Discrete-Time Fast Terminal Sliding Mode Control for Permanent Magnet Linear Motor

Haibo Du, *Member, IEEE*, Xiuping Chen, Guanghui Wen, *Senior Member, IEEE*, Xinghuo Yu, *Fellow, IEEE*, and Jinhu Lü, *Fellow, IEEE*

***Abstract*—The main objective of paper is to solve the position tracking control problem for permanent magnet linear motor by using the discrete-time fast terminal sliding mode control method. Specifically, based on the Euler's discretization technique, the approximate discrete-time model is first obtained and analyzed. Then, by introducing a new type of discrete-time fast terminal sliding surface, an improved discrete-time fast sliding mode control method is developed and an equivalent-control-based fast terminal sliding mode control law is subsequently designed. Rigorous analysis is provided to demonstrate that the fast terminal sliding mode control law can offer a higher accuracy than the traditional linear sliding mode control law. Numerical simulations and experimental results are finally performed to demonstrate the effectiveness of the proposed approach and show the advantages of the present discrete-time fast terminal sliding mode control approach over some existing approaches such as discrete-time linear sliding mode control approach and the PID control method.**

***Index Terms*—Digital control, Permanent magnet linear motor, Position control, Robustness, Terminal sliding mode.**

I. Introduction

PERM anent magnet linear motor (PMLM) is a conversion device that does not require any intermediate switching mechanism to convert electrical energy into linear motion [1]–[4]. Due to its many advantages such as high speed, large pushing force, and high precision, PMLM has been successfully applied in industry, military, and some other motion occasions which require high-speed, low thrust, small displacement, and high-precision position control [5], [6]. Meanwhile, the study of PMLM has attracted much attention from various fields, such as electronic industry, control engineering, etc. From the viewpoint of control engineering, the model of PMLM is a typical nonlinear multivariable system. Furthermore, the control performance of PMLM is potentially affected by various nonlinear factors such as unknown load and friction. Recently, the control issue of PMLM has become an important topic in filed of PMLM and how to improve the control performance of PMLM has obtained certain attention, see [7]–[9] and some references therein.

To solve the control problem of PMLM, many nonlinear control methods have been employed in the literature [10]–[16]. For example, a periodic adaptive compensation control method was proposed in [10]. In [11], by identifying various linear and nonlinear parameters of PMLM, an improved control scheme for precision motion control of PMLM was designed. Motivated by the fact that sliding mode control (SMC) method has been successfully applied in practice due to its distinguished features, such as easy implementation, strong robustness to parameter uncertainties and external disturbances [12]–[14], a control strategy for PMLM was designed in [15] based on sliding-mode control method and a proportional-integral-based equivalent disturbance observer. To cope with the effect of uncertainties and disturbances, an intelligent-complementary sliding-mode controller was proposed in [16] based on a radial-basis function-network.

However, most of the sliding mode controllers may only guarantee that the system state converges to the equilibrium asymptotically though the system trajectories achieve the sliding mode surfaces in finite time. To improve the dynamic response of closed-loop system, the terminal sliding mode control (TSMC) method was introduced in [17]–[20], which can ensure the finite-time convergence during the sliding mode stage. Partly motivated by the advantages of TSMC such as fast dynamic response and high control accuracy, the work [21] designed a TSMC-based position controller such that the PMLM's position can track the desired trajectory in finite time in the presence of disturbances. In [22], a composite TSMC method based on disturbance observer was proposed for PMSM speed regulation system. To handle the shortcoming that the TSMC has a slower convergence rate than the linear sliding mode controller (LSMC) when the system state is far away from the equilibrium, the fast terminal sliding mode control (FTSMC) method was proposed in [23], [24]. The

Manuscript received Month xx, 2xxx; revised Month xx, xxxx; accepted Month x, xxxx. This work was supported in part by the National Key Research and Development Program of China under Grant No. 2016YFB0800401, in part by the Foundation for Innovative Research Groups of the National Natural Science Foundation of China under Grant No. 61621003, in part by the National Nature Science Foundation of China under Grant Nos. 61673153, 61722303 and 61673104, in part by the Natural Science Foundation of Jiangsu Province of China under Grant No. BK20170079, in part by the Australian Research Council under Grant Nos. DE180101268 and DP170102303, and in part by the Fundamental Research Funds for the Central Universities of China under Grant Nos. JZ2017HGPA0163 and 2242016K41030. (*Corresponding author: Guanghui Wen.*)

H. Du and X. Chen are with the School of Electrical Engineering and Automation, Hefei University of Technology, Hefei, 230009, China (e-mail: haibo.du@hfut.edu.cn; 359772295@qq.com).

G. Wen is with the School of Mathematics, Southeast University, Nanjing 210096, China, and also with the School of Engineering, RMIT University, Melbourne VIC 3001, Australia (e-mail: wenguanghui@gmail.com).

X. Yu is with the School of Engineering, RMIT University, Melbourne VIC 3001, Australia (e-mail: x.yu@rmit.edu.au).

J. Lü is with the School of Automation Science and Electrical Engineering, State Key Laboratory of Software Development Environment, and Beijing Advanced Innovation Center for Big Data and Brain Machine Intelligence, Beihang University, Beijing 100083, China, also with the Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100190, China, and also with the University of Chinese Academy of Sciences, Beijing 100049, China (e-mail: jhlu@iss.ac.cn).

FTSMC method combines the advantages of the TSMC and the conventional LSMC together such that fast (finite-time) transient convergence both at a distance from and within a close range of the equilibrium can be obtained.

Since more and more controllers are implemented based on digital computers in practice, much attention has been recently paid on designing various discrete-time SMC laws. For example, the reaching-law-based discrete-time SMC laws were designed in [25], [26] and the equivalent-control-based discrete-time SMC laws were studied in [27], [28]. More recently, the discrete-time TSMC has attracted an increasing attention. Specifically, discretization effects on continuous-time TSMC and fast TSMC were respectively provided in [29] and [30], and the re-design of discrete-time TSMC was proposed in [31]. However, there are only a few results reported on the re-design issue of discrete-time fast TSMC systems.

Considering the importance of PMLM and the superiority of fast TSMC, this paper aims to design a new kind of discrete-time fast TSMC law for position control of PMLM. Specifically, a discrete-time model of PMLM is first obtained based on Euler's discretization. Then, by using traditional linear SMC method, a discrete-time linear SMC law is designed and the corresponding stability of closed-loop system is addressed. In the case of external disturbances, a compound strategy consisting of delayed estimation and dynamic compensation is employed to deal with the influence of disturbances. By performing rigorous analysis on the closed-loop system, the ultimate bounds for the sliding mode surface and steady-states are respectively obtained. To improve the control precision, based on the discrete-time fast TSMC method, an improved digital control algorithm, i.e., discrete-time fast TSMC algorithm, for PMLM is proposed. It is shown that the improved control algorithm can offer a higher control accuracy for sliding mode motion and steady-states of the closed-loop system no matter whether the disturbances are compensated or not.

The main contribution of this work is to design a novel nonlinear digital control algorithm (i.e., the discrete-time fast TSMC algorithm) for the position control system of PMLM such that the closed-loop system's performance can be improved. By performing rigorous theoretical analysis, the explicit relationship between the ultimate bound for the tracking error and the fractional power from the terminal SMC law is given, which shows that the higher control accuracy can be achieved by choosing appropriate fractional power. Simulation and experimental results are finally provided to verify the effectiveness of the proposed control method and show the advantages of the designed methods by comparing with some existing ones.

The rest of this paper is organized as follows. In Section II, the description of system model and the control objective are presented. Discrete-time SMC laws for PMLM are proposed in Section III. In Section IV, numerical simulations and experimental tests are performed to verify the effectiveness of theoretical analysis results. Finally, concluding remarks are given in Section V.

II. Description of System Model and Control Objective

A. Continuous-time model of PMLM

For a permanent magnet linear motor, the mathematical model is usually approximately described by a second-order system and is given in the form of [5]:

$$\begin{aligned} \dot{x}_1(t) &= x_2(t), \\ \dot{x}_2(t) &= -\frac{k_f k_e}{Rm} x_2(t) + \frac{k_f}{Rm} u(t) - \frac{d(t)}{m}, \\ y(t) &= x_1(t), \end{aligned} \tag{1}$$

where x_1 is the linear displacement, x_2 is the linear velocity, $u(t)$ is the control signal, R is the resistance, m is the motor mass, k_f is the force constant, k_e is the back electromotive force, and $d(t)$ can be considered as the lumped disturbances including the friction and ripple force.

B. Control objective

The control objective of this paper to design a position tracking controller for PMLM such that the reference position trajectory can be tracked. Without loss of generality, assume that the reference signal is $x_r(t)$, whose first-order and second-order derivatives are bounded.

For the brevity, denote

$$a = \frac{k_f k_e}{Rm}, \quad b = \frac{k_f}{Rm}, \quad F(t) = \frac{d(t)}{m}, \tag{2}$$

under which the equation (1) is rewritten as:

$$\begin{aligned} \dot{x}_1(t) &= x_2(t), \\ \dot{x}_2(t) &= -a x_2(t) + b u(t) - F(t), \\ y(t) &= x_1(t). \end{aligned} \tag{3}$$

Define

$$\begin{aligned} e_1(t) &= x_r(t) - x_1(t), \\ e_2(t) &= \dot{x}_r(t) - x_2(t), \end{aligned} \tag{4}$$

as the tracking errors for linear displacement and linear velocity signal, where $x_r(t)$ is the reference linear displacement, $\dot{x}_r(t)$ is the reference linear velocity. It can be obtained from (3) that the dynamical equation for the tracking errors has the following form:

$$\begin{aligned} \dot{e}_1(t) &= e_2(t), \\ \dot{e}_2(t) &= -a e_2(t) - bu + F(t) + a\dot{x}_r(t) + \ddot{x}_r(t). \end{aligned} \tag{5}$$

Based on the error equation, the control objective is to design a control law such that the tracking errors converge to zero. Although there have been some results on designing the position control laws for PMLM by using SMC method, see e.g., [15], [21], these designs are mainly based on continuous-time SMC theory. Different from these results, in this paper, it is assumed that the control law $u(t)$ is digitally implemented through a zero-order-holder (ZOH), i.e., $u(t) = u(kh)$ over the time interval $[kh, (k+1)h)$ with h being the sampling period, where $k \in \{0, 1, 2, \cdots, \} = \mathcal{Z}^+ \bigcup \{0\}$. In other words, the main objective of this paper is to design a discrete-time SMC law for PMLM, which is more appropriate to digital implementation.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIE.2018.2815942, IEEE Transactions on Industrial Electronics

Before moving on, the following two assumptions on disturbances and one lemma are presented which will be used in the subsequent analysis.

Assumption 2.1: The disturbance $F(t)$ is assumed to be bounded, i.e., $|F(t)| \leq d^*$ with a constant d^*.

Assumption 2.2: The derivative of disturbance is assumed to be bounded, i.e., $|\dot{F}(t)| \leq \delta^*$ with a constant δ^*.

Lemma 2.1: [29] Consider a scalar dynamical system

$$z(k+1) = z(k) - lz(k) + g(k). \tag{6}$$

If $|l| < 1$ and $|g(k)| \leq \gamma, \gamma > 0$, then the state $z(k)$ is always bounded and there is a finite number $K^* > 0$ such that $|z(k)| \leq \gamma/|l|, \quad \forall k \geq K^*$.

III. Design of Discrete-Time SMC Law for PMLM

In this section, we will employ the method of discrete-time SMC to design a digital control algorithm for PMLM.

Firstly, the method of Euler discretization is employed to obtain the discrete-time model of system (5), which is given as:

$$\begin{aligned} e_1(k+1) &= e_1(k) + he_2(k), \\ e_2(k+1) &= e_2(k) - hbu(k) - hae_2(k) \\ &\quad + h[a\dot{x}_r(k) + \ddot{x}_r(k)] + hF(k), \end{aligned} \tag{7}$$

where h is the sampling period. Based on the discrete-time model, we first design a traditional linear discrete-time SMC law and then propose an improved fast discrete-time terminal SMC law.

A. Designing a traditional linear discrete-time SMC law

For discrete-time system (7), by using the traditional discrete-time SMC method, the sliding mode surface is linear and is chosen as:

$$s(k) = Ce(k) = e_2(k) + c_1e_1(k), \tag{8}$$

with $0 < hc_1 < 1$. As that in [28], by using an equivalent control method and directly solving

$$s(k+1) = 0, \tag{9}$$

we get

$$\begin{aligned} &e_2(k) - hbu(k) - hae_2(k) + h[a\dot{x}_r(k) + \ddot{x}_r(k)] + hF(k) \\ &+ c_1[e_1(k) + he_2(k)] = 0. \end{aligned} \tag{10}$$

As a result, the equivalent control-based discrete-time SMC law is obtained as follows:

$$\begin{aligned} u(k) =& \frac{1}{hb}\Big[(1 + c_1h - ha)e_2(k) + c_1e_1(k) \\ &+ h[a\dot{x}_r(k) + \ddot{x}_r(k)] + hF(k)\Big]. \end{aligned} \tag{11}$$

1) Case 1: Assumption 2.1 is satisfied and the disturbance is not compensated: In this case, since the disturbance information $F(k)$ is unavailable, the final available controller should be

$$\begin{aligned} u(k) =& \frac{1}{hb}\Big[(1 + c_1h - ha)e_2(k) + c_1e_1(k) \\ &+ h[a\dot{x}_r(k) + \ddot{x}_r(k)]\Big], \end{aligned} \tag{12}$$

which results in the dynamical behavior of sliding mode state as

$$\begin{aligned} s(k+1) &= Ce(k+1) \\ &= hF(k). \end{aligned} \tag{13}$$

Under Assumption 2.1, the sliding mode state $s(k)$ is bounded by[1]

$$|s(k)| \leq d^*h = O(h), \forall k \in \mathcal{Z}^+, \tag{14}$$

which means that the sliding mode state $s(k)$ has an $O(h)$ boundary layer.

In the sequel, we will analyze the dynamical behavior of output tracking error $e_1(k)$. It follows from (7)-(8) that

$$\begin{aligned} e_1(k+1) &= e_1(k) + h[s(k) - c_1e_1(k)] \\ &= (1 - hc_1)e_1(k) + hs(k). \end{aligned} \tag{15}$$

By Lemma 2.1, it can be concluded that the state $e_1(k)$ is always bounded and the steady-state of tracking error e_1 will be bounded by

$$|e_1(\infty)| \leq \frac{h|s(\infty)|}{hc_1} \leq \frac{d^*}{c_1}h = O(h). \tag{16}$$

That is to say that the system output tracking error $e_1(k)$ has an accuracy with $O(h)$.

2) Case 2: Assumption 2.1 and Assumption 2.2 are satisfied and the disturbance is compensated: Since the disturbance information $F(k)$ is unavailable, under Assumption 2.2, it can be estimated by using delayed estimation method as that in [28], i.e.,

$$\begin{aligned} \hat{F}(k) =& F(k-1) \\ =& \frac{1}{h}[e_2(k) - e_2(k-1)] + bu(k-1) + ae_2(k-1) \\ &- [a\dot{x}_r(k-1) + \ddot{x}_r(k-1)]. \end{aligned} \tag{17}$$

Then the state $F(k)$ in the controller (11) can be substituted by the estimated value $\hat{F}(k)$, which leads to the available controller as follows

$$\begin{aligned} u(k) =& \frac{1}{hb}\Big[(1 + c_1h - ha)e_2(k) + c_1e_1(k) \\ &+ h[a\dot{x}_r(k) + \ddot{x}_r(k)] + h\hat{F}(k)\Big]. \end{aligned} \tag{18}$$

Under the discrete-time controller (18), the dynamical behavior of sliding mode state is given by

$$\begin{aligned} s(k+1) &= Ce(k+1) \\ &= h[F(k) - \hat{F}(k)] \\ &= h[F(k) - F(k-1)], \end{aligned} \tag{19}$$

[1] Throughout of this paper, the big O notation is referred to that function $f(h)$ is said to be of order $g(h)$ as $h \to 0$ and denoted as $f(h) = O(g(h))$, if there exist $\delta > 0$ and $M > 0$ such that $|f(h)| < M|g(h)|$ for $|h| < \delta$.

which is bounded by

$$|s(k)| \leq \delta^* h^2 = O(h^2), \quad \forall k \in \mathcal{Z}^+. \tag{20}$$

That is to say that the sliding mode state $s(k)$ has an $O(h^2)$ boundary layer. By a similar proof as that in Case 1, the system output tracking error $e_1(k)$ has also an accuracy with $O(h^2)$.

Remark 3.1: From the previous analysis, it can be found that the ultimate bound for the system steady output tracking error is determined by both the steady state of sliding mode state and the structure of sliding mode surface. Motivated by this observation, in the next subsection, we will employ a nonlinear sliding mode surface to improve the control accuracy.

B. Designing an improved discrete-time FTSMC law

In this section, an improved discrete-time fast terminal SMC law will be designed to improve the accuracy of the system output tracking error. At the first step, the discrete-time fast terminal sliding mode surface is chosen as

$$s(k) = e_2(k) + c_1 e_1(k) + c_2 \mathrm{sig}^{\alpha}(e_1(k)), \tag{21}$$

where $\mathrm{sig}^{\alpha}(e_1(k)) = \mathrm{sgn}(e_1(k)) \cdot |e_1(k)|^{\alpha}$, $0 < hc_1 < 1, c_2 > 0, 0 < \alpha < 1$.

As that in the previous subsection, based on the equivalent control method, directly solving

$$s(k+1) = 0, \tag{22}$$

leads to

$$\begin{aligned} u(k) =& \frac{1}{hb}\Big[(1 + c_1 h - ha)e_2(k) + c_1 e_1(k) \\ &+ h[a\dot{x}_r(k) + \ddot{x}_r(k)] \\ &+ hF(k) + c_2 \mathrm{sig}^{\alpha}(e_1(k) + he_2(k))\Big]. \end{aligned} \tag{23}$$

Similarly, the following two cases are respectively considered.

1) Case 1: Assumption 2.1 is satisfied and the disturbance is not compensated: In this case, the equivalent control-based discrete-time fast TSMC law is

$$\begin{aligned} u(k) =& \frac{1}{hb}\Big[(1 + c_1 h - ha)e_2(k) + c_1 e_1(k) \\ &+ h[a\dot{x}_r(k) + \ddot{x}_r(k)] \\ &+ c_2 \mathrm{sig}^{\alpha}(e_1(k) + he_2(k))\Big]. \end{aligned} \tag{24}$$

Under Assumption 2.1, the sliding mode state $s(k)$ is bounded by

$$|s(k)| \leq \lambda = d^* h = O(h), \quad \forall k \in \mathcal{Z}^+. \tag{25}$$

Next, the dynamical behavior of output tracking error $e_1(k)$ will be considered. It follows from (7) and (21) that

$$\begin{aligned} e_1(k+1) &= e_1(k) + h[s(k) - c_1 e_1(k) - c_2 \mathrm{sig}^{\alpha} e_1(k)] \\ &= (1 - hc_1)e_1(k) - hc_2 \mathrm{sig}^{\alpha} e_1(k) + hs(k). \end{aligned} \tag{26}$$

To analyze the stability of system (26), the following lemma is needed.

Lemma 3.1: [30] Consider the scalar dynamical system

$$z(k+1) = z(k) - l_1 \mathrm{sig}^{\alpha} z(k) - l_2 z(k) + g(k), \tag{27}$$

where $l_1 > 0$, $0 < l_2 < 1$, and $0 < \alpha < 1$. If $|g(k)| \leq \gamma, \gamma > 0$, then the state $z(k)$ is always bounded and there is a finite number $K^* > 0$ such that

$$|z(k)| \leq \psi(\alpha) \cdot \max\Big\{\Big(\frac{\gamma}{l_1}\Big)^{1/\alpha}, \Big(\frac{l_1}{1-l_2}\Big)^{\frac{1}{1-\alpha}}\Big\}, \quad \forall k \geq K^*, \tag{28}$$

where function $\psi(\alpha)$ is defined as

$$\psi(\alpha) = 1 + \alpha^{\frac{\alpha}{1-\alpha}} - \alpha^{\frac{1}{1-\alpha}}. \tag{29}$$

Theorem 3.1: For the error dynamical system (7) under the discrete-time fast TSMC law (24), if Assumption 2.1 holds, then the closed-loop system is stable and the ultimate bound for the output tracking error $e_1(k)$ could be of the order $O(h^2)$.

Proof: First, with the help of Lemma 3.1, it can be concluded from (26) that the state $e_1(k)$ is always bounded. In addition, it follows from (21) that

$$e_2(k) = s(k) - c_1 e_1(k) - c_2 \mathrm{sig}^{\alpha}(e_1(k)). \tag{30}$$

Since $e_1(k)$ is bounded and $s(k)$ is bounded from (25), then the state $e_2(k)$ is always bounded. That is to say that the stability of the closed-loop system can be guaranteed.

Second, as for the steady output tracking error, it follows from Lemma 3.1 that e_1 is bounded by

$$\begin{aligned} |e_1(\infty)| \leq \rho =& \psi(\alpha) \cdot \max\Big\{\Big(\frac{d^* h^2}{c_2 h}\Big)^{1/\alpha}, \Big(\frac{c_2 h}{1 - c_1 h}\Big)^{\frac{1}{1-\alpha}}\Big\} \\ =& \psi(\alpha) \cdot \max\Big\{\Big(\frac{d^* h}{c_2}\Big)^{1/\alpha}, \Big(\frac{c_2 h}{1 - c_1 h}\Big)^{\frac{1}{1-\alpha}}\Big\} \\ =& \psi(\alpha) \cdot \max\Big\{\big(O(h)\big)^{1/\alpha}, \big(O(h)\big)^{\frac{1}{1-\alpha}}\Big\}. \end{aligned} \tag{31}$$

Clearly, to get an optimal accuracy for the steady output tracking error, it is better to choose $\alpha = 1/2$ such that

$$\frac{1}{\alpha} = \frac{1}{1-\alpha} = 2, \tag{32}$$

which results in

$$|e_1(\infty)| \leq \rho = O(h^2). \tag{33}$$

■

Hence, compared with the linear sliding mode surface, the proposed fast terminal sliding mode surface can improve the accuracy of the steady output tracking error.

Next, we will consider the case when the disturbance can be compensated.

2) Case 2: Assumption 2.1 and Assumption 2.2 are satisfied and the disturbance is compensated: As shown in subsection III-A, the disturbance can be estimated and compensated by using delayed estimation method, which leads to the equivalent control-based discrete-time fast TSMC law

$$\begin{aligned} u(k) =& \frac{1}{hb}\Big[(1 + c_1 h - ha)e_2(k) + c_1 e_1(k) \\ &+ h[a\dot{x}_r(k) + \ddot{x}_r(k)] + h\hat{F}(k) \\ &+ c_2 \mathrm{sig}^{\alpha}(e_1(k) + he_2(k))\Big]. \end{aligned} \tag{34}$$

Theorem 3.2: For the error dynamical system (7) under the discrete-time fast TSMC law (34), if Assumption 2.1 and Assumption 2.2 hold, then the closed-loop system is stable and the ultimate bound for the output tracking error $e_1(k)$ could be in the order of $O(h^3)$.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIE.2018.2815942, IEEE Transactions on Industrial Electronics

Proof: Under Assumptions 2.1-2.2, by following a same proof as previous case, it can be concluded that the sliding mode state $s(k)$ is bounded by

$$|s(k)| \leq \delta^* h^2 = O(h^2), \quad \forall k \in \mathcal{Z}^+. \tag{35}$$

By using some similar statements as those employed in proving the stability of the closed-loop system in Theorem 3.1, the stability of the closed-loop system can be proved where the detailed proof is omitted for brevity. Let us analyze the dynamical behavior of output tracking error e_1. It follows from (26) and Lemma 3.1 that the steady output tracking error e_1 is bounded by

$$\begin{aligned} |e_1(\infty)| \leq \rho =& \psi(\alpha) \cdot \max\left\{\left(\frac{\delta^* h^3}{c_2 h}\right)^{1/\alpha}, \left(\frac{c_2 h}{1 - c_1 h}\right)^{\frac{1}{1-\alpha}}\right\} \\ =& \psi(\alpha) \cdot \max\left\{\left(\frac{\delta^* h^2}{c_2}\right)^{1/\alpha}, \left(\frac{c_2 h}{1 - c_1 h}\right)^{\frac{1}{1-\alpha}}\right\} \\ =& \psi(\alpha) \cdot \max\left\{\left(O(h)\right)^{2/\alpha}, \left(O(h)\right)^{\frac{1}{1-\alpha}}\right\}. \end{aligned} \tag{36}$$

Similarly, the optimal choice for the fractional power is $\alpha = 2/3$, which results in

$$2/\alpha = 1/(1 - \alpha) = 3, \tag{37}$$

which results in

$$|e_1(\infty)| \leq \rho = O(h^3). \tag{38}$$

■

The above analysis indicates that the FTSMC method can offer a higher control accuracy than that of LSMC method if the disturbance can be estimated and compensated.

Remark 3.2: Note that in Theorem 3.1 and Theorem 3.2, only the steady-state performance of the closed-loop system is discussed. Actually, for the dynamic performance of the closed-loop system, since the fast terminal sliding mode surface, i.e., (21), is employed, a faster dynamic response can still be guaranteed when the system state is close to the equilibrium point. The rigorous theoretical analysis about this issue for continuous-time FTSMC has been given in [23]. However, for the discrete-time FTSMC, it is very hard to give a qualitative conclusion about the dynamic performance of the closed-loop system. In the simulation section, the corresponding comparisons (i.e., Table III) are given to demonstrate that the discrete-time FTSMC can also offer a good dynamic performance.

Remark 3.3: Note that the work [32] has studied the continuous-time FTSMC for position control problem of PMLM. However, the main differences of the design of FTSMC in continuous-time case and discrete-time case lie in two aspects. 1) In practice, more and more controllers are implemented based on digital computers in practice, e.g., the implementation of the proposed control algorithm in this paper is based on the digital signal processor (DSP, TMS320F2812). Thus, the designed discrete-time fast terminal SMC law in this paper can be directly implemented. 2) Although the continuous-time FTSMC law can be digital implementation through different discretization methods (such as Euler's discretization), the stability analysis for the closed-loop system (i.e., the control plant is continuous-time but the controller is in the form of discrete-time) is not provided in most of cases (actually, the stability analysis is extremely difficult in this case, see for example, [33]). In this paper, the design of discrete-time FTSMC law is based on the discrete-time model and the corresponding stability analysis is successfully provided by developing new analysis methods for discrete-time systems.

The detailed design procedure for designing a discrete-time FTSMC algorithm for PMLM is summarized as follows:

- *Step 1: Obtain a discrete-time model of PMLM by using some discretization techniques.*
- *Step 2: Choose a discrete-time fast terminal sliding mode surface in the form of (21).*
- *Step 3: Design a discrete-time FTSMC algorithm in the form of:*

$$\begin{cases} (24), & \textit{without disturbance compensation;} \\ (34) \textit{ with } (17), & \textit{with disturbance compensation.} \end{cases}$$

Fig. 1 shows the block diagram of the discrete-time FTSMC for PMLM with disturbance compensation.

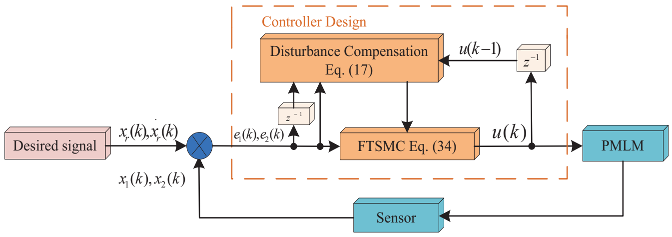


Fig. 1: The block diagram of the discrete-time FTSMC for PMLM.

IV. Simulation Results and Experimental Results

In this section, numerical simulations and experimental results are given to verify the effectiveness of the proposed control methods.

A. Simulation results

The system's parameters of PMLM considered in simulations are given in Table I.

Table I. System's parameters

Descriptions	Parameters
motor mass	$m = 5.4$ kg
resistance	$R = 16.8$ ohms
force constant	$k_f = 130$ N/A
back electromotive force	$k_e = 123$ V/m/s

The disturbance is composed of two parts, i.e., friction force and ripple force. Specifically, let

$$d = F_{fric} + F_{ripple}, \tag{39}$$

where F_{fric} is the friction force and F_{ripple} is ripple force. The friction force is defined as:

$$F_{fric} = [f_c + (f_s - f_c)e^{-(\frac{\dot{x}}{\dot{x}_s})^2} + f_v \dot{x}]\mathrm{sign}(\dot{x}), \tag{40}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIE.2018.2815942, IEEE Transactions on Industrial Electronics

where $f_c = 10$ N is the Coulomb friction coefficient, $f_s = 20$ N is the static friction coefficient, $f_v = 10$ N is the static friction coefficient and $\dot{x}_s = 0.1$ is the lubricant parameter. The ripple force is given as:

$$F_{fipple} = A_1 \sin(\omega x) + A_2 \sin(3\omega x) + A_3 \sin(5\omega x), \qquad (41)$$

with $A_1 = 8.5$, $A_2 = 4.25$, $A_3 = 2.0$ and $\omega = 314$ rad/s.

In this section, a *step signal* with an amplitude of 200 mm and a *sinusoidal signal* with an amplitude of 5 mm and the frequency of 1 rad/s, i.e., $x_r = 5\sin(t)$ are respectively considered as the desired displacement.

To achieve the position tracking control, three kinds of control algorithms are employed, i.e., the proposed discrete-time FTSMC, LSMC, and standard PID control. In simulations, the sample period h is chosen as 0.005(sec) to be consistent with the experiment. To make a relatively fair comparison, the control parameters of three kinds of control algorithms are repeatedly tested to obtain optimal parameters such that there is a good tradeoff between the dynamic performance and the steady-state performance of the closed-loop system. The controllers' parameters are given in Table II.

Table II. Controllers' parameters

Control algorithm	Control gains
PID	$k_p = 300, k_i = 50, k_d = 2$
LSMC	$c_1 = 3$
FTSMC	$c_1 = 1.5, c_2 = 1.5$

Case 1: the disturbance is not compensated

In this case, assume that the disturbance satisfies Assumption 2.1, but it can not be estimated and compensated. In addition, the fraction power α of proposed FTSMC law (24) is chosen as $\alpha = 1/2$.

1) Step response: the amplitude of step signal is chosen as 200 mm. Under the three kinds of control algorithms, the response curves for PMLM's displacement are shown in Fig. 2. It can be found that the proposed discrete-time FTSMC can offer a faster dynamic response and a smaller steady-state tracking error.

2) Tracking a sinusoid signal: a sinusoidal signal with an amplitude of 5 mm and frequency of 1rad/s is considered. Under the three kinds of control methods, the response curves are given in Fig. 3. In this case, it can be found that the proposed discrete-time FTSMC can significantly reduce the steady-state error.

Case 2: the disturbance is estimated and compensated

It is assumed that the disturbance satisfies Assumption 2.1 and Assumption 2.2. Hence, we can use the delay estimation method provided in (17) to estimate and compensate the disturbance. More specifically, the discrete-time LSMC (18) and the proposed discrete-time FTSMC (34) with $\alpha = 2/3$ are employed to solve the position tracking problem of PMLM.

1) Step response: the step signal is selected the same as that in Case 1 and the response curves of PMLM's displacement are plotted in Fig. 4. By comparing with Fig. 2, it can be found from Fig. 4 that the disturbance compensation strategy is effective. Furthermore, it can be seen from the numerical simulations that the improved discrete-time FTSMC algorithm

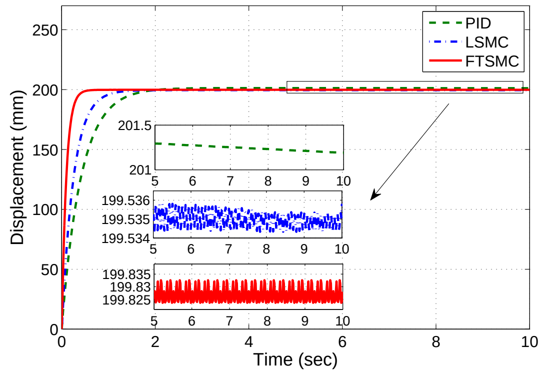


Fig. 2: The response curves for PMLM's displacement under step response in the absence of disturbance compensation.

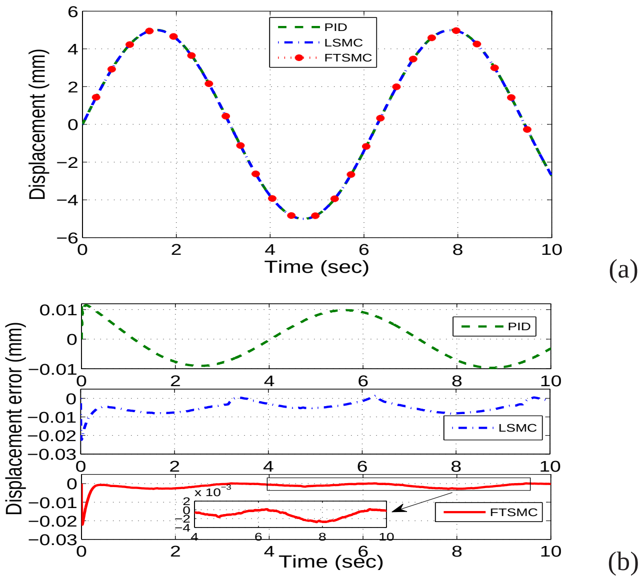


Fig. 3: The response curves for tracking a sinusoidal signal in the absence of disturbance compensation, (a) displacement, (b) displacement error.

is more effective by comparing with the other two control algorithms. Specifically, under the PID control algorithm and the discrete-time LSMC algorithm, the steady-state error of closed-loop system is 0 ∼ 1.5mm and −0.1 ∼ 0.1mm. Meanwhile, by using the proposed discrete-time FTSMC algorithm, it can offer a smaller steady-state error with −0.05 ∼ 0.05mm.

2) Tracking a sinusoid signal: in the presence of disturbance compensation, the response curves of PMLM's displacement for tracking a sinusoid signal under different control algorithms are provided in Fig. 5. On one hand, by comparing with Fig. 3, it can be found that the disturbance compensation strategy is effective. On the other hand, the proposed discrete-time FTSMC can significantly reduce steady-state error by comparing with the other two control algorithms.

For the convenience to compare the dynamic performance of the closed-loop system under different control algorithms, Table III gives the detailed dynamic performance index (i.e., the rise time $t_r(s)$ and settling time $t_s(s)$) under step response.

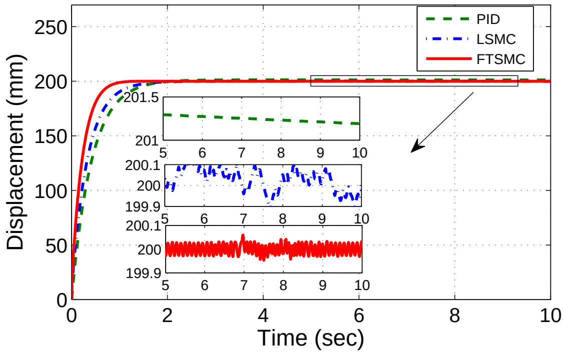
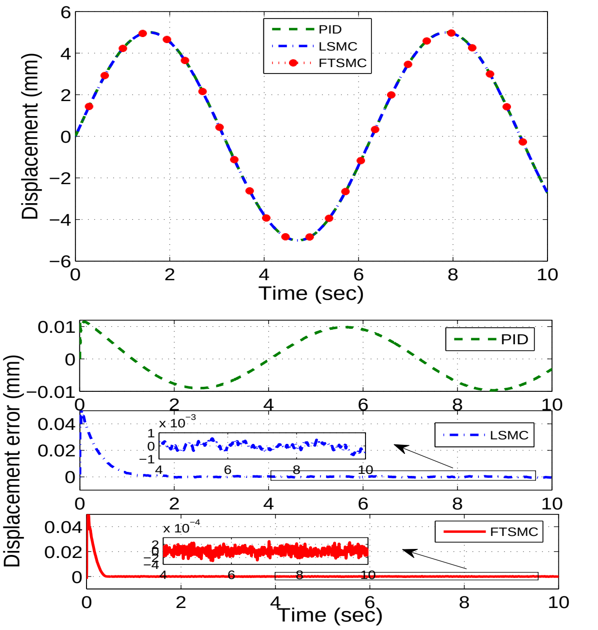


Fig. 4: The response curves for PMLM's displacement under step response in the presence of disturbance compensation.



(a)

(b)

Fig. 5: The response curves for tracking a sinusoidal signal in the presence of disturbance compensation, (a) displacement, (b) displacement error.

From Table III, it can be found that the proposed discrete-time FTSMC algorithm can offer a good dynamic performance whether the disturbance is compensated or not.

Table III. The comparisons of dynamic performance of closed-loop system under the step response.

Algorithms		Rise time (sec)	Settling time (sec)
	PID	0.892	1.515
Case 1	LSMC	0.790	1.460
	FTSMC	0.653	1.112
	PID	0.892	1.515
Case 2	LSMC	0.741	1.305
	FTSMC	0.487	0.800

B. Experiments results

To further investigate the effectiveness of the proposed control algorithm, some real time experiments are carried out. The experimental test setup configuration is depicted in Fig. 6 and Fig. 7, which is mainly comprised by PMLM, cSPACE control platform, computer with Matlab/Simulink, grating displacement sensor, linear motor driver. The specific implementation process of the proposed control algorithm in this paper is given as follow.

- *Step 1: The designed control algorithm is implemented by using the Matlab/Simulink software (Maltab 2008 version or higher version) to obtain the corresponding program (offline programming).*
- *Step 2: The Matlab/Simulink program is directly converted into C codes based on cSPACE control platform, which includes an automatic code generation software (offline programming).*
- *Step 3: Under the Code Composer Studio (CCS software) environment, the C codes are compiled by CCS software and then are downloaded to the DSP control board through the emulator (offline programming).*
- *Step 4: The final C codes (i.e., the proposed control algorithm) is implemented by a digital signal processor (DSP, TMS320F2812) in real time, where the sampling time is 5 ms, the instruction cycle is 6.67 ns, and the online process capability is 150 MIPS (online programming).*

The general specifications for the driver is given in Table IV.

Table IV. The general specifications of the driver.

Manufacturer	Elmo, Israel
Model	HAR 8/100
DC power supply	48.0 V
Current	3.0 A
Control gains of the current-loop	PI (k_p = 5.565, k_i = 13299)
Sampling time	100.0 μs
Switching frequency of the inverter	22.0 KHZ
Rating	630.0 W

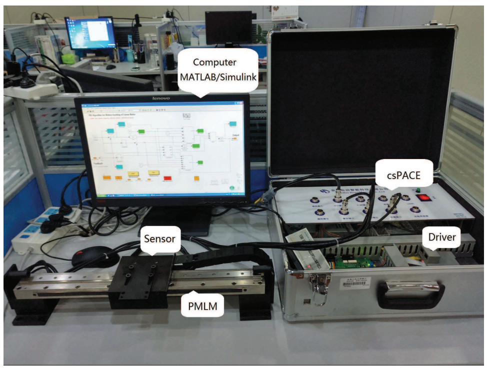


Fig. 6: Experimental setup.

As that in the simulation part, three kinds of control algorithms (i.e., PID, LSMC (18) with disturbance compensation (17), FTSMC (34) with disturbance compensation (17)) are considered and implemented by using the previous experimental platform. The sampled period h is chosen as 0.005(sec) and all the controllers' parameters are selected the same as those in subsection IV-A.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIE.2018.2815942, IEEE Transactions on Industrial Electronics

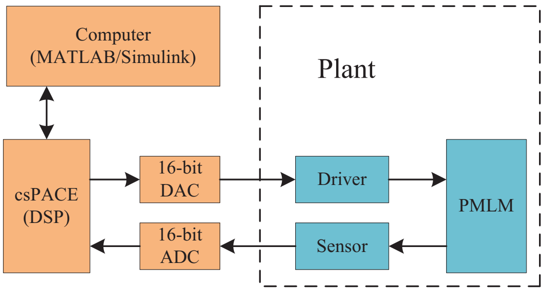


Fig. 7: The control block diagram of experimental system.

Under the three kinds of control algorithms, four cases will be considered in the experiments. First, as that in simulation part, *1) Step signal* and *2) Sinusoid signal* are added as the reference signals. The experimental results of displacement curves for step response are shown in Fig. 8. In addition, the response curves for the current-loop signals (i.e., i_q and i_q^*) are given in Fig. 9. When a sinusoid signal is taken as the reference signal, Fig. 10 and Fig. 11 give the corresponding response curves. It can be found that compared with the PID control algorithm and LSMC algorithm, the proposed FTSMC algorithm can offer a better dynamic performance and steady-state performance.

To quantitatively compare the steady-state performance of closed-loop system under the three kinds of control algorithms, Table V provides the detailed data about the maximum displacement error (MAXE), the average displacement error (MAE), and the standard deviation of displacement error (STDE), which are defined as follows:

$$\begin{aligned} MAXE &= \max|e_1(k)|, \\ MAE &= \frac{1}{1000}\sum_{k=1001}^{2000}|e_1(k)|, \\ STDE &= \sqrt{\frac{1}{1000}\sum_{k=1001}^{2000}(e_1(k)-MAE)^2}, \end{aligned} \tag{42}$$

where k is the sampling point for the displacement error and $k \in \{1001, \cdots, 2000\}$.

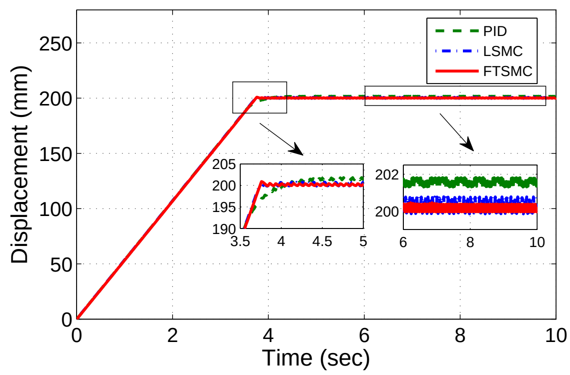


Fig. 8: The experimental results of PMLM's displacement under step response.

3) Robustness against the variations of mass and friction:

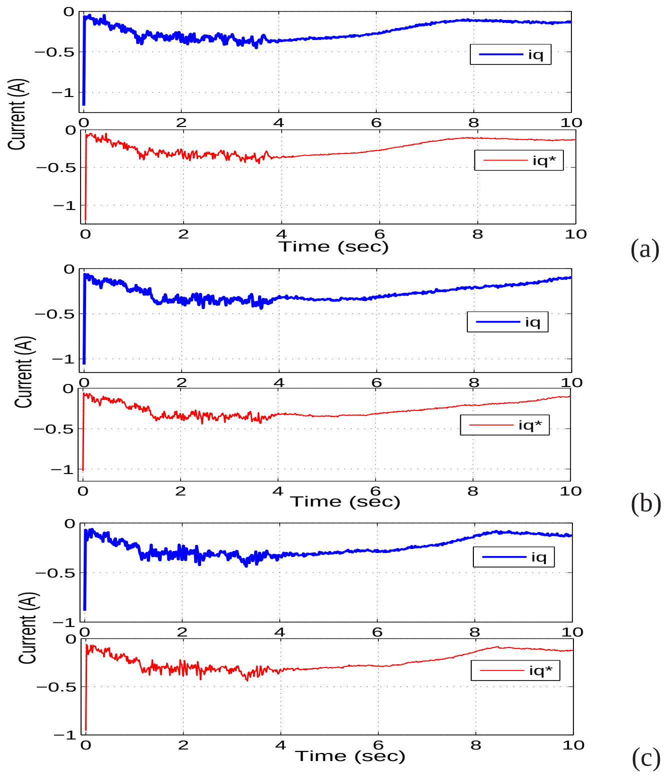


Fig. 9: The response curves of current signals i_q and i_q^* under step response (a) PID, (b) LSMC, (c) FTSMC.

To further study the effect of parameters' variations (the variations of friction is based on mass's change) on the PMLM control system, three cases, i.e., without payload, with 3kg, 5kg of additional payload are considered. The experimental comparison results are shown in Fig. 12, respectively. From the experimental results, it can be found that the proposed FTSMC algorithm demonstrates better robustness performance against the variations of of mass and friction. In addition, Table VI gives the quantitative comparison about the steady-state tracking control performance of the closed-loop system under the three kinds of control algorithms.

4) Robustness against the load disturbance:

In this case, the disturbance rejection ability of the control system is investigated. A disturbance load with 10N is added suddenly to the PMLM system. Under the three kinds of control algorithms, the response curves for the displacement error, current signals i_q and i_q^* are respectively shown in Fig. 13 and Fig. 14. From Fig. 13, it can be observed that the proposed method of FTSMC still has a better disturbance rejection ability.

V. Conclusions

This paper has investigated the position tracking problem for PMLM via an improved discrete-time SMC method. By employing a nonlinear discrete-time sliding mode surface (i.e., discrete-time terminal sliding mode surface) instead of the traditional linear sliding mode surface, it has been shown that the steady-state performance for the closed-loop system can be improved. In addition, the explicit relationship between

Table V. The comparisons of steady-state performance of the closed-loop system under the three control algorithms.

Control algorithm	PID		LSMC		FTSMC	
Reference signal	step	sinusoid	step	sinusoid	step	sinusoid
Maximum displacement error (mm)	1.8250	0.1681	0.7750	0.0500	0.4650	0.0173
Average displacement error (mm)	1.5359	0.0384	0.3073	0.0278	0.1465	0.0108
Standard deviation (mm)	0.2275	0.0259	0.3126	0.0136	0.1504	0.0047

Table VI. The comparisons of steady-state performance of the closed-loop system in the presence of the variations of mass.

Control algorithms	PID			LSMC			FTSMC		
Mass changes	0kg	3kg	5kg	0kg	3kg	5kg	0kg	3kg	5kg
Maximum displacement error (mm)	0.1681	0.1619	0.1928	0.0500	0.0522	0.0579	0.0173	0.0167	0.0141
Average displacement error (mm)	0.0384	0.0319	0.0366	0.0278	0.0216	0.0221	0.0108	0.0052	0.0045
Standard deviation (mm)	0.0259	0.0243	0.0314	0.0136	0.0119	0.0124	0.0047	0.0034	0.0028

the ultimate bound for the tracking error and the fractional power from the terminal SMC law is theoretically given, which provides a guidance on how to choose the optimal fractional power in practice. Simulation and experimental results have been performed to verify the theoretical analysis results and show the advantages of the present method over some existing ones as traditional linear SMC approach and PID method. Although only the position control problem of PMLM is considered in this paper, the developed nonlinear control algorithm is applicable for analysis and control of some other practical systems which can be modeled as second-order systems.

References

[1] K. Tan, S. Huang, and T. Lee, "Robust adaptive numerical compensation for friction and force ripple in permanent magnet linear motors," *IEEE Trans. Magn.*, 38(1), 221–228, 2002.

[2] T. Hu, W. Xue, and Y. Huang, "Active disturbance rejection control for permanent magnet linear motor," in *Proceedings of the 31st Chinese Control Conference*, pp. 296–301, Hefei, China, 25-27 July, 2012.

[3] J. Kim, S. Choi, K. Cho, and K. Nam, "Position estimation using linear hall sensors for permanent magnet linear motor systems," *IEEE Trans. Ind. Electron.*, 63(12), 7644–7652, 2016.

[4] M. Cheema, J. Fletcher, M. Farshadnia, D. Xiao, and M. Rahman, "Combined speed and direct thrust force control of linear permanent magnet synchronous motors with sensorless speed estimation using a sliding-mode control with integral action," *IEEE Trans. Ind. Electron.*, 64(5), 3489–3501, 2017.

[5] H. Ahn, Y. Chen, and Y. Dou, "State-periodic adaptive compensation of cogging and Coulomb friction in permanent-magnet linear motors," *IEEE Trans. Magn.*, 41(1), 90–98, 2005.

[6] C. Lei, J. Wu, Y. Chen, and J. Yang, "Auto-disturbance-rejection controller used in permanent-magnet linear motor control system," *Control Theory & Appl.*, 22(3), 423–428, 2005, (in Chinese).

[7] K. Tan, T. Lee, H. Dou, S. Chin, and S. Zhao, "Precision motion control with disturbance observer for pulsewidth modulated-driven permanent magnet linear motors," *IEEE Trans. Magn.*, 39(3), 1813–1818, 2003.

[8] M. Yan and Y. Shiu, "Theory and application of a combined feedback-feed forward control and disturbance observer in linear motor drive wire-EDM machines," *Int. J. Mach. Tool. & Manu.*, 48(3-4), 388–401, 2008.

[9] O. Tozoni, "Self-regulating permanent magnet linear motor," *IEEE Trans. Magn.*, 35(4), 2137–2145, 1999.

[10] K. Tan, T. Lee, and H. Dou, "Adaptive ripple suppression/compensation apparatus for permanent magnet linear motors," US, Patent US6853158, 2005.

[11] S. Chen, K. Tan, S. Huang, and C. Teo, "Modeling and compensation of ripples and friction in permanent-magnet linear motor using a hysteretic relay," *IEEE/ASME Trans. Mechatronics*, 15(4), 586–594, 2010.

[12] V. Utkin, Sliding modes in control and optimization, Berlin: Springer–Verlag, 1992.

[13] C. Edwards and S. Spurgeon, Sliding mode control: Theory and applications, London: Taylor and Francis, 1998.

[14] J. Zhang, M. Lyu, T. Shen, L. Liu, and Y. Bo, "Sliding mode control for a class of nonlinear multi-agent system with time-delay and uncertainties," *IEEE Trans. Ind. Electron.*, 65(1), 865–875, 2018.

[15] F. Cupertino, D. Naso, E. Mininno, and B.Turchiano, "Sliding-mode control with double boundary layer for robust compensation of payload mass and friction in linear motors," *IEEE Trans. Ind. Appl.*, 45(5), 1688–1696, 2009.

[16] F. Lin, J. Hwang, P. Chou, and Y. Hung, "FPGA-based intelligent complementary sliding-mode control for PMLSM servo-drive system," *IEEE Trans. Power Electron.*, 25(10), 2573–2587, 2010.

[17] Z. Man, A. Paplinski, and H. Wu, "A robust MIMO terminal sliding mode control scheme for rigid robotic manipulators," *IEEE Trans. Autom. Control*, 39(12), 2464–2469, 1994.

[18] X. Yu and Z. Man, "Model reference adaptive control systems with terminal sliding modes," *Int. J . Control*, 64, 1165–1176, 1996.

[19] Y. Wu, X. Yu, and Z. Man, "Terminal sliding mode control design for uncertain dynamic systems," *Syst. Control & Lett.*, 34(5), 281–287, 1998.

[20] X. Yu and Z. Man, "Multi-input uncertain linear systems with terminal sliding-mode control," *Automatica*, 34(3), 389–392, 1998.

[21] X. Mo and Q. Lan, "Finite-time integral sliding mode control for motion control of permanent-magnet linear motors," *Math. Probl. Eng.*, 4, 389–405, 2013.

[22] S. Li, M. Zhou, and X. Yu, "Design and implementation of terminal sliding mode control method for PMSM speed regulation system," *IEEE Trans. Ind. Informat.*, 9(4), 1879–1891, 2013.

[23] X. Yu and Z. Man, "Fast terminal sliding-mode control design for nonlinear dynamical systems," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, 49(2), 261–264, 2002.

[24] M. Xu, C. Chen, and Z. Wu, "Study of nonsingular fast terminal sliding-mode fault-tolerant control," *IEEE Trans. Ind. Electron.*, 62(6), 3906–3913, 2015.

[25] S. Qu, X. Xia, and J. Zhang, "Dynamics of discrete-time sliding-mode-control uncertain systems with a disturbance compensator," *IEEE Trans. Ind. Electron.*, 61(7), 3502–3560, 2014.

[26] W. Gao, Y. Wang, and A. Homaifa, "Discrete-time variable structure control systems," *IEEE Trans. Ind. Electron.*, 42(2), 117–122, 1995.

[27] V. Utkin, "Sliding mode control in discrete-time and difference systems," in *Variable Structure and Lyapunov Control, A.S.I. Zinober, Ed.*, New York: Springer–Verlag, 193(5), 87–107, 1994.

[28] W. Su, S. Drakunov, and U. Özgüner, "An $O(T^2)$ boundary layer in sliding mode for sampled-data systems," *IEEE Trans. Autom. Control*, 45(3), 482–485, 2000.

[29] S. Li, H. Du, and X. Yu, "Discrete-time terminal sliding mode control systems based on Euler's discretization," *IEEE Trans. Autom. Control*, 59(2), 546–552, 2014.

[30] H. Du, X. Yu, and S. Li, "Dynamical behaviors of discrete-time fast terminal sliding mode control systems," *Recent Advances in Sliding Modes: From Control to Intelligent Mechatronics*. X. Yu and M. Önder Efe (eds), pp. 77–97, 2015.

[31] K. Abidi, J. Xu, and J. She, "A discrete-time terminal sliding-mode control approach applied to a motion control problem," *IEEE Trans. Ind. Electron.*, 56(9), 3619–3627, 2009.

[32] Z. Mao, M. Zheng, and Y. Zhang, "Nonsingular fast terminal sliding mode control of permanent magnet linear motors," *Proceedings of 2016*

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIE.2018.2815942, IEEE Transactions on Industrial Electronics

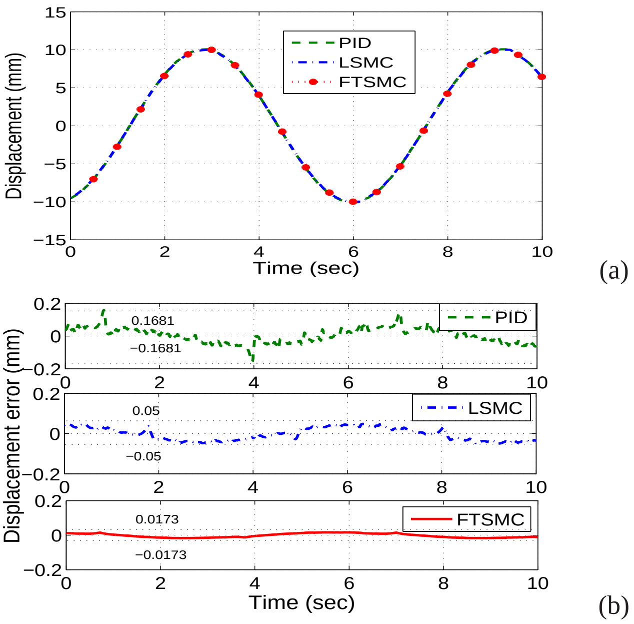


Fig. 10: The experimental results for tracking a sinusoidal signal (a) displacement (b) displacement error.

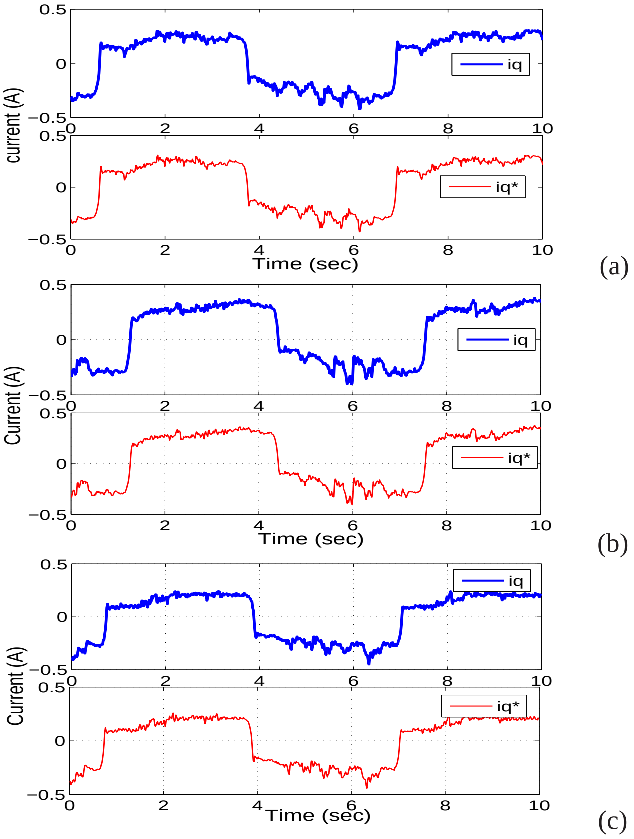


Fig. 11: The response curves of current signals i_q and i_q^* for tracking a sinusoidal signal (a) PID, (b) LSMC, (c) FTSMC.

Chinese Control and Decision Conference, pp. 649–653, Yinchuan, China, 28–30 May, 2016.

[33] X. Yu, J. Xu, Y. Hong, and S. Yu, "Analysis of a class of discrete-time systems with power rule," *Automatica*, 43(3), 562–566, 2007.

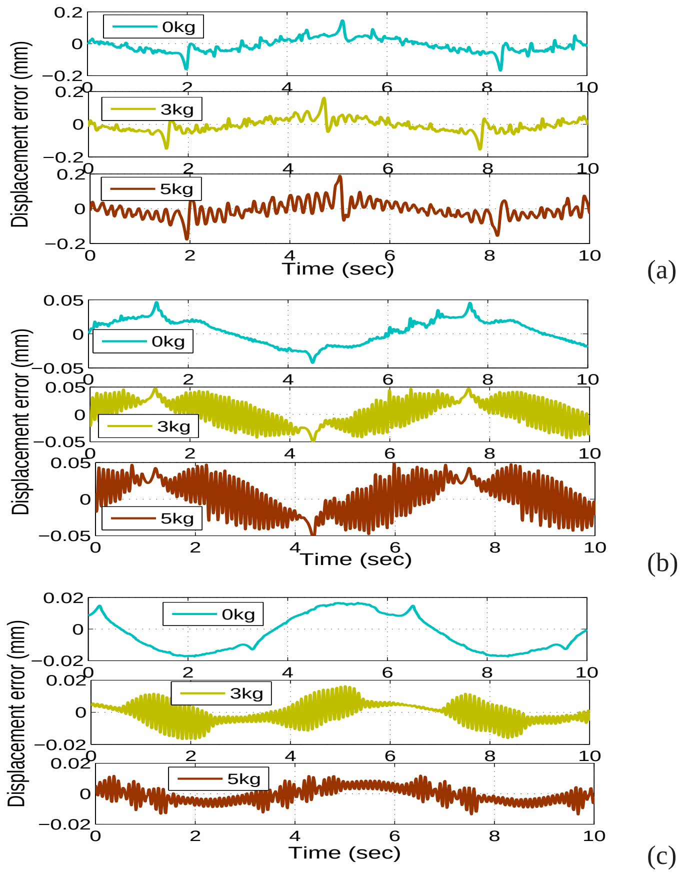


Fig. 12: The response curves for tracking a sinusoidal signal in the presence of the variations of mass (a) PID, (b) LSMC, (c) FTSMC.

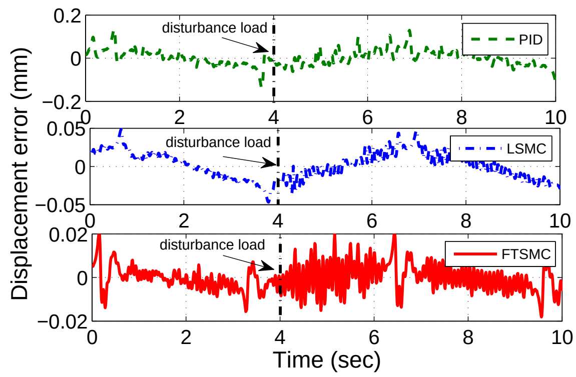
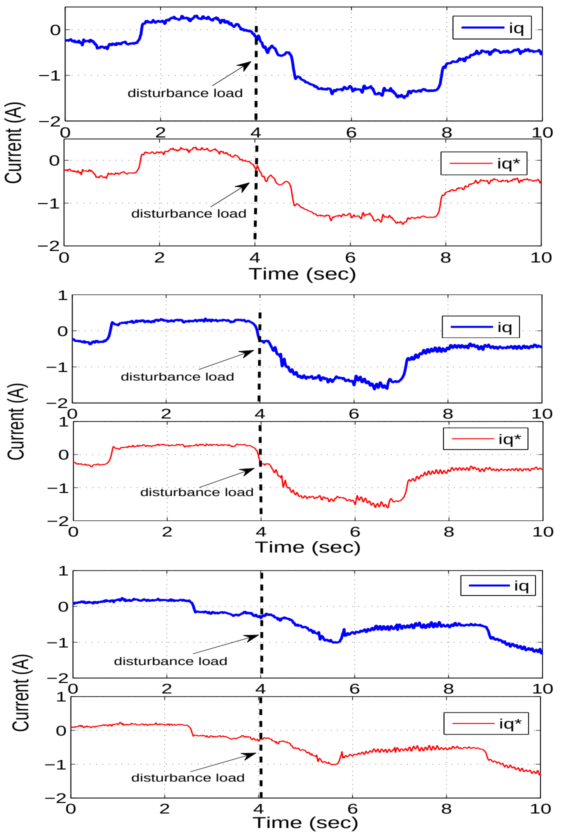


Fig. 13: The response curves of PMLM's displacement error for tracking a sinusoidal signal under a sudden disturbance load.

Haibo Du (M'12) received the B.Sc. degree in Mathematics from Anhui Normal University, China, in 2004, and the Ph.D. degree in Automatic Control from Southeast University, China, in 2012.

He is currently an Associate Professor in the School of Electrical Engineering and Automation, Hefei University of Technology. His research interests include nonlinear system control theory with applications to multi-agent systems, spacecraft, motors and robots.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIE.2018.2815942, IEEE Transactions on Industrial Electronics



(a) (b) (c)

Fig. 14: The response curves of current signals i_q and i_q^* for tracking a sinusoidal signal under a sudden disturbance load (a) PID, (b) LSMC, (c) FTSMC.

Dr. Du was a recipient of the Natural Science Award (Second Class) of the Ministry of Education in 2014 and a recipient of the First Prize of Anhui Province Natural Science Excellent Academic Paper in 2016.

Xiuping Chen received the B.E. degree in automatic control from the Chaohu University, Hefei, China, in 2015.

She is currently pursuing the M.E. degree in the School of Electrical Engineering and Automation, Hefei University of Technology, Hefei, China. Her current research interests include nonlinear system control theory with applications to motor control.

Guanghui Wen (S'11–M'13–SM'17) received the Ph.D. degree in mechanical systems and control from Peking University, Beijing, China, in 2012.

He is currently an Associate Professor with the School of Mathematics, Southeast University, Nanjing, China. His current research interests include cooperative control of multi-agent systems, analysis and synthesis of complex networks, cyber-physical systems, and robust control.

Dr. Wen was the recipient of the Best Student Paper Award in the 6th Chinese Conference on Complex Networks in 2010, the First Prize of Scientific and Technological Progress Award of Chinese Institute of Command and Control in 2016. Moreover, he was awarded a National Natural Science Fund for Excellent Young Scholars in 2017. He currently serves as an Editorial Board Member and an Associate Editor of the *Asian Journal of Control*.

Xinghuo Yu (M'92–SM'98–F'08) received BEng and MEng degrees in Electrical and Electronic Engineering from the University of Science and Technology of China, Hefei, China, in 1982 and 1984, and Ph.D. degree in Control Science and Engineering from Southeast University, Nanjing, China in 1988, respectively.

He is an Associate Deputy Vice-Chancellor and a Distinguished Professor of RMIT University (Royal Melbourne Institute of Technology), Melbourne, Australia. He is President of IEEE Industrial Electronics Society for 2018 and 2019. His research interests include control systems, complex and intelligent systems, and smart grids. He received a number of awards and honors for his contributions, including 2013 Dr.-Ing. Eugene Mittelmann Achievement Award of IEEE Industrial Electronics Society and 2018 M. A. Sargent Medal of Engineers Australia. He was named a Highly Cited Researcher by Clarivate Analytics (formerly Thomson Reuters) in 2015, 2016 and 2017.

Jinhu Lü (M'03–SM'06–F'13) received the Ph.D. degree in applied mathematics from the Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing, China, in 2002.

He was a Professor with RMIT University, Melbourne, VIC, Australia, and a Visiting Fellow with Princeton University, Princeton, NJ, USA. He is currently the Dean of the School of Automation Science and Electrical Engineering, Beihang University, China. He is also a Professor with the Academy of Mathematics and Systems Science, Chinese Academy of Sciences. He is also the Chief Scientist of the National Key Research and Development Program of China and a Leading Scientist of Innovative Research Groups of the National Natural Science Foundation of China. His current research interests include nonlinear circuits and systems, complex networks, multiagent systems, and big data.

Dr. Lü was a recipient of the prestigious Ho Leung Ho Lee Foundation Award in 2015, the State Natural Science Award thrice from the Chinese Government in 2008, 2012, and 2016, respectively, the Australian Research Council Future Fellowships Award in 2009, the National Natural Science Fund for Distinguished Young Scholars, and a Leading Scientist of the Ten Thousand Talents Program of China. He was a member of the Evaluating Committees of the IEEE Circuits and Systems Society, the IEEE Industrial Electronics Society, and the IEEE Computational Intelligence Society. He was the General Co-Chair of the 43rd Annual Conference of the IEEE Industrial Electronics Society in 2017. He was an Editor in various ranks for 15 SCI journals, including seven IEEE Transactions journals. He is a Highly Cited Researcher in engineering in 2014–2017.