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Research Article

Robust Tracking Control for Flexible Joint Robot Manipulators Using Variable Structure Compensator

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Abstract

Many researches have been carried out to investigate the tracking control problem of robot manipulators. The flexibility of the joints should be taken into account in both modeling and control if high performance is to be achieved. The problem of robust tracking control using a nominal feedback controller and a variable structure compensator for a flexible joint robot manipulator with uncertain dynamics is addressed in this note. It is shown that the effects of large system uncertainties can be eliminated and asymptotic convergence of the output tracking error can be guaranteed by using a variable structure compensator in the closed loop feedback control system. The proposed control scheme is applied on a two-degree of freedom flexible joint robot. A simulation study was carried out. The obtained results verify the effectiveness of the suggested control scheme.

Keywords: *Tracking control, Flexible joint robot, Tracking error, Variable structure compensator, Uncertainties, Chattering.*

Introduction

The basic ideas of the linear feedback control schemes are that some standard global linearization methods are used to linearized and decouple the nonlinear robot dynamics, and then a feedback controller is designed to achieve a good closed loop performance (C. Abdallah *et al*, 1991; R. Shouresi *et al*, 1990; E. Freund, 1982; M.W. Spong *et al*, 1987; N. Becker *et al*, 1988; C. Desoer *et al*, 1975; B.D. Anderson *et al*, 1989; T.J. Tran *et al*, 1984; M.S. Fadali *et al*, 1989; C. Y. Kuo *et al*, 1989). However, most of these schemes can provide only robust controllers that stabilize robotic manipulator systems, and the output tracking error cannot converge to zero. Further, the transient error response performance of the closed loop system cannot be specified directly in the design. Therefore, the development of high quality robust tracking control schemes which can guarantee strong robustness property and prescribed transient error response with stabilizing controllers becomes an important topic in the robotic control field.

Robust tracking controller for **(FJR)** is developed using voltage control strategy (M. M. Fateh, 2012), achieving pre-set performance on link position error (K. Artemisk *et al*, 2013) both are free of manipulator dynamics and nonlinearities. A novel observer-based robust dynamic feedback without velocity measurements was developed (Y. C. Chang *et al*, 2012) resulting tracking error as small as possible, In case of the set-point regulation problem it can be simplified to a linear time invariant controller. A variable structure control method with a mathematical tool is applied (S. Nandhakumar *et al*, 2013) to control errors in a controller that is robust to the model uncertainties. The proposed scheme is applicable to industrial robot for robust position control.

A novel robust decentralized controller for [FJR] is presented (M. M. Fateh *et al*, 2013). It is free from manipulator dynamics, so it can guarantee robustness to all uncertainties. It is simple, fast response and superior to torque control approaches. The application of sliding mode control concept for DC motor position control is described in (A. A. Ahmed *et al*, 2013). The gains of the (VSS) controller and the slope of the switching line are obtained mathematically and optimized. A fuzzy gain scheduling PI controller is presented (R. Kannan *et al*, 2013), as speed controller in (VSC). The design is simple and easy to implement. Tracking control of robot manipulator is concerned at (Ancai Zhang *et al*, 2013). The controller has two parts, one is based on a feedback linearization technique, and the other is based on the idea of equivalent input disturbance (EID) to compensate for uncertainties and disturbances to precisely track the desired trajectory.

In this note, we propose a robust tracking control scheme using a variable structure compensator in closed loop system for a flexible joint robot [FJR] manipulator. Here, the [FJR] is treated as a partially known system. The known dynamics are separated out and used to perform a linearization on the nonlinear robotic manipulator system. Then, a nominal feedback controller is designed to make the nominal system asymptotically track the desired reference signal and a variable structure compensator is

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designed to eliminate the effects of the unknown portion of the plant. Unlike most of the existing feedback control schemes in (R. Shouresi *et al,* 1990; C. Y. Kuo *et al,* 1989), the closed loop system using the proposed control scheme guarantees that the output tracking error asymptotically converges to zero with prescribed transient error response and behaves with a strong robustness property with respect to large system uncertainties. This is not only because a system uncertain bound is used for the variable structure compensator design, but also due to the fact that, on the sliding mode, the closed loop system is insensitive to the system uncertainties and some external disturbances.

Problem Formulation

Consider the dynamics of an n-joint robot manipulator system described by the following second order nonlinear vector differential equation

$$M(q)\ddot{q} + h(q,\dot{q}) = u(t) \tag{1}$$

Where q(t) is the n x 1 vector of joint angular positions, M(q) is the n x n symmetric positive definite inertia matrix, h(q,$\dot{q}$) is n x 1 vector containing coriolis, centrifugal forces and gravity torques, and u(t) is the n x 1 vector of applied joint torques (control input). Let a robotic manipulator system described by (1) have some known parts and some unknown parts, therefore, we can write

$$M(q) = M_0(q) + \Delta M(q) \tag{2}$$

$$h(q,\dot{q}) = h_0(q,\dot{q}) + \Delta h(q,\dot{q}) \tag{3}$$

where
$M_0(q) and\ h_0(q,\dot{q}) are\ known\ parts, \Delta M(q) and\ \Delta h(q,\dot{q})$ are unknown parts. Using expressions (2) and (3), dynamic equation (1) can be written in the following form:

$$M_0(q)\ddot{q} + h_0(q,\dot{q}) = u(t) + \rho(t) \tag{4}$$

Where

$$\rho(t) = -\Delta M(q)\ddot{q} - \Delta h(q,\dot{q}) \tag{5}$$

The following system with no uncertainties is defined as the "nominal system"

$$M_0(q)\ddot{q} + h_0(q,\dot{q}) = u_1 \tag{6}$$

Furthermore, the following assumptions are used in this note:

A (1) : $M_0(q)$ is invertible for all q.
A (2) : The nominal system in expression (6) is stabilizable.
A (3) : The system uncertainty $\rho(t)$ is bounded by a positive function as follows

$$\|\rho(t)\| < b_0 + b_1\|q(t)\| + b_2\|\dot{q}(t)\|^2 \tag{7}$$

Where positive numbers $b_0, b_1, and b_2$ are assumed to be known.
Remark 1: For practical control problems, the bound parameters in A(3) have to be estimated for each robotic manipulator. The detailed estimation technique has been developed in (Man Zhihong, 1993) based on (W. M. Grimm, 1990) for some neglected system dynamics.

The objective of this note is to develop a robust tracking control scheme for robotic manipulator system (1) with large system uncertainties, and guarantee that the output tracking error asymptotically converges to zero as time tends to infinity.

Tracking Control Scheme

Two steps are considered in the development of the robust tracking control scheme. First a nominal feedback controller is designed to make the nominal system asymptotically track the desired reference trajectory. Then, a variable structure compensator is designed to deal with the effects of the system uncertainties so that the output tracking error of the closed loop system with large system uncertainties asymptotically converges to zero.

Let q_r represent the desired trajectory that the robotic manipulator system must follow and the output tracking error be defined as

$$\in(t) = q - q_r \tag{8}$$

Using nominal system equation (6), we get the following linearized error system:

$$\dot{e} = Ae + Bv \tag{9}$$

Where

$$e = [\in^T, \dot{\in}^T]^T \tag{10}$$

$$A = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} \tag{11}$$

$$B = \begin{bmatrix} 0 \\ I \end{bmatrix} \tag{12}$$

$$v = M_0(q)^{-1}\left(u_1 - h_0(q,\dot{q})\right) - \ddot{q}_r \tag{13}$$

Lemma(1): The error e(t) in the error dynamics equation (9) for nominal system (6) asymptotically converges to zero if the following nominal feedback control law is used

$$u_1 = h_0(q,\dot{q}) + M_0(q)(Ke + \ddot{q}_r) \tag{14}$$

$where\ K = [-K_1, -K_2], K_1 \in R^{n\,x\,n}, K_2 \in R^{n\,x\,n}$, and matrix K is designed such that

$$A_1 = A + BK \tag{15}$$

is an asymptotically stable matrix
Proof: See (G. Leitman, 1981; H. Bermer, 1985; S. N. Singh, 1986).

Remark 2: The selection of the feedback gain matrix K in *Lemma(1)* is possible in view of Assumption A(2). Therefore, most linear control schemes such as pole placement and optimal control, can be applied to the design of the feedback gain matrix K (C. Abdallah *et al*, 1991; W.M.Brimm, 1990).

Next, we consider the variable structure compensator design. Let the control input in dynamic equation (1) has the following form:

$$u(t) = u_1 + u_0 \tag{16}$$

Where u_1 is designed for the nominal system (6) given in equation (14). u_0 is the compensator which is used to deal with the effects of the system uncertainties. Using equations (4), (10), and (14), we get the error dynamic equation for robotic manipulator system (1) in the following form:

$$\dot{e} = A_1 e + BM_0(q)^{-1}u_0 + BM_0(q)^{-1}\rho(t) \tag{17}$$

In order to use the variable structure technique to design the compensator control input u_0, we define a set of switching hyperplane variables in the error space passing through the origin.

$$S = Ce \tag{18}$$

Where $C = [C_1, C_2], matrices\ C_1 \in R^{n\,x\,n}\ and\ C_2 \in R^{n\,x\,n} are\ nonsingular\ and$

$$Re\lambda(-C_2^{-1}C_1) < 0 \tag{19}$$

The output tracking error $\in (t)$ for robotic manipulator system (1) with system uncertainties asymptotically converges to zero if the control input is designed such that

$$u(t) = u_1 + u_0 \tag{20}$$

Where u_1 is the nominal feedback controller given in expression (14) and u_0 is the variable structure compensator given as follows:

$$u_0 = \begin{cases} \frac{(S^T C_2 M_0(q)^{-1})^T}{\|S^T C_2 M_0(q)^{-1}\|^2} w & \|S\| \neq 0 \\ 0 & \|S\| = 0 \end{cases} \tag{21}$$

$$w = -S^T C A_1 e - \|S\| \|C_2 M_0(q)^{-1}\| (b_0 + b_1\|q\| + b_2\|\dot{q}\|^2) \tag{22}$$

Defining a Lyapunov function:

$$V = \frac{1}{2} S^T S \tag{23}$$

And differentiating V with respect to time, we have

$$\dot{V} = S^T\dot{S} = S^T[CA_1 e + CBM_0(q)^{-1}u_0 + CBM_0(q)^{-1}\rho(t)] = S^T C A_1 e + S^T C_2 M_0(q)^{-1}u_0 + S^T C_2 M_0(q)^{-1}\rho(t) = S^T C A_1 e + w + S^T C_2 M_0(q)^{-1}\rho(t)$$
$$= -\|S\|\|C_2 M_0(q)^{-1}\|(b_0 + b_1\|q\| + b_2\|\dot{q}\|^2) + S^T C_2 M_0(q)^{-1}\rho(t) < 0 \qquad \|S\| \neq 0 \tag{24}$$

Equation (24) is the reaching condition for the switching plane variable S to reach the sliding mode

$$S = Ce = 0 \tag{25}$$

On the sliding mode, error dynamics of the closed loop system has the following form

$$\dot{\in} = -C_2^{-1} C_1 \in \tag{26}$$

Therefore, the tracking error $\in$ converges to zero asymptotically.

Remark 3: Unlike most of feedback control schemes in (C. Abdallah *et al*, 1991; C. Y. Kuo *et al*, 1989), the applying of the variable structure compensator u_0 in the closed loop feedback control system can not only eliminate the effects of large system uncertainties, but also guarantees that the output tracking error asymptotically converges to zero. On the sliding mode, the convergence rate of the output tracking error can be arbitrarily fast by the suitable choice of matrix C in the sliding mode (25) or (26).

Remark 4: Due to the fact that the variable structure compensator is inserted in the closed loop feedback control system, chattering occur in the control input, which may excite unmodeled high-frequency dynamics (J. J. Slotine *et al*,1983). To eliminate chattering and reduce the amplitude of the control input, the following boundary layer compensator can be used in place of the variable structure compensator in equation (21).

$$u_0 = \begin{cases} \frac{(S^T C_2 M_0(q)^{-1})^T}{\|S^T C_2 M_0(q)^{-1}\|^2} w & \|S^T C_2 M_0(q)^{-1}\| \geq \delta \\ \frac{(S^T C_2 M_0(q)^{-1})^T}{\delta^2} w & \|S^T C_2 M_0(q)^{-1}\| < \delta \end{cases} \quad where\ \delta\ is\ a\ positive\ number \tag{27}$$

The above boundary layer controller offers a continuous approximation to the discontinuous variable structure control law in equation (21) inside the boundary layer and guarantees attractiveness to the boundary layer and ultimate boundedness of the output tracking error to within any neighborhood of the origin (G. Leitman, 1981; H. Bermer, 1985; S. N. Singh, 1986; M. J. Corless *et al*, 1981).

Dynamic Model For (FJR)

This section describes the dynamic model of the robot. This model is used for the design and control development. The dynamic model for flexible joint robot developed by (M. Spong, 1987) is adopted. It is derived for the experimental robot using Euler-Lagrange equation (M. Sponge *et al*, 1989), and it is given by the following equations:

$$M(q)\ddot{q} + C(q, \dot{q}) + B\dot{q} - K(q_m - q) + G(q) = -J^T F \tag{28a}$$

$$I_m \ddot{q}_m + B_m \dot{q}_m + K(q_m - q) = \tau \tag{28b}$$

Where q is the 2 x 1 link angular position vector, q_m is the 2 x 1 motor angular position vector, M (q) is the 2x2 manipulator inertia matrix, C (q,$\dot{q}$) is the 2x1 coriolos and centrifugal forces vector, K is 2x2 diagonal matrix with entries equal to the joint stiffness, G(q) is the 2x1 gravity force vector, J^T is the 2x2 transpose of the manipulator Jacobian, F is 2x1 forces vector at the end effector expressed in the reference frame, I_m is the 2x2 diagonal matrix with entries equal to the rotors inertia, B_m is the 2x2 diagonal matrix with entries equal to the coefficient of viscous damping at the motors, and τ is 2x1 applied motor torque vector.

The process of controlling the dynamic model given by equations (28) is difficult because the system is multi-input multi-output (MIMO) nonlinear. However, considering each link and its driving motor only reduces the system to two single input multi-output linear subsystems, which simplifies the identification and control process. (A. Massoud *et al*, 1993) Has implemented this identification technique on a two-link flexible joint experimental robot. The first subsystem is the first joint (the first motor and the first link) and the second subsystem is the second joint (the second motor and the second link). The following procedures are performed to control these two subsystems.

a) First, constrain the first subsystem by clamping the first link to the fixed table, and thus the second subsystem characteristic can be isolated, identified, and control.
b) To identify and control the first subsystem, the brake of the second motor is applied. Hence, the second subsystem is considered as extra mass add to the end of the first link.

Simulation Study

In order to illustrate the performance of the proposed robust controller, simulation study has been carried out. The simulation model is a two-degree of freedom flexible joint robot (FJR) manipulator with rotary joints. According to (28), its inertia matrix, coriolos and centrifugal vector and gravity vector can be described as follows (M. Spong, 1987).

$$M(q) = \begin{bmatrix} d_1 + 2d_2\cos(q_2) & d_3 + d_2\cos(q_2) \\ d_3 + d_2\cos(q_2) & d_3 \end{bmatrix}$$

$$C(q,\dot{q}) = \begin{bmatrix} -\dot{q}_2(2\dot{q}_1 + \dot{q}_2)\sin(q_2) \\ \dot{q}_2^2\, d_2 \sin(q_2) \end{bmatrix} \quad G(q_1,q_2) = \begin{bmatrix} (m_1+m_2)r_1\cos q_2 + m_2 r_2\cos(q_1+q_2) \\ m_2 r_2 \cos(q_1+q_2) \end{bmatrix}$$

Where

$$d_1 = I_1 + I_2 + a_1^2\, m_1 + l_1^2 m_{r2} + m_2(\,l_1^2 + a_2^2)$$
$$d_2 = 2\, m_2 l_1 a_2$$
$$d_3 = \,l_2 + \,a_2^2 m_2$$

Where I_1, I_2, m_1, m_2, a_1, a_2, l_1, l_2, and m_{r2} are the moment of inertia about an axis parallel to the axis of rotation passing through the center of mass, the mass, the distance from the center of rotation to the center of mass, length of the first and second link, respectively, and the mass of the second rotor. The nominal values of the system parameters used in simulation {the two-degree of freedom flexible joint robot [FJR]} are given in Table 1, (A. Massoud *et al*, 1993).

Desired reference signals are given by

$$q_{r1} = 1.25 - 1.4e^{-t} + 0.35e^{-4t}$$
$$q_{r2} = 1.25 + e^{-t} - 0.25e^{-4t} \tag{29}$$

In order to constrain the error dynamics on the sliding mode from the start to the end, we consider a situation characterized by the same initial values on the system and its reference signal (K. K. Young, 1988). In this example, the initial angular positions and velocities are selected as

$$[q_1(0), q_2(0)]^T = [q_{r1}(0), q_{r2}(0)]^T = [0.2, 2]^T$$
$$[\dot{q}_1(0), \dot{q}_2(0)]^T = [\dot{q}_{r1}(0), \dot{q}_{r2}(0)]^T = [0, 0]^T \tag{30}$$

The nominal system is assumed to be built from the known system dynamics. In this example, we let the desired error dynamics of the closed loop nominal system have the following form:

$$\ddot{\epsilon}_i + 5\,\dot{\epsilon}_i + 4\,\epsilon_i = 0 \qquad i = 1, 2. \tag{31}$$

Then, using pole placement method in (W. M. Brimm, 1990) for equation (15) in lemma (1), the feedback matrix K can be designed as:

$$K = \begin{bmatrix} -4 & 0 & -5 & 0 \\ 0 & -4 & 0 & -5 \end{bmatrix} \tag{32}$$

Sliding mode is prescribed as

$$S = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} e = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{33}$$

An off-line estimation method for uncertain bound parameters in equation (7), has been developed in (Man Zhihong, 1993) based on (W. M. Grimm, 1990). Using this method, the uncertain bound parameters in equation (7) are derived as follows:

$$b_0 = 30, \quad b_1 = 3.7, \quad b_2 = 1.1. \tag{34}$$

Adaptive Runge-Kutta 5th order with sampling interval $\Delta T = 0.01sec$ is used to solve the nonlinear differential equation numerically.

Results and Discussion

The obtained results of the simulation show the output tracking and the control inputs for the two-joint of the flexible manipulator, applying both of the control laws (nominal feedback controller and a variable structure compensator) or (nominal feedback controller and a boundary layer compensator). The joints of the manipulators are subjected to load disturbance shown in Figure 1.

Variable structure compensator

Figs. 2(a), (b) and Figs. 3(a), (b) show the system performance (the position tracking and the control input) for joint 1 and joint 2 respectively, using a nominal feedback controller and a variable structure compensator.

Table 1 Robot parameter from design and Sin Sweep Identification

	J_{l1} (Kg.m^2)	J_{l2} (Kg.m^2)	d_1 (Kg.m^2)	d_2 (Kg.m^2)	b_1 (N.m.s/rad)	b_2 (N.m.s/rad)
Sin Sweep			2.087	0.216	2.041	0.242
I - DEAS	0.2269	0.0429	2.110	0.223		

	b_{m1} (N.m.s/rad)	b_{m2} (N.m.s/rad)	k_1 (N.m/rad)	k_2 (N.m/rad)	J_{m1} (Kg.m^2)	J_{m2} (Kg.m^2)
Sin Sweep	1.254	0.119	125.56	31.27	0.1224	0.0168
I - DEAS			198.49	51.11	0.1226	0.017

Obviously, the effects of the system uncertainties are eliminated and good tracking performance is obtained (the joint angular positions closely track the desired reference signals). But the problem is that chattering occur in the control inputs and the amplitudes of the control signals are very large.

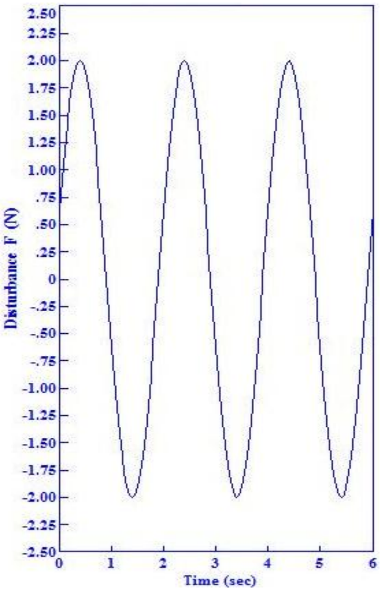

Fig1 Variation of load disturbance Sinsoud signal

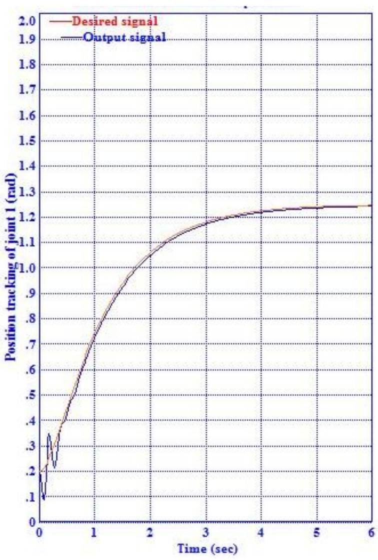

Fig.2 a Position tracking of joint 1 using feedback controller and variable structure compensator

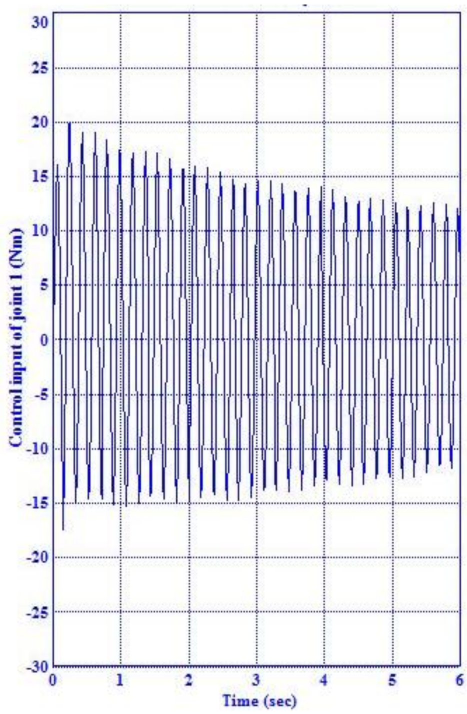

Fig. 2b Control input of joint 1 using feedback controller and variable structure compensator

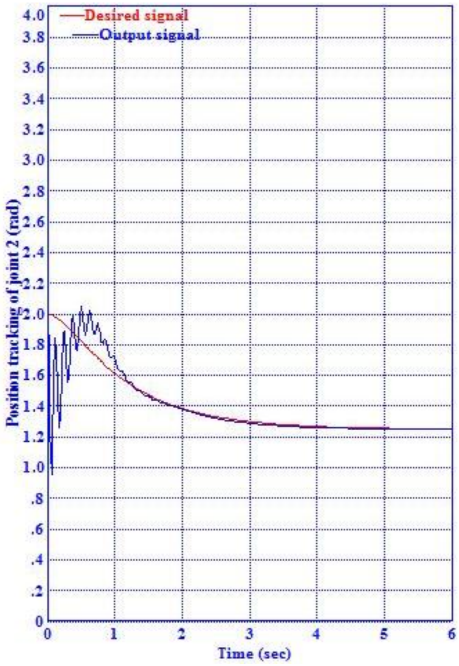

Fig.3 a Position tracking of joint 2 using feedback controller and variable structure compensator

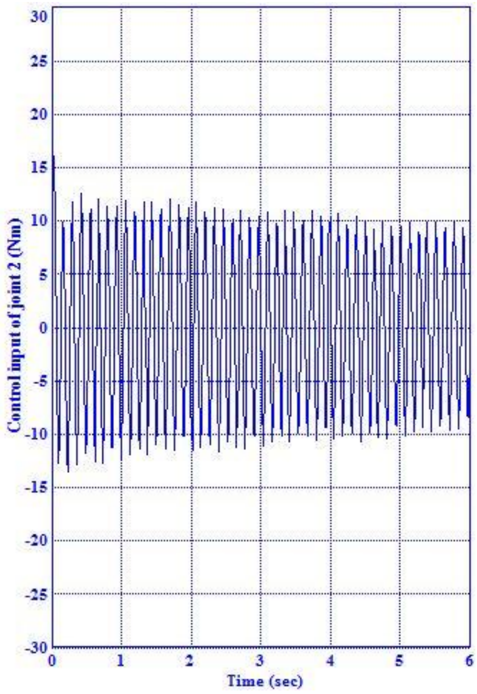

Fig. 3b Control input of joint 2 using feedback controller and variable structure compensator

Boundary layer compensator

Figs. 4(a), (b) and Figs. 5(a), (b) show the system performance (the position tracking and the control input) for joint 1 and joint 2 respectively, using a nominal feedback controller and a boundary layer compensator. Also, a good tracking performance is obtained as in the previous controller case. In addition to that, it can be seen that not only the chattering is eliminated, but also the amplitudes of the control input signals are greatly reduced.

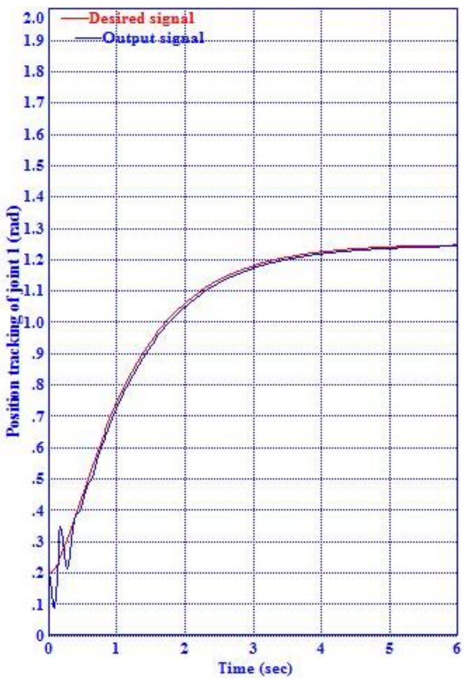

Fig.4 a Position control of joint 1 using feedback controller and boundary layer compensator

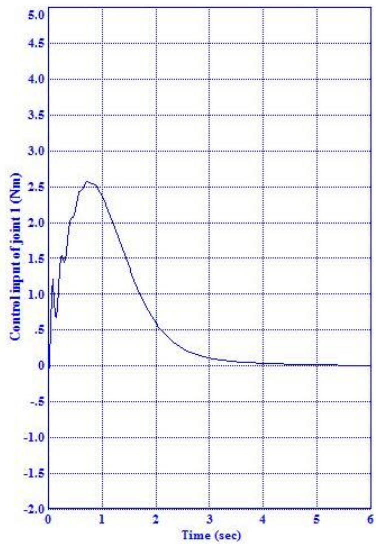

Fig.4 b Control input of joint 1 using feedback controller and boundary layer compensator

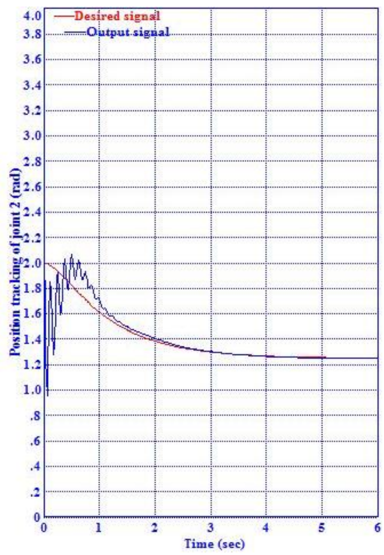

Fig.5 a Position control of joint 2 using feedback controller and boundary layer compensator

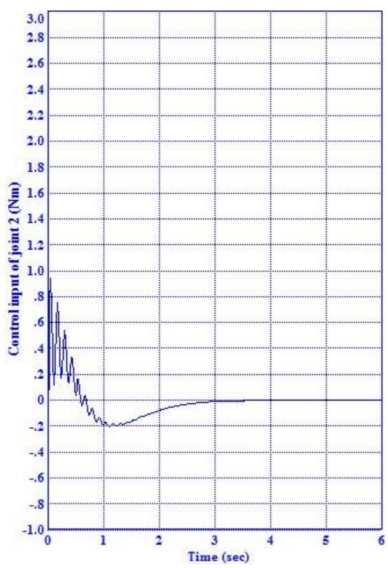

Fig.5 b Control input of joint 2 using feedback controller and boundary layer compensator

Conclusion

The problem of robust tracking control of a two-link direct drive robot with flexible joints and large system uncertainties has been investigated in this note. Several advantages of the proposed tracking control scheme have been summarized. These include strong robustness property with respect to large system uncertainties, arbitrary fast convergence of the output tracking error on the sliding mode (this means that it achieve a zero steady-state error), and the controller structure facilitating ease in robotic manipulator system programming and implementation. The results of the simulation study assure that the proposed control scheme achieve a higher control performance.

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