

# A tracking control design for linear motor using robust sliding mode learning control

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## ABSTRACT

In this paper, a tracking robust sliding mode learning control (SMLC) is proposed for a linear motor (LM) system. The proposed controller approach, SMLC, can guarantee a zero tracking error in the absence and presence of system uncertainties of the LM system. Unlike other classical sliding mode control (CSMC), the proposed control system is designed without any prior knowledge of the system perturbation which would facilitate control design and simplify its practical applications. To this end, a recursive learning technique is used which simultaneously adapted based on the previous information of the closed loop system stability. The system stability and convergence analysis are rigorously proved in the sense of the Lybenouve criteria. Finally, simulations results are presented to demonstrate the validity and effectiveness of the SMLC over the CSMC in terms of tracking performance and chattering alleviation.

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## 1. INTRODUCTION

Due to the rapid development of microcomputers and automatic control technology, the linear motor (LM) has brought a great deal of attention due to its useful and attractive properties. The main advantage of the LM is that it is broadly utilized in high precision motion and high-speed control systems. The design nature of LM is a direct drive system without adopting a conventional mechanical transmission. This makes the LM vital system to get rid of mechanical transmission issues such as friction, gear backlash, structural resonance, and stiffness variations [1].

From the aforementioned beneficial features, LM has been widely utilized in various applications such as dual stage actuation [2], real nanopositioning system [3], industrial gantry [4], high speed applications [5] to name a few. However, many uncertain factors may significantly degrade the control performance of LM tracking task. Examples of system uncertainties include: measurement noise, external unknown disturbances, parameter variations, and mechanical coupling. In recent years, many researchers have studied and developed various techniques to enhance the control performance of LM such as learning control [6], ripple suppression [7], pre-actuated multirate control [8], and sliding control [9].

An effective and powerful classical nonlinear controller was found in the literature to preserve the system stability in the presence of disturbances and uncertainties namely sliding mode controller (SMC). Owing to its robustness and fast convergence against system uncertainties and disturbances, SMC has been broadly utilized in several industrial applications such as robotic hand [10], quadrotor unmanned aerial vehicle (UAV)

[11], industrial robotic manipulator [12], magnetic bearing [13], permanent magnet synchronous machine [14], and piezoelectric actuator [15], [16]. However, the main shortcoming of the traditional SMC is that producing undesired chattering problem in control which makes SMC inappropriate for industrial applications [17]. In an industrial system, the occurrence of system chattering may lead to system hardware damage such as mechanical components and also may cause actuator saturation [18]. To alleviate the impact of the chattering problem, a number of efficient control approaches have been extensively investigated and developed. Some well-known techniques reported in the literature include: the boundary layer method [19], adaptive SMC [20], [21], high-order sliding mode [22], and adaptive fuzzy approach [23]. For instance, in [24], second order sliding mode control is utilized to integrate the discontinuous switching term and hence the chattering problem is reduced. However, the tracking error is suffered from asymptotic convergence. An alternative approach namely fast non-singular terminal sliding mode [1] is proposed. In this technique, to reach the control law, no switching element in the control input is used which can effectively get rid of the chattering effect. However, the unknown disturbance impacts the convergence neighborhood size of the tracking error [1].

Motivated by the recent success of the LM system and the robust SMC as well as their valuable application. The basic idea of this work is to explore a new way for the development of SMC based on [25]–[27] which will lead to improve the performance of the LM in terms of handling the occurrence of external uncertainties and eliminating the chattering phenomena. Inspired by the concept of the "Lipschitz-like condition" which proposed in [25], [26], our sliding mode learning control (SMLC) approach is established. From the previous approaches presented in [25]–[27], adopting Lipschitz-like condition enforces our controller to be independent on prior knowledge about system uncertainties. This is due to the uncertainties of the dynamics being implicitly embedded in the Lipschitz-like condition. Differ from the conventional SMC, the proposed SMLC yields no chattering problem in the close loop. Furthermore, through the simulation results and comparisons with conventional SMC, we demonstrate that the performance of the proposed method is an effective technique in terms of chattering effect elimination. Moreover, the proposed approach has the superiority over the conventional SMC schemes for trajectories tracking of varying frequencies triangular reference signal.

The rest of this paper is organized as being as. In section 2, we present the modelling of the linear motor system. The SMLC control design approach is described in section 3. In section 4, we discuss the stability and convergence analysis of the proposed approach. Experimental results are illustrated in section 5 highlights the advantages of the proposed method. Conclusion and further work discussion are given in the last section.

## 2. DYNAMIC MODELING OF LINEAR MOTOR SYSTEM

The experimental setup of the LM positioner system is depicted in Figure 1 (by Baldor electric company). The LM positioner has a travel range of up to 500 mm with a high level of resolution which can reach 1  $\mu m$ . A position encoder manufactured by Renishaw programmable logic controller (PLC) is attached to the end of the track rail to measure the instantaneous and precise position of the stage. The micro-positioning stage is designed to avoid any loss of transmitting energy by connecting directly to the LM. The voltage-to-current power amplifier, on the other hand, is used to feed the drive the LM by the control input signals as a current command. The power amplifier model is simply considered as a constant gain. The reason is that its bandwidth (i.e., 400 Hz) much higher than the LM dynamics.

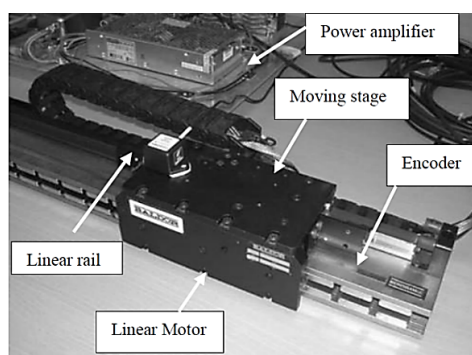


Figure 1. Experimental set up of the linear motor positioner

The mathematical model of the LM system is precisely developed and identified previously by [1]. By taking the advantage of adopting this model, we will proceed with the control design in the next section. Consequently, the LM model is represented here as shown in:

$$m\ddot{y}(t) = u(t) - f(t) - d(t) \quad (1)$$

where  $u(t)$  is the control input to be designed,  $y(t)$  indicates the linear displacement of the moving stage which is measured by encoder sensor,  $m$  is the total mass of the LM,  $d(t)$  is the external disturbance and  $f(t)$  is the lumped of the friction forces which is given by:

$$f(t) = f_v \dot{y}(t) + f_c \text{sgn}(\dot{y}(t)) \quad (2)$$

where  $f_v$  is the viscous friction and  $f_c$  is the coulomb friction level times the signum function  $\text{sgn}()$  of velocity. In this research, the system perturbations are gathered in one variable that with including the external disturbance, modeling errors, and other system uncertainties which is expressed as:

$$\Delta(t) = \Delta m + \Delta f_v + \Delta f_c + d(t) \quad (3)$$

where  $\Delta$  denotes the parameters variation between their actual and nominal values, the  $d(t)$  indicates the external disturbance and  $\Delta(t)$  is the lumped of system perturbations. It should be noted that there is an upper bound for these perturbation such that the following formula is valid:

$$|\Delta(t)| \leq \bar{\Delta}(t). \quad (4)$$

where  $\bar{\Delta}(t)$  is the upper bound of the system uncertainties. Unlike the former work [1]. In this paper, both variables (i.e.,  $\bar{\Delta}(t)$ )  $|\Delta(t)|$  are not required to be known through the design and implementation of the proposed controller. Therefore, the control design would be much simpler more flexible than the other robust controller that was designed based on prior knowledge of system perturbation. The final form of the LM dynamic can be rewritten as:

$$\ddot{y}(t) = \frac{1}{m}u(t) - \frac{1}{m}f(t) - \frac{1}{m}\Delta(t). \quad (5)$$

In the next section, we will proceed with the control design based on the aforementioned model of the LM system.

### 3. SMLC FORMULATION FOR THE LM SYSTEM

The aim of this research is to design a controller that can track different trajectories with high tracking performance in the presence of system perturbation. To this end, the SMLC design will be formulated as shown in. First, we define the tracking error as:

$$e(t) = y(t) - y_r(t) \quad (6)$$

where  $t$  is the time parameter,  $y$  is the real displacement of the LM which detected by encoder,  $y_r$  is the tracking reference that we aimed to design a controller to enforce the LM to follow  $y_r$  as precisely as possible with different circumstances. Next, the sliding variable is designed as shown in:

$$s(t) = \dot{e}(t) + \eta e(t) \quad (7)$$

where,  $\eta \in R$  and  $\eta > 0$ . In order to satisfy the sliding mode, the time derivative of (7) is derived by the following formula:

$$\dot{s} = \psi(t) + bu(t) \quad (8)$$

where  $\psi(t) = -\frac{1}{m}(f(t) + \Delta(t)) + \ddot{y}_r(t) - \eta \dot{e}(t)$ , and  $\Delta(t)$  indicates the lumped of system perturbation which includes the modeling errors, parameters variation and external disturbance. It should be noted that there is no prior knowledge to the bounds of these perturbations in the design of SMLC which is the main merits of using such a controller over other robust control methods. In order to proceed with the controller design we have adopted. In this work, a robust sliding based learning controller which is given by [25], [27]:

$$u(t) = u(t - \tau) - \delta u(t) \quad (9)$$

where  $u(t - \tau)$  is the previous sample of the control signal and  $\delta u(t)$  is the iterative learning term which is given by:

$$\delta u(t) = \begin{cases} \frac{1}{bs} \left( \lambda_1 \hat{V}(t - \tau) + \lambda_2 |\hat{V}(t - \tau)| \right), & \text{if } s \neq 0 \\ 0, & \text{if } s = 0 \end{cases} \quad (10)$$

where  $\tau$  is the time delay which is generally selected to be as small as the implementation hardware is allowed for instance it could be selected as one sampling period,  $\lambda_1$  and  $\lambda_2$  are the parameters of the controller to be designed. Meanwhile,  $\hat{V}(t - \tau) = \frac{V(t) - V(t - \tau)}{\tau}$  is the estimated derivative of the delayed Lyapunov candidate  $V(t - \tau)$  which is given by:

$$V(t - \tau) = \left( \frac{s^2(t - \tau)}{2} \right) \quad (11)$$

With a simple investigation into (10) and (9), it can be concluded that the control signal is a result of the contribution of two different terms. Thus, when the sliding mode is not satisfied (i.e.,  $s \neq 0$ ) the iterative learning term would be in charge (i.e.,  $\delta u$ ) to adjust the control effort to meet the sliding conditions. Meanwhile, when the sliding mode is satisfying part (i.e.,  $s = 0$ ) the only previous sample of the control signal would be the provider. Consequently, the continuity of control signal will be achieved, and thus the inherent chattering issue will be remarkably eliminated. This is the distinguished feature of the proposed controller over the CSMC, which can result in extending the lifespan of the LM system and enhance its performance. In the next section, the system stability and asymptotic convergence of the proposed SMLC for the LM system will be elaborated. It has been proved that if  $\tau$  is equal to the sampling time. Then, the flowing inequality can be hold [25], [27]:

$$|\dot{V}(t - \tau) - \hat{V}(t - \tau)| < \epsilon |\hat{V}(t - \tau)| \quad (12)$$

where  $0 < \epsilon \ll 1$ .

#### 4. SYSTEM STABILITY AND CONVERGENCE ANALYSIS

In order to prove the system stability we have introduced the following lemma consider the LM model in (5) under the proposed controller (9) with iteration learning term in (10), then a zero asymptotic convergence of the tracking error (6) will be achieved. Select the following candidate Lyapunov function.

$$V(t) = \left( \frac{s^2(t)}{2} \right). \quad (13)$$

Then the time derivative of  $V(t)$  along the system trajectory can be expressed as shown in:

$$\begin{aligned} \dot{V}(t) &= s(t) \dot{s}(t) \\ &= s(t) (\psi(t) + b u(t)) \\ &= s(t) [\psi(t) + b u(t - \tau)] - s(t) b \delta u(t). \end{aligned} \quad (14)$$

In view of (10) and (13), the first order derivative of  $V(t)$  can be rewritten as:

$$\dot{V}(t) = \dot{V}(t, t - \tau) - \lambda_1 \hat{V}(t - \tau) - \lambda_2 |\hat{V}(t - \tau)| \quad (15)$$

Assumption: suppose that the time interval  $\tau$  is selected to be small enough with continuity of the  $\dot{V}(t)$ , then the following inequality can be held [25].

$$|\dot{V}(t, t - \tau) - \dot{V}(t - \tau)| < \frac{1}{\beta} |\hat{V}(t - \tau)| \quad (16)$$

where  $\beta > 0$  is a large constant number chosen to satisfy specific conditions as will be illustrated late. It should be noted that the inequality (16) is known as Lipschitz-like [25], [27]. Based on (16),  $\dot{V}(t)$  in (15) can be written in the following format:

$$\dot{V}(t) < \frac{1}{\beta} |\hat{V}(t - \tau)| + \dot{V}(t - \tau) - \lambda_1 \hat{V}(t - \tau) - \lambda_2 |\hat{V}(t - \tau)|. \quad (17)$$

For the possibility of  $\dot{V}(t - \tau) > 0$ , we may rewrite (18) in the following format:

$$\dot{V}(t) < \dot{V}(t - \tau) + \left(\frac{1}{\beta} - \lambda_1\right)|\hat{V}(t - \tau)| - \lambda_2|\hat{V}(t - \tau)| \quad (18)$$

if the control parameters are chosen as shown in:

$$\beta \gg 1 \text{ and } 1 - \epsilon - \frac{1}{\beta} > \lambda_1 > \frac{1}{\beta}, \text{ yields} \quad (19)$$

$$\dot{V}(t) < \dot{V}(t - \tau) \quad (20)$$

The inequality (20) implies that the previous derivative of the Lyapunov function is always greater than the instantaneous value (i.e.,  $\dot{V}(t)$ ). Thus, the proposed controller in (9) along with learning term (10) is able to continue decreasing the instant derivative of Lyapunov function  $\dot{V}(t)$  from positive to negative value when  $\dot{V}(t - \tau) > 0$ . Consequently, a zero tracking error can be achieved due to the governing of the closed loop system trajectories to a stable region. On the other hand, when  $\dot{V}(t - \tau) < 0$ , then (18) can be rewritten in view of (12) as:

$$\begin{aligned} \dot{V}(t) &< \frac{1}{\beta}|\hat{V}(t - \tau)| + \hat{V}(t - \tau) + \epsilon|\hat{V}(t - \tau)| \\ &\quad - \lambda_1\hat{V}(t - \tau) - \lambda_2|\hat{V}(t - \tau)| \\ &< \left(\frac{1}{\beta} - 1 + \lambda_1 + \epsilon\right)|\hat{V}(t - \tau)| - \lambda_2|\hat{V}(t - \tau)| \end{aligned} \quad (21)$$

with the (19) criteria, it can be deduced that inequality (21) implies:

$$\dot{V}(t) < 0 \quad (22)$$

The aforementioned analysis proved the asymptotic stability of the closed loop system. In addition, the learning controller in (9) along with the correction term in (10) is able to guarantee the asymptotic converges of the sliding variable  $s(t)$ ,  $\dot{s}(t)$  in (7) and (8), respectively. Consequently, the tracking error  $e(t)$  in (6) asymptotically approaches to zero .

## 5. RESULTS AND DISCUSSION

In this section, simulation results will present to verify the effectiveness of the proposed controller for the LM system. For comparison reason, a CSMC based on the equivalent control techniques has been designed and conducted for the LM system. Following the same procedure of the proposed controller, the design CSMC is formulated for LM as shown in. First, when the sliding condition is satisfied (i.e.,  $s = 0$ ), the equivalent controller is derived as:

$$u_{eq} = f(t) + m(y_r(t) - \eta e(t)). \quad (23)$$

Next, the robust part is designed based on boundary layer technique to alleviate the inherent chattering issue and satisfy the stability condition (i.e.,  $s\dot{s} \leq 0$ ) which satisfy when  $\eta_s \geq \overline{\Delta}(t)$ . Thus, the candidate controller is given by:

$$u_r = -\eta_s \text{sat}(s). \quad (24)$$

where  $\eta_s$  is the controller gain and  $\text{sat}(s)$  is the saturation function that replaced the  $\text{sign}(s)$  function for chattering mitigation purposes. Finally, the simulation tests have been conducted for both controllers simultaneously under the same conditions as will be presented next.

### 5.1. A varying-frequency triangular motion tracking

With the two controllers aforementioned in the previous section, the simulation results of varying-frequencies triangular motion tracking are presented in Figure 2. The depicted tracking profile Figure 2(a) shows that both controllers can follow the reference signal precisely except for the sharp sudden change in track. Thus, an extra effort is provided by SMLC and CSMC to compensate this significant change and keep the LM on the track. Quantitatively, SMLC and CSMC controllers produce the root mean square (RMS) errors of  $0.46 \mu\text{m}$  and  $0.74 \mu\text{m}$  respectively. Hence, the proposed SMLC controller achieves better performance in terms of tracking error, which is 62% less than the CSMC controller in nominal conditions. These results

of tracking error are clearly presented in Figure 2(b) to show the superiority of the proposed SMLC over conventional SMC.

Figure 3(a), on the other hand, shows the control signal, it is clear that the SMLC has a smoother signal than the CSMC. The reason is that the SMLC has no explicit switching in the underline structure. Despite employing saturation function in the designing of CSMC, it still shows some chattering effect. To clearly show the chattering effect of both controllers, the frequency spectrum of the proposed controller, and CSMC is presented underneath the control effort (i.e., Figure 3(b)). Obviously, the SMLC has significantly treated the chattering issue in comparison with CSMC. For further investigation, the next subsection will investigate the same tests in the presence of system uncertainties.

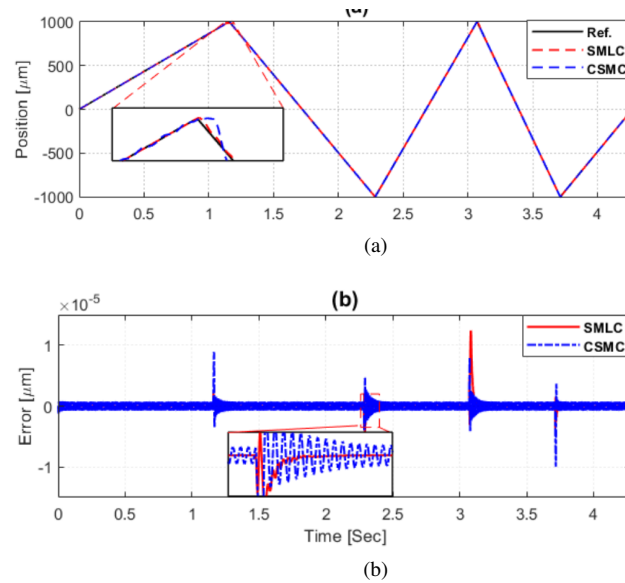


Figure 2. Tracking performance of the LM for varying-frequency triangular reference for both controllers

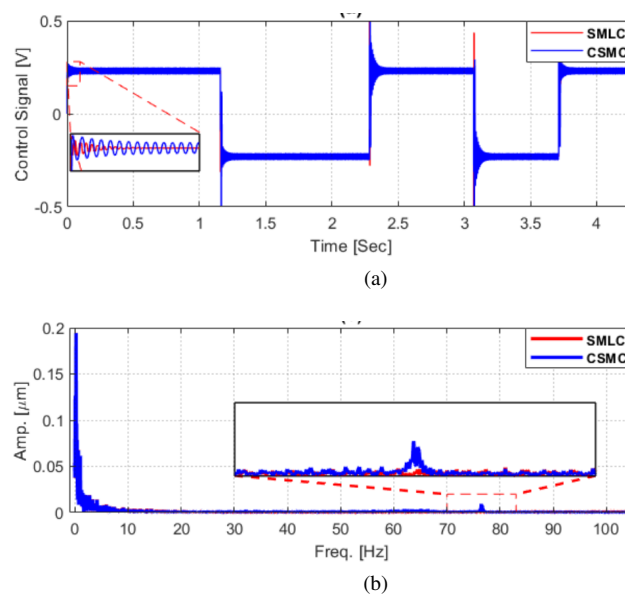


Figure 3. This figure are (a) the control signals of both controllers without uncertainties and (b) the frequency spectrum of the control efforts of SMLC and CSMC

## 5.2. Robustness verification

In order to prove the robustness property for the proposed controller, the same test has been carried out with the condition of mass variation. It should be noted that mass change in LM is the main uncertainty since it is usually used as transporting cart in industrial applications. Thus, the LM mass has been artificially modified by 1.5%. Normally, the CSMC would behave robustly. However, the cost of such behavior would appear at the control smoothness. Figure 4 shows the control signals of both controllers. Unlike the CSMC, the proposed SMLC is properly handled the system uncertainties with a much less chattering effect. The significant improvement of the SMLC in terms of the chattering effect is the result of the adopting learning term in the control structure. On the other hand, CSMC performance is degraded due to switching part. Thus, the proposed controller not only inherits the robustness property of CSMC, but also solved the issue properly. Thus, the SMLC performance has superiority over the CSMC in terms of tracking performance and chattering salivation.

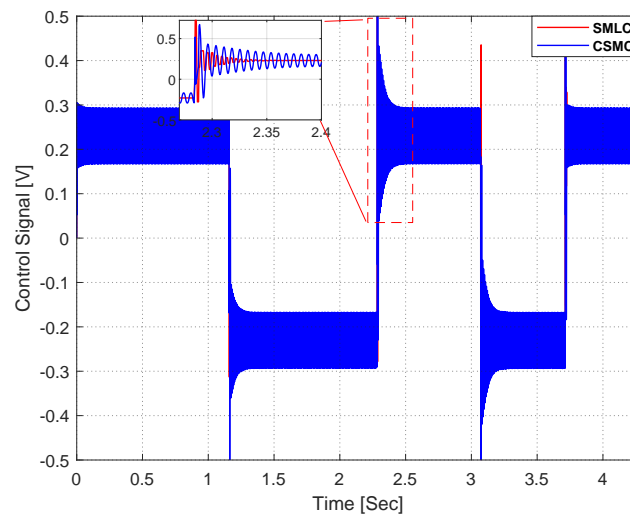


Figure 4. Control effort of both controller for uncertain system

## 6. CONCLUSION

This paper elaborates on the design, analysis, and verification of a continuous robust SMLC controller for the LM system. The convergence analysis has been theoretically proved. The system performance of the proposed controller has been verified via several simulation tests. Results show that the inherent chattering effect in CSMC has been significantly removed in the control signal of the proposed controller. Moreover, the SMLC performance has superiority over CSMC schemes for trajectories tracking of varying frequencies triangular reference signal. These results are conducted in the absence and presence of system uncertainties. For either case, the SMLC was able to precisely track these references with promising performance for the LM system without prior knowledge of the upper bound of system perturbation, which makes it simpler and easier in implementation and practical usage. Thus, it could be considered as an alternative control method for such mechatronics applications that required a robust control to achieve the targeted resolution without affecting the life span of their precious actuators. In the future work, we will elaborate on the practical part of such controller for the LM system with adaptive gain for further improvement in control system performance.




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