Self-Tuning Control of a Low-Friction Pneumatic Actuator Under the Influence of Gravity

Robert Richardson, Andrew R. Plummer, and Michael D. Brown

***Abstract*—Traditionally the positioning of pneumatic actuators has been limited to movement between preset stops or switches. The restricting factors preventing the use of pneumatic cylinders for accurate servo-control arise from highly nonlinear dynamic properties such as air compressibility and friction effects, which combine to severely degrade time response and positional accuracy. Many real systems are influenced by external gravity forces, which compound the problem of position control. A self-tuning system incorporating an external force balancing term is proposed using a low-friction cylinder. The low-friction cylinder is compared to conventional, sealed cylinders to demonstrate the increased performance.**

***Index Terms*—Low-friction cylinder, pneumatics, self-tuning control.**

I. Introduction

PNEUMATIC systems have been used in industry for many years automating simple industrial tasks. This is largely due to their inherent ability to provide low-cost, compact, safe actuation [1]. The control strategies employed on pneumatic cylinders are often simple, with the majority of applications relying on preset mechanical stops (bang–bang motion) for their position control. The restricting factors preventing wider use of pneumatic cylinders arise from highly nonlinear dynamic properties such as air compressibility and friction effects, which combine to severely degrade time response and positional accuracy [2]. Within the last decade new research initiatives have attempted to use pneumatics in applications that were previously limited to electric motors or hydraulics. The drive behind this research is that the cost advantage can be as high as 10 : 1. Surgenor and Iordanou [2] have compared pneumatic and electric actuators, and shown that similar performance can be obtained for the example of a gantry crane.

Work is ongoing to enable greater understanding of the physical properties behind pneumatics to enable more appropriate control schemes to be designed. Backe and Ohligschlager [3] analyzed the heat transfer behavior in pneumatic chambers, enabling the development of pressures to be described more exactly than in the past. Wong and Moore [4] examined the acceleration characteristics of pneumatic cylinders showing them to behave highly regionally.

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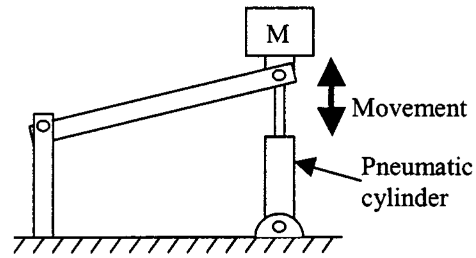

Fig. 1. Pneumatic test rig.

Recent developments in low-friction pneumatic actuators have been exploited. Ben-Dov and Salcudean [5] used low friction cylinders when developing a pneumatic actuator to accurately apply moderate levels of force. Ishida *et al.* [6]–[9] opted to use low-friction actuators in work relating to multi-layer neural networks.

Many control strategies have been employed in an attempt to overcome the nonlinearities present in pneumatic systems. Shih and Tseng [10] demonstrated that conventional PID control could be enhanced using a self-tuning strategy. Similar work was performed by Hamiti *et al.* [11] using a modified form of PI control. The integrator element was modified using a self-tuning strategy to reduce unwanted limit cycles produced by "stick-slip" effects. McDonell and Bobrow [12] performed adaptive control on a double acting cylinder to drive a rotary joint with an attached arm. Shing and Huang [13] compared the results of conventional proportional integral derivative (PID) control with self-tuning pole-placement control for a pneumatic cylinder. The pole-placement controller demonstrated faster response time, less overshoot, and improved steady-state response especially in the presence of load disturbances.

This present study examines the operation of a low-friction pneumatic cylinder under the influence of a constant external force such as a gravity force. Under these conditions, a balancing force must be produced by the control system to counteract this external force. A self-tuning algorithm is proposed to adapt to changeable plant parameters including the balancing force.

II. Experimental Apparatus

A. Test Rig

Experiments were performed on a test rig (Fig. 1) which enabled the force and displacement of a pneumatic cylinder to be measured. Low-friction pneumatic cylinders were used to minimize stiction effects, hence enabling smoother motion to be achieved. This work is part of an ongoing project to develop a physiotherapy robot [14], [15], for which smooth and predictable motion is essential.

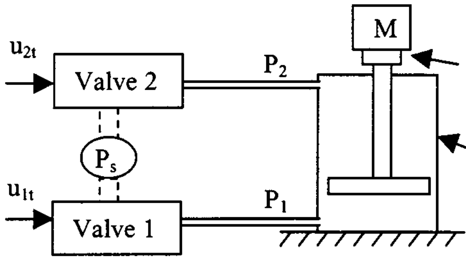

Fig. 2. Supplying air to the cylinder.

TABLE I
EQUIPMENT SPECIFICATIONS

Low Friction pneumatic cylinder - Airpot Airpel – Air bearing design	Bore dia: 18mm Stroke: 38mm
Conventional seal cylinder – Lip seal	Bore dia: 20mm Stroke: 80mm
Electro-pneumatic pressure control valves – SMC E– P Hyreg VY1100	Pressure range:0 – 8.8 bar Voltage Range: 1 – 5V
Pressure Transducer RS 249-3959	Pressure Range: 0 – 6 bar Accuracy (%FS) ± 0.1%
Force Transducer RDP 51/1117 - 01	Capacity: 890 N Accuracy (%FS) ± 0.5%
Mass (M)	4.5 kg
LDVT RDP D5/6000	Linear Range: ± 150mm Linearity (%FS) ± 0.2%

The pneumatic cylinder was supplied with air via two electro-pneumatic valves (Fig. 2). This allowed the pressure difference across the cylinder to be altered with software changes alone. A gain of 1.1 was used to increase the pressure P_2 to compensate for differences in piston area.

The position of the pneumatic cylinder was measured using an LVDT attached across the cylinder. A force sensor was attached between the cylinder and load to enable the friction within the cylinder to be estimated. Component specifications are contained in Table I.

B. Balance Pressure

In order for a zero control signal (u_t) to cause no change in response, it was necessary to create a difference in pressure between P_1 and P_2 to counteract the external force, effectively adding a constant value (B_p) to any control signal (Fig. 3). For controller design, the balance signal was considered part of the actual plant.

C. Controlling Two Valves with One Control Signal

In order to optimize the speed of airflow to and from the cylinder the valves needed to operate under choked conditions (maximum mass flow rate). For air, choked flow occurs for a pressure ratio less than 0.53.

The pressures P_1 and P_2 were increased by equilibrium pressure (P_{eq}) to operate under these conditions. A control strategy was formulated to control two valves from one control signal. This assumed the two valves to behave identically. The control signal and the balance factor (B_p) were halved, subtracted from

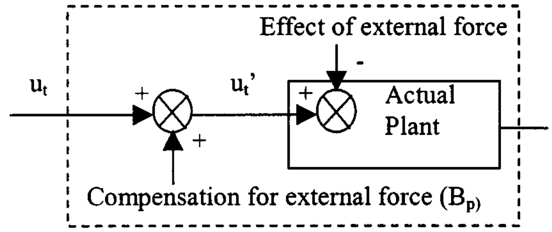

Fig. 3. Considering balance pressure as part of plant.

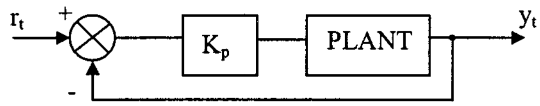

Fig. 4. Proportional control.

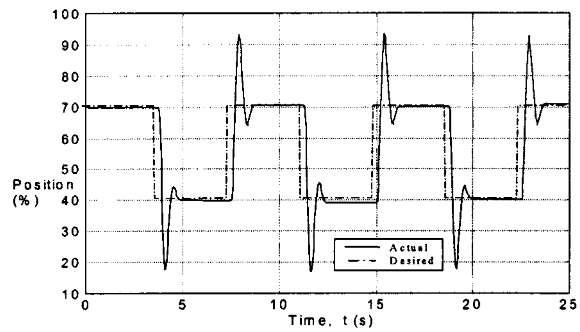

Fig. 5. Proportional control results ($K_p = 2.5$).

the top equilibrium signal and added to the bottom equilibrium signal

$$u_{1_t} = P_{eq} + \frac{u_t{}'}{2} \tag{1}$$

$$u_{2_t} = P_{eq} - \frac{u_t{}'}{2} \tag{2}$$

where:

$$u_t{}' = u_t + B_p. \tag{3}$$

III. Experimental Results

A. Proportional Control

Proportional control (Fig. 4) was performed on the pneumatic cylinder.

Using a proportional gain (K_p) of 2.5 the position response demonstrated the smallest steady-state error and fastest response time (Fig. 5). The large overshoot is unacceptable for precision control systems of this nature, so a more advanced control strategy is required.

B. Pole-Placement Control

Pole-placement is a common form of model-based control using the controller structure shown in Fig. 6.

Physical modeling of the valves and cylinder have shown the valves to have a model order of three and the cylinder to have a model order of two. The response time of the valves is significantly higher than that of the pneumatic cylinder, enabling the valve dynamics to be simplified to a single gain. The system

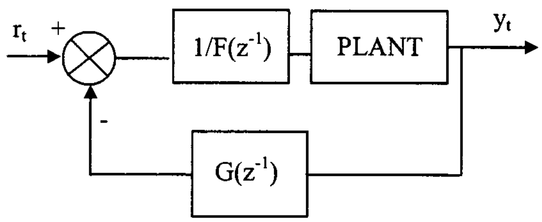

Fig. 6. Pole-placement control.

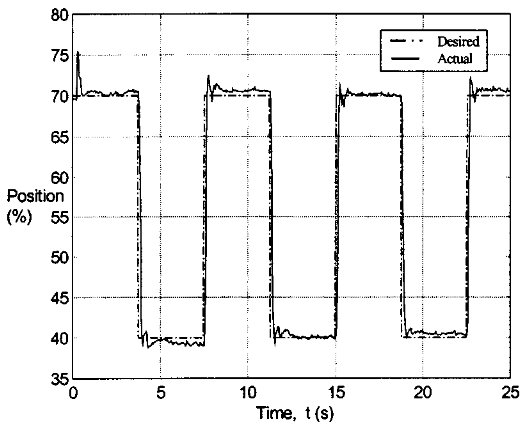

Fig. 7. Pole-placement control results.

can then be represented by a second-order model. Using data obtained from proportional control, a plant model was calculated using least squares parameter estimation

$$y_t = \frac{B(z^{-1})}{A(z^{-1})} \cdot u_t \tag{4}$$

$$A(z^{-1}) = 1 - 1.75z^{-1} + 0.75z^{-2} \tag{5}$$

$$B(z^{-1}) = 0.0591z^{-2}. \tag{6}$$

Using this plant model the coefficients $F(z^{-1})$ and $G(z^{-1})$ were calculated for specific closed-loop poles by solving the diophantine equation [14]. Pole-placement was performed on the pneumatic cylinder using closed-loop pole pairs at 0.4 ± 0.1 i. The resulting response is shown in Fig. 7.

The pole-placement results are superior to those obtained from proportional control with reduced overshoot and shorter rise time. These results do not demonstrate the changeable nature of the system (for example due to variations in system temperature) requiring a new plant model to be identified periodically. A self-tuning strategy was adopted to automatically obtain the correct plant model at the commencement of each session.

C. Self-Tuning Control

It was possible to reduce the number of parameters being estimated by assuming the plant always contains an integrating element [15]

$$y_t = \frac{b_2 z^{-2}}{(1 - z^{-1})(1 + a_1 z^{-1})} \cdot u_t. \tag{7}$$

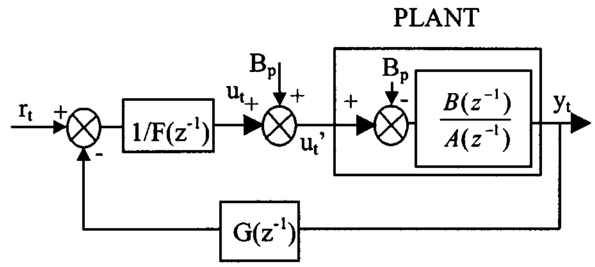

Fig. 8. Pole-placement control with balance pressure.

It was necessary to incorporate the balance pressure (B_p) into the self-tuning process as it varied between sessions, resulting in three parameters (a_1, b_2, B_p) being estimated.

The system including balance signal is shown in Fig. 8. Analyzing the plant to obtain a method of self-tuning the balance pressure

$$y_t(1 - z^{-1}) = \frac{b_2 z^{-2}}{1 + a_1 z^{-1}} \cdot u_t. \tag{8}$$

For ease of notation

$$y_t' = y_t(1 - z^{-1}) \tag{9}$$

$$\Rightarrow y_t' = \frac{b_2 z^{-2}}{1 + a_1 z^{-1}} \cdot u_t. \tag{10}$$

Substituting for u_t in (10) using (3)

$$\Rightarrow y_t'(1 + a_1 z^{-1}) = b_2 z^{-2} u_t' - b_2 B_p z^{-2}. \tag{11}$$

A parameter d can be estimated on line

$$d = -b_2 B_p. \tag{12}$$

The time delay (z^{-2}) of d can be ignored since B_p is a constant. Forming the regressor and parameter vectors necessary for recursive least squares self-tuning.

The regressor vector

$$\underline{\psi_t} = [y_{t-1}' \quad u_{t-2}' \quad 1]^T. \tag{13}$$

The parameter vector

$$\underline{\hat{\theta}_t} = [-a_1 \quad b_2 \quad d]^T. \tag{14}$$

The parameter vector is calculated online using standard recursive least squares identification equations [13], [14]. The balance value is then reconstructed from (12) and the plant model from (7). The coefficients $F(z^{-1})$ and $G(z^{-1})$ are recalculated using the following diophantine equation:

$$F(z^{-1})A(z^{-1}) + G(z^{-1})B(z^{-1}) = A_m. \tag{15}$$

Pole placement control can then be performed for the next sample interval using the $F(z^{-1})$ and $G(z^{-1})$ coefficients obtained from (15).

The step response of the system is seen to converge appropriately after an initial tuning transient (Fig. 9). The convergence of parameters a_1, b_2, and B_p is shown in Figs. 10–12.

IV. Advantages of Low Friction Cylinders

Low friction pneumatic actuators were used in these control experiments due to their small and predictable friction characteristics. The Airpel Airpot cylinder is a low-friction cylinder

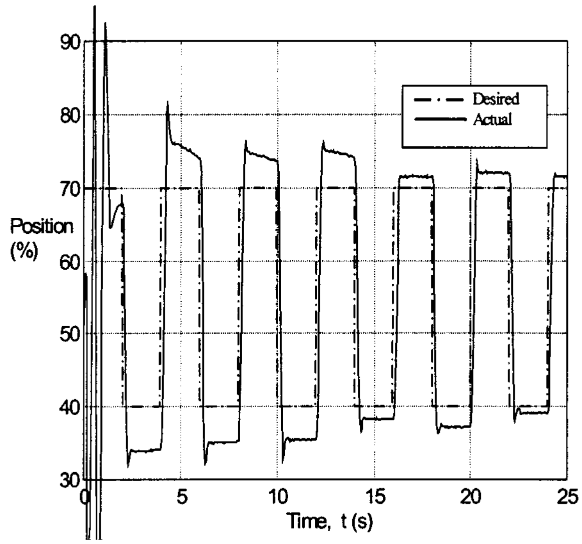

Fig. 9. Self-tuning position response.

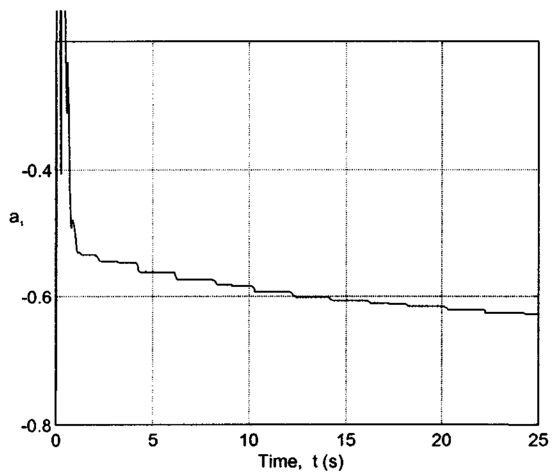

Fig. 10. Self-tuning parameter a_1.

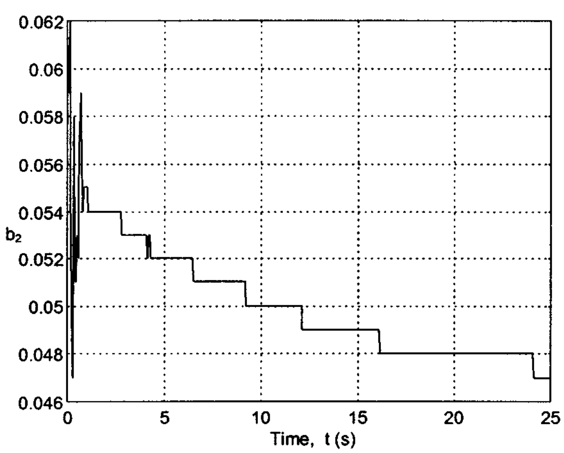

Fig. 11. Self-tuning parameter b_2.

based on an air bearing design [18]. This design reduces friction and stiction effects compared to modern conventional cylinders. In order to demonstrate the improved performance the frictional forces within the cylinder were calculated by examining the forces due to the pressures P_1 and P_2, and then subtracting

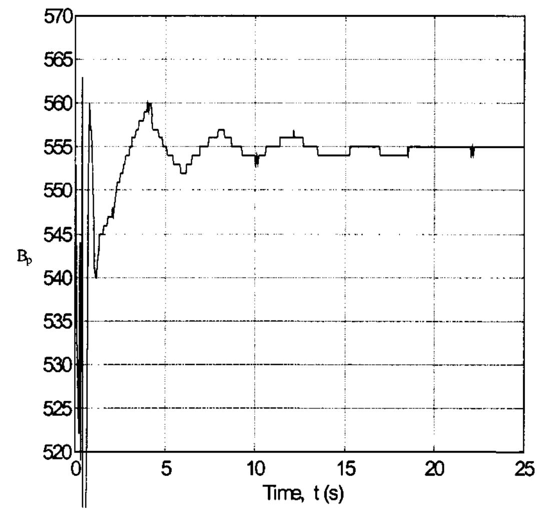

Fig. 12. Self-tuning parameter B_p.

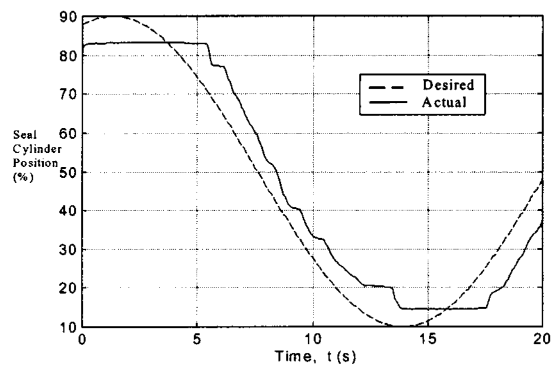

Fig. 13. Conventional cylinder sine wave position response.

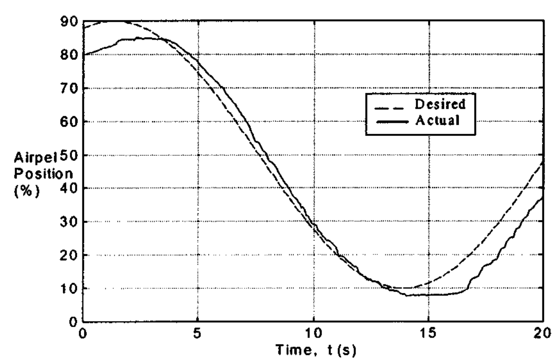

Fig. 14. Airpel sine wave position response.

the force applied externally by the cylinder (measured by the force sensor). Sine wave demand signals were used as frictional effects are more evident when a slow variation in position is required.

Comparing the position response of the conventional cylinder (Fig. 13) and the Airpel cylinder (Fig. 14) both using pole placement control, a much smoother response is achieved by the Airpel cylinder.

Examining the frictional characteristics of the two cylinders indicates the reason for the degradation in response of the conventional cylinder. The conventional cylinder experiences

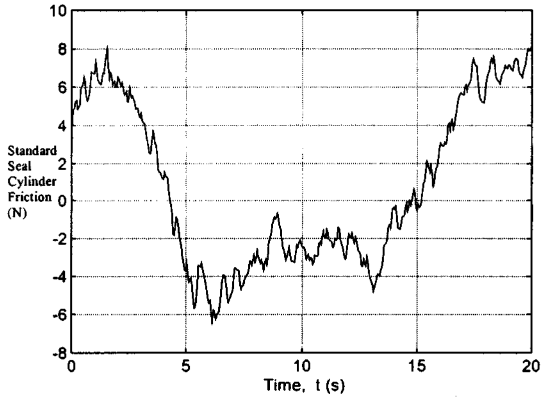

Fig. 15. Conventional cylinder friction characteristics.

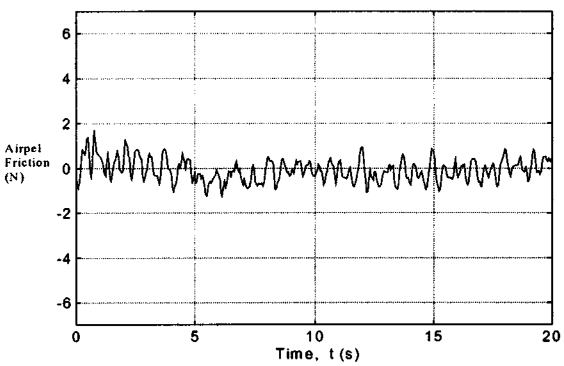

Fig. 16. Airpel friction characteristics.

large levels of friction and a stick-slip motion at low speed (Fig. 15), while the magnitude of the Airpel internal friction is much smaller (Fig. 16).

V. Conclusion

It has been demonstrated that low friction pneumatic cylinders offer real potential for modern precision control systems. The low friction nature enables far greater precision than that obtainable through modern conventional cylinder designs.

The self-tuning strategy shown here provides a method of obtaining correct operating parameters at the start of a session. Identifying an accurate balance pressure is crucial when a constant external force, such as gravity, is present.

References

[1] P. R. Moore, J. Pu, and R. Harrison, "Progression of servo pneumatic toward advanced applications," in *Proc. 5th Int. Fluid Power Workshop*, Bath, U.K., 1992, pp. 347–364.

[2] B. W. Surgenor and H. N. Iordanou, "Electric versus pneumatic servo control: A case study with a gantry crane apparatus," in *AMSE Winter Annu. Meet.*, New Orleans, LA, Nov. 28–Dec. 3, 1993.

[3] W. Backe and O. Ohligschlager, "A model of heat transfer in pneumatic chambers," *J. Fluid Contr.*, pt. 1, vol. 20, pp. 61–78, 1989.

[4] J. Pu, C. B. Wong, and P. R. Moore, "Acceleration characteristics of servo controlled pneumatic cylinder," *ASME, Fluid Power Syst. Technol.*, vol. 3, pp. 119–130, 1996.

[5] D. Ben-Dov and S. E. Salcudean, "A force controlled pneumatic actuator," *IEEE Trans. Robot. Automat.*, vol. 11, no. 6, pp. 906–911, Dec. 1995.

[6] Y. Ishida and A. Fujiwara, "An LQI control for pneumatic cylinders with disturbance observer," in *Proc. IASTED Int. Conf. Robot. Manufact.*, Honolulu, HI, Aug. 19–22, 1996.

[7] Y. Ishida, A. Fujiwara, and K. Katsumata, "An LQI control for pneumatic cylinders using multilayer neural networks," *J. Phys. A*, vol. 38, no. 2, 1997.

[8] Y. Ishida, X. Bao, and J. Song, "An application of MNN trained by MEKA for position control of a pneumatic cylinder," in *IEEE Int. Conf. Neural Networks*, vol. 2, 1997, pp. 829–833.

[9] Y. Ishida, F. Katsumata, and A. Fujiwara, "Neural network based adaptive I-PD controller for pneumatic cylinder," in *SICE '95*, Sapporo, Japan, July 26–28, 1995, pp. 1281–1284.

[10] M. Shih and S. Tseng, "Pneumatic servo-cylinder position control by PID-self tuning controller," *JSME Int. J.*, ser. C, vol. 37, no. 3, pp. 565–572, 1994.

[11] K. Hamiti, A. Voda-Besancon, and H. Roux-Boisson, "Position control of a pneumatic actuator under the influence of stiction," *Contr. Eng. Practice*, vol. 4, no. 8, pp. 1079–1088, 1996.

[12] B. McDonell and J. Bobrow, "Adaptive tracking control of an air powered robot actuator," *J. Dyn. Syst., Measurement, Contr.*, vol. 115, pp. 427–433, Sep. 1993.

[13] M. Shih and Y. Huang, "Pneumatic servo-cylinder position control using a self-tuning controller," *JSME Int. J.*, ser. 2, vol. 35, no. 2, 1992.

[14] M. E. Austin, J. A. Cozens, and B. B. Seedhom, "Motion control for robotic physiotherapy," in *Movic 98'*, vol. 3, Switzerland, 1998, pp. 1203–1206.

[15] R. Richardson, M. E. Austin, and A. R. Plummer, "Development of a physiotherapy robot," in *Proc. Int. Biomechatron. Workshop*, Apr. 19–21, 1999, , pp. 116–120.

[16] K. Astrom and B. Wittenmark, *Computer-Controlled Systems, Theory and Design*, 3rd ed. Englewood Cliffs, NJ: Prentice-Hall, 1997, pp. 165–223.

[17] N. D. Vaughan and A. R. Plummer, "Robust adaptive control for hydraulic servosystems," in *ASME Winter Annu. Meet.*, Dallas, TX, Nov. 25–30, 1990.

[18] M. Gabermann, "Near frictionless air cylinders provide precision pneumatic motion control system," *Power Conversion Intell. Motion*, vol. 21, no. 11, pp. 48–51, 1995.

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