Research on Pneumatic Muscle Position Control Based on Adaptive Backstepping Sliding Mode

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Abstract. Aiming at the nonlinearity and uncertainty of pneumatic muscles, an adaptive backstepping sliding mode control method is proposed. Using the three-element model of pneumatic muscles, an adaptive backstepping sliding mode controller for pneumatic muscles is designed, which is proved by Lyapunov theory. For the stability of the system, a simulation test platform is built in MATLAB. The simulation results show that the designed controller has fast convergence speed and strong robustness.

1. Introduction
Pneumatic muscle is a new type of pneumatic actuator. Compared with traditional actuators such as motors, it has the advantages of simple structure, small size, high safety, high power/weight ratio, and natural flexibility [1]. The MAS type pneumatic muscle produced by FESTO is shown in Figure 1. It is mainly composed of an inner rubber tube and an outer fiber layer. When inflated, the pneumatic muscle will contract along the axial direction and expand radially. When the gas in the pneumatic muscle cavity is gradually released, the pneumatic muscle returns to its original state under the action of the elasticity of the diaphragm.

Figure1. FESTO's MAS model pneumatic muscle

Pneumatic muscles are widely used in robotics systems, bionic equipment and other fields due to their many advantages. However, due to the strong nonlinearity of pneumatic muscles, it is difficult to achieve good performance of pneumatic muscles in different working environments if traditional control methods are used. For the position control of pneumatic muscles, researchers at home and
abroad have proposed a variety of control methods. Bao Chunlei and others reduced the PID feedback cycle and used Singmoid as the gain function to solve the disadvantages of slow neuron PID contraction speed and low control accuracy[2]. Repperger et al. tried methods such as adaptive backstepping control and sliding mode control, and pointed out that ordinary backstepping control methods have poor control effects, while adaptive backstepping control and sliding mode control can achieve satisfactory control effects[3-5]. Hesselroth[6] and others used neural networks to control pneumatic muscles, and after offline training, good tracking performance can be achieved. K.Osuka[7] linearized the pneumatic muscle model and used $H\infty$ theory to design the controller. Cai and Yamaura[8] used sliding mode control theory to design the pneumatic muscle controller.

Aiming at the nonlinearity and uncertainty of aerodynamic muscles, this paper designs an adaptive backstepping sliding mode controller based on the three-element model proposed by Reynolds. The ordinary backstepping control method has poor control effect and combines it with sliding mode control. The use range of backstepping control is increased, and adaptive control methods are added to estimate and compensate for the uncertainty of the model to ensure the accuracy of pneumatic muscle position control.

2. Design of adaptive backstepping sliding mode controller

The controller is designed based on the three-element model of pneumatic muscles. The model is a phenomenological model proposed by Reynolds. It is composed of spring, damping and contraction elements in parallel, and its expression is as follows:

$$M\ddot{x} + B(P)\dot{x} + k(P)x = F(P) - Mg$$  \hspace{1cm} (1)

$$K(P) = K_0 + K_1P$$  \hspace{1cm} (2)

$$B(P) = B_{0i} + B_{1i}P$$ \hspace{1cm} (3) \hspace{1cm} (shrink)

$$B(P) = B_{0d} + B_{1d}P$$ \hspace{1cm} (4) \hspace{1cm} (elongation)

$$F(P) = F_0 + F_1P$$  \hspace{1cm} (5)

Among them, M is the load mass; g is the acceleration of gravity; x=0 corresponds to the initial state of the pneumatic muscles fully extended without external force; P represents the internal pressure of the pneumatic muscles. K(P) and B(P) represent the spring coefficient and damping coefficient, respectively, and F(P) is the effective force provided by the contraction unit. According to the literature[9], the coefficients in the pneumatic muscle model are obtained, as shown in Table 1:

| Parameter | Value |
|-----------|-------|
| $F_0(\times 10^2)$ | 1.79 |
| $F_1$ | 1.39 |
| $k_0$ | 5.71 |
| $K_1(\times 10^{-2})$ | 3.07 |
| $B_{0i}$ | 1.01 |
| $B_{1i}(\times 10^{-3})$ | 6.91 |
| $B_{0d}(\times 10^{-1})$ | 6.00 |
| $B_{1d}(\times 10^{-4})$ | -8.03 |

Accurate modeling is the basis for achieving good control, but it is difficult to achieve accurate modeling of nonlinear and hysteretic systems. The uncertainty of the system model is compensated on the basis of the three-element model of pneumatic muscle. The model is as in formula (6):

$$\ddot{x} = f(x, \dot{x}) + b(x, \dot{x})P$$  \hspace{1cm} (6)

In (6):
\[ f(x, \dot{x}) = \frac{1}{M}(F_0 - Mg - B_0 \dot{x} - K_0 x) \]  \tag{7}

\[ b(x, \dot{x}) = \frac{1}{M}(F_1 - B_1 \dot{x} - K_1 x) \]  \tag{8}

Taking into account the uncertainty of the model, \( f \) and \( b \) in the expression are estimated values, and these uncertain factors and interference are unified into \( d(t) \). The model can be written as (9):

\[ \dot{x} = f + \Delta f + bP + \Delta bP + d_0(t) \]  \tag{9}

\( \Delta f \) and \( \Delta b \) are the uncertainty of the model, and \( d_0(t) \) is the disturbance. The final model can be written as equation (10):

\[ \dot{x} = f + bP + d \]  \tag{10}

Where \( d = \Delta f + \Delta bP + d_0(t) \), \( d \) represents the system’s unmodeled dynamics, parameter uncertainty and external disturbance synthesis, and \( d \leq |D| \).

2.1. Controller derivation and stability proof

The pneumatic muscle model is a second-order nonlinear system, which can be written as equation (11).

\[
\begin{aligned}
\left\{ \\
\dot{x}_1 &= x_2 \\
x_2 &= f + bp + d
\end{aligned}
\]  \tag{11}

Take tracking error:

\[ z_1 = x_1 - x_d \]  \tag{12}

Define the Lyapunov function:

\[ V_1 = \frac{1}{2} z_1^2 \]  \tag{13}

Then:

\[ \dot{V}_1 = z_1 \dot{z}_1 = z_1(x_2 - \dot{x}_d) \]  \tag{14}

Virtual control volume:

\[ x_{2v} = \dot{x}_d - c_1 z_1 \]  \tag{15}

Where \( c_1 \) is a positive constant.

Status error:

\[ z_2 = x_2 - x_{2v} \]  \tag{16}

When \( z_2 \to 0, V_1 = -c_1 z_1^2 \), we can get \( z_1 \to 0 \), and finally make \( x_1 \to x_d \).

Define the sliding surface

\[ s = c_2 z_1 + z_2 \]  \tag{17}

Since:

\[ \dot{z}_1 = x_2 - \dot{x}_d = z_2 + x_{2v} - \dot{x}_d = z_2 + \dot{x}_d - c_1 z_1 - \dot{x}_d = z_2 - c_1 z_1 \]  \tag{18}

So:

\[ s = c_2 z_1 + z_2 = c_2 z_1 + \dot{z}_1 + c_1 z_1 = (c_1 + c_2)z_1 + \dot{z}_1 \]  \tag{19}

Since \( c_1 > 0, c_2 > 0 \), if \( s = 0 \), then \( \dot{z}_1 = -(c_1 + c_2)z_1 \), we can find \( z_1 \to 0, z_2 \to 0 \).

Proceed to the next design:

\[ V_2 = V_1 + \frac{1}{2} s^2 \]  \tag{20}

Then:

\[ \dot{V}_2 = \dot{V}_1 + s \dot{s} = z_1 \dot{z}_2 - c_1 \dot{z}_1^2 + s(c_2 \dot{z}_1 + \dot{z}_2) \]
\[ = z_1 z_2 - c_1 \dot{z}_1^2 + s(c_2(z_2 - c_1 z_1) + \dot{x}_2 - \dot{x}_d + c_1 \dot{z}_1) \]
\[ = z_1 z_2 - c_1 \dot{z}_1^2 + s(c_2(z_2 - c_1 z_1) + f + bp + d - \dot{x}_d + c_1 \dot{z}_1) \]  \tag{21}

In order to estimate the parameter uncertainty and interference \( d \), adaptive control is introduced, assuming that the uncertain part of the model parameters and the external interference change slowly, that is, \( \dot{d} = 0 \), the third step of the design is carried out.

Assume:

\[ V_3 = V_2 + \frac{1}{2} \gamma \dot{d}^2 \]  \tag{22}

Among them, \( \dot{d} \) is the estimated value of \( d \), \( \dot{d} \) is the estimated error of \( d \), \( \dot{d} = d - \dot{d} \), and \( \gamma \) is a positive constant.
Then:
\[
\dot{V}_3 = \dot{V}_2 - \frac{1}{\gamma} \ddot{d} \dot{d}
\]
\[
= z_1 z_2 - c_1 z_1^2 + s(c_2 (z_2 - c_1 z_1) + f + b p + d - x_d + c_1 \dot{z}_1) - \frac{1}{\gamma} \ddot{d} \dot{d}
\]
\[
= z_1 z_2 - c_1 z_1^2 + s(c_2 (z_2 - c_1 z_1) + f + b p + d - x_d + c_1 \dot{z}_1) - \frac{1}{\gamma} \ddot{d} (\dot{d} - \gamma s)
\]
(23)

The design controller is:
\[
p = \frac{1}{6} (-c_2 (z_2 - c_1 z_1) - f - x_d - c_1 \dot{z}_1 - \dot{d} - h (s + \beta \text{sgn}(s)))
\]
(24)

Take the adaptive law as:
\[\dot{\delta} = \gamma s\]
(25)

Then:
\[
\dot{V}_3 = z_1 z_2 - c_1 z_1^2 - h s^2 - h \beta |s| = z_1 z_2 - c_1 z_1^2 - h (c_2 z_1 + z_2)^2 - h \beta |s| = z_1 z_2 - c_1 z_1^2 - h c_2^2 z_1^2 - 2 h c_2 z_1 z_2 - h z_2^2 - h \beta |s| = - \left( (c_1 + h c_2^2) z_1^2 + (2 h c_2 - 1) z_1 z_2 + h z_2^2 \right) - h \beta |s|
\]
(26)

The previous part can be written as quadratic:
\[
z^T Q z = \begin{bmatrix} c_1 + h c_2^2 & h c_2 - \frac{1}{2} \\ h c_2 - \frac{1}{2} & h \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}
\]
(27)

Then:
\[
\dot{V}_3 = -z^T Q z - h \beta |s|
\]
(28)

Where \( h > 0 \), as long as the quadratic form \( z^T Q z \) is positive definite, then \( \dot{V}_3 = -z^T Q z - h \beta |s| \leq 0 \). Make the quadratic form positive definite, then \( |Q| > 0 \), by choosing appropriate parameters, you can make \( |Q| > 0 \). According to the principle of LaSalle invariance, when \( \dot{V}_3 \equiv 0, z \equiv 0, s \equiv 0 \), then \( t \to \infty, z \to 0, s \to 0 \), so \( z_1 \to 0, z_2 \to 0 \), then \( x_1 \to x_d, \dot{x}_1 \to \dot{x}_d \), which proves the stability of the entire system.

3. Control system simulation

A simulation model of adaptive backstepping sliding mode control is built in the Matlab/Simulink simulation environment. The relevant parameters of the controller are shown in Table 2.

| Parameter | Value |
|-----------|-------|
| \(c_1\)   | 1     |
| \(c_2\)   | 9     |
| \(h\)     | 10    |
| \(\beta\) | 1     |
| \(\gamma\)| 30    |

The uncertainty and interference of the model are added as \( d = 2 \sin(0.1t) \). The sine curve tracking simulation is carried out in Matlab/Simulink environment. The amplitude of the sine signal is 0.04m and the offset is 0.03m. The simulation result is shown in Figure 2.
Figure 2. Tracking simulation results of sinusoidal signals

It can be seen from Figure 2 that the position tracking reaches a stable state in about 0.3s, and the tracking error thereafter is small, indicating that the adaptive backstepping slippage is based on the uncertainty of the aerodynamic muscle nonlinear modeling and external disturbances. Modular control has strong robustness and good tracking performance, which is suitable for the design of pneumatic muscle control system.

4. Conclusion
Aiming at the nonlinearity and uncertainty of pneumatic muscles, this paper proposes an adaptive backstepping sliding mode control strategy, which uses a three-element model of pneumatic muscles. Based on this model, an adaptive backstepping sliding mode controller is designed. The control method is used to realize the simulation of the position control of the pneumatic muscles. The simulation results show that the adaptive backstepping sliding mode control method can make the system track the desired signal quickly and effectively, and has strong robustness.

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