

Model-free tracking control via adaptive dynamic sliding mode control with application to robotic systems

Mohammad Reza Shokoohinia^{1,†}, Mohammad Mehdi Fateh²

^{1,2} Department of Electrical and Robotic Engineering, Shahrood University of Technology, 3619995161 Shahrood, Iran.

A *In this paper, a novel model-free control scheme is developed to enhance the tracking performance of robotic systems*
B *based on an adaptive dynamic sliding mode control and voltage control strategy. In the voltage control strategy, actuator*
S *dynamics have not been excluded. In other words, instead of the applied torques to the robot joints, motor voltages are*
T *computed by the control law. First, a dynamic sliding mode control is designed for the robotic system. Then, to enhance the*
R *tracking performance of the system, an adaptive mechanism is developed and integrated with the dynamic sliding mode*
A *control. Since the lumped uncertainty is unknown in practical applications, the uncertainty upper bound is necessary in the*
C *design of the dynamic sliding mode controller. Hence, the lumped uncertainty is estimated by an adaptive law. The stability*
T *of the closed-loop system is proved based on the Lyapunov stability theorem. The simulation results demonstrate the*
superior performance of the proposed adaptive dynamic sliding mode control strategy.

Article Info

Keywords:

Model-Free Tracking Control,
Adaptive Dynamic Sliding Mode Control,
Robotic Systems, Voltage Control Strategy.

Article History:

Received 2019-09-10
Accepted 2020-06-14

I. INTRODUCTION

Since robotic systems are always affected by the environmental disturbances, it is necessary to develop robust and adaptive controllers to suppress the effects of them [1-6]. Sliding mode control (SMC) is a well-known robust control technique that has good tracking performance due to its robustness against the uncertainties and disturbances.

However, this control strategy suffers from the chattering problem, due to the discontinuous control law [7-9]. A common method adopted to improve the chattering is to

replace the switching function by the saturation function. Since the chattering is reduced by this method, an indefinite steady-state error is also caused depending on the selection of the boundary layer. Thus, the chattering and accuracy become a tradeoff problem in this design [10,11]. Another technique is to reduce the switching gain in the controller. However, if the controller is not powerful enough to confront the uncertainties, the robustness of SMC becomes poor. Dynamic sliding mode control (DSMC) is an effective scheme to reduce the control chattering. The time derivative of the control signal is considered as the new control variable for the augmented system in which the augmented system includes the original system and the integrator. In DSMC, the chattering problem can be effectively reduced due to the integration method in obtaining the control signal [12-14]. However, similar to SMC, the uncertainty bound should be

[†]Corresponding Author: mshokoohinia@yahoo.com
Department of Electrical and Robotic Engineering, Shahrood University of Technology, Shahrood, Iran

known in the design of DSMC. In this paper, to overcome this problem, the uncertainty is estimated using an adaptive mechanism. In [15-19], the Fourier series expansion is used for the controller design. These methods require more computation, whereas the proposed method is simpler and can alleviate the computation burden. Many studies focused on the torque control strategy (TCS) of robotic systems. In this strategy, the control law computes the torques which should be produced by the motors. The system actuators should be excited, so that they produce the desired torques. However, the actuator dynamics are not considered in the TCS and its input is not calculated in this strategy. To solve the aforementioned problem, voltage control strategy (VCS) has been developed which is more effective and requires less computation [20-23]. As a result, voltage-based approaches are superior. Therefore, in this paper, using VCS, an adaptive DSMC is developed for robust control of robotic systems.

The purpose of this paper is developing an adaptive dynamic sliding mode controller for tracking control of robotic systems. The proposed method is model-free and does not require the robot dynamics. The proposed method does not need the uncertainty upper bound. In fact, the lumped uncertainty is estimated using an adaptive rule. Using Lyapunov direct method, it is guaranteed that the tracking errors converge to zero.

The remainder of the paper is organized as follows. Section 2 introduces the robotic problem formulation. In Section 3, the proposed adaptive dynamic sliding mode controller is designed. Stability analysis is presented in Section 4. Simulation results are discussed in Section 5. Our conclusions are given in Section 6.

II. Problem Formulation

The dynamics of a robotic system can be described as [24]

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

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

$$R I_a + K_m r^{-1}\dot{q} + \xi = v(t) \quad (3)$$

Where $\xi = L\dot{I}_a + d$, q is the vector of joint positions, V is the vector of motor voltages, I_a is the vector of motor currents and d is a vector of external disturbances. The details are completely explained in [15].

Substituting τ_l from (1) into (2) results in

$$J_m r^{-1}\ddot{q} + B_m r^{-1}\dot{q} + r(D(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q)) = K_m I_a \quad (4)$$

Using (4), one can calculate I_a as

$$I_a = k_m^{-1} \left((J_m r^{-1} + rD)\ddot{q} + (B_m r^{-1} + rC)\dot{q} + rG \right) \quad (5)$$

Substitution of (5) into (3) yields

$$v = Rk_m^{-1} \left((J_m r^{-1} + rD)\ddot{q} + (B_m r^{-1} + rC)\dot{q} + rG \right) + k_m r^{-1}\dot{q} + \xi \quad (6)$$

Now, (6) can be rewritten as

$$\begin{aligned} v &= \bar{D}\ddot{q} + \bar{C}\dot{q} + \bar{G} + \xi \\ \bar{D} &= Rk_m^{-1}(J_m r^{-1} + rD) \\ \bar{C} &= Rk_m^{-1}(B_m r^{-1} + rC) + k_b r^{-1} \\ \bar{G} &= Rk_m^{-1}rG \end{aligned} \quad (7)$$

We can rewrite (7) as

$$\begin{aligned} v &= \dot{q} + g \\ g &= \bar{D}\ddot{q} + \bar{C}\dot{q} + \bar{G} + \xi - \ddot{q} \end{aligned} \quad (8)$$

III. The proposed Adaptive Dynamic Sliding Mode Control

The structure of the proposed adaptive controller is shown in Fig. 1. In this block-diagram, error, the first and second sliding surfaces, adaptive rule, and integrating the control signal have been clearly illustrated.

The tracking error (e) and its time derivatives (\dot{e} , \ddot{e}) are defined as follows:

$$\begin{aligned} e &= q_d - q \\ \dot{e} &= \dot{q}_d - \dot{q} \\ \ddot{e} &= \ddot{q}_d - \ddot{q} \end{aligned} \quad (9)$$

Now, define a sliding surface as follows:

$$s(t) = \dot{e}(t) + a_1 e(t) + a_2 \int_0^t e(\tau) d\tau \quad (10)$$

The time derivative of (10) becomes

$$\dot{s}(t) = \ddot{e} + a_1 \dot{e} + a_2 e \quad (11)$$

Substituting \ddot{e} from (9) into (11) results in

$$\dot{s}(t) = \ddot{q}_d - \ddot{q} + a_1 \dot{e} + a_2 e \quad (12)$$

Using (8), (12) can be written as

$$\dot{s}(t) = \ddot{q}_d - v + g(t) + a_1 \dot{e} + a_2 e \quad (13)$$

The secondary sliding surface is considered as

$$\sigma(t) = \dot{s}(t) + b_1 s(t) + b_2 \int_0^t s(\tau) d\tau \quad (14)$$

The time derivative of (14) becomes

$$\dot{\sigma}(t) = \ddot{s}(t) + b_1 \dot{s}(t) + b_2 s(t) \quad (15)$$

Using (10) and (13), (15) can be written as

$$\begin{aligned} \dot{\sigma}(t) &= (\ddot{q}_d - v + g(t) + a_1 \dot{e} + a_2 e) + b_1 (\dot{q}_d - v + g(t) + \\ & a_1 \dot{e} + a_2 e) + b_2 (\dot{e}(t) + a_1 e(t) + a_2 \int_0^t e(\tau) d\tau) \end{aligned} \quad (16)$$

Using (8) and (9), we have

$$\ddot{e} = \ddot{q}_d - v + g \quad (17)$$

Substitution of (17) into (16) yields

$$\begin{aligned}
 \dot{\sigma}(t) = & \ddot{q}_d - \dot{v} + \dot{g}(t) + a_1(\ddot{q}_d - v + g) + a_2\dot{e} + b_1\ddot{q}_d \\
 & - b_1v + b_1g(t) + a_1b_1\dot{e} + a_2b_1e + b_2\dot{e}(t) + a_1b_2e(t) \\
 & + a_2b_2 \int_0^t e(\tau) d\tau = \ddot{q}_d - \dot{v} + (a_1 + b_2)(\ddot{q}_d - v) \\
 & + (a_1 + b_2)g(t) + \dot{g}(t) + (a_2 + a_1b_1 + b_2)\dot{e} \\
 & + (a_2b_1 + a_1b_2)e + a_2b_2 \int_0^t e(\tau) d\tau
 \end{aligned} \quad (18)$$

we can rewrite (18) as

$$\dot{\sigma}(t) = \ddot{q}_d - \dot{v} + \mu_1 Y(t) + f(t) + \mu_2 \dot{e} + \mu_3 e + \mu_4 \int_0^t e(\tau) d\tau \quad (19)$$

Where $Y(t) = \ddot{q}_d - v$, $f(t) = \mu_1 g + \dot{g}$, $\mu_1 = a_1 + b_2$, $\mu_2 = a_2 + a_1b_1 + b_2$, $\mu_3 = a_2b_1 + a_1b_2$ and $\mu_4 = a_2b_2$. The control law in adaptive DSMC is proposed by

$$\begin{aligned}
 \dot{v}_{ADSMC} = & \ddot{q}_d + \mu_1 Y(t) + \mu_2 \dot{e} + \mu_3 e + \\
 & \mu_4 \int_0^t e(\tau) d\tau + \hat{f} + v_r
 \end{aligned} \quad (20)$$

$$v_{ADSMC}(t) = \int_0^t \dot{v}_{ADSMC}(\tau) d\tau$$

where \hat{f} is the estimation of f and v_r is the robust control term which will be calculated in the next section. It follows from (19) and (20) that

$$\begin{aligned}
 \dot{\sigma} = & \hat{f} - v_r \\
 \tilde{f} = & f - \hat{f}
 \end{aligned} \quad (21)$$

The sampling interval in the experiment is short enough as compared with the variation of f , thus, the term f is also assumed to be a constant during the estimation (i.e. $\tilde{f} = f - \hat{f} \rightarrow \dot{\tilde{f}} = -\dot{\hat{f}}$) [25-28].

$$\dot{V} = \sigma \dot{\sigma} - \frac{1}{\gamma} \tilde{f} \dot{\tilde{f}} \quad (23)$$

Using $\dot{\sigma}$ defined in (21) we have

$$\dot{V} = \sigma(\hat{f} - v_r) - \frac{1}{\gamma} \tilde{f} \dot{\tilde{f}} \quad (24)$$

The adaptive law can be proposed as follows:

$$\dot{\hat{f}} = \gamma \sigma \quad (25)$$

Using (25), one can easily conclude that

$$\dot{V} = -\sigma v_r \quad (26)$$

where the robust control term is selected as follows:

$$v_r = k \sigma \quad (27)$$

Substituting (27) into (26), we have

$$\dot{V} = -k \sigma^2 \quad (28)$$

Therefore, it has been guaranteed that $\dot{V} \leq 0$. Using Barbalat's lemma [29], it can be found the tracking error asymptotically converges to zero.

Remark: The final Lyapunov function for the total robotic system is the sum of Lyapunov function as defined in (22).

V. SIMULATION RESULTS

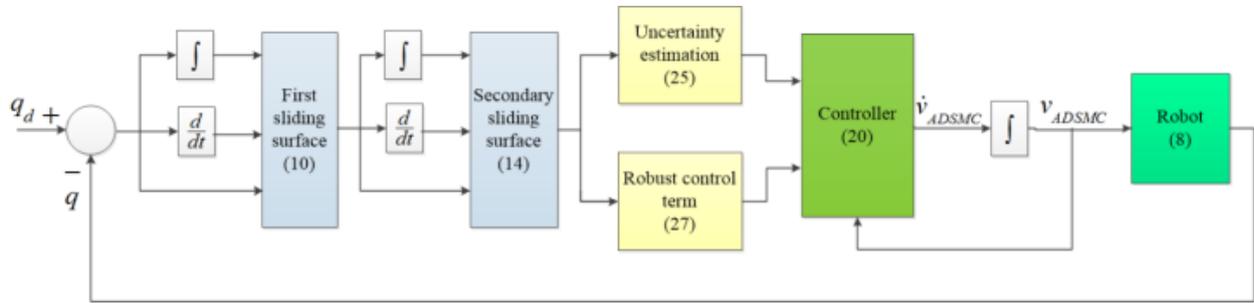


Fig.1. The configuration of the proposed control system

IV. STABILITY ANALYSIS

Consider a Lyapunov function candidate:

$$V = \frac{1}{2} \sigma^2 + \frac{1}{2\gamma} \tilde{f}^2 \quad (22)$$

Differentiating the Lyapunov function, we have

In order to demonstrate the performance of the proposed controller, an articulated robot is considered, with a symbolic representation given in Fig. 2. The parameters of the robotic system are presented in [30]. The Denavit–Hartenberg (DH) parameters of the robot and the parameters of permanent magnet dc motors are given in Table 1 and Table 2, respectively. The external disturbance d is a step function

with the amplitude of 2 volts which is inserted into the system at $t = 6\text{sec}$. The maximum voltage of each motor is set to $v_{\max} = 40V$. The desired position for each joint is formulated by

$$q_d = 1 - \cos(\pi t / 7) \tag{29}$$

This desired trajectory is shown in Fig. 3. The sliding surface parameters have been selected as $a_1 = 10, a_2 = 0.1, b_1 = 20, b_2 = 0.2$. The parameters γ and k have been set to 3000 and 10, respectively.

TABLE I

The Denavit–Hartenberg parameters

Link	θ	d	a	α
1	θ_1	$d_1 = 0.28$	0	$\frac{\pi}{2}$
2	θ_2	0	$a_2 = 0.76$	0
3	θ_3	0	$a_3 = 0.93$	0

TABLE II

The motor parameters

Motor	R	J_m	B_m	K_m	r	L
1,2,3	1.26	0.0002	0.001	0.26	0.01	0.001

Fig. 4 shows the tracking performance of ADSMC. According to Fig. 4, it can be found that the proposed controller design procedure performs well and has fast tracking performance. Also, the control inputs are depicted in Fig. 5. As shown in this figure, these signals are smooth and do not exceed the allowable values. From Figs. 4 and 5, the simulation results indicate that the favorable tracking performance is obtained.

Now, the proposed method is compared with the DSMC method. In the DSMC, the control signal is as follows:

$$\dot{v}_{DSMC} = \ddot{q}_d + \mu_1 \Upsilon(t) + \mu_2 \dot{e} + \mu_3 e + \mu_4 \int_0^t e(\tau) d\tau + \rho \operatorname{sgn}(\sigma), \quad |f| < \rho \tag{30}$$

$$v_{DSMC}(t) = \int_0^t \dot{v}_{DSMC}(\tau) d\tau$$

The value of ρ is selected as 20. In the DSMC method, the sliding surface parameters are chosen as the proposed method, i.e. $a_1 = 10, a_2 = 0.1, b_1 = 20, b_2 = 0.2$. The tracking performance and control signals of the DSMC method are shown in Figs. 6 and 7, respectively. According to Fig. 6, it is observed that the tracking performance of the DSMC method is very weak in comparison with the proposed method, and

this method cannot track the specified trajectory with the given initial conditions. In order to achieve better performance, the sliding surface parameters are selected as $a_1 = 100, a_2 = 400, b_1 = 200, b_2 = 600$ in the DSMC. The corresponding tracking errors and control efforts are shown in Figs. 8 and 9, respectively. As illustrated in Fig. 8, the tracking performance of the DSMC is improved, but it is still weak comparing to the proposed ADSMC method. Consequently, according to Figs. 4-9, it is concluded that the suggested ADSMC method has a significant advantage over the DSMC method regarding the tracking performance.

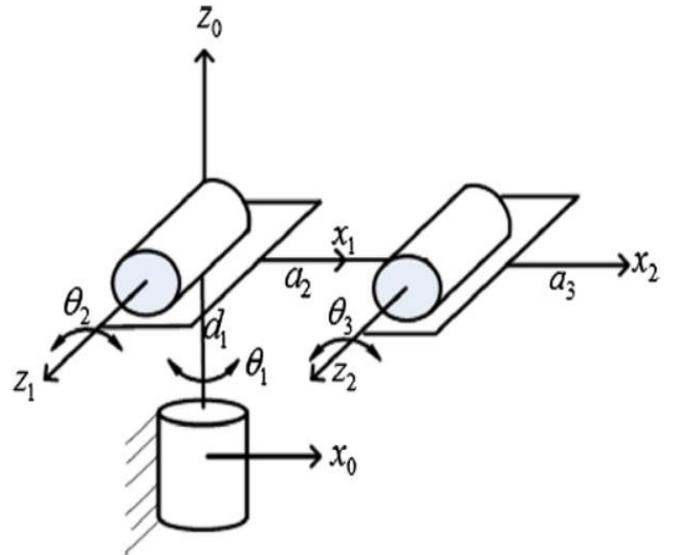


Fig. 2. The symbolic representation of the articulated robot

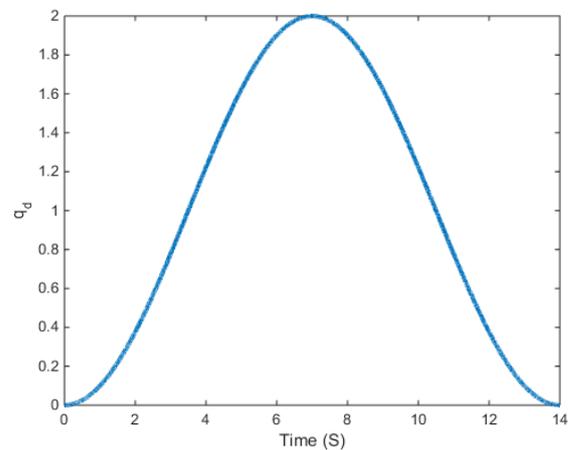


Fig. 3. The desired trajectory

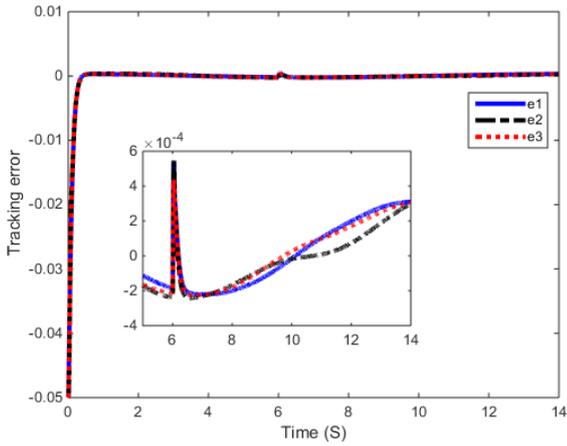


Fig. 4. The tracking errors of Adaptive DSMC

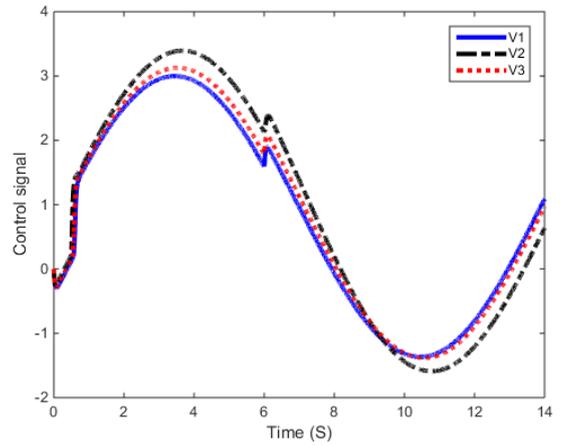


Fig. 7. The voltages of motors using DSMC

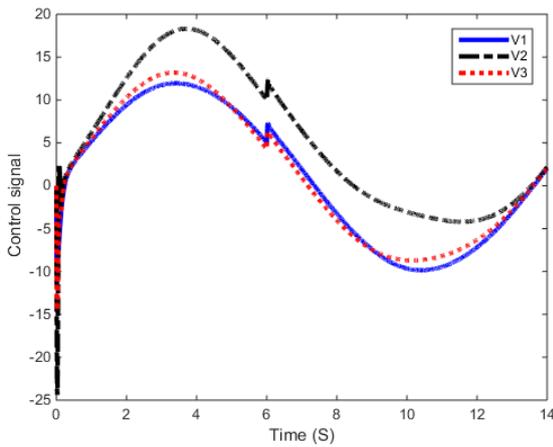


Fig. 5. The voltages of motors in the proposed method

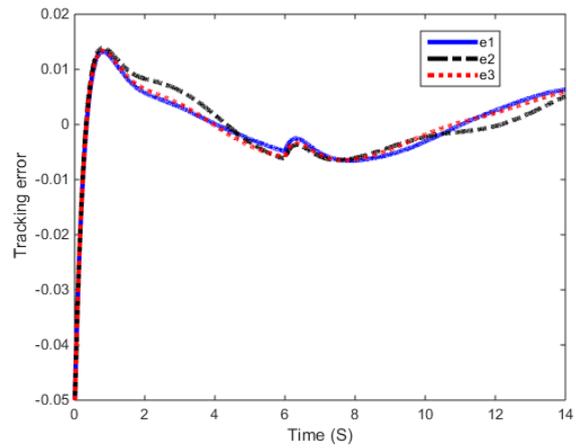


Fig. 8. The tracking errors using DSMC

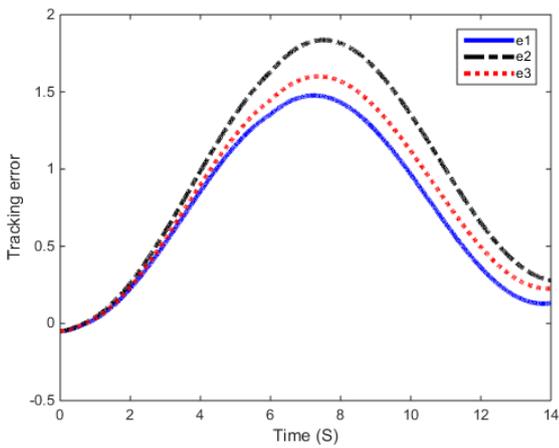


Fig. 6. The tracking errors using DSMC

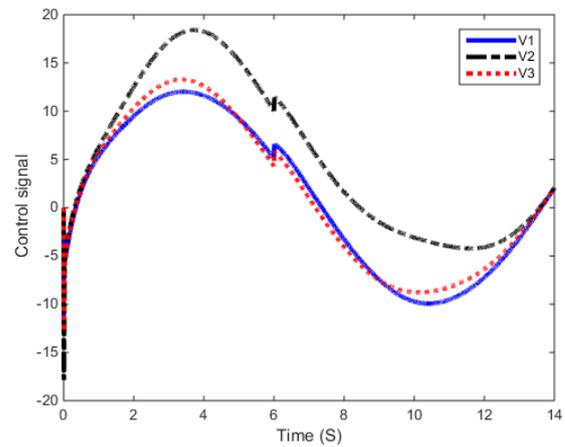


Fig. 9. The voltages of motors using DSMC

Remark: Increasing the parameter k will increase the amplitude of the control signal and actuator saturation will occur. For example if $k = 100$, the control signal will exceed the permitted range. For the sliding surface parameters a_1 and b_1 , small values such as 1 or 2 will result in poor tracking performance and the tracking errors

cannot converge to zero. For the sliding surface parameters a_2 and b_2 , large values will increase the overshoot in the tracking error profile. Due to these issues, the controller parameters have been adjusted using the trial and error process. Also, optimization algorithms such as PSO, BA, ILCOA, GA, OSA, WOA or GPEA [31-44] can be used for tuning the controller parameters.

Finally, in order to show the efficiency of using the second sliding surface, the performance of the proposed method is compared with that of the conventional sliding mode control [40] in which the control signal is designed as:

$$v_{SMC} = \ddot{q}_d + a_1 \dot{e} + a_2 e + \rho \operatorname{sgn}(\sigma), \quad |g| < \rho_1 \quad (31)$$

Where $\rho_1 = 10$, $a_1 = 100$ and $a_2 = 400$.

The tracking errors and control signals related to the conventional sliding mode control are illustrated in Fig. 10 and Fig. 11, respectively. As it can be seen the control signals are affected by the chattering phenomenon which is not desirable. In fact, in conventional sliding mode control, we are faced with the chattering problem. In order to overcome this problem, dynamic sliding mode control can be used. Moreover, in order to reduce the tracking error, adaptive dynamic sliding mode control is proposed in this paper. These comparisons reveal the superiority of the proposed method.

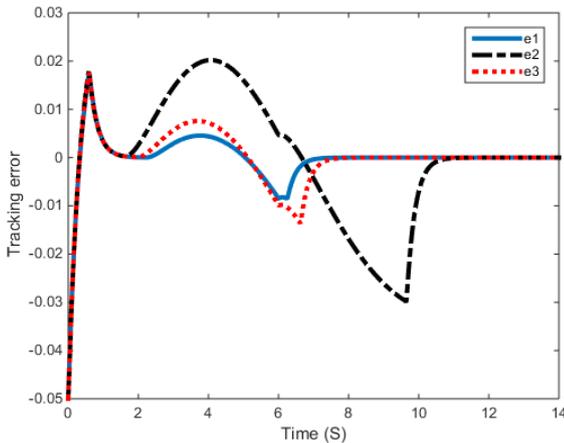


Fig.10. The tracking errors in conventional sliding mode control

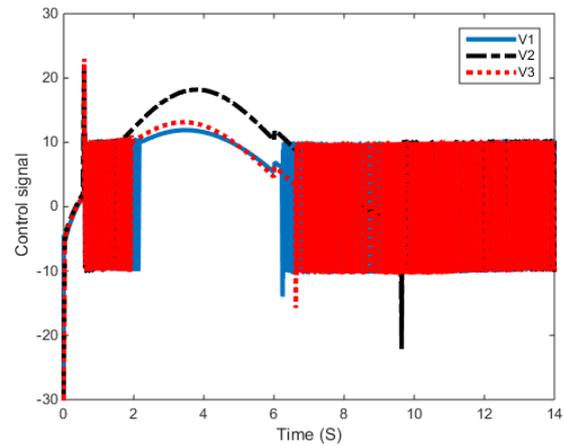


Fig. 11. The control signals in conventional sliding mode control

VI. Conclusion

A new approach based on an adaptive dynamic sliding mode control and VCS has been developed for tracking control of robotic systems. First, a Dynamic sliding mode control scheme has been designed properly. Then, in order to reduce the chattering, an adaptive mechanism has also been developed. The control signal is designed using voltage control strategy. The stability of the robotic system has been proven based on the Lyapunov criteria. The computer simulation results show that the voltage-based adaptive dynamic sliding mode controller can perform successful control and achieve desired tracking performance.

REFERENCES

- [1] Y. Su, C. Zheng, and P. Mercorelli, "Robust approximate fixed-time tracking control for uncertain robot manipulators", *Mechanical Systems and Signal Processing*, Vol. 135, (2020) p.106379.
- [2] R. Gholipour, M.M. Fateh, "Robust Control of Robotic Manipulators in the Task-Space Using an Adaptive Observer Based on Chebyshev Polynomials", *Journal of Systems Science and Complexity*, (2020). <https://doi.org/10.1007/s11424-020-8186-0>.
- [3] M. Bekrani, M. Heydari, and S.T. Behrooz, "An Adaptive Control Method Based on Interval Fuzzy Sliding Mode for Direct Matrix Converters", *International Journal of Industrial Electronics, Control and Optimization*, Vol. 3, No. 2, (2020), 159-171.
- [4] S.H. Shahalami, and F. Rajab Nejad, "Design of Adaptive Back-Stepping Controller for Chaos Control in Boost Converter and Controller Coefficients Optimization Using CHPSO Algorithm", *International Journal of Industrial Electronics, Control and Optimization*. Vol. 3, No.3, (2020), 249-257.
- [5] A. Haqshenas M, M.M. Fateh, and S.M. Ahmadi, "Adaptive control of electrically-driven nonholonomic wheeled mobile robots: Taylor series-based approach with guaranteed asymptotic stability", *International Journal of*

- Adaptive Control and Signal Processing, (2020), <https://doi.org/10.1002/acs.3104>.
- [6] S.M. Ahmadi, and M.M. Fateh, "Task-space control of robots using an adaptive Taylor series uncertainty estimator", *International Journal of Control*, Vol. 92, No. 9, (2019), 2159-2169.
- [7] M. Van, S.S. Ge and H. Ren, "Finite time fault tolerant control for robot manipulators using time delay estimation and continuous nonsingular fast terminal sliding mode control", *IEEE transactions on cybernetics*, Vol. 47, No. 7, (2017), 1681-1693.
- [8] R. Gholipour, A. Khosravi and H. Mojallali, "Multi-objective optimal backstepping controller design for chaos control in a rod-type plasma torch system using Bees Algorithm", *Applied Mathematical Modelling*, Vol. 39, No. 15, (2015), 4432-4444.
- [9] S. Park and S. Rahmdel, "A new fuzzy sliding mode controller with auto-adjustable saturation boundary layers implemented on vehicle suspension", *International Journal of Engineering-Transactions C: Aspects*, Vol. 26, No. 12, (2013), 1401-1410.
- [10] Y. Zhao, P. Huang and F. Zhang, "Dynamic modeling and Super-Twisting Sliding Mode Control for Tethered Space Robot", *Acta Astronautica*, Vol. 143, (2018), 310-321.
- [11] G. Chen, B. Jin, Y. Chen, "Nonsingular fast terminal sliding mode posture control for six-legged walking robots with redundant actuation", *Mechatronics*, Vol. 50, (2018), 1-15.
- [12] F.J. Lin, S.Y. Chen K.K. Shyu, "Robust dynamic sliding-mode control using adaptive RENN for magnetic levitation system", *IEEE Transactions on Neural Networks*, Vol. 20, No. 6, (2009), 938-951.
- [13] S.Y. Chen, S.S. Gong, "Speed tracking control of pneumatic motor servo systems using observation-based adaptive dynamic sliding-mode control", *Mechanical Systems and Signal Processing*, Vol. 94, (2017), 111-128.
- [14] S. Wen, M.Z. Chen, Z. Zeng, X. Yu and T. Huang, "Fuzzy control for uncertain vehicle active suspension systems via dynamic sliding-mode approach", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, Vol. 47, No. 1, (2017), 24-32.
- [15] S. Khorashadizadeh and M.M. Fateh, "Uncertainty estimation in robust tracking control of robot manipulators using the Fourier series expansion", *Robotica*, Vol. 35, No. 2, (2017), 310-336.
- [16] S. Khorashadizadeh and M.H. Majidi, "Chaos synchronization using the Fourier series expansion with application to secure communications", *AEU-International Journal of Electronics and Communications*, Vol. 82, (2017), 37-44.
- [17] R. Gholipour and M.M. Fateh, "Adaptive task-space control of robot manipulators using the Fourier series expansion without task-space velocity measurements", *Measurement*, Vol. 123, (2018), 285-292.
- [18] M.R. Shokoohinia and M.M. Fateh, "Robust dynamic sliding mode control of robot manipulators using the Fourier series expansion", *Transactions of the Institute of Measurement and Control*, <https://doi.org/10.1177/0142331218802357>, 2018.
- [19] M.R. Shokoohinia, M.M. Fateh, and R. Gholipour, "Design of an adaptive dynamic sliding mode control approach for robotic systems via uncertainty estimators with exponential convergence rate", *SN Applied Sciences*, Vol. 2, No. 2, (2020), 1-11.
- [20] M.M. Fateh and M. Sadeghijaleh, "Voltage control strategy for direct-drive robots driven by permanent magnet synchronous motors", *International Journal of Engineering-Transactions B: Applications*, Vol. 28, No. 5, (2015), 709-716.
- [21] M.M. Fateh and A. Arab, "Robust control of a wheeled mobile robot by voltage control strategy", *Nonlinear Dynamics*, Vol. 79, No. 1, (2015), 335-348.
- [22] S. Khorashadizadeh and M.M. Fateh, "Robust task-space control of robot manipulators using Legendre polynomials for uncertainty estimation", *Nonlinear Dynamics*, Vol. 79, No. 2, (2015), 1151-1161.
- [23] R. Gholipour and M.M. Fateh, "Observer-based robust task-space control of robot manipulators using Legendre polynomial", In *Electrical Engineering (ICEE), 2017 Iranian Conference on* (pp. 766-771). IEEE, (2017).
- [24] M.W. Spong, S. Hutchinson and M. Vidyasagar, "Robot modeling and control", (Vol. 3, pp. 187-227). New York: Wiley, (2006).
- [25] F.J. Lin, S.G. Chen and I.F. Sun, "Intelligent sliding-mode position control using recurrent wavelet fuzzy neural network for electrical power steering system" *International journal of fuzzy systems*, Vol. 19, No. 5, (2017), 1344-1361.
- [26] F.J. Lin, S.G. Chen and I.F. Sun, "Adaptive backstepping control of six-phase PMSM using functional link radial basis function network uncertainty observer", *Asian Journal of Control*, Vol. 19, No. 6, (2017), 2255-2269.
- [27] R. Gholipour and M.M. Fateh, "Designing a Robust Control Scheme for Robotic Systems with an Adaptive Observer", *International Journal of Engineering, Transactions B: Applications*, Vol. 32, No. 2, (2019), 270-276.
- [28] F. Lin, S. Chen and C. Hsu, "Intelligent Backstepping Control Using Recurrent Feature Selection Fuzzy Neural Network for Synchronous Reluctance Motor Position Servo Drive System", *IEEE Transactions on Fuzzy Systems*, Vol. 27, No. 3, (2019), 413-427.
- [29] J.J.E. Slotine and W. Li, "Applied nonlinear control", (Vol. 199, No. 1). Englewood Cliffs, NJ: Prentice hall, (1991).
- [30] M.M. Fateh and S. Khorashadizadeh, "Robust control of electrically driven robots by adaptive fuzzy estimation of uncertainty", *Nonlinear Dynamics*, Vol. 69, No. 3, (2012), 1465-1477.
- [31] E. Salahshour, M. Malekzadeh, R. Gholipour, and S.Khorashadizadeh, "Designing multi-layer quantum neural network controller for chaos control of rod-type plasma torch system using improved particle swarm optimization", *Evolving Systems*, Vol. 10, No. 3, (2019), 317-331.
- [32] R. Gholipour, J. Addeh, H. Mojallali, and A. Khosravi, "Multi-objective evolutionary optimization of PID controller by chaotic particle swarm optimization", *International Journal of Computer and Electrical Engineering*, Vol. 4, No. 6, (2012), 833-838.
- [33] R. Gholipour, H. Mojallali, and S.M.K., Akhlaghi, "A Novel Particle Swarm Optimization with Passive Congregation via Chaotic Sequences", *International Journal of Computer and Electrical Engineering*, Vol. 4, No. 6, (2012), 809-815.
- [34] R. Gholipour, A. Khosravi, and H. Mojallali, "Suppression of chaotic behavior in duffing-holmes system using back-stepping controller optimized by unified particle swarm optimization algorithm", *International Journal of*

Engineering, Transactions B: Applications, Vol. 26, No. 11, (2013), 1299-1306.

- [35] R. Gholipour, A. Khosravi, and H. Mojallali, "Parameter estimation of loran chaotic dynamic system using bees algorithm", *International Journal of Engineering, Transactions C: Aspects*, Vol. 26, No. 3, (2013), 257-262.
- [36] N. Pourmousa, S.M. Ebrahimi, M. Malekzadeh, and M. Alizadeh, "Parameter estimation of photovoltaic cells using improved Lozi map based chaotic optimization Algorithm", *Solar Energy*, Vol. 180, (2019), 180-191.
- [37] J. Farzaneh, R. Keypour, and A. Karsaz, "A novel fast maximum power point tracking for a PV system using hybrid PSO-ANFIS algorithm under partial shading conditions", *International Journal of Industrial Electronics, Control and Optimization*, Vol. 2, No. 1, (2019), 47-58.
- [38] H. Moradi CheshmehBeigi, and A. Mohamadi, "Torque Ripple Minimization in SRM Based on Advanced Torque Sharing Function Modified by Genetic Algorithm Combined with Fuzzy PSO", *International Journal of Industrial Electronics, Control and Optimization*, Vol. 1, No. 1, (2018), 71-80.
- [39] M. Dehghani, Z. Montazeri, O.P. Malik, A. Ehsanifar, and A. Dehghani, "OSA: Orientation Search Algorithm", *International Journal of Industrial Electronics, Control and Optimization*, Vol. 2, No. 2, (2019), 99-112.
- [40] N. Ghaffarzadeh, and H. Faramarzi, "A new whale optimization algorithm based fault location method by focusing on dispersed model of the transmission line", *International Journal of Industrial Electronics, Control and Optimization*, (2020), doi: 10.22111/ieco.2020.32027.1218.
- [41] M.E.B. Aguilar, D.V. Coury, R. Reginatto, and R.M. Monaro, "Multi-objective PSO applied to PI control of DFIG wind turbine under electrical fault conditions", *Electric Power Systems Research*, Vol. 180, (2020), p.106081, <https://doi.org/10.1016/j.epsr.2019.106081>.
- [42] Z. Hu, X. Xu, Q. Su, H. Zhu, and J. Guo, "Grey prediction evolution algorithm for global optimization", *Applied Mathematical Modelling*, Vol. 79, (2020), 145-160.
- [43] M. Kohler, M.M. Vellasco, and R. Tanscheit, "PSO+: A new particle swarm optimization algorithm for constrained problems", *Applied Soft Computing*, Vol. 85, (2019), p.105865, <https://doi.org/10.1016/j.asoc.2019.105865>.
- [44] A. Taheri, and N. Asgari, "Sliding Mode Control of LLC Resonant DC-DC Converter for Wide Output Voltage Range in Battery Charging", *International Journal of Industrial Electronics, Control and Optimization*, Vol. 2, No. 2, (2019), 127-136.



Mohammad Reza Shokoohinia received his M. Sc. degree in Control engineering at Garmsar University, Iran in 2012. He is now a Ph. D. candidate in Control engineering at Shahrood University of Technology. His research interests include Dynamic Sliding Mode Control, Robotics and Intelligent Systems.

E-mail: mshokoohinia@yahoo.com (Corresponding author).



Mohammad Mehdi Fateh received his M. Sc. degree in electrical engineering from Tar-biat Modares University, Iran in 1991. He received his Ph. D. degree in robotic Engineering from Southampton University, UK in 2001. He is a full professor with the Department of Electrical and Robotic Engineering at Shahrood University of Technology, Iran. His research interests include nonlinear, robust and fuzzy control, robotics and intelligent systems.

E-mail: mmfateh@shahroodut.ac.ir