OBSERVER-BASED OUTPUT FEEDBACK VARIABLE STRUCTURE CONTROL WITH APPLICATION TO A TWO-LINK MANIPULATOR

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Abstract: This paper proposes an approach to design dynamic output feedback sliding mode controllers for mismatched uncertain systems that are subject to perturbations in the output measurements. An asymptotic observer is first developed for the estimation of both the system state and unknown input. These estimates are then used to implement the equivalent control and the robust control for the system's desired sliding dynamics. Simulation and experimental results obtained for the Pendubot, a two-link manipulator, are presented to demonstrate the validity of the approach.

Keywords: variable structure control, dynamic output feedback, matching conditions, two-link manipulator.

1. INTRODUCTION

Variable structure control (VSC), well known for its prominent advantage of robustness, in practice may encounter an implementation problem due to the requirement of physical availability of all the system states. To overcome this difficulty, output measurements can be used for feedback. The problem of sliding mode control design for uncertain systems using only output information has been widely investigated. In Heck and Ferry (1989), a direct output feedback design is proposed for variable structure systems by selecting a suitable matrix to satisfy the reaching condition. The output dependent sliding surface is proposed in Żak and Hui (1993), with some matching conditions given on the sliding surface design. In Edwards and Spurgeon (1995), the design problem of a sliding surface can be brought equivalently to a static output feedback problem. Numerical approaches based on nonlinear optimization schemes were developed for the synthesis of the output feedback gain (Heck *et al.*, 1995, Bag *et al.*, 1997). In Edwards and Spurgeon (1998), a parameterization of both the sliding surface and the dynamic compensator was proposed. As later noted, these numerical schemes are applicable under certain structural conditions and restricted only to a specific class of sliding surface (Edwards and Spurgeon, 2000). In this context, the design of asymptotic observers and dynamic compensators is very important for output feedback sliding mode control (Diong and Medanic, 1992; Oh and Khalil, 1995).

Using dynamic output feedback, Kwan (1996) proposed a modified sliding mode controller for single-input single-output systems in an attempt to relax the matching conditions given in (Żak and Hui, 1993). A low switching frequency dynamic output feedback sliding mode controller with two-set sliding surfaces was proposed for systems having only parametric uncertainty (Shyu *et al.*, 2000). In Kim *et al.* (2000), a Riccati inequality approach was used to design robust sliding surfaces for a class of uncertain systems, where disturbances satisfy the matching condition while parametric uncertainty is structured but mismatched. Extending the idea of Kwan (1996) to multi-input multi-output systems, the dynamic output feedback variable structure controller proposed in Shyu *et al.* (2001) did not involve estimates of the state but a bound of a state linear functional. With the sliding function and the equivalent control being linear functions of the state, linear functional observers were designed for their reconstruction when implementing output feedback sliding mode control (Ha *et al.*, 2003). In these papers external disturbances have to be referred to in the control channel, i.e. satisfy the matching condition. Furthermore, unmodelled sensor dynamics may, in practice, affect the control system performance (Żak *et al.*, 1989). Also, other disturbance sources to the measured output vector should be taken into account, particularly in fault detection and isolation problems (Commault *et al.*, 2002).

This paper proposes an approach using observer-based dynamic output feedback sliding mode control for unmatched variable structure systems where the output measurements are perturbed by disturbances. Theoretical development is applied to a two-link robotic manipulator.

2. PROBLEM FORMULATION

Consider a class of uncertain systems described by the following equations

$$\dot{x}(t) = Ax(t) + Bu(t) + Wf(x,t) \tag{1a}$$

$$y(t) = Cx(t) + Df(x,t), \tag{1b}$$

where $x(t) \in R^n$, $u(t) \in R^m$ and $y(t) \in R^p$ are respectively the state, control and measured output, and A, B, C and D are real constant matrices of appropriate dimensions. The measurements are perturbed by sensor unmodelled dynamics and/or disturbances $f(x,t)$, which are an unknown vector field on R^q. Matrix $W \in R^{n \times q}$ is a known real constant matrix. Our objective is to design a sliding mode controller for the system (1) using only the perturbed output measurements $y(t)$. The idea is first to design an asymptotic observer for estimating simultaneously the system states and disturbances from the measured output vector, and then to design a suitable sliding mode controller using the state and disturbance estimates.

In order to proceed, let us first introduce the following assumptions:

Assumption 1: The triplet (A,B,C) is controllable and observable.

Assumption 2: Matrices B, D and W have full column rank. And also matrix $[D \;\; CW]$ has full column rank, i.e.

$$rank[D \;\; CW] = m + q. \tag{2}$$

Remark 1: Disturbances to system (1) do not need to satisfy the common matching condition for variable structure systems, and also it is not necessary to know *a priori* about their bound, $\|f(x,t)\|$.

Remark 2: There is no need to select a matrix $F \in R^{m \times p}$ such that the sliding matrix $S \in R^{m \times n}$ satisfies the condition $S = FC$, where $F \in R^{m \times p}$ is the sliding function matrix, as required in (Żak and Hui, 1993, Shyu *et al.*, 2001).

3. STATE AND INPUT ESTIMATION

The problem of estimating simultaneously the state of a dynamic system and its unknown input has been of interest for example in machine tool and manipulator applications, where the cutting force of a machine tool or the exerting force/torque of a robotic system needs to be estimated. For linear systems, a model error compensator based on the output estimation error has been proposed to estimate the unknown input, and to be incorporated with an extended Kalman filter to estimate the state (Tu and Stein, 1996). For nonlinear systems, the problem of asymptotically estimating the system state and input has been addressed in Coreless and Tu (1998), where the nonlinear part, expressed as a state-dependent and time varying function, is also the unknown input. Here, exact asymptotic estimation is not achieved, the system state and input can however be estimated to any desired degree of accuracy. In this section, an asymptotic observer is designed to estimate both the system states $x(t)$ and disturbances $f(t)$ using the measured output signals $y(t)$. For this, let us introduce the following notation

$$\xi(t) = \begin{bmatrix} x(t) \\ f(t) \end{bmatrix} \in R^{(n+q)}, \quad E = [I_n \;\; 0], \quad \bar{A} = [A \;\; W],$$
$$H = [C \;\; D], \tag{3}$$

where E, $\bar{A}$ and H are real constant matrices of appropriate dimensions, and I_n is an n-dimensional unity matrix. The system described by (1-2) can then be expressed as

$$E\dot{\xi}(t) = \bar{A}\xi(t) + Bu(t) \tag{4a}$$

$$y(t) = H\xi(t), \tag{4b}$$

and the state and input estimation problem of (1) is now that of designing an observer for the generalized system (4) such that $\hat{\xi}(t)$ converges asymptotically to $\xi(t)$.

Consider now the following state observer for the system (4)

$$\dot{\omega}(t) = N\omega(t) + Ly(t) \tag{5a}$$

$$\hat{\xi}(t) = \omega(t) + Qy(t), \tag{5b}$$

where $\omega(t) \in R^{n+q}$ is the observer state, and $\hat{\xi}(t)$ denotes the state estimation vector of $\xi(t)$. Matrices N, L, and Q are to be determined such that estimate $\hat{\xi}(t)$ converges asymptotically to $\xi(t)$.

Define $e(t)$ as the error between $\xi(t)$ and its estimate $\hat{\xi}(t)$ as

$$e(t) = \hat{\xi}(t) - \xi(t). \tag{6a}$$

Substituting (5b) and (4b) into (6a) gives

$$e(t) = \omega(t) + (QH - I_{n+q})\xi(t) . \quad (6b)$$

Let T be an $(n+q)\times n$ matrix defined by

$$TE + QH = I_{n+q} , \quad (7)$$

then (6b) becomes

$$e(t) = \omega(t) - TE\xi(t) , \quad (8)$$

and we have the following proposition.

Proposition: *$\hat{\xi}(t)$ is an asymptotic estimate of $\xi(t)$. if there exists a matrix $T \in R^{(n+q)\times n}$, defined by (7), such that the following condition holds:*

$$\begin{cases} NTE + LH - T\bar{A} = 0 \\ TB = 0 \\ N \text{ Hurwitz.} \end{cases} \quad (9)$$

Proof: (to be given in Ha and Trinh, 2004).

From Proposition 1, the design of the observer (5) is reduced to the problem of finding the matrices T, N, L and Q so that conditions (7) and (9) are satisfied. The following theorem gives the observer design equations.

Theorem 1: *For the observer (5), the estimate $\hat{\xi}(t)$ converges asymptotically to $\xi(t)$ if there exist matrices $Z \in R^{(n+q)\times(n+p)}$ and $F \in R^{(n+q)\times p}$ such that matrix $N = (\Phi + Z\Psi - FH)$ is Hurtwitz, where*

$$\Phi = \Lambda\bar{A} , \ \Lambda = \begin{bmatrix} I_{n+q} & 0 \end{bmatrix}\Sigma^+\begin{bmatrix} I_n \\ 0 \end{bmatrix}, \ \Sigma = \begin{bmatrix} E & B \\ H & 0 \end{bmatrix},$$

$$\Psi = \Omega\bar{A} , \ \Omega = (I_{n+p} - \Sigma\Sigma^+)\begin{bmatrix} I_n \\ 0 \end{bmatrix}, \text{ and}$$

$\Sigma^+ = (\Sigma^T\Sigma)^{-1}\Sigma^T$ is a generalised inverse of Σ.

Proof: (to be given in Ha and Trinh, 2004).

Remark 3: The observer design can be accomplished with the determination of matrix $Z \in R^{(n+m)\times(n+r)}$ such that the system pair $\{H, (\Phi + Z\Psi)\}$ is detectable, or of matrix $F \in R^{(n+m)\times r}$ such that the pair $\{-\Psi, (\Phi - FH)\}$ is detectable.

Since matrices Φ, Ψ, H, Λ and Ω are all known, the design of observer (5) is now reduced to the search for the two matrices Z and F as suggested in Theorem 1. Once they are found, matrices T, Q, and N can be obtained respectively by

$$T = \Lambda + Z\Omega , \quad (10a)$$

$$Q = \bar{\Lambda} + Z\bar{\Omega} , \quad (10b)$$

$$N = \Phi + Z\Psi - FH , \quad (10c)$$

where

$$\bar{\Lambda} = \begin{bmatrix} I_{n+q} & 0 \end{bmatrix}\Sigma^+\begin{bmatrix} 0 \\ I_p \end{bmatrix}, \ \bar{\Omega} = (I_{n+p} - \Sigma\Sigma^+)\begin{bmatrix} 0 \\ I_p \end{bmatrix}, \quad (11a)$$

$$\Phi = \Lambda\bar{A} , \ \Psi = \Omega\bar{A} . \quad (11b)$$

Matrix L can then be derived as

$$L = F + NQ . \quad (12)$$

A computationally-efficient way to obtain matrices Z and F is given in the following corollary.

Corollary 1: *The estimation error $e(t)$ of observer (5) converges asymptotically to zero if there exist matrices $P = P^T > 0$, Z, and F; such that the following Riccati inequality is satisfied*

$$\Phi^T P + P\Phi + \Psi^T Z^T P + PZ\Psi - H^T F^T P - PFH < 0 . \quad (13)$$

Proof: (to be given in Ha and Trinh, 2004).

4. CONTROLLER DESIGN

The design of sliding mode control for system (1) includes the selection of a sliding function so that the sliding motion when restricted to the sliding surface is stable, and then the derivation of a control law to enforce sliding mode in the sliding surface. The sliding function

$$\sigma(x,t) = [\sigma_1(x,t) \ \sigma_2(x,t) \ \ldots \ \sigma_m(x,t)]^T = Sx(t), \quad (14)$$

where $S \in R^{m\times n}$, can be determined such that the sliding mode dynamics in the sliding surface

$$\mathsf{S} = \{x \in R^n \mid \sigma = Sx(t) = 0\} , \quad (15)$$

have $(n\text{-}m)$ desired eigenvalues $\lambda_1, \lambda_2, \ldots, \lambda_{n-m}$. With a sliding margin chosen as λ_* one can obtain the state feedback control matrix $K \in R^{m\times n}$ using pole placement to assign for the closed-loop system the desired eigenstructure $\{\lambda_1, \lambda_2, \ldots, \lambda_{n-m}, \lambda_*, \ldots, \lambda_*\}$, i.e.

$$\det(\lambda I_n - A^*) = (\lambda - \lambda_1)(\lambda - \lambda_2)\ldots(\lambda - \lambda_{n-m})(\lambda - \lambda_*)^m , \quad (16)$$

where $A^* = A + BK$. The sliding matrix S in (15) can then be computed as any basis of the null space of $(\lambda_* I_n - A^*)^T$, $\ker\{(\lambda_* I_n - A^*)^T\}$ (Ha *et al.*, 2003). Since the system state is not physically available, let us consider the sliding function as follows

$$\hat{\sigma}(x,t) = S\hat{x}(t) = S(x(t) + e_x(t)) , \quad (17)$$

where $e_x(t) = [I_n \ \ 0]e(t)$ with $e(t)$ as the observer error defined in (6a) and subject to the error dynamics $\dot{e}(t) = Ne(t)$ with N derived in (10c). The proposed dynamic output feedback sliding mode controller is given in the following theorem.

Theorem 2:
For system (1) with desired sliding dynamics (15) and matrix (SB) being nonsingular, if the control law

is $u(t) = u_E(t) + u_R(t)$, *where the equivalent control is*

$$u_E(t) = -(SB)^{-1}S\bar{A}\hat{\xi}(t), \tag{18a}$$

the robust control is

$$u_R(t) = -(SB)^{-1}\left\|S([I_n \ \ 0]N - \bar{A})\right\|\left\|e(t)\right\| sign(\hat{\sigma}), \tag{18b}$$

in which $\hat{\sigma} = S\hat{x}(t) = S[I_n \ \ 0]\hat{\xi}(t)$ *and* $sign(\hat{\sigma}) = [sign(\hat{\sigma}_1)\ldots sign(\hat{\sigma}_m)]^T$, *then the system state vector* $x(t)$ *asymptotically converges to zero.*

Proof: (Omitted here due to the page limit).

5. APPLICATION TO A TWO-LINK MANIPULATOR

5.1 Pendubot: Modelling

The set-up used in this paper is the Pendubot (Spong *et al.*, 2001), a two-link robotic manipulator as shown in Figure 1. Its dynamics can be obtained using Lagrangian equations of motion:

$$\tau = J(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q), \tag{19}$$

where τ is the vector of the torque applied to the links, $q = [q_1, q_2]^T$ is the vector of joint angle positions,

$J(q) = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix}$, and where

$$d_{11} = m_1 l_{c1}^2 + m_2(l_1^2 + l_{c2}^2 + 2l_1 l_{c2}\cos q_2) + J_1 + J_2$$
$$d_{12} = d_{21} = m_2(l_{c2}^2 + l_1 l_{c2}\cos q_2) + J_2, d_{22} = m_2 l_{c2}^2 + J_2,$$
$$C(q,\dot{q}) = \begin{bmatrix} h\dot{q}_2 & h\dot{q}_2 + h\dot{q}_1 \\ -h\dot{q}_1 & 0 \end{bmatrix}, \ h = -m_2 l_1 l_{c2}\sin q_2,$$

and

$$g(q) = \begin{bmatrix} (m_2 l_{c1} + m_2 l_1)g\cos q_1 + m_2 l_{c2} g\cos(q_1 + q_2) \\ m_2 g l_{c2}\cos(q_1 + q_2) \end{bmatrix}.$$

The system parameters m_1, l_1, l_{c1}, J_1, m_2, l_2, l_{c2}, J_2, and g are respectively the total mass of link one, the length of link one, the distance to the centre of mass of link 1, the moment of inertia of link one about its centroid, the total mass of link two, the length of link two, the distance to the centre of mass of link 2, the moment of inertia of link two about its centroid, and the gravitational acceleration. They can be grouped together into a new parameter set as:

$$\theta_1 = m_1 l_{c1}^2 + m_2 l_1^2 + J_1, \ \theta_2 = m_2 l_{c2}^2 + J_2$$
$$\theta_3 = m_2 l_1 l_{c2}, \ \theta_4 = m_1 l_{c1} + m_2 l_1, \ \theta_5 = m_2 l_{c2} \tag{20}$$

For a control design that neglects friction, these five parameters are all that are needed. They can be identified using the energy theorem to form equations that can be solved for the unknown parameter by a least squares problem (Gautier and Khalil, 1998). Substituting these parameters into (19) yields the following matrices:

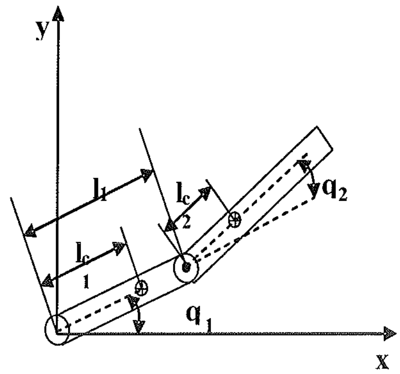

Fig. 1: Schematic of the Pendubot

$$D(q) = \begin{bmatrix} \theta_1 + \theta_2 + 2\theta_3\cos q_2 & \theta_2 + \theta_3\cos q_2 \\ \theta_2 + \theta_3\cos q_2 & \theta_2 \end{bmatrix}$$
$$C(q,\dot{q}) = \begin{bmatrix} -\theta_3\sin(q_2)\dot{q}_2 & -\theta_3\sin(q_2)\dot{q}_2 - \theta_3\sin(q_2)\dot{q}_1 \\ \theta_3\sin(q_2)\dot{q}_1 & 0 \end{bmatrix}$$
$$g(q) = \begin{bmatrix} \theta_4 g\cos q_1 + \theta_5 g\cos(q_1 + q_2) \\ \theta_5 g\cos(q_1 + q_2) \end{bmatrix}. \tag{21}$$

By selecting $x_1 = q_1, x_2 = \dot{q}_1, x_3 = q_2, x_4 = \dot{q}_2$, the state equations are given by

$$\dot{x}_1 = x_2, \ \dot{x}_2 = \ddot{q}_1, \ \dot{x}_3 = x_4, \ \dot{x}_4 = \ddot{q}_2, \tag{22}$$

where

$$[\ddot{q}_1 \ \ \ddot{q}_2]^T = D(q)^{-1}\tau - D(q)^{-1}C(q,\dot{q})\dot{q} - D(q)^{-1}g(q).$$

Denoting $\tau = [u \ \ 0]^T$ and ignoring small terms $x_2 x_4, x_2^2$ and x_4^2, the motion equation of the Pendubot around its equilibrium points can be brought into the form:

$$\begin{aligned} \dot{x} &= Ax(t) + Bu(t) + Wf(x,t) \\ y(t) &= Cx(t) + Df(x,t), \end{aligned} \tag{23}$$

where $x = [x_1, x_2, x_3, x_4]^T$ is the state vector, $u(t)$ is the torque applied to the first link, $y = [y_1, y_2]^T$ is the output vector, and $f(x,t)$ is a nonlinear vector field. The system matrices are

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \ B = \mu\begin{bmatrix} 0 \\ \theta_2 \\ 0 \\ -\theta_2 \end{bmatrix}, \ W = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix},$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & \beta \end{bmatrix}, D = \begin{bmatrix} \alpha \\ 0 \end{bmatrix},$$

where $\mu = (\theta_1\theta_2 - \theta_3{}^2)^{-1}$; and α and β are coefficients representing the level of perturbations in the output measurements. The expression for the nonlinear function $f(x,t)$ is rather complicated, in the mid ($x_1 = -\pi/2, x_3 = \pi$) and top ($x_1 = \pi/2, x_3 = 0$) positions it can be given as

$$f = \mu[u\theta_3 \cos x_3 + g\theta_3\theta_4 \cos x_1 \cos x_3 - g\theta_1\theta_5 \cos(x_1 + x_3)] \quad (24)$$

5.2 Simulation results

The Pendubot mentioned above is identified with the following parameters (in SI units) (Gautier and Khalil, 1998):

$$\theta_1 = 0.0761,\ \theta_2 = 0.0662,\ \theta_3 = 0.0316,$$
$$\theta_4 = 0.9790,\ \theta_5 = 0.3830$$

With g=9.8 m/s^2 and $\alpha = 0.005$, $\beta = 0.001$, the designed feedback gain K=[0.5000 0.5298 -0.5000 -0.5293], the sliding margin λ_*= -16.3639, one can compute the sliding matrix as S=[0.0431 -0.7058 -0.0431 0.7058]. The observer matrices N, L, and Q in (5) can be obtained by computing matrix F according to the detectable property of the system pair given in Remark 3 and equations (10)-(12). One can now derive the control laws from (18) as $u_E(t) = K_E\hat{\xi}(t)$, and

$u_R(t) = K_R\|e(t)\| sign(S[I_n \quad 0]\hat{\xi}(t))$,

where K_E = [0 0.0019 0 -0.0019 0.0305] and K_R = 61.0160.

Shown in Figure 2 are the simulated responses around the midpoint equilibrium of the joint angles and their estimates where the latter represented in broken lines. A perturbation of the form (24) is used for the sake of simulation. Figure 3 depicts the responses of the control force $u(t)$ and the perturbation $f(x,t)$ and its estimate.

The simulation results indicate that the proposed observer can estimate asymptotically both the state and unknown input and the output feedback sliding mode controller can be designed for an uncertain mismatched system.

5.3 Experimental results

The proposed estimation and control schemes were implemented on the Pendubot shown in Figure 1.

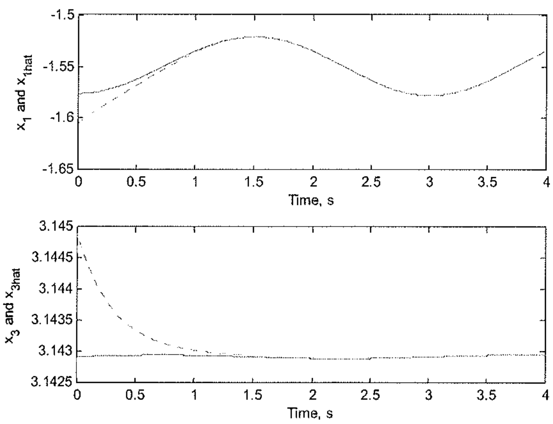

Fig. 2. Joint angles and estimates

The hardware description of this mechatronics kit was introduced in Spong *et al.* (2001). Figure 4 and 5 show the actual responses and their estimates respectively for the joint angles q_1 and q_2 around the mid position ($x_1 = -\pi/2, x_3 = \pi$) after the swinging-up phase. The control response of the proposed controller is shown in Figure 6 as u_{SMC}, and is compared with u_{SF}, the default control using state feedback (Spong *et al.*, 2001). It can be seen that the estimates converge at the mid position.

Experimental results verify that the proposed dynamic output feedback sliding mode controller can be used for uncertain systems that do not need to satisfy the matching conditions. This advantage is achieved thanks to the asymptotic convergence of the error of the state and input observer.

6. CONCLUSION

We have presented an approach to dynamic output feedback sliding mode control for mismatched uncertain systems where output measurements are perturbed by an unknown input. The features of the proposed technique include (i) state and input simultaneous estimation, and (ii) no matching conditions required for the design of variable structure control. A two-link robotic manipulator is used to verify the validity of the control schemes, in both computer simulation and experimental tests.

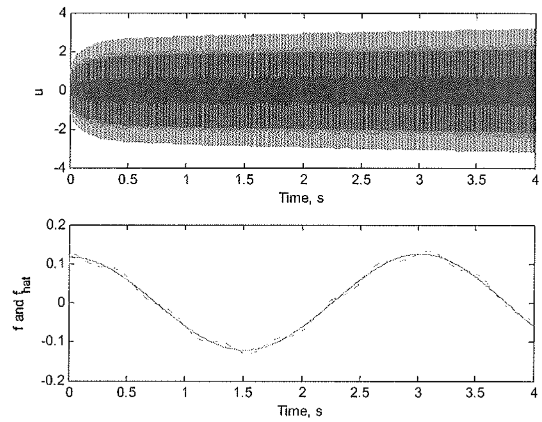

Fig. 3. Control force and perturbation

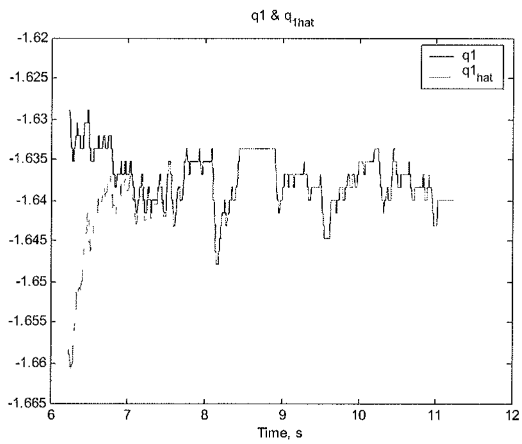

Fig. 4. First joint angle and estimate

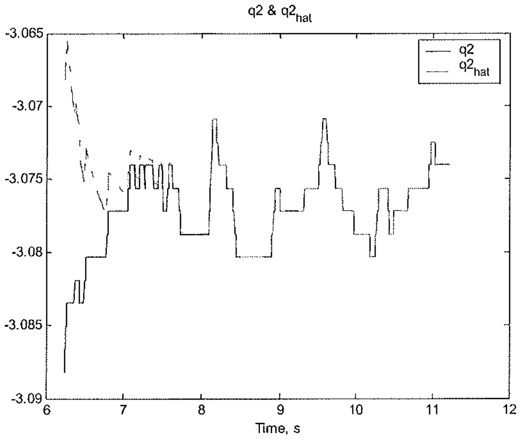

Fig. 5. Second joint angle and estimate

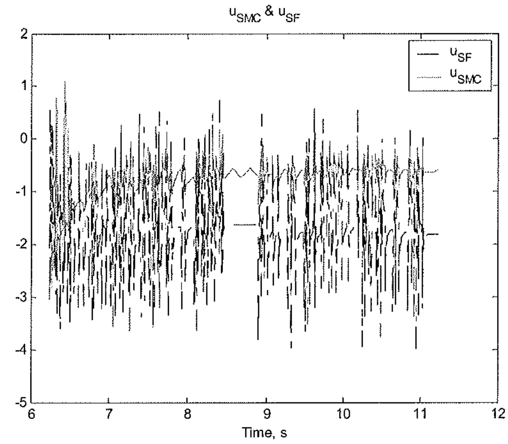

Fig. 6. Control response

7. ACKNOWLEDGEMENT

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