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Abstract

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3D Printable Vacuum-Powered Soft Linear Actuators

Charbel Tawk, Geoffrey M. Spinks, Marc in het Panhuis, and Gursel Alici

Abstract— Soft robots which are made of highly deformable materials are ideal to operate in unstructured environments and to interact safely with humans. This work presents directly 3D printed linear soft vacuum actuators (LSOVA), that are manufactured in a single step without requiring any post-processing and support material, using a low-cost and open-source fused deposition modeling 3D printer. LSOVA have multiple advantages such as high bandwidths ($\sim 6.49\text{Hz}$), high output forces ($\sim 27\text{N}$) and long lifetimes ($\sim 21,500$ cycles). Finite element models and analytical models are developed to accurately predict the performance of LSOVA in terms of blocked force and linear stroke. The LSOVAs can be directly used in diverse soft robotic applications such as soft artificial muscles, soft prosthetic fingers for prosthetic hands and soft adaptive grippers for gripping applications.

I. INTRODUCTION

Conventional robots are becoming smarter and more capable of performing tasks involving high precision, high accuracy, large forces and high speeds [1]. Although these conventional robotic systems are widely used in factories, they are still not capable of operating safely alongside humans as they are made of stiff and rigid materials [2]. Soft robots which are made of highly deformable and compliant materials are ideal to operate in unstructured and dynamic environments. These soft robotic systems can interact safely with humans due to their inherent softness. Ideally, all the components of a soft robot including actuators, sensors, power sources and mechanical structures should be made of deformable and compliant materials [3]. However, developing entirely soft robots remains a challenge for scientists and engineers. One of the primary and most important components of a functional soft robot is soft actuators. Developing dexterous soft actuators which can facilitate the soft and adaptive interaction between soft robots and their environments is one of the fundamental steps in the

process of developing such robots. Soft pneumatic actuators are widely used to drive and operate diverse soft robotic systems. The most common types of soft pneumatic actuators used are McKibben actuators [4], fiber-reinforced actuators [5–8], and PneuNets [9–11]. These actuators are activated using a positive pressure source to drive diverse soft robots and soft structures [12–19]. These soft pneumatic actuators can be fabricated using several manufacturing techniques such as molding and additive manufacturing including 3D printing based on fused deposition modeling (FDM) [20,21], stereolithography [22] and multi-material 3D printing [23–25]. Another type of soft pneumatic actuators that is powered by vacuum was also developed to drive diverse soft robotic systems and structures [26–29]. Soft vacuum actuators have multiple advantages compared to positive-pressure actuators. First, vacuum actuators shrink upon activation which make them ideal for applications where space requirements are limited. Second, the actuators rely on negative pressure which provides a fail-safe feature in contrast to conventional pneumatic actuators. The soft structure of conventional soft pneumatic actuators expands upon activation resulting in high stress gradients. Finally, soft vacuum actuators are more durable and reliable.

The soft vacuum actuators reported in the literature [26–29] are fabricated using complex manufacturing techniques that require multiple and laborious steps to fabricate them [16, 30]. In this work, we developed directly 3D printed soft actuators that generate a linear motion when activated with negative pressure as shown in Fig. 1. These linear soft vacuum actuators (LSOVA) have multiple advantages compared to existing soft vacuum actuators. First, they can be easily and rapidly manufactured using a low-cost and open source FDM 3D printer, without requiring any post-processing and support material. Second, they generate high output forces. A single actuator can generate a blocked force of 27N and a lifting force of 26N when activated with 95.7% vacuum. Third, the actuators have a high actuation speed. The bandwidth of the LSOVA ranges between 3.47Hz and 6.49Hz. Fourth, the performance of the actuators in terms of blocked force and linear stroke can be accurately predicted using finite element modeling and a geometric model. Fifth, the actuators remain functional, under a continuous supply of vacuum, after failure. The performance of LSOVA is not affected by minor air leaks or structural damage. Finally, the LSOVA can be directly used in various robotic applications such as soft artificial muscles, soft prosthetics and soft adaptive grippers.

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TABLE I
PERFORMANCE PARAMETERS OF LSOVA

Parameter	1C–	2C–	3C–	4C–	5C–
	LSOVA	LSOVA	LSOVA	LSOVA	LSOVA
L_0	16.00	29.00	42.00	55.00	68.00
V_i	3922.72	7883.13	11843.55	15803.97	19764.40
m	3.16	5.27	7.49	9.46	11.09

δ	6.05	14.58	21.95	28.63	35.03
T_r	60.00	59.00	60.00	64.00	94.00
T_d	631.00	578.00	564.00	570.00	560.00
F_b	27.02	26.56	27.27	27.62	27.66
ω_b	6.49	5.91	5.62	4.69	3.47
L_t	21571	24981	23857	25046	22450

L_0 : Original Length (mm), V_i : Internal Volume (mm³), m : Mass (g), δ : Linear Deformation (mm), T_r : Rise Time (ms), T_d : Decay Time (ms), F_b : Blocked Force (N), ω_b : Estimated Bandwidth (Hz), L_t : Lifetime (Cycles)

II. MATERIALS AND METHODS

A. Modeling and Fabrication of LSOVA

The computer-aided design (CAD) models of LSOVA were designed in Autodesk Fusion 360 (Autodesk Inc.) with 3mm thick horizontal walls that separate the different vacuum chambers to prevent the structure from collapsing in the lateral direction as shown in Fig. 1. (a). The dimensions of LSOVA are shown in Fig. 1. (a) and listed in Table I. The LSOVA samples were prepared with 1 to 5 vacuum chambers in series and are designated XC-LSOVA with X representing the number of vacuum chambers in each 3D printed linear actuator. The 3D models were sliced in a commercial 3D printing software, Simlify3D (Simplify3D LLC, OH). The printing parameters were optimized to obtain airtight actuators using an open-source FDM 3D printer (FlashForge Inventor, USA) [31].

Fig. 1. (a) Dimensions and cross-sectional view of a 1C-LSOVA. W:20mm, H: 10mm, d:3mm, t:0.90mm, α :110° – These dimensions are the same for each cell of the actuator (b) Initial position of a 5C-LSOVA when no vacuum is applied. (c) Final position of 5C-LSOVA when 95.7% vacuum is applied (Table I).

B. TPU Material Model

The stress-strain relationship of the thermoplastic poly(urethane) (NinjaFlex, NinjaTek, USA) used to 3D print the soft actuators was experimentally obtained to understand its behavior. Tensile tests were conducted on the TPU according to the ISO 37 standard where the samples were stretched by 800% at a rate of 100mm/s using an electromechanical Instron Universal Testing machine (Instron8801). The stress-strain data of the TPU was used to develop a hyperelastic material model for use in finite element modeling. A Mooney-Rivlin 5-parameter model was used to model the behavior of the TPU. The model was implemented in ANSYS Workbench (Release 16.2, ANSYS, Inc.) to perform finite element simulations on the soft actuators to predict their quasi-static behavior.

III. MODELLING OF LSOVA

A. Finite Element Modeling

The soft actuators were meshed using higher order tetrahedral elements. Both ends of LSOVA were constrained and a negative pressure was applied on the internal walls. In addition, frictional contact pairs were defined between the internal walls since they touch when the actuators deform. The finite element simulations were performed in ANSYS Workbench to predict the blocked force and linear stroke of LSOVA. The experimental blocked force data matched the FEM results with an acceptable difference of less than 5% in most cases, as shown in Table II. There is a larger difference between the experimental and FEM displacement results. The main reason is that during the 3D printing process the first few layers of each horizontal wall sagged and fell due to poor bridging performance by NinjaFlex which resulted in thick plastic residuals that limited the linear displacement of the actuators.

TABLE II
FINITE ELEMENT RESULTS FOR LSOVA DEFORMATION AND BLOCKED FORCE

Parameter	1C- LSOVA	2C- LSOVA	3C- LSOVA	4C- LSOVA	5C- LSOVA
δ_e	6.05	14.58	21.95	28.63	35.03
δ_{FEM}	8.65	16.55	23.97	31.94	39.47
$\Delta\delta$	42.98	13.51	9.20	11.56	12.67
$F_{b, exp}$	27.02	26.56	27.27	27.62	27.66
$F_{b, FEM}$	28.30	28.49	28.59	28.56	28.66
ΔF_b	4.72	7.26	4.85	3.39	3.62

δ_e : Experimental Deformation (mm), δ_{FEM} : FEM Deformation (mm), $F_{b, exp}$: Experimental Blocked Force (N), $F_{b, FEM}$: FEM Blocked Force (N), $\Delta\delta$: Difference Between δ_e and δ_{FEM} (%), ΔF_b : Difference Between $F_{b, exp}$ and $F_{b, FEM}$ (%)

B. Analytical Model

An analytical model was derived to estimate the blocked force of the LSOVA. The free-body diagram of a 1C-LSOVA is shown in Fig. 2. and all the parameters of the model are listed in Table III.

The output blocked force can be expressed as:

$$F_{out} = F_p + 2T_x \quad (1)$$

where

$$F_p = \pi R_i^2 P \quad (2)$$

From Laplace's Law, we can write:

$$T = R_e P S_e \quad (3)$$

where S_e is the effective width of the thin walls which was computed by considering the flattened frustum shown in Fig. 2c.

The relationship between LSOVA inner and outer radii and the flattened frustum inner and outer radii can be expressed as follows:

$$r_i = R_i L / (R_o - R_i) \quad (4)$$

$$r_o = R_o L / (R_o - R_i) \quad (5)$$

and the effective radius of the flattened frustum can be computed from the following equation:

$$r_e = L / \ln(r_o / r_i) \quad (6)$$

The effective length of the frustum can be now computed as follows:

$$S_e = r_e \theta_e \quad (7)$$

where

$$\theta_e = (R_o - R_i) / L \quad (8)$$

The horizontal component of the tension can now be written as follows

$$T_x = T \sin \theta_c = R_c P S_e \sin \theta_c \quad (9)$$

Finally, the output blocked force becomes

$$F_{out} = P(\pi R_i^2 + 2R_c S_e \sin \theta_c) \quad (10)$$

The difference between the experimental blocked force listed in Table II and the analytical blocked force listed in Table III for a 1C-LSOVA is 7.20%. The analytical model predicted the blocked force of LSOVA with reasonable accuracy. The analytical model assumes that the walls are rigid and behave like rigid links. Therefore, the experimental blocked force is less compared to the analytical blocked force due to the softness of the TPU used to 3D print the soft actuators.

The relationship between the linear stroke (D) and the angle θ_c can be written as follows (Fig. 2):

$$D = 2L \sin \theta_c \quad (11)$$

The difference between the analytical linear stroke and the experimental linear stroke of 8.57mm is 14.94%. This difference is reasonable since the real deformation is limited by the thick plastic residuals that limited the linear displacement of the actuators. This proves that the analytical model is effective enough to estimate the blocked force and output linear stroke of the LSOVA.

TABLE III
1C-LSOVA ANALYTICAL MODEL PARAMETERS

Parameter	Value
F_{out}	28.97
F_p	24.05
T_x	4.92
P	98.19
R_i	8.83
R_o	12.87
R_c	0.50
r_i	14.04
r_o	20.47
r_e	17.05
L	6.43
S_e	67.35
D	9.85
θ_c	50.00
θ_e	226.35

F_{out} : Output Force (N), F_p : Pressure Force (N), T_x : Thin Wall Horizontal Tension (N), P : Input Negative Pressure (kPa), R_i : LSOVA Inner Radius (mm), R_o : LSOVA Outer Radius (mm), R_c : Radius of Curvature (mm), r_i : Flattened Frustum Inner Radius (mm), r_o : Flattened Frustum Outer Radius (mm), r_e : Flattened Frustum Effective Radius

(mm), L : Thin Wall Length (mm), S_e : Thin Wall Width (mm), D : Linear Stroke (mm), θ_c : LSOVA Angle ($^\circ$), θ_e : Frustum Effective Angle ($^\circ$)

Fig. 2. Free-Body Diagram (FBD). (a) LSOVA FBD (b) Frustum side view (c) Flattened frustum

IV. LSOVA CHARACTERIZATION

A. Step Response

The step responses of the distinct LSOVAs were obtained using a high-resolution laser sensor (Micro-Epsilon, optoNCDT 1700-50) that measured their linear displacement upon activation with 95.7% vacuum as shown in Fig. 3. The rise time and decay time of each LSOVA are listed in Table I. The rise time of LSOVA is 25 times less than the rise time reported in [27], at least 3 times less than the rise time reported in [28] and 8 times less than the rise time reported in [29].

B. Hysteresis

The relationship between the input negative pressure and the linear displacement of a 5C-LSOVA is shown in Fig. 4. The linear displacement was measured when the input negative pressure was ramped up and down by a step of $\Delta P = -10$ kPa. The actuator exhibited hysteresis with a largest difference of 26.27mm occurring at $P = -20$ kPa.

C. Actuation Frequencies and Bandwidths

The maximum actuation frequency of LSOVA was obtained by activating the structure with 95.7% vacuum. The actuation frequency decreased with an increase in the number of vacuum chambers since the actuators with a high number of cells have a larger internal volume to evacuate, and subsequently more time is needed to fill them with air at the atmospheric pressure. The bandwidths of the distinct LSOVAs were estimated from their experimental step responses (Fig.3.). The bandwidths of LSOVA are listed in Table I. The bandwidth of a 1C-LSOVA is 32 times greater than the bandwidth reported in [26] and 5.9 times greater than the bandwidth reported in [27]. The bandwidths of the other soft vacuum actuators in [28,29] are not reported. Similarly, the bandwidth of a 5C-LSOVA is 17 times greater than the bandwidth reported in [26] and 3.5 times greater than the bandwidth reported in [27].

Fig. 3. Step response curves of various LSOVA consisting of different numbers of vacuum chambers.

Fig. 4. Hysteresis curve of a 5C-LSOVA.

D. Blocked Force

The actuators were restricted from moving by constraining both ends to measure their blocked force. The blocked force of each LSOVA was measured using a force gauge (5000g, FG-5005, Lutron Electronic Enterprise CO., LTD) when 95.7% vacuum was applied. The forces generated by the LSOVA are listed in Table I. The blocked force reported in [27] varied between 90N and 428N based on various designs. The blocked force produced by LSOVA is lower compared to the blocked force reported in [27]. In [28], two types of soft vacuum linear actuators with different material properties were reported where the blocked force of the LSOVA is 8 times larger than the blocked force of the first actuator reported and comparable with the blocked force of the second actuator reported. Similarly, the blocked force of the LSOVA is 68 times larger compared to the blocked force of the first design reported in [29] and 30 times larger compared to the blocked force of the second design

reported.

Fig. 5. Creep experiment. Pressure and displacement (the bottom curves) curves of LSOVA.

E. Creep

The actuators experienced no creep when their internal pressure was kept constant for a period of 35 minutes as shown in Fig. 5. Their position was monitored to detect any drift resulting from creep. The position of the actuators remained unchanged during the activation period. The pressure of the system changed slightly by 0.32% for the longest actuator during the experiment, causing a negligible change in the actuator stroke, due to minor air leakage from fittings and connectors.

F. Lifetime

The number of cycles that the actuators sustained before failure was measured. In each actuation cycle, the actuators were activated to achieve full contraction using 90% vacuum. The LSOVA performance remained unchanged prior to failure. The lifetimes of the actuators are listed in Table I. The lifetime of LSOVA is significantly higher compared to the reported lifetime of other 3D printed soft actuators [20,22].

V. APPLICATIONS OF LSOVA

A. Soft Artificial Muscle

The actuators can be used as soft artificial muscles to generate high forces. A 5C-LSOVA was used to move an elbow joint by an angle of 45° as shown in Fig. 6. The artificial muscle can lift a maximum load of 0.5kg. The linear displacement of the artificial muscle decreased when the load increased.

B. Soft Prosthetic Finger

A monolithic prosthetic finger with flexural joints was fabricated based on the same 3D printing method used in [32]. The tendon-driven soft prosthetic finger was coupled with a 5C-LSOVA actuator. The actuator pulled the tendon upon activation with 95.7 % vacuum causing the prosthetic

Fig. 6. Elbow joint (a) Unloaded (b) Unloaded and activated with 95.7% vacuum (c) Loaded with a 0.5kg weight and not activated (d) Loaded with a 0.5kg weight and activated with 95.7% vacuum. Soft finger (e) Open position (f) and closed position. Soft gripper grasping (g) a screw driver (21.61g) (h) a plier (54.35g) (i) and scissors (30.58g) upon activation with 95.7% vacuum. Soft gripper grasping (j) a cup (11.32g) (k) a bottle (45.94g) (l) a plastic container (1000g) (m) and a flexible paper cylinder (4.95g) upon activation with 95.7% vacuum.

finger to bend. The soft prosthetic finger can grasp various objects as shown in Fig. 6.

C. Soft Adaptive Gripper

A soft gripper based on the same monolithic soft fingers was developed. The gripper was driven by one 5C-LSOVA coupled with tendons that run through the soft fingers. The gripper lifted a load of 1.0kg. The geometry of the fingers was not optimized but used only for demonstration purpose. The gripper grasped different objects with various weights, shape, textures and stiffnesses as shown in Fig. 6.

VI. CONCLUSION

In this work, we have directly 3D printed linear soft actuators, LSOVA, that can be activated through vacuum. The actuators were 3D printed using a low-cost open-source FDM 3D printer, without requiring any post-processing and support material. The vacuum actuators generate high output forces and large rectilinear displacements. In addition, the behavior of LSOVA can be accurately predicted in terms of blocked force and linear stroke using finite element modeling and a geometric model. We have tailored these actuators for various robotic applications such as artificial muscles, prosthetics and adaptive grippers.

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