New Adaptive Sliding Mode Controller for Depth Control of Autonomous Underwater Robot

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ABSTRACT:
Sliding mode control is a robust controller against modeling imprecisions and external disturbances, successfully employed to the dynamic positioning of autonomous underwater robot. In order to improve the performance of the whole system, the discontinuity in the control law must be smoothed out to avoid the undesirable chattering, unwanted ripples. One of the disadvantages of conventional sliding mode is great vulnerability in the presence of noise. The adoption of a properly designed thin boundary layer has proven to be effective in completely eliminating chattering and also noise and some initial condition causing undesirable chattering phenomenon, unwanted ripples in the control input. This paper describes the development of a depth control system for autonomous underwater robot. In this paper we used the sliding surface term and its derivation with adaptive gains in control law instead of the sign function with fixed gain. The proposed controller has been designed to solve great vulnerability of sliding mod control at the presence of noise. The stability and convergence properties of the closed-loop system are analytically proved using Lyapunov stability theory. Simulation results are presented in order to demonstrate the control system performance.

KEYWORDS: Adaptive sliding mode, Noise cancellation, Underwater vehicle, Noise cancellation

1. INTRODUCTION

About 70% of the Earth's surface is covered with water which is like an empire of natural resources. In order to utilize these resources, mankind depends on developing underwater vehicles and employing them. So knowing these vehicles is important. Many control methods have been used on these devices such as intelligent methods, nonlinear control, adaptive control and linear control. Due to the highly nonlinear nature of the autonomous underwater vehicles (AUV), controllers employed within it, should be accurate and they are robust against noise and uncertainty.

The inherent nature of the nonlinear dynamics of underwater vehicles, the variability of the ocean environment and the uncertainty in the model provides good conditions for intelligent and fuzzy logic control AUV. Fuzzy controller for AUV is studied in [1-4], and intelligent controller is verified as in [5-8]

Dynamics of AUV often have been obtained under different assumptions. However these assumptions may induce modeling errors and can cause severe control problems in many practical applications. So in some papers, nonlinear controller is considered as in [9-11]

Due to the parameter uncertainties and unknown disturbances on the dynamics of underwater vehicles, many researches are entered in field of adaptive control.

J. Yuh and Colleagues applied an adaptive controller to small UUV in very shallow water [12], and Sid Zhao applied this controller with disturbance observer for an autonomous underwater robot, ODIN III, which was robust with respect to external disturbance and uncertainties in system [13].

Reference [14] shows model of AUV is considered non-minimum phase. An indirect adaptive control system is designed for the depth control. The control system consists of a gradient based identifier for online parameter estimation, an observer for state estimation, and an optimal controller.

Sliding mode control (SMC) is robust to model uncertainty and to external disturbances.

Reference [15] and [16] designed an adaptive fuzzy sliding mode controller for the depth and heading regulation of underwater robot which compensated the disturbances. An adaptive sliding surface designed for a class of multi input nonlinear systems with

perturbations and regulation problem is solved base on the Lyapunov stability and backstepping technique, as in [17].
Reference [18] proposed a methodology based on the blend of a sliding mode controller and an adaptive fuzzy system, because it used advantages of both systems and releases the required knowledge of model. A direct model reference adaptive fuzzy control (MRAFC) of nonlinear systems designed with application to robot manipulator tracking control is proposed in [19], however to make the actual joint trajectories of robot, MRAFC is combined with feedforward PD control.
Extensive studies have been done on sliding mode controller and it is applied to many applications, but it inherits a discontinuous control action and then chattering will occur when the states are near the sliding surface.
In this paper, adaptive sliding mode algorithm is employed for trajectory tracking of underwater vehicle in depth channel. Stability, asymptotic convergence to minimize the tracking error and boundedness of the close-loop signals are assured by Lyapunov stability theory. Results show that the proposed control law can provide fine performance in trajectory tracking problem and control input, despite external disturbances and noise.

DYNAMIC MODEL

The equations of motion for underwater vehicles can be presented with respect to an inertial reference frame or to a body-fixed reference frame. For control purposes, the dynamic model of underwater vehicles are commonly expressed with respect to the inertial reference frame by the position/attitude vector $x=[x,y,z,\phi,\theta,\psi]^T$, In the particular case of remotely operated vehicles, the distance between buoyancy and gravity centers is usually large enough to keep the roll (ϕ) and pitch (θ) angles small, i.e. $\phi\approx 0, \theta\approx 0$. Besides the self-stabilizing property, this design characteristic allows the vertical motion (heave) of the vehicle to be considered decoupled from the motion in the horizontal plane. So, keeping this in mind and considering Morison equation, the vertical motion along z-axis can be described by

$$m\ddot{z}+c\dot{z}|\dot{z}|+d=u \tag{1}$$

Where z is the depth, u is the control input (thrust force), d is the disturbance caused by external forces, c is the coefficient of the hydrodynamic quadratic damping and m represents vehicle's mass plus the hydrodynamic added mass. With respect to the dynamic model, the following physically motivated assumptions can be made:

Assumption 1. The parameter $m(t)$ is time-varying and unknown but positive and bounded, i.e. $0\le m_{\min}\le m(t)\le m_{\max}$
Assumption 2. The parameter $c(t)$ is time-varying and unknown but bounded, i.e. $c_{\min}\le c(t)\le c_{\max}$. as in [20].

DEPTH CONTROL

We used Sliding mod controller for the described system in previous section in first subsection, and then we will design adaptive sliding mode controller in the second sub section. A comparison between the performance of the proposed controller with sliding mode controller is discussed in the next section.

3.1. Sliding mode control

Let $S(t)$ be a sliding surface defined in the state space by the equation $s(\tilde{z},\dot{\tilde{z}})=0$, with the function $s:R^2\to R$ satisfying

$$s(\tilde{z},\dot{\tilde{z}})=\dot{\tilde{z}}+\lambda\tilde{z} \tag{2}$$

Where,

$$\tilde{z}=z-z_d \tag{3}$$

S is the tracking error, $\dot{\tilde{z}}$ is the time derivative of $\tilde{z}$, z_d is the desired trajectory and λ is a strictly positive constant. Regarding the development of the control law, the following assumptions must be made:
Assumption 3. The states $z,\dot{z}$ are available.
Assumption 4. Furthermore $z,\dot{z}$ and $\ddot{z}$ are available and with known bounds.

In most papers, the problem of controlling the vertical motion of a remotely operated underwater vehicle, governed by (2), defined a control law composed by an equivalent control $u=c\dot{z}|\dot{z}|+m(\ddot{z}_d-\lambda\dot{\tilde{z}})$ and a discontinuous term $-K\,\mathrm{sgn}(s)$

$$u=c\dot{z}|\dot{z}|+m(\ddot{z}_d-\lambda\dot{\tilde{z}})-K\,\mathrm{sgn}(s) \tag{4}$$

Where K is the control gain and $\mathrm{sgn}(.)$ is defined as

$$\mathrm{sgn}(s)=\begin{cases}-1 & if\ x<0\\ 0 & if\ x=0\\ 1 & if\ x>0\end{cases} \tag{5}$$

In the conventional SMC, K is considered constant and to cancel the chattering it is necessary to use the saturation function instead of sign function as following:

$$u = c\dot{z}\left|\dot{z}\right| + m(\ddot{z}_d - \lambda\dot{\tilde{z}}) - Ksat(\frac{s}{\varphi}) \qquad (6)$$

Where $sat(x)$ is defined as

$$sat(x) = \begin{cases} \operatorname{sgn}(x) & if\ |x| > 1 \\ x & if\ |x| \le 1 \end{cases} \qquad (7)$$

it can be easily verified that (3) is sufficient to impose the sliding condition

$$\frac{1}{2}\frac{d}{dt}s^2 \le -\eta|s| \qquad (8)$$

Where η is a strictly positive constant related to the reaching time[5]. As shown in the simulations, with the presence of external disturbances, the controller has a good track unevenness may occur in the control input. The proposed adaptive sliding mode controller provides smooth control input.

3.2. ADAPTIVE SLIDING MODE CONTROLLER

In the proposed controller the sliding surface differential is used and K is calculated with an adaptive equation. Using the proposed controller, the results caused more adequate effect on the smoothness of the control input, compared with sliding mode control in the initial time.

$$\dot{s} = \ddot{\tilde{z}} + \lambda\dot{\tilde{z}} \qquad (9)$$

$$\gamma = [s, \dot{s}] \qquad (10)$$

It is assume the modeling error is bounded and the upper bound is $d_0 + d_1\|\tilde{z}\|$, which d_0, d_1 are positive constant and disturbance is bounded $\|d\| < \beta$.

Defining a new parameter θ:

$$\theta_i = \beta + d_0 + d_1\|\tilde{z}\| \qquad (11)$$

Proposed control input is:

$$u = c\dot{z}\left|\dot{z}\right| + m(\ddot{z}_d - \lambda\dot{\tilde{z}}) - k_1 s - k_2\dot{s} \qquad (12)$$

Which rewritten as follow:

$$u = c\dot{z}\left|\dot{z}\right| + m(\ddot{z}_d - \lambda\dot{\tilde{z}}) - \sum_{i=1}^{2} k_i\gamma_i \qquad (13)$$

Where,

$$k_i = \hat{\theta}_i + \eta + \mu_i \qquad (14)$$

Where, μ_i is positive constant.
with conditions as follow:

$$(\hat{\theta}_i - \theta_i) < (\lambda - \alpha)\|\dot{\tilde{z}}\| \ , \lambda < \alpha \qquad (15)$$

Where $\|.\|$ is defined as Euclidean norm, and $\hat{\theta}_i$ is estimates of θ_i

Adaptive law inspired by J. Yuh [12], [13] defined as follows:

$$\dot{\hat{\theta}}_i = f\|\tilde{e}\|\|\gamma_i\| \qquad (16)$$

Define $\tilde{e}$ as follow:

$$\tilde{e} = \dot{\tilde{z}} + \alpha\tilde{z} \qquad (17)$$

Where, f is positive constant.

Theorem: the tracking error e asymptotically converges to zero and the parameter estimation converge to certain bounds with the above adaptive sliding mode controller.

Proof: construct the Lyapunov function as follows:

$$V = \frac{1}{2}m\tilde{e}^2 + \frac{1}{2}\|\gamma_i\|^{-1} f^{-1}(\theta_i - \hat{\theta}_i)^2 + \frac{1}{2}s^2 \ , i = 1,2 \qquad (18)$$

$$\dot{\tilde{z}} = \dot{z} - \dot{z}_d \qquad (19)$$

Combineing (1), (3) and (12), the error equation can be obtained as follows:

$$m\ddot{\tilde{z}} = -m\lambda\dot{\tilde{z}} - k_1 s - k_2\dot{s} - d \qquad (20)$$

Differentiating (18) along (20) with respect to time yields:

$$\dot{V} = \tilde{e}m(\ddot{\tilde{z}} + \alpha\dot{\tilde{z}}) - \|\gamma_i\|^{-1} f^{-1}(\theta_i - \hat{\theta}_i)\dot{\hat{\theta}}_i + s\dot{s} \qquad (21)$$

From (1), (9), (14)

$$\dot{s} = (-k_1 s - k_2\dot{s} - d)/m \qquad (22)$$

$$\begin{aligned}\dot{V} &= \tilde{e}(-m\lambda\dot{\tilde{z}} - k_1 s - k_2\dot{s} - d + m\alpha\dot{\tilde{z}}) - \|\gamma_i\|^{-1} f^{-1}(\theta_i - \hat{\theta}_i)(f\|\tilde{e}\|\|\gamma_i\|) \qquad (23)\\ &- k_1 s^2 - k_2 s\dot{s} \\ &= m(-\lambda + \alpha)\tilde{e}\dot{\tilde{z}} - k_1 s\tilde{e} - k_2\dot{s}\tilde{e} - (\theta_i - \hat{\theta}_i)\|\tilde{e}\| \\ &- k_1 s^2 - k_2 s\dot{s} - d\tilde{e} \\ &= m(-\lambda + \alpha)\tilde{e}\dot{\tilde{z}} - k_1 s(\tilde{e} + s) - k_2\dot{s}(\tilde{e} + s) - (\theta_i \\ &- \hat{\theta}_i)\|\tilde{e}\| - d\tilde{e} \\ &\le m(-\lambda + \alpha)\|\tilde{e}\|\|\dot{\tilde{z}}\| - (\tilde{e} + s)(k_1 s + k_2\dot{s}) - (\theta_i \\ &- \hat{\theta}_i)\|\tilde{e}\| - d\tilde{e} \\ &= (m(-\lambda + \alpha)\|\dot{\tilde{z}}\| + (\hat{\theta}_i - \theta_i))\|\tilde{e}\| - k_1 s^2 - k_1 s\tilde{e} \\ &- k_2\dot{s}(\tilde{e} + s) - d\tilde{e}\end{aligned}$$

From (22)

$$= (m(-\lambda + \alpha)\|\dot{\tilde{z}}\| + (\hat{\theta}_i - \theta_i))\|\tilde{e}\| - k_1 s(s + \tilde{e})(1 - \frac{k_2}{m + k_2}) + \frac{dk_2(\tilde{e} + s)}{m + k_2} - d\tilde{e}$$

From (2), (15) and (17) $\dot{V}$ is reduced to $\dot{V} <$ ●
Therefore, the tracking error will asymptotically go to zero and the parameter estimation $\hat{\theta}$ will also asymptotically converge to θ.

2. SIMULATION RESULT

To evaluate the proposed controller, it is compared with the conventional SMC. The results of the simulations are shown in the following figures. Finally the controller performance was evaluated in the presence of noise. It was considered that the model parameters, m and c, were perfectly known. Regarding controller and model parameters, the following values were chosen

$$m = 55\,kg\,, c = 250 Kg/m\,, \eta = 0.1\,, \varphi = 0.01$$

$$z_d = 0.5(1-\cos(0.1\pi t)), \lambda = 0.6,\ f = .5, \alpha = 0.8$$

The uncertainty of the parameters is modeled as $m = m(1+0.1\sin(0.1\pi t))$, $c = c(1+0.1\sin(0.1\pi t))$

For conventional sliding mode $k = 13$, has been considered. The results of the SMC are shown in Fig. 1, Fig. 2 and Fig. 3 and the results of the proposed adaptive sliding mode controller are shown in Fig. 4, Fig. 5 and Fig. 6. Disturbance is random function which its amplitude is limited to [-1, 1]. Therefore, we've only shown the simulation results for this disturbance that is actuated at t=15sec and is ended at t=35sec.

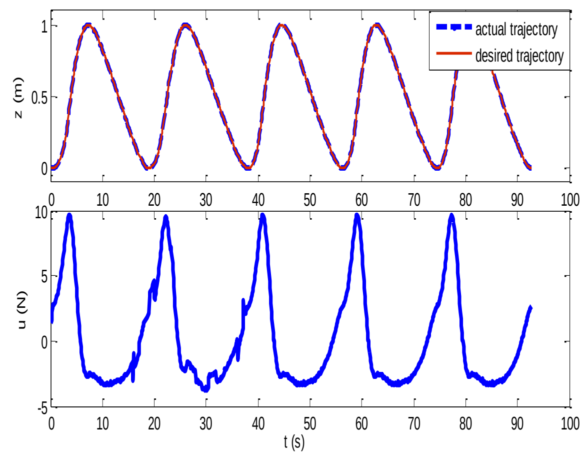


Fig. 1. The conventional SMC with z(0)=0

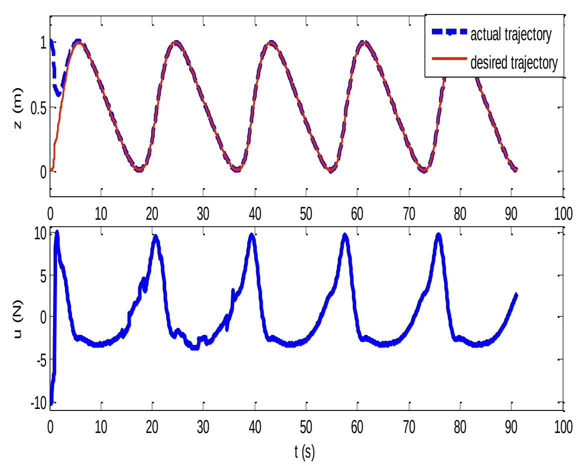


Fig. 2. The conventional SMC with z(0)= 1

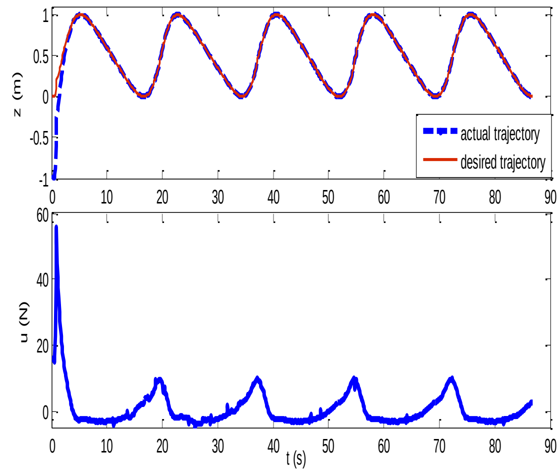


Fig. 3. The conventional SMC with z(0)= **-1**

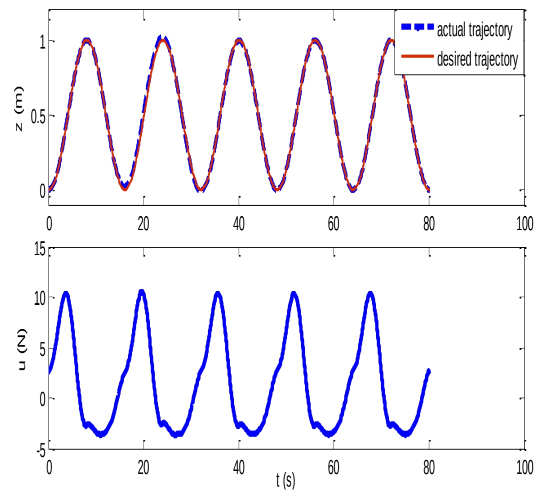


Fig. 4. The proposed controller with z(0)=0

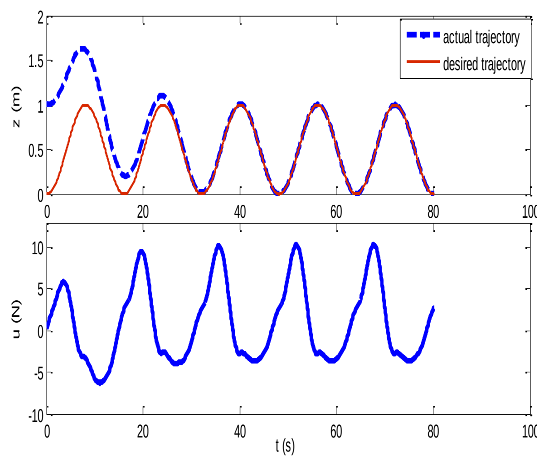


Fig. 5. The proposed controller with z(0)=1

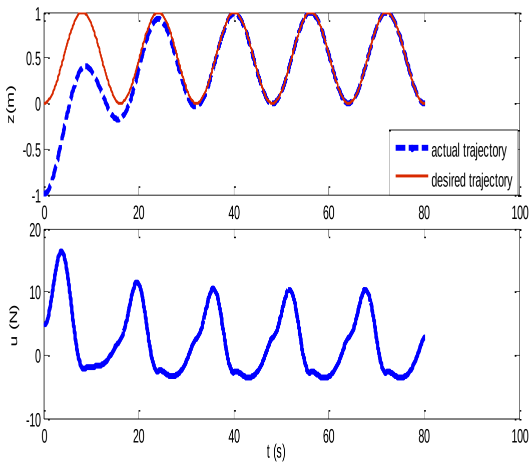
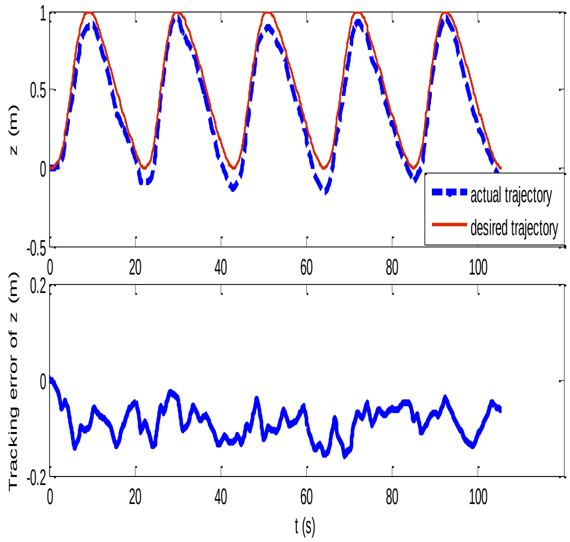
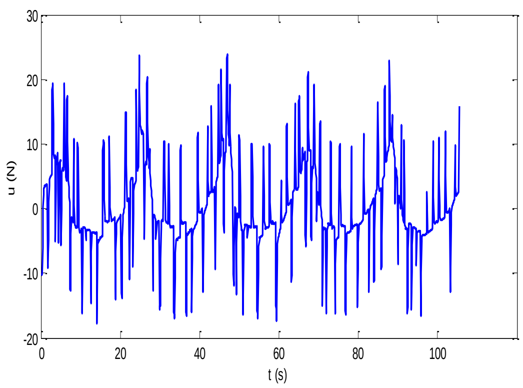


Fig. 6. The proposed controller with z(0)= -1

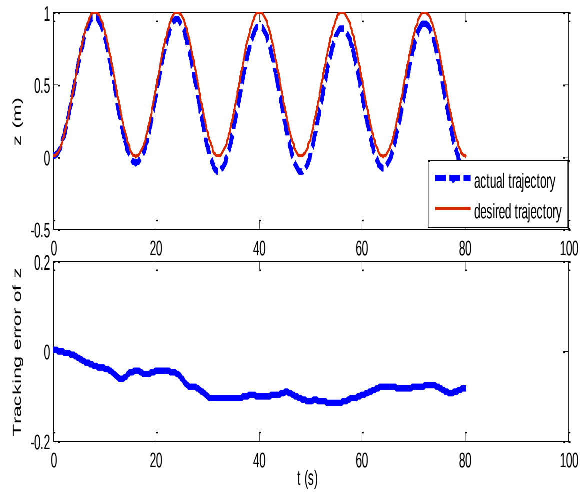


(a). Vertical displacement and tracing error

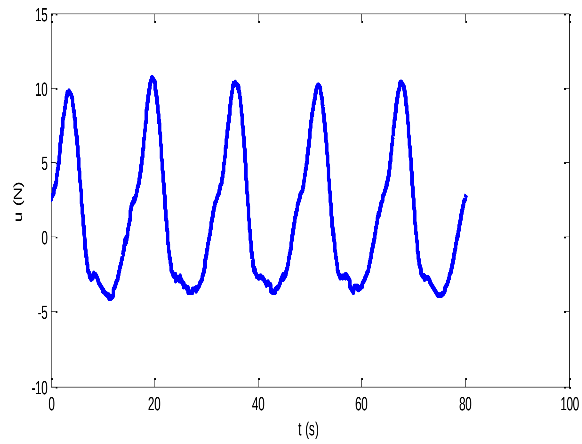


(b). Control input (thrust force)

Fig. 7. The conventional SMC with noise at the output



(a). Vertical displacement and tracking error



(b). Control input (thrust force)

Fig. 8. The proposed controller with noise at the output

As shown in the figures, the conventional SMC tracks the desired trajectory with K=13, in an adequate way. When the initial conditions are not zero, in the initial time, there are some unwanted ripples and unexpected sharp peak in the input signal of the controller (unexpected sharp peak is equal to 60(N) in Fig. 3). In this case, the input signal started at -10(N) for positive initial condition (Fig. 2) and started at 18(N) for negative initial condition (it means that, robot is set at lower depth than desired depth) (Fig. 3). In the proposed controller, in the initial time, when initial condition is not zero, there are no ripple and no unexpected sharp peak in the input signal of the controller. The value of K obtained during the simulation is less than 5, so the desired track will be obtained. The input signal is started at 2.5(N) for positive initial condition (Fig. 5) and at 5(N) for negative initial condition (Fig. 6) and in latter case maximum peak is about 15 N (against maximum peak in conventional sliding mode that is 60 N), But converge to the desired trajectory is slower than the conventional SMC. As a comparing Fig. 7 and Fig. 8, the proposed adaptive sliding mode controller is not vulnerable against noise, while the conventional sliding mode controller has too much chattering at the control signal.

3. CONCLUSION

In this paper, the adaptive sliding mode controller is applied for the depth equation of an underwater robot. Using this controller, ripples and unexpected sharp peak of the input control signal were canceled and control signal was smoother than conventional sliding mod controller and the tracking is adequate and acceptable. The result of the simulations shows the validity of the proposed controller. In proposed controller the value of K obtained during the simulation is less than K in conventional SMC, and this value of K resulted in a desired track, but converge to the desired trajectory is slower than the conventional SMC. According to the simulation results, the proposed controller has been solved the problem of great vulnerability in the presence of noise, which is one of the disadvantages of conventional sliding mode.

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