A MODIFIED OBSERVER-BASED SLIDING MODE CONTROLLER FOR ROBOT MANIPULATORS

BỘ ĐIỀU KHIỂN TRƯỢT DỰA TRÊN BỘ QUAN SÁT MỚI CHO CÁC TAY MÁY ROBOT CÔNG NGHIỆP

Nguyen Ngoc Hoai An[1], Truong Thanh Nguyen[2], Vo Anh Tuan[1]*

[1]*The University of Danang - University of Technology and Education*
[2]*University of Ulsan*

*Corresponding author: voanhtuan2204@gmail.com

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Abstract - Sliding mode control (SMC) is widely adopted by the control community due to its robustness, accuracy, and ease of implementation. Ideally, the switching part of the SMC should be able to compensate for parametric uncertainties while also minimizing chattering. The letter develops a SMC scheme based on the estimated uncertainties from an uniform second-order sliding mode observer (USOSMO). Using the proposed control scheme, chattering is effectively reduced and control performance is enhanced expressively compared to conventional SMC because uncertainty estimations have been achieved with greater accuracy and faster convergence. Finally, a simulation example of a 3 DOF robot manipulator using the developed controller is given to illustrate its effectiveness.

Key words - Sliding mode control (SMC); second-order sliding mode observer; robotic manipulators

Tóm tắt - Bộ điều khiển trượt được cộng đồng điều khiển áp dụng rộng rãi do tính mạnh mẽ, chính xác và dễ thực hiện của nó. Lý tưởng nhất là phần chuyển mạch của bộ điều khiển trượt phải có khả năng bù đắp cho những thành phần bất định về tham số đồng thời giảm thiểu hiện tượng Chattering. Bài báo phát triển một phương pháp điều khiển trượt dựa những thành phần bất định ước tính được từ một bộ quan sát bậc hai đồng nhất (USOSMO). Sử dụng phương pháp điều khiển được đề xuất, hiện tượng Chattering được giảm thiểu một cách hiệu quả và hiệu suất điều khiển được nâng cao rõ rệt so với bộ điều khiển trượt truyền thống vì ước lượng của các thành phần bất định đã đạt được với độ chính xác cao hơn và hội tụ nhanh hơn. Cuối cùng, một ví dụ mô phỏng của một tay máy Robot 3 bậc tự do sử dụng bộ điều khiển đã phát triển được mang lại để mô tả tính hiệu quả của nó.

Từ khóa - Điều khiển trượt (SMC); bộ quan sát trượt bậc hai; robot công nghiệp

1. Introduction

In manufacturing industries, robot manipulators are widely used to improve the quality of large-scale products. It is however difficult to obtain the precise dynamic models of robot manipulators since they are complex, highly nonlinear, and highly coupled. Robotic manipulators require a variety of robust control schemes to accomplish their task, including nonlinear PD computed torque control [1], computed torque control (CTC) [2], SMC [3], adaptive control [4], and neural network controller [5]. Among these methods, SMC is a simple, effective, and powerful design method against uncertain components.

To identify uncertain components in nonlinear systems, a number of estimation methods have been proposed including sliding mode observer (SMO) [6], high gain observer [7], USOSMO [8], and extended high gain observer [9]. It is the USOSMO that has the lowest estimation error among them. Therefore, in order to implement this control scheme, the USOSMO would be used.

The paper presents a novel observer-based control scheme that uses the USOSMO to estimate uncertain components including uncertainties and disturbances. Using this control scheme, chattering is effectively reduced and control performances are enhanced because uncertainty estimations have been achieved with greater accuracy. Finally, a simulation of this control strategy is given to illustrate its effectiveness.

2. Dynamic model of the robot manipulators

The dynamical model of a robot is detailed in the expression as:

$$H(\varphi)\ddot{\varphi} + V(\varphi,\dot{\varphi})\dot{\varphi} + G(\varphi) + f_r(\dot{\varphi}) + \tau_d = \tau(t) \quad (1)$$

in which $\varphi, \dot{\varphi}, \ddot{\varphi} \in \mathscr{R}^{n\times 1}$ correlate with position, velocity, and acceleration of the robot's joints. $H(\varphi) \in \mathscr{R}^{n\times n}$ is the inertia matrix, $V(\varphi,\dot{\varphi}) \in \mathscr{R}^{n\times n}$ stands for the matrix of Coriolis and centrifugal force, $G(\varphi) \in \mathscr{R}^{n\times 1}$ is the gravity matrix, $f_r(\dot{\varphi}) \in \mathscr{R}^{n\times 1}$ stands for the friction vector, $\tau \in \mathscr{R}^{n\times 1}$ stands for the control torque vector, and $\tau_d \in \mathscr{R}^{n\times 1}$ is the disturbance vector.

Making a transformation of Eq. (1) to get:

$$\ddot{\varphi} = H^{-1}(\varphi)[\tau(t) - V(\varphi,\dot{\varphi})\dot{\varphi} - G(\varphi) - f_r(\dot{\varphi}) - \tau_d] \quad (2)$$

Let $x = [x_1, x_2]$ as the state vector, where x_1, x_2 correspond to $\varphi, \dot{\varphi} \in \mathscr{R}^{n\times 1}$. Then, (2) can be written in state space from as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \Theta(x,t) + \delta(x,\tau_d) + J(x_1)\tau(t) \end{cases} \quad (3)$$

where $\Theta(x,t) = -H^{-1}(\varphi)[V(\varphi,\dot{\varphi})\dot{\varphi} + G(\varphi)] \in \mathscr{R}^{n\times 1}$ and $J(x_1) = H^{-1}(x_1) \in \mathscr{R}^{n\times n}$ are smooth nonlinear functions, and $\delta(x,\tau_d) = -H^{-1}(\varphi)[f_r(\dot{\varphi}) + \tau_d] \in \mathscr{R}^{n\times 1}$ represents the lumped uncertainty.

For the design of a control scheme in the next section, it is necessary to make the following assumption.

Assumption 1: $\delta(x,\tau_d)$ is supposed to be constrained by: $\|\delta(x,\tau_d)\| \le \bar{\delta}$ with $\bar{\delta}$ is a positive constant.

Assumption 2: The time derivative of $\delta(x,\tau_d)$ is supposed to be constrained by: $\|\dot{\delta}(x,\tau_d)\| \le \delta^*$ with δ^* is a positive constant.

3. Observer design

For all uncertainties, the USOSMO is constructed to compensate its effects [10]:

$$\begin{cases} \varepsilon_0 = x_2 - \hat{x}_2 \\ \dot{\hat{x}}_2 = J(x_1)\tau + \Theta(x,t) + \hat{\delta} + \pi_1\Psi_1(\varepsilon_0) \\ \dot{\hat{\delta}} = -\pi_2\Psi_2(\varepsilon_0) \end{cases} \quad (4)$$

where π_1, π_2 represent user-designed parameters of observer which are selected based on the set [11]. $\hat{x}_2$ is the estimated value of x_2, $\hat{\delta}$ is the estimated value of $\delta(x,\tau_d)$ which is the observer's output. $\tilde{\delta} = \hat{\delta} - \delta$ is defined as the estimation error of the observer where $\tilde{\delta}$ is supposed to be bounded $|\tilde{\delta}| \le \varrho$, ϱ is a known constant. $\Psi_1(\varepsilon_0)$ and $\Psi_2(\varepsilon_0)$ are selected as [11]:

$$\begin{cases} \Psi_1(\varepsilon_0) = [\varepsilon_0]^{0.5} + \alpha[\varepsilon_0]^{1.5} \\ \Psi_2(\varepsilon_0) = 0.5[\varepsilon_0]^0 + 2\alpha\varepsilon_0 + 1.5\alpha^2[\varepsilon_0]^2 \end{cases} \quad (5)$$

where α is positive constant.

Proof of observer's convergence:

Subtracting Eq. (4) from Eq. (3), the estimation dynamics errors are as follows:

$$\begin{cases} \dot{\varepsilon}_0 = -\pi_1\Psi_1(\varepsilon_0) + \tilde{\delta} \\ \dot{\tilde{\delta}} = -\pi_2\Psi_2(\varepsilon_0) - \dot{\delta} \end{cases} \quad (6)$$

Obviously, Eq. (6) has a form of uniform robust exact differentiator [11]. Therefore, ε_0 and $\tilde{\delta}$ will approach zero in a predefined time.

4. Proposed controller design

Define respectively $e = x_1 - x_d$ and $\dot{e} = x_2 - \dot{x}_d$ as the position error and velocity error where x_d and $\dot{x}_d$ stand for the preferred position and velocity, x_1 and x_2 represent the measured position and velocity.

Based on the tracking errors, the sliding surface is designed as:

$$s = \dot{e} + \beta e \quad (7)$$

where β is positive constant.

Using dynamic (3) to calculate the derivative of Eq. (7) according to time, we gain:

$$\begin{aligned} \dot{s} &= \ddot{e} + \beta\dot{e} \\ &= \Theta(x,t) + \delta(x,\tau_d) + J(x_1)\tau(t) - \ddot{x}_d + \beta(x_2 - \dot{x}_d) \end{aligned} \quad (8)$$

Following is a description of how the control law is designed:

$$\tau(t) = -J^{-1}(x_1)\begin{pmatrix} \Theta(x,t) - \ddot{x}_d + \beta(x_2 - \dot{x}_d) + \hat{\delta} \\ +\Gamma s + (\bar{\delta} + \varrho)\mathrm{sign}(s) \end{pmatrix} \quad (9)$$

in which ϱ is a positive constant and Γ represents a positive diagonal matrix.

Proof of the controller's stability:

Applying control torque to Eq. (9) yields:

$$\dot{s} = \tilde{\delta} - \Gamma s - \bar{\delta}\mathrm{sign}(s) - \varrho\mathrm{sign}(s) \quad (10)$$

To demonstrate the stability of the proposed strategy, we select Lyapunov function as $\mathscr{L} = 0.5s^2$. Therefore, the derivative of $\mathscr{L}$ according to time is obtained by:

$$\begin{aligned} \dot{\mathscr{L}} &= s\dot{s} \\ &= s\big(\tilde{\delta} - \Gamma s - \bar{\delta}\mathrm{sign}(s) - \varrho\mathrm{sign}(s)\big) \\ &= s\tilde{\delta} - \Gamma s^2 - \bar{\delta}|s| - \varrho|s| \\ &\le -\varrho|s| \end{aligned} \quad (11)$$

As $\varrho > 0$, $\dot{\mathscr{L}}$ is negative semidefinite, ie, $\dot{\mathscr{L}} \le -\varrho|s|$. It implied that the convergence of s to zero is guaranteed based on Lyapunov principle. Consequently, the tracking errors will be converged to zero.

5. Numerical simulation results

This scheme was verified by simulations on a 3-DOF robot manipulator using MATLAB/SIMULINK. SOLIDWORKS and SIMMECHANICS of MATLAB/ SIMULINK are used to design the robot's mechanical model. An illustration of the robot's kinematics is depicted in Figure 1. For more details on the structure and parameters of the robot system, readers can find them in the study [12]. To demonstrate the proposed strategy's effectiveness, a comparison is conducted between it and the conventional SMC [3] in some respects such as robustness resistance to uncertain components, steady-state errors, and chattering removal capabilities.

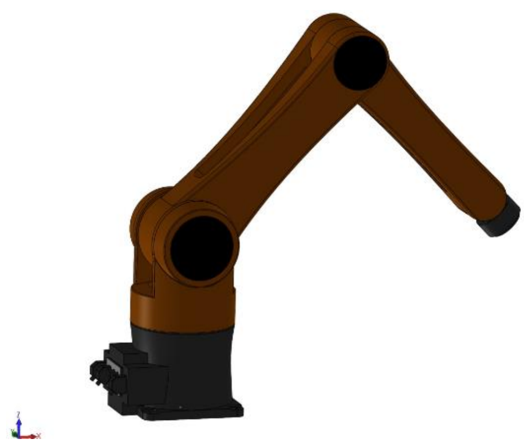

Figure 1. *An illustration of the robot's kinematics*

The robot's task is to follow a following configured trajectory. X-axis: X=0.85-0.01t (m); Y-axis: Y=0.2+0. 2 sin(0.5t) (m); and Z-axis: Z=0.7+0. 2 cos(0.5t) (m).

To simulate the influence of interior uncertainties and exterior disturbances, these terms are assumed as $\Delta H(\varphi) = 0.3H(\varphi)$, $\Delta V(\varphi,\dot{\varphi}) = 0.3V(\varphi,\dot{\varphi})$, $\Delta G(\varphi) = 0.3G(\varphi)$,

$$\tau_d = \begin{bmatrix} 6\sin(2t) + 4\sin(t/2) + 2\sin(t) + 3[\varphi_1]^{0.8} \\ 5\sin(2t) + 1\sin(t/2) + 2\sin(t) + 2[\varphi_2]^{0.8} \\ 7\sin(2t) + 3\sin(t/3) + 2\sin(t) + 3[\varphi_3]^{0.8} \end{bmatrix} (\mathrm{N.m}),$$

and $f_r(\dot{\varphi}) = \begin{bmatrix} 0.01[\dot{\varphi}_1]^0 + 2\dot{\varphi}_1 \\ 0.01[\dot{\varphi}_2]^0 + 2\dot{\varphi}_2 \\ 0.01[\dot{\varphi}_3]^0 + 2\dot{\varphi}_3 \end{bmatrix}$ (N.m).

The SMC's control input is set as:

$$\tau(t) = -J^{-1}(x_1)\begin{pmatrix} \Theta(x,t) - \ddot{x}_d + \beta(x_2 - \dot{x}_d) \\ +\Gamma s + (\bar{\delta} + \varrho)\mathrm{sign}(s) \end{pmatrix} \quad (12)$$

where $\beta, \varrho, \bar{\delta}$ are positive constants and Γ is a positive diagonal matrix.

The correspondingly selected control parameters for each controller are reported in Table 1.

Table 1. *Selected parameters of the control methods*

1	Parameter	Value
SMC(12)	$\beta; \varrho; \bar{\delta}; \Gamma$	10; 0.1; 16; diag(10,10,10)
Proposed Scheme(9)	$\beta; \varrho; \Gamma$ $\pi_1; \pi_2; \alpha$	10; 0.1; diag(10,10,10) 10; 60; $2\sqrt{30}$

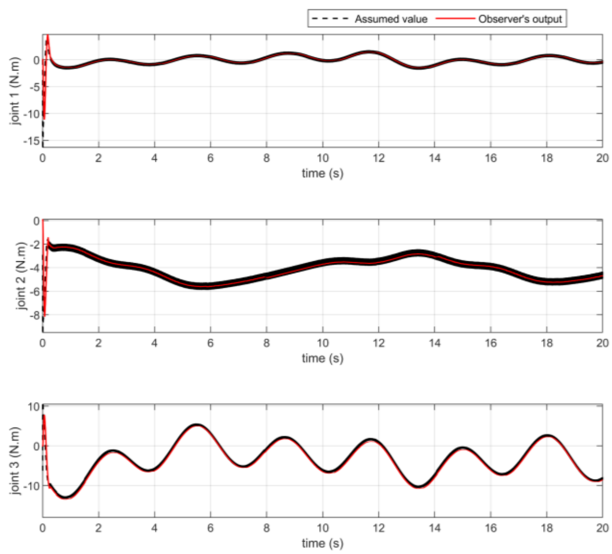

Figure 2. *The USOSMO's outputs*

In Figure 2, USOSMO obtains exact estimations of uncertain terms to offer for the control loop. Accordingly, the proposed controller uses only the sliding gain ϱ to compensate for the approximation error from the observer output that contributed to reducing chattering phenomena in control signals.

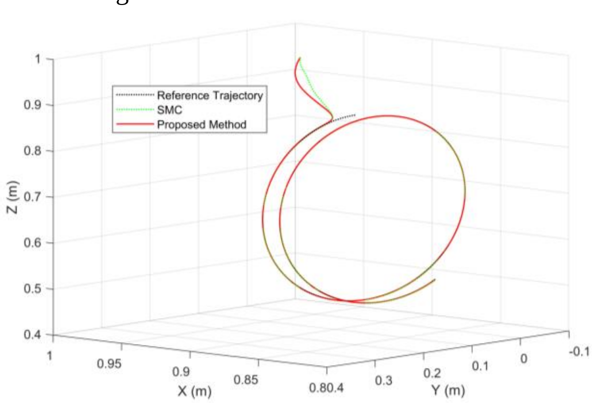

Figure 3. *Trajectory tracking performance*

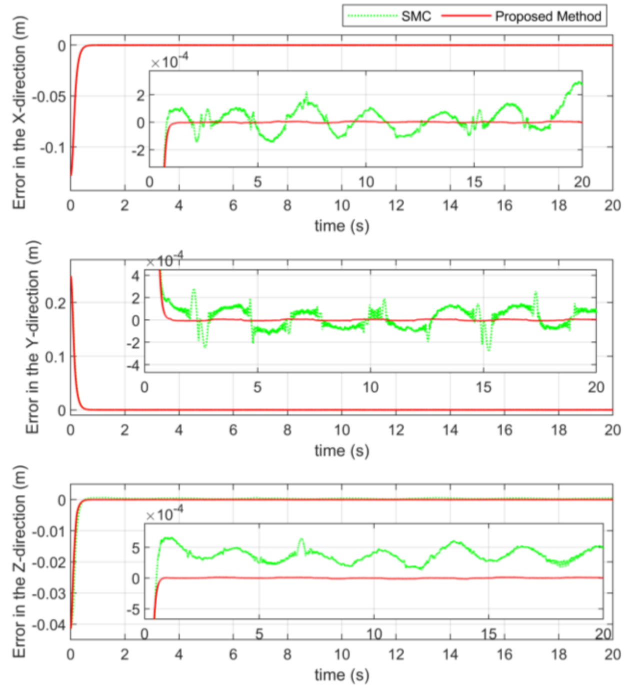

Figure 4. *Trajectory tracking errors corresponding to the X, Y, and Z axis*

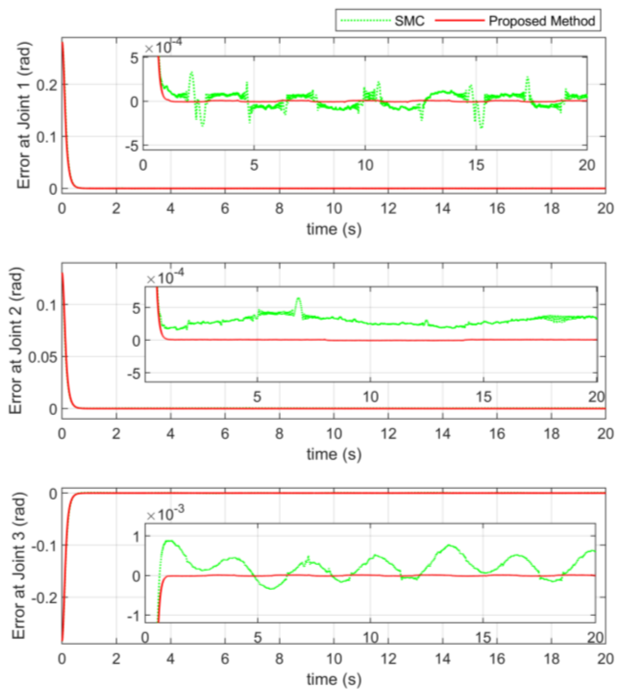

Figure 5. *Trajectory tracking errors corresponding to each joint*

The simulation control performance is shown in Figures 3 – 5. Through a comparison of the tracking performance in Figures 3 - 5, the proposed controller achieved better tracking accuracy with small steady-state control errors and they are much smaller than the SMC's control errors because the proposed controller with the USOSMO has robust properties against uncertain terms. In addition, the proposed controller's torques are smoother than the SMC's torques, as illustrated in Figure 6. We can see that the chattering behavior in the control input of the proposed controller is mostly eliminated without losing its robustness.

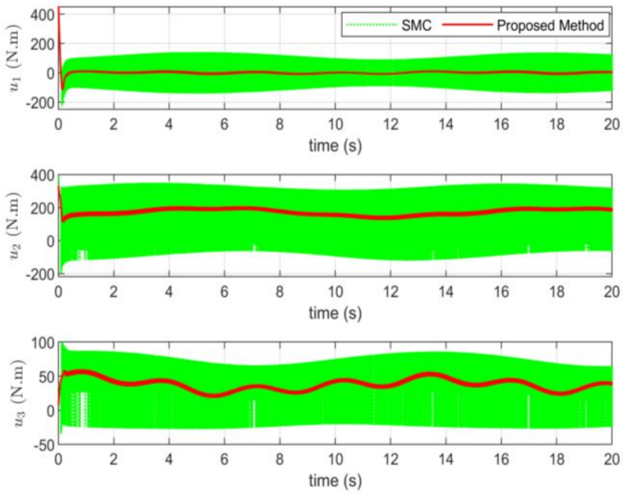

Figure 6. *Control torques: the SMC versus the proposed method*

6. Conclusion

The letter developed a SMC scheme based on the estimated uncertainties using an USOSMO. The chattering has been effectively reduced and control performances has been enhanced expressively compared to conventional SMC because uncertainty estimations have been achieved with great accuracy and fast convergence. The effects of input disturbances and parametric uncertainties can be minimized by a design with a wide operating range. It was confirmed that the proposed controller performed well and was efficient. It is possible to implement the proposed strategy in any robot manipulator.

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