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Adaptive Disturbance Rejection Sliding Mode Control for Robots via an Orthogonal Functions-Based Estimator

Reza Gholipour[1] | Alireza Khosravi[1] | Mohammad Reza Shokoohinia[2]

[1]Department of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran
[2]Department of Electrical and Robotic Engineering, Shahrood University of Technology, Shahrood, Iran
Corresponding author's email: rezagholipourr@gmail.com

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ABSTRACT

This paper presents an innovative adaptive sliding mode controller with disturbance rejection for robotic manipulators. The proposed approach employs orthogonal functions-based estimation to handle system uncertainties, while an adaptive mechanism is introduced to estimate the unknown upper bounds of external disturbances. Moreover, the dynamics of the robot actuators, namely the motors, are explicitly considered in the control law design. Three adaptive laws are proposed in this work. The first addresses the estimation of the parameters of orthogonal functions, the second deals with the approximation error, and the third concerns the estimation of the upper bound of external disturbances. Furthermore, a robust control term is proposed to compensate for the approximation error. Stability of the closed-loop system is ensured using Lyapunov theory. The performance of the proposed controller is evaluated through simulations on a SCARA robotic manipulator and compared with conventional and dynamic sliding mode control schemes in terms of tracking accuracy, control effort, and disturbance rejection.

NOMENCLATURE

q	Joint position vector	K_m	Motor torque constant matrix
$D(q)$	Robot's inertia matrix		
$C(q,\dot{q})\dot{q}$	Centrifugal force vector	R	Motor resistance
$G(q)$	Gravitational force vector	L	Motor inductance
τ_l	Joint torque vector	I_a	Motor current
J_m	Motor inertias		
B_m	Damping coefficients		
r	Gear ratios		

I. Introduction

Over the past few decades, sliding mode control (SMC) has gained significant attention in the control community due to its inherent robustness against model uncertainties and external disturbances, its capability for finite-time convergence, and its relatively straightforward design procedure [1-8]. SMC has been successfully implemented in a wide range of dynamic systems, including but not limited to industrial robotic manipulators, autonomous underwater vehicles, spacecraft attitude control systems, power converters, and electric drive systems [9-15].

The methodology of SMC is typically divided into two distinct phases: the reaching phase and the sliding phase. During the reaching phase, the control law ensures that the system trajectories are driven toward a predefined sliding surface within a finite time interval. Once the trajectories intersect this surface, the system enters the sliding phase, where the states evolve along the surface and asymptotically approach the origin. Traditional SMC schemes often employ linear sliding surfaces, which lead to asymptotic convergence of the system states during the sliding motion [16, 17].

Robotic manipulators have found diverse applications across several domains, including agriculture, medicine, sports, automotive manufacturing, as well as marine and aerospace industries [18-28]. For instance, agricultural robotic arms are categorized using various classification schemes depending on specific criteria. Based on their operational functions in the field, these robotic manipulators can be grouped into categories such as harvesting, weeding, seeding, disease and pest detection, spraying, and plant management systems [18]. Moreover, according to the employed harvesting and cultivation techniques, robotic arms are further classified into Cartesian manipulators, articulated jointed arms, high-degree-of-freedom hybrid arms, and multi-arm systems [29]. Another classification approach considers the environmental context in which the robots operate, dividing them into greenhouse, dry field, paddy field, and orchard robotic arms. Over the past years, comprehensive research on these diverse types of agricultural robotic arms has yielded significant advancements, establishing a robust technical foundation essential for the advancement of precision agriculture [18]. Therefore, the design of an effective control system plays a critical role in ensuring the precise and reliable operation of robotic arms.

The design procedure of sliding mode control (SMC) is relatively simple, and the resulting controller exhibits strong robustness against external disturbances, parameter variations, and unmodeled dynamics. However, two major drawbacks are associated with conventional SMC. The first and most critical issue is the chattering phenomenon, which arises due to the discontinuous nature of the control law. The second limitation is the requirement for a known upper bound on system uncertainties. To address these issues, this paper proposes an approach in which system uncertainties are approximated using Legendre polynomials, and the upper bound of external disturbances is estimated through an adaptive law.

In recent years, the estimation and compensation of system uncertainties in adaptive control using orthogonal functions such as Legendre polynomials have attracted considerable research interest [30, 31]. In [32], an adaptive controller was introduced for robotic systems. However, the proposed control framework in [32] does not include any uncertainty estimator. In contrast, the proposed approach in this study employs a Legendre polynomial-based uncertainty estimator to address uncertainties. Moreover, the uncertainties in [32] are assumed to be constant over time, while in the present study, the uncertainties are considered to be time-varying.

The main contributions of this paper can be summarized as follows: (i) Design of an adaptive sliding mode control framework that takes into account the dynamics of the robot actuators, (ii) Estimation of system uncertainties using orthogonal functions due to their simple structure, (iii) Design of three adaptive laws for estimating the parameters, approximation errors, and bounds of disturbances, (iv) Achievement of Lyapunov-based stability and robust performance against uncertainties and disturbances, and (v) Design of a robust control term to compensate for approximation errors.

The structure of this paper is as follows: In Section II, a mathematical description of robotic systems, including manipulators and actuators, is presented. Section III details the design of the proposed adaptive sliding mode controller incorporating an orthogonal functions-based estimator. A Lyapunov-based stability analysis is presented in Section IV. Section V presents the simulation results. Section VI discusses the limitations of the proposed method, and Section VII outlines potential future research directions. Finally, Section VIII concludes the paper.

II. Modeling of Robotic Systems Including Manipulators and Actuators

The dynamics of the robotic system, including both the manipulator and the actuators, are formulated as follows [33-35]:

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau_l \tag{1}$$

$$J_m r^{-1}\ddot{q} + B_m r^{-1}\dot{q} + r\tau_l = K_m I_a \tag{2}$$

$$RI_a + K_m r^{-1}\dot{q} + L\dot{I}_a + d = U \tag{3}$$

In the above equations, U and d represent the motor voltage and external disturbance vectors, respectively.

Substituting equation (1) into (2) gives:

$$I_a = K_m{}^{-1}((J_m r^{-1} + rD)\ddot{q} + (B_m r^{-1} + rC)\dot{q} + rG) \tag{4}$$

By substituting the above equation into (3), we obtain:

$$U = RK_m{}^{-1}((J_m r^{-1} + rD)\ddot{q} + (B_m r^{-1} + rC)\dot{q} + rG) + K_m r^{-1}\dot{q} + L\dot{I}_a + d \tag{5}$$

It can be reformulated as:

$$\begin{aligned} U &= \bar{D}\ddot{q} + \bar{C}\dot{q} + \bar{G} + L\dot{I}_a + d \\ \bar{D} &= RK_m{}^{-1}(J_m r^{-1} + rD) \\ \bar{C} &= RK_m{}^{-1}(B_m r^{-1} + rC) + K_m r^{-1} \\ \bar{G} &= RK_m{}^{-1} rG \end{aligned} \tag{6}$$

Using (6), we have:

$$\begin{aligned} U &= \ddot{q} + \Upsilon + d \\ \Upsilon &= \bar{D}\ddot{q} + \bar{C}\dot{q} + \bar{G} + L\dot{I}_a - \ddot{q} \end{aligned} \tag{7}$$

Here, Υ denotes the uncertainties and nonlinearities of the system.

III. Design of the Proposed Adaptive Sliding Mode Controller Incorporating an Orthogonal Functions-Based Estimator

The tracking error and its derivatives, along with a sliding surface, are defined as follows:

$$e = q_d - q \rightarrow \dot{e} = \dot{q}_d - \dot{q} \rightarrow \ddot{e} = \ddot{q}_d - \ddot{q} \quad (8)$$

$$s = \dot{e} + \lambda e \quad (9)$$

By substituting (7) into (8), the following equation is obtained:

$$\ddot{e} = \ddot{q}_d - \ddot{q} = \ddot{q}_d + \Upsilon + d - U \quad (10)$$

By differentiating the sliding surface and substituting (10) into it, we obtain:

$$\dot{s}(t) = \ddot{e} + \lambda\dot{e} = \ddot{q}_d + \Upsilon + d - U + \lambda\dot{e} \quad (11)$$

According to (11), the proposed control law is designed as follows:

$$U = \ddot{q}_d + \hat{\Upsilon} + \hat{d} + \lambda\dot{e} + U_r \quad (12)$$

Where $\hat{\Upsilon}$ and $\hat{d}$ denote the estimations of system uncertainties and external disturbances, respectively, and U_r represents the robust control term.

Substituting (12) into (11) yields:

$$\dot{s}(t) = \Upsilon - \hat{\Upsilon} + d - \hat{d} - U_r \quad (13)$$

The equations for an orthogonal function, such as Legendre polynomials, are defined as follows [30, 36]:

$$\begin{aligned} (i+1)\zeta_{i+1}(x) &= (2i+1)x\zeta_i(x) - i\zeta_{i-1}(x) \\ i &= 1, \dots, m-1 \\ \zeta_0(x) = 1,\ \zeta_1(x) &= x,\ \zeta_2(x) = 0.5(3x^2-1) \end{aligned} \quad (14)$$

Since the uncertainty functions in control systems are generally time-dependent, we introduce x as a mapping that transforms the time variable, ranging from zero to infinity, into the bounded interval $[-1,1]$. In this study, x is defined as $x = \sin(\omega_0 t)$.

At this point, the system uncertainty Υ is approximated using Legendre polynomials:

$$\begin{aligned} \Upsilon &= P^T\Psi + \varepsilon, \\ P &= [p_0 \ \ p_1 \ \ \dots \ \ p_m]^T, \\ \Psi &= [\zeta_0 \ \ \zeta_1 \ \ \dots \ \ \zeta_m]^T \end{aligned} \quad (15)$$

$$\hat{\Upsilon} = \hat{P}^T\Psi \quad (16)$$

Here, P and Ψ denote the vector of Legendre parameters and the vector of Legendre basis functions, respectively, while ε represents the approximation error.

Applying (15) and (16) yields:

$$\begin{aligned} \tilde{\Upsilon} = \Upsilon - \hat{\Upsilon} &= P^T\Psi + \varepsilon - \hat{P}^T\Psi \\ &= (P - \hat{P})^T\Psi + \varepsilon \\ &= \tilde{P}^T\Psi + \varepsilon \end{aligned} \quad (17)$$

Assuming that the external disturbance is bounded by $|d| \leq \rho$, the disturbance is estimated as follows:

$$\hat{d} = \hat{\rho}\,sign(s) \quad (18)$$

By substituting (17) and (18) into (13), the following expression is obtained:

$$\dot{s}(t) = \tilde{P}^T\Psi + \varepsilon + d - \hat{\rho}\,sign(s) - U_r \quad (19)$$

IV. Lyapunov-Based Stability Analysis

A Lyapunov candidate function is defined as

$$V = \frac{1}{2}s^2 + \frac{1}{2\eta}\tilde{\rho}^2 + \frac{1}{2\theta}\tilde{P}^T\tilde{P} + \frac{1}{2\vartheta}\tilde{\varepsilon}^2 \quad (20)$$

Taking the time derivative of the Lyapunov function yields:

$$\dot{V} = s\dot{s} - \frac{1}{\eta}\tilde{\rho}\dot{\hat{\rho}} - \frac{1}{\theta}\tilde{P}^T\dot{\hat{P}} - \frac{1}{\vartheta}\tilde{\varepsilon}\dot{\hat{\varepsilon}} \quad (21)$$

Employing (19), the following is derived:

$$\begin{aligned} \dot{V} = s\big(\tilde{P}^T\Psi + \varepsilon + d - \hat{\rho}\,sign(s) - U_r\big) - \frac{1}{\eta}\tilde{\rho}\dot{\hat{\rho}} \\ - \frac{1}{\theta}\tilde{P}^T\dot{\hat{P}} - \frac{1}{\vartheta}\tilde{\varepsilon}\dot{\hat{\varepsilon}} \end{aligned} \quad (22)$$

The first adaptation law is proposed as follows:

$$\dot{\hat{P}} = \theta s\Psi \quad (23)$$

By applying this adaptation law, equation (22) becomes:

$$\dot{V} = s(\varepsilon + d - \hat{\rho}\,sign(s) - U_r) - \frac{1}{\eta}\tilde{\rho}\dot{\hat{\rho}} - \frac{1}{\vartheta}\tilde{\varepsilon}\dot{\hat{\varepsilon}} \quad (24)$$

Now, the robust control term is designed as follows:

$$U_r = \hat{\varepsilon} + ks \quad (25)$$

Inserting (25) into (24) leads to:

$$\dot{V} = s(\tilde{\varepsilon} + d - \hat{\rho}\,sign(s) - ks) - \frac{1}{\eta}\tilde{\rho}\dot{\hat{\rho}} - \frac{1}{\vartheta}\tilde{\varepsilon}\dot{\hat{\varepsilon}} \quad (26)$$

Where $\tilde{\varepsilon} = \varepsilon - \hat{\varepsilon}$. Subsequently, the second adaptation law is proposed as follows:

$$\dot{\hat{\varepsilon}} = \vartheta s \quad (27)$$

By applying this adaptation law, equation (24) is obtained as follows:

$$\begin{aligned} \dot{V} &= s(d - \hat{\rho} sign(s) - ks) - \frac{1}{\eta}\tilde{\rho}\dot{\hat{\rho}} \\ &= sd - \hat{\rho}|s| - ks^2 - \frac{1}{\eta}\tilde{\rho}\dot{\hat{\rho}} \\ &\leq |s||d| - \hat{\rho}|s| - ks^2 - \frac{1}{\eta}\tilde{\rho}\dot{\hat{\rho}} \\ &\leq \rho|s| - \hat{\rho}|s| - ks^2 - \frac{1}{\eta}\tilde{\rho}\dot{\hat{\rho}} \\ &= \tilde{\rho}|s| - ks^2 - \frac{1}{\eta}\tilde{\rho}\dot{\hat{\rho}} \end{aligned} \quad (28)$$

The third adaptation law is now introduced as:

$$\dot{\hat{\rho}} = \eta|s| \quad (29)$$

Substituting the above adaptation law into (28) yields:

$$\dot{V} \leq -ks^2 \quad (30)$$

Hence, based on $\dot{V} \leq 0$ and by invoking Barbalat's Lemma [37], the stability of the closed-loop system is guaranteed.

Remark 1: This is a fact that time delays are inherent in many physical systems. Incorporating such delays would necessitate a fundamental restructuring of the mathematical proofs—specifically through the use of augmented subsystems, Pade approximations, or integral inequality lemmas to handle the delayed states [38-40]. Given the complexity of these derivations, a comprehensive analysis of the system's robustness against time-varying delays is identified as a significant and necessary direction for future research.

V. Simulation Results

Consider a SCARA-type robotic manipulator with the configuration illustrated in Fig. 1. The maximum permissible input voltage for each actuator is limited to $U_{max} = 40\,V$. The parameters of the robotic system are selected as $m_1 = 11.94Kg$, $m_2 = 37.973Kg$, $m_3 = 0.263Kg$, $a_1 = 0.33m$, $a_2 = 0.27m$, $R = 1.26$, $L = 0.001$, $K_m = 0.26$, $r = 0.01$, $J_m = 0.0002$, and $B_m = 0.001$, while the parameters of the proposed adaptive controller are set to $\lambda = 10$, $\eta = 0.001$, $\theta = 750$, $\vartheta = 1$, $k = 1$ and $\omega_0 = \pi/14$. The initial conditions for the positions of the joints are chosen as $q(0) = (0.04 - 0.05\; 0.06)^T$.

The reference trajectories for the robot joints are defined as follows:

$$q_d = 0.6(1 - \cos(\pi t/14)) \quad (31)$$

The reference trajectory is illustrated in Fig. 2. The external disturbance considered for the simulation is a pulse signal, as depicted in Fig. 3.

The tracking errors and control signals are depicted in Figs. 4 and 5, respectively. . As shown in Fig. 4, the tracking errors converge appropriately to zero, demonstrating accurate trajectory tracking. . In addition, the control signals presented in Fig. 5 remain within permissible ranges and do not exhibit chattering behavior, confirming the appropriateness of the control inputs. The estimated Legendre polynomial coefficients are shown in Fig. 6, where all parameters remain bounded. Collectively, Figs. 4 to 6 confirm the effectiveness of the proposed controller in both trajectory tracking and disturbance rejection.

In order to assess the effectiveness of the proposed controller and its ability to suppress chattering, its performance is compared with that of a conventional sliding mode controller (SMC) [32], whose control signal is provided below.

$$U_{SMC} = \ddot{q}_d + \lambda\dot{e} + \Gamma_{smc} sign(s), \qquad |\Upsilon + d| \leq \Gamma_{smc} \quad (32)$$

Where Γ is an upper bound on the aggregate of external disturbances and system uncertainties. Here, the values of λ and Γ are selected as 10 and 10, respectively.

It should be emphasized that, in practical applications, the use of a conventional sliding mode controller faces difficulties due to the unavailability of the upper bounds of external disturbances and system uncertainties.

Figures 7 and 8 respectively illustrate the tracking errors and control inputs corresponding to the conventional sliding mode controller.

Although the tracking errors are satisfactory, Fig. 8 reveals that the control signals exhibit noticeable chattering. Hence, this method is not suitable for controlling the robotic system under consideration.

As a second comparison study, the proposed approach is evaluated against dynamic sliding mode control (DSMC) [41]. Owing to the integral action in dynamic sliding mode control, the chattering effect can be considerably attenuated. The control signal in this method is designed as follows.

$$\begin{aligned} \dot{U}_{DSMC} &= \ddot{q}_d + \delta_1\Lambda + \delta_2\dot{e} + \delta_3 e + \delta_4\int_0^t e(\tau)d\tau \\ &\quad + \mathcal{L}_{dsmc} sign(\sigma_2), \\ U_{DSMC} &= \int_0^t \dot{U}_{DSMC}(\tau)d\tau, \\ \sigma_1 &= \dot{e} + \varrho_1 e + \varrho_2\int_0^t e(\tau)d\tau, \\ \sigma_2 &= \dot{\sigma}_1 + b_1\sigma_1 + b_2\int_0^t \sigma_1(\tau)d\tau \end{aligned} \quad (33)$$

Where

$$\delta_1 = \varrho_1 + b_1, \delta_2 = \varrho_2 + b_2 + \varrho_1 b_1, \delta_3 = \varrho_1 b_2 + \varrho_2 b_1, \delta_4 = \varrho_2 b_2; \Lambda = \ddot{q}_d - \mathrm{U}_{DSMC}; \Phi = \Upsilon + d; \left|\delta_1 \Phi + \dot{\Phi}\right| \leq \mathcal{L}_{dsmc} \tag{34}$$

In the above equations, σ_1 and σ_2 denote the primary and secondary sliding surfaces in the DSMC method. The controller parameters are chosen as follows: $\varrho_1 = 30, \varrho_2 = 200, b_1 = 60, b_2 = 400,\ \mathcal{L}_{dsmc} = 10$.

The corresponding tracking errors and control inputs are depicted in Figs. 9 and 10, respectively. In comparison with conventional sliding mode control, a substantial reduction in control chattering is observed, resulting in a more desirable control signal profile. Subsequently, the tracking performance of this method is compared with that of the proposed controller. As can be seen from Figs. 4 and 10, the proposed method exhibits better tracking performance in both transient and steady-state phases. In contrast, the dynamic sliding mode control achieves tracking in an oscillatory manner.

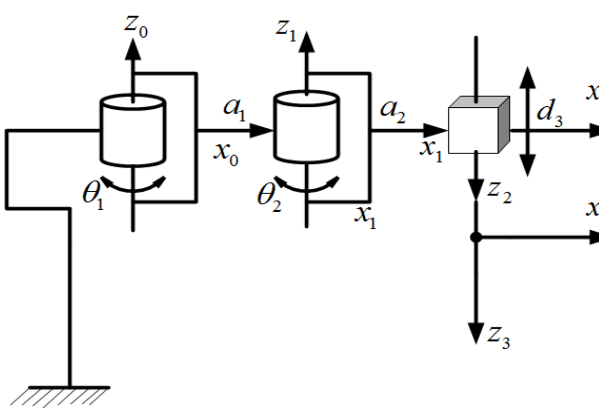

Fig. 1. Configuration of the SCARA robot [42]

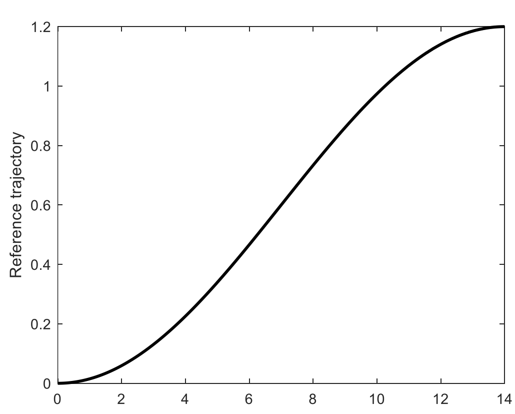

Fig. 2. Desired trajectory profile

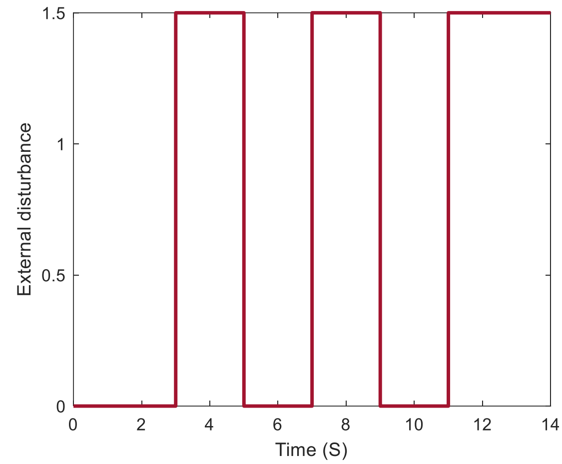

Fig. 3. External disturbance profile

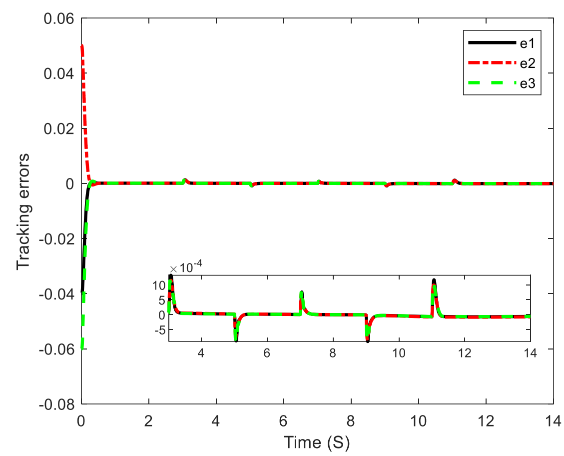

Fig. 4. Tracking errors under the proposed adaptive controller

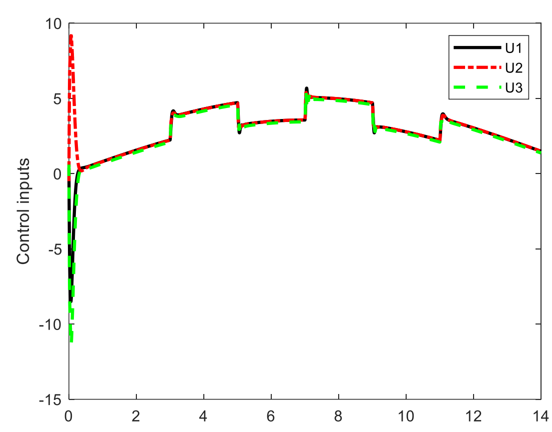

Fig. 5. Control signals under the proposed adaptive controller

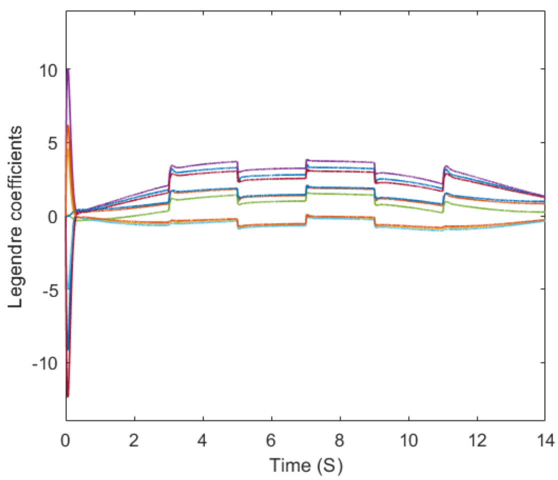

Fig. 6. Legendre parameters profiles

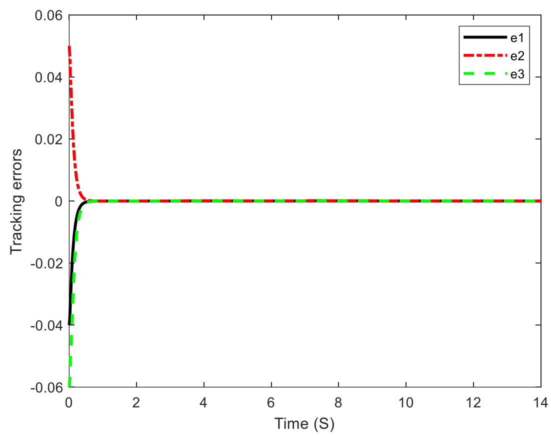

Fig. 7. Tracking errors under the conventional SMC method

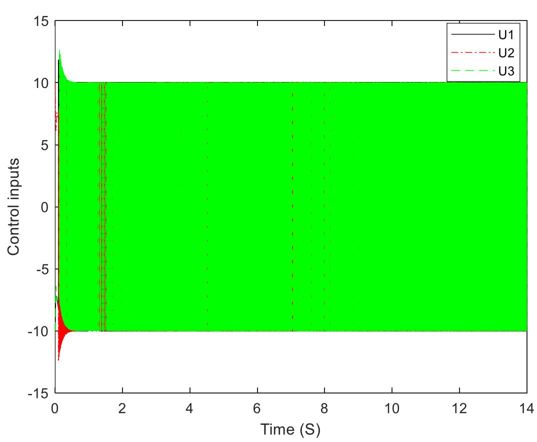

Fig. 8. Control signals under the conventional SMC method

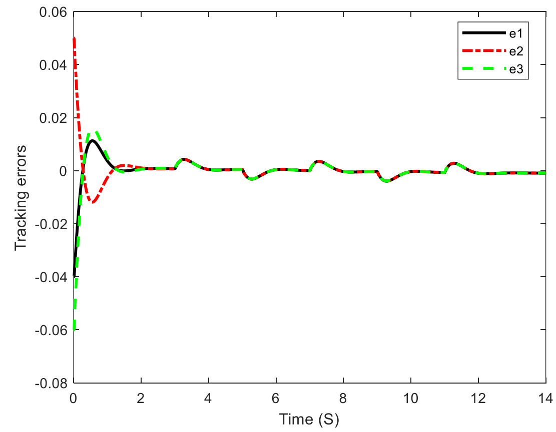

Fig. 9. Tracking errors under the Dynamic SMC method

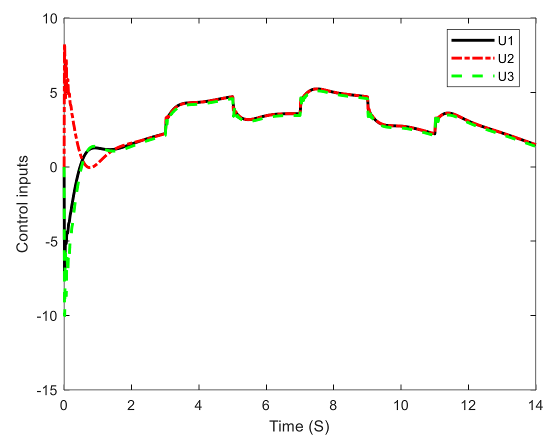

Fig. 10. Control signals under the Dynamic SMC method

VI. Limitations

The proposed adaptive sliding mode controller assumes the availability of velocity signals; in practical implementations, observer-based estimation may be required. The number of Legendre polynomial terms introduces a trade-off between approximation accuracy and computational complexity. Additionally, the controller parameters are tuned empirically, which could be improved in future studies using intelligent optimization algorithms.

VII. Future Research Directions

Future work may focus on the following directions: tuning the parameters of the proposed adaptive controller using novel optimization methods [43-50], incorporating observer-based velocity estimation, extending the proposed method to flexible robotic manipulators, and exploring alternative uncertainty estimation techniques.

VIII. Conclusions

An adaptive sliding mode control structure has been developed by integrating system uncertainty estimation via orthogonal functions and the upper bound of external disturbances through an adaptive law into the sliding mode control framework. Moreover, the proposed control scheme has eliminated the need for a priori knowledge of the upper bound of external disturbances, as it has employed an adaptive law to estimate this bound online. Legendre polynomials have been employed for estimating system uncertainties due to their simple structure. The control law has been formulated to compute the input voltages directly applied to the motors. The simulation results have demonstrated the effectiveness of the proposed method.

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Reza Gholipour was born in Gilan, Iran. He received the M.Sc. and Ph.D. degrees in Electrical Engineering (Control) from Babol Noshirvani University of Technology and Shahrood University of Technology, Iran, respectively. He is currently working as a researcher and academic lecturer in advanced control systems. His research interests include robotic systems, chaotic dynamics, and marine vessels, with a particular focus on adaptive control methodologies. His research activities encompass adaptive, nonlinear, fuzzy, and robust control, as well as chaos control, adaptive observer design, and uncertainty estimation. He has published more than 20 papers in prestigious international journals.

Alireza Khosravi received the Ph.D. degree in control engineering from the Iran University of Science and Technology (IUST), Tehran, Iran. He is currently an Associate Professor with the Department of Electrical Engineering, Babol Noshirvani University of Technology, Babol, Iran. His research interests include robust and optimal control, modeling and system identification, as well as intelligent and robotic systems.

Mohammad Reza Shokoohinia received the M.Sc. and Ph.D. degrees in Control Engineering from Garmsar University, Iran, and Shahrood University of Technology, Iran, respectively. His research interests include nonlinear control, fuzzy control, dynamic sliding mode control, adaptive control, uncertainty estimation, and robotic systems.