New structure of pneumatic networks actuators for soft robotics

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Abstract: Pneumatic actuators (referred to as pneu-nets) are drawing increasing attention due to their high customisability, ease of fabrication and innate softness. The actuator’s ability to bend is one of the important parameters characterising its performance and related to its structure. Some structures are developed. In this work, a new structure (NS) pneu-nets is developed, and its bending ability is compared with the currently common Mosadegh pneu-nets structure (developed by Mosadegh). These two are analysed in two aspects: the trajectories of the pneu-nets actuator’s tip, and the defined angle of bending. The results indicate that the NS pneu-nets actuators are able to achieve greater bending at higher pressures and can be lightweight. These pneumatic actuators provide improved structure for soft robotics.

1 Introduction

A robot can be classified as hard or soft by its underlying materials. Rus and Michael defined soft robots as systems which are capable of autonomous behaviour with a range of biological materials [1], and ‘soft’ refers to the outer structure of the robot. The materials used for soft robot fabrication include polymers [2, 3], elastomers [4], hydrogels [5, 6], and granules [7]. The model of actuation is another key factor for a soft robot, such as pneumatic [8, 9], electrical [10], or chemical [11].

The structure of soft robots is composed of soft materials or/and actuators which can either become part of the structure, such as electro-active-polymer, or be located externally to the structure, such as cable-driven robots. Degrees of freedom of a soft robot hinges on the actuators [12]. One of the active research areas in soft robotics is soft actuators [13]. Li et al. believe soft actuators should be one of the key determinants for walking assistance for daily life [14]. Soft actuators actuated by pneumatic power obtain particular interest because pressurised air has a lot of advantages (lightweight, inexpensive, easily fabricated, non-linear motion with simple inputs, and simple control) [15, 16]. Pneu-nets are developed by the Whitesides Research Group at Harvard, and Sun et al. created two measurement setups to characterise actuators of pneu-nets, analysed the measured force/torque outputs and the step responses to certain pressure input of pneu-nets [17]. By using embedded pneu-nets, Ilievski et al. demonstrated a new design that provides a range of behaviours and a test bed for new materials [4], and Shephers et al. demonstrated a new design for soft tentacles based on micropneumatic networks [19].

In the related literature, bending ability of the actuators is one of important parameters characterising performance. For example, Polygerinos et al. used a soft actuator with integrated channels that function as pneu-nets to produce bending motions conforming with the human finger motion [20]. Mosadegh et al. demonstrated that more chambers for a given length and thinner inside walls enabled greater bending at lower pressures [15].

We also note that bending ability of the actuators is influenced by the design parameters of the pneu-nets structure and the material properties of their walls [21, 22]. Mosadegh et al. focus on the effect of varying actuator geometries, such as the wall thickness, the number of chambers and height, on the pressure required to achieve bending [15]. Nishioka et al. proposed a pleated structure made of plastic to achieve structural deformation [23]. This paper developed a new structure (NS) of pneu-nets (adjusting chamber’s morphology), based on the pneu-nets architecture described previously. The pneu-nets actuators with the new chamber can easily generate large bending at the higher air pressures. Furthermore, the mass of the entire actuator can be reduced.

2 Design of pneu-nets actuators

In terms of the structure of pneu-nets, based on sPN structure (the extensible layer that contains chambers connected by a single channel), Mosadegh et al. designed the fPN structure (the extensible layer that contains gaps between the inside walls of each chamber, Fig. 1 – top). In the paper, an NS of pneu-nets actuators is proposed that is based on the pneu-net principle of operation. The NS of pneu-nets actuators has a different shape of the chambers compared with the literature [4]. As presented in the literature [20] (the Mosadegh structure, MS), this new pneu-NS consists of two parts: an inextensible base layer composed of a piece of paper embedded in elastomer, and the main body which expands when inflated (Fig. 1 – top). However, the two structures have different chamber morphology. The left and right walls of the NS’s chambers have a curved surface, the left and right inside walls of the MS’s chambers are flat (Fig. 1 – bottom).

In this paper, we will make an actuator with 11 chambers (\(t = 11\)). Each chamber is 8 mm long, 15 mm high, and 15 mm wide.

3 Finite elements method

The output behaviours of the NS and MS pneu-nets actuators are geometrically predicted and analysed by finite element modeling (FEM) methods. This is convenient to observe and not too difficult to analyse the output behaviours of the NS pneu-nets actuators instead of refabricating and restesting the actuator every time the radius of curvature of the right and left walls’ curved surface is changed. It makes it easier to compare the two constructs. FEM is often used in robots design. In this paper, a second-order hyperelastic mathematical model was used to describe the extension and compression phases of the material with coefficients \(C_1 = 0.11, C_2 = 0.02, \) density \(D = 1130\) kg/m\(^3\) and assumed isotropic, and Elastosil M4601 Silicone rubber was chose. Moreover, the response of paper was captured with Young's modulus of 6.5 GPa, Poisson's ratio of 0.2 and density of 750 kg/m\(^3\). A more materials and parameters set requirements can be found in the literature [20]. The bending shape response of the
two structure simulated soft pneu-nets actuator was shown in Fig. 2.

Fig. 3 indicates the trajectories of the MS and NS pneu-nets actuators tip measured with FEM. The trajectory of the free end of the two actuators is tracked and plotted them using a graph that allowed comparison of the positions of NS pneu-nets actuators and MS pneu-nets actuators by the FEM.

Fig. 1 Top: Front view of the ‘PneuNets’ soft actuator. Bottom: Cross-sectional views of the chambers: \( r \) the radius of curvature of the right and left curved surface walls of the NS

Fig. 2 Bending shape response for the soft pneu-nets actuator (a) MS, and (b) NS \( r = 0.03 \text{ m} \) at same pressures (30 MPa)

Owing to gravity of the pneu-nets actuators sag, the trajectory’s initial position points (the pressure is equal 0 kPa) start at lower points than \((0, 0)\). The gravity of the MS pneu-nets actuator is greater than the NS actuator, so the initial position point of MS pneu-nets actuators is lower than the initial position point of NS pneu-nets actuators. On the other hand, with the increase of the radius of curvature \( r \), the gravity of MS pneu-nets actuators increases, so NS pneu-nets actuators with the lowest radius of curvature reach the highest initial position point.

4 Trajectory of the tip

Fig. 3 indicates the trajectories of the MS and NS pneu-nets actuators tip measured with FEM. The trajectory of the free end of the two actuators is tracked and plotted them using a graph that allowed comparison of the positions of NS pneu-nets actuators and MS pneu-nets actuators by the FEM.
At the lower air pressures, the trajectories of these pneu-nets actuators are basically equal. With the increase of air pressures, however they are obviously different. It is found that the NS pneu-nets actuators bend to a larger degree than MS pneu-nets actuators, and NS pneu-nets actuators with the lower radius of curvature enabled greater bending than the ones with the higher radius of curvature at the same pressures. Notably, the bending abilities in the $X$ and $Y$ directions are different.

Fig. 4 shows the results of applying 0, 10, 20 and 30 kPa of air pressures to MS pneu-nets actuators and NS pneu-nets actuators, respectively ($r=0.03, 0.04$ and 0.05 m). Fig. 4a indicates displacement of the tip of each actuator in the $X$ direction, and Fig. 4b is in the $Y$ direction. Compared with the MS pneu-nets actuator, the NS pneu-nets actuators largely bend in both the $X$ direction and the $Y$ direction at higher pressures. Radius of curvatures play a key role for NS pneu-nets actuators in bending response to pressure where the lower radius of curvatures was most sensitive.

Fig. 5 demonstrates the average rate of change of NS and MS pneu-nets actuators in the $X$ direction and the $Y$ direction. For example, in terms of the $X$ direction, the average rate of change is the slope of the line which passes through two sets of points $(P_{i-1}, X_{i-1})$ and $(P_i, X_i)$, where $P_i$ represents pressures and $X_i$ is the displacement value in the $X$ direction at the $i$th measurement occasion. The change in $X_i$ divided by the change in pressures $W_X$ is the absolute value of the slope of the line connecting two points

$$W_X = \left| \frac{X_i - X_{i-1}}{P_i - P_{i-1}} \right| \quad (1)$$

Similarly, the change in $Y_i$ divided by the change in pressures $W_Y$ is the absolute value of the slope of the line connecting two points

$$W_Y = \left| \frac{Y_i - Y_{i-1}}{P_i - P_{i-1}} \right| \quad (2)$$

where, $n$ represents the number of measurement $i = 1, 2, 3, \ldots, n$.

From Fig. 5, it is confirmed that the average rate of change of NS and MS pneu-nets actuators largely change in the $X$ direction, however the change in the $Y$ direction is not so large. The NS pneu-nets actuators with lower radii of curvature show greater average rate of change with a higher change in pressures. For example, the average rates of change from the 0.03 m radius of curvature are always greater than the average rate of change from the 0.05 m radius of curvature from 20 to 30 kPa.

5 Angle of bending

To analyse the bending performance, a new parameter (the angle of bending $\theta$) was developed in this paper. The angle of bending was defined as the angle between the horizontal line ($X$-axis) and the line $DT$ (in Fig. 6).

According to the geometric relationship, the angle of bending $\theta$ can be obtained by the following equation:

$$\theta = \arctan\left( \frac{Y}{X} \right)$$

where $X$ and $Y$ are the displacements in the $X$ and $Y$ directions, respectively.
\[ \theta = \begin{cases} \arccot \left( \frac{112 - x}{y} \right) & (x < 112) \\ \frac{\pi}{2} & (x = 112) \\ \frac{\pi}{2} + \arccot \left( \frac{x - 112}{y} \right) & (x > 112) \end{cases} \] (3)

Fig. 7 indicates the angle of bending of the MS and NS pneu-nets actuators’ tips measured with FEM. The angle of bending of both the MS and NS pneu-nets actuators are approximately equal at the lower pressures. It is obvious that increasing the air pressures increases the angle of bending, and the angle of bending of MS pneu-nets actuators is larger than the angle of bending of NS pneu-nets actuators with increasing air pressures. The radius of curvature of NS pneu-nets actuators also affects the angle of bending where there is a decrease in radius of curvature correlated to an increase in the angle at a given pressure. For example, the NS pneu-nets actuator with 0.03 m radius of curvature reaches maximal deformation with 44.63 kPa at this pressure, whereas the MS pneu-nets actuator deflects only 119.22°. (The maximal deformation is the state in which both end tips of the actuator are attached each other.)

As described previously, the initial position point of MS pneu-nets actuators is lower than the initial position point of NS pneu-nets actuators. Therefore, at the initial position, the angle of bending of MS pneu-nets actuators is greater than the angle of bending of NS pneu-nets actuators.

6 Conclusions

In this paper, an NS pneu-nets actuator consisting of a larger bend at higher air pressures was developed. The bending ability between the MS pneu-nets actuators and the MS pneu-nets actuators is analysed from two aspects. These are the trajectories of the MS and NS pneu-nets actuators' tip and the angle of bending. It found that the NS pneu-nets actuators bend basically the same as MS pneu-nets actuators at lower air pressure, but larger than MS pneu-nets actuators at higher air pressure (The role of gravity is greater than the role of air pressure).

Decreasing radius of curvature of the right and left inside walls of MS pneu-net's chambers thins the right and left inside walls. Empirically, the chambers with thinner inside walls enabled greater bending at given air pressures [15]. So, on the one hand, the bending performance of MS pneu-nets actuators increases with a decreased radius of curvature. On the other hand, the mass of pneu-nets actuators decreases with a decreased radius of curvature. The kinetic energy when it contacts with humans mechanically can be reduced considerably [23]. Compared with the MS pneu-nets actuators, the NS pneu-nets actuators can be lightweight and inexpensive.

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8 References

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