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Design and Computational Modeling of a 3D Printed Pneumatic Toolkit for Soft Robotics

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Abstract

Soft and compliant robotic systems have the potential to interact with humans and complex environments in more sophisticated ways than rigid robots. The majority of the state-of-the-art soft robots are fabricated with silicone casting. This method is able to produce robust robotic parts, yet its results are difficult to quantify and replicate. Silicone casting also limits design complexity as well as customization due to the need to make new molds. As a result, most designs are tailored for simple, individual tasks, that is, bending, gripping, and crawling. To address more complex engineering challenges, this work presents soft robots that are fabricated by using multi-material three-dimensional printing. Instead of monolithic designs, we propose a pneumatic modular toolkit consisting of a bending and an extending appendage, as well as rigid building blocks. They are assembled to achieve different tasks. We show that the performance of both appendages is (1) repeatable, that is, the same internal pressure results in the same rotation or extension across multiple specimens and repetitions, and (2) predictable, that is, the respective deformations can be modeled by using finite element analysis. Using multiple instances of both building blocks, we demonstrate the versatility of this toolkit by assembling and actuating a gripper and a crawling caterpillar. The reliability of the mechanics of the building blocks and the assembled robots show that this simple toolkit can serve as a basis for the next generation of soft robots.

Keywords: modular robot, pneumatic actuation, 3D printed soft robotics

Introduction

RESPONDING TO THE shortcomings of classical robotics, soft robotics (SR) has been a rapidly expanding field. Where rigid robots need well-developed sensors, motors, and control systems to interact with irregular environments, a soft robot's morphology and compliance can simplify these challenges and enable greater robotic capabilities. Their intrinsic compliance addresses existing human-robot interaction issues while offering the possibility to embed control directly into the material at a low production cost.

With material properties close to those found in some animals, the elastomers and silicones used in SR have been a base for bioinspired design, for example, from a fish^{1,2} to an octopus,³ as well as caterpillars and worms,^{4,5} all of whose dynamic behavior has been mimicked in recent work.⁶ They have been used in a range of fields, from medical⁵ to industrial handling and military.⁶

Shepherd *et al.*⁷ argue that pneumatic actuation is predominant in SR because (1) compressed gases are readily available, (2) they have little to no direct impact on their environment, (3) the near-ideal properties of air support rapid actuation, and (4) it is lightweight. Most pneumatic SR prototypes have been fabricated by using variations of silicone casting techniques. The low cost⁴ and wide-ranging availability of silicone materials are offset by the difficulty of processing and obtaining reproducible results.^{8,9} This affects their mass production. In addition, in a field where the goal is to achieve the highest degree of freedom possible, the fabrication processes restrict the robots' mobility to a single defined movement. They also limit the possibility of a systematic, optimized design approach.^{4,5,10}

Considering the challenges of the current fabrication methods, this work's approach is to demonstrate that by using multi-material three-dimensional (3D) printing, it is possible to achieve similar mobility for biomimetic applications as

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with silicone. In addition, where most research focuses on a single design, the goal of this work is to develop a pneumatic-based toolkit that can replicate some predominant SR applications: a gripper and a crawler. For this, both a bending and an extending appendage (bender and extender) are designed and fabricated, and then assembled in varying arrangements to create SRs with the desired functions. We are also able to predict their behavior through both experimental testing and simulation.

The usual design paradigm used for pneumatically actuated SR is to combine two material layers with different stiffness and use their mechanical asymmetry to obtain the desired deformation.⁶ Mosadegh *et al.*¹¹ demonstrate its application in a single bender, in which they use deformable chambers to induce the motion. Shepherd *et al.*⁷ show an example with their multigait robot, whose five different pneumatic networks combine the effect of the benders to generate a crawling-like motion. In a similar vein, Katzschmann *et al.*¹² developed a fish whose tail swings left and right as its internal chambers are pressurized. Trying to bypass the limitations of silicone casting, MacCurdy *et al.*¹³ printed a hexapod robot altogether by using a modified 3D printer that incorporates a liquid-filled linear actuator within the structure. Due to the use of a stiff printed material, the actuators undergo a rapid yet small deformation.

The design approach to SR has mostly consisted of trial and error, manual fabrication and has resulted in designs that are difficult to replicate. Considering that controllability and accuracy are key features for a successful robot, there is a necessity for more robust design, manufacturing, and dynamic prediction models. The aim of this article is, thus, to bridge the current gap by developing a toolkit consisting of a set of repeatable and robust pneumatic appendages, whose behaviors are predicted through both testing and numerical simulation.

Methods

Design and fabrication

The proposed toolkit consists of a bending and an extending appendage, as well as a set of rigid connectors. First, the design and fabrication of both the bender and the extender are detailed (Fig. 1). Four main design goals are defined based on previous research in four-dimensional printing^{13,14} and in pneumatic actuators.^{1,5,11} The designs should (1) be easy to fabricate and postprocess, (2) be able to actuate rapidly in response to increase in pressure, (3) provide a range of displacements or rotation for various applications, and (4) be easy to assemble, disassemble, and reassemble.

The first goal is achieved by fabricating all parts of this toolkit with a commercial material jetting 3D printer, Stratasys Objet500 Connex3, using commercial materials Vero-WhitePlus (a stiff polymer) and Agilus30 (a compliant elastomer), as well as digital blends between the two materials to achieve a range of materials with different stiffnesses. The removal of support material, dissolved by using a chemical solution (2% NaOH, 1% Na₂SiO₃), is simplified by eliminating the enclosed volumes in the designs. The second and third goals are achieved by evaluating the actuation pressure, speed, and displacement against designs found in literature by using similar mechanisms. The last is demonstrated through the assembly of two robots by using the same components.

The bending appendage consists of a number of compliant asymmetric bellows.^{10,15} When pressurized, each bellows bulges out. This results in a difference in the overall displacement between two sides of the bellows, which creates an overall rotation. The maximum rupture strain of the commercially available Agilus30 is $\sim 270\%$,¹⁶ whereas for some silicones such as Ecoflex, this value can reach up to 900%.¹⁷ The combination of incremental displacement of the bellows

FIG. 1. (a) Full bending appendage model and detail section view, including the female connector. (b) Full linear appendage model and detail section view, including the female connector. (c) Bending appendage in undeformed and deformed state; the α indicates the bending angle; (d) linear appendage in undeformed and deformed state; the Δd indicates the deformation measurement.

allows similar bending capacities while ensuring the strain stays below rupture.

The extending appendage is inspired by the pleated geometries used by MacCurdy *et al.*¹³ and Shepherd *et al.*¹⁸ However, these linear appendages achieved relatively small displacements of up to 20% extension or contraction. By increasing the pleat angle to 50° and using a more compliant material, the appendage presented in this work has an extension of up to 150%.

The connectors are designed for ease of assembly. They are designed to sustain a pressure on the order of 0.05 MPa, considering that the appendage's maximum deformation is reached around 0.03 MPa for the bender and 0.04 MPa for the linear extender. These values were determined experimentally and in simulation for both appendages. The desired strength is achieved by using a twist-and-lock mechanism; the male connector has two pins that slide into two rails and lock into place when twisted 45°. It is also fitted with a small O-ring dimensioned to be in compression once the connection is locked to ensure an airtight connection.

Simulation

Finite element analysis (FEA) is used to predict the mechanical behavior of the appendages. Nonlinear static simulations are conducted on one bellow as opposed to the whole appendage in Abaqus CAE. This resulted in a significantly reduced computational effort and improved convergence for more extreme deformation states.

Two analyses are performed for the bending appendage, one with a half bellows for the extremities (Fig. 2a) and one with a full bellows for the rest of the body (Fig. 2b). The first model is fixed (translation and rotation) on one end and has a planar constraint on the other; the second is symmetric

cally constrained on one end and has a planar constraint on the other. The planar constraint ensures that nodes on the boundary between two bellows cannot separate or penetrate each other. The linear appendage is modeled with a single set of boundary conditions (Fig. 2c), and the displacement on one face of the bellows is set to zero.

A uniform pressure of 0.05 MPa is applied on the inside surfaces of the bellows. The transient effects of air and air-flow are neglected as we are interested in the steady-state behavior. Gravity is not modeled as appendages are positioned flat on a testing bench during experiments. When used in an assembly, they may be positioned in all orientations.

Agilus30 is modeled as an isotropic material and follows a second-order polynomial hyperelastic approximation⁶; the coefficients are obtained through uniaxial testing. Its strain energy is defined by Rivlin and Saunders¹⁹ as

$$W = \sum_{i=0}^n \sum_{j=0}^n C_{ij} \cdot (I_1 - 3)^i \cdot (I_2 - 3)^j$$

where I_1 and I_2 are the two strain invariants of the left Cauchy Green deformation tensor. The C_{ij} constants are given in Table 1. VerowhitePlus adopts the material model in literature.²⁰ Strain-rate dependencies are neglected.

The resulting deformations of the two types of appendages are calculated by using the displacements of a set of nodes with respect to a reference set for a single bellow, and they are then combined to represent a full appendage.

Experimental setup

To verify the repeatability and predictability of each appendage design, a test setup is developed. It is designed to sustain minimal pressure loss and provides a pressure reading as close to the outlet as possible. A solenoid valve controls the flow, so that the test conditions are the same between experiments.

Three specimens are tested for both types of appendages. Pressure is ramped in increments of 0.003 MPa up to 0.035 MPa. The rotations and extensions as well as the corresponding pressure readings are captured photographically (Fig. 3) and analyzed. The angle achieved by the bending appendage is recorded by using a line on the base that is attached to the outlet and a line on the other end (Fig. 1). The displacement of the extending appendage is recorded as the displacement of a point on the end of the appendage.

Results

Appendages

Angle versus pressure plots are shown for both types of appendages in Figure 4. The bending appendage shows a linear behavior as consistent with the assumption that most

FIG. 2. Boundary conditions defined in the Finite Element Analysis (FEA) of both types of appendages. Two sets of conditions are used for the bending appendage: one for the end (a), one for the rest of the body (b), and one is used for the extending appendage (c).

TABLE 1. SECOND-ORDER POLYNOMIAL APPROXIMATION COEFFICIENTS FOR AGILUS BLACK

$C10$	$C01$	$C20$	$C11$
-0.4889	0.7147	0.07929	-0.2704
$C02$	$D1$	$D2$	
0.4709	0.4574	0.0	

FIG. 3. Experimental setup of the two appendages. The inlet controls the magnitude of the pressured air. The solenoid valve delivers air to the outlet based on a waveform supplied by the microcontroller. The manometer reads the outlet pressure. This is correlated with the rotation or the extension as recorded by the camera. **(a)** An overhead summary of the entire setup, **(b)** a close-up of the pressure control mechanism.

deformation occurs in bending through the expansion of the air chambers in the upper half of the bellows. The separation of the two vertical walls in the air chamber increases the length of the upper half of the bellows, forcing the lower half to curve. This behavior is predominant for pressure from 0 to 0.035 MPa, and from 0 to 160°. With a further increase in pressure, a radial expansion is observed, along with buckling of the lower surface. The FEA simulation of the single bending bellows has a maximum stress of 0.844 MPa and a minimum stress of 2.95×10^{-3} MPa for a maximum deformation of 1.855 mm.

With the extending appendage, due to the increase in the pleat angle past the horizontal line, the system becomes meta-stable and in some instances bistable. As the simulation is pressure controlled, only the positively sloped portion of the stress-strain relationship is captured. This meta-stability explains the nonlinear increase in angle w.r.t. to pressure at ~ 0.004 MPa. The stress peak of the linear appendage lies at 2.937 MPa and its minimum at 8.322×10^{-3} MPa for a maximum deformation of 6.329 mm.

During experimental testing, both appendages present consistent and repeatable behavior. The bender reaches 160° at 0.035 MPa. The error bars in Figure 4b represent the range of response of five tests. This deviation ranges from 2% to 14.3%. The solid line represents the mean. The linear appendage reaches on average 19.3 mm at 0.044 MPa. As it is difficult to control the time of triggering of the meta-stable design, the error increases at a pressure of 0.004 MPa.

FIG. 4. Simulation and experimental results of the two types of appendages. **(a)** Bending appendages, undeformed and deformed; **(b)** extending appendages FEA model, undeformed and deformed; **(c)** angle to pressure deformation for bending appendage; **(d)** displacement to pressure deformation for extending appendage. Plots show FEA simulation results versus mean, maximum and minimum measured data points.

FIG. 5. Soft robotic assemblies. (a–d) Gripper motion sequence: (a) no actuation, (b) gripper is lowered onto the vial, (c) bending appendages are pressurized, (d) the object is grasped. (e–g) Crawler motion sequence: (e) no actuation, (f) fully actuated (g) deflating; time is indicated at the *top right corner*, and distance can be read on the ruler.

The measured deformation for different pressures varies from 0.7% to 7% with respect to the mean, which is represented by the error bars in Figure 4d.

A strong correlation exists between the simulated and measured deformation. The model predicts deformations accurately up to 160° for the bender and 95% of the total deformation for the linear appendage. Figure 4b and d shows the deformation stages captured at different pressures during testing and compares them with the simulation results. Both simulations are good qualitative and quantitative approximations for values below 0.035 MPa.

SR assemblies

After the mechanical characterization of the appendages, the next task is to demonstrate their versatility by creating different soft robots.

The first example demonstrates a soft gripper that can grasp and hold up objects of different shapes and sizes. The gripper is composed of four bending appendages, each placed at 90° to each other. Each one is equipped with a small gripping foot for better grasp. They are activated simultaneously at 0.12 MPa. Since all connectors in the proposed toolkit allow airflow, only one inlet is needed to deliver pressure to the bending appendages.

As shown in Figure 5a–d, to pick up an object, the gripper is first lowered onto the object so that its flexible members can adapt to its shape. The gripper is then pressurized, which causes all four appendages to bend and curl around the object; finally, the object is lifted. Tests are performed by using a round specimen of 10 g and a glass vial of 20 g.

A crawler is developed by using the toolkit. Figure 5e–g shows, in turn, how two bending and two linear appendages are combined to build a crawler. The linear motion increases the reach of each step, and the bending motion gives the crawler a better hold to pull itself forward. The assembly is actuated with 1.5 s on/off 0.15 MPa pulses. Further combinations and changes in inlet configuration as well as changes in pulse pressure and length give control over speed and range of motion for every crawler design. The fastest crawler reached up to a speed of 10.7 mm/s or 0.073 body lengths/s.

Discussion

All appendages printed for this research are fabricated within 3 h by using a material jetting multi-material printer. This eliminates the need to prepare molds and to cure silicone. Compared with silicone casting, the manual fabrication effort is shifted from the molding and curing steps to part cleaning steps. Although the support material is mostly dissolved by using a chemical solution (2% NaOH, 1% Na_2SiO_3), each actuator needs approximately five additional minutes of manual cleaning and water-jetting. Designing and cleaning one actuator is still less time consuming than casting the same specimen in silicone.

The produced parts have small variability, which, in turn, facilitates the prediction of their mechanical behavior and the behavior of the assembled designs.

In terms of functionality, this work shows that it is possible to achieve similar results with multi-material 3D printing as with silicone casting, without the processing disadvantages that the latter brings (Table 2). This is also a marked

TABLE 2. COMPARISON IN PERFORMANCE BETWEEN SIMILAR BENDING APPENDAGES IN LITERATURE

Bending appendage	Fabrication	Pressure (MPa)	Angle
Our design	3D printed	0.03	160°
Ref. ²⁰	Silicone	0.05	150°
Ref. ²¹	3D printed	0.04	50°
Ref. ²²	Silicone + woven fabric	0.12	300°

3D, three-dimensional.

improvement on similar 3D printed designs by increasing the range of rotation three-fold.²¹

A similar comparison is made between the performance of our designs and that of similar grippers and crawlers (Table 3). With similar 3D printed grippers, we are able to sustain much higher pressure while maintaining the same mass, thus being able to grip heavier objects. With the crawler, we are able to achieve higher speed with lower pressure requirements than silicone counterparts.

The toolkit shown here has multiple possible applications. First, it can be used as a rapid prototyping tool for further SR research. In the longer term, when more durable materials are developed for this manufacturing method, the modular aspect of this toolkit could be used, for example, in the handling of complex shapes, changing single parts of the system to adapt to different products.

The modularity of the SR toolkit allows for the design of a variety of known SR applications using the two same building blocks. They are quickly assembled, disassembled, and reconfigured to perform a range of different tasks. For instance, one could easily reconfigure the crawler to adopt a bipedal movement by adding a pressure divider in the connector and creating two inlets.

Considering the repeatability of the deformation cycles and of the manufacturing process, a simplified simulation

TABLE 3. COMPARISON IN PERFORMANCE BETWEEN SIMILAR SOFT ROBOTICS IN LITERATURE AND THE PRESENTED DESIGNS

Grippers			
	Fabrication	Pressure (MPa)	Mass (g)
Our design	3D printed	0.12	30
Ref. ⁷	Silicone	0.5	300
Ref. ²¹	3D printed	0.02	33.2
Ref. ²³	Silicone	“a lot”	540
Ref. ¹¹	Silicone	n.a.	<40
Ref. ²⁴	Silicone	0.1	220
Crawlers			
	Fabrication	Pressure (MPa)	Speed (m/h)
Our design	3D printed	0.15	38.5
Ref. ⁷	Silicone	0.50	13.0
Ref. ²¹	Silicone	0.2–0.6	36.2
Ref. ¹⁴	Silicone	0.14	18.0

n.a., the authors of Ref.¹¹ provide no indication of the pressure used to activate the gripper.

model could be derived to predict the motion of both the appendages and their assemblies.

Both the adaptiveness of this robotic toolkit and a predictive model²² are of great benefit when linked with the generative design of robots that can tackle complex and changing environments. For example, the behavior of the appendages can be used in a generative design and optimization loop, as Moseley *et al.*²³ did for silicone SR.

One limiting factor of the toolkit is the material degradation. As with most photopolymers, Agilus30's mechanical properties degrade over time under exposure to ultraviolet light. Future work is needed to address the issue and focus on robust and soft biocompatible materials for realistic applications. Another limitation of this work and pneumatically actuated SR, in general, is control. A computer-controlled two-valve system was developed for the present testing, which might limit other assemblies in need of multiple separate actuation modes. A next step is to develop a more efficient valve control system and explore the possibilities of untethered pneumatic actuation in 3D printing.²⁴

Conclusion

We present a 3D printed pneumatic toolkit based on a bending and linear appendage that shows reliable and predictable performance. To demonstrate the toolkit, we show examples of SR designs for gripping and crawling, highlighting their versatility through reconfiguration. This builds on the same principle as previously published approaches to modular SR and here, using a 3D printed toolkit, achieves the same versatility while shortening the design and fabrication stages as well as extending the customization potential. The reproducibility of the results and precise control of material stiffness placement and utilization are further enhanced through 3D printing. Despite the poor material durability of 3D printed elastomers, the toolkit is a practical development platform for SR. Its application could grow further with the development of more robust printing materials.

Author Disclosure Statement

No competing financial interests exist.

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