# Fuzzy Control with Friction Compensation for a Pneumatic Positioning System

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Abstract: In this paper, a fuzzy control with friction compensation is developed to deal with a nonlinear pneumatic positioning system characterized with friction, unknown system model, and external disturbance. In order to enhance the positioning accuracy, a control scheme is designed for compensating the friction effect of the moving stage. Positioning experiments based on the derived control strategy were performed to show and validate the proposed control performance. As two experimental examples of positioning results in a total of 30 experimental trials for the stepwise input positioning controls, the positioning accuracy with less than 30nm was verified for both forward and backward actuations with step commands. Hence, the control scheme provided in this paper that could significantly improve the positioning performance of a traditional pneumatic positioning system is demonstrated.

## 1 INTRODUCTION

Pneumatic positioning device is one of the most important facilities in automation industry with major applications found in end positions control. However, due to the nature of the air medium being compressible and the friction force existing on sliding surfaces being nonlinear, it is very difficult to achieve high-precision position control using pneumatic actuating devices. With the need of improving the positioning accuracy, many studies were largely performed in implementing suitable controllers with different strategies. In order to improve the positioning performance of pneumatic positioning systems, many control methods have been proposed, such as sliding mode control (Paul et al., 1994; Song and Ishida, 1996; Korondi and Gyeviki, 2006), observer-based adaptive sliding mode control (Liu et al., 2013), adaptive multilayer neural network control (Gross and Rattan, 1998), fuzzy PWM control (Shih and Ma, 1998), and the scheme of pneumatic system combined with piezoelectric actuators (Liu et al., 2004; Chiang et al., 2005; Liu and Jiang, 2007). In addition, it has been also reported as effectiveness to compensate the stick-slip phenomenon by adding a velocity compensation signal to the servo valve (Pai and Shin, 2003) and by using a piezoelectric dither (Liu et al., 2011).

In this paper, a fuzzy control with friction compensation is proposed to achieve the high positioning performance for a pneumatic positioning system. Furthermore, it is proven that the proposed control scheme can obtain the positioning accuracy with less than 30nm in an experimental pneumatic positioning system.

## 2 PNEUMATIC POSITIONING SYSTEM

The pneumatic positioning system is schematically shown in Figure 1 and the photograph of experimental equipment is shown in Figure 2. A pneumatic cylinder (Airpel, ø10×12mm) is fixed to the base. The target object of sliding table with a dimension of 35×25×35mm rests on the V-grooved base. The pneumatic cylinder is controlled by a proportional valve (Festo, MPYE-5-M5-010B). A 12-bit digital-to-analog (D/A) converter is used to transfer the control command to the proportional



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valve (PV) via a power amplifier. A non-contact type linear encoder (Renishaw, RGH25F2000) with the resolution of 10 nm is mounted beside the sliding table and the displacement of sliding table is measured by the linear encoder through digital input/output (DIO) ports. To avoid environmental disturbance, the experimental setup is set on an anti-vibration air table.

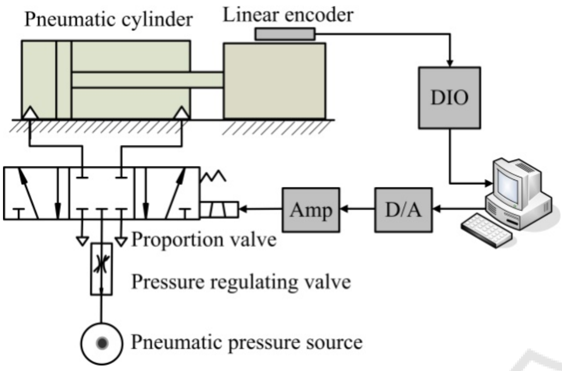



Figure 1: Pneumatic positioning system.

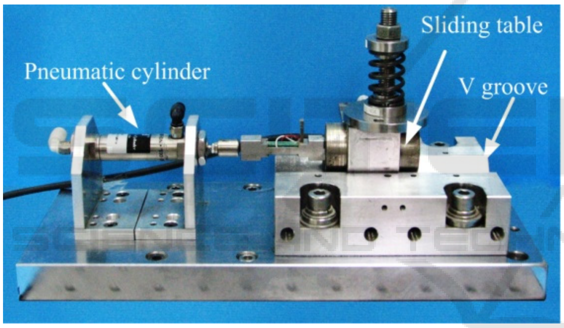



Figure 2: Photograph of the experimental equipment.

## 3 FUZZY CONTROL WITH FRICTION COMPENSATION

Due to the factors of air compressibility, the moving friction, and the external disturbance, the pneumatic positioning system is usually considered as a kind of nonlinear time-varying system with dead-zone input caused by the proportional valve. An exact mathematical model of pneumatic positioning system is difficult to be constructed and obtained for designing a suitable controller specified in terms of a concise mathematical model. Hence, a fuzzy control which can provide an effect means of dealing with the approximate and inexact model of the controlled system is applied to control the pneumatic positioning system in this paper. The framework of fuzzy controller can be composed of four parts, fuzzification, inference mechanism, defuzzification, and knowledge base, as shown in Figure 3.

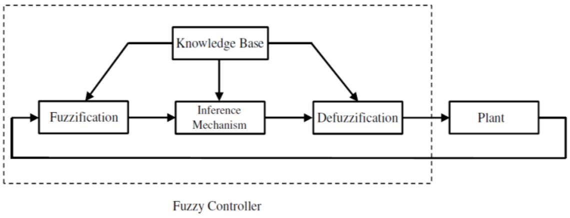



Figure 3: Fuzzy controller in the overall control structure.

Defining a displacement tracking error as

$$e(t) = x_d(t) - x(t) \qquad (1)$$

where $x(t)$ is the sliding table displacement and $x_d(t)$ is the reference command. In this paper, the fuzzy controller is built by considering the tracking error $e(t)$ and its variation $\dot{e}(t)$ as premises variables. For practical implementation, the membership functions are chosen with triangular shapes for the fuzzy variables, as shown in Figure 4.

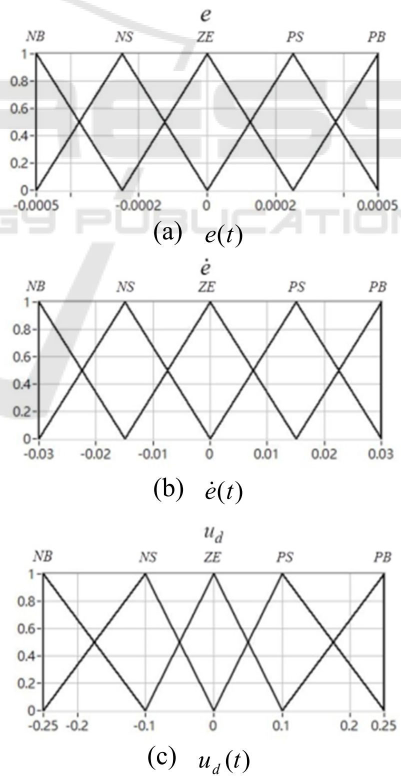



Figure 4: Membership functions.

Labels fuzzy sets NB, NS, ZE, PS, and PB respresent negative big, negative small, zero, positive big, positive small, respectively and their corresponding membership functions are depicted in Figure 4. The Mamdani fuzzy inference method is used in this paper. The inference rule is described as follows:

$$\textit{IF input } A_i \textit{ is } \tilde{A}_i \textit{ and input } B_i \textit{ is } \tilde{B}_i \textit{ THEN output } O_i \textit{ is } \tilde{O}_i$$

where $A_i$, $B_i$, and $O_i$ are input variables and output variable of fuzzy control system. $\tilde{A}_i$, $\tilde{B}_i$ and $\tilde{O}_i$ are fuzzy sets representing input and output of fuzzy control system, respectively. Then, the fuzzy rule table is established in Table 1.

Table 1: The rule table.

| $u_d$ ($\dot{e}$ \ $e$) | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|
| NB | NB | NB | NS | NS | ZE |
| NS | NB | NS | NS | ZE | PS |
| ZE | NS | NS | ZE | PS | PS |
| PS | NS | ZE | PS | PS | PB |
| PB | ZE | PS | PS | PB | PB |

The output of the fuzzy controller is still a linguistic variable. As a plant under control requires a nonfuzzy value of control, the fuzzy control output must be converted into a numerical value by a so-called center of area method (COA). In this method, the defuzzification is carried out by computing the center of area of the consequence fuzzy sets resulting from the inference mechanism. All supports of fuzzy sets are considered in calculating the output. The output equation is

$$u_0 = \frac{\sum_{i=1}^{n} \max(\tilde{O}_i \cdot w_i)}{\sum_{i=1}^{n} w_i} \tag{2}$$

where $w_i$ is the membership value and $\tilde{O}_i$ is the output of inference mechanism.

As shown in Figure 5, the proposed control scheme is composed of a fixed voltage, a fuzzy controller, and a friction compensator in this paper. The controller output gives a bigger preset fixed voltage into the system to reduce the rise time while the control system has a bigger tracking error which is bigger than a preset value (i.e. $|e(t)| > c_1$) or to overcome the static friction in the beginning. When the tracking error converges to be equal to or smaller than the preset value (i.e. $|e(t)| \le c_1$), the controller output is switched from the fixed voltage part to the fuzzy control with friction compensator. Firstly, the fuzzy control is applied to produce the input value $u_0$. The fuzzy control method has been described previously. While the tracking error reduces gradually, the output of fuzzy control also follows the tracking error to reduce gradually. The sliding table will not move under the effect of friction and then it results in a bigger tracking error. In order to overcome this problem, there is a design strategy for compensating the friction effect to achieve a more precise positioning accuracy. Hence, the friction compensator start to work when the tracking error is bigger than a preset value (i.e. $|e(t)| > c_2$).

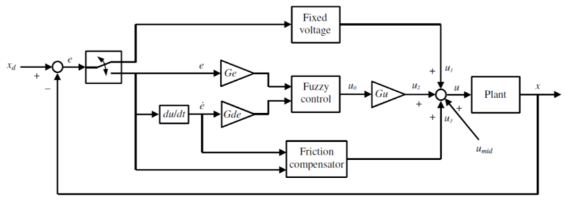



Figure 5: Block diagram of fuzzy control with friction compensation.

# 4 EXPERIMENTAL RESULTS

In the experimental analysis and validation of the position control performance for the proposed control scheme on the pneumatic positioning system, two step-typed reference command signals are set as:

Experiment 1: 5000μm for 0~6 second, 10000μm for 6~12 second, and 5000μm for 12~18 second.

Experiment 2: 8000μm for 0~6 second, 6000μm for 6~12 second, and 10000μm for 12~18 second.

The fixed voltages and control gains are set and displayed in Table 2 for experiments 1 and 2.

Table 2: Fixed voltage and Control gains.

| Control values | Experiment 1 | Experiment 2 |
|---|---|---|
| Fixed voltage | 0.15V, -0.1V | 0.25V, -0.08V |
| *Ge* | 1 | 1 |
| *Gde* | 1 | 1 |
| *Gu* | 2 | 1.2 |

Preset values $c_1$ and $c_2$ of tracking error for switching control and starting friction compensator are chosen to be equal to 0.5mm and 20nm, respectively. For the friction compensator, the schematic diagram of friction compensation design is shown in Figure 6.

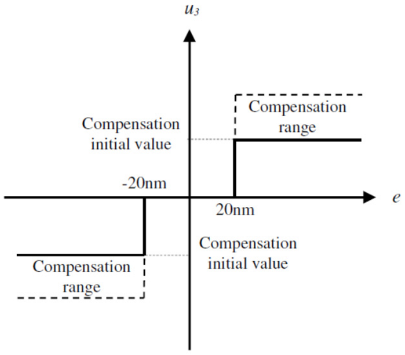


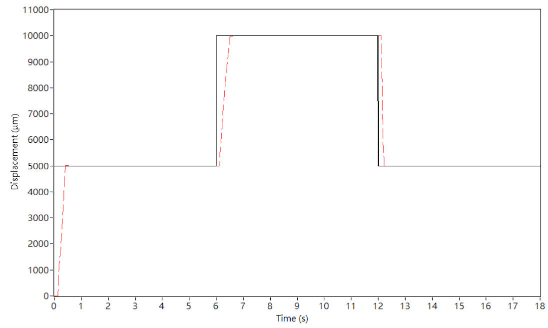

Figure 6: Schematic diagram of compensation design.

All the compensation values are set and displayed in Table 3 for experiments 1 and 2. The increasing value or the reducing value is the raising quantity or reducing quantity for every 0.005 second in experiments.

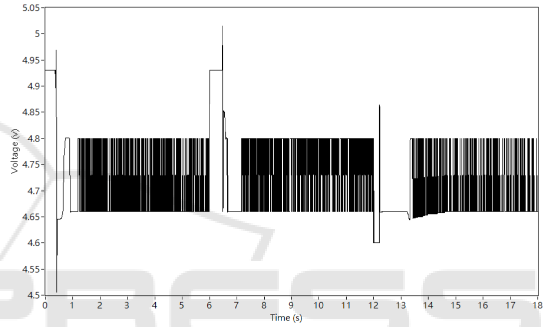
Table 3: Compensation Design Parameters.

| Compensation Parameters | Compensation Values (Experiment 1) | Compensation Values (Experiment 2) |
|---|---|---|
| Compensation Range ( $e > 20\text{nm}$ ) | 0.07V~0.13V | 0.08V~0.12V |
| Compensation Initial Value ( $e > 20\text{nm}$ ) | 0.07V | 0.08V |
| Increasing Value ( $e > 20\text{nm}$ ) | 0.005V | 0.003V |
| Decreasing Value ( $e > 20\text{nm}$ ) | -0.005V | -0.005V |
| Compensation Range ( $e < -20\text{nm}$ ) | -0.07V~-0.03V | -0.035V~-0.02V |
| Compensation Initial Value ( $e < -20\text{nm}$ ) | -0.03V | -0.02V |
| Increasing Value ( $e < -20\text{nm}$ ) | 0.005V | 0.001V |
| Decreasing Value ( $e < -20\text{nm}$ ) | -0.002V | -0.001V |

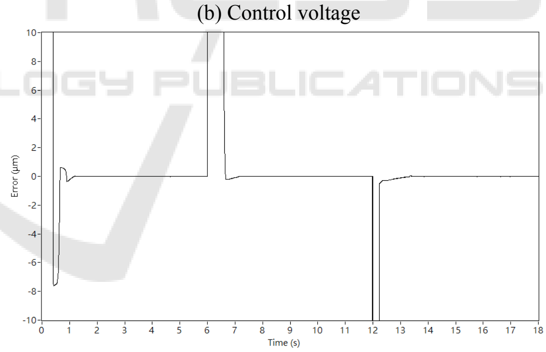
Figures 7 and 8 show that the experimental results of positioning control were performed in Experiments 1 and 2, respectively. From the displacement responses of sliding table shown in Figure 7 (a) and Figure 8 (a), it is indicated that the sliding table can reach the target position in 1 second. Control input voltages of proportion valve are displayed in Figure 7 (b) and Figure 8 (b). Figure 7 (d) and Figure 8 (d) shows that all the steady-state errors are smaller than 30nm in Experiments 1 and 2. It is indicated distinctly that the proposed control scheme can achieve a high positioning accuracy. In addition, since positioning stability is an important performance index for control system, a total of 30 experimental trials for Experiment 1 and Experiment 2 were performed individually. It is noted that all the steady-state error with smaller than 30nm are confirmed in all experiment trials.



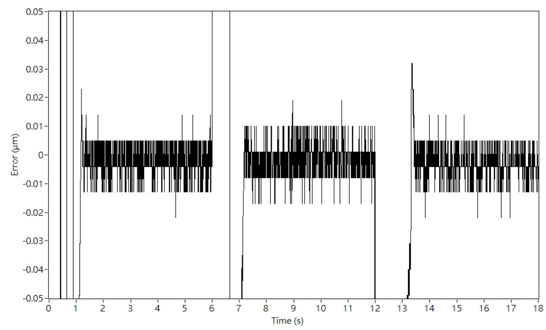

(a) Sliding table displacement and reference command.




(b) Control voltage

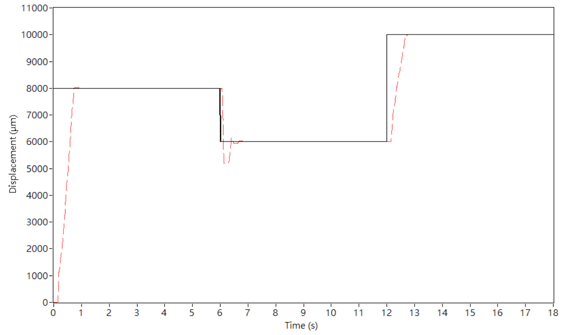



(c) Tracking error ( $\pm 10\mu\text{m}$ range)

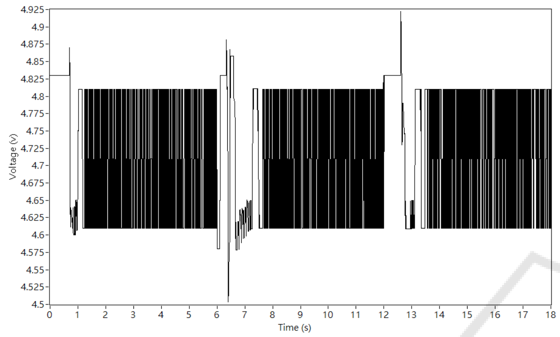



(d) Tracking error ( $\pm 50\text{nm}$ range)

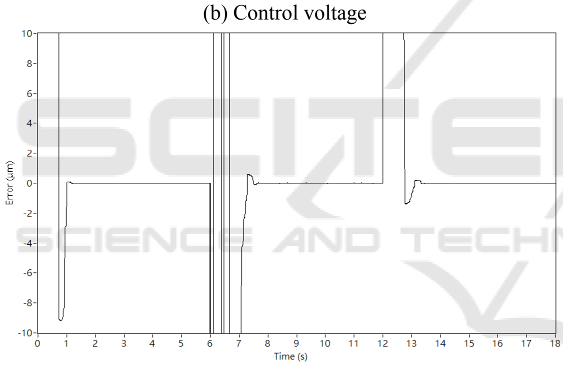
Figure 7: Time responses of fuzzy control with friction compensation in experiment 1.



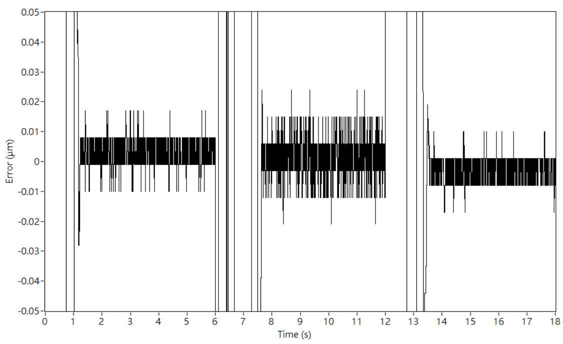

(a) Sliding table displacement and reference command.




(b) Control voltage




(c) Tracking error ($\pm 10\mu m$ range)




(d) Tracking error ($\pm 50nm$ range)

Figure 8: Time responses of fuzzy control with friction compensation in experiment 2.

# 5 CONCLUSIONS

In this paper, a control scheme of fuzzy control with friction compensation was proposed and applied to the pneumatic positioning system. Through experimental examinations, the proposed control scheme that could significantly improve the positioning performances in the pneumatic positioning system was demonstrated and confirmed. Main results are given as follows,

(1) The fuzzy control with friction compensation could be successfully applied to the pneumatic positioning system with the positioning accuracy under nanometer order.

(2) According to 30 experimental positioning trials for stepwise forward and backward actuation commands, the positioning accuracy with less than 30nm on the pneumatic positioning system was verified in this paper.

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