Adaptive Decentralized Control of Robot Manipulators Driven by Current-Fed Induction Motors

Su-Hau Hsu and Li-Chen Fu

***Abstract*—In this paper, an adaptive decentralized control scheme with a rotor-flux observer is proposed for the tracking control of robot manipulators actuated by current-fed induction motors. To cope with all parametric uncertainties in the electromechanical systems, an adaptive law is designed so that all the signals of closed-loop systems are bounded, and the tracking errors in position, velocity and rotor fluxes converge to a residual set.**

***Index Terms*—Adaptive control, decentralized control, induction motors, manipulators.**

I. Introduction

Due to their simple structures, high reliability, high power output, and low cost, induction motors are widely adopted in industrial applications. However, if induction motors are utilized as actuators for servo applications in robot manipulators, it is difficult to achieve high-performance manipulation actuation owing to the unavailability of measurement of the rotor flux and parametric uncertainty [6], [7]. Because of important advances in power electronics, induction motors have recently been successfully operated in the current-command mode [2]. Then, one decentralized control approach for robot manipulators driven by current-fed induction motors has been proposed [4]. Although this approach only requires simple hardware for implementation due to its decentralization nature, it is applied without any parametric uncertainties of electromechanical systems, which is not convenient in practical applications. This paper proposes an adaptive decentralized control scheme for the tracking control of robot manipulators actuated by current-fed induction motors to overcome such a problem.

This paper is organized as follows. Section II shows the dynamic model of a robot manipulator driven by current-fed induction motors. In Section III, the adaptive decentralized control scheme is developed. Section IV presents numerical studies on the first three-joint dynamics of a robot, PUMA 560, driven by current-fed induction motors. Finally, some concluding remarks are stated in Section V.

II. Problem Statement

Under the usual assumptions, such as linearity of the magnetic circuits, and equal inductances with negligible iron losses, for a general n-link rigid manipulator driven by current-fed induction motors, the dynamic model is derived as follows [4]:

$$D(q)\dot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau_m + d(t,q,\dot{q}) \tag{1a}$$

$$\dot{\psi}_{i\_1} = -a_i\psi_{i\_1} - n_{p,i}n_{g,i}\dot{q}_i\psi_{i\_2} + m_i a_i u_{i\_1} \tag{1b}$$

$$\dot{\psi}_{i\_2} = -a_i\psi_{i\_2} + n_{p,i}n_{g,i}\dot{q}_i\psi_{i\_1} + m_i a_i u_{i\_2} \tag{1c}$$

where $t \in [0,\infty)$ denotes time, $q = [q_1,\ldots,q_n]^{\mathrm{T}}$ and $\dot{q} = [\dot{q}_1,\ldots,\dot{q}_n]^{\mathrm{T}} \in \mathrm{R}^n$ are the joint position and velocity of the robot manipulator, respectively, ψ_{i_1} and $\psi_{i\_2} \in \mathrm{R}$ are the robot fluxes of the ith induction motor, u_{i_1} and $u_{i\_2} \in \mathrm{R}$ are the current inputs of the ith induction motor, $D(q) \in \mathrm{R}^{n\times n}$ is the inertial matrix, $C(q,\dot{q})\dot{q} \in \mathrm{R}^n$ is the vector of the Coriolis and centrifugal force, $g(q) \in \mathrm{R}^n$ is the vector due to the gravitational force, and $d(t,q,\dot{q}) \in \mathrm{R}^n$ is the friction input vector. Let $n_{g,i}, n_{p,i}, R_{r,i}, L_{r,i}$ and $m_i \in \mathrm{R}, i \in \{1,\ldots,n\}$, denote the speed ratio, poles number, rotor resistance, rotor inductance and mutual inductance of the ith induction motor, respectively, such that $a_i \equiv R_{r,i}/L_{r,i}$, and $\mu_i \equiv n_{p,i}m_i/L_{r,i}$. In (1a), $\tau_m = [\tau_{m,1},\ldots,\tau_{m,n}]^{\mathrm{T}} \in \mathrm{R}^n$ with $\tau_{m,i} = n_{g,i}\mu_i[\psi_{i\_1}u_{i\_2} - \psi_{i\_2}u_{i\_1}]$, is the vector of torque input. This dynamic model has properties that will be used in the controller design [8].

- P1) The matrix $D(q)$ is symmetric positive-definite and satisfies $\mu_d I \le D(q) \le \mu_D I, \forall q \in \mathrm{R}^n$, for some constants $\mu_d, \mu_D > 0$.
- P2) The matrix $C(q,\dot{q})$ satisfies $\|C(q,\dot{q})\|_2 \le \mu_C\|\dot{q}\|_2, \forall q,\dot{q} \in \mathrm{R}^n$, for some constant $\mu_C > 0$.
- P3) The vector $g(q)$ satisfies $\|g(q)\|_2 \le \mu_G, \forall q \in \mathrm{R}^n$, for some constant $\mu_G > 0$.
- P4) The matrix $\dot{D}(q) - 2C(q,\dot{q})$ is skew-symmetric.

Let $q_d : [0,\infty) \to \mathrm{R}^n$ such that $q_d(t)$ for all $t \ge 0$ denotes the desired joint position trajectory of robot manipulators, and let $\Psi_{d,i} : [0,\infty) \to \mathrm{R}, i \in \{1,\ldots,n\}$, such that $\Psi_{d,i}(t)$ for all $t \ge 0, i \in \{1,\ldots,n\}$, is the desired trajectory of the rotor flux modulus of the ith induction motor. In this study, an adaptive decentralized control scheme is designed such that the joints of robot manipulators and rotor fluxes in the square modulus of each induction motor follow the desired profiles.

III. Adaptive Controller Design

For robot manipulators, the tracking position error is defined as $e \equiv q - q_d$, and an auxiliary signal is defined $s \equiv \dot{e} + \Lambda e$, where the matrix $\Lambda = \mathrm{diag}(\lambda_1,\ldots,\lambda_n) > 0$. From (1a), we have

$$\dot{e} = -\Lambda e + s \tag{2a}$$

$$D(q)\dot{s} = -C(q,\dot{q})s + \tau_m - v(t,q,\dot{q}) \tag{2b}$$

where the vector

$$\begin{aligned} v(t,q,\dot{q}) &= D(q)(\dot{q}_d + \Lambda\dot{e}) + C(q,\dot{q})(\dot{q}_d + \Lambda e) \\ &\quad + g(q) - d(t,q,\dot{q}) \end{aligned} \tag{3}$$

is the disturbance in (2b). For induction motors, the tracking error of rotor fluxes is defined as $e_{\psi,i}(t) \equiv \psi_{i\_1}^2(t) + \psi_{i\_2}^2(t) - \Psi_{d,i}(t), i \in \{1,\ldots,n\}$. Some technical assumptions are employed as follows.

- A1) The signal $q_d(\cdot)$ and the time derivatives $\dot{q}_d(\cdot), \dot{q}_d(\cdot)$ are all bounded time-varying signals.
- A2) The friction input in (1) satisfies $d(t,q,\dot{q}) = [d_1(t,q_1,\dot{q}_1),\ldots,d_n(t,q_n,\dot{q}_n)]^{\mathrm{T}}$ with $|d_i(t,q_i,\dot{q}_i)| \le d_{i\_1} + d_{i\_2}|q_i| + d_{i\_3}|\dot{q}_i|$, for all $t \ge 0, q_i, \dot{q}_i \in \mathrm{R}$, for some constants d_{i_1}, d_{i_2}, and $d_{i\_3} \ge 0, i \in \{1,\ldots,n\}$.
- A3) The pole number of each induction motor is given.
- A4) The signal $\Psi_{d,i}(\cdot), i \in \{1,\ldots,n\}$, and their derivatives are all bounded. Further, the signal $\Psi_{d,i}(\cdot), i \in \{1,\ldots,n\}$, satisfies $\Psi_{d,i}(0) \ge 0$ and $\Psi_{d,i}(t) > 0$ for all $t \ge 0$.
- A5) The parameter $a_i > 1.5\ (\Omega/\mathrm{H}), i \in \{1,\ldots,n\}$.
- A6) The parameters $R_{r,i}, L_{r,i}$ and $m_{,i}, i \in \{1,\ldots,n\}$, are unknown but bounded by $R_{r,i,\max} \ge R_{r,i}, 0 < L_{r,i,\min} \le L_{r,i}$, and $m_{i,\max} \ge m_i$ where the constants $R_{r,i,\max}, L_{r,i,\min}$, and $m_{i,\max} > 0$ are known.
- A7) $\psi_{i\_1}(0), \psi_{i\_2}(0), i \in \{1,\ldots,n\}$ are given.

Manuscript received March 7, 2003; revised July 8, 2004 and September 11, 2004. Recommended by Technical Editor R. V. Patel. This work was supported by the National Science Council, R.O.C. under the Grant NSC 93-2213-E-002-045.

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Digital Object Identifier 10.1109/TMECH.2005.852453

Remark 1: If an estimation of the bounds of those parameters of the induction motors is available, assumption (A6) is easy to satisfy. Thus, it is estimated that $a_i \leq a_{i,\max} \equiv R_{r,i,\max}/L_{r,i,\min}, \mu_i \leq \mu_{i,\max} = n_{p,\max} L_{r,i,\max}/m_{i,\min}$ where $n_{p,\max} = \max\{n_{p,1}, \ldots, n_{p,n}\}$.

The adaptive decentralized control law of the current inputs $u_{i\_1}(\cdot)$ and $u_{i\_2}(\cdot), i \in \{1, \ldots, n\}$, is defined as

$$\begin{bmatrix} U_{i\_11} & U_{i\_12} \\ U_{i\_21} & U_{i\_22} \end{bmatrix} \begin{bmatrix} u_{i\_1} \\ u_{i\_2} \end{bmatrix} = \begin{bmatrix} \tau_{\text{adaptive},i} \\ \hat{a}_i \left[\hat{\psi}_{i\_1}^2 + \hat{\psi}_{i\_2}^2\right] + \frac{1}{2}\dot{\Psi}_{d,i} - \rho_i z_i \end{bmatrix} \tag{4}$$

where $U_{i\_11} = -n_{g,i}\eta_i\hat{\psi}_{i\_2}, U_{i\_12} = n_{g,i}\eta_i\hat{\psi}_{i\_1}, U_{i\_21} = \hat{m}_i\hat{a}_i\hat{\psi}_{i\_1}$, and $U_{i\_22} = \hat{m}_i\hat{a}_i\hat{\psi}_{i\_2}$,. In (4), the constant $\rho_i > 0, i \in \{1, \ldots, n\}$, the signals $\tau_{\text{adaptive},i}(\cdot), z_i(\cdot)$, and $\eta_i(\cdot), i \in \{1, \ldots, n\}$, are defined as $\tau_{\text{adaptive},i} = u_i - \theta_{i\_3}s_i^3$, and $z_i = \hat{\psi}_{i\_1}^2 + \hat{\psi}_{i\_2}^2 - \Psi_{d,i}$, with

$$\dot{\eta}_i = \begin{cases} -[\eta_i A_{i\_1} + A_{i\_2}], & \text{if } \eta_i > \mu_{i,\max} + \delta_{i\_1} \\ \xi_{i\_1}, & \text{if } \eta_i \leq \mu_{i,\max} + \delta_{i\_1} \end{cases} \tag{5}$$

and $\eta_i(0) > \mu_{i,\max} + \delta_{i\_1}, \theta_{i\_j} > 0, i \in \{1, \ldots, n\}, j \in \{2, 3\}$, the signal $u_i(\cdot), i \in \{1, \ldots, n\}$, being defined as

$$u_i = \begin{cases} -\frac{1}{\varepsilon}\hat{\theta}_{i\_1}^2 s_i - \theta_{i\_2}s_i, & \text{if } \hat{\theta}_{i\_1}|s_i| \leq \varepsilon_i \\ -\hat{\theta}_{i\_1}\text{sgn}\,[s_i] - \theta_{i\_2}s_i, & \text{if } \hat{\theta}_{i\_1}|s_i| > \varepsilon_i \end{cases} \tag{6}$$

the signals $A_{i\_1}(\cdot)$ and $A_{i\_2}(\cdot), i \in \{1, \ldots, n\}$, being defined as

$$A_{i\_1} = n_{g,i}^2 k_{\mu,i}^2 s_i^2 \left[u_{i\_1}^2 + u_{i\_2}^2\right], \quad k_{\mu,i} = \eta_i/(\eta_i - \mu_{i,\max}) \tag{7a}$$

$$A_{i\_2} = 2n_{g,i}|s_i| \left[\left|\hat{\psi}_{i\_2}\right| |u_{i\_1}| + \left|\hat{\psi}_{i\_1}\right| |u_{i\_2}|\right] \tag{7b}$$

and the constant $\delta_{i\_1}, \xi_{i\_1} > 0, i \in \{1, \ldots, n\}$, being the designed ones. In (6), the signal $\varepsilon_i(\cdot), i \in \{1, \ldots, n\}$, is defined by $\dot{\varepsilon}_i = -p_i\varepsilon_i + w_i, \varepsilon_i(0) > 0$, where the constant $p_i, w_i > 0$. The time-varying signal $\varepsilon_i(\cdot), i \in \{1, \ldots, n\}$, is used as the boundary layer in our approach. Since the rotor fluxes of induction motors are immeasurable, the rotor-flux observer is designed as

$$\dot{\hat{\psi}}_{i\_1} = -\hat{a}_i\hat{\psi}_{i\_1} - n_{p,i}n_{g,i}\dot{q}_i\hat{\psi}_{i\_2} + \hat{m}_i\hat{a}_i u_{i\_1} \tag{8a}$$

$$\dot{\hat{\psi}}_{i\_2} = -\hat{a}_i\hat{\psi}_{i\_2} + n_{p,i}n_{g,i}\dot{q}_i\hat{\psi}_{i\_1} + \hat{m}_i\hat{a}_i u_{i\_2} \tag{8b}$$

$i \in \{1, \ldots, n\}$, with $\hat{\psi}_{i\_1}^2(0) + \hat{\psi}_{i\_2}^2(0) > 0$, where the signals $\hat{\psi}_{i\_1}(\cdot)$ and $\hat{\psi}_{i\_2}(\cdot)$ are the estimates of $\psi_{i\_1}(\cdot)$ and $\psi_{i\_2}(\cdot)$, respectively. The adaptive law for parametric uncertainty is designed as

$$\dot{\hat{\theta}}_{i\_1} = \gamma_{i\_1}|s_i| - \sigma_{i\_1}\hat{\theta}_{i\_1}, \quad \hat{\theta}_{i\_1}(0) \geq 0 \tag{9a}$$

$$\dot{\hat{a}}_i = \begin{cases} -\hat{a}_i A_{i\_3}, & \text{if } \hat{a}_i > a_{i,\max} + \delta_{i\_2} \\ \xi_{i\_2}, & \text{if } \hat{a}_i \leq a_{i,\max} + \delta_{i\_2} \end{cases} \tag{9b}$$

$$\dot{\hat{m}}_i = \begin{cases} -\hat{m}_i(t)A_{i\_4}(t), & \text{if } \hat{m}_i(t) > m_{i,\max} + \delta_{i\_3} \\ \xi_{i\_3}, & \text{if } \hat{m}_i(t) \leq m_{i,\max} + \delta_{i\_3} \end{cases}. \tag{9c}$$

with $\hat{a}_i(0) > a_{i,\max} + \delta_{i\_2}, \hat{m}_i(0) > m_{i,\max} + \delta_{i\_3}$, where the constants $\gamma_{i\_1}, \sigma_{i\_1}, \delta_{i\_1}, \delta_{i\_2}, \xi_{i\_1}$, and $\xi_{i\_2} > 0, i \in \{1, \ldots, n\}$ are the designed ones, and the signal $A_{i\_3}(\cdot), A_{i\_4}(\cdot), i \in \{1, \ldots, n\}$, are defined, respectively, as

$$A_{i\_3} = [\hat{\psi}_{i\_1} - \hat{m}_i u_{i\_1}]^2 + [\hat{\psi}_{i\_2} - \hat{m}_i u_{i\_2}]^2 \tag{10a}$$

$$A_{i\_4} = a_{i,\max}^2 \left[u_{i\_1}^2 + u_{i\_2}^2\right] \tag{10b}$$

We adopt the norm of the vector-valued signals as follows: For signals $x : [0, \infty) \to \mathrm{R}^n, \|x\|_T$, the norm of $x(\cdot)$ for $T > 0$, is defined as $\|x\|\|_T \equiv \sup_{t \in [0,T]}\|x(t)\|_2$. A useful lemma is guaranteed now:

Lemma 1: If there exists a constant $T > 0$ such that $\|s\|_T$ exists, then there are positive constants β_1, β_2, and β_3 such that for all $t \in [0, T]$,

$$\|v[t, q(t), \dot{q}(t)]\|_2 \leq \beta_1 + \beta_2\|s\|_T + \beta_3\|s\|_T^2. \tag{11}$$

Proof: The proof is referred to that in [5] and omitted here. The performance of the proposed scheme is given as follows.

Theorem 2: Under assumption (A1)–(A7), consider robotic manipulators driven by current-fed induction motors (1) with the control law, (4), flux observer, (8), and adaptive law, (9). Then, all the signals are bounded, and further, the position tracking error $e(\cdot)$, velocity tracking error $\dot{e}(\cdot)$, and tracking error of the fluxes $e_{\psi,i}(\cdot), i \in \{1, \ldots, n\}$, will converge to a residue set whose size can be reduced by using the smaller $w_{\max}$ and $\sigma_{1,\max}$, where $w_{\max} = \max\{w_1, \ldots, w_n\}$, and $\sigma_{1,\max} = \max\{\sigma_{1\_1}, \ldots, \sigma_{n\_1}\}$.

Proof: The proof proceeds in the following four steps.

Step 1: Prove that if there exists a $T > 0$ such that $\|s\|_T$ exists, then the current inputs $u_{i\_1}(t)$ and $u_{i\_2}(t), i \in \{1, \ldots, n\}$, are well-defined for all $t \in [0, T]$, and $z_i(t)$ is monotonically decreasing from $t = 0$ to $t = T$. According to current inputs (4), and flux observer, (8), we have $\dot{z}_i = -2\rho_i z, i \in \{1, \ldots, n\}$, which implies that $z_i(t)$ is monotonically decreasing from $t = 0$ to $t = T$ so that $\hat{\psi}_{i\_1}^2(t) + \hat{\psi}_{i\_2}^2(t) \neq 0, i \in \{1, \ldots, n\}$, for all $t \in [0, T]$ when assumption (A4) is valid. Since the updated parameter for induction motors are always bounded and positive, the current inputs given in (4) are well-defined for all $t \in [0, T]$.

Step 2: Prove that $(1/2)\sum_{i=1}^n[\tilde{\psi}_{i\_1}^2(t) + \tilde{\psi}_{i\_2}^2(t)] + (1/4)\sum_{i=1}^n [\hat{a}_i(t) - a_i]^2 + (1/4)\sum_{i=1}^n[\hat{m}_i(t) - m_i]^2$ is monotonically decreasing from $t = 0$ to $t = T$. Consider the Laypunov-like function as

$$V_1 = \frac{1}{2}\sum_{i=1}^n \left[\tilde{\psi}_{i\_1}^2 + \tilde{\psi}_{i\_2}^2\right] + \frac{1}{4}\sum_{i=1}^n[\hat{a}_i - a_i]^2 + \frac{1}{4}\sum_{i=1}^n[\hat{m}_i - m_i]^2. \tag{12}$$

Computing $\dot{V}_1(t)$ yields that for all $t \in [0, T]$

$$\dot{V}_1(t) = -\sum_{i=1}^n (a_i - 1)\left[\tilde{\psi}_{i\_1}^2(t) + \tilde{\psi}_{i\_2}^2(t)\right] \leq 0. \tag{13}$$

From (13), it follows that the statement in Step 2 is valid.

Step 3: Prove that the signal $s(\cdot)$ are bounded. Consider the Laypunov-like function as

$$V_2 = \frac{1}{2}s^{\mathrm{T}}D[q(t)]s + \frac{1}{2}\sum_{i=1}^n \left[\tilde{\psi}_{i\_1}^2 + \tilde{\psi}_{i\_2}^2\right] + \frac{1}{2}\sum_{i=1}^n z_i^2 + \frac{1}{4}\sum_{i=1}^n [\hat{a}_i - a_i]^2 + \frac{1}{4}\sum_{i=1}^n [\hat{m}_i - m_i]^2 + \frac{1}{4}\sum_{i=1}^n [\eta_i - \mu_i]^2. \tag{14}$$

Computing $\dot{V}_2(t)$ yields that

$$\dot{V}_2(t) \leq \sum_{i=1}^n s_i(t)\tau_{\text{adaptive},i}(t) + \|s(t)\|_2\|v[t, q(t), \dot{q}(t)]\|_2$$

$$-\sum_{i=1}^{n}(a_i-1.5)\left[\tilde{\psi}^2_{i\_1}(t)+\tilde{\psi}^2_{i\_2}(t)\right]$$
$$-2\sum_{i=1}^{n}\rho_i z_i^2(t) \tag{15}$$

where property (P4) is applied. Hence, we have

$$\dot{V}_2(t) \le -\theta_{3,\min}\frac{1}{n}\|s(t)\|_2^4+\|s(t)\|_2\|v[t,q(t),\dot{q}(t)]\|_2$$
$$-\sum_{i=1}^{n}(a_i-1.5)\left[\tilde{\psi}^2_{i\_1}(t)+\tilde{\psi}^2_{i\_2}(t)\right]$$
$$-2\sum_{i=1}^{n}\rho_i z_i^2(t) \tag{16}$$

where $\tau_{\mathrm{adaptive},i}, i\in\{1,\ldots,n\}$, is taken into to account. Now assume that the signal $s(\cdot)$ is unbounded. Then there is always a smallest time $T_1\ge 0$ such that $s(T_1)=l_1$ for large $l_1\in \mathrm{R}$, and we have

$$\dot{V}_2(t) \le -\theta_{3,\min}\frac{1}{n}\|s(t)\|_2^4+\|s(t)\|_2\left(\beta_1+\beta_2 l_1+\beta_3 l_1^2\right)$$
$$-\sum_{i=1}^{n}(a_i-1.5)\left[\tilde{\psi}^2_{i\_1}(t)+\tilde{\psi}^2_{i\_2}(t)\right]$$
$$-2\sum_{i=1}^{n}\rho_i z_i^2(t) \tag{17}$$

for all $t\in[0,T_1]$, where Lemma 1 is applied. Considering a sufficiently lager l_1 and following the conclusion in Steps 1 and 2, it follows due to the first term in the right-hand side of (17) that the $s(T_1)\neq l_1$ is bounded, which is in contradiction with our previous assumption. Thus, the signal $s(\cdot)$ is bounded.

Step 4: Prove that all the signals are bounded, and that the signals $s(\cdot)$ and $e_{\psi,i}(\cdot), i\in\{1,\ldots,n\}$, converge asymptotically to a residual set whose size can be reduced by using smaller $w_{\max}$ and $\sigma_{1,\max}$. Now consider the Lyapunov-like function as follows:

$$V_3=\frac{1}{2}s^{\mathrm{T}}D[q(t)]s+\frac{1}{2}\sum_{i=1}^{n}\left[\tilde{\psi}^2_{i\_1}+\tilde{\psi}^2_{i\_2}\right]+\frac{1}{2}\sum_{i=1}^{n}z_i^2$$
$$+\frac{1}{4}\sum_{i=1}^{n}[\hat{a}_i-a_i]^2$$
$$+\frac{1}{4}\sum_{i=1}^{n}[\hat{m}_i-m_i]^2+\frac{1}{4}\sum_{i=1}^{n}[\eta_i-\mu_i]^2$$
$$+\frac{1}{2}\sum_{i=1}^{n}\gamma_{i\_1}^{-1}\left[\hat{\theta}_{i\_1}-\theta^*_{i\_1}\right]^2 \tag{18}$$

where the constant $\theta^*_{i\_1}>0, i\in\{1,\ldots,n\}$, is desirable but unknown for $\theta_{i\_1}(\cdot)$, $i\in\{1,\ldots,n\}$. From the time derivative of (18) along the trajectories of the closed-loop system, we conclude that for sufficiently large $\theta^*_{1,\min}=\min\{\theta^*_{1\_1},\ldots,\theta^*_{n\_1}\}$

$$\dot{V}_3(t)\le -\theta_{2,\min}\|s(t)\|_2^2$$
$$-\sum_{i=1}^{n}(a_i-1.5)\left[\tilde{\psi}^2_{i\_1}(t)+\tilde{\psi}^2_{i\_2}(t)\right]$$
$$-2\sum_{i=1}^{n}\rho_i z_i^2(t)-\frac{1}{2}\sum_{i=1}^{n}\gamma_i^{-1}\left[\hat{\theta}_{i\_1}(t)-\theta^*_{i\_1}\right]^2$$
$$+\sum_{i=1}^{n}\varepsilon_i(t)+\frac{1}{2}\sum_{i=1}^{n}\gamma_i^{-1}\sigma_{i\_1}\theta^{*2}_{i-1} \tag{19}$$

for all $t\ge 0$, where $\theta_{2,\min}=\min\{\theta_{1\_2},\ldots,\theta_{n\_2}\}$. The inequality, (19), implies that the signals $s(\cdot), \tilde{\psi}_{i\_1}(\cdot)$, $\tilde{\psi}_{i\_2}(\cdot), \hat{\theta}_{i\_1}(\cdot)-\theta^*_{i\_1}, i\in\{1,\ldots,n\}$, converge asymptotically to a residual set, centered at the zero, whose size can be reduced by $w_{\max}$ and $\sigma_{1,\max}$ such that the signals $e(\cdot), \dot{e}(\cdot)$, and $e_{\psi,i}(\cdot), i\in\{1,\ldots,n\}$, have the same converging property. Finally, since the signals in (5), (9b), and (9c) are bounded, all of the signals are bounded.

TABLE I
DESIGN PARAMETERS IN SECTION IV ($I=1,2,3$)

Parameter	Value	Parameter	Value	Parameter	Value
λ_i	50	δ_{i_3}	0.0015	$\mu_{i,\max}$	4
θ_{i_2}	120	ξ_{i_1}	0.001	σ_{i_1}	0.5
θ_{i_3}	1	ξ_{i_2}	0.001	p_i	0.5
γ_{i_1}	50	ξ_{i_3}	1×10^{-5}	w_i	0.1
δ_{i_1}	0.015	$a_{i,\max}$	10	ρ_i	3
δ_{i_2}	0.015	$m_{i,\max}$	0.085	$n_{g,i}$	10

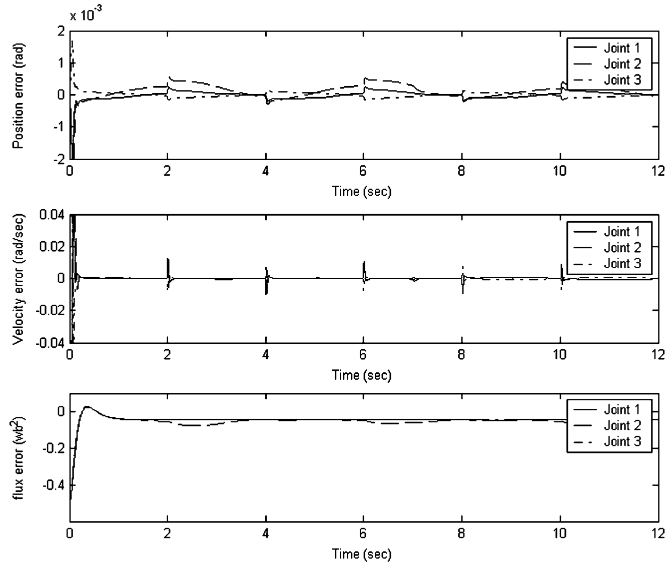

Fig. 1. Tracking errors.

IV. SIMULATION RESULTS AND DISCUSSION

In order to demonstrate the performance of the proposed scheme, simulation studies on the first three-DOF of a robot, PUMA 560, driven by current-fed induction motors are discussed now [1], [3], [7], in which the nominal value of the rotor resistance is 0.53 Ω. The rotor-resistance variation is the same as that in [6]. We consider the desired joint trajectory as $q_d(t)=[q_{d,1}(t),q_{d,2}(t),q_{d,3}(t)]^{\mathrm{T}}$ where $q_{d,1}(t)=(\pi/4)-(\pi/4)\cos((\pi/2)t)$ (rad), $q_{d,2}(t)=-(\pi/4)-(\pi/4)\cos((\pi/2)t)$ (rad), and $q_{d,3}(t)=(\pi/4)+(\pi/4)\cos((\pi/2)t)(\mathrm{rad})$. In addition, the flux reference signal $\Psi_{d,i}(t)\in R, i\in\{1,2,3\}$, is $\Psi_{d,i}(t)=0.5$ (wb^2). The initial conditions of the electromechanical system in this simulation study were $q_1(0)=0$ (rad), $q_2(0)=-\pi/2$ (rad),

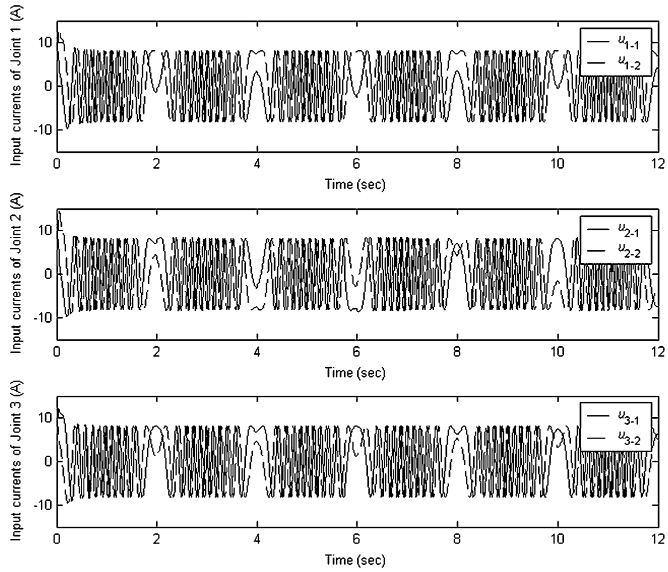

Fig. 2. Current inputs.

$q_3(0) = \pi/2$ (rad), and $\dot{q}_i(0) = 0$ (rad/s), $\psi_{i\_j}(0) = 0$ (wb), $i \in \{1,2,3\}, j \in \{2,3\}$. The value of design parameters was shown in Table I. The initial conditions of the adaptive decentralized control scheme were $\hat{\psi}_{i\_j}(0) = 1$ (wb), $\hat{\theta}_{i\_1}(0) = 1, \hat{a}_i(0) = 11, \hat{m}_i(0) = 0.095, \eta_i(0) = 5, \varepsilon_i(0) = 0.5, i \in \{1,2,3\}$, and $j \in \{1,2\}$. Fig. 1 indicates that all of the tracking errors converge to a residual set, centered at the origin. Fig. 2 displays that all the currents inputs are bounded.

V. Conclusion

This paper proposed an adaptive decentralized control scheme with a rotor-flux observer for tracking control of robot manipulators actuated by current-fed induction motors was proposed. Due to the decentralized manner, it can be implemented with simple hardware. To handle parametric uncertainty in the electromechanical systems, an adaptive law was designed such that all of the signals are bounded and the tracking errors of position, velocity, and rotor fluxes converge to a residual set, centered at the origin, whose size can be reduced by using proper value of design parameters. A satisfactory numerical study of a robot, PUMA 560, driven by current-fed induction motors was provided to verify the effectiveness of the proposed scheme.

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Modeling and Design of Polymer-Based Tunneling Accelerometers by ANSYS/MATLAB

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***Abstract*—A prototype design of an inexpensive polymer-based tunneling accelerometer is described in this paper. Instead of silicon, polymethyl methacrylate (PMMA) is used as the mechanical material. By using silicon molds fabricated by conventional lithography and wet-etching techniques in hot embossing, PMMA structures can be replicated within 20 min. The performance of the tunneling sensor can be estimated and improved based on mechanical-level analysis by ANSYS and system-level analysis by MATLAB. The nonlinear tunneling mechanism and electrostatic actuation are linearized using small-signal approximation. To enhance the stability and broaden the bandwidth of the tunneling accelerometer system, a feedback control system with one zero and two poles is designed. The dynamic range of the system is greatly enhanced. The bandwidth of the closed-loop system is approximately 15 kHz.**

***Index Terms*—Feedback control system, hot embossing, polymer, tunneling accelerometer.**

I. Introduction

Electron tunneling effect has been extensively investigated, developed, and used in many applications, since Binning and Rohrer were awarded the Nobel Prize for their original design of the scanning tunneling microscope (STM) in 1986 [1]–[4]. High-performance accelerometers are in great demand in many applications such as acoustic measurement, seismology, and navigation. Considerable research work on accelerometers has been reported by several groups [5]–[8]. Compared to other common and well-developed accelerometers such as capacitive, piezoresistive, piezoelectric accelerometers, tunneling accelerometers may easily achieve higher sensitivity and higher resolution with smaller size due to the exponential relationship between the tunneling current and the tunneling gap. However, tunneling sensors are usually more difficult to be fabricated than others. Since tunneling current can only be observed when the gap between the tunneling tip electrode and its counter electrode is in the range of 10 Å, tunneling sensors normally operate in closed-loop mode. Several models and systems were developed for tunneling accelerometers [6]–[8].

Polymer-based microelectromechanical systems (MEMS) have gained a broad theoretical interest and practical applications in the past 10 years [9]–[13]. Polymers offer many advantages for sensor technology. They are low cost, flexible, chemically and biologically compatible, and easy to be processed. Polymer microsensors are becoming more and more important, and can be low-cost alternatives to the silicon-based or glass-based microsensors.

Manuscript received July 27, 2004; revised March 17, 2005 and April 20, 2005. Recommended by Technical Editor I.-M. Chen. This work was supported in part by Grants NSF/LEQSF (2001-04)-RII-02, DARPA DAAD19-02-1-0338, and by NASA (2002)-Stennis-22.

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Digital Object Identifier 10.1109/TMECH.2005.852451