Journal of Engineering and Applied Sciences 2 (6): 1066-1073, 2007

Disturbance Observer Based Tracking Control for Robot Manipulators with Model Uncertainty

[1,2]Farah Bouakrif, [1]Djamel Boukhetala and [1]Fares Boudjema
[1]Department of Electrical Engineering, National Polytechnic School, Algiers
[2]Department of Automatic Engineering, University of Jijel, B.P. 98, Jijel 18000, Algeria

Abstract: This study presents a disturbance observer based tracking control for robotic manipulators. The tracking control problem is formulated as a disturbance rejection problem, with the mechanical nonlinearities, unmodeled dynamics and external disturbances lumped into the disturbance term. The global stability of the composite controller and observer is guaranteed, this result is based on Lyapunov theory. In simulation, the tracking control of a two link manipulator is used as an example to verify the proposed algorithm, when the Coulomb and Viscous friction is considered as an external disturbance.

Key words: Tracking control, disturbance observer, nonlinearities, robot manipulator

INTRODUCTION

During the last decade the class of rigid robot systems has been the subject of intensive research in the field of systems and control theory, particulary owing to the inherent nonlinear nature of rigid robots. A large variety of control methods for this class of systems have been proposed. These control methods may be classified according to the objective that is defined for the end-effector of the robot. One frequently encountered objective in robot control is point-to-point control, also known as regulation, although this objective is rather restrictive. For this reason, the trajectory tracking or motion control objective for robots has become increasingly popular, since it significantly extends the application area of robots. A great variety of controllers, referred to as model-based robot motion controllers, have been developed. These controllers can roughly be classified into two categories. The first category consists of inverse dynamics or computed torque controllers (Lhu *et al*., 1980; Lewis *et al*., 1993) which achieve the trajectory tracking objective by feedback linearization of the nonlinear robot dynamics. The second category consists of passivity based controllers (Desoer and Vidyasagar, 1975; Paden and Panja, 1988) which reshape the robot system's mechanical energy in order to achieve the tracking objective.

For the implementation of these control methods, exact knowledge of the system dynamics of a robot is required. In practice, there is always some parametric uncertainty in the dynamic of a robot. As a natural consequence, the robot control problem in the presence of model uncertainties has been analyzed extensively. There are basically two underlying philosophies to the control of uncertain systems: The adaptive control philosophy and the robust control philosophy. In the adaptive approach, one designs a controller which attemps to learn the uncertain parameters of the particulary system and, if properly designed will eventually be a best controller for the system in question, a discussion of adaptive controllers in robotics may be found in (Ortega and Spong, 1989). In the robust approach, the controller has a fixed-structure which yields acceptable performance for a given plant-uncertainty set, a comprehensive survey of robust control theory is available in (Dorato, 1987).

Many adaptive robot control scheme assume that the structure of the manipulator dynamics is known and/or the unknown parameters influence the system dynamics in an affine manner (Kwon and Book, 1994). It has also be demonstrated (Colbalugh *et al*., 1995) that these adaptive controllers may lack robustness against unmodeled dynamics, sensor noise and other disturbances.

The control problem for a nonlinear system under disturbances has been developed and applied in engineering over two decades. Nakao *et al*. (1987) proposed firstly the concept of disturbance obser ver 'DO' as compensating unknown disturbance. Chan (1995) uses a DO in electronic component assembly, while Ohishi and Ohde (1994) give an example of the use of a DO in collision. Moreover, DO's have been used in robotic manipulators for force feedback and hybrid position/force control where the DO works as a torque

Corresponding Author: Farah Bouakrif, Department of Electrical Engineering, National Polytechnic School, Algeria

sensor (Murakami *et al*., 1993; Komada *et al*., 1993). Furthermore, friction is a cammon phenomenon in mechanical systems. One of the most promising methods is observer-based control, where a variable structure DO has been proposed (Linand and Kuroe, 1995) and a nonlinear observer for a special kind of friction, i.e., Coulomb friction, has been proposed by Friedl and Park (1992). It has been further modified and implemented on robotic manipulators by Tafazoli *et al.* (1998). However, a specific model of friction has not been used in the DO proposed by Chen *et al.* (2000) but the combination between the observer and the controller has not been made. In (Chen, 2004) a DO based control approach for nonlinear systems under disturbances has been proposed, but only semiglobal stability condition of the composite controller-observer has been established.

In this study, we present a new disturbance observer based tracking control design, where all the system uncertainties and external disturbances are lumped into the disturbance term. Since the model uncertainty and parameter variations are considered as part of the disturbance, exact model knowledge is not required. The global stability condition of the composite nonlinear controller and the nonlinear disturbance observer is established, this result is based on Lyapunov theory. Simulation results on two-link manipulator show the asymptotic convergence of tracking error, when the Coulomb and Viscous friction is considered as an external disturbance.

DYNAMIC EQUATIONS OF ROBOT MANIPULATORS

For the sake of simplicity, a two-link robotic manipulator is considered in this paper. The main idea is readily extended to the more general case. The nominal dynamic equations of a two-link robotic manipulator can be described by:

$$\tau = M_n(q)\ddot{q} + C_n(q,\dot{q})\dot{q} + G_n(q) \quad (1)$$

Where $q(t)$, $\dot{q}(t)$, $\ddot{q}(t)$ $\in R^n$ denote the link position, velocity and acceleration vectors, respectively, the subscript $(\cdot)_n$ denotes nominal functions, $M_n(q(t)) \in R^{n\times n}$ represents the link inertia matrix, $C_n(q(t),\dot{q}(t)) \in R^{n\times n}$ represents centripetal-Coriolis matrix, $G_n(q(t)) \in R^{n\times 1}$ represents the gravity effects and $\tau(t) \in R^{n\times 1}$ represents the torque input vector.

The dynamic equation of the true plant is assumed to be

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + w(q,\dot{q},t) \quad (2)$$

Where $M(q) = M_n(q) + \Delta M(q)$, $C(q,\dot{q}) = C_n(q,\dot{q}) + \Delta C(q,\dot{q})$, $G(q) = G_n(q) + \Delta G(q)$ are the real system matrices. represents the disturbance vector. $w(q,\dot{q},t) \in R^n$ Therefore, the dynamic equation of the true plant is

$$\tau = M_n(q)\ddot{q} + C_n(q,\dot{q})\dot{q} + G_n(q) + d(q,\dot{q},\ddot{q},t) \quad (3)$$

Where

$$d(q,\dot{q},\ddot{q},t) = \Delta M(q)\ddot{q} + \Delta C(q,\dot{q})\dot{q} + \Delta G(q) + w(q,\dot{q},t) \quad (4)$$

The dynamic Eq. (3) has the following properties (Berghuis, 1993).

P1: $M_n(q)$ is symetric and positive definite matrix, for all $q \in R^n$.

P2: The inertia and centripetal-Coriolis matrices satisfy the following skew-symetric matrix

$$X^T(\dot{M}_n(q,\dot{q}) - 2C_n(q,\dot{q}))X = 0 \ \forall X \in \Re^n \quad (5)$$

In this study, the following lemma are used

Lemma 1: (Lozano and Taoutaou, 2001). Consider the stable linear system

$$\dot{e} = Ae + Br \quad (6)$$

If $r \in L_2$ then $e \in L_2 \cap L_\infty$ and $e \to 0$.

Proof: (Lozano and Taoutaou, 2001a).

Lemma 2: (Lozano and Taoutaou, 2001b). Consider the continuous function f: $R_+ \to R^n$, if f, $\dot{f} \in L^\infty_n$ and $f \in L_2$, thenn $\lim_{t\to\infty} f(t) = 0$.

In the following, we will introduce a tracking control algorithm which is referred to as the disturbance observer based tracking control and the global asymptotic stability is guaranteed.

DISTURBANCE OBSERVER BASED TRACKING CONTROL

We propose the following control

$$\tau = M_n(q)\ddot{q}_d + C_n(q,\dot{q})\dot{q}_d + G_n(q) + K_pE(t) + \hat{d}(q,\dot{q},\ddot{q},t) \quad (7)$$

Where $q_d(t)$, $\dot{q}_d(t)$, $\ddot{q}_d(t)$ $\in R^n$ denote the desired position, velocity and acceleration vectors, respectively, $E(t) = q_d(t)-q(t)$ and K_p is positive definite diagonal gain matrix.

Theorem: Given the two-lin robotic manipulator (3) with the tracking controller (7) and the disturbance estimation $\hat{d}(q,\dot{q},\ddot{q},t)$ is obtained from:

$$\dot{z} = \phi^{-1}\ddot{q}_d + \alpha\,\dot{q}_d + \mu^{-1}\psi E \quad (8)$$

$$\hat{d} = z - p(q,\dot{q}) \quad (9)$$

If

$$p(q,\dot{q}) = \begin{bmatrix} \beta\left(j_1 + 2X\cos(q_2)\right)\dot{q}_1 + \beta\left(j_2 + X\cos(q_2)\right)\dot{q}_2 \\ \beta\left(j_2 + X\cos(q_2)\right)\dot{q}_1 + \beta\, j_3\dot{q}_2 \end{bmatrix} \quad (10)$$

- The function $p(q,\dot{q})$ in (9) is chosen as
- $K_p = \mu + I_{n\times n}$

Then $\lim_{t\to\infty} E(t) \to 0$ and $\lim_{t\to\infty} E_d(t) \to 0$.

Where j_1, j_2, j_3 and X are inertial parameters, which depend on the masses of the links, motors and tip load and the lengths of the links, $\mu = \mathrm{diag}\{\mu_1, \quad \mu_1\}$, $\psi = \mathrm{diag}\{\psi_1, \quad \psi_1\}$, $\beta = \frac{\psi_1}{\mu_1(\mu_1+1)}$ and $(\mu_1, \Psi_1$ are positive constants.
$\phi^{-1} = \mu^{-1}\psi\, K_p^{-1}M_n$, $\alpha = \frac{d}{dt}\left(\phi^{-1}(t)\right)$, $E(t) = q_d(t) - q(t)$
$E_d(t) = \hat{d}(q,\dot{q},\ddot{q},t) - d(q,\dot{q},\ddot{q},t)$ and $I_{n\times n}\in R_{n\times n}$ is an identity matrix.

Proof: Substituting (7) to (3), we obtain

$$M_n\ddot{E}(t) + C_n\dot{E}(t) + K_pE(t) = -E_d(t) \quad (11)$$

We define $y^T = \left[\dot{E}^T\, E^T\, (F-E_d)^T\right]$ and choose as a Liapunov function candidate

$$V(y) = \frac{1}{2}y^TP\,y \quad (12)$$

Where

$$P = \begin{bmatrix} M_n & 0 & 0 \\ 0 & \mu+I_n & \mu \\ 0 & \mu & \mu \end{bmatrix} \quad (13)$$

and the vector F is to be determined.
Hence

$$V = \frac{1}{2}\dot{E}^TM_n\dot{E} + \frac{1}{2}E^T\left(\mu+I_n\right)E + \frac{1}{2}E^T\mu\left(F-E_d\right)$$

$$+\frac{1}{2}\left(F-E_d\right)^T\mu E + \frac{1}{2}\left(F-E_d\right)^T\mu\left(F-E_d\right) \quad (14)$$

Since, in general, there is no prior information about the derivative of the disturbance d, it is reasonable to suppose that

$$\dot{d} = 0 \quad (15)$$

Which implies that the disturbance varies slowly relative to the obsever dynamics.

The time-derivative of (14), evaluated along (11), (15), according to property (P.2) and choosing $K_p = \mu + I_n$, we obtain

$$\dot{V} = E^T\left(\mu\dot{F} - \mu\dot{\hat{d}}\right) + F^T\left(\mu\dot{F} - \mu\dot{\hat{d}} + \mu\dot{E}\right) - E_d^T\left(\mu\dot{F} - \mu\dot{\hat{d}} + \mu\dot{E} + \dot{E}\right) \quad (16)$$

Choosing

$$\begin{cases} \mu\dot{F} - \mu\dot{\hat{d}} + \mu\dot{E} = -\phi F \\ \mu\dot{F} - \mu\dot{\hat{d}} \qquad = -\psi E \\ \mu\dot{F} - \mu\dot{\hat{d}} + \mu\dot{E} + \dot{E} = 0 \end{cases} \quad (17)$$

Where μ and ψ are diagonal, positive definite matrices and ϕ^{-1} is symetric, positive definite matrix to be determined.
Hence

$$F = \phi^{-1}\dot{E} \quad (18)$$

$$\dot{\hat{d}} = \phi^{-1}\ddot{E} + \alpha\,\dot{E} + \mu^{-1}\psi E \quad (19)$$

Where $\alpha = \frac{d}{dt}\left(\phi^{-1}(t)\right)$.
Therefore, we have

$$\dot{V} = -\dot{E}^T\left(\phi^{-1}\right)^T\dot{E} - E^T\psi E \quad (20)$$

hence

$$\dot{V} = -\dot{E}^T\phi^{-1}\dot{E} - E^T\psi E \quad (21)$$

From (19), we note that the disturbance estimation is not practical to implement, because, the acceleration signal $\ddot{q}$ is not available in many robotic manipulators and it is also difficult to construct the acceleration signal from the velocity signal by differentiation due to measurement noise.

For landing this problem, we define an auxiliary variable vector.

$$z = \hat{d} + p(q,\dot{q}) \quad (22)$$

Where $z\epsilon R^2$. The designed function vector $p(q,\dot{q})$ is to be determined.

Analysis of stability: The analysis of stability is in two parts. In the first part we demonstrate that $\lim_{t\to\infty} E(t) \to 0$ and in the second part, we demonstrate that $\lim_{t\to\infty} E_d(t) \to 0$.

Part 1: From (21), $\dot{V}$ is a negative semi-definite function, this result is not sufficient to demonstrate the asymptotic stability and we can conclude only the stability of the system ($\dot{E}$, E and (F-E_d) are bounded). Therefore, the lemma 2 is required to complete the proof of asymptotic stability and it is sufficient to show that $E\epsilon L^n_2$, to conclude that $\lim_{t\to\infty} E(t) \to 0$.
$E\epsilon L^n_2$ if there exists some constant, γ, such that

$$\gamma \geq \int_0^\infty \|E(t)\|^2 dt \quad (23)$$

We note that

$$\dot{E}^T\phi^{-1}\dot{E} > 0 \quad (24)$$

From (21) and (24), we can write

$$\frac{d}{dt}V(\dot{E}(t),E(t),e(t)) \leq -E^T\psi E \quad (25)$$

Where e(t) = F(t)-E_d (t).

Using theorem of Rayleigh-Ritz (Lozono and Taoutaou, 2001b) (25) becomes

$$\frac{d}{dt}V(\dot{E}(t),E(t),e(t)) \leq -\psi_m \|E(t)\|^2 \quad \forall E(t) \in R^n \quad (26)$$

where ψ_m denotes the minimum eigenvalue of Ψ.
Integrating the two membres of (26), we obtain

$$\int_{V(\dot{E}(0),E(0),e(0))}^{V(\dot{E}(\infty),E(\infty),e(\infty))} dV(\dot{E}(t),E(t),e(t)) \leq -\psi_m \int_0^\infty \|E(t)\|^2 dt \quad (27)$$

hence

$$V(\dot{E}(\infty),E(\infty),e(\infty)) - V(\dot{E}(0),E(0),e(0)) \leq -\psi_m \int_0^\infty \|E(t)\|^2 dt. \quad (28)$$

We note that $V(\dot{E}(t),E(t),e(t))$ is a positive definite function, then

$$V(\dot{E}(\infty),E(\infty),e(\infty)) \geq 0 \quad (29)$$

From (28) and (29), we can conclude that

$$-V(\dot{E}(0),E(0),e(0)) \leq -\psi_m \int_0^\infty \|E(t)\|^2 dt \quad (30)$$

hence

$$\gamma \geq \int_0^\infty \|E(t)\|^2 dt \quad (31)$$

Where $\gamma = \frac{V(\dot{E}(0),E(0),e(0))}{\psi_m}$, which implies that $E\epsilon L^n_2$, then $\lim_{t\to\infty} E(t) \to 0$.

Part 2: Let the function $p(q,\dot{q})$ in (22) be given by the following Equation

$$p(q,\dot{q}) = \phi^{-1}\dot{q} \quad (32)$$

hence

$$\frac{dp(q,\dot{q})}{dt} = \phi^{-1}\ddot{q} + \alpha\,\dot{q} \quad (33)$$

Where $\alpha = \frac{d}{dt}\left(\phi^{-1}(t)\right)$.

Invoking (22) and (33) with (19) yields

$$\dot{z} = \dot{\hat{d}} + \frac{dp(q,\dot{q})}{dt}$$
$$= \phi^{-1}\ddot{q}_d + \alpha\,\dot{q}_d + \mu^{-1}\psi E \quad (34)$$

From (11), we have

$$\ddot{q} = \ddot{q}_d + M_n^{-1}C_n\dot{E} + M_n^{-1}K_pE + M_n^{-1}E_d \quad (35)$$

From (15), (33), (34) and (35), we obtain

$$\dot{E}_d = \dot{\hat{d}} = \left(\alpha - \phi^{-1}M_n^{-1}C_n\right)\dot{E} + \left(\mu^{-1}\psi - \phi^{-1}M_n^{-1}K_p\right) E - \phi^{-1}M_n^{-1}E_d \quad (36)$$

Choosing

$$\psi = \mu\phi^{-1}M_n^{-1}\left(\mu + I_n\right) \quad (37)$$

and

$$K_p = \mu + I_n \quad (38)$$

We have

$$\dot{E}_d = \Gamma E_d + \Theta\, \dot{E} \quad (39)$$

Where $T = -\phi^{-1} Mn^{-1}$, $\Theta = (\alpha - \phi^{-1} M_n^{-1}. C_n)$
From (37) and (38), we obtain

$$\phi^{-1} = \mu^{-1}\psi\ \left(\mu + I_n\right)^{-1} M_n \quad (40)$$

and

$$\Gamma = -\mu^{-1}\psi\ K_p^{-1} \quad (41)$$

Since M_n is symetric, positive definite matrix, $\mu = \mathrm{diag}\left\{\mu_1, \mu_1\right\}$, $\psi = \mathrm{diag}\left\{\psi_1, \psi_1\right\}$, $K_p = \mu + I_n$ and $(\mu_1\ \psi_1)$ are positive constants, then, it is clear that ϕ^{-1} is symetric, positive definite matrix and Γ is a stable matrix.

Therefore, using lemma 1, it is sufficient to show that $\dot{E} \in L_2^{\,n}$, to conclude that $\lim_{t\to\infty} E_d(t) \to 0$.
$\dot{E} \in L_2^{\,n}$ if there exists some constant, λ, such that

$$\lambda \geq \int_0^{\infty} \left\|\dot{E}(t)\right\|^2 dt \quad (42)$$

We note that

$$E^T\psi E \geq 0 \quad (43)$$

From (17), (21) and (43), we can write

$$\frac{d}{dt}V(\dot{E}(t), E(t), F(t) - E_d(t)) \leq -\dot{E}^T\phi^{-1}\dot{E} \quad (44)$$

Using same idea of the part 1, we find

$$\lambda \geq \int_0^{\infty} \left\|\dot{E}(t)\right\|^2 dt \quad (45)$$

Where $\lambda = \dfrac{V(\dot{E}(0), E(0), e(0))}{\phi_m}$ and ϕ_m denotes the minimum eigenvalue of ϕ^{-1}.

Therefore, $\dot{E} \in L_2^{\,n}$ and then $\lim_{t\to\infty} E_d(t) \to 0$.

The estimation $\hat{d}$ approaches the disturbance d if (37) and (38) are verified. Hence, the function $p(q,\dot{q})$ must be selected such that ϕ^{-1} satisfies the Eq. 40.

The inertia matrix M(q) for a two-link manipulator is given by (Gawthrop and Smith, 1996).

$$M(q) = \begin{bmatrix} j_1 + 2X\cos(q_2) & j_2 + X\cos(q_2) \\ j_2 + X\cos(q_2) & j_3 \end{bmatrix} \quad (46)$$

Where j_1, j_2, j_3 and X are inertial parameters, which depend on the masses of the links, motors and tip load and the lengths of the links.
From (40) and (46), we have.

$$\phi^{-1} = \begin{bmatrix} [(j_1 + 2X\cos(q_2))\beta(j_2 + X\cos(q_2)) \\ \beta(j_2 + X\cos(q_2))\beta j_3 \end{bmatrix} \quad (47)$$

Where $\beta = \dfrac{\psi_1}{\mu_1(\mu_1 + 1)}$.
Hence

$$\alpha = \begin{bmatrix} -2X\beta_1\sin(q_2) & -X\beta_1\sin(q_2) \\ -X\beta_2\sin(q_2) & 0 \end{bmatrix} \quad (48)$$

and from (32), we have

$$p(q,\dot{q}) = \begin{bmatrix} \beta\ \left(j_1 + 2X\cos(q_2)\right)\ \dot{q}_1 + \beta\ \left(j_2 + X\cos(q_2)\right)\ \dot{q}_2 \\ \beta\ \left(j_2 + X\cos(q_2)\right)\ \dot{q}_1 + \beta\ j_3\dot{q}_2 \end{bmatrix} \quad (49)$$

which completes the proof.

NUMERICAL SIMULATION RESULTS

Consider a two-link manipulator with masses m_1, m_2, lengths l_1, l_2 and angles q_1, q_2 then the model equations can be written as (3).

The elements of M(q) are given by
$m_{11} = m_2l^2{}_2 + 2m_2l_1l_2\cos(q_2) + (m_1 + m_2)l_1{}^2{}_1$, ,$m_{12} = m_{21} = m_2\ l^2{}_2\ m_2l^2{}_2\cos(q_2)$, $m22 = m_2\ l_2^2$.

The elements of $C(q,\dot{q})$

$C_{11} = -m_2 l_1 l_2 \sin(q_2)\dot{q}_2$, $C_{12} = -m_2 l_1 l_2 \sin(q_2)\dot{q}_2$

$C_{21} = m_2 l_1 l_2 \sin(q_2)\dot{q}_1$, $C_{22} = 0$.

The elements of G(q)

$G_1 = m_2 l_2 \sin(q_2 + q_1) + (m_1 + m_2) l_1 g \cos(q_1)$, $G_2 = m_2 l_2 \sin(q_2 + q_1)$

In the following we will compare the simulation results of the two cases (nominal case and true plant).

The nominal parameter values are assumed to be

$$\bar{m}_1 = 0.4[\text{kg}],\ \bar{m}_2 = 0.6[\text{kg}],\ \bar{l}_1 = 1[\text{m}],\ \bar{l}_2 = 1.4[\text{m}]$$

The rue plant parameters are assumed to be $m_1 = 0.6$ [kg], $m_2 = 0.8$ [kg], $l_1 = 1.6$ [m].

The Coulomb and Viscous friction is considered as an external disturbance.

Friction simulation: The external disturbance considered is Coulomb and Viscous friction, given by

$$d(\dot{q}) = c_1 \text{sign}(\dot{q}) + c_2\dot{q} \qquad (50)$$

The pparameters for first and second links in the simulation are given by

$$c_1 = [0.00941\ 0.0176]^T \text{N.m} \qquad (51)$$

$$c_2 = [0.00156\ \ 0.0088]^T \text{N.m/rad/s}. \qquad (52)$$

There are some problems in using the friction model (50) in simulation directly. One is due to the discontinuity of the friction characteristics at zero velocity, a very small step size is required for testing zero velocity. The other is that when the velocity is zero, or the system is stationary, the friction is indefinite and depends on the controlled torque. In the simulation, to improve the numerical efficiency, a revised friction model, which is modified from (Karnopp, 1985) is adopted. The revised friction model can be described by

$$d_r = d + \left(T_r - d\right) e^{-(\dot{q}/l)^2} \qquad (53)$$

Where d is given by (50), d_r is the revised friction, l is a small positive scalar and T_r is given by

$$T_r(t) = \begin{cases} K & t > K \\ t & -K \le t \le K \\ -K & t < -K \end{cases} \qquad (54)$$

Where K is a positive scalar.

When the velocity is within a very small area near zero, defined by l, the friction d_r is equal to the applied torque T. When the velocity is greater than this, the second term in the above expression vanishes and the friction d_r given by this revised model is equal to the friction given by (50). In the simulation, l is chosen as 0.001.

Simulation results: Simulation parameters: K_p= diag {9001, 9001}, Ψ = diag {1000,1000}, μ = diag {9000,9000}.

The desired trajectories are

$$q_{d1}(t) = \frac{\pi}{2} \sin(2\pi t) + \pi \text{ rad}; 0 \le t \le 3$$

$$q_{d2}(t) = 0.2\sin(2\pi t) + 1 \text{ rad}; 0 \le t \le 3.$$

The simulation results of the nominal case and true plant are shown in Fig. 1 and 2, respectively. We can see that the real tracjectory follows the desired trajectory well in both cases and the control algorithm works well.

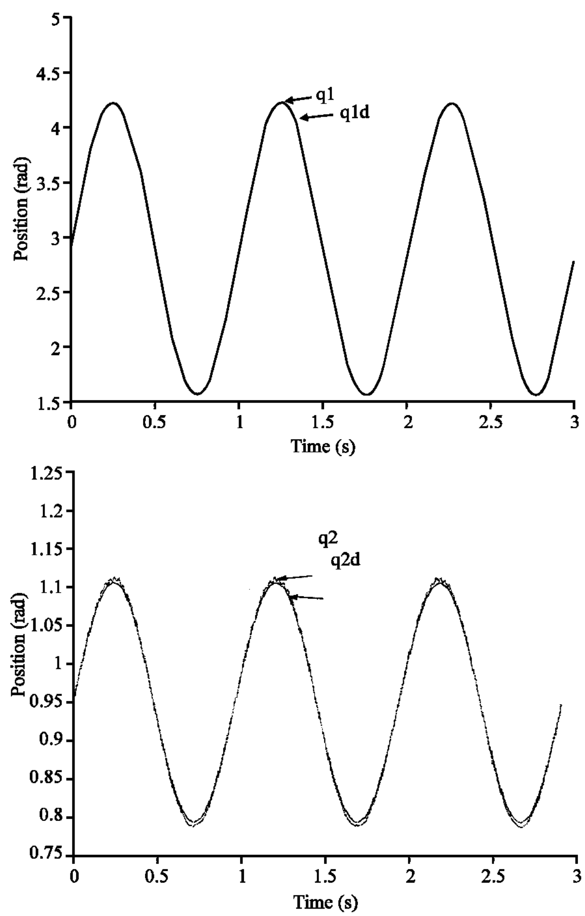

Fig. 1: Desired and real position for the two-link manipulator (Nominal case)

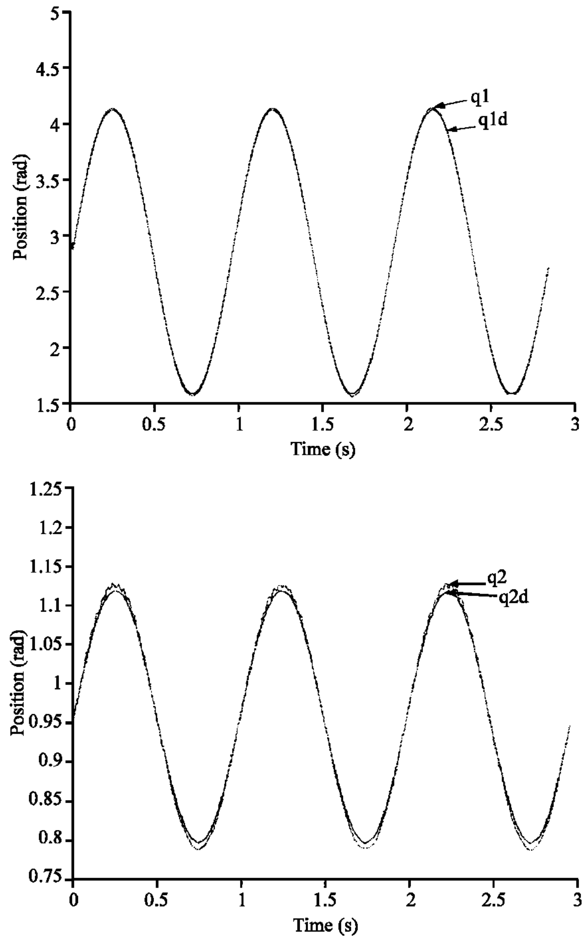

Fig. 2: Desired and real position for the two-link manipulator (the true plant)

CONCLUSION

This study has presented a disturbance observer based tracking control sheme for robotic manipulators. The system uncertainty, unmodeled dynamics and external disturbances are lumped as the overall disturbance. Therefore, the prposed algorithm requires little knowledge of system structures. Following the procedure presented in this paper, a disturbance observer based tracking control is constructed which is asymptotically stabilizing in the sense of Lyapunov. Even though the theory is developed for constant disturbances, it was shown that, the observer exhibits satisfactory performance. A two link robotic manipulator is used as an application example.

REFERENCES

Berghuis, H., 1993. Model based control: From theory to practice, Ph.D. Thesis, University of Twent, the Netherlands.

Chan, S.P., 1995. A disturbance observer for robot manipulators with application to electronic components assembly, IEEE Trans. Ind. Electron., 42: 487-493.

Chen, W.H., 2004. Disturbance observer based control for nonlinear systems. IEEE/ASME Trans. Mechatr., 9, No. 4.

Chen, W.H., D.J. Ballance, P.J. Gawthrop and J.O' Reilly, 2000. A nonlinear disturbance observer for robotic manipulators. IEEE Trans. Indus. Electron., 47: 932-938.

Colbalugh, R., K. Glass and H. Seraji, 1995. Performance-based adaptive tracking control of robot manipulators. J. Robotic Sys., 12: 517-530.

Desoer, C.A. and M. Vidyasagar, 1975. Feedback systems: input-output properties (New York: Academic, 1975).

Dorato, P., 1987. Ed., Robust control. New York, IEEE Press.

Friedl, B. and Y.J. Park, 1992. On adaptive friction compensation. EEE Trans. Automat. Contr., 37: 1609-1612.

Gawthrop, P.J. and L.P.S. Smith, 1996. Metamodeling: Bond Graphs and Dynamic Systems NewYork, Prentice-Hall.

Karnopp, D., 1985. Computer simulation of strick-stip friction in mechanical dynamic systems. ASME J. Dynam. Syst. Meas. Contr., 107: 100-103.

Komada, S., K. Nomura, M. Ishida and T. Hori, 1993. Robust force control- based on compensation for parameter variations ofdynamic environment. IEEE Trans. Ind. Electron., 40: 89-95.

Kwon, D.S. and W.J. Book, 1994. A time-domain inverse dynamic tracking control of a single-link flexible manipulator, ASME J. Dynamic Measurement Control, 116: 193-200.

Lewis, F.L., C.T. Abdallah and D.M. Dawson, 1993. Control of robot manipulators (New York, MacMillan).

Linand, H.N. and Y. Kuroe, 1995. Decoupling Control of Robot Manipulators by Using Variable Structure Disturbance Observer. Proc. IEEE Ind. Electron. Conf., pp: 1266-1271.

Lozano, R. and D.Taoutaou, 2001a. Identification et commande adaptative (Hermes Science Publications).

Luh, J.Y.S., M.W. Walker and R.C.P. Paul, 1980. Resolved-acceleration control of mechanical manipulators. IEEE Trans. On Automatic Control, AC-25, pp: 468-474.

Murakami, T., F. Yu and K. Ohnishi, 1993. Torque sensorless control in multidegree of freedom manipulator. IEEE Trans. Ind. Electron., 40: 259-265.

Nakao, M., K. Ohnishi and K. Miyachi, 1987. A Robust Decentralized Joint Control Based on Interference Estimation. Proc. IEEE Int. Conf. Robotics and Automation, pp: 326-331.

Ohishi, K. and H. Ohde, 1994. Collision and Force Control for Robot Manipulator with Ou Force Sensor. Proc. IEEE Ind. Electron. Conf., pp: 766-771.

Ortega, R., M.W. Spong, 1989. Adaptive motion control of rigid robots: A Tutorial, Automatica, 25: 877-888.

Paden, B. and R. Panja, 1988. Globally asymptotically stable PD + controller for robot manipulators. Int. J. Control, 47: 1697-1712.

Tafazoli, S., C.W. De Silva and P.D. Lawrence, 1998. Tracking control of an electrohydraulic manipulator in the presence of friction. IEEE Trans. Control Sys. Tech., 6: 401-411.