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Model-Free Tracking Control via Adaptive Dynamic Sliding Mode Control With Application To Robotic Systems

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ABSTRACT

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

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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 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

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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]

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

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

$$RI_a + K_m r^{-1}\dot{q} + \xi = v(t) \tag{3}$$

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

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

Using (4), one can calculate I_a as

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

Substitution of (5) into (3) yields

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

Now, (6) can be rewritten as

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

We can rewrite (7) as

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

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:

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

Now, define a sliding surface as follows:

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

The time derivative of (10) becomes

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

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

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

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

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

The secondary sliding surface is considered as

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

The time derivative of (14) becomes

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

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

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

Using (8) and (9), we have

$$\ddot{e} = \ddot{q}_d - v + g \tag{17}$$

Substitution of (17) into (16) yields

$$\begin{aligned}\dot\sigma(t) &= \dddot q_d - \dot v + \dot g(t) + a_1(\ddot q_d - v + g) + a_2\dot e + b_1\ddot q_d \\ &- b_1 v + b_1 g(t) + a_1 b_1\dot e + a_2 b_1 e + b_2\dot e(t) + a_1 b_2 e(t) \\ &+ a_2 b_2\int_0^t e(\tau)d\tau = \dddot q_d - \dot v + (a_1+b_2)(\ddot q_d - v) \\ &+ (a_1+b_2)g(t) + \dot g(t) + (a_2 + a_1 b_1 + b_2)\dot e \\ &+ (a_2 b_1 + a_1 b_2)e + a_2 b_2\int_0^t e(\tau)d\tau\end{aligned} \tag{18}$$

we can rewrite (18) as

$$\dot\sigma(t) = \dddot q_d - \dot v + \mu_1\Upsilon(t) + f(t) + \mu_2\dot e + \mu_3 e + \mu_4\int_0^t e(\tau)d\tau \tag{19}$$

Where $\Upsilon(t) = \ddot q_d - v$, $f(t) = \mu_1 g + \dot g$, $\mu_1 = a_1 + b_2$, $\mu_2 = a_2 + a_1 b_1 + b_2$, $\mu_3 = a_2 b_1 + a_1 b_2$ and $\mu_4 = a_2 b_2$. The control law in adaptive DSMC is proposed by

$$\begin{aligned}\dot v_{ADSMC} &= \dddot q_d + \mu_1\Upsilon(t) + \mu_2\dot e + \mu_3 e + \\ &\mu_4\int_0^t e(\tau)d\tau + \hat f + v_r \\ v_{ADSMC}(t) &= \int_0^t \dot v_{ADSMC}(\tau)d\tau\end{aligned} \tag{20}$$

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

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

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].

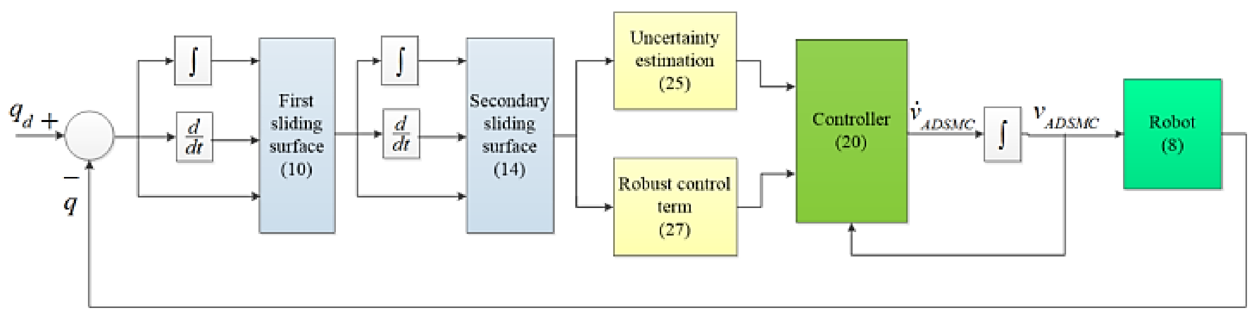

Fig.1. The configuration of the proposed control system

IV. STABILITY ANALYSIS

Consider a Lyapunov function candidate:

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

Differentiating the Lyapunov function, we have

$$\dot V = \sigma\dot\sigma - \frac{1}{\gamma}\tilde f\dot{\hat f} \tag{23}$$

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

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

The adaptive law can be proposed as follows:

$$\dot{\hat f} = \gamma\sigma \tag{25}$$

Using (25), one can easily conclude that

$$\dot V = -\sigma v_r \tag{26}$$

where the robust control term is selected as follows:

$$v_r = k\sigma \tag{27}$$

Substituting (27) into (26), we have

$$\dot V = -k\sigma^2 \tag{28}$$

Therefore, it has been guaranteed that $\dot V \le 0$. 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

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

$$q_d = 1 - \cos(\pi t / 7) \qquad (29)$$

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:

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

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.

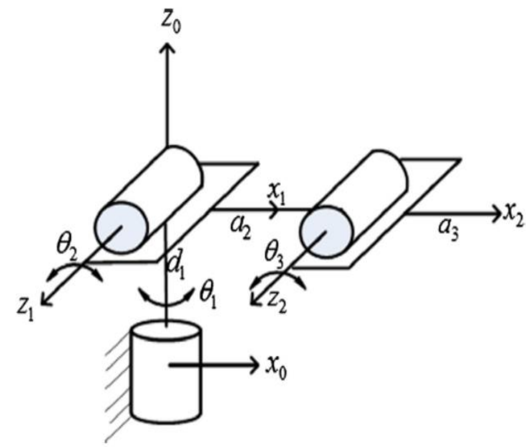

Fig. 2. The symbolic representation of the articulated robot

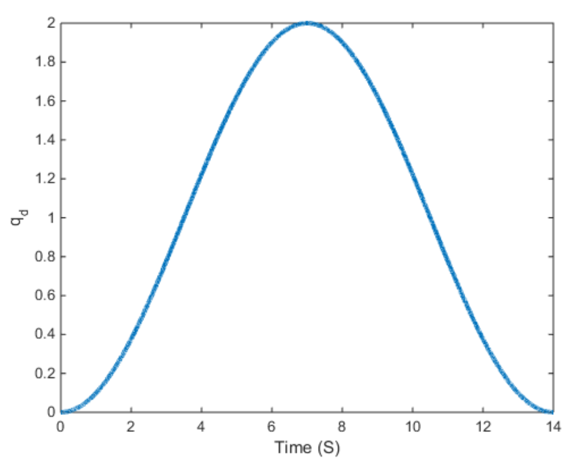

Fig. 3. The desired trajectory

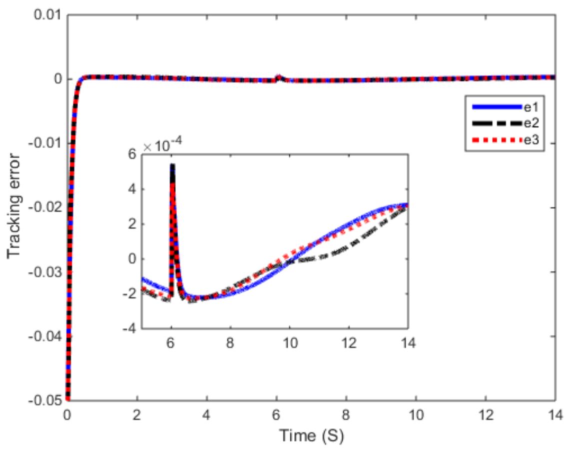

Fig.4. The tracking errors of Adaptive DSMC

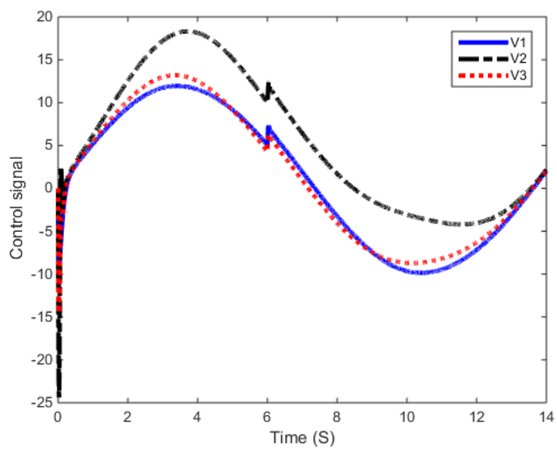

Fig.5. The voltages of motors in the proposed method

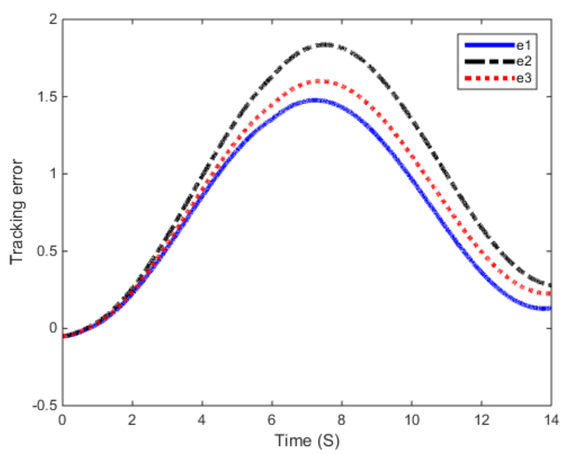

Fig. 6. The tracking errors using DSMC

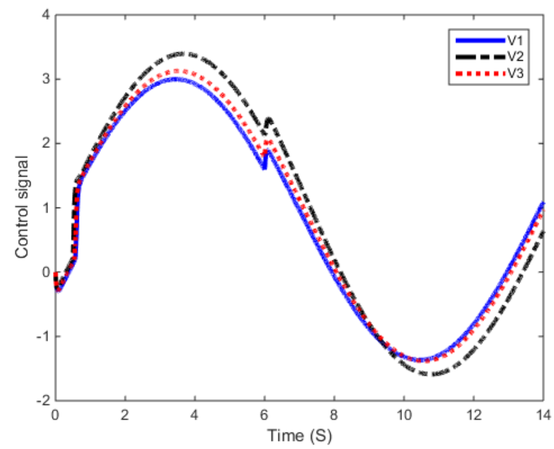

Fig. 7. The voltages of motors using DSMC

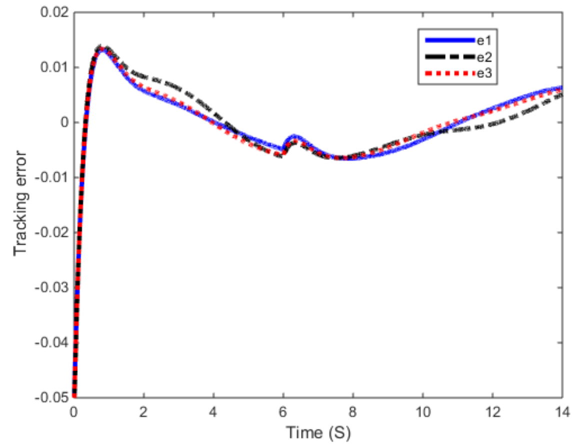

Fig.8. The tracking errors using DSMC

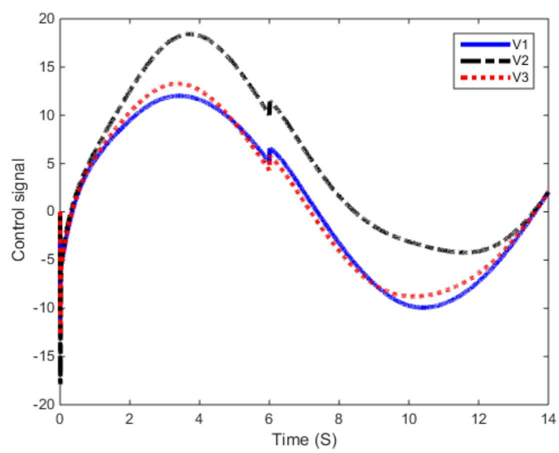

Fig. 9. The voltages of motors using DSMC

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:

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

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.

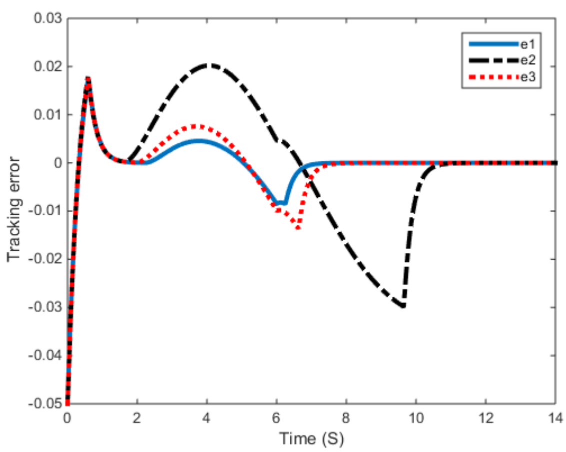

Fig.10. The tracking errors in conventional sliding mode control

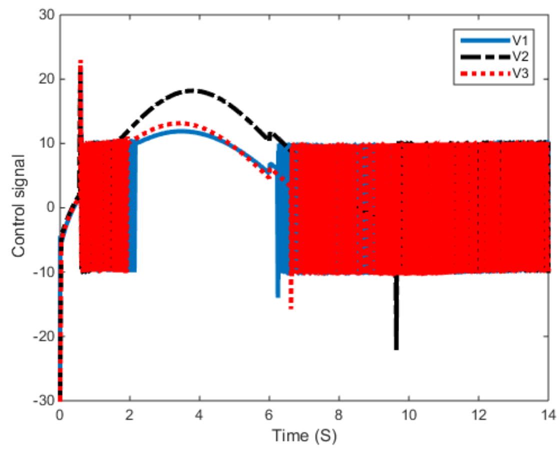

Fig. 11. The control signals in conventional sliding mode control

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.

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