The bending control of the soft pneumatic finger

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Abstract. A soft finger is derived from the multi-chambers structure of PneuNets actuators. It includes the top extensible layer with ten pleated chambers and the bottom constraint layer. This soft finger is made of the same silicone rubber material, and the thickness of the bottom layer was increased to replace the hard material as the constraint layer. A model between the bending degree of the soft finger and input pneumatic pressure is constructed to describe the bending characteristics. And the finite element method is utilized to analyze the behaviors of the soft finger. It can be seen that the bending angle will fluctuate with the fluctuation of the input pneumatic pressure. The purpose of the bending control is to reduce the pressure fluctuations in the inner cavity of the soft finger through the control strategy. The bending control is realized by PID, PI, nonlinear PID, and PID based on the endocrine system (ES-PID). Compared to other algorithms, the ES-PID controller can improve the positioning accuracy and better adjust the pressure fluctuations in the inner cavity of the soft finger.

1. Introduction

The soft robot has many advantages, such as innate softness, being easily fabricated, inexpensive and lightweight. The soft robot has great potential to adapt to unstructured environments because of its high flexibility, which is appropriate for gripping and holding delicate and fragile objects. According to these existing articles, the grasping principle of soft robotic gripper can be classified into three categories: i) actuation, ii) controlled stiffness[1, 2], iii) adhesion[1, 3]. The properties of the operated object will affect the actuated method, sensor placement, integration, and control methods[1]. Several typical soft grippers actuated by pneumatic actuators have been designed and fabricated. A soft gripper built by Harvard University is actuated by the pneumatic actuators with six fingers, which are inspired from the structure of starfish[4]. And this structure of the soft gripper embedded a series of chambers that can hold fragile objects like a human hand[5]. Other researchers design a soft composite finger with adjustable joint stiffness[6]. A soft robotic gripper combined pneumatic actuator and gecko-inspired adhesives can not only realize the grasping function of existing soft gripper properties but also generate new capabilities[7]. Under pneumatic actuation, the soft PneuNets actuator with oblique chambers can realize bending and twisting motion to grasp some objects of different shapes[8]. Until now, the pneumatic actuation is the most common form of the soft actuator to realize the large movement and high power density.

The majority of these existing pieces of literature currently focused on the development of soft material, structural design and modeling of the soft robot. The more important point is that pressure fluctuations in the inner cavity of the soft robot seriously affect the deformation accuracy. Now, most
studies focus on the deformation of soft robots, but less on the pressure fluctuation in the inner cavity of the soft robot. In this paper, the deformation of a soft finger is studied by using different control algorithms, and the pressure fluctuations in the inner cavity are compared with each algorithm.

In the following sections, the structure design of the soft finger is shown in Section 1. Then, Section 2 describes the bending model of a soft finger based on the PneuNets actuator. The finite element method using ABAQUS software is utilized to analyze the deformation of the soft finger in Section 3. Next, several experiments are performed to test the bending performance based on different control strategies. At last, a conclusion is presented in Section 5.

2. The Structure Design of Soft Finger
The design of the soft finger is inspired from the multi-chambers type of PneuNets actuators\(^\text{[9]}\). The typical bending PneuNets actuator is composed of two parts: extensible layer and inextensible layer (or called constraint layer)\(^\text{[10]}\). The chamber of a soft pneumatic actuator with a semicircular cross-section can optimally achieve smaller radial expansion, and also increase axial elongation and reduce radial expansion\(^\text{[11]}\). Our design is based on the same material, and those relevant parameters are modified to achieve the corresponding deformation performance.

From the cross-section view shown in Figure 1, \(h_1\) is the height of a single chamber, \(d\) is the axial thickness of one chamber, \(t_p\) is the wall thickness of the chamber, and \(d_1\) denotes the distance between adjacent chambers. \(t\) is the thickness of the bottom layer, and \(h_2\) is the height of the air channel. The bottom layer is set as the harder extension layer by increasing the thickness of the bottom layer. For the proposed soft finger, the thickness of the bottom layer was increased to replace the hard material as the inextensible layer.

![Figure 1. The detailed parameters of the single soft finger.](image)

3. Bending Mathematical Model of the Soft Finger
According to the Euler-Bernoulli law, the curvature radius is obtained from the equation as

\[
\frac{M}{EI} = \frac{1}{R}
\]

where \(M\) is the bending moment generated by pneumatic pressure, \(E\) is Young's modulus, \(I\) is the moment of inertia. \(R\) is the curvature radius of the soft actuator.

The relationship between the curvature radius and the bending angle is described as

\[
\frac{1}{R} = \frac{\theta}{L}
\]

where \(\theta\) is the bending angle of this soft finger. \(L\) is the axial length of the curved part.

The bending torque is shown as

\[
M_i = PA_i e_i
\]

where \(P\) is the pneumatic pressure, \(A_i\) is the inner area of the chamber, \(e_i\) is the effective distance between the centroid of the cavity and the neutral axis.

According to the equation (1)-(3), the bending angle is the function of the bending moment.

\[
\theta = \frac{M_i L}{EI}
\]

This soft actuator can be divided into multiple submodules. One submodule contains two parts:
one big chamber and one small chamber as described in Figure 2. For one submodule, \( L_i \) (including the length of big chamber-\( L_1 \) and the length of small chamber-\( L_2 \)) is the length of the chamber.

\[
L_i = d_i, \quad L_1 = d_i \tag{5}
\]

The area of the big or small chamber, respectively, is presented as

\[
A_i = \frac{\pi h_i^2}{2}, \quad A_s = \frac{\pi h_s^2}{2} \tag{6}
\]

where \( A_i \) and \( A_s \) are the inner area of the big and the inner area of the small chamber, respectively. \( h_i \) is the inner radius of the big chamber, and \( h_s \) is the inner radius of the small chamber.

Assume that the centerline of the constraint layer is the neutral axis. The effective distance between the centroid of the cavity and the neutral axis can be expressed as

\[
e_i = \frac{2h_i}{\pi} + \frac{t}{2}, \quad e_s = \frac{2h_s}{\pi} + \frac{t}{2} \tag{7}
\]

where \( t \) is the thickness of the constraint layer. \( e_i \) and \( e_s \), respectively, denote the effective distance between the centroid of the big and small chamber and the neutral axis.

So the bending angle of one submodule is calculated as

\[
\theta_i = \theta_1 + \theta_2 = \frac{A_i(t + \frac{2h_i}{\pi})d_1}{EI_1} + \frac{A_s(t + \frac{2h_s}{\pi})d_1}{EI_2} \left[ \frac{\pi h_i^2(t + \frac{2h_i}{\pi})}{2} + \frac{\pi h_s^2(t + \frac{2h_s}{\pi})}{2} \right] \tag{8}
\]

where \( \theta_i \) is the bending angle of one submodule, \( \theta_1 \) is the bending angle of the big chamber, and \( \theta_2 \) is the bending angle of the small chamber.

\[
\theta = N \times \theta_i \tag{9}
\]

where \( \theta \) is the bending angle of the soft finger, and \( N \) denotes the number of these submodules. The parameters of the soft actuator, such as the thickness of the wall, the height of PneuNets, and the number of PneuNets, will seriously affect the bending curvature and force performance.

4. The Analysis based on Finite Element Method

The finite element method (FEM), analyzing the output behaviors of the soft actuator, is often utilized in designing and analyzing robot systems. The silicone rubber (Ecoflex 30) is chosen for the fabrication material of soft fingers. This model of the soft finger was analyzed by ABAQUS (CAE software) to detail the behavior of the soft actuator under different pressure inputs.

The hyperelastic material Yeoh mathematical model is introduced to demonstrate the nonlinear stress-strain behavior of the soft finger. Its strain potential energy \( E_a \) based on the typical second-order Yeoh mathematical model is presented as

\[
E_a = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 \tag{10}
\]

where these coefficients \( (C_{10}, C_{20}) \) of the silicone rubber are used to describe the extension and compression performance. And \( I_1 \) is the three invariants of the Green deformation tensor. These coefficients \( (C_{10}, C_{20}) \) of Ecoflex30 silicone rubber are set to 0.11 and 0.02, respectively.

The finite element analysis of this soft finger is performed by using pneumatic pressure input. The bending shape response of this soft finger is presented in Figure 2. The deformation mechanism of this soft finger is described by the different pneumatic pressure inputs. The results demonstrate that the bending degree increased with the pressure input increasing.

The flex-sensor attached to the bottom layer of the soft finger records the data of the bending degree, and a force gauge is connected with the fingertip of this finger. These experimental results are shown in Figure 3. It can be seen from this figure that the relationship between bending degree and the input pneumatic pressure changes gently at the beginning of bending deformation. The adjacent chamber contact has a significant effect on bending performance as the input air pressure increases.
But there is a difference between the simulation and the actual output of bending deformation. The reasons for the difference between simulation and experiment are as follows: i). during the fabrication of the soft finger, the thickness of the top layer of the soft finger is not completely the same, but slightly different due to the narrow gap of these chambers and poor fluidity of silicone rubber material. ii). the flex-sensor placement of the constraint layer and the stiffness of the flex-sensor will also affect the deformation in the actual experiment. iii) the deformation of the soft finger during the experiment was not at a constant rate under applied pressure.

Figure 3. The variation trend with different pneumatic pressure input: (a): bending degree; (b) force.

5. Experiments
To test the performance of the soft finger, the relevant experimental setup is built in this paper, as shown in Figure 4. The proportional valve (SMC, ITV0050-3BS) is utilized to control the flow of the pneumatic supply. The air pressure sensor (CFsensor Ltd, XGZP6847, 0-40kpa) feeds the measured signal (the pneumatic pressure of the inner cavity) back to the control panel (Arduino Mega 2560 board). And the flex-sensor (4.5”, spectra symbol) is measured the actual bending angle for the soft finger. The generated force of the soft finger is measured by using a push-pull gauge (push-pull gauge HP-50; Yueqing Handpi Instruments Co., Ltd).
5.1. PID control of soft finger

To improve the bending performance of the soft finger, a PID controller is utilized to tune the PWM output voltage. This PWM output voltage is used to operate the SMC valve. The pressure sensor can measure the internal air pressure of the soft finger. When the air pressure feedback by the pressure sensor is larger than the set threshold, the PID control will fail, or vice versa. The threshold is set to prevent the soft finger from expanding too much and becoming damaged. The set threshold is set as 20kpa. The PID controller is implemented on Arduino Mega 2560 board with Matlab Simulink.

\[
V = T \left( k_1 e(t) + k_2 \int e(t) dt + k_3 \frac{de(t)}{dt} \right)
\]

where \( V \) is the PWM output voltage, \( e(t) \) is the bending error, \( T \) is the power factor of the PID controller. Since the soft robot is easily damaged when the air pressure is too high, the existence of \( T \) can prevent the input air pressure from being too high and thus play a protective role.

The bending response and pneumatic pressure of the soft finger are shown in Figure 5. The control parameters of PI control are \( P=10, I=0.5 \). But the control parameters of PID control are \( P=10, I=0.5, D=0.1 \). From the description of this figure, the differential item of the PID controller has a great influence on the soft system. So the PI control is more suitable than the PID control for bending control of the soft finger.

5.2. ES-PID control of soft finger

To improve the positioning accuracy, a nonlinear PID control was used to operate the soft finger. The nonlinear PID control in this paper is inspired from the active disturbance rejection control (ADRC)[14]. The parameters of nonlinear PID were regulated through error signal \( e(t) \). The nonlinear PID parameters are described in Table 1.
\[ f_{al}(e, \alpha, \delta) = \begin{cases} |e| \text{sgn}(e) & |e| > \delta \\ \frac{e}{\delta} & |e| \leq \delta \end{cases}, \quad \delta > 0 \]

\[ U = \beta \ast f_{al}(e, \alpha, \delta) + \beta \ast f_{al}(e, \alpha, \delta) + \beta \ast f_{al}(e, \alpha, \delta) \]

(12)

Table 1. The parameters of nonlinear PID.

| parameter | \( \alpha_0 \) | \( \alpha_1 \) | \( \alpha_2 \) | \( \beta_0 \) | \( \beta_1 \) | \( \beta_2 \) | \( \delta \) |
|-----------|---------------|---------------|---------------|-------------|-------------|-------------|--------|
| value     | 1             | 0.9           | 0.01          | 0.5         | 80          | 0.1         | 5      |

To further improve the pressure fluctuation of the soft finger, the real-time control parameters were realized by using the hormonal regulation method of the endocrine system\textsuperscript{[15]} through error signal \( e(t) \). The endocrine system (ES) uses correction factor to adjust the control parameters\textsuperscript{[15-16]}. The correction factor is described as

\[ S_i = \frac{|e(t)|}{|e(t)| + \alpha_i} + \beta_i \]

(13)

This article introduces this correction factor of endocrine system to adjust PID control parameters. The schematic of the ES-PID control strategy is shown in figure 6.

Figure 6. The schematic of the ES-PID control strategy

The PID controller based on the endocrine system (ES-PID) based on variable structure control is presented as

\[ V = k(e(t)) \ast e(t) + k(e(t)) \ast \int e(t) dt + k(e(t)) \ast \frac{de(t)}{dt} \]

\[ k(e(t)) = \begin{cases} 500 & e > 5 \\ 60 \ast S & e \leq 5 \end{cases} \]

\[ k(e(t)) = \begin{cases} 100 & e > 5 \\ 200 / S & e \leq 5 \end{cases} \]

\[ k(e(t)) = \begin{cases} 0.005 & e > 5 \\ 0.005 \ast S & e \leq 5 \end{cases} \]

(14)

Figure 7 and figure 8 present the experimental result of the ES-PID control. Compared to the PI control, the nonlinear PID control can improve the positioning accuracy, and also reduce the fluctuation of pneumatic pressure of the soft finger. However, the adjustment calculation of nonlinear PID control is more cumbersome, and the experimental effect can be further improved. It can be observed that the positioning accuracy can realize great improvement by using the ES-PID control. It can be seen from these figures that the experimental results of ES-PID have obvious advantages compared to the other two control algorithms. The most important thing is: under ES-PID controller, the pressure fluctuation inside the soft finger is the smallest, which leads to the highest accuracy of the steady-state process of bending deformation.
Figure 7. The 25° experimental results: (a) bending response; (b) pneumatic pressure fluctuation.

Figure 8. The 30° experimental results: (a) bending response; (b) pneumatic pressure fluctuation.

6. Conclusions
A soft finger based on the multi-chambers type of PneuNets actuator is designed to realize a large bending deformation. The soft finger consists of two parts: the top extensible layer of ten pleated chambers and the bottom constraint layer. To analyze the behaviors of a soft finger, the finite element method is utilized to simulate the relationship between the bending deformation and pneumatic pressure input. In addition to the fact that the structure parameters have a greater impact on the bending deformation, the input pneumatic pressure is more intuitive for the deformation of the soft finger. Reducing the pneumatic pressure fluctuation can improve the bending accuracy. The flex-sensor is used to record the actual bending angle for the soft finger in the actual experiment, and the pressure sensor can measure the pneumatic pressure of the inner cavity of the soft finger. Several control algorithms, such as PI, PID, nonlinear PID, and ES-PID, are applied to the soft finger. In these controllers, ES-PID controller has the best effect. It obviously reduces the pressure fluctuation of the inner cavity of the soft finger, and better adjusts the steady-state accuracy of bending deformation.

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