Practical Design of an Iterative Learning-Sliding Mode Controller for Electro-Pneumatic

Shao-Juan Yu, Xiang-Dong Qi, Ru-Cheng Han, Feng Pan

Electron and Information engineering DEP, Taiyuan University of science and technology
Taiyuan. ShanXi.China 030024

Yushao66@public.ty.sx.cn

Abstract

The approach of combing the iterative learning control algorithm with the variable structure control is presented. The reasonable controller is designed and applied to electro-pneumatic servo system. It is able to accommodate smooth transition between different controllers without undue transient effects. Specifically in this work, the proposed controller can not only provide good position and pressure tracking abilities but also is able to obtain the good robustness. The convergence of the proposed algorithm is given. Simulation results are given to show the scheme is valid.

Keyword: iterative learning control, variable structure control, electro-pneumatic servo system

I. Introduction

The main idea in most pneumatic systems is to harness the power of compressed air and convert it into mechanical energy to perform different kinds of work. Commonly seen pneumatic actuation applications include air tools like jackhammers and power drills. In recent times, pneumatics actuation has also caught the eyes of the robotic community. Here, the main area of interest is a special type of manufacturing application. [2] It is called blow-molding process and it also used a pneumatic system. Pneumatic systems have many advantages over conventional electro-hydraulic or electro-mechanical systems It is relatively cheap and easy to build system design is very flexible and can ranged from lightweight, compact domestic appliances to heavy-duty industrial applications. They also have many disadvantages mainly because it is difficult to control such systems unlike hydraulic and electrically powered actuators, which generally have second order dynamics, pneumatic actuators are characterized by higher order dynamics. With third or even fourth order dynamics, the system tends to become unstable if PID feedback gains are high. In addition, the characteristics of compressible air flow contribute a highly nonlinear component to the overall system dynamics. The compressibility of air also causes the system to have poor damping and low stiffness. As air lacks lubricating properties unlike hydraulic fluid, there is a significant amount of static and sliding friction resulting from moving parts. These are also highly nonlinear components, which fundamentally limits the achievable performance of any controller used. Finally, accuracy and repeatability of pneumatic actuators are poor at low velocities, whereas accuracy of hydraulic and electro-mechanical ones is usually satisfactory at all velocities.

In this paper, the challenge is to provide some possible control strategy that will attempt to overcome the above-mentioned known problems. Although pneumatic systems are hard to control, the continued progress of control technology in nonlinear systems has slowly helped to outweigh its many disadvantages. As a result, pneumatic systems will carry on playing an even greater role in the coming days of the industry.

Most controllers used for pneumatic control found in the literature are programmable logic controllers, and commands are executed using simple limit switches. Closed-loop control for such systems is normally not available due to their strong nonlinearities. Servo-controlled pneumatic systems came later in the development of pneumatic actuation. As it is expensive to acquire pneumatic servo valves, they are not common in the industry; however, conventional PID controller suffers from problems of gain tuning when there is variation in payload and supply pressure. There are a few authors who experimented with the idea of using adaptive tracking control for pneumatic systems. The main limitation of adaptive controllers is that it requires the designer to provide a good estimate of system's dynamic structure and this requires a good knowledge of system dynamics. In manufacturing systems, there are a lot of processes that require a particular task to repeat indefinitely like blow molding and glass forming. Thus, it makes perfect sense to employ a controller that will make use of previous trajectory tracking information to improve the performance of present tracking ability.

Above all, The main controller used in this paper is an iterative learning-sliding mode controller, In a previous work, some preliminary investigations concerning the possibilities offered by the combined use of two nonlinear control techniques, namely “iterative learning control (ILC)”[4] and “Variable Structure control (VSC) or sliding-mode control”.[1] As for system performance, iterative learning control can ensure the convergence of iteration function direction moreover variable structure control can ensure the convergence of time axes direction. The remarkable characteristic of iterative learning control is control method easy and track accuracy high, Iterations will make output trajectory be able to be accurately tracked at will. But iterative learning control is not as good as sliding mode Variable Structure in robustness. The sliding mode variable structure control theory has provided effective means to design robust state feedback controllers for uncertain dynamic system.

The central feature of the VSC system is the so-called skidding mode on the sliding surface within which the system remains insensitive to internal parameter variations and extraneous disturbance satisfying the so-called matching condition. However, for variable structure adopts non-continue switching control law, so the state of system produces high frequency chattering. This is the extrusive holdback in the application of the method. It results in that the accuracy of system is reduced. Thus the control methods in corroborating Variable Structure with iterative learning control are presented and applied to electro-pneumatic servo system. The method not only keeps the advantage of two methods, but also restrains the imperfect of two methods. It makes the system keep high accuracy and strong robustness at the same time.

This paper is divided into 5 sections. Section 1 gives an overall introduction of the notion of pneumatic systems, its past and present controllers. Section 2 provides the description of electro-pneumatic servo system. Section 3 shows the controller design that is used for simulation testing. Section 4 presents simulation results. Section 5 concludes the paper and provides some possible future work. Finally, a list of references used in this paper is attached at the back of section 5.

II. Description of electro-pneumatic servo system

In this paper, several major additional nonlinearities have been included to provide a much better system representation of a standard pneumatic-driven actuator system. The major modeling augmentation include a stick-slip friction model, a non-linear calibration between the valve position and input voltage, and several hard limits like supply pressure, and valve opening saturation. Then, the model is later used to examine the utility of iterative learning-sliding mode control. During the modeling process, due to the difficulty involved in solving general nonlinear equations, all the governing equations will be put together in block diagram form and then simulated using Matlab's Simulink program. Simulink will solve these nonlinear equations numerically, and provide a simulated response of the system dynamics.

A. *Actuator dynamics*

The cylinder and piston dynamics are governed by a standard Newtonian force balance equation shown below:

$$\begin{aligned} M\ddot{x}+b\dot{x}+k_5 x+F_{friction} &= A_r(P_r-P_{atm}) \\ &-A_b(P_b-P_{atm}) \end{aligned} \tag{1}$$

M is load mass of actuator, b is damping coefficient, K_s is spring constant, A_r is rod area, P_r is rod pressure , P_{atm} is atmospheric pressure , A_b is bore area, P_b is bore pressure, The atmospheric pressure is assumed to be 14.7 psi. The main nonlinearity in Equation (1) is the term $F_{friction}$ the cylinder seal friction, which plays a major role in the tracking error of the system.

B. *Air pressure dynamics*

The air pressure dynamics at each side of the cylinder are treated differently. Using this formulation, one is able to arrive at the dynamic equations governing the behavior of the air pressure at the bore-side and rod-side of the cylinder. They are given in the following equations:

$$\frac{dp_r}{dt}=\frac{f_r}{x}s_r+k\frac{p_r}{x}\cdot\frac{dx}{dt} \tag{2}$$

$$\frac{dp_b}{dt}=\frac{f_b}{L-x}s_b+k\frac{p_b}{L-x}\cdot\frac{dx}{dt} \tag{3}$$

f_r is rod side non-linear function, f_b is bore side non-linear function , s_r rod-side valve area opening , s_b is bore-side valve area opening , L is stroke length, k is ratio of specific heat, The Equation in either (2) or (3) can be viewed as an addition of an inflow and an outflow term of air in either chamber. They are commonly called the compressibility equations. The constant k is the ratio of specific heat and is approximated to be 1.4. The nonlinear functions, f_b and f_r , can be thought as varying flow gains when air is entering the cylinder chamber. They will be discussed further in the next section. s_r and s_b are the valve area openings, and they are the controller inputs to the entire model.

C. *Servovalve dynamics*

Even though the valve is viewed as a static system, the air moving in and out of the valve possessed a flow-choking phenomenon that is captured inside the nonlinear functions, f_b and f_r . The functions have the following form in detail:

$$f_b = \frac{kT_b}{A_b} \cdot \sqrt{\frac{2R}{T_b}} \cdot P_u \cdot Y[\frac{P_d}{P_u}] \tag{4}$$

$$f_r = \frac{kT_r}{A_r} \cdot \sqrt{\frac{2R}{T_r}} \cdot P_u \cdot Y[\frac{P_d}{P_u}] \tag{5}$$

The temperatures T_b and T_r are the temperatures of the air on the left and right side of the cylinder. The constant R is the universal gas constant. The functions $Y(x)$ in Equations(4)、(5) determine whether a flow will be choked inside an orifice and make uses of the ratio of downstream to upstream pressure .The notion of upstream pressure and downstream pressure is reversed whenever the piston is moving in an opposite direction.

III. Design of iterative learning–sliding mode controller

The main goal of this research project is to devise a suitable controller that will provide effective position and pressure tracking ability of a specific reference profile. Much of the challenges involved in designing such a controller lie in the immense nonlinearities inherent in a pneumatic system. However, many research attempts have been made to control such a system and have demonstrated varied success. Each type of controller has its own limitations and constraints. In this research thesis, an iterative learning-sliding mode control technique will be used to control above system.

A. *The iterative learning control method*

An interesting trace control method, ILC, is in the spot light lately, especially for those objects with repeat motion characteristics [5-9].There have been several investigations of using ILC to carry out repetitive tasks that will either track a periodic reference trajectory or reject a periodic disturbance. These applications spread widely across a wide range of industries [10-12]. Based on above theory, ILC technique is employed on an electro-pneumatic system in this paper. As a result, the successful usage of ILC on a highly nonlinear pneumatic actuator will have significant contribution to the ILC research community. Also, the research effort carried here will also help the industry gain more confidence in using ILC to control highly nonlinear repetitive processes.

Iterative Learning Control techniques have already reached a good level of development. Many researchers have introduced such techniques, almost independently, during the last few years. In order to briefly introduce the use of the ILC method within the problem considered in this work, let us analyses convergence of the P-type learning control for the equation as follow.

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \end{aligned}$$

When the closed-loop P-type learning rule is adopted,

$$u_{i+1}(k) = u_i(k) + (\ddot{e}_{i+1}(k) + L\dot{e}_{i+1}(k) + Pe_{i+1}(k)$$

Convergence is a solution to the problem under consideration IFF

$$\left\|(I + CBP)^{-1}\right\| < 1 .$$

Where $x \in R^n$ is a state vector, $u \in R^m$ is an input vector, $y \in R^p$ is an output vector, and A, B, C are real matrices of appropriate dimensions that are possibly values estimated. Without loss of generality, B and C are supposed fully known. The variable k denotes sampling time and i denotes the iteration time. L and P is learning gain..

B. *The variable structure control method*

In recent years, the sliding mode control methodology has been widely used for robust control of nonlinear systems. Sliding mode control, based on the theory of variable structure systems, has attracted a lot of research on control systems for the last two decades.[3] The salient advantage of sliding mode control is robustness against structured and unstructured uncertainties. In path tracking systems, however, the system invariance properties are observed only during the sliding phase. In the reaching phase, tracking may be hindered by disturbances or parameter variations.

Choose sliding mode manifold and control laws as follows: $S = Ce + \dot{e}$

$$S = [s_1 s_2]^T \in R^n, C = diag[c_1 c_2] \in R^{2\times2}$$
$$e = [e_1 e_2]^T \in R^2$$
$$e_i = \theta_{di} - \theta_i (i = 1, 2 \ldots n)$$

θ_{di} is desiring angle displacement of the joint, θ_i is practical angel displacement of the joint. And control laws as follows: $u = u_{eq} + \psi s_{pi}$

Where sliding mode equivalent control

$$\psi = [\psi_1 \psi_2] \in R^{2\times4}$$
$$S_{pi} = [S^T \int S^T dt]^T \in R^4$$

The ψ_1 is a positive definite matrix, the ψ_2 is defined as follow

$$\psi_2 = \begin{cases} \psi_2 & if \|S\| \ \langle \varepsilon \\ 0^{2\times2} & if \|S\| \rangle \varepsilon \end{cases}$$

$$\varepsilon = \sum_{i=1}^{n} |\varepsilon_i|, \varepsilon_i = \hat{e}_i (i = 1, 2 \ldots n) .$$

C. *Combined ILC and VSC techniques*

As a consequence of the above, it then follows (provided the accuracy condition can be met) that ILC could be sufficient, by itself, to completely solve the stability and control problem relevant to the correct execution of a generic step.

However, a major problem could arise from the necessity of using small values for the boundary size ε, in order to prevent equilibrium instability and consequently sliding or detaching.

This would in turn require high values for the feedback parameter, which could prevent the feasibility of the whole iterative learning structure.
To overcome this possible drawback, already mentioned idea is just that of combining both VSC and ILC approaches, as it will be described in the following section.
The two different approaches, both suitable for the control of the highly non-linear structure have been previously described separately. In this section, the way of combining the two techniques, in order to enhance the advantages of the two, while reducing their drawback, is discussed. Actually, the integration of the two techniques can be easily performed since the two theories present features whose compatibility is not difficult to be achieved, at least in the case of a situation organized as follows:

– Set $i = 0$.
– Assuming the system starting from the rest position, perform the i-th trial of movement by applying signal $u_i(t)$ till the first time instant t_i where the following condition is violated $\|s\| = \|\dot{e}_i + Ke_i\| \le \Delta$. From time t_i on, only apply the VSC technique (which will however imply a forced evolution of the errors within a bound layer induced by the chosen Δ). Moreover record $e_i, \dot{e}_i, \ddot{e}_i$ with in the interval $[0, t_i]$.
– At the end of the whole time control interval (step executed) reposition the system in the original rest posture.
– Set, $i = i + 1$, define $u_i = u_{i-1} - (\ddot{e}_{i-1} + L\dot{e}_{i-1} + Pe_{i-1})$, $t \in [0, \bar{t}_{i-1}]$.

Such conjectures can however be validated on the basis of the following result.
Theorem: consider the combined action of VSC and ILC Techniques as described in the previous procedural steps 1)-4). Moreover, refer to the boundary size ε introduced by the chosen value for Δ in the VSC context.

Then, convergence is guaranteed provided the condition.

$$\left\| I - \{AJ^{-1}(\theta)\}^{-1}[\bar{A}\bar{J}^{-1}(\bar{\theta})] \right\| < 1$$

Where, J is arithmetic operators, which defined as follow $J(\theta) = \frac{\partial}{\partial\theta}$.

Is met for all vectors corresponding to vectors located in the time varying ball $\|\theta - \theta_d\| \le \varepsilon$.

And L, P are chosen in such a way that the polynomial $\det[Is^2 + Ls + P]$.

IV. Simulation results

The main focus here is to formulate an iterative learning–sliding mode controller to track a simple, smooth position and pressure profile. Only the main results obtained from using the method on the simplified model is discussed in the second section. There are three main groups in the simulink nonlinear model. One group comprises of the rod-side dynamics, the other group is the bore-side dynamics and the last group is the piston/cylinder dynamics. Several Matlab's m-files are used in the construction of this model. These m-files include the stick-slip friction model that is encoded into the Matlab programming language. The results of simulation were presented in two Figures as follows.

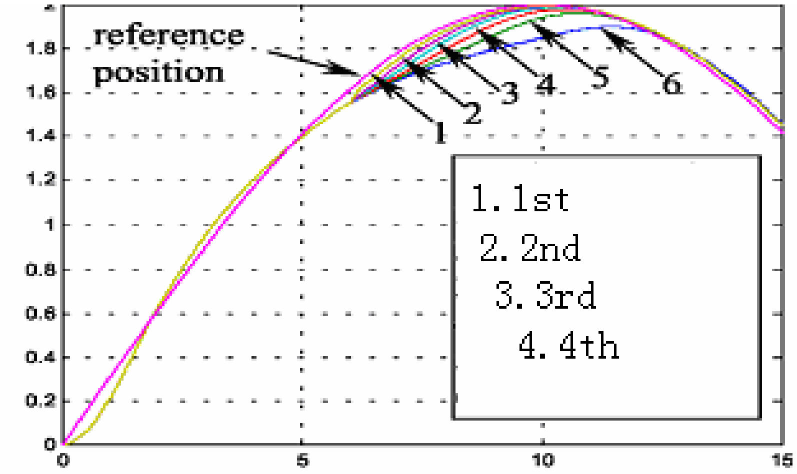

Fig. 1. Position tracking curve

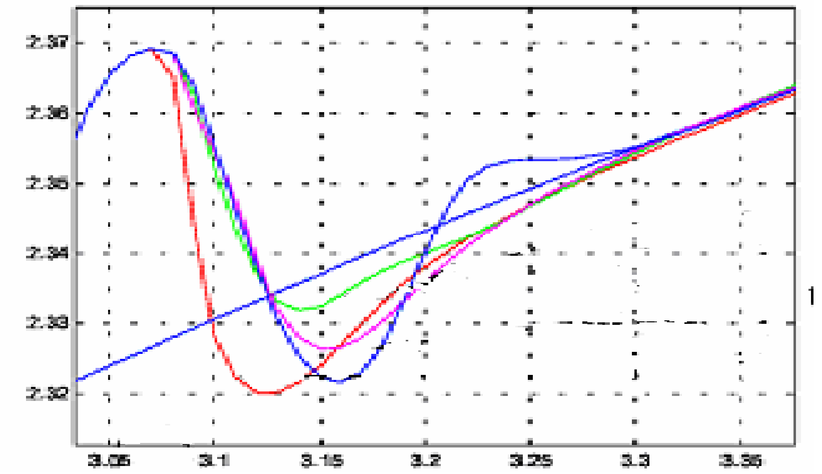

Fig. 2. Pressure tracking curve

Fig.1 shows the position tracking results using the controller. Initially, a simple proportional controller is implemented through a trial and error method to get the system to stabilize before iterative learning–sliding mode controller is implemented. From the figure, one sees that the tracking error converges to near zero after only the 2nd iteration. This result is very encouraging and it shows the ‘powerful’ capabilities of the method explicitly.

Fig.2 shows the pressure tracking results using the controller. From the figure, it seems like there is zero error tracking after the 1 st iteration! However, by observing the error signal plots more closely, it is not hard to observe that there is a decrease in the error signals from trial to trial. This means that there is a continuous tracking error improvement for new iteration performed.

Two sets of the results are shown in Fig3. It shows the position profiles of simulated response without disturber and with disturber.

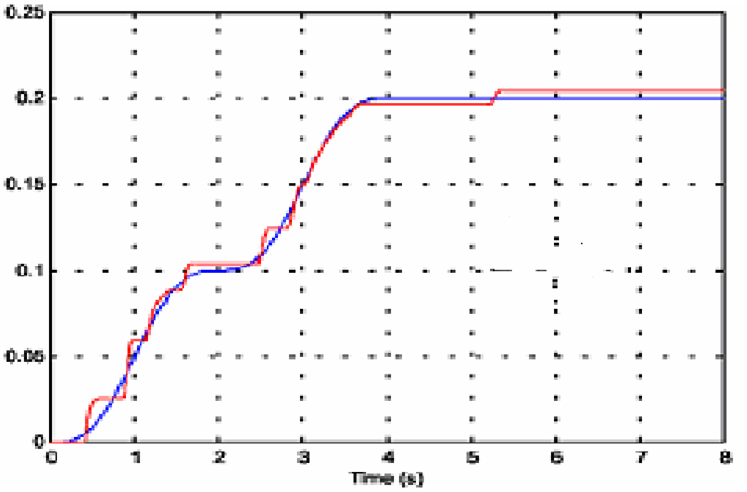

Fig. 3. Position response (Blue: without disturber, Red: with disturber)

V. Conclusion

This paper is then used to examine the feasibility of iterative learning–sliding mode control for electro-pneumatic systems to enhance their position and pressure servo tracking capability. Not only the high accuracy but also the good robustness is obtained. The simulation results show that the effectiveness of the method to the system.

In the future, more work can be done on the nonlinear model to make it handle bidirectional movement. As usual, both open loop simulation and experimental responses can be used together to validate the accuracy and robustness of the bi-directional nonlinear model. The primary reason for doing so is because evaluation of newer and better controllers can be tested on this truly representative nonlinear model before they are implemented on the Airobot system. Other possible areas of research include testing both the simulation model and the Airobot system with actual industrial position and pressure reference profile to prove its applicability to the industry.

Acknowledgements

The authors appreciate the subvention of Shanxi Youth Science Found (20041018) (P.R. China).

References

[1] S.R. Pandian, Y.Hyakawa, Y.Kanazawa, Y.Kamoyama, and S.Kawamura, "Practical Design of a Sliding Mode Controller for Pneumatic Actuators," *Journal of Dynamic Systems, Measurements and Contro,* Vol. 119, ASME,1997,pp.666-674.

[2] R.B. Van and G.M.Bone, "Accurate Position Control of a Pneumatic Actuator Using On/Off Solenoid Valves," *Transactions on Mechatronics,* Vol. 2, IEEE/ASME, 1997,pp.195-204.

[3] J.Tang and G.Walker, "Variable Structure Control of a Pneumatic Actuator," *Journal of Dynamic Systems, Measurements and Contr,* Vol. 117, ASME, 1995,pp.88-92.

[4] H.L.Havlicsek, "Iterative Learning Control of Injection Molding," *University of Illinois at Urbana-Champaign, Dept. of MIE, Master Thesi,* 1998.

[5] R. Horowitz, "Learning Control of Robot Manipulator," *Journal of Dynamic Systems, Measurements and Contro,* Vol. 115, ASME, 1993,pp.402-411.

[6] M. Norrlöf, "Iterative Learning Control-Analysis, Design and Experiments":*Department of Electrical Engineering, Linkoping University, Division of Automatic Control, Department of Electrical Engineering, Linkopings universitet*, Sweden: SE-581 83 Linkoping,2000.

[7] K.L.Moore, "a matrix fraction approach to high-order iterative control: 2-D dynamics through repetition-domain filtering. Proceedings of the 2nd International Workshop on Multidimensional(nD)Systems," Poland :Czocha Castle,Lower Silesia,2000:pp.99～104.

[8] M.X.Sun and D.W. Wang , "Analysis of nonlinear discrete-time systems with higher-order iterative learning control.Dyna.Control", 11(1),2001,pp: 81～96.

[9] D. A. Madhukar, "Convergence and robustness of iterative learning control for strongty positive system," *Asian Journal of control* ,2002.

[10] D.H.Owens and K.Feng, "Parameter optimization in iterative learning control,".*Iternational Journal of Control*, 2003, pp.1059-1069.

[11] J.J.Hätönen, D.H.Owens and K.L.Moore."An algebraic approach to iterative learning control,"*Int.J.control*,10 January,vol.77,no.1, 2004,pp.45-54.

[12] A.Tayebi, "Adaptive iterative learning control for robot manipulators". *Automatic*, 40,2004, pp.1195～1203.

Shaojuan Yu was born in Shanxi, China, in 1971. She received the B.S. and M.S. degrees from taiyuan university of science and technology, taiyuan, china, in 1994 and in 1999, respectively. Since 1994, she joined the department of automation, university

Xiangdong Qi was born in Shanxi, China, in 1967. he received the B.S. and M.S. degrees from taiyuan university of science and technology, taiyuan, china, in 1989 and in 1999,respectively.Since 1989, he joined the department of automation, university of science and technology, where he is now an associate professor. His research interests is intelligent control.

Rucheng Han was born in Shanxi**, China, in 1959.** he received the B.S. and M.S. degrees from taiyuan university of science and technology, taiyuan, china, in 1978 and in 1991,respectively.Since 1982, he joined the department of automation, university of science and technology, where he is now an professor. His research interests include nonlinear control and intelligent control.