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STIFFNESS REGULATION AND POSITION CONTROL TECHNOLOGY OF A PNEUMATIC MUSCLE ROBOT ARM

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ABSTRACT

In the case that the high compliance and high safety are required, the use of pneumatic muscle for robot joints is a good choice. In this paper, a bio-mimic structure of pneumatic muscle robot arm is introduced and the differential pressure principle is applied to control the arm. In order to solve the practical problems that difficult regulation with pneumatic muscle and the lower accuracy of position control, a proportional stiffness regulation method with easy implementing feature is presented through theoretical analysis and experiments. On this basis, the position control of the joint with pneumatic muscle is implemented, for which the adaptive and self-learning neural-PSD controller is adopted. Tests indicate that the joint stiffness is easy to regulate by the method and joint operation shows a quick response and high accuracy.

KEY WORDS

Pneumatic muscle, Robot arm, Stiffness regulation, Adaptive neural-PSD controller

NOMENCLATURE

F	:	Contraction force	[N]
P	:	Input pressure	[MPa]
D	:	Muscle diameter	[m]
L	:	Muscle length	[m]
ε	:	Muscle contraction ratio	[%]
α	:	Muscle braided angle	[rad]
θ	:	Joint angle	[rad]
T	:	Joint toque	[Nm]
R	:	Radius of sprocket wheel	[m]
C	:	Joint stiffness	[Nm/rad]
u	:	Output of the controller	[MPa]
x	:	State variable	[rad]
e	:	Track error	[rad]

INTRODUCTION

Most robotic rotary joints are driven by electric servo-motors, step-by-step motors or sometimes by hydraulic motors. The joint structures driven by these actuators are usually complicated, heavy and lack of compliance. However, the human arm is light and flexible with the human musculature. So it is expected to find a kind of actuator with which the maximum similarity in function and shape of human arm would be acquired based on the artificial pneumatic muscle.

There are two main problems for a robot arm driven by pneumatic muscle, that is, difficult regulation on joint stiffness and low accuracy in position control. Thus it is very important to investigate technique approaches for effective stiffness regulation and high precise position control with artificial pneumatic muscle.

In this paper, the research is focus on these problems. After describing the mechanical structure and working principle of the robot arm driven by pneumatic muscles, a proportional stiffness regulation method with easy implementing feature is presented through theoretical analysis and experiments. On this basis, the position control method for the joint is studied, which use the adaptive and self-learning neural-PSD control mode.

BIO-MIMETIC STRUCTURE AND WORKING PRINCIPLE OF THE ROBOT ARM

In most joints driven by electric motors or hydraulic motors, for regulating the speed difference between the driving motors and the actuating parts speed reducers must be used[1]. In this case the joints are lack of compliance due to their great stiffness. However, if pneumatic muscles are used to drive the joints the speed reducers can be removed owing to their suitable action speed.

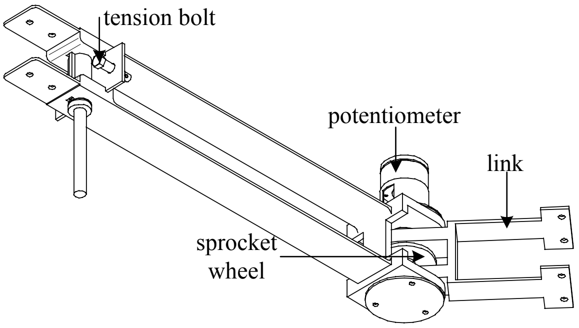


Figure 1 Mechanical structure of the robot arm

Figure 1 shows the mechanical structure of the robot arm developed by authors. From Figure 1 it can be seen that the pneumatic muscles are fixed on the arm skeleton, which transmits torque by a chain and a sprocket wheel when contracting with pressurized air. For regulating the initial length of the pneumatic muscles, a tension bolt is mounted on an end of the muscle skeleton. A potentiometer is used for measuring the rotary angle of the joint. The robot arm is about 300mm in length, 45mm in width, and 1.8kg in weight.

Figure 2 shows the working principle of the joint driven by two pieces of pneumatic muscles. At the initial state, both muscles are charged with air under initial pressure P_0, and the rotary angle θ of the joint is zero. If the pressure are increased by ΔP in a pneumatic muscle and the pressure is decreased by ΔP in another pneumatic muscle, the joint would rotate around the direction with a contracting muscle owing to pressure increasing until the new force balance is reached.

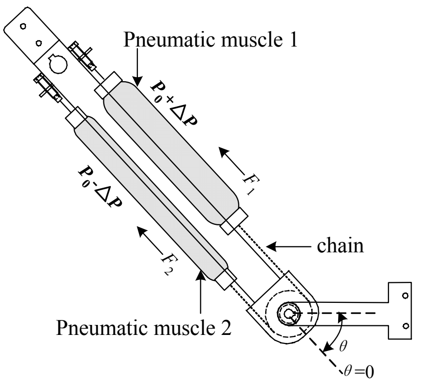


Figure 2 Working principle of the joint driven by pneumatic muscles

METHOD OF PROPORTIONAL STIFFNESS REGULATION

Requirement of Stiffness Regulation on Pneumatic Arms

The merit of use of a pneumatic muscle to drive a joint is with high compliance. However this leads to the decreasing of the stiffness. In some case for some tasks, the high stiffness is needed when overcoming greater loads, while the low compliance is permissible. Thus the stiffness regulation according to different tasks in robot working process is required. For this the force/length/pressure relation model of the pneumatic muscle should be built up.

The Force/Length/Pressure Relation Model

The pneumatic muscle used in our research is Mckibben muscle with 250mm in length, 20mm in width, 45g in weight, maximum pulling force with 0.5MPa is 250N. The force/length/pressure relation model is originally proposed in literature[2] as follows.

$$\begin{cases} F = \dfrac{\pi D_0^2}{4} P\left(a(1-k\varepsilon)^2 - b\right) \\ \varepsilon = \dfrac{(L_0 - L)}{L_0} \\ a = \dfrac{3}{\tan^2(\alpha_0)}, b = \dfrac{1}{\sin^2(\alpha_0)} \end{cases} \tag{1}$$

For the muscle in our research, the initial parameters in Eq. (1) can be given as: D_0=13.4mm, L_0=197mm, α_0=21°, k=1.14. Figure 3 shows the comparison between experiment results and the theoretical results from Eq. (1). It can be seen that both results are well coincident[3].

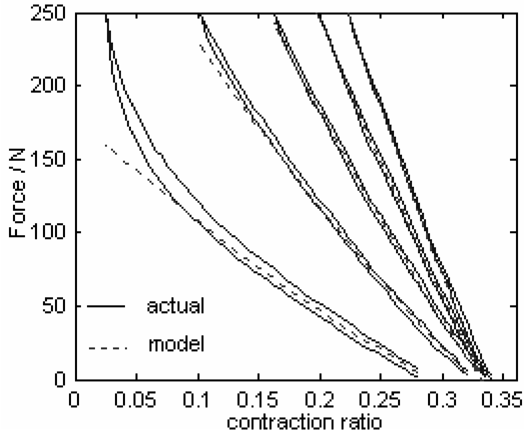


Figure 3 Comparison between experiment results and the theoretical results

Proportional Regulation of Joint Stiffness

Using the force/length/pressure relation model, the joint torque Eq.(2) can be derived according to its working process

$$T = K_1 \Delta P - K_2 P_0 \theta \tag{2}$$

Where K_1 and K_2 are constants, dependent on pneumatic muscle's initial parameters(L_0 ,D_0 ,α_0 ,k)and structural parameters (ε_0 , R) of the robot arm. In Eq. (2), when T=0 at balanced position the term of $K_2 P_0 \theta$ will equal the term $K_1 \Delta P$. This derives following expression on θ and ΔP

$$\theta = \frac{K_1}{K_2 P_0} \Delta P = G \Delta P \tag{3}$$

Where G is a static gain of θ with ΔP.

The angular stiffness is the derivative of the torque function and can be expressed as

$$C = \frac{dT}{d\theta} = K_2 P_0 \tag{4}$$

Because K_2 is a constant, the joint stiffness C is directly proportional to the initial pressure P_0 in the pneumatic muscle. With the increasing of the initial pressure P_0, the joint stiffness is increased. This feature can be used to actively regulate the joint stiffness when necessary.

Experiments for Regulation on Joint Stiffness

To validate the method to regulation on joint stiffness C, experiments are carried out, in which the output torque T and the joint angle θ must be measured to obtain the stiffness C from Eq. (4). Because of the limitation of the mechanical structure, it is very difficult to directly measure the output torque, so an indirect method is planed. As seen in Eq. (5), the static stiffness C is expressed as a function of K_1 and G and is also a function of θ and ΔP. If θ and ΔP can be measured, the static stiffness C can be calculated by Eq. (5).

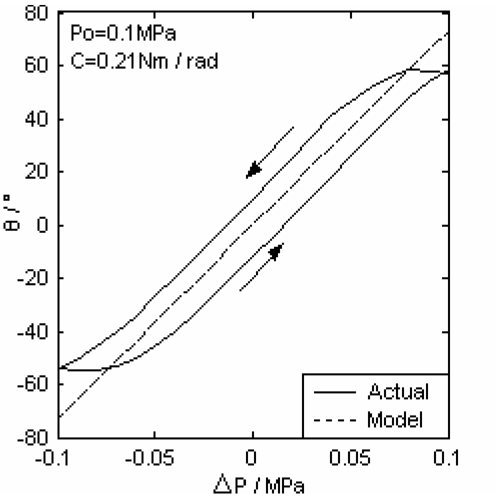
$$C = \frac{K_1 \Delta P}{\theta} = \frac{K_1}{G} \tag{5}$$

We can define the joint compliance coefficient F as

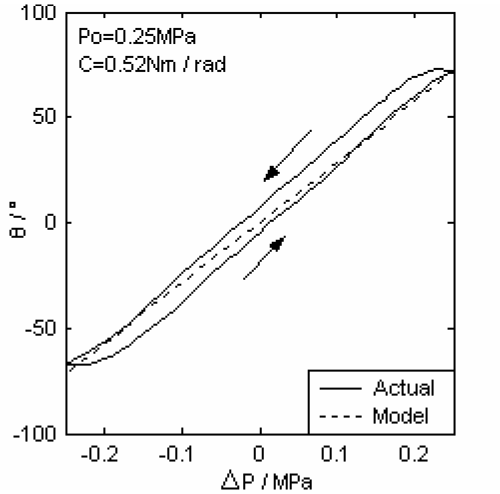
$$F = -\frac{d\theta}{dT} = -\frac{1}{K_2 P_0} = -\frac{1}{C} \tag{6}$$

From Eq. (6), we can see that the F is inversely proportional to C. The increasing of F means decreasing C.

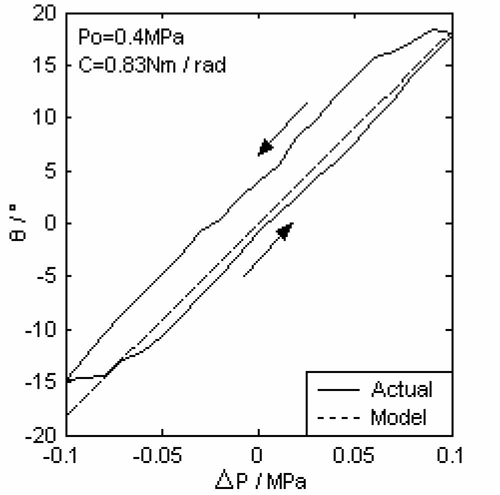
Figure 4(a) ~ (c) shows the variation of measured θ with ΔP with P_0=0.1MPa、0.25MPa、0.4MPa. From Figure 4, the G can be obtained by the slopes of the curves. Figure 5 shows the comparison between the model value and the measured value of the static gain G.



(a) P_0=0.1MPa



(b) P_0=0.25MPa



(c) P_0=0.4MPa

Figure 4 Variation of measured θ with ΔP

From Figure 5, it can be seen that the actual static gain G is very close to the theoretical value.

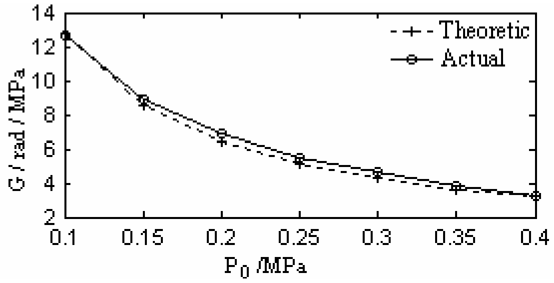


Figure 5 Comparison of the static gain G

Figure 6 shows the comparison between the model value and the measured value of the joint stiffness C. From Figure 6, it can be seen that the joint stiffness C is very close to the theoretical value. Therefore it can be deduced that the theoretical C calculated by Eq. (5) can be used in real time controlling algorithm substituting the measured value.

For usual robot joint the stiffness or compliance is a fixed value when the structure is made, while for that driven by pneumatic muscles the stiffness or compliance can be regulated by regulating input pressure at any time. This provides the possibility of regulating the joint stiffness according to different loads or tasks in the joint controlling algorithm. On this basis, further controlling algorithm can be researched with different joint stiffness.

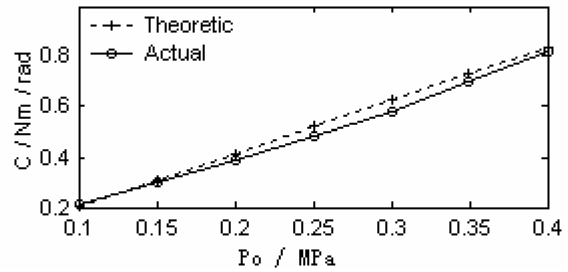


Figure 6 Comparison of the joint stiffness C

ADAPTIVE SINGLE NEURAL PSD POSITION CONTROL SYSTEM DESIGN WITH DIFFERENT JOINT STIFFNESS

Joint angle θ can be controlled in open-loop according to Eq. (3). However, because of its large hysteresis as shown in Figure 4, to obtain high accuracy θ could not be controlled merely by open-loop mode. So a suitable closed-loop control method should be studied and adopted.

Controller Design

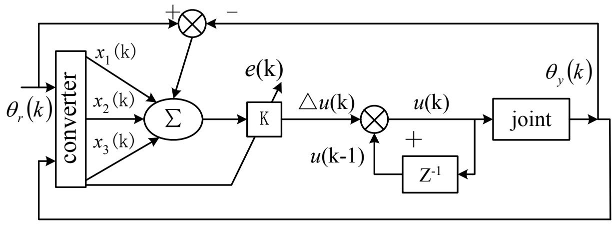


Figure 7 Diagram of adaptive single neural PSD control

Due to the air compressibility, the non-linearity and hysteresis in operation of pneumatic muscles, it is difficult to establish an accurate linear discrete model through experimental data. Therefore, to avoid the obstacle of the impossible accurate model, an adaptive and self-learning neural PSD controller without model is developed.

Diagram of this adaptive single neural PSD controller is shown in Figure 7[4][5].

The PSD controller is expressed as

$$u(k) = u(k-1) + K\sum_{i=1}^{3} w_i'(k)x_i(k) \tag{7}$$

Where $u(k)$ is the output value of the controller, corresponding to the input pressure variation in pneumatic muscle; K is the proportional coefficient of neural (K>0); $x'_i(k)$ (i=1,2,3) is state variable; $w'_i(k)$(i=1,2,3) is weight corresponding to $x'_i(k)$, $x'_i(k)$ can be expressed as

$$\begin{cases} x_1(k) = e(k) = \theta_r(k) - \theta_y(k) \\ x_2(k) = \Delta e(k) = e(k) - e(k-1) \\ x_3(k) = \Delta^2 e(k) = e(k) - 2e(k-1) + e(k-2) \end{cases} \tag{8}$$

Where $\theta_r(k)$ and $\theta_y(k)$ are the set point and the actual value of joint angle. $w'_i(k)$ can be expressed as

$$w_i'(k) = w_i(k) / \sum_{i=1}^{3} |w_i(k)| \tag{9}$$

Learning arithmetic of $w_i(k)$ is

$$\begin{cases} w_1(k+1) = w_1(k) + \eta_I z(k)u(k)[e(k) + \Delta e(k)] \\ w_2(k+1) = w_2(k) + \eta_P z(k)u(k)x_1(k)[e(k) + \Delta e(k)] \\ w_3(k+1) = w_3(k) + \eta_D z(k)u(k)x_1(k)[e(k) + \Delta e(k)] \end{cases} \tag{10}$$

Where η_I , η_P and η_D are learning rates of Integral, Proportional and Derivative terms of the controller.

The system performance is sensitive to Proportional coefficient K in controller. As K increases, the system response will become significantly faster, but the system could become unstable when K is sufficiently large. K can be regulated by the following learning arithmetic

$$\begin{cases} K(k) = K(k-1) + C\dfrac{K(k-1)}{T_v(k-1)} \\ \qquad for \quad sign(e(k)) = sign(e(k-1)) \\ K(k) = 0.75K(k-1) \\ \qquad for \quad sign(e(k)) \neq sign(e(k-1)) \end{cases} \tag{11}$$

$T_V(k)$ is given as follows

$$T_v(k) = T_v(k-1) + L^* sign\left(|\Delta e(k)| - T_v(k-1)|\Delta^2 e(k)|\right) \tag{12}$$

Where $0.025 \le C \le 0.05$, $0.05 \le L \le 0.1$. With the increasing of L, initial value of $T_V(k)$ and $K(k)$, regulation ratio of $K(k)$ is increased.

Experimental Results of PSD Control

To demonstrate the effectiveness of the controller, an experiment is carried out. The input pressures in pneumatic muscles are provided using pressure proportional valves with a time delay of 30ms being able to meet the requirement of the controller. By adjusting the input voltage of the pressure proportional valve, the force and contraction of pneumatic muscles can be controlled. The control algorithm and software are implemented using LabVIEW on a Pentium Ⅳ computer. The chosen sampling time interval is 30ms. Due to limitation of the range of normal working pressure the output value of the controller should be restricted as follow

$$0 < P_0 \pm \Delta P < 0.5MPa \tag{13}$$

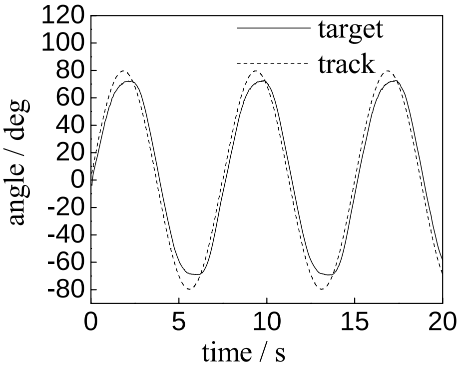


Figure 8 Response for a sine wave with open-loop (cycle=7.5s)

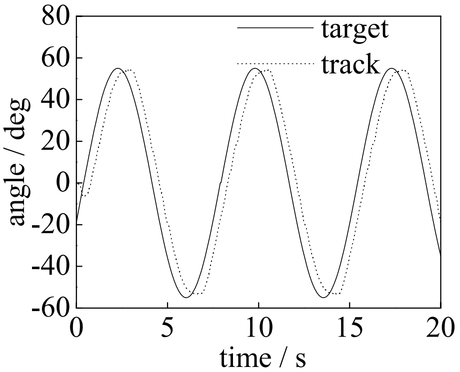
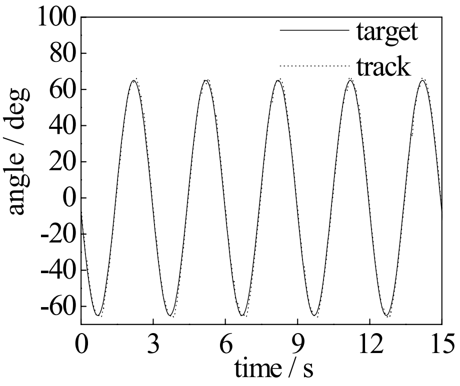
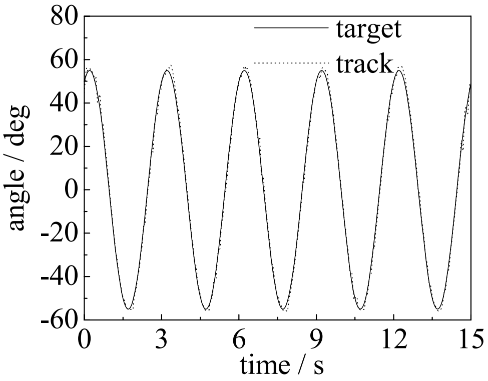


Figure 9 Response for a sine wave with PID (cycle=7.5s)



(a) P_0=0.25MPa



(b) P_0=0.15MPa

Figure 10 Response for a sine wave with adaptive single neural PSD (cycle=3s)

Figure 8 shows the steady state response for a sine wave with an open-loop control mode. From Figure8, it can be seen that there are two defaults in output with open loop, one is the bigger track error between the target values and the track values and another is the longer response time.
Figure 9 shows the steady state response for a sine wave with a simple PID control mode. From Figure 9, it can be seen that the track error is decreased with the simple PID control mode.

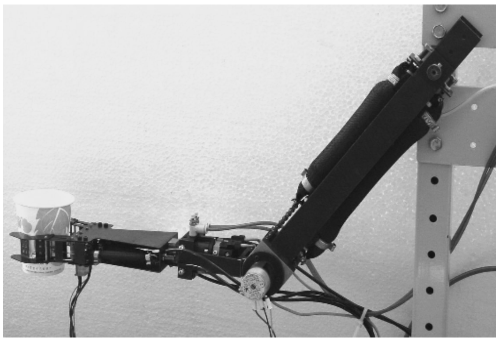


Figure 11 Practical operation of the arm

Figure 10(a) shows the steady state response for a sine wave with adaptive single neural PSD (P_0=0.25MPa). Figure 10(a) shows the steady state response under the same conditions in Figure 10(b) but with different initial input pressure (P_0=0.15MPa). From Figure10(a) and (b) it can be seen that the track error and response time are all decreased with adaptive single neural PSD control mode.
Figure 11 shows a practical operation of the robot arm in grasping a paper cup. This is need necessary compliance and sufficient stiffness when the cup is full of water. With the help of the stiffness regulation method and the adaptive PSD control mode, the arm could complete the operation task without any problems.

CONCLUSION

In the case that the high compliance and high safety are required, the use of pneumatic muscle for robot joints is a good choice.
There are two main problems for a robot arm driven by pneumatic muscle, that is, difficult regulation on joint stiffness and low accuracy in position control. In this paper, the research has focused on these problems. First the mechanical structure and working principle of the robot arm driven by pneumatic muscles are introduced. Then a proportional stiffness regulation method with easy implementing feature is presented, which is derived from theoretical analysis and has been validated by experiments. On this basis, the position control method for the joint is studied, which use the adaptive and self-learning neural-PSD control mode. Experiments have shown that the adaptive PSD control mode is suitable for the joints driven by pneumatic muscles and has a good performance with smaller track error and shorter response time.

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