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Abstract

© 2020 IEEE. This work reports on soft pneumatic bending sensing chambers that are directly 3D printed without requiring any support material and postprocessing using a low-cost and open-source fused deposition modeling (FDM) 3D printer and a commercially available soft thermoplastic polyurethane (TPU). These bending sensing chambers have multiple advantages including very fast response to any change in their internal volume, linearity, negligible hysteresis, repeatability, reliability, stability over time, long lifetime and very low power consumption. The performance of these soft sensing chambers is accurately predicted and optimized using finite element modeling (FEM) and a hyperelastic material model for the TPU used for 3D printing. The soft sensing chambers are tailored to several soft robotic applications such as bending sensors for bilateral control of soft robotic fingers and structures and soft wearable gloves for remote control of soft monolithic robotic fingers and adaptive grippers.

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3D Printed Soft Pneumatic Bending Sensing Chambers for Bilateral and Remote Control of Soft Robotic Systems

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Abstract—This work reports on soft pneumatic bending sensing chambers that are directly 3D printed without requiring any support material and postprocessing using a low-cost and open-source fused deposition modeling (FDM) 3D printer and a commercially available soft thermoplastic polyurethane (TPU). These bending sensing chambers have multiple advantages including very fast response to any change in their internal volume, linearity, negligible hysteresis, repeatability, reliability, stability over time, long lifetime and very low power consumption. The performance of these soft sensing chambers is accurately predicted and optimized using finite element modeling (FEM) and a hyperelastic material model for the TPU used for 3D printing. The soft sensing chambers are tailored to several soft robotic applications such as bending sensors for bilateral control of soft robotic fingers and structures and soft wearable gloves for remote control of soft monolithic robotic fingers and adaptive grippers.

I. INTRODUCTION

Soft robotic concepts and devices are ideal for developing safe human-machine interfaces that are made of highly deformable and soft materials [1]. Recently, diverse soft untethered robots were developed to prove and demonstrate that such robots are more suitable in some robotic areas compared to traditional rigid-bodied robots [2]. Conventional robotic systems are made of stiff and rigid materials and components and therefore cannot operate safely alongside humans and in unstructured environments [3]. Ideally, an entirely soft robot should be made completely of soft and flexible materials that can undergo and sustain large deformations repeatedly [4]. Soft robots require dexterous soft actuators, robust soft sensors and electronics, resilient deformable and flexible structures and compliant power

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Figure 1. Soft pneumatic bending sensing chambers computer-aided design (CAD) models and dimensions. (a) Soft 3D printed bending chamber. (b) Soft 3D printed bending chamber with the solid air pressure sensor attached. (c) Top view of the assembly. (d) Soft sensor dimensions: l : 34.0, r : 15.0, t_1 : 0.80, t_2 : 2.0, t_3 : 3.0, w_1 : 15.6, w_2 : 4.35. All dimensions are in mm. (e) Isometric view of the assembly. (f) A cross-sectional view along the length of the soft 3D printed chamber.

sources (i.e., compliant batteries) [4]. One of the challenges of soft robotics is the development of functional soft and deformable sensors. Soft robotic sensors must be able to sustain large and repeatable deformations and provide acceptable performance. Several resistive strain sensors were developed for soft robots including flex sensors [5, 6], conductive inks [7-9], ionic conductive liquids [10], liquid metals [11-13], fabrics and textiles [14, 15], resistive 3D printable thermoplastics [16], soft and elastic compressive foam sensors [17] and ultra-thin piezoresistive sensors [18] combined with 3D printable soft monolithic structures [19]. Also, capacitive soft sensors were developed for pressure sensing [20, 21], tactile sensing [22] and strain sensing [23] in several robotic applications. Similarly, strain, curvature, texture and force optical sensors were developed for use in soft prosthetic hands [24]. Some of these sensors have several limitations such as hysteresis, drift, short lifetime or slow response in addition to their laborious manufacturing methods which require multiple fabrication steps before their integration in soft robotic systems.

Also, pneumatic sensing soft structures have been developed for various robotic applications. An air bladder that can be embedded in a shoe to monitor and detect human gait phases was developed by winding a soft silicone tube and connecting it to a pressure sensor [25]. A pneumatic soft sensor for measuring the contact force and curvature in a soft gripper was fabricated using conventional molding and casting techniques that use commercial silicone rubbers [26]. A soft three-axis force sensor, based on radially symmetric

pneumatic chambers was designed and fabricated by casting silicone rubber [27]. A tactile soft sensor based on a commercially available latex tube that was connected to a pressure sensor was demonstrated for co-operative robots [28]. A method for rapidly prototyping interactive robot skins using 3D printing and analog pressure sensors was presented [29]. Several building blocks were designed to offer different modes of deformation such as bending and twisting. Also, 3D printed pneumatic controls were developed for haptic feedback applications based on the same printing method [30].

These 3D printed soft pneumatic structures were fabricated using high-cost 3D printers and flexible materials with limited performance in terms of deformation. The remaining soft pneumatic structures were fabricated using either commercially available flexible and stretchable silicone tubes or conventional casting and molding techniques involved in developing soft robots [31].

In this work, we present directly 3D printed soft pneumatic bending sensing chambers that can be rapidly fabricated without requiring support material and postprocessing using a low-cost and open-source fused deposition modeling (FDM) 3D printer and a commercially available soft thermoplastic polyurethane (TPU). These bending soft sensors have multiple advantages including very fast response to any change in their internal volume, linearity, negligible hysteresis, repeatability, reliability, stability over time, long lifetime and very low power consumption. The performance of these sensors can be accurately predicted and optimized using finite element modeling (FEM) and a hyperelastic material model for the TPU used for 3D printing. These soft sensors can be used in diverse soft robotic applications such as bending sensors for bilateral control of soft robotic fingers and structures and soft wearable gloves for remote control of soft adaptive grippers.

I. MATERIAL AND METHODS

A. Modeling and Fabrication

The computer-aided design (CAD) models of the soft pneumatic bending sensing chambers were modeled in Autodesk Fusion 360 (Autodesk Inc.). A commercial slicer (Simplify3D Inc.) was used to slice the CAD models of the bending chambers. The printing parameters were adjusted and optimized in the slicer based on recent studies [32-38] to 3D print airtight soft pneumatic bending sensing chambers. The optimized printing parameters are listed in Table I. The TPU used is NinjaFlex (NinjaTek, USA) which is a commercially available soft material. A low-cost and open-source FDM 3D printer (FlashForge Inventor, FlashForge Corporation) was used to 3D print the soft bending sensing chambers.

B. TPU Characterization and Material Model

A uniaxial stress-strain test was performed on the 3D printed TPU to obtain its stress-strain relationship. The tensile tests were conducted on the TPU samples according to the ISO 37 standard where all the samples were stretched by 800% at a rate of 100mm/s using an electromechanical Instron Universal Testing machine (Instron8801). To assess

the effect of the infill pattern on the behavior of the TPU, two different infill patterns, crosswise and longitudinal, were used to 3D print the test samples. For each type of Infill 8 samples were tested. The infill pattern had an insignificant effect on the behavior of the TPU, as shown in Fig. 2. The TPU was modeled as a hyperelastic material. A 5-Parameter Mooney-Rivlin material model was implemented based on the average experimental stress-strain data. The parameters of the material model are listed in Table II. This model was implemented in ANSYS Workbench (Release 19.1, ANSYS, Inc.) to perform the FE simulations.

TABLE I. OPTIMIZED PARAMETERS IN SIMPLY3D FOR 3D PRINTING AIRTIGHT AND FUNCTIONAL SOFT PNEUMATIC BENDING SENSING CHAMBERS.

Parameter	Value	Unit
Resolution Settings		
Primary Layer Height	0.1	mm
First Layer Height	0.09	mm
First Layer Width	0.125	mm
Extrusion Width	0.4	mm
Ooze Control		
Coast at End	0.2	mm
Retraction Settings		
Retraction Length	4	mm
Retraction Speed	40	mm/s
Speed Settings		
Default Printing Speed	10	mm/s
Outline Printing Speed	8	mm/s
Solid Infill Speed	8	mm/s
First Layer Speed	8	mm/s
X/Y Axis Movement Speed	50	mm/s
Z Axis Movement Speed	20	mm/s
Temperature Settings		
Printing Temperature	240	°C
Heat Bed Temperature	32	°C
Cooling Settings		
Fan Speed	50	%
Infill Settings		
Infill Percentage	100	%
Infill/Perimeter Overlap	30	%
Thin Walls and Movements Behavior		
Allowed Perimeter Overlap	25	%
External Thin Wall Type	Perimeters Only	-
Internal Thin Wall Type	Allow Single Extrusion Fill	-
Avoid Crossing Outline	ENABLED	-
Detour Factor	100	-
Additional Settings		
Extrusion Multiplier	1.15	-
Top Solid Layers	5	-
Bottom Solid Layers	5	-
Outline/Perimeter Shells	25	-
Wipe Nozzle	DISABLED	-
Support Material	DISABLED	-

TABLE II. OPTIMIZED PARAMETERS IN SIMPLY3D FOR 3D PRINTING AIRTIGHT AND FUNCTIONAL SOFT PNEUMATIC BENDING SENSORS.

Hyperelastic Material Model	Material Constant	Value	Unit
5-Parameter Mooney Rivlin	C10	-0.233	MPa
	C01	2.562	MPa
	C20	0.116	MPa
	C11	-0.561	MPa
	C02	0.900	MPa
	Incompressibility Parameter D1	0.000	MPa ⁻¹

Figure 2. TPU stress-strain data.

II. FINITE ELEMENT MODELING

Finite element simulations were performed on the soft pneumatic bending sensing chambers to optimize their topology in order to predict their behavior under an input mechanical bending load and to obtain a linear relationship between the applied mechanical bending load and the change in their internal volume. The FEM simulations were performed in ANSYS Mechanical where a Static Structural Analysis is implemented. The CAD models were meshed using higher order tetrahedral elements. Contact pairs were defined between the internal walls that come into contact when large mechanical deformations are applied to the bending sensing chambers. In terms of boundary conditions, Fixed Support was defined on one side of the soft structure and a Displacement Support was imposed on their opposite end to simulate the bending deformation applied. The FEM simulations proved that a linear relationship exists between the applied mechanical load and the change in the internal volume of the bending sensor, as shown in Fig. 3. Ideally, a relationship exists between the change in the internal volume of the soft pneumatic bending sensing chamber and the experimental pressure change ($P_1V_1 = P_2V_2$) obtained due to the mechanical deformation applied. Therefore, FEM can be used to predict the behavior of the bending sensing chambers and to optimize their topology to meet specific design requirements.

III. OBJECTIVE, CONCEPT AND DESIGN

The objective is to design 3D printed pneumatic bending sensing chambers that can be fabricated using low-cost FDM 3D printers and commercially available soft materials. The design and dimensions of the chambers are shown in Fig. 1. The geometry of the chambers was optimized using FEM to obtain a linear relationship between the input mechanical bending deformation and the output pressure. The minimum thickness for the thin walls is 0.8mm. This thickness was used to ensure that the 3D printed soft sensing chambers are airtight and flexible. Thicker walls can result in a stiffer structure that is harder to bend. The length of the chamber can be chosen depending on the application required. A

triangular groove with a base of 4.0mm and a height of 1.0mm can be added to obtain a local bending joint at a specific position along the length of the sensor, as shown in Fig. 1.

Figure 3. Soft pneumatic bending sensing chamber final design FEM results. Inset: FEM deformed model.

IV. CHARACTERIZATION OF THE SOFT BENDING CHAMBERS

The experimental setup used to characterize a single soft pneumatic sensing chamber is illustrated in Fig. 4. The bending chamber was printed along with a soft hinge made of the same material. A linear displacement was applied to pull the tendon and consequently bend the soft hinge and thus the chamber by the desired angle.

Figure 4. Characterization experimental setup of the soft pneumatic bending sensing chamber.

A. Linearity and Hysteresis

The linearity and hysteresis of the soft bending sensing chambers were assessed. Fig. 5 shows that the chambers exhibit a linear behavior and have insignificant hysteresis. This proves that these sensing chambers can be used easily and reliably in soft robotic control applications.

B. Repeatability and Reliability

The soft bending sensing chamber was activated repeatedly for 500 cycles at a frequency of 1.0Hz to assess its repeatability. The sensing chamber generated a repeatable and consistent signal during the activation period, as shown in Fig. 6 and Fig. 7. This proves that these sensing chambers are reliable for use in soft robotic applications.

Figure 5. Soft bending sensors linearity and hysteresis data.

C. Stability Over Time

The soft bending sensing chamber was bent for 30 minutes where its internal pressure was measured and monitored to assess its stability. Fig. 8 shows that the internal pressure of the soft chamber remained the same during the activation period. This result proved that the sensing chamber generated a stable signal without any drift over time and confirmed that its soft 3D printed structure is airtight.

Figure 6. Soft pneumatic bending sensor repeatability signal for 500 cycles at a frequency of 1.0Hz.

D. Lifetime

A single soft bending sensing chamber was repeatedly activated to assess its performance in terms of lifetime. The

sensor sustained more than 150,000 activation cycles without failure. This result shows that these sensing chambers can be used in soft robotic structures where repeatable deformations are involved for long periods.

Figure 7. Soft pneumatic bending sensor repeatability signal for 25 cycles at a frequency of 1.0Hz.

E. Power Consumption and Response Time

These soft bending sensing chambers are not by themselves sensors. However, solid air pressure sensors are required to sense the volume change upon their deformation. We used commercially available and analog air pressure sensors (ABPDANT015PGAA5, 0–15psi Gauge, 0.25% accuracy, Honeywell International Inc.) that can be directly connected to the soft bending structure to measure the volume change (i.e., pressure change), as shown in Fig. 1. The power consumption of a single analog pressure sensor is 13.5mW [39]. These sensors have a response time of 1.0ms [39].

Figure 8. Soft pneumatic bending sensor stability over time (SOT) signal.

V. APPLICATIONS IN SOFT ROBOTICS

These soft bending sensing chambers can be tailored to

diverse soft robotic applications including bending sensors for bilateral control of soft robotic fingers and structures and soft wearable gloves for soft adaptive grippers telecontrol.

A. Robotic Fingers Bilateral Control

The soft bending sensors can be directly integrated into soft robotic fingers for simple and accurate bilateral control applications. In this scenario, we have 3D printed a soft monolithic robotic finger with three flexural hinges using the same FDM printing method, as shown in Fig. 9. To demonstrate the use of these sensors in bilateral control applications we placed a single bending soft sensing chamber along the back of a soft robotic master finger to detect its position, as shown in Fig. 9. The tendon-driven slave 3D printed monolithic robotic finger is directly connected to a servo motor. There is a direct relationship between the output pressure of the bending sensing chamber placed on the master finger and the servo motor angle. The slave fingers can follow accurately the movements imposed on the master finger, as shown in Fig. 9 and Video S1. The objective of this demonstration was to prove that a single bending sensing chamber can be used for accurate bilateral control.

Figure 9. Soft 3D printed monolithic robotic fingers bilateral control using a master robotic finger (right) and a slave robotic finger (left). (a) The initial position of the robotic fingers. (b) – (e) The slave finger following the same position imposed on the master finger.

B. Soft Wearable Glove for Robotic Fingers Telecontrol

A soft robotic wearable glove based on five bending sensing chambers was developed for the telecontrol of soft robotic devices. Here, we demonstrate the soft glove using only the index finger to control a soft monolithic robotic finger, as shown in Fig. 10. The soft glove can be used to control the soft robotic finger remotely, as shown in Fig. 10 and Video S1.

C. Soft Wearable Glove for Soft Grippers Telecontrol

The same soft wearable glove was used to control a soft adaptive gripper, as shown in Fig. 11 and Video S1. The soft gripper can be controlled remotely with great accuracy and precision using the soft glove to grasp a wide variety of objects with different weights, shapes, sizes, textures and stiffnesses. These gloves can be used to control soft structures remotely.

VI. CONCLUSION

In this work, we have developed soft pneumatic bending sensing chambers that can be directly manufactured using a low-cost and open-source FDM 3D printer without requiring support material and postprocessing. The soft bending sensing chambers have multiple advantages including very

Figure 10. A Soft 3D printed monolithic robotic finger (left) controlled using the soft wearable glove (index finger only). (a) Initial position. (b) – (f) The robotic finger following the same position imposed on the index finger using the soft glove.

Figure 11. A soft 3D printed three-finger adaptive gripper controlled using the soft wearable glove. The soft gripper is controlled to pick and place different objects including (a) a small lunch box (24.04g), (b) a plastic clamp (41.99g), (c) a marker (10.51g) and (d) a soft and deformable 3D printed robot (9.99g).

fast response, linearity, insignificant hysteresis, repeatability, reliability, stability over time, long lifetime and low power consumption. The soft bending chambers were optimized using FEM to obtain a linear relationship between the input mechanical bending deformation and the output pressure.

These soft bending sensing chambers can be used in diverse soft robotic applications including bending sensors for soft robotic fingers and structures bilateral control and soft

wearable gloves for soft robotic fingers and adaptive grippers telecontrol.

In future work, the soft bending sensing chambers that make the soft wearable glove will be integrated on each joint of the finger to obtain the position of each joint. The soft glove will be developed as a standalone wearable device that can be directly used. Also, for the master finger in the bilateral control application, each of its joints will be assigned a soft bending sensing chamber to demonstrate it with a slave finger that has an actuator on each joint.

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