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Proceedings of the 6th JFPS International
Symposium on Fluid Power, TSUKUBA 2005
November 7-10, 2005

A SLIDING MODE FUZZY FORCE TRACKING CONTROLLER FOR PNEUMATIC CYLINDERS

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ABSTRACT

The problem of control of force exerted by pneumatic cylinders on the environment is of interest in industrial automation and systems such as legged robots. In this paper, a sliding mode fuzzy force control algorithm is proposed for pneumatic cylinders. The environment is assumed to be “soft” or compliant and modeled as a spring. The advantage of the new controller is that being based on fuzzy logic, knowledge of the cylinder dynamics or disturbances such as friction is not necessary. The control law implementation is based explicitly on contact force measurements. The proposed algorithm is simple, robust, and easy to implement. Results of experimental implementation are presented to illustrate the practical effectiveness of the new method.

KEY WORDS

Fuzzy force control, Sliding mode, Pneumatic cylinders, Soft environment

INTRODUCTION

Pneumatic actuators and systems are widely used in industrial automation because of their advantages of low-cost and high payload-to-weight/volume ratios. Further, they find applications in robotics, rehabilitation systems, as well as energy conversion.
However, further development and use of pneumatic actuators is limited by their difficulty of precise control. Pneumatic actuators have nonlinear, high-order dynamics and parametric uncertainties due to friction and air compressibility. The performance of conventional PID controller is limited under these conditions.
Accurate position and trajectory control of pneumatic actuators and air motors has been achieved by means of advanced control techniques such as sliding mode control and adaptive control, e.g. [1]-[3]. These techniques are developed based on full-order model-based compensation for the nonlinear dynamics which includes the chamber pressure dynamics. The performance achieved is comparable to that of conventional electric actuators [4].
Interaction with an environment is involved in many industrial assembly and automation operations, as well as systems such as legged robots and object handling.

Thus, the control of the contact force exerted on the environment is a major task. There are basically two types of environment: one is 'hard" environment with infinite stiffness while the other is "soft" environment which undergoes deformation and can be modeled as spring, damper and mass system.

The problem of force control has been extensively studied for electrically actuated mechanisms and manipulators as well as hydraulic actuators, e.g. [5]-[6]. However, limited research has been conducted for the case of force control of pneumatic actuators and pneumatic robots, e.g. [7]-[10]. It has focused on linearized or nonlinear model-based force control and therefore is either limited in accuracy or complex to implement.

Intelligent control methods, using fuzzy, neural nets, or genetic algorithms, are well-suited for force control of pneumatic actuators, since they are not model-based and the environment is often unknown. However, research on intelligent control of pneumatic cylinders has mainly been limited to position control, e.g., [11]-[12].

The authors have recently applied the sliding mode control (SMC) approach to pneumatic cylinders in contact with a "hard" environment, i.e., the environment with infinite stiffness [13]. The SMC has advantages of simplicity, high performance, and robustness to matched uncertainties. However, in the absence of good model-based compensation – which requires knowledge of high-order system dynamics – the technique requires large switching gains which may lead to chattering and excitation of unmodeled dynamics. The adaptation of the switching gains further requires knowledge of system dynamics [2].

In this paper, we consider the force tracking control problem for pneumatic cylinders in contact with a "soft" environment, which is modeled as a spring of finite stiffness. In order to avoid modeling the high-order dynamics of cylinder and valves for controller design, we focus on the fuzzy logic approach for tuning gains. As is well known, fuzzy logic controllers are effective intelligent controllers for various applications, e.g., [14]. Because fuzzy controllers are often designed based on intuitive standpoint, they are often more understandable. However, due to the linguistic expression of fuzzy controller, it is difficult to guarantee the stability of control systems. Nevertheless, by designing sliding mode type fuzzy logic controller, the performance and stability can be ensured and meanwhile the number of fuzzy rules can be reduced [15].

The proposed sliding mode fuzzy controller (SMFC) has the advantages of not requiring knowledge of the cylinder and valve dynamics, and ensures precise and robust performance in the presence of disturbances through adaptation of switching gains and parameters. Experimental results are presented for an industrial-type cylinder to illustrate the effectiveness of the proposed SMFC.

DYNAMICS OF CYLINDERICAL ACTUATORS

Consider the schematic shown in Fig.1 of a pneumatic cylinder in contact with a soft environment modeled as a spring. Proportional servovalves are used at the two chambers to precisely control the air flow.

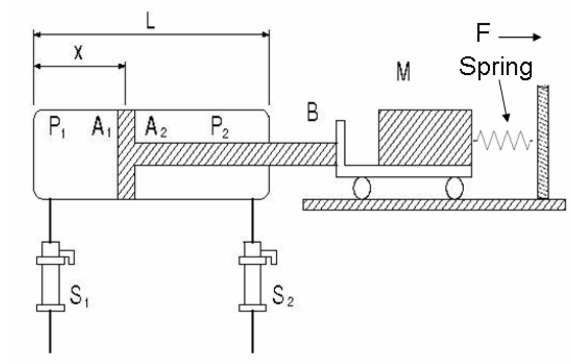

Figure 1. Model of cylindrical actuator

Here, P_1, P_2 are the chamber air pressures, A_1, A_2 are the ram areas, and S_1 , S_2 are the valve cross-section areas. M is the mass of the external payload and the piston, and B is the coefficient of viscous friction and the damping. x is the position of the piston endpoint, and L is the stroke of the piston. F is the force exerted on the environment, represented here as a spring.

The dynamics of piston motion is given by

$$M\ddot{x} + B\dot{x} + d + F = A_1(P_1 - P_a) - A_2(P_2 - P_a) \quad (1)$$

where P_a is the atmospheric pressure, and d represents disturbance due to static and Coulomb friction. Assuming, without loss of generality, that A_1=A_2=A, the piston dynamics becomes

$$M\ddot{x} + B\dot{x} + d + F = A(P_1 - P_2) \quad (2)$$

Under the assumption of no friction, from Eq. (2) we have

$$P_1 - P_2 \equiv \Delta P = \frac{1}{A}(M\ddot{x} + B\dot{x} + F) \quad (3)$$

The dynamics of pressures P_1 and P_2 is expressed by nonlinear relations as [1]

$$\dot{P}_1 = \frac{f_1}{x}\frac{e_1}{h_1}u_1 - k\frac{\dot{x}}{x}P_1 \quad (4)$$

$$\dot{P}_2 = \frac{f_2}{(L-x)}\frac{e_2}{h_2}u_2 - k\frac{\dot{x}}{(L-x)}P_2 \qquad (5)$$

where h_i and e_i are positive constants, f_1 and f_2 are nonlinear functions and u_i are voltage inputs to the valves $(i = 1,2)$.

Further, the valve dynamics is usually quite fast compared to the piston and pressure dynamics, and so can be neglected.

If the piston is in contact with the environment at x, the force on the environment can be modeled as a pure elastic restoring force as [5]

$$F = K(x - x_e) \qquad (6)$$

where K is the coefficient of stiffness, and the equilibrium point of contact x_e is treated as constant for a stationary environment.

Equations (2)-(6) can be combined to express the system dynamics in terms of the contact force F and its derivatives. Model-based feedback (and feedforward) control for force tracking can then be designed using explicit force measurements. The details of this procedure are omitted here due to lack of space.

Note that the above dynamic equations are not used in the design of the SMFC. However, they can be used to obtain bounds on the switching gains and parameters of the controller as well as proof of stability.

DESIGN OF SLIDING MODE FUZZY FORCE CONTROLLER

Sliding Mode Controller

In the trajectory tracking problem, the force trajectory is required to track the reference force trajectory $F_r(t), t \in [0,T]$, where T is the terminal time. We assume that the desired force and its first two derivatives $\dot{F}_r(t), \ddot{F}_r(t)$ exist and are continuous over $t \in [0,T]$.

From the literature on force control of single and multiple manipulators, it is well known that integral force control provides both robustness and elimination of steady state error, e.g., [16]. So, we introduce an additional state variable in the form of $\int_0^t F d\tau$.

Accordingly, the state vector of the resulting second-order system is defined as

$$\mathbf{X} = \left[\int F d\tau \quad F\right]^T \text{ and } \mathbf{X}_r = \left[\int F_r d\tau \quad F_r\right]^T$$

Let the force tracking error be

$$\mathbf{E} = \left[\int \Delta F d\tau \quad \Delta F\right]^T = \mathbf{X}_r - \mathbf{X}$$

For the sliding mode controller, we choose a linear, time-invariant sliding surface as

$$s(t) = \mathbf{c}^T \mathbf{E} \qquad (7)$$

where $\mathbf{c}^T = (c_1 \quad 1)$ and c_1 is a real constant. Note that on the sliding surface, s(t) = 0, which means that when the system state is on the sliding surface the system dynamics if of first order as

$$c_1 \int \Delta F d\tau + \Delta F = 0$$

Therefore, by choosing $c_1 > 0$, we can ensure that the reduced-order subsystem is stable on the sliding surface.

Next, we choose the switching feedback gains to guarantee that the sliding surface is reached from anywhere in the state space. The sliding mode controller gains are obtained from the condition for reachability of the sliding surface:

$$s\dot{s} < 0 \qquad (8)$$

We specify the control algorithm in the form [13]

$$u_i = \mathbf{\Phi}_i^T \mathbf{E} + \Lambda_i \operatorname{sgn}(s), (i = 1,2) \qquad (9)$$

where $\mathbf{\Phi}_i = (\varphi_{i1} \quad \varphi_{i2})^T$ and

$$\varphi_{i1} = \begin{cases} \alpha_{i1} & , \text{ if } \quad s\int \Delta F d\tau > 0 \\ \beta_{i1} & , \text{ if } \quad s\int \Delta F d\tau < 0 \end{cases}$$

$$\varphi_{i2} = \begin{cases} \alpha_{i2} & , \text{ if } \quad s\Delta F > 0 \\ \beta_{i2} & , \text{ if } \quad s\Delta F < 0 \end{cases}$$

and Λ_i is a scalar relay gain.

Fuzzy Gain-Tuning

Consider the sliding surface and the sliding mode controller as defined by Eqs. (7), (9). The control performance largely depends on the values of parameter c_1 and the feedback/relay gains. In order to avoid the problems of gain tuning with regular SMC, in this section we propose to use the Mamdani-type fuzzy logic controller (FLC) to adaptively tune these gains based on several sets of fuzzy rules. The structure of the proposed sliding mode force controller is shown in Fig. 2.

The general form for the *j*-th rule of a single-input, single-output Mamdani-type FLC is as follows:

Rule R_j:

IF z is A_j THEN y is B_j $\quad j = 1,2,\dots,m$

where z is the input variable to the controller, y is the output variable, and A_j and B_j are the fuzzy sets for z and y respectively.
Next, we fuzzify the normalized z by means of predefined triangular membership function of the elements z as in Fig. 3.
Finally, we use the correlation-minimum inference method to geometrically sum the consequences of the active associations and apply centroid defuzzification to find the crisp values of normalized y . Then, we denormalize it to obtain the actual output value. The resulting equations are given by Eqs. (10) – (12).

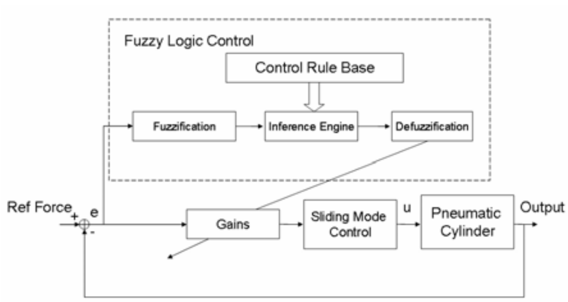

Figure 2. Sliding mode fuzzy force controller

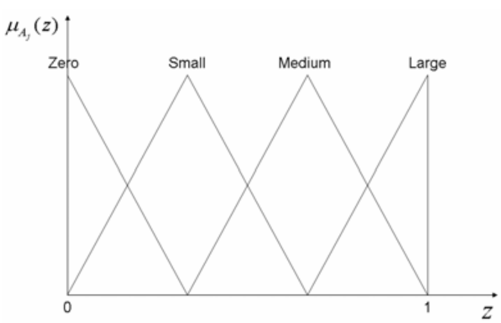

Figure 3. Fuzzification of z

$$\mu_{R_j} = \sup\min\{\mu_{A_j}(z) \quad \mu_{B_j}(y)\} \tag{10}$$

$$\mu_{C_j} = \sup\min\{\mu_{R_1}(y) \quad \mu_{R_2}(y) \quad \ldots \quad \mu_{R_m}(y)\} \tag{11}$$

$$Y = \frac{\int \mu_{C_j}(y) y dy}{\int \mu_{C_j}(y) dy} \tag{12}$$

where μ_{R_j} is the output of the membership function value of the specific input value according to the specific fuzzy rule. μ_{C_j} is the overall output of the membership function of the specific input by taking the minimum value among different output membership values. Y is the actually output obtained by defuzzification.
The parameter c_1 determines the slope of the sliding line and therefore, the larger it is the faster will the system response be. Therefore, based on this characteristic we set up the fuzzy rules as shown in Table 1.
The fuzzy logic tuning for the gains α_{i1}, α_{i2} and Λ_i is similar to that for c_1 based on different inputs and fuzzy rules, e.g. Table 2 shows the rule base for tuning α_{i1}. For simplicity of implementation, we may set $\beta_{ij} = -\alpha_{ij}$.

Table 1 Rule base for c_1

Fuzzy Rules	$\left\lvert\int \Delta F d\tau\right\rvert$			
	Zero	Small	Medium	Large
c_1	Zero	Small	Medium	Large

Table 2 Rule base for α_{i1}

Fuzzy Rules	$\left\lvert\int \Delta F d\tau\right\rvert$			
	Zero	Small	Medium	Large
α_{i1}	Zero	Small	Medium	Large

EXPERIMENTAL RESULTS

The effectiveness of the proposed sliding mode fuzzy force controller is illustrated in this section with results of experimental implementation on an industrial double-acting piston-driven pneumatic cylinder. The experimental setup used is shown in Fig. 4.
The external payload is moved by the piston against a soft environment. In the experiments, two 3-port 2-way proportional servovalves are connected to the left and right side input ports of the pneumatic cylinder respectively.
The force sensor reading is fed to the control program through a 12-bit A/D converter, and the output to the servovalves are from a D/A converter in the PCI data acquisition card inside a desktop PC, based on a 2 GHz Pentium processor. The program is written in Visual C++, and implemented with a sampling period of about 1 msec. The integral force error is obtained as difference

of the desired integral force signal and the numerically integrated values of the filtered force signal.

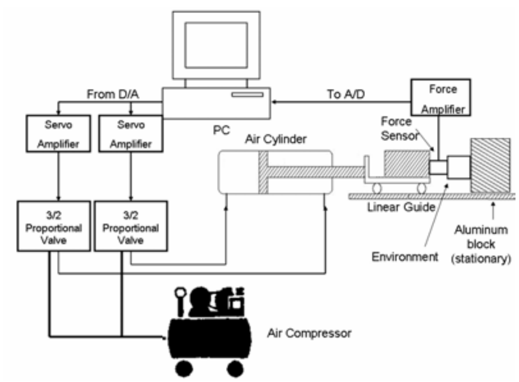

Figure 4. Schematic of experimental system

Figure 5 shows the case of tracking a cycloid trajectory. While the trajectory tracking is accurate, there is a significant initial error due to static friction [17].
Figures 6 and 7 show the results of tracking low and high frequency sine wave reference trajectories without payload, respectively. It can be seen that the tracking performance is accurate and robust with reference to speed of reference trajectory.
In order to investigate the robustness of the proposed sliding mode fuzzy controller, experiments with various payloads have been conducted. Figures 8 and 9 show the results of tracking low and high frequency sine wave with the payload of 3 kg. By comparing to Figure 6 and 7, the results show that the proposed controller provides a robust performance with different payload. However, there is significant error for each case due to the friction. The results presented here highlight the important role of cylinder and servovalve friction in limiting the accuracy of force tracking by pneumatic cylinders. This result is similar to earlier findings on effect of friction on cylinder position tracking [17]. Future research will focus on the friction learning and compensation to improve the controller's performance.

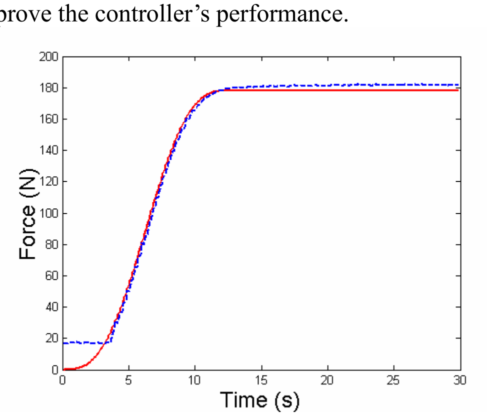

Figure 5. Tracking of cycloid force trajectory

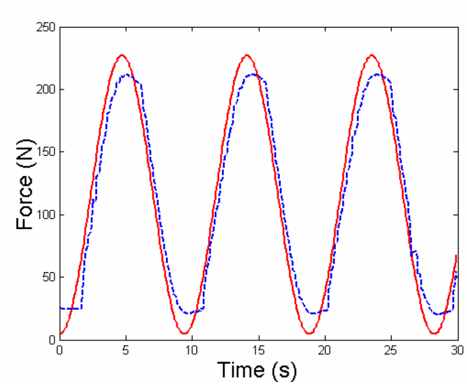

Figure 6. Tracking of low frequency sine wave without payload

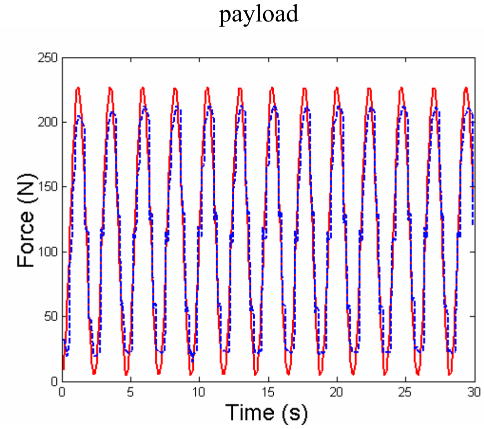

Figure 7. Tracking of high frequency sine wave without payload

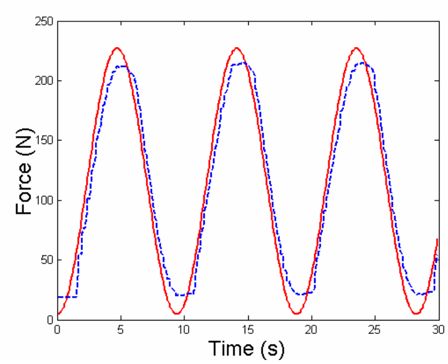

Figure 8. Tracking of low frequency sine wave with the payload of 3 kg

The major advantage of SMFC is that instead of manually tuning gains as in PI and conventional sliding mode control, the fuzzy gain tuning makes use of heuristic fuzzy logic rule base to adapt the gains. This adaptation of gains also can be expected to result in significant energy efficient performance.

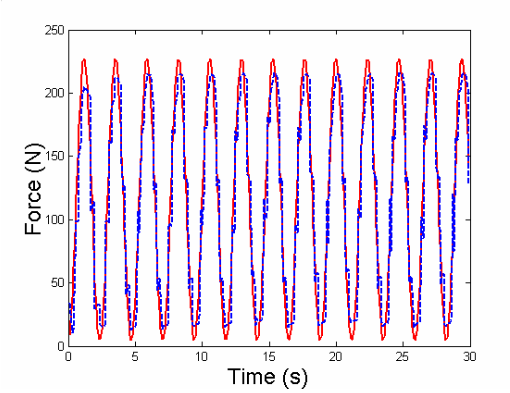

Figure 9. Tracking of high frequency sine wave with the payload of 3 kg

CONCLUSION

A sliding mode fuzzy force controller for control of interaction forces of a pneumatic cylinder actuator in contact with a "soft" environment has been proposed in this paper. The proposed controller has the advantages of simple and easy implementation and robust performance for trajectory tracking. The experimental results validate the effectiveness and robustness of the proposed controller.

ACKNOWLEDGEMENT

The authors would like to thank SMC Corporation for their support of the research.

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