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Practical tracking control of linear motor via fractional-order sliding mode ☆

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In this work, a novel discrete-time fractional-order sliding mode control (SMC) scheme is proposed, which guarantees the desired tracking performance of a linear motor control system. By using Euler's discretization method, a discrete-time model is firstly established for the linear motor, which includes the nonlinear friction and the uncertainties. Considering the practicability of the engineering application, a new discrete-time fractional-order sliding surface is constructed by taking the Grünwald–Letnikov definition based fractional-order difference of the tracking error into account. Compared to the classical integer-order sliding surface, by the proposed fractional-order sliding surface in this work, a better performance can be achieved due to the memory effect of the fractional calculus. To drive the system trajectories to the predefined sliding surface in finite sampling steps, a novel equivalent control is then designed, which can adjust the switching control input adaptively. Meanwhile, the theoretical analysis for the tracking error of the linear motor system is presented, and the practical reachability of the sliding surface is validated by numerical simulations. Finally, the effectiveness of the proposed control strategy is verified by a group of tracking experiments on a linear motor platform.

1. Introduction

Control of linear motors has received extensive attentions in recent years (Zheng, Wang, Man, Jin, & Fu, 2014). Compared with traditional rotary motors, there is no mechanical transmission such as the belts, leadscrews and worm gear drives in linear motors, therefore, the properties of high precision, fast response and zero backlash can be obtained in linear motors. Moreover, the absence of mechanical wear results in excellent reliability and long lifetime. Nowadays, linear motors have been widely used in industrial systems such as the train propulsion (Jo, Lee, Han, Lee, & Lee, 2017), the aircraft launch system (Mu, Chai, Sun, & Wang, 2015), and the industrial gantry (Lu, Chen, Yao, & Wang, 2008).

Recently, many researchers' endeavors have been focused on improving the positioning accuracy of the linear motor systems, such as optimizing the mechanism and electronic structures, developing new magnetic materials, using proper winding methods and creating a moving magnetic field. To mention a few, Zhang et al. in Zhang, Zhou, Duan, and Kou (2016) proposed a new ring winding structure for linear motors, resulting in the reduction of the thrust ripple and improvement of the precision further. A novel structure of stair-shaped auxiliary teeth applied on the linear motors was addressed to reduce the end edge detent force in Kim, Park, Jung, and Kim (2017). To achieve the desired positioning accuracy of linear motor systems, suitable control strategies are necessary. There are many approaches to develop the control methods for linear motor system. For example, an adaptive fuzzy-PID controller was designed for the speed loop of the linear motor system in Su, Yang, Shi, and Wu (2014). An $\mathcal{H}_\infty$ optimal control was conducted to maintain the robustness of the system in Shieh, Tung, and Lin (2002), and a nonsingular sliding mode control (SMC) strategy was adopted for positioning in Kumar and Ganapathy (2015) and Zheng et al. (2014). Among these control methods, SMC has many good characteristics, such as insensitivity to external disturbances, high accuracy and simplicity of the design procedure, making it an effective method to deal with the nonlinear behavior of the linear motors (Shi, Xia, Liu, & Rees, 2006). Because of these merits, SMC has been widely used in aerospace (Chen, Li, & Song, 2017), power electronics (Liu et al., 2017) and other fields.

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Generally speaking, SMC consists of continuous-time SMC and discrete-time one. Most of the researchers paid much attention to continuous-time SMC since its clear physical meaning (Wu, Zheng, & Gao, 2013), and it has been proven that the continuous-time SMC is an effective approach to keep robustness when the modeling uncertainties and disturbances exist in systems (Erbatur, Kaynak, & Sabanovic, 1999). For discrete-time SMC, there are relatively few papers that have been reported corresponding to their continuous-time counterpart. However, as more and more modern control systems are controlled by digital processors, the discrete-time SMC has attracted much attention in recent years. It has been found that discretizing the continuous-time SMC to get the discrete-time SMC is not appropriate, since it will result in chattering, periodic orbits and even instability (Ma, Wu, & Xiong, 2016; Yu, Xu, Hong, & Yu, 2007). To solve these problems, the concept of discrete-time SMC is proposed and then widely studied (Su, Drakunov, & Özgüner, 2000). For example, the sufficient condition for the existence of discrete-time SMC and the stability problem have been studied by Sarpturk, Istefanopulos, and Kaynak (1987); a nonlinear SISO SMC was presented and a notion of relative degree was established in Sira-Ramirez (1991). Similar to the procedure of classical continuous-time SMC, the discrete-time sliding surface with desired feature should be firstly designed for discrete-time SMC. By introducing the proper reaching law (Gao & Hung, 1993) or equivalent control (Su et al., 2000), the system can be driven to the designed sliding surface monotonically.

The sliding variable of the discrete-time SMC, that is also called as quasi-sliding mode (Janardhanan & Bandyopadhyay, 2007), moves around the sliding surface in the certain boundary layer. In practical engineering applications, considering the existence of disturbances and uncertainties, the sliding surface and the control law should be well designed to reduce the thickness of the boundary layer. Researchers have proposed many application examples from their own field. For example, Abidi et al. applied the discrete-time terminal SMC law to Piezomotor-driven linear motion stage in Abidi, Xu, and She (2009). Lin et al. designed a robust discrete-time SMC for the fluid power electrohydraulic actuator system in Lin, Shi, and Burton (2013). Ma et al. proposed a discrete reaching law with improved quasi sliding mode domain of discrete-time SMC and applied it to real piezoelectric actuator device in Ma et al. (2016). Unfortunately, for linear motors, as far as we know, only a few works for discrete-time SMC have been studied because of the complexity of the application environment and the high demands in performance. For example, Veselic et al. used Euler velocity estimation to improve the discrete-time SMC (Veselic, Perunicic-Drazenovic, & Milosavljevic, 2010), but the parametric uncertainties of the system was not taken into consideration and the chattering phenomenon was not discussed. Acary et al. designed a chattering-free discrete-time SMC with state observer and disturbance objection to reduce the chattering phenomenon during the control and to promote the precision accordingly in Acary, Brogliato, and Orlov (2012), however, there was no engineering example to valid the results because of the presence of unmodeled friction and changing payloads in linear motors. In this work, our focus is on designing an engineering-suitable SMC strategy to improve the positioning accuracy and fast response of the linear motors.

With this aim, a better and novel sliding surface should be carefully designed. Inspired by the memory merits of the fractional calculus, we find that fractional-order sliding mode is well suitable for the application because the fast response and small overshoot can be achieved at the same time. In fact, the fractional calculus has a long history which can be traced back to 300 years ago (Podlubny, 1998), but it was only studied in the pure mathematics field because of the unclear physical meanings. In recent years, the concept of fractional calculus has been widely implemented in viscoelastic system, polarization process, electromagnetic waves and many other fields (Lu & Chen, 2010; Monje, Chen, Vinagre, & Xue, 2010). In control community, it was found that fractional-order controller can enhance the robustness and performance of the control system (Luo & Chen, 2012). Combining continuous-time SMC with fractional-order calculus, some effective control schemes have been applied to improve the quality of the control system in industrial fields in recent years (Sun & Ma, 2017), such as the hydraulic manipulators (Wang, Luo, Gu, & Li, 2015), the permanent magnet synchronous motors (Zhang, Pi, & Luo, 2012). However, as far as we know, few works applying the fractional calculus to discrete-time SMC schemes have been reported in literature.

In this work, we will study the discrete-time fractional-order SMC design with its application for the tracking control of a linear motor. The main contributions of this work can be summarized as follows:

- A discrete-time fractional-order sliding surface is proposed to achieve good performance. Due to the memory effect introduced by the fractional-order difference, the status on the fractional-order sliding surface will reach equilibrium point with faster response. By using the Grünwald–Letnikov based fractional-order definition, the proposed sliding surface can be rewritten as the multi-delay form, the stability condition is presented by using *D*-composition method.
- A novel switching control scheme is proposed which can dynamically adjust the control input to reduce the thickness of the boundary layer. Consequently, a higher tracking precision can be achieved by proposed controller compared to the classical integral controller.
- An implementation strategy for the discrete-time SMC on linear motor platform with parametric uncertainties and nonlinear friction disturbances is carried out, and the effectiveness is verified by experiments.

The rest of the paper is organized as follows. The model of the linear motor platform is given in Section 2. Section 3 presents some preliminaries of the fractional calculus. The main results on the SMC design are presented in Section 4. The simulation and experiment results are shown in Section 5, and we conclude this work in Section 6.

2. Plant modeling

To facilitate the discussion, this section first introduces the experimental platform for the linear motor positioning system (production of Akribis company) which is shown in Fig. 1. The 2-DOF positioning platform consists of a moving stage and three linear motors, which has a 700 mm travel range in X-direction and 650 mm in Y-direction. In this paper, as an example, the positioning of moving stage in X-direction is considered and the positioning precision is guaranteed by a high-accuracy linear optical encoder (with a resolution of 50 nm).

Based on the work in Zheng and Fu (2010), the simplified continuous-time model can be presented as

$$\dot{p} = v, \tag{1}$$

$$m\dot{v} = (1 - k_m)(k_f u - f - d), \tag{2}$$

$$f = k_c \mathrm{sgn}(v) + k_v v, \tag{3}$$

where m is the mass of the moving stage, p and v refer to the absolute position and the velocity, respectively. $0 \leq k_m < 1$ stands for the gain variation due to the load mass, k_f is the voltage-to-force amplifier gain and d denotes the lumped uncertainty that consists of unmodeled system dynamics and external disturbances. The