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INCREMENTAL FUZZY SLIDING MODE CONTROL OF PNEUMATIC MUSCLE ACTUATORS

Chia-Jui Chiang and Ying-Chen Chen

Department of Mechanical Engineering
National Taiwan University of Science and Technology
No. 43, Sec. 4, Keelung Rd., Da'an Dist., Taipei City 106, Taiwan
cjchiang@mail.ntust.edu.tw

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Abstract. *The pneumatic muscle actuator (PMA) is a pliable pneumatic actuator characterized by its extremely high power-to-weight and power-to-volume ratios. The PMA is considered one of the most promising actuators especially for the applications that require greater proximity between the humans and the robots. Fast and precise control of the PMA, however, is difficult to achieve due to its highly nonlinear and hysteresis behaviors. In order to overcome those problems and achieve accurate and consistent tracking performance of a PMA actuated manipulator, an intelligent nonlinear feedback control algorithm is proposed in this paper. Specifically, the fuzzy logic based controller is chosen to cope with the complex and nonlinear dynamics of the PMA and a sliding surface is adopted to reduce the number of fuzzy rules. The integral action of the fuzzy sliding mode controller (FSMC) is implemented using the incremental algorithm to reduce the oscillations. Experimental results show that, compared to the conventional proportional-integral-derivative (PID) controller, the proposed control strategy achieves more accurate performance tracking sinusoidal reference trajectories of various frequencies.*

Keywords: Pneumatic muscle actuator, Fuzzy logic control, Sliding mode control, Nonlinear control

1. **Introduction.** The pneumatic muscle actuator (PMA) is one of the most promising pneumatic actuation systems for new types of industrial robots [1]. The advantages of PMA include high power-to-weight and power-to-volume ratios, cleanness, ease of maintenance, inherent safety, low cost and ready availability. As a result, the PMA is potentially one of the most promising actuators for the applications that require greater proximity between the humans and the robots. Due to the compressibility of the air and the elasticity of the PMA, however, it is difficult to achieve fast and precise control of the PMA [2].

In order to realize satisfactory control performance, many control methods have been proposed to solve these challenging problems in controlling the PMA. The complex and nonlinear dynamics of the PMA make it a challenging yet appealing system for model-based control design. In [3], a second order nonlinear differential equation is used to describe the PMA dynamics, based on which a gain scheduling tracking controller is developed. In [4], a physics-based nonlinear model is developed, based on which a sliding mode control approach is applied to achieving robustness against model uncertainties and disturbances. In [5], on-off solenoid valves are used to control the PMA pressures in the inner loop and a PID controller is augmented in the outer loop to achieve position tracking of a single degree of freedom manipulator. In [6], hysteresis compensation is implemented in a cascaded control strategy to improve the position tracking performance

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of a single PMA-mass system. In [13], a Prandtl-Ishlinskii model is used to approximate the hysteresis behavior of a dual PMA system, based on which a feedforward controller is developed. The feedforward controller combined with a sliding mode feedback controller is then applied to tracking control of the dual PMA system with the performance examined at 0.125 Hz. In [14], an integral-type sliding mode controller combined with a gray-box-model-based estimator is employed for position tracking control of a one-dimensional PMA-spring system at 1 Hz. In [16], a 3rd-order sliding surface is used in the sliding mode control structure for the position tracking control of a single PMA up to 1 Hz. In [17], a PID controller in the inner loop and a feedback/feedforward control structure in the outer loop are augmented for position tracking of a single PMA with fast switching valves up to 0.1 Hz.

On the other hand, the intelligent control methods have been proposed to control the PMA without detailed modeling of its complex dynamics. In [7], the PMA is modeled as a mass-spring-damper system and the coefficients for the spring and damper are represented by a nonlinear fuzzy model. In [8], the PID control gains are switched based on the external load estimate obtained from a learning vector quantization neural network so as to achieve precise position control under various external loads. In [9], the PID feedback controller is augmented with a feedforward controller developed based on a fuzzy model and the control performance is examined at various load conditions. In [10], a feedforward/feedback control structure is adopted and each sub-controller is developed based on fuzzy logic. The tracking results of a PMA actuated robot up to 0.2 Hz are shown. In [11], extra degrees of freedom are incorporated into a PID-based control structure and the tracking performance is examined up to 0.25 Hz. In [15], a feed-forward controller is combined with a self-organizing fuzzy feedback controller for tracking control of a loaded PMA up to about 0.15 Hz. In [19], a feedforward/feedback control structure is applied to tracking control of a two-dimensional PMA-spring robot up to 0.5 Hz. The adaptive learning feedforward controller is developed based on neural network and modified differential evolution algorithm, and two PID feedback controllers are augmented for independent control of the two muscles.

In an effort to achieve accurate tracking performance of a PMA actuated manipulator, a nonlinear feedback control algorithm is proposed in this paper. Specifically, the fuzzy-logic based controller is chosen to cope with the complex and nonlinear dynamics of the PMA and a sliding surface is adopted to reduce the number of fuzzy rules. The integral action of the fuzzy sliding mode controller (FSMC) is implemented using the incremental algorithm for improvement of the tracking performance. Experimental results show that, compared to the conventional proportional-integral-derivative (PID) controller, the proposed control strategy achieves more accurate performance tracking sinusoidal reference trajectories of various frequencies.

The rest of this paper is organized as follows. Section 2 describes experimental setup of the one axis pneumatic muscle actuated robot arm used in the study. Section 3 introduces the incremental fuzzy sliding mode control (IFSMC) algorithm developed in the paper. Section 4 examines the performance of the PMA actuated manipulator tracking sinusoidal trajectories of various frequencies. Section 5 concludes this paper and points out possible extensions of this work.

2. **Experimental Setup.**

Figure 1 shows the schematic diagram of a one axis PMA actuated manipulator. The architecture consists of two pneumatic muscle actuators (FESTO MAS-20-200N) with 20 mm internal diameter and 200 mm nominal length. The two muscles are labelled with PMA_1 and PMA_2 in Figure 1. The manipulator arm weighs around 104 g and the length l is 235 mm. The pneumatic muscle actuated system is supplied

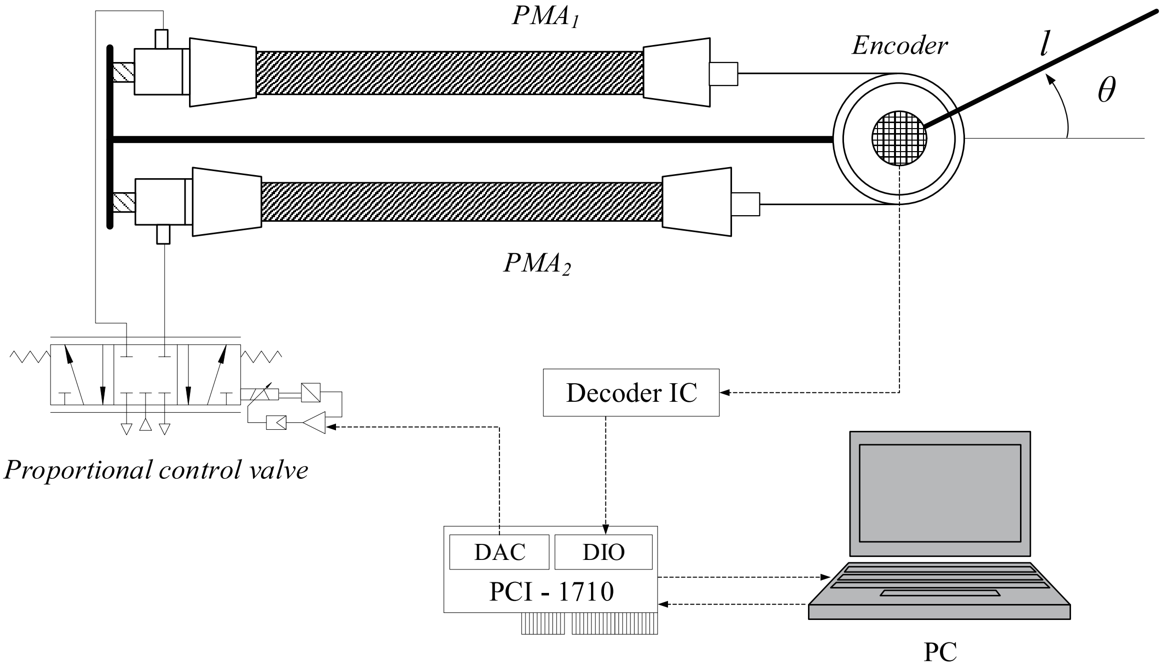

FIGURE 1. Schematic diagram of the PMA actuated system

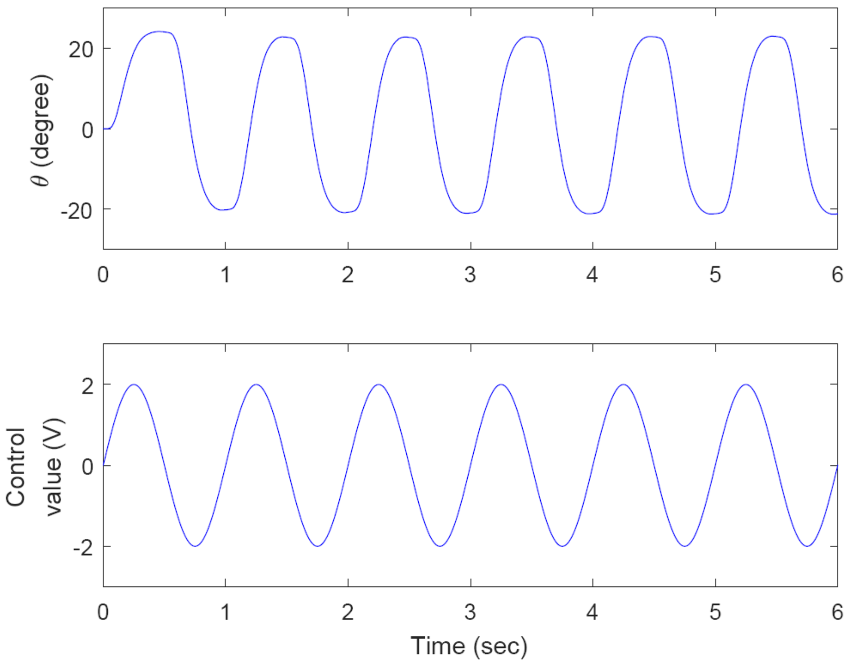

FIGURE 2. Open-loop test of the PMA actuated system

with compressed air regulated to 4 bar. A proportional control valve (Festo MPYE-5-1/8-CF-010-B) is used to control the flow in and out of the two PMAs and thus the rotating motion. The rotating angle θ is measured using an encoder (Nemicon HES-2048-2MD) with resolution of 2048 pulses per revolution and the digital signal decoding is carried out using a decoder IC (HTCL-2020). The controller is implemented in a PC with Advantech PCI-1710 board and the sampling time used in the experiments is 10 ms.

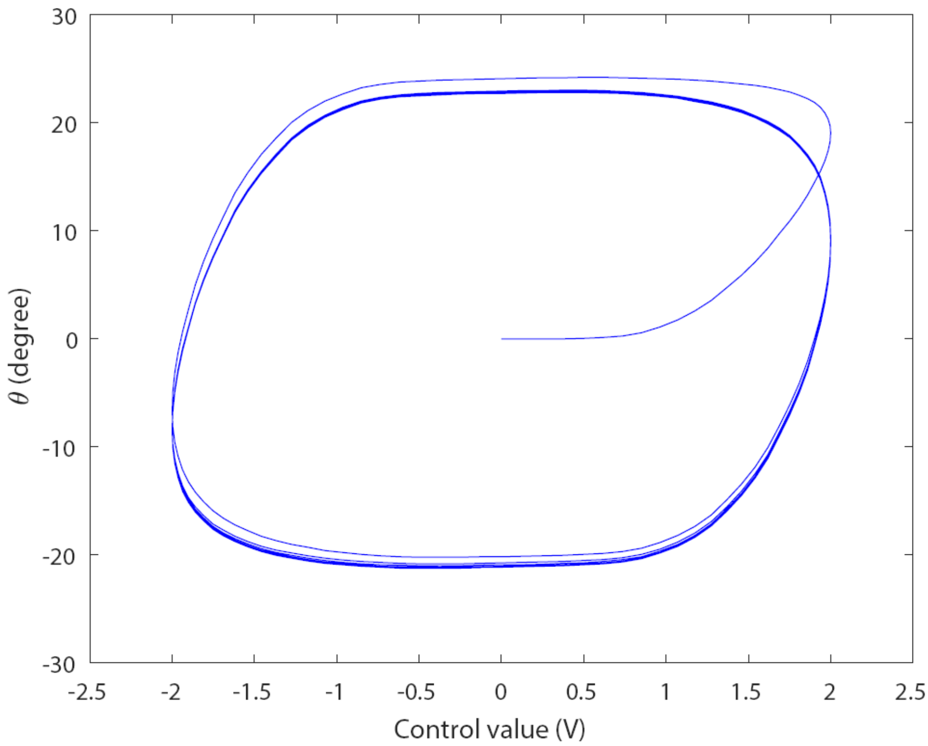

FIGURE 3. Asymmetric hysteresis relation between the rotating angle and the control value in the open-loop test

In order to understand the dynamic characteristics of the PMA actuated manipulator, open loop test is conducted. Figure 2 shows the open-loop response of the rotating angle θ when a sinusoidal control command of 1 Hz is applied to the proportional control valve. The manipulator gradually reaches its extremes as one of the muscles is inflated while the other is deflated. The extreme positions reached at both ends ($+23.16°$ and $-21.36°$ at steady state respectively) are apparently different due to the stiffness difference between the two muscles. As a result, Figure 3 shows that the hysteresis behavior between the rotating angle θ and the control input is asymmetric. The asymmetric hysteresis behavior results from the nonlinear dynamics in the dual-PMA system, the stiffness difference between the two muscles, and the nonlinearity in the proportional control valve. The complex and nonlinear dynamics in the PMA actuated manipulator thus make this control problem a challenging yet appealing task. As a result, a fuzzy-logic based controller is proposed in Section 3.

3. **Incremental Fuzzy Sliding Mode Control (IFSMC) Algorithm.** The block diagram of the incremental fuzzy sliding mode control (IFSMC) algorithm is shown in Figure 4. Fuzzy-logic based controller is chosen to cope with the complex and nonlinear dynamics of the PMA actuated manipulator shown in Section 2. A sliding surface is adopted to reduce the dimension of the input space and the number of fuzzy rules [12]. The integral action of the fuzzy sliding mode controller (FSMC) is implemented using the incremental algorithm to reduce the oscillations.

The conventional fuzzy logic control theory involves fuzzification, a fuzzy rule base, a fuzzy inference engine and defuzzification. Conventionally, the fuzzy rule base depends both on the error e and error difference Δe, resulting in complicated fuzzy rules and membership functions. To reduce the dimension of the input and thus the number of fuzzy rules, a fuzzy sliding surface $s = 0$ is introduced with the sliding variable s defined

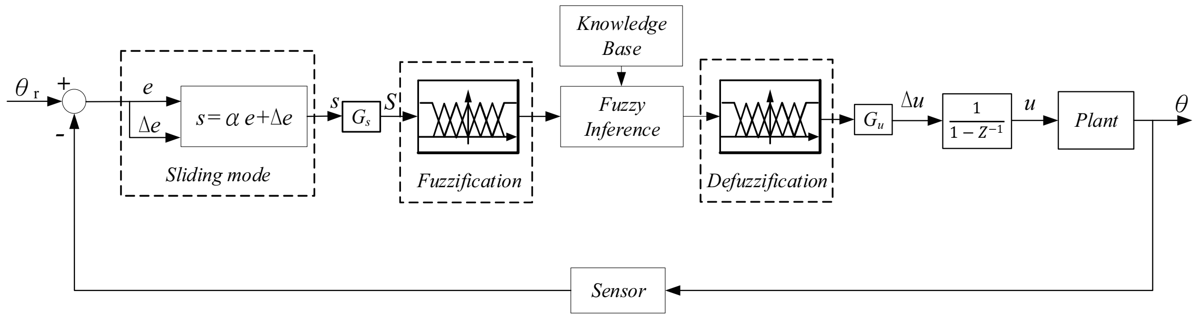

FIGURE 4. Block diagram of the incremental fuzzy sliding mode controller (IFSMC)

as follows

$$s(k) = \alpha e(k) + \Delta e(k) \tag{1}$$

where the tracking error $e(k) = \theta_r(k) - \theta(k)$ is the difference between the reference angle θ_r and the measurement of the angle θ, $\Delta e(k) = e(k) - e(k-1)$ is the error difference and α is a strictly positive constant which determines the bandwidth of the sliding mode control law and is typically limited by the mechanical properties of the system, time delay in the actuators and the available computing power [18]. In practice, the tuning of this single scalar is often conducted experimentally. The control objective is then to force the system into the sliding surface so that tracking error is reduced. The normalized input variable S to the fuzzification process is obtained by multiplying a scaling factor G_s to the sliding variable s:

$$S = G_s \cdot s. \tag{2}$$

The choice of number of fuzzy sets is generally a balance between precision and transparency. In this paper, in order to achieve accurate tracking performance of the PMA actuated manipulator, the universe of the variable S is partitioned into nine fuzzy sets $[NVB_s\ NB_s\ NM_s\ NS_s\ ZO_s\ PS_s\ PM_s\ PB_s\ PVB_s]$ characterized by triangular membership functions. Similarly, the nine fuzzy sets for the control output are defined as $[NVB_u\ NB_u\ NM_u\ NS_u\ ZO_u\ PS_u\ PM_u\ PB_u\ PVB_u]$. The linguistic variables represented by those labels of fuzzy sets are defined in Table A.1. The fuzzy inference implements fuzzy control rules by using the single input to single output mapping. The defuzzification process is conducted based on the height method (also called center average defuzzifier) to obtain the incremental control value Δu of the fuzzy sliding mode controller.

$$\Delta u = G_u \frac{\sum h_i \cdot y_i}{\sum h_i} \tag{3}$$

where the parameter h_i is the fuzzy membership weighting, y_i is the center point of each fuzzy set, and G_u is the control output gain of the fuzzy sliding mode controller. Finally, the absolute control signal u of the IFSMC can be obtained

$$u(k) = u(k-1) + \Delta u. \tag{4}$$

4. **Experimental Results.** In this section, the tracking performance of the incremental fuzzy sliding mode controller (IFSMC) developed in Section 3 is examined tracking sinusoidal reference trajectories of various frequencies. The fuzzy rule matrices are $[-1.0\ -0.6\ -0.4\ -0.2\ 0\ 0.2\ 0.4\ 0.6\ 1.0]$ for the control input and $[-1.2\ -0.65\ -0.5\ -0.18\ 0\ 0.18\ 0.5\ 0.65\ 1.2]$ for the control output. Figure 5 shows the resulting triangular input membership function and the output singletons. The parameters used in the IFSMC throughout this section are $\alpha = 1$, $G_s = 0.5$ and $G_u = 0.75$. The principles for

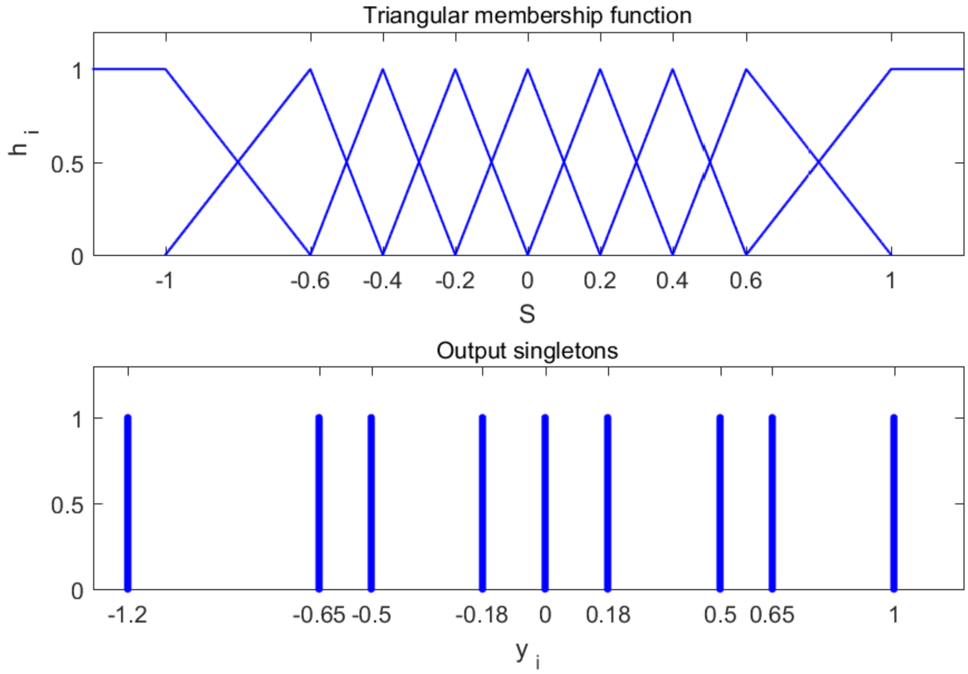

FIGURE 5. Triangular input membership function and output singletons

the tuning of control parameters α and G_s are introduced in Section 3 whereas the control output gain G_u is obtained experimentally via trial-and-error. In order to illustrate the effectiveness of the IFSMC, the closed-loop results with the IFSMC are compared to the results with a conventional PID controller. Specifically, the PID controller is implemented as follows

$$u_{PID}(k) = K_p e(k) + K_i e_i(k) + K_d \Delta e(k). \tag{5}$$

The parameters used in the PID controller are $K_p = 0.15$, $K_d = 0.1$, and $K_i = 0.02$. The principles for the tuning of control parameters K_p, K_d, and K_i are to reduce the maximum error, chattering and rise time at different operating conditions via trial-and-error through experiments. In Section 4.1, the performance of the IFSMC and the PID controller tracking sinusoidal reference trajectories of various frequencies is examined. In Section 4.2, the performance of the IFSMC and the PID controller tracking a sinusoidal reference trajectory of mixed frequencies is examined.

4.1. **Tracking sinusoidal reference trajectories of various frequencies.** In this section, the IFSMC and the PID controller are compared tracking sinusoidal reference trajectories ranging from 0.25 Hz to 1 Hz. Figure 6 shows the experimental results tracking a sinusoidal trajectory of 0.25 Hz in frequency and $\pm 20°$ in amplitude. As can be seen from Figure 6, significantly larger tracking error is observed when the PID control strategy is applied, especially when the manipulator is changing direction, resulting from the hysteresis effect of the dual-PMA system. The IFSMC, on the other hand, is able to compensate for the complex and nonlinear dynamics observed in Section 2 and achieves better tracking performance with maximum tracking error less than 0.46°.

Figure 7 shows the experimental results when the IFSMC and PID are applied to tracking a sinusoidal trajectory of 0.5 Hz in frequency and $\pm 20°$ in amplitude. As can be seen from Figure 7, the PID controller results in significant errors when the manipulator is changing direction and serious oscillatory response is observed while tracking the steeper slope. The IFSMC, on the other hand, is able to quickly compensate for the tracking

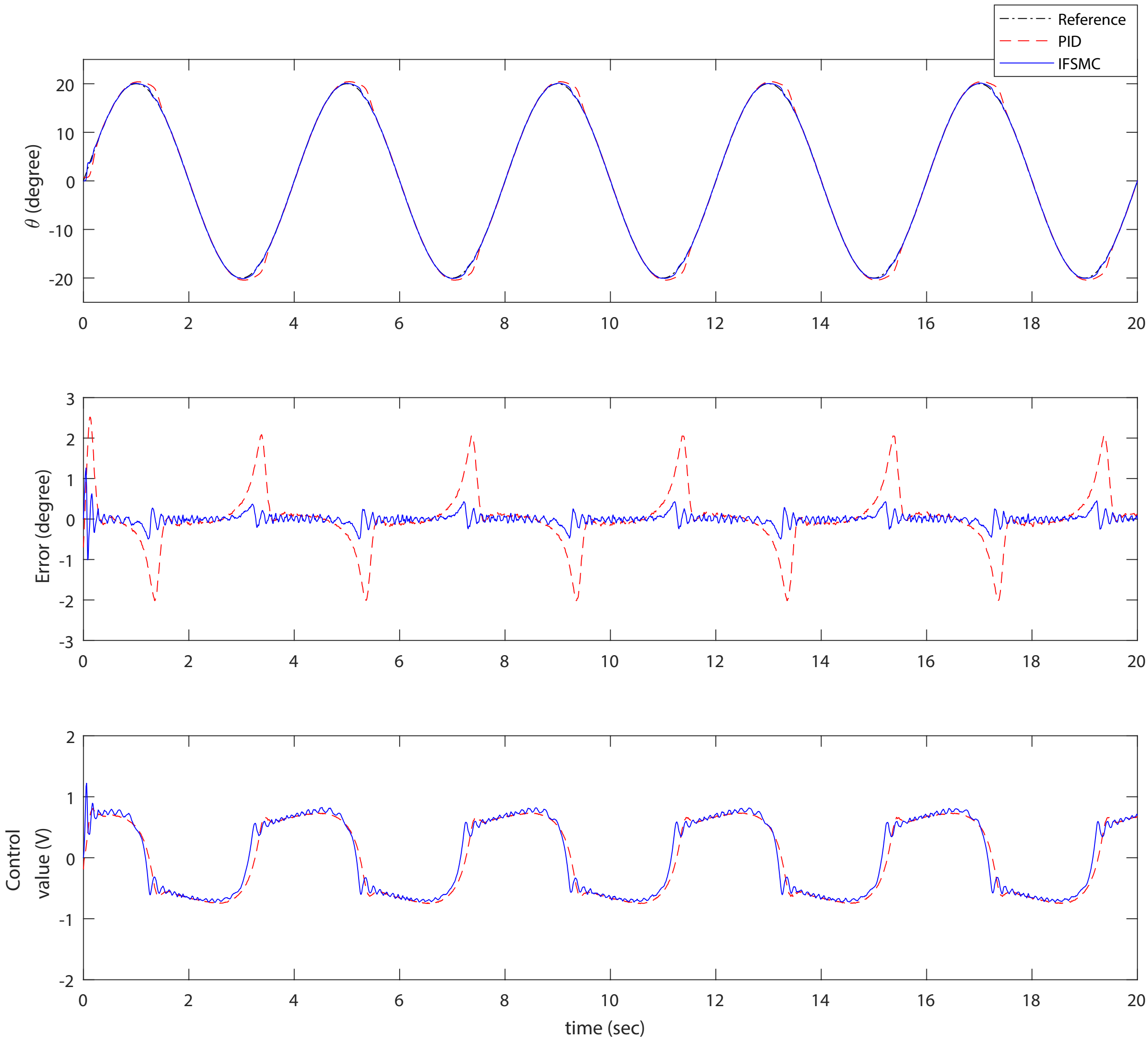

FIGURE 6. Experimental results of IFSMC and PID tracking a sinusoidal trajectory of 0.25 Hz in frequency and ±20° in amplitude

error of the PMA actuated manipulator, especially when the manipulator is changing direction. The maximum tracking error achieved by the IFSMC is less than 1.01°. At the same time, the oscillatory behavior is significantly reduced by the IFSMC while tracking the steeper slopes.

Figure 8 shows the experimental results tracking a sinusoidal trajectory of 1 Hz in frequency and ±20° in amplitude. Figure 8 shows that when PID controller is applied the tracking error can be as large as 8°, resulting from the hysteresis effect of the PMAs. The IFSMC, on the other hand, is able to produce faster control command resulting in significantly better tracking performance. Specifically, the maximum error achieved by the IFSMC tracking the sinusoidal trajectory of 1 Hz is reduced to less than 1.77° at steady state.

Figure 9 summarizes steady state control performance achieved by the IFSMC and the PID controllers tracking sinusoidal reference trajectories of various frequencies. In all the cases we have studied, the IFSMC controller achieves better control performance, especially at higher frequencies. The maximum errors occur when the manipulator is changing directions resulting from the hysteresis effect of the PMAs. The IFSMC controller

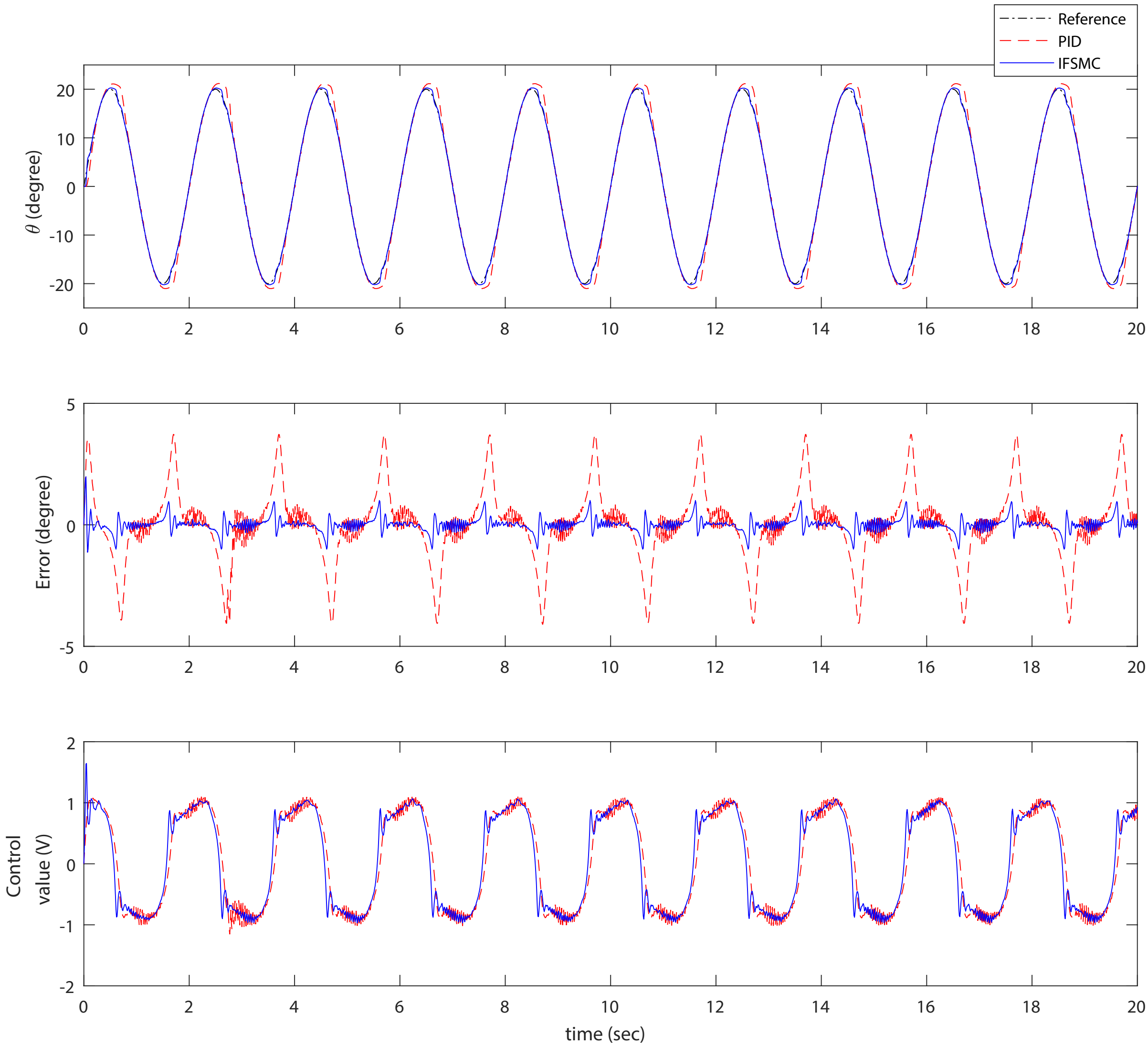

Figure 7. Experimental results of the IFSMC and PID tracking a sinusoidal trajectory of 0.5 Hz in frequency and ±20° in amplitude

achieves reduced errors by compensating for the complex and nonlinear dynamics of the PMA actuated manipulator and generating faster control command to the proportional control valve. At higher frequencies, oscillatory behaviors become noticeable when the PID controller is applied to tracking the steeper slopes. The IFSMC, on the other hand, is able to significantly eliminate the oscillatory behavior. The mean absolute errors (MAEs) in one steady-state cycle achieved by the IFSMC controller summarize the accurate and consistent tracking performance in reducing both the maximum tracking error and the magnitude of oscillation.

4.2. **Tracking a sinusoidal reference trajectory of mixed frequencies.** In this section, we compare the performance of the IFSMC and the PID controller tracking a sinusoidal reference trajectory of mixed frequencies.

$$\theta_r(k) = 15\sin(2\pi f_1 k\Delta t) + 10\sin(2\pi f_2 k\Delta t) + 5\sin(2\pi f_3 k\Delta t) \quad (6)$$

where $f_1 = 0.1$ Hz, $f_2 = 0.3$ Hz, $f_3 = 0.5$ Hz and $t = 10$ ms is the sampling time. In other words, the reference trajectory is a sum of three sinusoids. Figure 10 shows the control performance achieved by the IFSMC and PID controller tracking the sinusoidal trajectory

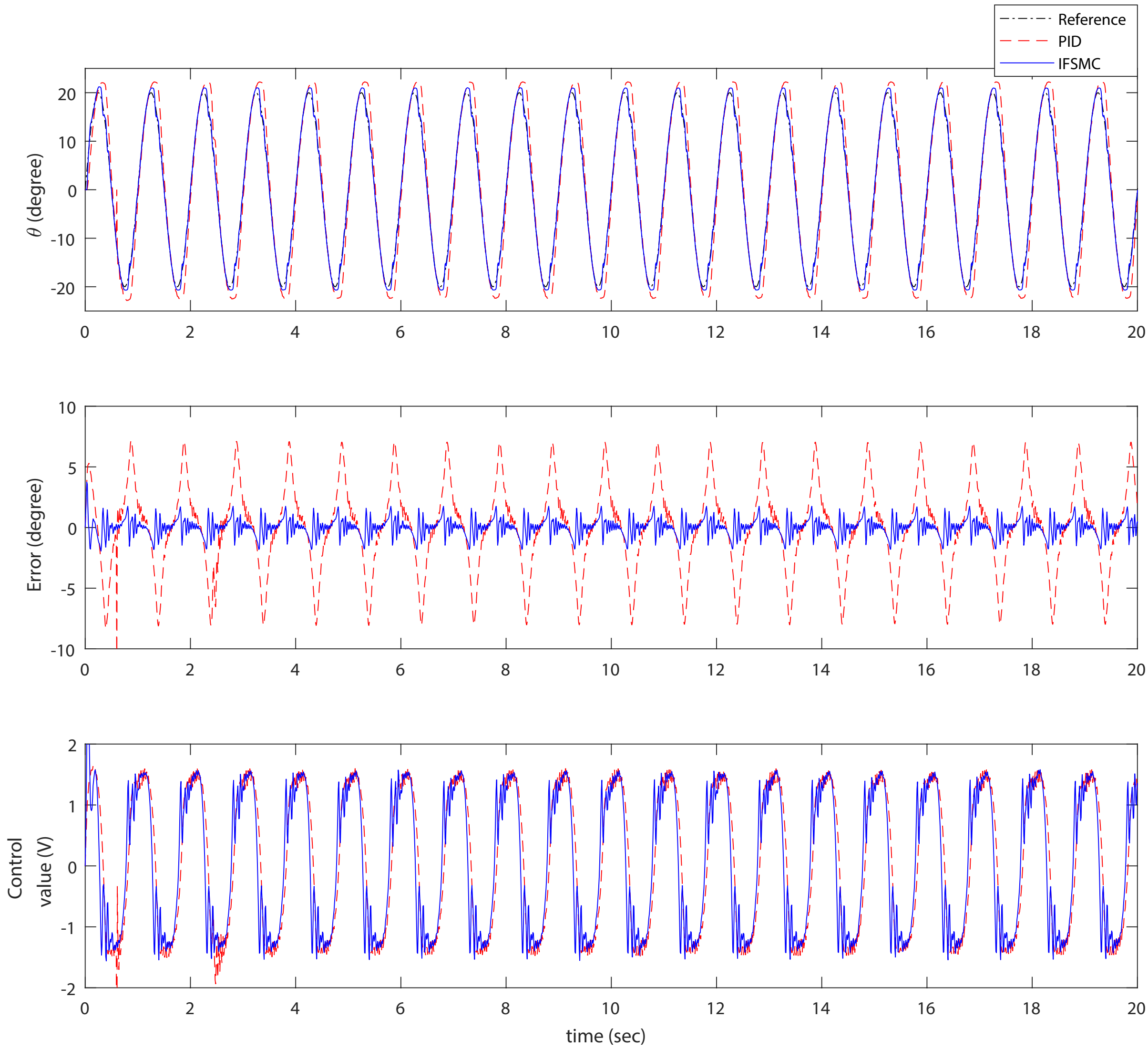

FIGURE 8. Experimental results of the IFSMC and PID tracking a sinusoidal trajectory of 1 Hz in frequency and $\pm 20^{\circ}$ in amplitude

of mixed frequencies. The IFSMC controller still manages to better the performance of the conventional PID controller. On the contrary, when the PID controller is applied, considerably larger tracking errors are observed when the manipulator is changing direction and serious oscillatory behavior is observed while tracking the steeper slope.

5. **Conclusions.** The incremental fuzzy sliding mode controller (IFSMC) developed in this paper achieves more accurate tracking performance compared to the conventional proportional-integral-derivative (PID) controller. The IFSMC strategy provides robustness with reduced number of fuzzy rules whereas the integral action is implemented using the incremental algorithm so as to further improve the tracking performance. Experimental results show that, compared to the conventional PID controller, the proposed control strategy achieves more accurate performance tracking sinusoidal reference trajectories of various frequencies. In the future, an adaptive learning algorithm can be added for auto-tuning of the control gains in the IFSMC so as to achieve accurate performance tracking reference trajectories of even wider frequency ranges.

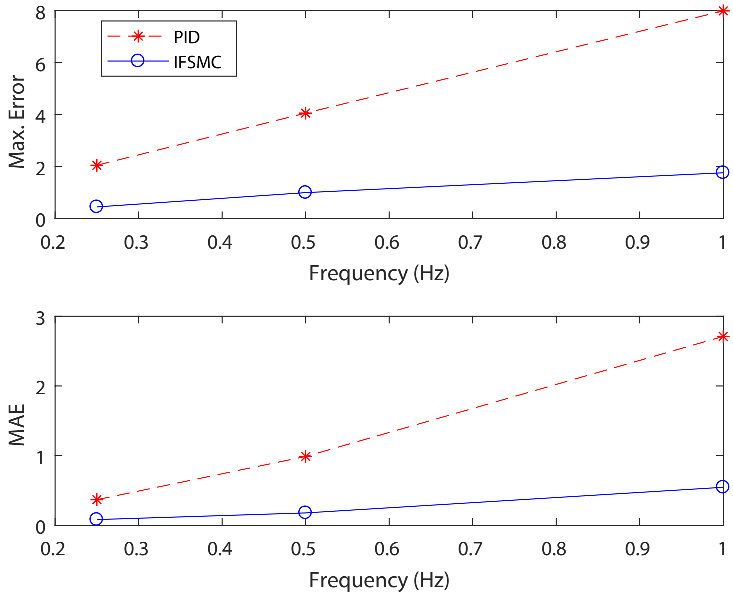

FIGURE 9. The maximum errors and mean absolute errors at steady state when IFSMC and PID are applied to tracking sinusoidal reference trajectories of various frequencies

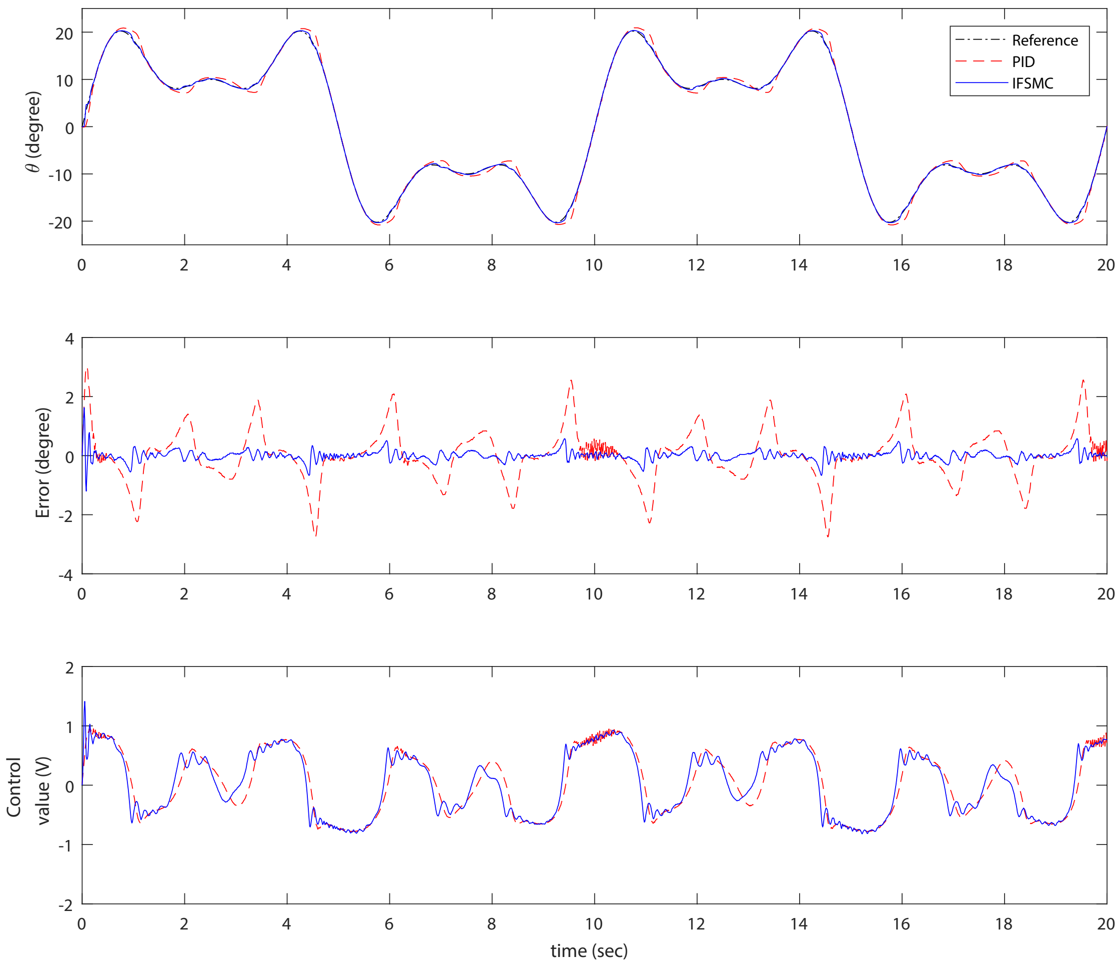

FIGURE 10. Experimental results of the IFSMC and PID tracking a sinusoidal trajectory of mixed frequencies

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Appendix A. See Table A.1

TABLE A.1. List of parameters and their values, if constant

Parameters	Definition	Value
α	Weighting on the tracking error	1.0
θ	Rotating angle of the manipulator arm, degree	
θ_r	Reference angle of the manipulator arm, degree	
G_s	Scaling factor of the FSMC	0.5
G_u	Control gain to the FSMC	0.75
K_d	Differential gain for the PID controller	0.1
K_i	Integral gain for the PID controller	0.02
K_p	Proportional gain for the PID controller	0.15
NB	Negative Big	
NM	Negative Medium	
NVB	Negative Very Big	
PB	Positive Big	
PM	Positive Medium	
PVB	Positive Very Big	
S	Normalized input to the FSMC	
ZO	Zero	
e	Tracking error, degree	
e_i	Numerical integral of the tracking error e, degree-s	
Δe	Error difference, degree	
h_i	The fuzzy membership weighting	
l	Length of the manipulator arm, mm	235
s	Sliding variable	
u	Control command to the proportional control valve, V	
y_i	Center point of each fuzzy set	