PDMS-BASED DUAL-CHANNEL PNEUMATIC MICROACTUATOR USING SACRIFICIAL MOLDING FABRICATION TECHNIQUE

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ABSTRACT

This paper presents a novel polydimethylsiloxane-based dual-channel bellows-structured pneumatic actuator, fabricated through sacrificial molding technique. A finite element analysis was performed to find the optimum structure and analyze the bending performance of the square-bellows actuator. The actuator was fabricated using acrylonitrile butadiene-styrene-based sacrificial mold to form the channel and bellow structures with an overall actuator size of 5 × 5 × 27.6 mm^3. The experimental validation has revealed that the actuator attained a smooth bi-directional bending motion with maximum angles of -25° and 35° and force of -0.168 and 0.212 N under left and right channel actuation, respectively, at 100 kPa pressure. Hence, the state-of-the-art dual channels square-bellows actuator was able to achieve an optimum bi-directional bending with low input pressure, which would push the boundaries of soft robotics towards the development of more safe and flexible robotic surgical tools.

KEYWORDS

Soft actuator, dual-channel actuator, pneumatic actuator, catheter.

INTRODUCTION

The technical evolution in the field of robotics has enabled the development of advanced surgical systems to facilitate minimally invasive surgery (MIS) procedures, which resulted in a reduction in postoperative pain, shorter hospital stays, improved cosmetics and reduced risk of wound infection [1]. An MIS utilizes an endoscope to access the interior organs or tissue inside the body of the patient, via three to five incisions of 5-15 mm in size. Therefore, preliminary insertion of a small catheter is essential without sacrificing its ability to maneuver. Initially, the endoscopes were driven by thin steel wires and springs [2], which were further evolved to shape memory alloy (SMA) for better actuation [3]. SMA works on the phenomena of shape-memory effect, which occurs when the SMA is deformed at the martensitic phase and then heated up to austenitic phase to regain its original shape [4, 5]. Besides being bulky, thermally-driven SMA can offer strong force capabilities, however, lags to offer a smooth bending motion, while the heat dissipation issue can be hazardous during the MIS procedure.

In contrast to rigid actuators, many researchers have also deployed soft actuators for developing flexible endoscopes and catheters. Soft actuators made from highly compliant materials draws heavily from the way in which living organisms move and adapt to their surroundings [6]. The structure of the soft actuator consists of internal channel(s), while the applied pneumatic or hydraulic pressure to its channel(s), causes elastic deformations in its structure, which results in actuation [7]. A soft actuator can offer pre-designed motions with multiple degrees of freedom (DoF), high flexibility, adaptability and safety [8], which make it a promising candidate for endoscopic applications. In this respect, the authors in [9] developed a pneumatic soft-actuator-based flexible bronchoscope, which can perform bending and twisting motions. Another soft-actuator-based colonoscope was developed by the authors in [10]. The device was verified experimentally for its effectiveness on a large intestine phantom model. Indeed, soft actuators have found enormous applications in medical robotics, especially MIS applications. However, to develop a complex and miniaturize structured soft actuator, the fabrication would be quite difficult through conventional molding or casting process, which involves very low repeatability, while its almost impossible to extract the channel forming mold.

In this study, a novel polydimethylsiloxane (PDMS)-based dual-channel bellows-structured pneumatic actuator is fabricated through sacrificial molding technique using acrylonitrile butadiene styrene (ABS) material. In addition, the structural parameters of the actuator were characterized and analyzed, while its bending performance is validated, and its force is determined experimentally.

DESIGN AND SIMULATIONS

The design of the proposed pneumatic dual channel actuator consists of square-shaped bellows in its structure to provide a bi-directional bending motion, while PDMS was selected due to biocompatibility and possible feature size. The structural parameters of the dual-channel square bellows actuator were characterized by keeping the wall-thickness, *WT*, bellows width, *BW*, and bellows spacing, *BS*, number of bellows, *B*, and the length, *L*, constant (see Fig. 1), while the actuator width, *W*, to height, *H*, ratio was varied to develop two models with structural parameters tabulated in Table 1.

Finite element analysis (FEA) was performed to simulate the bending behavior of the actuator design using

Table 1: Structural parameters of the dual-channel square-bellows actuator (Models 1 and 2).

Model	Structural Parameters (mm)					
	H × W	BS	BW	WT	B	L
1	3 × 5	1	2.4	0.7	8	27.6
2	5 × 5	1	2.4	0.7	8	27.6

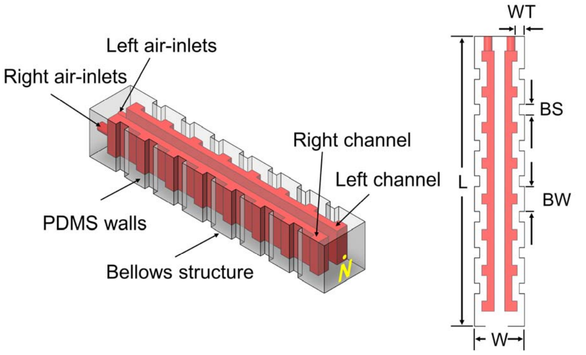


Figure 1: Structural design of the dual-channels square-bellows actuator.

MARC® software. The nodes were connected to form elements, which were further combined to forms the overall structure of the actuator in MARC® software. Next, the material properties of the PDMS were defined by inserting the values of Young's modulus, $E = 0.57\ MPa$ and Poisson's ratio, $\mu = 0.5$. For the boundary conditions, each of the two channels was marked with maximum input face-load pressure of 100 kPa, applied linearly during the simulation through respective contact table at a load-case value of 1000 increments. For holding the actuator, a fixed-displacement along x, y, and z-axes was applied at one end of the actuator. A reference node, N, was marked at the center of the bending end of the actuator (see Fig. 1), to track the displacement covered by the actuator during the simulation, which was further utilized for calculating the bending angle, θ, of the actuator [11]. Applying a pneumatic pressure to the left channel of the bellows actuator raises contraction and expansion in its structure, which results in a bending motion towards the right direction (see Fig. 2), and vice versa. By keeping all the above settings of MARC® constant, two actuator models were simulated and analyzed for θ.

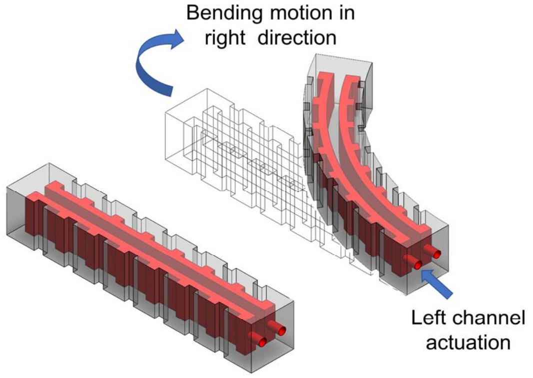


Figure 2: Working principle of the dual-channels square-bellows pneumatic actuator (Model 2).

Bending Angle (θ) Calculations

As highlighted in the previous section, that for tracking the bending displacement, N was selected at the center of the bending side of the actuator. For θ calculation, a right-angled triangle, $\overline{MNO}$, was marked on the resulted simulation profile of the actuator (see Fig. 3). Considering that N as one corner of the right-angled triangle, the side $\overline{ON}$ of the right-angled triangle represents the displacement, Y, covered by the actuator along the $-y$-axis. While performing the bending motion with respect to N, the actuator also covered displacement along the $-z$-axis, which resulted in a reduction in length, $L_{reduced}$ from its total length, L_{total}, (see Fig. 3). The side $\overline{OM}$ of the right-angled triangle represents the change in length or new length, L_{new}, determined from the relation; $L_{new} = L_{total} - |L_{reduced}|$. Thus, by applying the trigonometric functions expressed in Eqn. (1) and (2), the θ achieved by each actuator model was calculated against the respective input pressure, as follows:

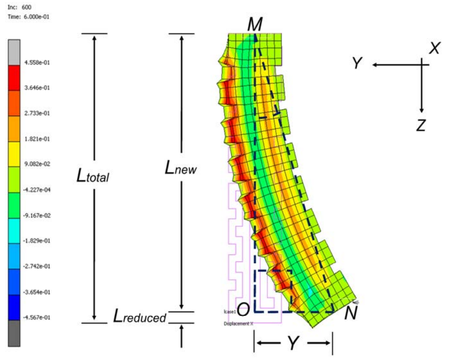


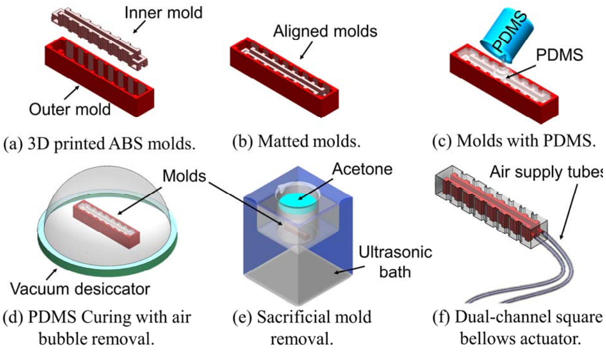
Figure 3: Simulation results of the bellows actuator (Model 2) at 60 kPa pressure.

$$\tan\theta = \frac{Perpendicular}{Base} = \frac{|Y|}{L_{new}} \tag{1}$$

$$\theta = \tan^{-1}\frac{|Y|}{L_{new}} \tag{2}$$

FABRICATION PROCESS

The novel fabrication method adopted for developing the actuator involves the preliminary fabrication of two sacrificial molds. Once the PDMS is cured, the sacrificial molds were dissolved to extract the complex bellows-structured actuator. In this regard, different soluble materials were tested and finally, acetone soluble ABS material was selected for the process. First, the inner and outer sacrificial ABS-based molds were designed (see Fig. 4a) in SolidWorks® software, and then, 3D printed. The actual 3D printed molds are shown in Fig. 5 (a). Both sacrificial molds were aligned, matted and glued (see Fig. 4b). Next, the PDMS (Sylgard® 184 Part-A/B) mixed in 10:1, was poured onto the matted molds (see Fig. 4c). To remove the air bubbles from uncured PDMS, the sacrificial molds were placed in a vacuum desiccator for 40 minutes (see Fig. 4d). Then, the sacrificial molds with PDMS were cured using a hot plate at 90°C. i.e. below the melting temperature of ABS (220°C) for 40 minutes. Once the PDMS was cured, the sacrificial molds were dissolved in acetone using an ultrasonic bath at 45°C for 1 hour (see Fig. 4e). Finally, the actuator was ready for extraction. The developed actuator was rinsed with



(a) 3D printed ABS molds. (b) Matted molds. (c) Molds with PDMS.

(d) PDMS Curing with air bubble removal. (e) Sacrificial mold removal. (f) Dual-channel square bellows actuator.

Figure 4: Fabrication process using sacrificial molding technique.

isopropanol, DI water and dried.

The actuator was sealed from one end, while two silicone tubes were inserted from the other end to connect the actuator with pneumatic supply (see Fig. 4f). The final fabricated actuator is shown in Fig. 5 (b). The developed fabrication technique was followed to fabricate both Models 1 and 2.

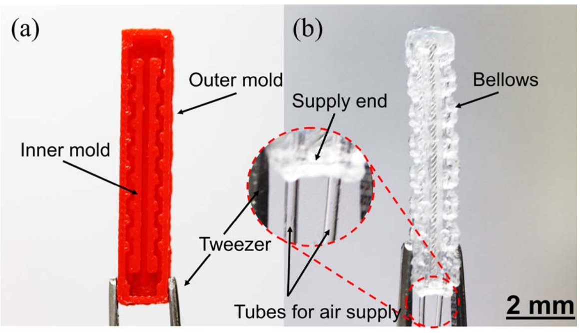


Figure 5: Fabrication results of the bellows actuator; (a) Sacrificial molds. (b) Extracted actuator.

RESULTS AND DISCUSSION

In this section, the discussion focusses on the simulation and experimental results attained by the bellows actuator (Model 1 and Model 2).

Simulation Results

The FEA-based simulation results of both actuator models have revealed that the presence of bellows and PDMS material has imposed strong effects on attaining smooth bending motion at low pressure by the proposed structural design of actuator. The maximum bi-directional θ achieved by the actuator's Models 1 and 2, from individual actuation of its channels was ± 9° and ± 17° at 100 and 65 kPa, respectively, as presented in Fig. 6 and Table 2. The simulation results revealed that both actuator models have shown a uniform and symmetrical behavior in terms of θ along *-yz-axes* with equal and opposite magnitude.

Experimental Setup and Results

To evaluate the performance of each actuator model, the experimental setup shown in Fig. 7 was used. The setup consisted of an air compressor, 24V DC supply to operate the regulator and control valve, and silicone tubes to supply the controlled and regulated pneumatic input from the electric compressor to the actuator. Fig. 7 (b) shows the experimental setup installed for validating the bending performance of the actuator. The θ attained by each model was recorded against a maximum applied pressure up to 100 kPa. At input pressure of 65 kPa, it was observed that Model 2 attained bi-directional θ of -16° and 18° under left and right channel actuations, respectively. While at 100 kPa, Model 2 attained θ of -25° and 35° under left and right channel actuation, respectively, (see Fig. 8), which was higher than Model 1 as tabulated in Table 2.

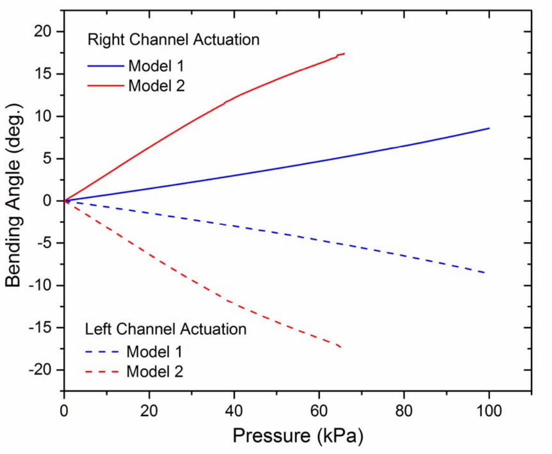
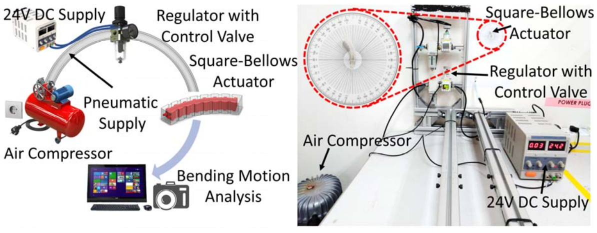


Figure 6: Simulation results of Models 1 and 2.



(a) (b)

Figure 7: Experimental setup; (a) Setup illustration. (b) Actual Setup.

Furthermore, the output bending force attained by Model 2 was also measured experimentally. A high

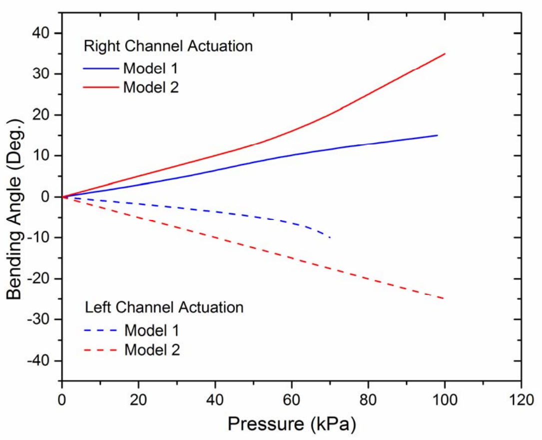


Figure 8: Experimental results of Models 1 and 2.

Table 2: Simulation and experimental results of the Models 1 and 2.

Results	Pressure (kPa)	Bending Angle (θ)			
		Left Channel Actuation		Right Channel Actuation	
		Model 1	Model 2	Model 1	Model 2
Simulation	65	-5°	-17°	5°	17°
	100	-9°	-	9°	-
Experiment	65	-10°	-16°	10°	18°
	100	-	-25°	15°	35°

functionality digital force gauge ZTA-5N (IMADA Co., Ltd Kanowari, Toyohashi, Japan) was used to perform this measurement. From the output bending force resulted from Model 2 (see Fig. 9), it can be observed that the bellows actuator almost followed a proportional relationship against the input pressure. Thus, Model 2 attained a smooth bi-directional bending force up to -0.168 and 0.212 N under left and right channel actuation, respectively, against a maximum pressure up to 100 kPa.

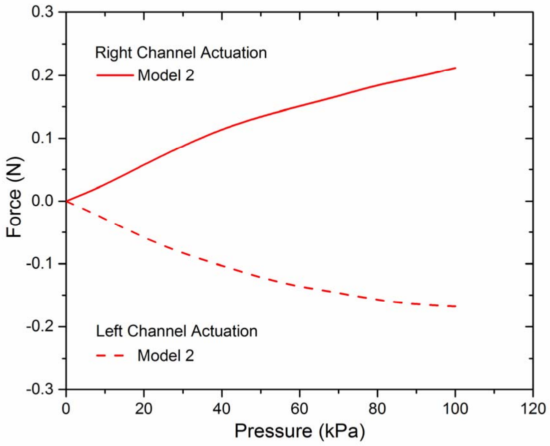


Figure 9: Experimental results for bending force (N).

CONCLUDING REMARKS

In this study, a PDMS-based dual-channel square-bellows pneumatic actuator was developed through novel sacrificial molding technique. In order to understand the effects of volume of air trapped inside the soft actuator on its bending motion, the structural parameters of the actuator were characterized to develop Model 1 ($3 \times 5 \times 27.6$ mm^3) and Model 2 ($5 \times 5 \times 27.6$ mm^3). Indeed, the experimental validation has revealed that Model 2 with greater volume performed better than Model 1. The optimum θ values attained by Model 2 i.e. -25° and 35° with force of -0.168 and 0.212 N under left and right channel actuation respectively, have made it suitable candidate to be deployed in developing flexible medical tools. Hence, the state-of-the-art bellows actuator developed through proposed fabrication technique would enable the fabrication of more complex soft actuator designs. The future direction of this research will mainly focus on further miniaturization of bellows structured soft actuator using standard photo-lithography technique.

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REFERENCES

[1] Cuschieri, A., "Whither minimal access surgery: tribulations and expectations", *Am. J. Surg.*, vol.169, pp. 9-19, 1995.

[2] Hirose, S., *Biologically inspired robots: snake-like locomotors and manipulators*, Oxford University Press, 1993.

[3] Otsuka, K., & Kakeshita, T., "Science and technology of shape-memory alloys: new developments", *MRS Bulletin*, vol. 27, pp. 91-100, 2002.

[4] AbuZaiter, A., Nafea, M., Faudzi, A. A. M., Kazi, S., & Ali, M. S. M., "Thermomechanical behavior of bulk NiTi shape-memory-alloy microactuators based on bimorph actuation", *Microsyst. Technol.,* vol. 22, pp. 2125-2131, 2016.

[5] AbuZaiter, A., Nafea, M., & Ali, M. S. M., "Development of a shape-memory-alloy micromanipulator based on integrated bimorph microactuators", *Mechatronics*, vol. 38, pp.6-28, 2016.

[6] Trivedi, D., Rahn, C. D., Kier, W. M., & Walker, I. D., "Soft robotics: Biological inspiration, state of the art, and future research", *Appl. Bionics Biomech.*, vol. 5, pp. 99-117, 2008.

[7] Yoshioka, R., "Development of pneumatic rubber actuator of 400μm in diameter generating bi-directional bending motion", in *Robot. Biomim. IEEE Conference,* Bali, Dec 5-10, 2014, pp. 1-6.

[8] Rus, D., & Tolley, M. T., "Design, fabrication and control of soft robots", *Nature*, vol. 521, pp. 467-475, 2015.

[9] Surakusumah, R. F., "Development of a half sphere bending soft actuator for flexible bronchoscope movement", in *Robot. Manuf. Autom. IEEE Symposium*, Kuala Lumpur, Dec 15-16, 2014, pp. 120-125.

[10] Wakimoto, S., "Development of large intestine endoscope changing its stiffness", in *Robot. Biomim. IEEE Conference*, Guilin, Dec 19-23, 2009, pp. 2320-2325.

[11] Rehman, T., Faudzi, A. A. M., Dewi, D. E. O., & Ali, M. S. M., "Design, characterization, and manufacturing of circular bellows pneumatic soft actuator", *Int. J. Adv. Manuf. Technol.*, vol. 93, pp. 4295-4304, 2017.

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