Fuzzy Self-Adaptive Sliding Mode Control for Pneumatic Cylinder Rod-Piston Motion Precision Control.

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Abstract. This paper presents the Fuzzy Self-Adaptive Sliding Mode Controller (FSASMC) designed to control a pneumatic cylinder rod-piston motion and precision. The pneumatic system is widely used in the industry due to its advantages such as high weight to power ratio, high traveling speed, clean fluid medium, and cost-effective in terms of price and maintenance. However, due to the high nonlinearity behavior of pneumatic system, the position control of the pneumatic system is still a challenging task. The most critical part of controlling the pneumatic system with various motion is in giving a stable pressure in chambers, while the rod-piston motion is precisely controlled with any shape of inputs with minimum friction. Therefore, FSASMC is proposed to cater to this matter with fast responses through Sliding Mode Control (SMC) and dynamic stability in pressures through Fuzzy Self-adaptive tuning using Fuzzy Logic Control (FLC). The proposed control system is verified, and analysis was emphasized on steady-state error, velocity, pressure in pneumatic cylinder chambers, and frictional force. Simulation results show that the proposed controller approach performing fast-tracking error on pneumatic rod-piston motion with a very low steady-state error, no oscillation and stable in air pressures.

1. Introduction
The pneumatic system is one of the standard actuators in industrial automation with advantages of high power to weight ratio, cost-effective in terms of price and maintenance, simple structure, and cleanliness fluid medium. However, the pneumatic system has difficulty in high accuracy control due to its high nonlinearity behaviors, such as friction, non-smooth nonlinearities of pneumatic valve and compressibility of air. These will results in very low stiffness leading to the low natural frequency and low damping system as well [1]. On the other hand, position control of pneumatic system performance such as cylinder rod-piston positioning, is limited to a variety of parameters and disturbances. Recently, many researchers have extensively studied in this area emphasized on developing various control approaches for pneumatic precision of motion from the model-free to model-based approach or maybe both. Model-free control approach such as PID-based control [2-7], fuzzy logic control (FLC) [8-10] and neural network (NN) based control [11, 12] are actively developed and implemented on actual system. It is different to the model-based approaches such as sliding mode control (SMC) [13-15] and model predictive control (MPC) [16, 17] that have a minimal number in practical usage due to the depending on the accurate model plant system information. However, this type of control playing a main role in giving more robust in handling a highly nonlinear system such as the pneumatic system and gets practical with the advance of computer processing technology.

SMC is one of the popular model-based approaches due to its simplicity and has immune advantages over the parameter of uncertainties and external disturbance [18]. The behavior can be seen when the
states of the system have reached the sliding surface; they are no longer affected by the dynamics of the system but had governed by sliding surface dynamics. Thus, this control system becoming endurance to any uncertainties parameters of the input signal. However, the chattering phenomenon by the SMC system will cause high-frequency switching with dynamic behavior. In order to overcome this problem, various method of solutions has been proposed such as boundary layer in [19-21], adaptive law in [22-24], fuzzy sliding mode integration in [25], and neural network fuzzy sliding integration in [26]. The most critical part in controlling the pneumatic system with various motion is in giving a stable pressure in chambers while the rod-piston is precisely controllable with any shape of control inputs and minimum friction as well.

Therefore, this research has taken the initiative to propose an alternative approach in combination with both SMC and FLC named Fuzzy Self-Adaptive SMC (FSASMC) control. The proposed FSASMC is designed to provide robust control on the pneumatic proportional valve with a double-acting cylinder (PPVDC) for rod-piston motion with any shapes of control input. The paper is organized as follows: Section 2 discussed the mathematical model of the pneumatic system. Section 3 discussed the proposed control system design. Section 4 will be focused on the result and analysis performances for the pneumatic rod-piston precision as well as other pneumatics parameters. The conclusion is drawn in Section 5.

2. Fuzzy Self-Adaptive Sliding Mode Controller Design

In order to achieve the precise motion of the pneumatic rod-piston, it is essential to focus the stable chamber pressure in producing smooth and faster changes on the piston motion. Therefore, the combination of both SMC and FLC named as Fuzzy Self-Adaptive SMC (FSASMC) control is proposed to cater to both fast response and uncertainties in PPVDC rod-piston motion control.

![Figure 1. Overall PPVDC system model plant](image)

Sliding Mode Control (SMC) is the model-based control methodology that requires the plant model information to synthesize the controller regarding the desired performance characteristics. As mentioned earlier, a PPVDC model plant is used in this study emphasized on controlling the precision of the rod-piston. Therefore, the SMC design need to consider all the dynamics system in PPVDC as shown in Figure 1, that contains; cylinder rod-piston dynamics, frictional force dynamics, pressure dynamics, and valve dynamics [10]. The configuration of the closed-loop of the pneumatic position control using SMC control contains two major components; equivalent control component and a robust control component. Regarding the PPVDC model plant in [10], the state-space of the model plant can be represented in the following standard canonical form that consider major states of PPVDC system. It includes both normalized mass flow rate of the fixed area of the valve orifice \( \phi_1 \) and \( \phi_2 \), acceleration of the rod-piston.
\( \dot{x}_{rpx} \) with both internal and external force frictions, \( F_f \) and \( F_L \), as well as total mass \( M \) of the systems [10] and effective area of valve orifice \( A_{pv} \) as from Equation (1) to (3) as follows:

\[
\dot{x}_{rpx} = f(x) + g(x)A_{pv} \tag{1}
\]

\[
f(x) = \frac{r \dot{x}_{rpx} - \dot{F}_f + \dot{F}_L}{M} \tag{2}
\]

\[
g(x) = \frac{Y_1 \phi_1 + Y_2 \phi_2}{M} \tag{3}
\]

where,

\[
r = \frac{k_P A_1^2}{V_1} + \frac{k_P A_2^2}{V_2}, Y_1 = \frac{kRT_A}{V_1}, Y_2 = \frac{kRT_A}{V_2}
\]

with \( k, R \) and \( T \) are representing the ratio of specific heats of air, ideal constant of gas and absolute temperature of the air respectively. \( M = M_L + M_{sp} \) is total weight between load mass \( (M_L) \) and rod-piston mass \( (M_{sp}) \). On the other hand, \( V_1 \) and \( V_2 \) are both the volume of air of each chamber respectively. \( P_i (i=1,2) \) are pressure in both cylinder chambers, effective area of valve orifice \( (A_{pv}) \) can be expressed as in Equation (4) as follows [27]:

\[
A_{pv} = w x_{pv} \tag{4}
\]

where \( \omega \) is the valve orifice gradient area and \( x_{pv} \) is the valve orifice spool position, in which \( x_{pv} \) can be expressed as Equation (5) as follows;

\[
x_{pv} = k_{pv} u \tag{5}
\]

with the control input signal \( (u) \) can be described with the Equation (6) as follows;

\[
u = \frac{A_{pv}}{w k_{pv}} \tag{6}
\]

As expressed in Equation (1), \( f(x) \) and \( g(x) \) are the nonlinear dynamics function and control gain of the system, respectively, which also known as uncertainties parameters. The sliding surface \( (s) \) in the SMC component is expressed as Equation (7) as follows:
\[ s = \left( \frac{\partial}{\partial t} + \lambda \right)^2 e \]  

(7)

where \( \lambda \) is the positive finite constant of the control gain bandwidth and the rod-piston position error is defined as Equation (8) as follows:

\[ e = x_{rp} - x_d \]  

(8)

where \( x_{rp} \) and \( x_d \) are the rod-piston position and desired position, respectively. By differentiating Equation (7), first order of sliding surface (\( \dot{s} \)) can be expressed as Equation (9) as follows:

\[ \dot{s} = \ddot{e} + 2\lambda \dot{e} + \lambda^2 \dot{\dot{e}} \]  

(9)

and by substituting Equation (1) into Equation (9), \( \dot{s} \) can be expanded as Equation (10) as follows:

\[ \dot{s} = \left[ f(x) + g(x)A_{pv} - \ddot{x}_d \right] + 2\lambda \dot{e} + \lambda^2 \dot{\dot{e}} \]  

(10)

Let’s \( \dot{s} = 0 \) and equivalent control component (\( A_{pv, eq} \)) can be derived as Equation (11) as follows:

\[ A_{pv, eq} = \frac{\ddot{x}_d - f(x) - 2\lambda \dot{e} - \lambda^2 e}{g(x)} \]  

(11)

Then, the robust control law is obtained by adding a robust control component (\( A_{pv, ro} \)) as Equation (12) and (13) as follows:

\[ A_{pv} = A_{pv, eq} + A_{pv, ro} \]  

(12)

\[ A_{pv, ro} = -\frac{G_{ro}}{g(x)} \cdot \text{sat} \left( \frac{s}{\varphi} \right) \]  

(13)

with \( \varphi \) represents the thickness of the boundary layer. Thus, \( A_{pv} \) with SMC system for PPVDC rod-piston control can be expressed as Equation (14) by substituting Equation (11) and (13) into Equation (12), and the overall SMC design for this system is shown as Figure 2.
2.1. Fuzzy Self-Adaptive Design

For the proposed FSASMC, a multiple-input multiple-output (MIMO) FLC is designed for dynamic tuning on both $\lambda$ and $G_m$ of SMC as shown in Figure 3. The Mamdani-type [28] is used where the input and output of the fuzzy system are linguistic variables with two attendances and two consequences. These two input variables linguistic are from the rod-piston position error ($e$) as expressed in Equation (18) and rate change of rod-piston position error ($\Delta e$) (see Figure 4(a)), while $\lambda$ and $G_m$ are the outputs gains for SMC that obtained by fuzzy inference calculations as shown in Figure 4(b). The linguistic variables of input and output parameters of FLC are designed with seven sections by the membership function, as shown in Table 1. For the input variables; negative large (NL), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM) and positive large (PL) while for the output are very-very small (VVS), very small (VS), small (S), medium (M), large (L), very large (VL) and very-very large (VVL) are set. FLC works on the knowledge base containing IF-THEN sets linguistic rules for undetermined predicates and fuzzy control mechanism. In this design, the base rule with two antecedences and two consequence are as follows:

“If $e$ is NL and $\Delta e$ is NL, then $\lambda$ and $G_m$ is M and M, respectively”.

The MIN-MAX method was used for the fuzzy inference method while the defuzzification method used for the FSASMC controller is the center of gravity (COG) method which can be expressed as Equation (15) as follows:

$$
\xi^* = \frac{\int_{\xi^1}^{\xi^n} \xi \mu(\xi) d\xi}{\int_{\xi^1}^{\xi^n} \mu(\xi) d\xi}
$$ (15)
where $\zeta^* = \lambda$, $n$ is the number of rules, $\mu$ represents the fuzzy membership function values from $\mu_i...\mu_n$ and $u$ is the crisp output signal. The domain of fuzzy subset is in range of $\{-1 1\}$ and the overall triangular shape function is selected for membership function input and output as shown in Figure 4. Figure 5 shows the control surface plot of $f_0 = \lambda = G_{ro}$.

Table 1 Designed Fuzzy rules set for $\lambda$ and $G_{ro}$

| $\lambda$ | $e$ |
|-----------|-----|
| $G_{ro}$  |     |
| NL        | M   | S   | VS  | VVS | VS  | S   | M   |
| M         | M   | S   | VS  | VVS | VS  | S   | M   |
| NM        | L   | M   | S   | VS  | S   | M   | L   |
| L         | L   | M   | S   | VS  | S   | M   | L   |
| NS        | VL  | L   | M   | S   | M   | L   | VL  |
| VL        | VL  | L   | M   | S   | M   | L   | VL  |
| $\Delta e$ | ZO  |     |     |     |     |     |     |
| VVL       | VL  | L   | M   | L   | VL  | VVL |
| VVL       | VL  | L   | M   | L   | VL  | VVL |
| PS        | VL  | L   | M   | S   | M   | L   | VL  |
| VL        | VL  | L   | M   | S   | M   | L   | VL  |
| PM        | L   | M   | S   | VS  | S   | M   | L   |
| L         | M   | S   | VS  | S   | M   | L   |
| PL        | M   | S   | VS  | VVS | VS  | S   | M   |
| M         | S   | VS  | VVS | VS  | S   | M   |
3. Results and Analysis

The proposed FSASMC is verified with the PPVDC model through simulation using MATLAB/SIMULINK environment. For the performance and analysis purposes, the designed pneumatic plant also simulated with the fine-tuned PID controller. On the other hand, the payloads were set in simulation for 5kg as an external disturbance to the system. As shown in Figure 6, rod-piston position with FSASMC shows a fast step response in achieving the desired position with just a minor overshoot and no undershoot if compared to the PPVDC with PID controller. Despite the presence of payloads, FSASMC can handle the vibration in less than 1.5 secs compared to the PID in the PPVDC position before steady states. A similar performance happens on multi-step input simulations where FSASMC able to control the precision of rod-piston displacement with minor oscillation and a concise rising time.
The vibration or oscillation reduction can be related to both cylinder chambers at every change of displacement values (refer Figure 7), as shown in Figure 8. PPVDC rod-piston movement with FSASMC can control with a bit high pressure at about 0.03MPa higher than PPVDC with PID, but minor oscillations at every change of the rod-piston displacement as shown in Figure 8(a) and 8(b). Both pressures on chambers shows only a single spike that a bit high on each change of rod-piston displacement period (refer Figure 7) for the case of PPVDC with FSASMC as compared to PPVDC with PID. The effect of vibration in-cylinder also can be seen in velocity performance, as shown in Figure 9 in which seems proportional to the internal frictional forces, as shown as viscous frictional forces in Figure 10.
Figure 8. Sample of pressure in cylinders’ chamber performances between FSASMC and PID on PVDC; (a) Cylinders’ Chamber 1, (b) Cylinders’ Chamber 2

Table 2. Performance and robustness of the controllers

| Performance      | Controller | PID       | FSASMC    |
|------------------|------------|-----------|-----------|
| Rise Time        | 0.0737 s   | 0.1000 s  |
| Settling Time    | 1.5499 s   | 1.1747 s  |
| Overshoot        | 3.6353 mm  | 0.5510 mm |
| Undershoot       | 1.2290e-34 mm | 0 mm     |
| Peak             | 0.1036 m   | 0.1006 m  |
| Peak Time        | 1.3185 s   | 1.2540 s  |

As shown in Figure 11, massive spike and high oscillation occurred for PPVDC displacement speed with PID control if compared to the PPVDC with proposed FSASMC that only single high pulse on each change of displacement value. Table 2 shows a summary of PPVDC rod-piston precision performances between the PID and FSASMC control system.

Figure 9. Sample of PPVDC velocity performances with multistep responses; PID vs. FSASMC
4. Results and Analysis

The proposed FSASMC control system for PPVDC rod-piston position control is presented and verified. The simulation and analysis were done by comparing both FSASMC with a conventional PID controller on PPVDC rod-piston precision. The overall results show that the FSASMC controller performs better than the conventional PID controller on PPVDC rod-piston precision in minor steady-state error with almost no oscillation in the rising period as compared to the PID controller. For the multi-step response case, the frictional force from the internal friction of the cylinder is controllable with FSASMC when the velocity of the piston able to be rapidly sustained and suppressing oscillation (frictional force $\rightarrow$ static force). Unstable pressure in chambers by internal friction contributes to the uncontrollable vibration in the first rising period of the step response (every change of displacement), and FSASMC able to reduce this scenario by left only one overshoot on piston motion. The single spike does not affect much of the displacement performance as discussed in section 3. As for the future task, the proposed FSASMC will be applied on the actual PPVDC system, and some modifications for improvements may apply according to the hardware constraints and all other uncertainties.

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