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Higher Order Sliding Mode Control of Uncertain Robot Manipulators

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Abstract— **This paper proposes a higher order sliding mode controller for uncertain robot manipulators. The motivation for using high order sliding mode mainly relies on its appreciable features, such as high precision and elimination of chattering in addition that assure the same performance of conventional sliding mode like robustness. Instead of a regular control input, the derivative of the control input is used in the proposed control law. The discontinuity in the controller is made to act on the time derivative of the control input. The actual control signal obtained by integrating the derivative control signal is smooth and chattering free. The stability and the robustness of the proposed controller can be easily verified by using the classical Lyapunov criterion. The proposed controller is tested to a three-degree-of-freedom robot to prove its effectiveness.**

Keywords—High order sliding mode; robot control; Lyapunov method

I. INTRODUCTION

Control under uncertainty condition is one of the main topics of the modern control theory. Among the existing control techniques [1-3], sliding mode control [4-6] is a powerful method to control nonlinear systems having uncertainties and disturbances. In this method, states are forced to move along a chosen manifold in the state space, called the sliding surface [7]. After reaching the sliding manifold, the system becomes totally insensitive to parametric uncertainty and external disturbances.

In spite of the robustness property of the sliding mode control, its main disadvantage is the chattering phenomenon. It is the high frequency finite amplitude oscillations occurring due to the discontinuous control signal. This phenomenon is extremely dangerous to the actuator of electromechanical systems.

Several approaches are proposed to eliminate chattering. One such is to replace the sign function in a small area of the surface by a smooth approximation, which is the so-called boundary layer control [8]. Then the chattering is reduced but accuracy and robustness are deteriorated. Another technique uses the observer design. This approach exploits a localization of the high frequency phenomenon in the feedback loop by introducing a discontinuous feedback control loop which is closed through an asymptotic observer of the plant [9]. Consequently, it suppresses the high frequency oscillations of the control input [9]. Recently, new approach has been proposed called higher order sliding mode [10-16]. Instead of influencing the first sliding surface time derivative, the sign function is acting on its higher time derivative. Keeping the main advantage of standard sliding mode control, the chattering effect is eliminated and higher order precision is provided [7]. In the case of r^{th} order sliding mode control, the objective is to keep the sliding variable and its $r-1$ first time derivatives to zero through discontinuous function acting on the r^{th} time derivative of the sliding variable.

Many papers are available in the case of second order sliding mode control [17-20]. Arbitrary order sliding mode controllers have recently been proposed in [21-25]. In [23], the proposed algorithm assure tuning only one gain parameter of the higher order sliding mode control. However, the convergence rate cannot be arbitrary selected. The problem of the algorithms in [24] is parameter adjustment. Indeed, there is no explicit condition for the gain tuning. Therefore, the convergence cannot easily be made arbitrary fast or slow. The approach given in [21] proposes higher order sliding mode based on linear quadratic approach. In spite of their advantages (constructive approach, practical applicability), its major drawback is that the higher order sliding mode control is only practical. The system trajectory reaches the small neighborhood of the origin in finite time. In [22], the authors use the integral sliding mode control and guarantee the establishment of a higher order sliding mode. The advantages of this algorithm are easy to implement and guarantee the robustness of the system during the entire response. But it directly depends on the initial conditions of the system and complex off-line computations are needed before starting the control action. A higher order sliding mode control based on geometric homogeneity is developed in [25]. The control of

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this approach [25] suffers from the undesired phenomenon of chattering.

This paper proposes a higher order sliding mode control applied to robotic manipulator in uncertainty condition. The main attributes of the proposed controller are robustness and finite time stabilization which are the basic properties of a higher order sliding mode controller. Moreover, the chattering phenomenon, in the control input, is eliminated. Indeed, the discontinuity is used in the derivative of the control, instead in the control.

The outline of this paper is as follows. Section 2 presents the robot model. In section 3, the second order sliding mode controller is designed for uncertain robot manipulator. The controller eliminates the chattering in the control input. Section 4 presents simulation results to demonstrate the efficiency and advantages of the proposed controller. Section 5 concludes the paper.

II. ROBOT MODEL

According to the Lagrange theory [26], the dynamic equation of n-joint robot manipulator can be described by

$$M(q)\ddot{q} + C(q,\dot{q}) + G(q) = \tau + d(t) \tag{1}$$

Where $q \in R^n$ is the vector of joint angles, $M(q) \in R^{n\times n}$ is the inertia matrix, $C(q,\dot{q}) \in R^n$ is the Coriolis and Centrifugal terms, $G(q) \in R^n$ is the gravitational torque, $\tau \in R^n$ is the vector of the torque produced by actuators, and $d(t) \in R^n$ is the vector of bounded input disturbance, $\|d(t)\| < d_1$ where $d_1 > 0$.

Assuming that the system described by (1) has parts which are known $M_0(q)$, $C_0(q,\dot{q})$, $G_0(q)$ and unknown $\Delta M(q)$, $\Delta C(q,\dot{q})$, $\Delta G(q)$, then

$$M(q) = M_0(q) + \Delta M(q,\dot{q}) \tag{2}$$
$$C(q,\dot{q}) = C_0(q,\dot{q}) + \Delta C(q,\dot{q}) \tag{3}$$
$$G(q) = G_0(q) + \Delta G(q) \tag{4}$$

From (2)-(4), (1) can be written in the following form

$$M_0(q)\ddot{q} + C_0(q,\dot{q}) + G_0(q) = \tau + \rho(t) \tag{5}$$

Where $\rho(t) = -\Delta M(q)\ddot{q} - \Delta C(q,\dot{q}) - \Delta G(q) + d(t)$.

The control objective is to assure the tracking of the angular position to the desired position in finite time, with robustness and without chattering.

III. HIGH ORDER SLIDING MODE CONTROL OF ROBOT MANIPULATOR

Consider the robot manipulator model and define the desired trajectory as

$$Q_d(t) = [q_d(t) \quad \dot{q}_d(t)]^T$$

Where $q_d(t) \in R^n$ is the vector of desired joint angular and $\dot{q}_d(t)$ is the vector of desired angular velocities.
Define the tracking error vector as

$$e = \begin{pmatrix} q - q_d(t) \\ \dot{q} - \dot{q}_d(t) \end{pmatrix} = \begin{pmatrix} e_1 \\ e_2 \end{pmatrix} \tag{6}$$

The matrix form corresponding to the robot model (1), without uncertainty, is

$$\dot{e} = Ae + F(q,\dot{q}) + B(q)\tau = f(e,\tau) \tag{7}$$

Where

$$A = \begin{pmatrix} 0 & I_n \\ 0 & 0 \end{pmatrix},\ F(q,\dot{q}) = \begin{pmatrix} 0 \\ -\ddot{q}(t) - M(q)^{-1}\left(C(q,\dot{q}) + G(q)\right) \end{pmatrix}$$

$$B(q) = \begin{pmatrix} 0 \\ M(q)^{-1} \end{pmatrix}$$

A sliding surface is chosen for the system (7), in the following form

$$S = C\,e \tag{8}$$

Such that $C = \begin{pmatrix} C^{'} & I_n \end{pmatrix}$ and $C^{'} = diag(c_1, c_2, ..., c_n)$.

Define the new system formed by $y_1 = S$ and $\dot{y}_2 = \dot{S}$, then

$$\begin{cases} \dot{y}_1 = y_2 \\ \dot{y}_2 = \varphi(e) + \psi(e)\dot{\tau} \end{cases} \tag{9}$$

Where $\varphi(e) = C\dfrac{\partial f(e,\tau)}{\partial e}\dot{e}$ and $\psi(e) = C\dfrac{\partial f(e,\tau)}{\partial \tau}$.

In (9), the time derivative of the control input $\dot{\tau}$ would be designed to act on the higher order derivative of the sliding surface. Hence, instead of the actual control τ, the time

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derivative control, $\dot{\tau}$ would be used as the control input. The new control $\dot{\tau}$ would be designed as a discontinuous signal, but its integral (the actual control τ) would be continuous thereby eliminating the high frequency chattering.
Matrices $\varphi(e)$ and $\psi(e)$, in (9), consist of nominal parts $\overline{\varphi}(e)$ and $\overline{\psi}(e)$ which are known a priori and uncertain parts $\Delta\varphi(e)$ and $\Delta\psi(e)$ which are unknown and we suppose that are bounded. Thus we have

$$\begin{cases} \varphi(e) = \overline{\varphi}(e) + \Delta\varphi(e) \\ \psi(e) = \overline{\psi}(e) + \Delta\psi(e) \end{cases} \tag{10}$$

Using (10), the r^{th} order sliding mode system can be written as

$$\begin{cases} \dot{y}_1 = y_2 \\ \dot{y}_2 = \overline{\varphi}(e) + \overline{\psi}(e)\,\dot{\tau} + \Delta P(e,t) \end{cases} \tag{11}$$

where $\Delta P(e,t) = \Delta\varphi(e) + \Delta\psi(e)\dot{\tau}$ include all uncertain parameters and external disturbance.
To determine a high order sliding mode control, a novel surface is defined for the system (11) as

$$\sigma = y_2 + D\, y_1 \tag{12}$$

where $D = diag(D_i)$, $i = 1,\dots,n$, such that σ satisfy

$$\dot{\sigma} = -N(\sigma + W\, sign(\sigma)) \tag{13}$$

where $N = diag(N_i)$ and $W = diag(W_i)$, $N_i > 0$, $W_i > 0$, $i = 1,\dots,n$.
Differentiating (12) and using (11) and (13), the derivative of the control is expressed as

$$\dot{\tau} = -\overline{\psi}(e)^{-1}\left(\overline{\varphi}(e) + D\, y_2 + N(\sigma + W\, sign(\sigma))\right) \tag{14}$$

where

$$N_i W_i > \left|\Delta P_i(e,t)\right| \tag{15}$$

Theorem. Consider the robot model (7), if the gains N_i and W_i fulfill the condition (15) the control law (14) ensures the establishment of the 2nd order sliding mode in the sliding surface S, i.e. the trajectory of the system converges asymptotically to zero.

Proof.
A Lyapunov function V is selected as

$$V = \frac{1}{2}\sigma^T\sigma \tag{16}$$

Differentiating (16) and using (12) and (11), one obtain

$$\dot{V} = \sigma^T\sigma = \overline{\varphi}(e) + \overline{\psi}(e)\,\dot{\tau} + \Delta P(e,t) + D\, y_2$$

Substituting (14) and simplifying, then

$$\begin{aligned} \dot{V} &= \sigma^T\left(-N(\sigma + W\, sign(\sigma)) + \Delta P(e,t)\right) \\ &\le -\left\|\sigma^T N\sigma\right\| - \sum_{i=1}^{n}\sigma_i N_i W_i\, sign(\sigma_i) + \sum_{i=1}^{n}\sigma_i \Delta P_i(e,t) \\ &\le -\left\|\sigma^T N\sigma\right\| - \sum_{i=1}^{n}\left|\sigma_i\right|(N_i W_i - \left|\Delta P_i(e,t)\right| \end{aligned}$$

Then, using (15) yields $\dot{V} < 0$.
Therefore, asymptotic convergence to a domain $S = 0$ is guaranteed from any initial condition.
As is evident from (14), $\dot{\tau}$ is discontinuous but integration of $\dot{\tau}$ yield a continuous control law $\dot{\tau}$. Hence, the undesirable high frequency chattering of the control signal is alleviated.

IV. SIMULATION RESULTS

The proposed higher order sliding mode control is applied to a three degree freedom robot manipulator. The model of this robot is simulated by using MATLAB Simulink platform with fixed step size of 0.001.
The robot model is defined by the following equation [27]

$$\begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & M_{22} & M_{23} \\ M_{13} & M_{23} & M_{33} \end{pmatrix}\begin{pmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{pmatrix} + \begin{pmatrix} C_1 \\ C_2 \\ C_3 \end{pmatrix} + \begin{pmatrix} G_1 \\ G_2 \\ G_3 \end{pmatrix} = \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{pmatrix} + \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix}$$

where :

$$\begin{aligned} M_{11} &= 2b_1\cos q_2 + 2b_2\cos(q_2+q_3) + 2b_3\cos q_3 + a_1 \\ M_{12} &= b_1\cos q_2 + b_2\cos(q_2+q_3) + 2b_3\cos q_3 + a_2 \\ M_{22} &= a_2 + 2b_3\cos q_3 \\ M_{13} &= b_2\cos(q_2+q_3) + b_3\cos q_3 + a_3 \\ M_{23} &= a_3 + b_3\cos q_3 \\ M_{33} &= a_3 \end{aligned}$$

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$$a_1 = J_1 + m_1 L_{c1}^2 + J_2 + m_2 (L_1^2 + L_{c2}^2) + J_3 + m_3 (L_1^2 + L_2^2 + L_{c3}^2)$$
$$a_2 = J_2 + m_2 L_{c2}^2 + J_3 + m_3 (L_2^2 + L_{c3}^2)$$
$$a_3 = J_3 + m_3 L_{c3}^2$$

$$C_1 = -b_1 \dot{q}_2 (2\dot{q}_1 + \dot{q}_2) \sin q_2 - b_2 (2\dot{q}_1 + \dot{q}_2 + \dot{q}_3)(\dot{q}_2 + \dot{q}_3) \sin(q_2 + q_3)$$
$$- b_3 \dot{q}_3 (2\dot{q}_1 + 2\dot{q}_2 + \dot{q}_3) \sin q_3$$
$$C_2 = b_1 \dot{q}_1^2 \sin q_2 + b_2 \dot{q}_1^2 \sin(q_2 + q_3) - b_3 (2\dot{q}_1 + 2\dot{q}_2 + \dot{q}_3) \dot{q}_3 \sin q_3$$
$$C_3 = b_2 \dot{q}_1^2 \sin(q_2 + q_3) + b_3 (\dot{q}_1 + \dot{q}_2)^2 \sin q_3$$

$$b_1 = m_2 L_1 L_{c2} + m_3 L_1 L_2$$
$$b_2 = m_3 L_1 L_{c3}$$
$$b_3 = m_3 L_2 L_{c3}$$

$$G_1 = k_1 \cos q_1 + k_2 \cos(q_1 + q_2) + k_3 \cos(q_1 + q_2 + q_3)$$
$$G_2 = k_2 \cos(q_1 + q_2) + k_3 \cos(q_1 + q_2 + q_3)$$
$$G_3 = k_3 \cos(q_1 + q_2 + q_3)$$

$$k_1 = (m_1 L_{c1} + m_2 L_1 + m_3 L_1) g$$
$$k_2 = (m_2 L_{c2} + m_3 L_2) g$$
$$k_3 = m_3 L_{c3} g$$

The nominal values of m_1, m_2 and m_3 are assumed to be [27]

$$m_{10} = 0.5\ Kg,\ m_{20} = 1\ Kg,\ m_{30} = 0.2\ Kg$$

and the other system parameters are assumed to be known [27]

$$J_1 = 0.12\ Kg\, m^2 \quad L_1 = 0.5 m$$
$$J_2 = 0.25\ Kg\, m^2 \quad L_2 = 0.5 m$$
$$J_3 = 0.3\ Kg\, m^2 \quad L_{c1} = 0.25 m$$
$$L_{c2} = 0.35\ m \quad L_{c3} = 0.15 m$$
$$g = 9.81 m / s^2$$

We suppose that we have an uncertainty on masses of the order $\pm 10\%$ (fig. 1-3), and the disturbance vector is $d(t) = [d_1(t) \quad d_2(t) \quad d_3(t)]^T$ where

$$d_1(t) = 0.2 \sin(3t) + 0.02 \sin(26\pi t)$$
$$d_2(t) = 0.1 \sin(3t) + 0.01 \sin(26\pi t)$$
$$d_3(t) = 0.1 \sin(3t) + 0.01 \sin(26\pi t)$$

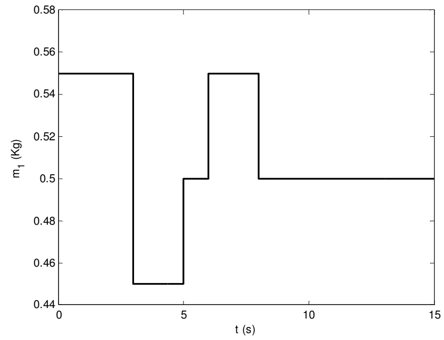

Fig. 1. Variation of the mass m_1 .

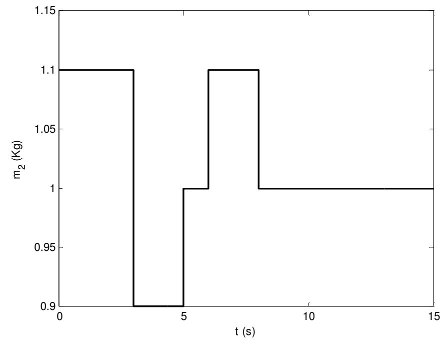

Fig. 2. Variation of the mass m_2 .

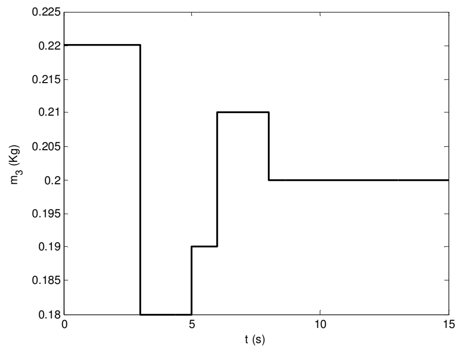

Fig. 3. Variation of the mass m_3 .

The control objective is to design a robust control law such that the angular positions q_1, q_2 and q_3 evolved from the following initial conditions

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$$[q_1(0) \quad q_2(0) \quad q_3(0)]^T = [-0.2 \quad -0.2 \quad -0.4]^T$$
$$[\dot{q}_1(0) \quad \dot{q}_2(0) \quad \dot{q}_3(0)]^T = [0 \quad 0 \quad 0]^T$$

track the desired angular positions q_{d1}, q_{d2} and q_{d3} defined as

$$q_{d1} = 1.25 - \frac{7}{5}\exp(-t) + \frac{7}{20}\exp(-4t)$$
$$q_{d2} = 1.25 - \frac{7}{5}\exp(-t) + \frac{7}{20}\exp(-4t)$$
$$q_{d3} = 1 - \frac{7}{5}\exp(-t) + \frac{7}{20}\exp(-4t)$$

After many simulations, the high order sliding mode is obtained for the following parameter of the two sliding surfaces and the control: $c_1 = c_2 = c_3 = 2$, $D_1 = 10$, $D_2 = 8$, $D_3 = 15$, $N_1 = 100$, $N_2 = 10$, $N_3 = 700$, $W_1 = 10$, $W_2 = 60$ $W_3 = 1$.

Figs. 4-6 show the tracking error, the control input, the sliding surface S and the state trajectory of each joint obtained by using the proposed high order sliding mode controller. It is obvious that the proposed controller ensures finite time convergence of tracking error of three joint and robustness. From control signal it is clear that the control input has a negligible chattering especially in beginning, then it is smooth having no chattering. A second order sliding mode is achieved on the sliding surface S and its components reach zero in finite time. It is also chatterless. The state trajectory of the system evolves without chattering.

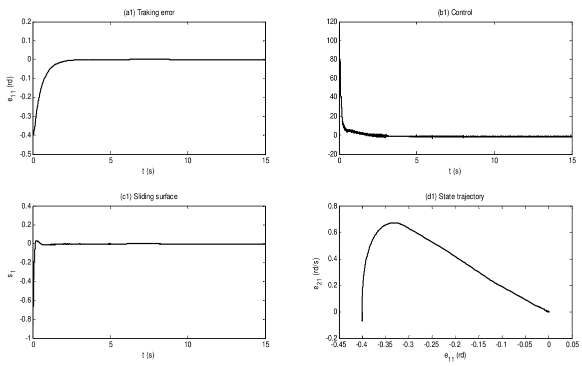

Fig. 4. Tracking of the first joint.

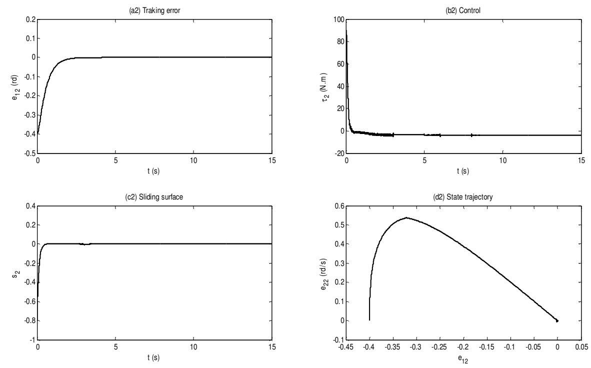

Fig. 5. Tracking of the second joint.

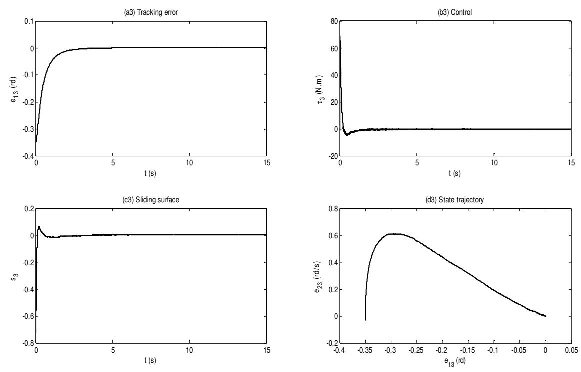

Fig. 6. Tracking of the third joint.

The results of the sliding surface σ are presented in figure 7. The three sliding surface converge to zero in finite time.

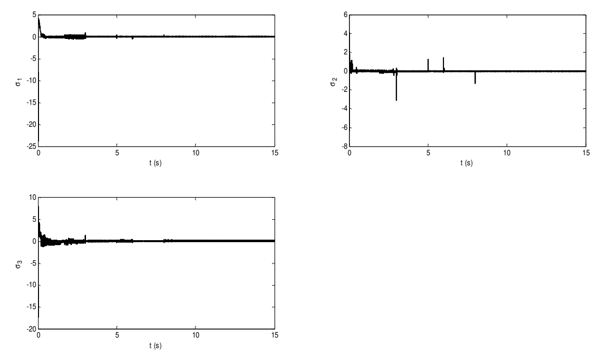

Fig. 7. Sliding surface σ.

The sliding variable σ converges to zero in finite time. A first order sliding mode control is then established on this surface.

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Because the discontinuity act on the first derivative of σ, their components present the chattering phenomenon.

V. CONCLUSION

In this paper, we have presented the design of the robust high order sliding mode control for the tracking problem of rigid robot manipulators. The main feature of this work is assuring a smooth high order sliding mode control. The time derivative of the control acts on the second derivative of the sliding surface. Therefore the obtained control law is continuous and robust. The proposed controller guarantees a finite time convergence of the tracking error. Also this controller has eliminated the chattering phenomenon without losing robustness property and precision. Hence, the proposed controller is highly suitable for practical applications. The stability of the controlled system is proved by using Lyapunov stability criterion. Simulation results demonstrate the efficacy and advantage of the proposed controller.

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