuator achieved a 45° pronation at a pressure of 60 kPa.

The final design of our soft robotic hand by integrating all these actuators, sensors and structures can be found in Fig. 3.

5 Conclusions and Future Work

This work shows that the design of a set of behaviors in soft-robotic products does not have to be limited to making use of existing components. In fact, these behaviors can be deeply embedded in the integral design of a robot's actuators, sensors and structures. We showed that it is possible to design bending actuators, rotational actuators, bidirectional actuators, and sensing air chambers using mono-material SLS, and create a robotic hand with it for the purpose of human-machine interfacing, in this case for interactively shaking hands.

Since the hand was created using mono-material AM, the design freedom was limited because differences in extensibility had to be created through designing the shape of the bellow's walls. In contrast, when using multi-material in AM, relative differences in behavior can also be created through compositions of complex structures of both rigid and soft materials. Thereby, a desired behavior could be addressed more easily—see [2] for an example.

References

1. Deimel, R., Brock, O.: A novel type of compliant and underactuated robotic hand for dexterous grasping (2015). http://doi.org/10.1177/0278364915592961
2. Doubrovski, E.L., Tsai, E.Y., Dikovsky, D., Geraedts, J.M.P., Herr, H., Oxman, N.: Computer-aided design voxel-based fabrication through material property mapping: a design method for bitmap printing. Comput. Aided Des. **60**, 3–13 (2015)
3. Freyer, H., Breitfeld, A., Ulrich, S., Bruns, R., Wulfsberg, J.: 3D-printed elastomeric bellow actuator for linear motion, pp. 29–32 (2014)

4. Kier, W., Smith, K. K.: Tongues, tentacles and trunks : the biomechanics of movement in muscular-hydrostats, March 1985. http://doi.org/10.1111/j.1096-3642.1985.tb01178.x
5. Maccurdy, R., Katzschmann, R., Kim, Y., Rus, D.: Printable Hydraulics: A Method for Fabricating Robots by 3D Co-Printing Solids and Liquids, pp. 3878–3885 (2016)
6. Marchese, A.D., Katzschmann, R.K., Rus, D.: A recipe for soft fluidic elastomer robots. Soft Robot. **2**(1), 7–26 (2015). http://doi.org/10.1089/soro.2014.0022
7. Mosadegh, B., Polygerinos, P., Keplinger, C., Wennstedt, S., Shepherd, R.F., Gupta, U., Whitesides, G.M.: Pneumatic networks for soft robotics that actuate rapidly. Adv. Funct. Mater. **24**(15), 2163–2170 (2014)
8. Peele, B.N., Wallin, T.J., Zhao, H., Shepherd, R.F.: 3D printing antagonistic systems of artificial muscle using projection stereolithography. Bioinspiration Biomimetics **10**(5), 055003 (2015)
9. Polygerinos, P., Wang, Z., Galloway, K.C., Wood, R.J., Walsh, C.J.: Soft robotic glove for combined assistance and at-home rehabilitation. Robot. Auton. Syst. **73**, 135–143 (2015). http://doi.org/10.1016/j.robot.2014.08.014
10. Rus, D., Tolley, M.T.: Design, fabrication and control of soft robots. Nature **521**(7553), 467–475 (2015)
11. Shepherd, R.F., Ilievski, F., Choi, W., Morin, S.A., Stokes, A.A., Mazzeo, A.D., Whitesides, G.M.: Multigait soft robot. Proc. Natl. Acad. Sci. **108**(51), 1–4 (2011)
12. Slyper, R., Hodgins, J.: Prototyping robot appearance, movement, and interactions using flexible 3D printing and air pressure sensors, p. 1 (2012)
13. Zhao, H., Li, Y., Elsamadisi, A., Shepherd, R.: Scalable manufacturing of high force wearable soft actuators. Extreme Mech. Lett. **3**, 89–104 (2015)