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Design and Experimental Verification of Adaptive Sliding Mode Control for Precision Motion and Energy Saving in Feed Drive Systems

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ABSTRACT Energy consumption of computer numerical controlled (CNC) machines is one of the critical issues in the industrial community owing to the round-the-clock operation of these machines. Recently, there is a great demand for reducing energy consumption in various industries due to production costs and environmental factors such as global warming and climate change. For this reason, many researchers are focusing on reducing the energy consumption of industrial machines. In previous studies, feedback controllers with fixed gains have been designed to feed a drive system, whereby high control gains are set to enhance tracking performance. Contrarily, high control gains cause high consumption of energy, and this property was less concerned in the previous studies. By allowing adaptation of the control gains so that they change according to disturbance variations, energy consumption may be reduced. This paper focuses on energy saving in feed drive systems by using adaptive sliding mode control with a nonlinear sliding surface. Stability of the proposed control system is proved based on the Lyapunov stability theory, and the convergence of the system trajectory to the sliding surface is guaranteed. The effectiveness of the proposed method has been confirmed by simulation and experiment. The experimental results for a certain trajectory verified that the proposed controller could reduce the consumed energy by 3.4% on average and enhance the tracking performance by reducing the maximum tracking error by 45% on average. In addition to that, the control input variance could be reduced by 12.6%.

INDEX TERMS Adaptive control, energy reduction, feed drives, machine tools, precision control, sliding mode.

I. INTRODUCTION

Owing to limited reserve of nonrenewable energy sources and environmental factors such as global warming and climate change, energy sources must be used efficiently [1], [2]. The industrial community, particularly manufacturing sector is estimated to deplete about one-third of world energy consumption [3]. Reducing energy consumption in industrial machines can reduce overall production costs and enhance industrial competitiveness. Because production machines, such as machine tools, operate continuously for a long time, even a small percentage of energy reduction can effectively lower production costs and reduce environmental damage caused by energy generation systems. Feed drive systems generally take the highest percentage of motion systems in the industrial community. They are widely applied in CNC machines, industrial robots, and precision assembly equipments and so on. These applications are considered as one of the major sources of high-energy consumption because they run for a long time all over the world. Hence, the optimization of energy consumption in industrial machines is critical and it is increasingly attracting many researchers [4]–[12].

Although several methods have been proposed in former studies for enhancing the motion of feed drive systems, great efforts were required for developing controllers to improve the tracking performance of each individual system [13]–[22]. Furthermore, responding to the demand for high-speed machining, recent studies concentrated on

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controllers that could improve the machining accuracy. Since machine tools are normally composed of linear motion segments, which limit the machine movement for certain geometries and thus compromises precision of machined parts, several studies came out with interesting methods for generating smooth trajectories and developing controllers for high-speed motions [23]–[25]. To meet these requirements, a survey of recent literature shows that sliding mode control (SMC) has been recognized as a sufficient tool to design robust controllers for complex high-order nonlinear dynamic plants operating under various uncertainty conditions [10], [25]–[29]. It has many good features like invariance to matched uncertainty, robustness against perturbation, and simplicity in design. Adaptive nonlinear sliding mode control with a nonlinear sliding surface for feed drive systems was designed in [30], and its effectiveness was verified.

Despite the previous studies, a comprehensive literature review in energy consumption modeling and energy efficiency evaluation for energy-saving in manufacturing is required owing to the fact that some related concepts are not clear and the precision models still need to be promoted in this field [1]. While some studies such as [2] focus on integrating machine selection and operation sequence for reducing energy consumption of machine tools, control design can be used as an inexpensive and effective approach towards energy saving while enhancing the machining accuracy. Simultaneous efforts to enhance tracking performance and reduce the energy required to operate industrial machines, especially feed drive systems, are the key motivation for this study.

In previous studies of our group, several methods for controlling feed drive systems were proposed including a novel sliding mode controller with a nonlinear sliding surface to reduce energy consumption in a ball screw feed drive system [31]. With the nonlinear sliding surface, the damping ratio of the control system can be changed from a low initial value to a high final value in order to achieve fast system response without overshoot, and hence better performance with less energy consumption are simultaneously achieved. The effectiveness of using a nonlinear sliding surface in reducing energy consumption by a feed drive system was proved, whereby energy consumption was reduced by about 12.9% in comparison to sliding mode control with a linear sliding surface. Despite the good performance of the controller proposed in [31], its design needs a knowledge of uncertainty bound that practically could be a difficult task to know. In case that this bound is overestimated, it will yield the excessive gain, which implies higher control input magnitude that causes more energy consumption unnecessarily.

On the other hand, a sliding mode contouring control with a nonlinear sliding surface and a gain scheduling technique for feed drive systems was proposed in [32]. Through simulation analysis, the authors showed that this method could decrease the contour error by about 31.48% without any change in energy consumption in comparison to non-adaptive sliding mode control. Although the controller was considered as adaptive sliding mode control, the adaptive gain was defined by $K_c = \int \rho S_m^2 dt$, where ρ is the positive scalar adaption rate and S_m is the sliding variable [33]. This means that, the adaptive gain keeps increasing until the upper limit is reached. The problem with this adaptive law is that K_c has an impact on the control input only during the reaching phase, but when the sliding variable is equal to zero (sliding phase), the adaptive law has no impact on the control input. Furthermore the author has not provided any analysis on how energy can be saved by using this method. In order to save energy in feed drive systems, not only the reaching phase but also the sliding phase should be considered when designing adaptive sliding mode control.

Based on the discussion above, in this study, design and experimental verification of adaptive sliding mode control (ASMC) using a nonlinear sliding surface for reducing energy consumption are proposed. The objective is to raise awareness of energy issues in feed drive systems and to elaborate the advantage of adaptive sliding mode control in reducing the energy consumption while providing satisfactory tracking performance. The stability of the proposed control system is proved by using the Lyapunov stability theory, whereby the system trajectories converge to the sliding surface. Simulation and experiments were performed to confirm the effectiveness of the proposed method and the results were compared to the controller in [31], which is a nonlinear sliding mode control with no adaptation. It was shown that the proposed method achieved better performance by reducing energy consumption by 3.4% and tracking error by 46% with a trifolium trajectory. In addition control input variance was reduced by 12.6%.

The rest of the paper is organized as follows: A plant dynamics model of a typical X-Y table is presented in section II. Controller design and stability analysis are presented in section III. Section IV gives simulation and experimental results to validate the effectiveness of the proposed method followed by concluding remarks in section V.

II. DYNAMICS MODEL OF X-Y TABLE

The dynamics of a typical lead-screw feed drive based X-Y table is represented by the following decoupled second order system:

$$
\begin{aligned}
&M\ddot{x} + C\dot{x} + d = f,\\
&\qquad M = \mathrm{diag}\,(m_i)\,, \quad C = \mathrm{diag}\,(c_i)\,, \quad i = 1,\ 2,\\
&\qquad f = [f_1,\ f_2]^T\,, \quad d = [d_1,\ d_2]^T\,,\\
&\qquad x = [x_1,\ x_2]^T,
\end{aligned}
\tag{1}
$$

where M and C are the table mass and viscous friction coefficient matrices, respectively. d, f, and x are the disturbances to the system, the driving forces, and positions of the i^{th} drive axis, respectively. Each drive axis has an attached servo motor that provides rotational motion and transmits it to a lead screw via a coupling, the rotation of the lead screw is transformed into linear movement of the table by the feed drive axes. The corresponding motor dynamics is represented as follows:

$$\begin{aligned} N\ddot{\theta} + H\dot{\theta} + \tau &= K_t i_a, \\ N &= \operatorname{diag}(n_i), \quad H = \operatorname{diag}(h_i), \\ K_t &= \operatorname{diag}(k_{t_i}), \quad \theta = [\theta_1,\ \theta_2]^T, \\ \tau &= [\tau_1,\ \tau_2]^T, \quad i_a = [i_{a_1}, i_{a_2}]^T, \end{aligned} \tag{2}$$

where N, θ, and H, represent the inertia matrix, the rotational angle vector, and viscous friction coefficient matrix of the motors, respectively. τ, K_t, and i_a are the torque vector required to drive the feed drive system, torque constant matrix, and input current vector, respectively. The relationships between f, τ, x, and θ are represented by the following equation:

$$f_i = \frac{2\pi\tau_i}{p_i}, \quad x_i = \frac{p_i\theta_i}{2\pi}, \tag{3}$$

where p_i is the pitch of the i^{th} drive axis. Equations (1), (2), and (3) lead to the following plant dynamics.

$$\begin{aligned} u &= J_e\ddot{x} + B_e\dot{x} + d, \\ J_e &= \operatorname{diag}\left(\frac{4\pi^2\, n_i + m_i p_i^2}{p_i^2}\right), \\ B_e &= \operatorname{diag}\left(\frac{4\pi^2\, h_i + c_i p_i^2}{p_i^2}\right), \\ u &= K_\mu i_a,\ K_\mu = \operatorname{diag}\left(\frac{2\pi k_{t_i}}{p_i}\right), \end{aligned} \tag{4}$$

where J_e and B_e are the equivalent inertia and friction coefficients representing combined linear and rotary coefficients. The tracking error of the system is given as follows:

$$\begin{aligned} e &= x_r - x, \\ e &= [e_1,\ e_2]^T, \quad x_r = [x_{r_1}, x_{r_2}]^T, \end{aligned} \tag{5}$$

where x_r is the desired position vector. The error dynamics of the feed drive system can be written as

$$\ddot{e} = \ddot{x}_r - J_e^{-1}(u - d - B_e\dot{x}). \tag{6}$$

III. CONTROLLER DESIGN

Designing an adaptive nonlinear sliding mode controller involves two steps: The first step is to select the sliding surface in which the system tracks a desired trajectory and the controlled dynamics is exponentially stable. The second step is to design a control law which drives the system to the desired sliding surface in a finite time.

A. SLIDING SURFACE DESIGN

To improve the control performance, a nonlinear sliding surface is employed [31]. Fig. 1 illustrates the step response of three different second order systems. System (a) has a large damping ratio, therefore the system response is very slow with larger tracking error and smaller energy consumption. In system (b) which has a small damping ratio, the system response is very fast with a large overshoot which increases energy consumption. System (c) takes advantages of systems (a) and (b) such that the damping ratio is allowed to change from a low initial value to achieve fast response to a high final value to prevent the overshoot. This variable damping ratio is achieved by using a nonlinear sliding surface with which reduction of the energy consumption is achieved while maintaining the motion accuracy. The following nonlinear sliding surface is considered [31]:

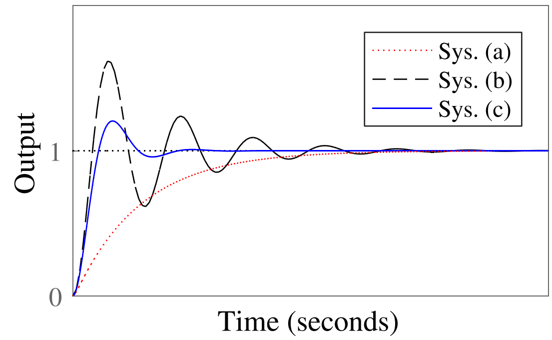

FIGURE 1. System response with different damping ratios. System (a) with high damping ratio, System (b) with low damping ratio, System (c) with nonlinear damping ratio.

$$\begin{aligned} s &= [A\ I]\begin{bmatrix} e \\ \dot{e} \end{bmatrix} \\ A &= \operatorname{diag}(\lambda_i + \psi_i\gamma_i). \end{aligned} \tag{7}$$

where, λ_i is the linear term of the sliding surface, it is chosen such that dominant poles have a low damping ratio. γ_i is a positive definite matrix for adjusting the damping ratio, and ψ_i is a non-negative differentiable function which changes the damping ratio of the system from its low initial value to a high final value as the output changes from its initial value to the desired value. Based on the nonlinear function presented in [34] for a step-type reference trajectory, ψ_i in this paper is presented as follows:

$$\begin{aligned} \psi_i &= \frac{\beta_i}{(1 - \exp(-1))}\left\{\exp\left[\left(\frac{\dot{x}_i}{\dot{x}_{r_i}}\right)^2 - 1\right] - \exp(-1)\right\}, \\ \dot{x}_{r_i} &\neq 0, \end{aligned} \tag{8}$$

where β_i is the positive tuning parameter that determines the final damping ratio. If the system output is far from the desired point, the magnitude of ψ_i becomes small, this provides a low damping ratio and speeds up the system response. On the sliding surface, that is when $s = 0$, we have

$$\dot{e} = -Ae, \tag{9}$$

where A is not a constant matrix. To verify the stability of the sliding surface $s = 0$, the following Lyapunov function is considered:

$$V = \frac{1}{2}ee^T \tag{10}$$

Substituting (9) into the time derivative of V leads to

$$\dot{V} = -eAe^T \tag{11}$$

Since A is a positive definite matrix, the asymptotic stability is guaranteed.

B. ADAPTIVE CONTROL DESIGN

The control law is designed such that from any initial condition, the trajectory of the system is attracted toward the sliding surface. Based on the proposed sliding surface and the feed drive dynamics, the following control law is designed:

$$u = J_e\left\{\ddot{x}_r + A\dot{e} + \hat{K}s - Be\right\} + Q\text{sign}(s) + B_e\dot{x}$$
$$B = \text{diag}\left(\frac{d\psi_i}{dt}\gamma_i\right),\ \hat{K} = \text{diag}\left(\hat{k}_i\right) \tag{12}$$

where $\hat{K}$ is the adaptive gain and $Q \in R^{2\times 2}$ is a diagonal matrix with diagonal elements q_i chosen from the maximum bound of the uncertainty as follows:

$$q_i \geq \max(d_i). \tag{13}$$

The adaptive law is chosen based on the idea in [35] as follows:

$$\dot{\hat{k}}_i = \begin{cases} \bar{k}_i|s_i|\text{sign}(|s_i| - \epsilon_i) & \text{if } \hat{k}_i > \alpha_i \\ \mu_i & \text{otherwise} \end{cases}, \tag{14}$$

where ϵ_i, α_i, μ_i, and $\bar{k}_i$ are positive constants. The parameter μ_i is introduced in order to obtain positive values for $\hat{k}_i$. Once sliding mode is established ($|s_i| < \epsilon_i$), the proposed gain adaptation law (14) lets the gain $\hat{k}_i$ decrease. In other words, the gain $\hat{k}_i$ will be kept at the smallest level that allows a given accuracy of stabilization of the sliding surface. This adaptation law maintains an adequate gain magnitude with respect to disturbances.

1) STABILITY ANALYSIS

The following Lyapunov function candidate is considered:

$$V_i = \frac{1}{2}s_i^2 + \frac{1}{2}(\hat{k}_i - k_i^*)^2 \tag{15}$$

where k_i^* is an upper bound of the control gain $\hat{k}_i$ so that

$$\hat{k}_i \leq k_i^*$$

The time derivative of Lyapunov function in (15) is written as follows:

$$\dot{V}_i = s_i\dot{s}_i + \left(\hat{k}_i - k_i^*\right)\dot{\hat{k}}_i \tag{16}$$

From the time derivative of the sliding surface in (7) and the adaption rule for the controller gain $\hat{k}_i$ in (14), the time-derivative of V_i becomes

$$\dot{V}_i = s_i\left\{(\lambda_i - \psi_i\gamma_i)\dot{e}_i + \ddot{e}_i - \frac{d\psi_i}{dt}\gamma_i e_i\right\}$$
$$+ \left(\hat{k}_i - k_i^*\right)\bar{k}_i|s_i|\text{sign}(|s_i| - \epsilon_i) \tag{17}$$

Substituting Eqs. (6) and (12) into (17) leads to

$$\dot{V}_i = s_i\left\{-\hat{k}_i s_i - q_i\text{sign}(s_i) + d_i\right\}$$
$$+ \left(\hat{k}_i - k_i^*\right)\bar{k}_i|s_i|\text{sign}(|s_i| - \epsilon_i),$$
$$= |s_i|\left\{-\hat{k}_i - q_i + d_i + \left(\hat{k}_i - k_i^*\right)\bar{k}_i\text{sign}(|s_i| - \epsilon_i)\right\} \tag{18}$$

We consider the following two cases for the stability analysis.

- **Case 1** When $|s_i| \geq \epsilon_i$ as in the first condition in Eq. (14), $\left(\hat{k}_i - k_i^*\right)\bar{k}_i\text{sign}(|s_i| - \epsilon_i)$ is non positive, and
$$\dot{V}_i < 0. \tag{19}$$
- **Case 2** When $|s_i| < \epsilon_i$ as in the second condition in Eq. (14), $\left(\hat{k}_i - k_i^*\right)\bar{k}_i\text{sign}(|s_i| - \epsilon_i)$ is non negative. By choosing q_i as
$$q_i \geq \left(\hat{k}_i - k_i^*\right)\bar{k}_i + d_i \tag{20}$$
we have
$$\dot{V}_i < 0, \tag{21}$$
and the system stability is guaranteed.

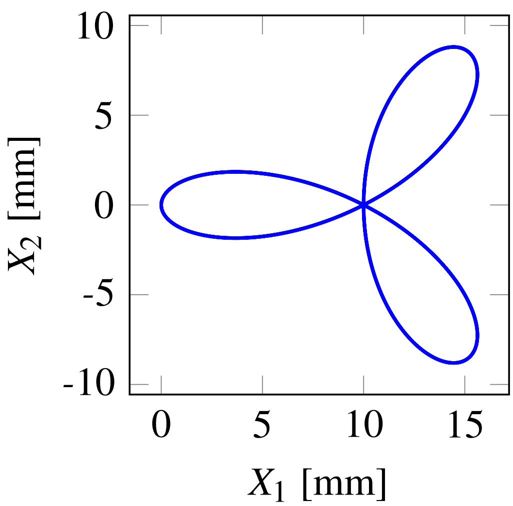

FIGURE 2. Reference trajectories.

IV. SIMULATION AND EXPERIMENT

To validate the effectiveness of the proposed method, simulation and experiment were conducted. A trifolium trajectory in Eq. (22) and Fig. 2 was used. Results were compared to sliding mode control without adaptation. In addition, the performance of the proposed method (ASMC) is compared to the one in [32] by simulation.

$$x_{r_1} = r^*\cos\left(\frac{2\pi t}{T}\right),\quad x_{r_2} = r^*\sin\left(\frac{2\pi t}{T}\right),$$
$$r^* = r\cos\left(\frac{2\pi t}{T}\right)\left\{4\sin^2\left(\frac{2\pi t}{T}\right) - 1\right\}, \tag{22}$$

TABLE 1. System parameters.

Axis	m_i (kg)	c_i (Nsmm^{-1})	n_i (kgm^2)	h_i (Nms/rad)
1	8.0	102.48	0.05	0.31
2	2.5	140.90	0.05	0.31

TABLE 2. Controller parameters.

Control	λ_i (s^{-1})	γ_i (s^{-1})	β_i	q_i (ms^{-2})	k_i (s^{-1})
ASMC	40	1.8	10	0.3	variable
SMC	40	1.8	10	0.3	80

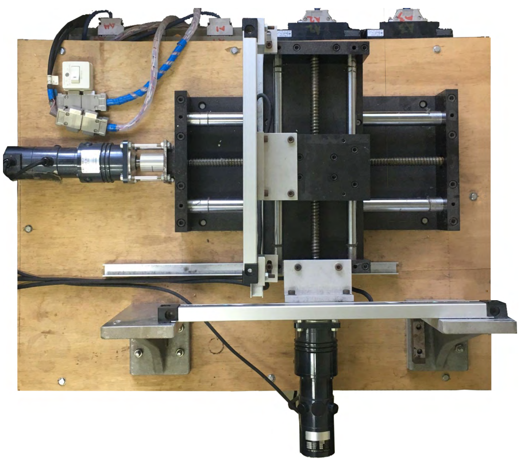

FIGURE 3. Biaxial feed drive system.

where r is the radius and T is the total time to complete the trajectory. System and controller parameters are given in Tables 1 and 2 respectively. These parameters were used for both simulation and experiment.

A. EXPERIMENTAL SETUP

A typical biaxial lead-screw feed drive system (Fig. 3) was used for the experiment. The feed drive system comprises of a table that is coupled by two lead-screw drives, which are driven by DC-servo motors connected to each drive axis. Rotary encoders (equivalent resolution: 0.025 μm) were used to measure the actual position of the table. The velocity signal was calculated by means of numerical differentiation of the measured position. The control law was implemented using C^{++} program on a personal computer with a sampling time of 5ms.

B. SIMULATION RESULTS

Fig. 4 show simulation results of tracking performance. The initial tracking error is large because reference trajectory was implemented by typical G-code that generates constant velocity motion profiles. However, it could be seen that the

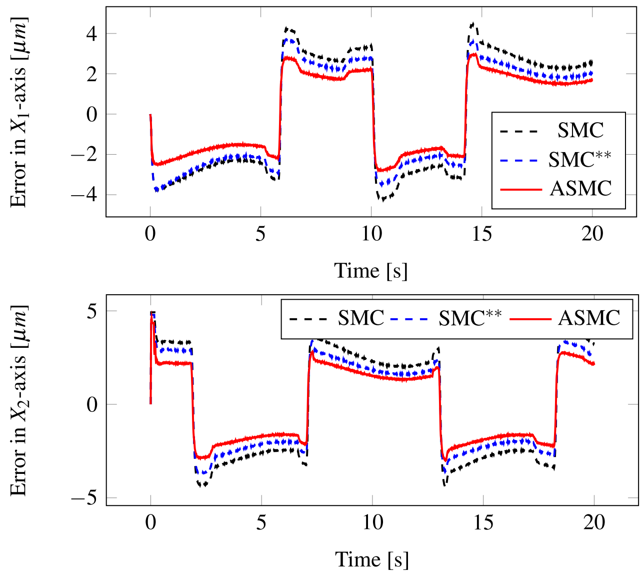

FIGURE 4. Simulation results of tracking performance.

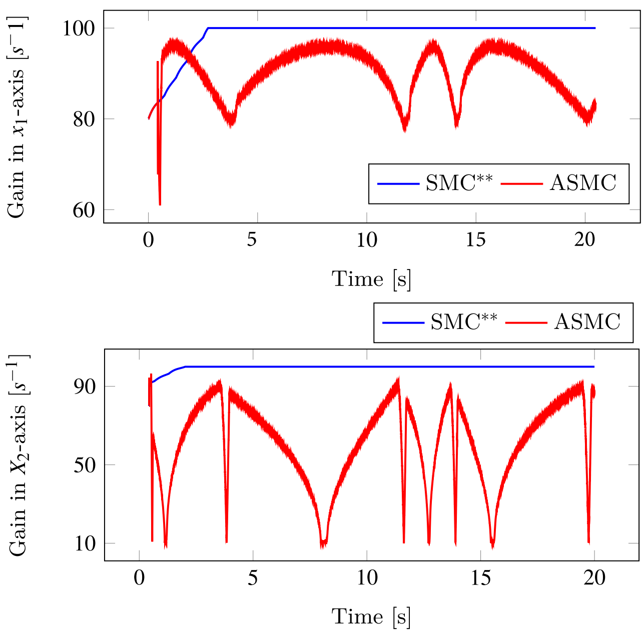

FIGURE 5. Adaptive gain K_c.

ASMC achieved better tracking performance than the SMC. The ASMC reduced the average tracking error by 33%. The SMC** in Fig. 4 is the tracking error results when the gain adaptation law $K_c = \int \rho S_m^2 dt$ in [32] was used. The values of ρ and the upper bound for K_c were set to 0.8 and 100 s^{-1}, respectively. It could be seen that ASMC yielded a better performance over SMC** because the proposed adaptive law varies according to the tracking error while the one [32] stays at the upper limit, as shown in Fig. 5. Summary of simulation results are shown in Table 3.

TABLE 3. Summary of simulation results.

Controller	Tracking error [μm]			
	Maximum		Mean	
	X_1-axis	X_2-axis	X_1-axis	X_2-axis
SMC	4.46	4.18	0.34	0.50
ASMC	2.96	2.82	0.23	0.33

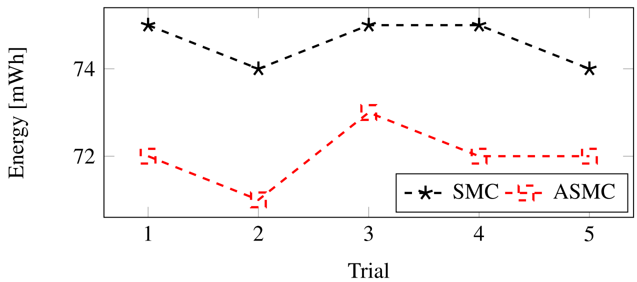

FIGURE 6. Experimental results of energy consumption.

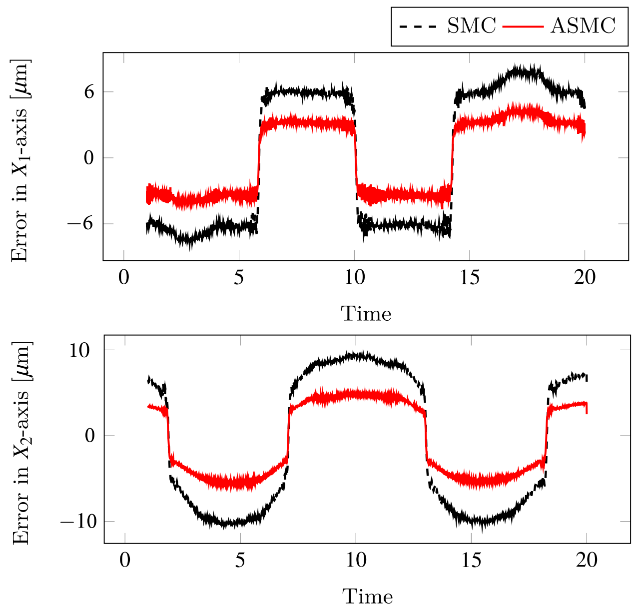

FIGURE 7. Experimental results of tracking performance.

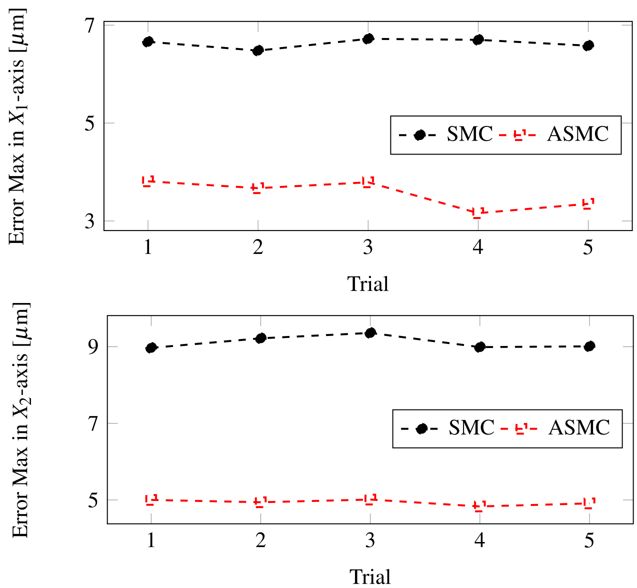

FIGURE 8. Experimental results of maximum tracking error.

C. EXPERIMENTAL RESULTS

In order to confirm the effectiveness of the proposed method in performance enhancement and energy saving, experiment was conducted for the trifolium trajectory. In the first case, the aim was to confirm the effectiveness of the proposed approach in reducing the tracking error by comparing the performance of ASMC to SMC. In this comparison, the same parameters were used for both controllers so as to conduct a fare comparison except the gain $\hat{K}$, which is varying for the case of ASMC. However, the initial gain $\hat{K}$ for the ASMC was set at the same value to that of the SMC. The controllers' parameters in Table 2 were used in the experiment the same as simulation. Electrical energy consumption was measured by power Hi-tester (HIOKI 3334 AC/DC), and results were compared to those of SMC with no adaptation. The same experiment was repeated five times to ensure the repeatability of the proposed method. Fig. 6 shows the consumed electrical energy for five trials. In all trials the proposed controller (ASMC) consumed less energy than the SMC. The ASMC reduced the energy consumption by 3.4% for the trifolium trajectory. Experimental results for tracking errors and control input voltages are taken from 1s after the start of an experiment. Fig. 7 shows tracking error results in which the ASMC achieved better tracking performance than the SMC by reducing the average tracking error by 50% and 43.7% in X_1 and X_2 drive axes, respectively. Fig. 8 shows maximum absolute values of the tracking errors for five trials. Input voltage is shown in Fig. 9 whereby the proposed method has smoother input voltage than SMC, which has more chattering especially in X_1-axis. The summary of experimental tracking performance and energy consumption results are shown in Table 4 and 5, respectively. In addition, the control input variance was calculated by the following equation:

$$\sigma_i^2 = \frac{\sum_{j=1}^{N} u_{ij}^2}{N} - \bar{u}_i^2 \tag{23}$$

where σ_i is the standard deviation, u_{ij} is the control input value at the j^{th} sampling instant of the i^{th} drive axis, $\bar{u}_i$ is the mean of all control input values of the i^{th} drive axis, and N is the total number of the sampling instants. Fig. 10 shows the control input variance from which it can be seen that the proposed approach achieved smaller control input variance

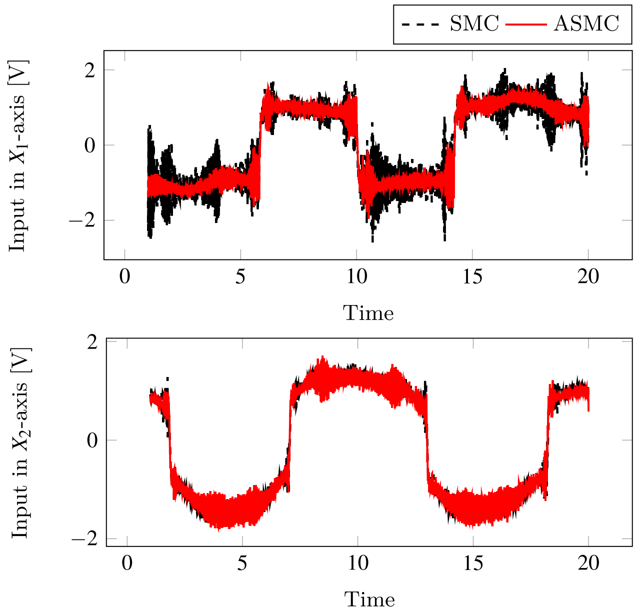

FIGURE 9. Experimental input voltage.

TABLE 4. Summary of experimental tracking performance results.

Controller	Tracking error [μm]			
	Maximum		Mean	
	X_1-axis	X_2-axis	X_1-axis	X_2-axis
SMC	6.72	9.36	0.16	1.28
ASMC	3.81	5.01	0.08	0.72

TABLE 5. Summary of experimental input variance and energy consumption results.

Controller	Input variance [V]		Energy consumption [mWh]
	Mean		Mean
	X_1-axis	X_2-axis	
SMC	1.30	1.36	74.6
ASMC	1.04	1.19	72.0

than SMC in both axes. From these results it is clear that ASMC achieves better performance than SMC. In the second case, we confirm the effectiveness of the proposed method in saving energy under similar tracking performance using the same trajectory. To achieve the similar tracking performance for both SMC and the proposed ASMC, the linear term λ_i of the sliding surface was increased from $40\,s^{-1}$ to $80\,s^{-1}$. Hereinafter, the SMC with raised linear-term gain is referred as SMC*. The experiment was repeated five times and results were compared to that of the proposed method. By increasing the linear-term gain, the total energy consumed by SMC* increased from the average of 74.6 to 83.1 mW h. Fig. 11 shows the energy results for the five trials in which the two controllers have similar tracking performance, and the

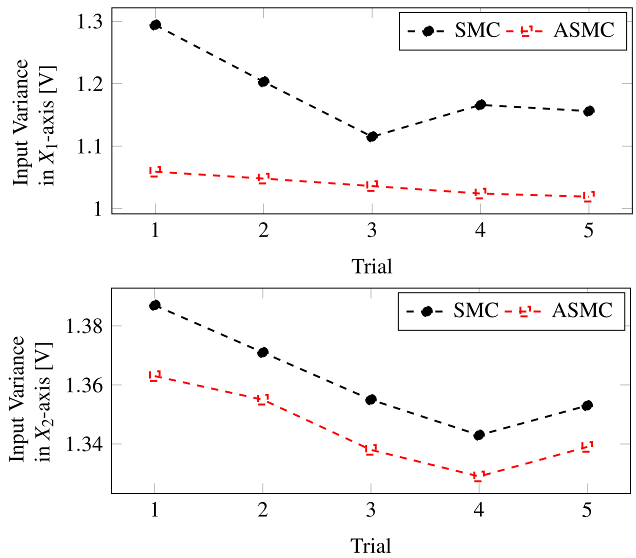

FIGURE 10. Experimental input variance.

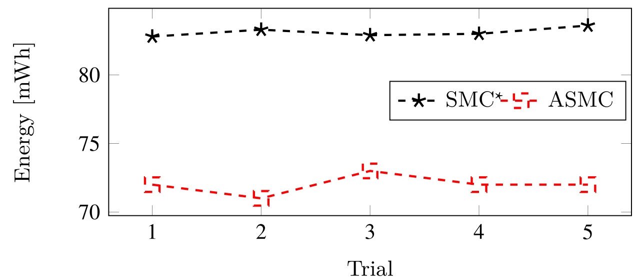

FIGURE 11. Experimental results of energy consumption under similar tracking performance.

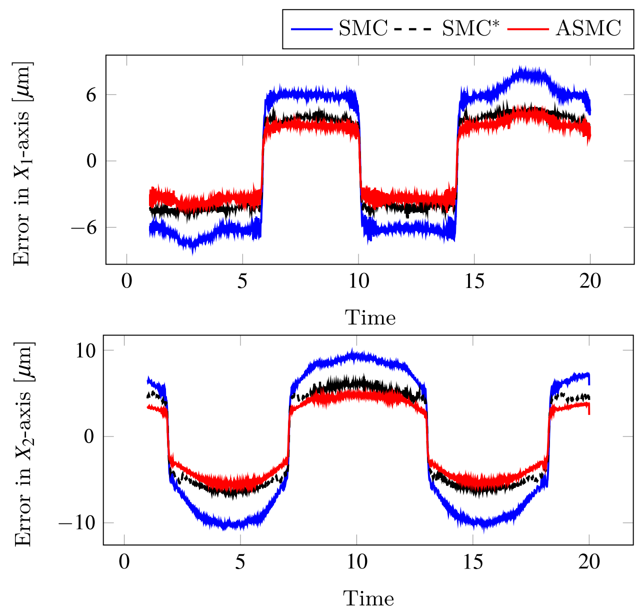

FIGURE 12. Experimental results of tracking error under similar tracking performance.

SMC consumes more of energy. Fig. 12 shows the tracking performance for the two cases, case one for similar parameters while case two its where λ_i was increased in SMC so

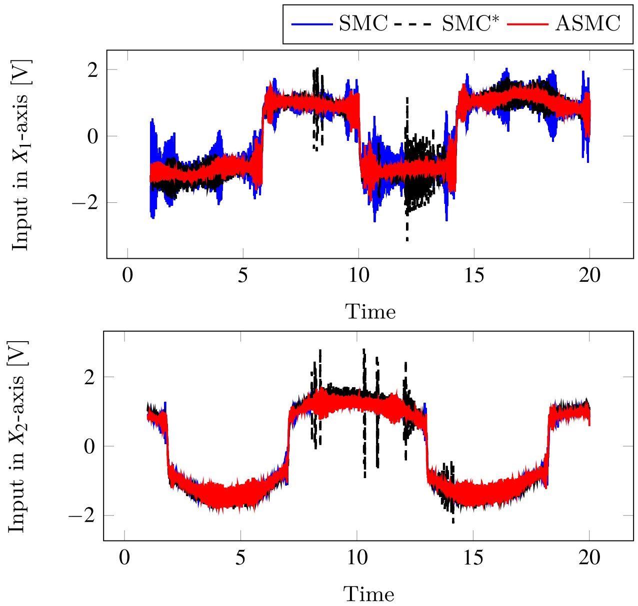

FIGURE 13. Experimental input voltage under similar tracking performance.

as to achieve similar tracking performance as ASMC. The corresponding input signals are shown on Fig. 13, where the control input for SMC has more chattering than that of ASMC. The control input variance for SMC* increased from 1.14 to 1.16V in X_1-axis, and from 1.28 to 1.47V in X_2-axis in comparison to the SMC. The proposed method (ASMC) achieved smaller input variance of 1.04V and 1.19V in X_1 and X_2-axes, respectively.

V. CONCLUSION

In this paper, adaptive sliding mode control with a nonlinear sliding surface for precision motion and energy saving of feed drive systems has been proposed. Simulation and experiment were conducted to demonstrate the effectiveness of the proposed method in terms of energy saving and tracking performance enhancement in feed drive systems. Results were compared to that of sliding mode control without adaptation to evaluate the performance of the proposed one. Results show that the energy consumption, tracking error, and control input variance of the proposed controller were smaller than those of non-adaptive sliding mode control. The proposed controller could reduce the consumed energy by 3.4% for a trifolium trajectory. In addition, the tracking performance could be enhanced by reducing the maximum tracking error by 45%. In addition the proposed method achieved smaller control input variance by 12.6% in comparison to the SMC. Because we use a typical ball-screw based X-Y table for verifying the effectiveness, the proposed controller can be widely applied in various industrial systems.

REFERENCES

[1] L. Zhou, J. Li, F. Li, Q. Meng, J. Li, and X. Xu, "Energy consumption model and energy efficiency of machine tools: A comprehensive literature review," *J. Cleaner Prod.*, vol. 112, pp. 3721–3734, Jan. 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0959652615006617. doi: 10.1016/j.jclepro.2015.05.093.

[2] Y. He, Y. Li, T. Wu, and J. W. Sutherland, "An energy-responsive optimization method for machine tool selection and operation sequence in flexible machining job shops," *J. Cleaner Prod.*, vol. 87, pp. 245–254, Jan. 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0959652614010464. doi: 10.1016/j.jclepro.2014.10.006.

[3] H.-S. Yoon, E.-S. Kim, M.-S. Kim, J.-Y. Lee, G.-B. Lee, and S.-H. Ahn, "Towards greener machine tools—A review on energy saving strategies and technologies," *Renew. Sustain. Energy Rev.*, vol. 48, pp. 870–891, Aug. 2015. [Online]. Available: http://www.sciencedirect.com/science/article/ pii/S1364032115002609. doi: 10.1016/j.rser.2015.03.100.

[4] S. Hu, F. Liu, Y. He, and T. Hu, "An on-line approach for energy efficiency monitoring of machine tools," *J. Cleaner Prod.*, vol. 27, pp. 133–140, May 2012. doi: 10.1016/j.jclepro.2012.01.013.

[5] U. Götze, H.-J. Koriath, A. Kolesnikov, R. Lindner, and J. Paetzold, "Integrated methodology for the evaluation of the energy-and cost-effectiveness of machine tools," *CIRP J. Manuf. Sci. Technol.*, vol. 5, no. 3, pp. 151–163, 2012. doi: 10.1016/j.cirpj.2012.04.001.

[6] O. I. Avram and P. Xirouchakis, "Evaluating the use phase energy requirements of a machine tool system," *J. Cleaner Prod.*, vol. 19, nos. 6–7, pp. 699–711, 2011. doi: 10.1016/j.jclepro.2010.10.010.

[7] R. Neugebauer, M. Wabner, H. Rentzsch, and S. Ihlenfeldt, "Structure principles of energy efficient machine tools," *CIRP J. Manuf. Sci. Technol.*, vol. 4, no. 2, pp. 136–147, 2011. doi: 10.1016/j.cirpj.2011.06.017.

[8] F. Draganescu, M. Gheorghe, and C. V. Doicin, "Models of machine tool efficiency and specific consumed energy," *J. Mater. Process. Technol.*, vol. 141, no. 1, pp. 9–15, 2003. doi: 10.1016/S0924-0136(02)00930-5.

[9] C. Okwudire and J. Rodgers, "Design and control of a novel hybrid feed drive for high performance and energy efficient machining," *CIRP Ann.*, vol. 62, no. 1, pp. 391–394, 2013. doi: 10.1016/j.cirp.2013.03.139.

[10] A. El Khalick Mohammad A. M., N. Uchiyama, and S. Sano, "Energy saving in feed drive systems using sliding-mode-based contouring control with a nonlinear sliding surface," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 2, pp. 572–579, Apr. 2015. doi: 10.1109/TMECH.2013.2296698.

[11] N. Uchiyama, Y. Ogawa, A. El Khalick M, and S. Sano, "Energy saving in five-axis machine tools using synchronous and contouring control and verification by machining experiment," *IEEE Trans. Ind. Electron.*, vol. 62, no. 9, pp. 5608–5618, Sep. 2015. doi: 10.1109/TIE.2015.2437354.

[12] N. Uchiyama, K. Goto, and S. Sano, "Analysis of energy consumption in fundamental motion of industrial machines and experimental verification," in *Proc. Amer. Control Conf. (ACC)*, Jul. 2015, pp. 2179–2184. doi: 10.1109/ACC.2015.7171056.

[13] B. Bandyopadhyay and D. Fulwani, "High-performance tracking controller for discrete plant using nonlinear sliding surface," *IEEE Trans. Ind. Electron.*, vol. 56, no. 9, pp. 3628–3637, Sep. 2009. doi: 10.1109/TIE.2008.2007984.

[14] Z. Lin, M. Pachter, and S. Banda, "Toward improvement of tracking performance nonlinear feedback for linear systems," *Int. J. Control*, vol. 70, no. 1, pp. 1–11, 1998. doi: 10.1080/002071798222433.

[15] Y. He, B. M. Chen, and C. Wu, "Improving transient performance in tracking control for linear multivariable discrete-time systems with input saturation," *Syst. Control Lett.*, vol. 56, no. 1, pp. 25–33, 2007. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0167691106001265. doi: 10.1016/j.sysconle.2006.07.006.

[16] G. Cheng, K. Peng, B. M. Chen, and T. H. Lee, "Improving transient performance in tracking general references using composite nonlinear feedback control and its application to high-speed *XY*-table positioning mechanism," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 1039–1051, Apr. 2007. doi: 10.1109/TIE.2007.892635.

[17] B. Bandyopadhyay and D. Fulwani, "A robust tracking controller for uncertain MIMO plant using non-linear sliding surface," in *Proc. IEEE Int. Conf. Ind. Technol.*, Feb. 2009, pp. 1–6. doi: 10.1109/ICIT.2009.4939667.

[18] M. Chen, S. S. Ge, and B. Ren, "Adaptive tracking control of uncertain MIMO nonlinear systems with input constraints," *Automatica*, vol. 47, no. 3, pp. 452–465, Mar. 2011. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0005109811000409. doi: 10.1016/j.automatica.2011.01.025.

[19] H. Zhang and F. L. Lewis, "Adaptive cooperative tracking control of higher-order nonlinear systems with unknown dynamics," *Automatica*, vol. 48, no. 7, pp. 1432–1439, 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0005109812001811. doi: 10.1016/j.automatica.2012.05.008.

[20] H. Du, S. Li, and C. Qian, "Finite-time attitude tracking control of spacecraft with application to attitude synchronization," *IEEE Trans. Autom. Control*, vol. 56, no. 11, pp. 2711–2717, Nov. 2011. doi: 10.1109/TAC.2011.2159419.

[21] Z. Li, X. Liu, W. Ren, and L. Xie, "Distributed tracking control for linear multiagent systems with a leader of bounded unknown input," *IEEE Trans. Autom. Control*, vol. 58, no. 2, pp. 518–523, Feb. 2013. doi: 10.1109/TAC.2012.2208295.

[22] P. Ouyang, J. Acob, and V. Pano, "PD with sliding mode control for trajectory tracking of robotic system," *Robot. Comput.-Integr. Manuf.*, vol. 30, no. 2, pp. 189–200, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0736584513000689. doi: 10.1016/j.rcim.2013.09.009.

[23] B. Sencer, K. Ishizaki, and E. Shamoto, "A curvature optimal sharp corner smoothing algorithm for high-speed feed motion generation of nc systems along linear tool paths," *Int. J. Adv. Manuf. Technol.*, vol. 76, nos. 9–12, pp. 1977–1992, Feb. 2015. doi: 10.1007/s00170-014-6386-2.

[24] K. R. Simba, G. Heppeler, B. D. Bui, Y. M. Hendrawan, O. Sawodny, and N. Uchiyama, "Bézier curve based trajectory generation and nonlinear friction compensation for feed drive contouring control," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 1944–1951, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2405896317307346. doi: 10.1016/j.ifacol.2017.08.388.

[25] J. Zheng, H. Wang, Z. Man, J. Jin, and M. Fu, "Robust motion control of a linear motor positioner using fast nonsingular terminal sliding mode," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 4, pp. 1743–1752, Aug. 2015. doi: 10.1109/TMECH.2014.2352647.

[26] X. Li, H. Zhao, X. Zhao, and H. Ding, "Dual sliding mode contouring control with high accuracy contour error estimation for five-axis cnc machine tools," *Int. J. Mach. Tools Manuf.*, vol. 108, pp. 74–82, Sep. 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0890695516300529. doi: 10.1016/j.ijmachtools.2016.05.007.

[27] X.-C. Xi, W.-S. Zhao, and A.-N. Poo, "Improving CNC contouring accuracy by robust digital integral sliding mode control," *Int. J. Mach. Tools Manuf.*, vol. 88, pp. 51–61, Jan. 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0890695514001230. doi: 10.1016/j.ijmachtools.2014.08.005.

[28] J. Yang and Y. Altintas, "A generalized on-line estimation and control of five-axis contouring errors of cnc machine tools," *Int. J. Mach. Tools Manuf.*, vol. 88, pp. 9–23, Jan. 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0890695514001229. doi: 10.1016/j.ijmachtools.2014.08.004.

[29] L. Dong and W. C. Tang, "Adaptive backstepping sliding mode control of flexible ball screw drives with time-varying parametric uncertainties and disturbances," *ISA Trans.*, vol. 53, no. 1, pp. 110–116, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0019057813001390. doi: 10.1016/j.isatra.2013.08.009.

[30] M. R. Msukwa, N. Uchiyama, and B. D. Bui, "Adaptive nonlinear sliding mode control with a nonlinear sliding surface for feed drive systems," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2017, pp. 732–737. doi: 10.1109/ICIT.2017.7915450.

[31] A. El Khalick Mohammad, N. Uchiyama, and S. Sano, "Reduction of electrical energy consumed by feed-drive systems using sliding-mode control with a nonlinear sliding surface," *IEEE Trans. Ind. Electron.*, vol. 61, no. 6, pp. 2875–2882, Jun. 2014. doi: 10.1109/TIE.2013.2275975.

[32] A. Farrage and N. Uchiyama, "Adaptive sliding mode contouring control with a nonlinear sliding surface for feed drive systems," in *Proc. 56th Annu. Conf. Soc. Instrum. Control Eng. Jpn. (SICE)*, Sep. 2017, pp. 230–235. doi: 10.23919/SICE.2017.8105473.

[33] A. Merabet, R. Beguenane, J. S. Thongam, and I. Hussein, "Adaptive sliding mode speed control for wind turbine systems," in *Proc. 37th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2011, pp. 2461–2466. doi: 10.1109/IECON.2011.6119696.

[34] B. Bandyopadhyay, F. Deepak, and K.-S. Kim, *Sliding Mode Control Using Novel Sliding Surfaces*. Berlin, Germany: Springer-Verlag, 2009.

[35] F. Plestan, Y. Shtessel, V. Brégeault, and A. Poznyak, "New methodologies for adaptive sliding mode control," *Int. J. Control*, vol. 83, no. 9, pp. 1907–1919, 2010. doi: 10.1080/00207179.2010.501385.

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