ISSN 2229-5518

A Novel Position Control System for 1-DOF Belt Drive System

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Abstract— This paper introduces the design and position control of a 1-DOF belt drive mechanism. The belt type actuator and DC motor include for the mechanical part of the device. In this system, the human-robot contact position need to constant for increase the accurate positioning. In traditional control methods, accurate and good position tracking are often difficult to control. Proxy- based sliding mode control is selected to control the tracking accuracy of 1-DOF belt drive mechanism, that is based on friction compensation. The experimental results show the high precision position tracking and minimize steady-state error can be received due to the proposed method.

Index Terms— Proxy, position control, human-robot interaction, friction, sliding mode controller, belt drive

1 Introduction

VARIOUS industrial applications of mechatronic systems such as CNC machining, rolling, assembling, welding, packaging or material handling and medical application require highly dynamic motions which have to be precisely executed by a machine (e.g. robotic manipulator, conveyor belt, machine-tool or rolling mill). Higher bandwidth of the control loops is needed in order to meet the increasing demands for precision and dynamics of the controlled motion.

1-DOf belt-drive mechanism is designed for precision and accurate trajectory tracking control. Belt drives are widely used in different fields of human activity to transmit the mechanical energy from the rotating shaft to the objects of the control. There are many examples of belt drives implementation in our life such as cars, audio and video devices, computer devices, etc. In industry, such drives can be used for objects control positioning or transportation.

This paper proposes position control of the system. Good tracking accuracy and precision are two essential components demanded in robotic applications. Both of these traits are important since it will lead to good performance of the control system. Additionally, the traditional PID control scheme has oscillations (overshoots and undershoots), discrepancy to the set point (desired) tracking, unexpected results from robot's movement which leads to the motion lag, and so on. By using traditional PID control law, the accurate, safe and overdamped motion cannot be received.

To overcome the imprecision and instability of classical PID control, the suitable controllers are required to stable and precise the trajectory tracking. The derivation of mathematical model and control strategy of the nonlinear sliding mode control (SMC) for 2-DOF parallel manipulator hydraulic servo system in [13], it has high frequency chattering. Many other authors presented the control law of proxy-based sliding mode control (PSMC) scheme [1], [2], [3], [4], [5], and [6]. In normal operation, PSMC can generate accurate, safe and overdamped motion.

In most of the robotic mechanisms, electromechanical actuators such as servo motors are used and that usually face with high friction forces. The effect of friction causes the instability and degrades the system performance. To overcome nonlinear torque which is then scaled and summed into the main feedback loop.

Generalized Maxwell-slip (GMS) friction model used in friction compensation by a switching adaptive controller [7]. Friction compensator presented by authors [8] and [9] that improve the performance of the electromechanical actuator position control. Sliding mode contouring controller that used adaptive friction compensation for 3-DOF machine tools [10]. In this paper describes a proposed position controller that PSMC controller extended with friction compensator. This method attains reliable performance and nosie attenuation than PID and PSMC controllers.

The rest of this paper is organized as follows: the mechanical design of 1-DOF belt drive mechanism is introduced in Section II. In section III, the overviews of control strategies that include proxy-based sliding mode control (PSMC), friction compensation (FC) and proposed position controller. Section IV presents the experimental results and concluding remarks offer in section V.

2 System Overview

To acquire the accurate positioning, the crucial aspect is how to construct the perfect design of the mechanism. The proposed design for the 1-DOF belt drive mechanism is described in Fig. 1.

2.1 Mechanical Desgn

The proposed design is acceptable for 1-DOF belt drive mechanism. This design can easily grip and whoever can easy-to-use. The outside measurements of the proposed design are 16 cmx 3 cmx 3.5 cm for length, height and width respectively.

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ISSN 2229-5518

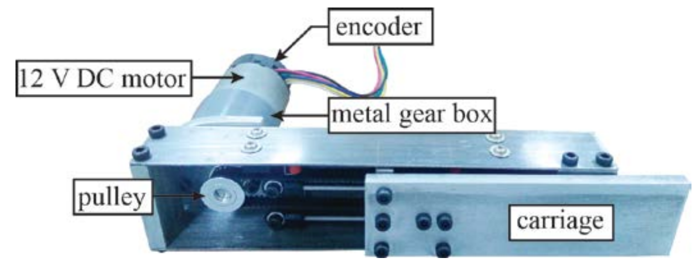


Fig.1. 1-DOF belt drive mechanism

The powerful 12 V brushed DC motor with a 100:1 metal gearbox and an integrated quadrature encoder is fixed on the back side of the device. The resolution of the encoder was 64 counts per revo-lution of the motor shaft, which corresponds to 6533 counts per revolution of the gearbox's output shaft.

The motor turns a set of pulleys and connects with timing belt employed on the shafts. Timing belt drive transforms the rotational motion to linear motion. The frame is attached with 7 cm length and 3 mm of two steel shafts. The carriage on the shafts and timing belt are connected for linear motion. The operator operates the setup, the motor is rotated and the timing belt pulled the sliding carriage. Thereafter, the carriage will be moved up and down along the steel shafts.

By providing the programmable contact position, the device decreases the necessary level of the operator's skill and increase the accurate positioning. This device helped the user to maintain the constant contact position within its usable range of motion. The device can grant the small amount of motion between human-robot interaction.

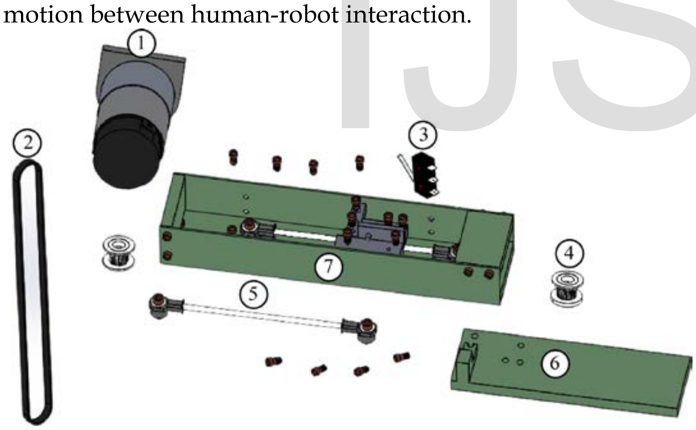


Fig. 2. Exploded View of the Force Control 1-DOF Belt Drive Mechanism

Descriptions of the components of Fig.2 are

- 1 – Pololu 12 V DC servo motor,
- 2 – timing belt drive linear actuator,
- 3 – limit switch,
- 4 – belt pulley,
- 5 – shaft,
- 6 – carriage and
- 7 – protective cover.

3 Control Strategies

This section presents the control laws for use in proposed position controller. Proxy-based sliding mode control that modified the traditional sliding mode control (SMC) and extended the PID controller. The friction compensator reduces the friction effect of the electromechanical actuator.

3.1 Proxy-Based Sliding Mode Control (PSMC)

Nowadays, many control methods have been developed. The PSMC controller can receive accurate position tracking during normal operation. The block diagram of PSMC is illustrated in Fig. 3. In PSMC control law, the actual controlled object is connected with a virtual object called a proxy, through a virtual coupling type PID controller. To track the desired distance, an ideal sliding mode controller controlled the position of proxy. The sliding mode control algorithm used to control the proxy is given by

$$f_{SMC} = F\,\mathrm{sgn}(x_d - q + H(\dot{x}_d - \dot{q})) \quad (1)$$

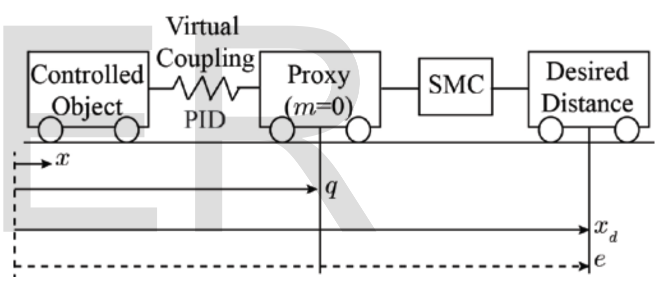
where x_d, q and H are the desired position, the proxy position and time constant. f_{SMC} is sliding mode control force and F denotes the actuator force magnitude limit. The proxy kindly coincides to its desired distance.

The PID type virtual coupling force can be expressed as follows:

$$f_{PID} = K\dot{a} + La + B\ddot{a} \quad (2)$$

where, $a = \int (q - x)dt$ and PID controller gains are K, L and B respectively.

Fig. 3. Principle of PSMC



The equation of motion of the proxy is

$$m\ddot{q} = f_{SMC} - f_{PID} \quad (3)$$

The proxy mass can be set to zero. Thereafter, $f = f_{PID} = f_{SMC}$ is satisfied and the equation (2) and (3) can be rewritten as follows:

$$\sigma = x_d - x + H(\dot{x}_d - \dot{x}) \quad (4a)$$

$$0 = K\dot{a} + La + B\ddot{a} - F\,\mathrm{sgn}(\sigma - \dot{a} - H\ddot{a}) \quad (4b)$$

$$f = K\dot{a} + La + B\ddot{a} \quad (4c)$$

The equations (4) is called the proxy-based sliding mode control (PSMC). Accurate position tracking is achieved and the characteristics of chattering is avoided by PSMC. The control procedure of PSMC is described as follow:

$$\sigma(k) = x_d(k) - x(k) + H\left(\frac{\nabla x_d(k)}{T} - \frac{\nabla x(k)}{T}\right) \quad (5a)$$

$$f^{*}(k) = \frac{B + KT + LT^{2}}{H + T}\sigma(k) + \frac{KH - B + LT(2H + T)}{(H + T)T}a(k-1) - \frac{KH - B + LTH}{(H + T)T}a(k-2) \quad (5b)$$

$$f(k) = F\text{sat}\left(\frac{f^{*}(k)}{F}\right) \quad (5c)$$

$$a(k) = \frac{(2B + KT)\,a(k-1) - Ba(k-2) + T^{2}f(k)}{B + KT + LT^{2}} \quad (5d)$$

where x_d and x are the desired position and the actual position of the controlled object. Discrete time index and backward difference operator are denoted by k and ∇. F (k) is the output force of PSMC controller. H represents time constant and T is sampling interval. The values of controller parameters for the device is shown in TABLE 1. PSMC reduce overshoots and distance error rather than traditional position controllers.

The PSMC controller has been applied to the position control belt drive mechanism, the performance was boosted and good tracking results were achieved. Nevertheless, its tracking accuracy was poor and PSMC controller cannot exactly reach the desired distance and it also have the tracking error. The performance of PSMC controller has steady-state tracking error and inaccurate motion because of the friction effect of geared actuator. The friction effect is disturbance in device movement and the accurate position tracking cannot achieve.

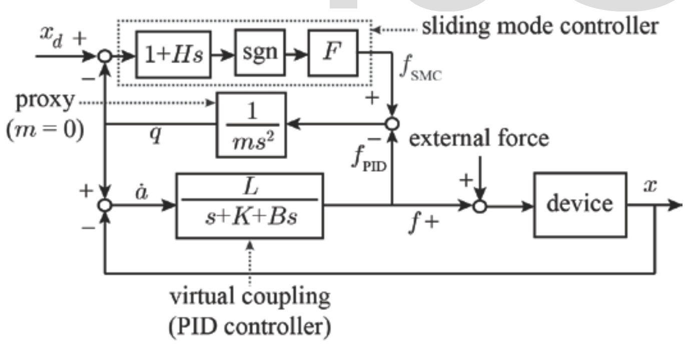


Fig.4. Block diagram of PSMC Controller

TABLE 1
PID and PSMC contrllers' Parameters

Parameter	K	B	L	F	H
Unit	N/m	Ns/m	N/ms	N	s
Value	200	0.8	20	255	0.2

3.2 Friction Compensation

Friction is a nonlinear phenomenon, an interacting force between objects in touch. Friction directly influences the system tracking accuracy and stability. Its effects are very important aspect in electromechanical systems. To achieve accurate control of electromechanical systems, friction modeling and identification are firstly needed to test. The elimination of friction upgrades the control performances. For presliding regime, the ramp type actuator torque was applied to the device. This is shown as follow:

$$\tau = \begin{cases} rt & \text{if } rt < \tau_{max} \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

where r = 0.1 Nm/s

For sliding region, the another set of experiments was performed to identify the friction force as a function of the velocity. By using proxy-based sliding mode control (PSMC), the distance of the device can control to track sinusoidal motion.

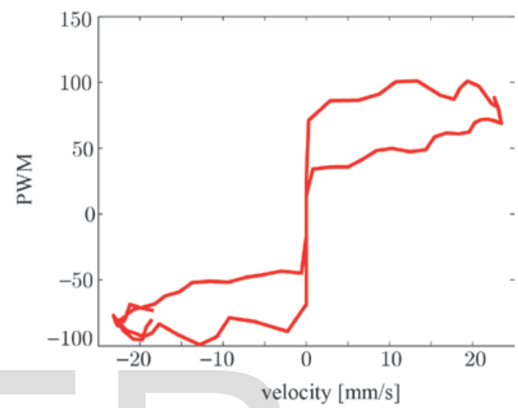


Fig.5. Obtained data from friction identification

In this experiment, some different distances were recorded and the frequency of sinusoidal motion is 0.2 Hz. The example of obtained data values is described in Fig. 5. By collecting the data of the half of the maximum velocity and the median value of torque of its correspondent torque values from Fig. 5, the friction-velocity characteristics curve (Fig. 6) is acquired.

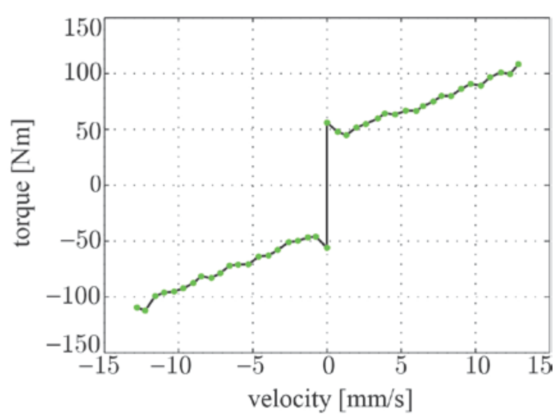


Fig.6. Friction-velocity charateristics curve

Here, the angular velocity was obtained by differentiating the encoder signal. The principle of friction identification is the evaluating of motor voltage while motor has constant angular velocity. Friction forces of the device can compensate by following equation:

$$F = \begin{cases} F_{c+} + (F_{s+} - F_{c+})\exp\left(-\left(|v|/v_{s+}\right)^{\delta+}\right) & \text{if } v > 0 \\ -F_{c-} - (F_{s-} - F_{c-})\exp\left(-\left(|v|/v_{s-}\right)^{\delta-}\right) & \text{if } v < 0 \end{cases} \quad (7)$$

where, F_s, F_c and F denoted static friction force, coulomb friction force and friction force. The relative velocity is v, the Stribeck velocity is v_s and δ represents the empirical constant. The parameter values will be used in friction compensation presented in TABLE 2.

TABLE 2
Parameters for Friction Compensation

Parameter	F_{s+}	F_{c+}	v_{s+}	δ_+	Fs-	F_{c-}	v_{s-}	δ_-
Unit	Nm	Nm	mm/s	_	Nm	Nm	mm/s	_
Value	56	45	1.305	1	56	46	0.755	1

3.3 Proposed Position Controller

The target of the proposed controller is to achieve accurate position tracking with overcome the effects of friction. The PSMC controller is not enough to receive accurate trajectory tracking. Proposed position controller, which is composed of proxy-based sliding mode control and friction compensation. The input to the proposed position controller is the encoder signal x, and the output is the torque u (k). The equation of proposed position controller is:

$$u(k) = f(k) + F \quad (6)$$

where, u (k) denoted the proposed controller output force, f (k) is PSMC output force and F is friction force. The block diagram of the proposed position control system is demonstrated in Fig. 7.

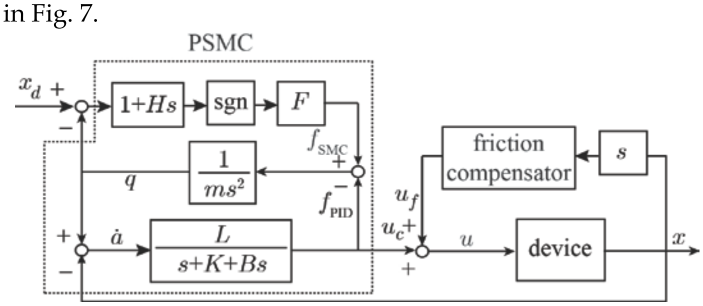


Fig.7. Block diagram of proposed position control scheme

4 Experimental Results

To prove the profit of proposed control method, 1-DOF belt drive mechanism, shown in Fig. 1 is used. The control laws are implemented on an Arduino (MEGA) 2560 type micro-controller with 16-MHz clock frequency. The PC and micro-controller connected with USB cable. The PC is used for data monitoring and off-line data processing.

In this control system, the device's actual distance x is compared with desired distance x_d because the device will be operated due to the contact position between human-robot interaction. The major characteristics of the proposed position control scheme are proxy-based sliding mode control and the friction compensation. By using the following schemes, the experi-ments were performed:

- PID: (2)
- PSMC: (5)
- PSMC+FC:(8)

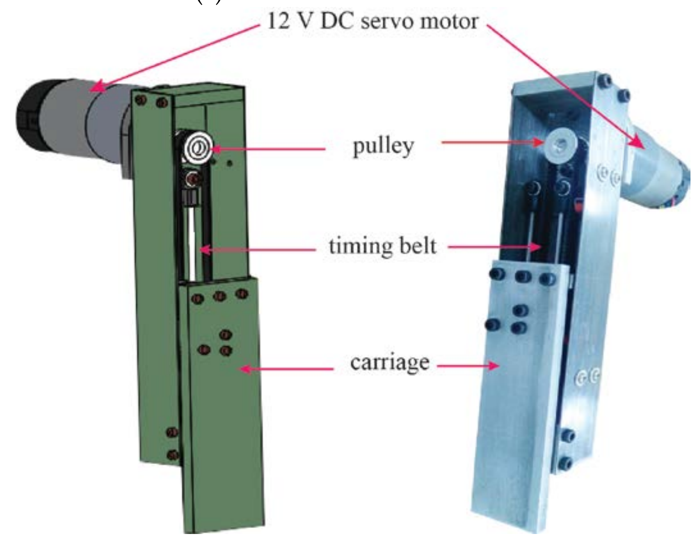


Fig.8. Solid model (left) and photo (right) of the position control belt drive mechanism

The proposed controller performed a set of experiments to prove the overdamped action. For that reason, discontinuous desired distance was supplied to all controllers. The derived results of the step response by the PID, PSMC and proposed control schemes with all subjects are illustrated in Fig. 9. During the tests, carriage distance, error distance and PWM measurements are collected. The distances between three orientations are 5 mm, 10 mm and 15 mm. The difference desired distances were tested for rigid control of trajectory tracking. The PID gains (K, B and L) have been chosen by trial and error method. The low gains of PID controller can produce the good performance of the system.

However, PID controller gain chose high gains, the performance of the system become progressively worse and it has vibration, overshoots and high PWM value. In such case, the PID controller produces oscillation and large amount of steady-state error. The position error has also intolerably large value for high precision systems. In human-robot interaction, the unsafe condition of the PID controller must be eliminated and the more acceptable controller is required.

Many researches [1], [2], [3] and [4] have been validated the effectiveness of PSMC that enhanced the performance of the system and safer than PID controller. PSMC controller can permit high controller gains and it limits the PWM value. By using the limit PWM value, PSMC shows the overdamped behavior, smooth response and approaches the desired distance without overshoot. PSMC controller has small amount of steady-state error and it reduces the convergence error of PID controller. The results clearly described the PSMC is successful in eliminating vibration and overshoots. In another experiment, similar to position control with PID controller, but with the difference that, the upgrade performance of the system can be seen by using PSMC controller.

However, the performance of the system by applying

PSMC controller cannot convergence to the desired distance. The position tracking control requires improvement in order to reach the desired distance. Because of the mechanism is composed with gear, timing belt, pulleys and the effect of friction cannot neglect. Friction also plays a major role in control-system performance. Friction limits the precision of positioning and pointing systems, and can give rise to instabilities. The effects of friction can be alleviated to some extent by friction compensation. For control applications it is useful to have simple models that capture the essential properties of friction. Indeed, friction is known to have memory-dependent behavior.

Therefore, the model based friction compensation is used to compensate nonlinear friction in the system. By removing the effect of friction from the belt-drive mechanism can enhance the performance of the human-robot interaction. The proposed controller is applied to the 1-DOF belt drive mechanism to compare the performance with other controllers. The control parameters used for PID, PSMC and PSMC+FC were selected as illustrated in TABLE 1 and TABLE 2.

By surveying the experimental results, PID controller produces oscillation and large amount of steady-state error (34%). On the other hand, PSMC controller shows the overdamp behavior and approaches the desired distance without overshoot. PSMC controller has 22% of steady-state error and it reduces the convergence error of PID controller. However, it cannot reach the desired distance. After applying the proposed controller to the system, it is clearly show that the performance of the system.

In Fig. 9, the system performance is accurate and safe trajectory tracking at x_d = 5 mm. At x_d = 10 mm and x_d = 15 mm, the system responded with a little bit overshoot and it has 2 % of error. As the result of error distance in Fig. 7, the proposed controller reduces the steady-state error to the smallest error and upgrade the system performance. This controller proved the smoother response that is able to solve the overshoot problem, steady-state error and friction effect in the actuator.

In Fig. 10, the same procedure is repeated in sine wave reference with frequency 0.2 Hz. Next, the dynamics performances of the proposed controller are also conducted. The amplitude changing is also carried out with sinewave reference and it is observed that the proposed controller is able to preserve its robustness by reducing the position tracking error. The proposed controller guarantees overdamped response and this control method compensates the effect of friction from the belt-driven mechanism. Moreover, the proposed controller can achieve better performance than other controllers and this can upgrade the operational safety of belt-driven mechanism. The proposed method maximizes the effectiveness of the 1-DOF belt drive mechanism. The proposed method can be exactly used in many other applications.

5 Conclution

The proposed design of 1-DOF belt drive mechanism has been presented in this paper. The device with timing belt type actuator, an easy-to-use the mechanism improves the performance of positioning control. This device can be used in several applications such as medical, industrial and so on. The experimental results reveal a good architecture to utilize belt drive mechanism for position controlled.

In this paper, the proposed position controller was formulated as the function of the positioning error. The use of force instead of positioning error should be analyzed in the future work.

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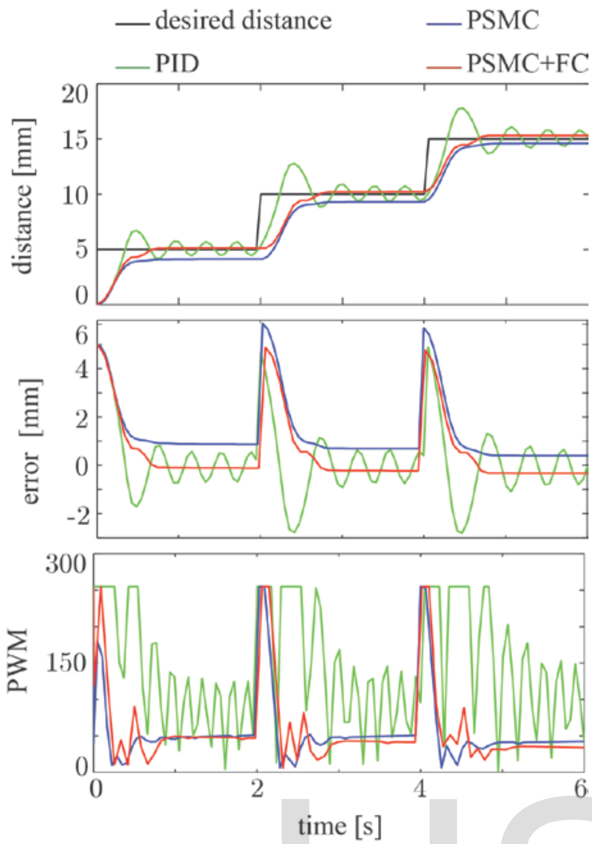

Fig.9. Tracking performances comparison for PID, PSMC and PSMC with friction compensator with step response.

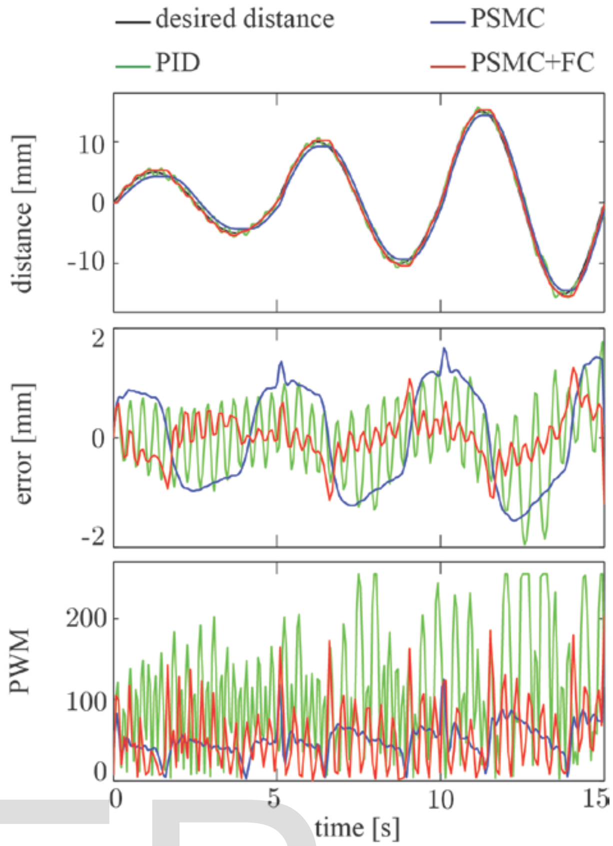

Fig. 10 Tracking performances comparison for PID, PSMC and PSMC with friction compensator with sinusoidal tracking.