Implementation of Robust Adaptive Controller with Switching Action for Direct Drive Manipulators

Eung-Seok Kim, Mee-Seub Lim, Kwon-Ho Kim, and Kwang-Bae Kim

Abstract

In this paper, adaptive controller with switching action is designed for rigid body robot manipulators to ensure the uniform stability of the manipulator system without a priori knowledge of the unmodeled dynamics. It will be shown that the parameter estimates are bounded independent of the other closed-loop signals boundedness, and also shown that the tracking error belongs to the normalized error bound via mathematical analisys. The robustness and performance of the proposed adaptive controller is investigated for the two-link direct drive manipulator actuated by VRM(Variable Reluctance Motor).

I. Introduction

In conventional adaptive controllers for mechanical manipulators [1]-[3], the dynamics of an actuator and its servo system have not been considered to control the manipulator motion. As a result, the stability and performance of those controllers are degraded by the effect of these dynamics. In the implementation of a manipulator controller, we can not apply the control input to the mechanical manipulator but to the servo system of its actuator. Therefore, we must consider an unmodeled dynamics of manipulator system such as an actuator and its servo mechanism.

In [4], a robust adaptive controller for manipulators actuated by the permanent magnet dc motor has been analyzed to show the existence of a region of attraction from which all signals remain bounded. That controller, however, has not been represented to improve the output tracking performance, and not analyzed to control the manipulator actuated by other servo system. In [5], a robust adaptive controller with respect to the generalized unmodeled dynamics of manipulators has been represented to control the motion of manipulator. In that approach, stability of the closed-loop system is satisfied under the assumption that the upper bound of induced operator norm of the unmodeled dynamics or the stability margin of that excited by the control input is known. This assumption, however, is very restrictive to design a robust controller. In [6], a third order dynamic model including motor dynamics for robots actuated by dc motors was represented for high performance control at high operating speeds. It is drawbacks that the design model is complicated and the dynamics of a motor driving system is ignored and joint accelerations are required to adopt the conventional controllers [1]-[5] including the nonlinear adaptive controller presented in that paper.

We can regard the conventional manipulator model for motion control as the reduced-order model of full dynamics including the servo mechanisms. To design a robust adaptive controller with high performance, we use the reduced-order model instead of full model of manipulator system, and consider the effects of unmodeled dynamics and bounded disturbance in control system design. To guarantee the boundedness of parameter estimates independent of the boundedness of all other closed-loop signals, we first propose a parameter adaptation law with respect to unmodeled dynamics and bounded disturbances of robot manipulators. We also propose a passivity-based adaptive controller with switching action for compensation of unmodeled dynamics to guarantee the uniform stability of the closed-loop system. We show that the proposed adaptive controller ensures the boundedness of all signals in the closed-loop

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system and the tracking error belongs to the *normalized* residual error set. To show the robustness of proposed adaptive controller, we represent an experimental result for the two-link direct drive manipulator.

This paper is organized as follows. In Section II, we introduce a manipulator model with unmodeled dynamics and the control objective. Section III is devoted to design of robust adaptive controller with respect to unmodeled dynamics and bounded disturbance. The closed-loop system stability and output tracking performance are also investigated in that Section. The performance of the proposed controller will be tested by using an experiment in Section IV.

II. Problem Formulation

Consider the dynamic equation for an n degree-of-freedom rigid link manipulator. A manipulator model with unmodeled dynamics represented in [1],[4],[5], may be generalized as follows :

$$(D(q)+J)\ddot{q}+(D(q,\dot{q})+B)\dot{q}+G(q)=u+\eta+d \quad (1)$$

$$\eta=H_1[g_1(\dot{q})](t)+H_2[g_2(q)](t)+H_3[g_3(u)](t) \quad (2)$$

where

1) $q\in R^n$ is a joints position vector,
2) $D(q):R^n\to R^{n\cdot n}$ is a symmetric positive definite matrix of a link inertia for all $q\in R^n$,
3) $J\in R^{n\cdot n}$ is a constant diagonal positive definite matrix of a actuator inertia,
4) $C(q,\dot{q}):R^n\times R^n\to R^n$ is a Coriolis and centrifugal force vector,
5) $B\in R^{n\cdot n}$ is constant diagonal positive definite matrix of a actuator viscous friction,
6) $G(q):R^n\to R^n$ is a gravitational force vector,
7) $u\in R^n$ is a control input,
8) $d\in R^n$ is a bounded disturbance including the measurement error and Coulomb friction, etc.,
9) $\eta\in R^n$ is an external input due to unmodeled dynamics,

and $H_i, i=1,2,3,$ with appropriate dimensions, are linear operators with rational transfer matrices, representing the unmodeled part of the robot system dynamics with the actuator and its servo system dynamics. $g_i, i=1,2,3,$ are certain vector functions of $\dot{q},q,u,$ respectively. We make the following assumptions about the manipulator model (1)-(2) :

(A1) : $\|g_1(\dot{q})\|_\cdot \; \|g_2(q)\|_\infty\le f_{2(q)}$ for some known $f_1(\dot{q}),f_2(q)$ which are bounded for bounded $\dot{q},q,$, and $\|H_1\|_\infty\le\gamma_1,\|H_2\|_\infty\le\gamma_2$, for some unknown constants $\gamma_1>0,\gamma_2>0$;

(A2) : $\|g_3(u)\|_\infty\le\|u\|_\infty$ and $\|H_3\|_\infty\le\mu_m$, and , for some unknown constant $\mu_m>0$;

(A3) : $x^T[\dot{D_A}(q)-2C(q,\dot{q})]x=0,\forall_x\in R^n$;

(A4) : q_d, are bounded,

where we denote $\|\cdot\|$ as the Euclidean vector norm and $\|\cdot\|_\infty$ as the L_∞ vector norm or the induced operator norm, and $D_A(q)=D(q)+J$. Assumptions (A1)-(A2) represent that $g_1(\dot{q}),g_2(q),g_3(u)$ satisfy the relative boundedness conditions and H_1,H_2,H_3 gains of are finite. We note that the bounds of γ_1,γ_2,μ_m are not required to design an adaptive controller. Assumption (A3) is a necessary condition to satisfy the passivity property of the closed-loop system, and this can be satisfied by adjusting $D(q),C(q,\dot{q})$.

The control objective is, for a given desired position q_d to generate control input u for the manipulator (1)-(2) so that all signals in the closed-loop system are bounded and the joint position tracks q_d as close as possible.

III. Design Of Robust Adaptive Controller

In this section, we design a robust adaptive controller based on modifications of the passivity-based adaptive controller, and investigate the output tracking performance of the proposed controller. To do this we first use the signals represented in [2] as follows :

$$\dot{q}_r=\dot{q}_d-\Lambda q_e,\quad q_e=q-q_d, \quad (3)$$

$$\varepsilon=\dot{q}-\dot{q}_r=\dot{q}_e+\Lambda q_e, \quad (4)$$

where $\Lambda=\Lambda^T>0$. Let us define $\|\cdot\|_s$ as a supremum of the Euclidean vector norm, and define $\|X(t)\|_m$ for all real matrix $X(t)$ as follows :

$$\|X(t)\|_m=sup_t\left\{\sum_i\sum_j x(t)_{ij}^2\right\}^{\frac{1}{2}},\forall t\ge t_o, \quad (5)$$

where $x(t)_{ij}$ is an *ij*-th element of a matrix $X(t)$. Let us also define the parameter error $\tilde{\theta}=\hat{\theta}-\theta$ and $Y\in R^{n\cdot p}$ as

$$Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)=D_A(q)\ddot{q}_r+C(q,\dot{q})+G(q)+B\dot{q} \quad (6)$$

with $\theta\in R^p$ the unknown constant vector. In consideration of the unmodeled dynamics, bounded disturbance, parameter variations, we propose the robust control law with switching action as follows :

$$\begin{aligned}u&=\hat{D}_A(q)\ddot{q}_r+\hat{C}(q,\dot{q})+\hat{G}(q)-\beta_1\xi_1-\beta_2\xi_2-\beta_3\xi_3\\&=Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\theta}-\beta_1\xi_1-\beta_2\xi_2-\beta_3\xi_3\end{aligned} \quad (7)$$

where $\xi_i=[\xi_{i1},\cdots,\xi_{in}]^T,i=1,2,3$ and $\xi_{ik},k=1,\cdots,n,$, are as follows :

$$\xi_{1k}=\begin{cases} \|\varepsilon\|_s sign[\varepsilon_k], & \text{if } \|\varepsilon\|_s \|\varepsilon_k\| > \delta_1, \\ \varepsilon_k, & otherwise, \end{cases} \quad (8)$$

$$\xi_{2k}=\begin{cases} \|f_1+f_2\|_\infty^2 \|\varepsilon\|_s sign[\varepsilon_k], & \text{if } \|f_1+f_2\|_\infty \|\varepsilon\|_s \|\varepsilon_k\| > \delta_2, \\ \|f_1+f_2\|_\infty^2 \varepsilon_k, & otherwise, \end{cases} \quad (9)$$

$$\xi_{3k}=\begin{cases} \|Y\|_m^2 \|\varepsilon\|_s sign[\varepsilon_k], & \text{if } \|Y\|_m^2 \|\varepsilon\|_s \|\varepsilon_k\| > \delta_3, \\ \|Y\|_m^2 \varepsilon_k, & otherwise, \end{cases} \quad (10)$$

where $\beta_i, \delta_i, i=1,2,3,$ are some positive constants. Substituting (7) into (1) we obtain the closed-loop error system as

$$D_A(q)\dot{\varepsilon}+C(q,\dot{q})\varepsilon = Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\tilde{\theta}-\beta_1\xi_1-\beta_2\xi_2-\beta_3\xi_3+\eta+d. \quad (11)$$

Normalizing data as well as eliminating the pure integral action of adaptation law guarantees the boundedness of the estimates, irrespective of the boundedness of other signals in the closed-loop system [7]. This approach, however, does not satisfy the perfect cancellation of the manipulator nonlinearity and parameter uncertainty. In order to satisfy the perfect cancellation of those, we first propose the modified parameter adaptation law of [7]-[8] which can guarantees the boundedness of the estimates without data normalization as follows :

$$\dot{\tilde{\theta}}=-\Gamma Y^T(q,\dot{q},\dot{q}_r,\ddot{q}_r)\varepsilon-\Gamma\sigma\hat{\theta}, \quad (12)$$

$$\sigma=\begin{cases} 0, & \text{if } \|\hat{\theta}\| \le M_0, \\ \sigma_0\|Y^T\varepsilon\|^2, & \text{if } \|\hat{\theta}\| \le M_0, \end{cases} \quad (13)$$

where . $\Gamma=\Gamma^T>0, \sigma_0>0$ The above proposed adaptation law (12)-(13) guarantees the boundedness of the parameter estimates independent of other signals boundedness, and the control law (7)-(10) ensures the uniform stability of the closed-loop system.

Theorem : For $\mu_m \in (0,1)$ and bounded $\hat{\theta}$, all signals in the closed-loop system (1)-(2), (7)-(11), (12)-(13) are bounded, and there exists a finite time $t_f \ge t_0 \ge 0$ such that $\|\cdot\|_\infty, \|\cdot\|_s, \|\cdot\|_m$ are positive constants for all $t \ge t_f > t_0$. Furthermore, the tracking error belongs to the normalized residual error set E given by

$$E=\left\{\varepsilon \mid \lim_{T\to\infty} \sup_T \frac{1}{T}\int_{t_f}^{t_f+T}\|\varepsilon\|^2 dt \le \frac{\gamma_\mu^2 \Delta_1^2}{B_m^2}\right\} \quad (14)$$

where $\gamma_\mu, \Delta_1, \Delta_2,$ and B_m are some positive constants.

Proof : We show that the parameter estimates are bounded independent of the boundedness of other signals in the closed-loop system. Let us define the positive definite function as follows :

$$V_1=\frac{1}{2}\tilde{\theta}\Gamma^{-1}\tilde{\theta}. \quad (15)$$

Derivating V_1 we obtain

$$\dot{V}_1 \le -\sigma\|\hat{\theta}\|^2+\|Y^T\varepsilon\|\|\hat{\theta}\|. \quad (16)$$

If $\|\hat{\theta}\| \le M_0$, $\|\hat{\theta}\|$ then is bounded by M_0 . Therefore we consider only for the otherwise case. Substituting (13) into (16), we obtain

$$\dot{V}_1 \le -\sigma_0\left\{\|Y^T\varepsilon\|\|\hat{\theta}\|-\frac{1}{2\sigma_0}\right\}^2+\frac{1}{4\sigma_0} \quad (17)$$

where $\dot{d}_1<0$ whenever $V_1>V_{10}$ for some fixed constant $V_{10}>0$. Hence, $\hat{\theta}$ and $\tilde{\theta}$ are bounded independent of the boundedness of other signals in the closed-loop system. This implies that uniform stability of the closed-loop system is satisfied with perfect cancellation of the nonlinearity. Let us define the positive definite function as

$$V_2=\frac{1}{2}\{\varepsilon^T D_A(q)\varepsilon+\tilde{\theta}^T\Gamma^{-1}\tilde{\theta}\}. \quad (18)$$

derivating

$$\begin{aligned}\dot{V}_2 = & \frac{1}{2}\varepsilon^T\{\dot{D}_A-2C\}\varepsilon+\varepsilon^T Y\tilde{\theta}-\tilde{\theta}^T Y^T\varepsilon-\sigma\tilde{\theta}^T\hat{\theta} \\ & -B_1\varepsilon^T\xi_1-B_2\varepsilon^T\xi_2-B_3\varepsilon^T\xi_3+\varepsilon^T\eta+\varepsilon^T d.\end{aligned} \quad (19)$$

In the above, we can show that $\varepsilon^T Y\tilde{\theta}$ the manipulator nonlinearity is canceled perfectly by the proposed parameter adaptation law which satisfies the independent boundedness of $\hat{\theta}$. Considering (A1)-(A2), we can write the above equation as

$$\begin{aligned}\dot{V}_2 = & -B_1\varepsilon^T\xi_1-B_2\varepsilon^T\xi_2-B_3\varepsilon^T\xi_3-\sigma\tilde{\theta}^T\hat{\theta}+\gamma_m \\ & \{\|g_1\|_\infty+\|g_2\|_\infty\}\|\varepsilon\|+\mu_m\|u\|_\infty\|\varepsilon\|+\gamma_d\|\varepsilon\|\end{aligned} \quad (20)$$

where $\gamma_d \ge \|d\|, \gamma_m=\max(\gamma_1,\gamma_2)$. We consider only for the case of $\|\cdot\|>\delta_i, i=1,2,3,$ in (8)-(10) since we can easily shown that all signals in the closed-loop system are bounded for otherwise case. Using the control input (7) with (8)-(10), we obtain

$$\begin{aligned}\dot{V}_2 \le & -B_1\mu_1\|\varepsilon_s\|\varepsilon\|-\sigma\tilde{\theta}^T\hat{\theta}+\gamma_d\|\varepsilon\| \\ & -B_2\mu_1\|f_1+f_2\|_\infty^2\|\varepsilon\|_s\|\varepsilon\| \\ & +\gamma_m\|\varepsilon\|\{\|g_1\|_\infty+\|g_2\|_\infty\}\|\varepsilon\| \\ & -B_3\mu_1\|Y\|_m^2\|\varepsilon\|_s\|\varepsilon\|+\mu_m\gamma_{\theta 2}\|Y\|_m\|\varepsilon\|\end{aligned} \quad (21)$$

where $\mu_1(=1-\mu_m), \gamma_{\theta 2}(\ge\|\theta\|)$ are positive constants. We note that the inequality $\|\varepsilon\|_s \ge \|\varepsilon\|$ is satisfied, and that the inequality $-\sigma\tilde{\theta}^T\hat{\theta} \ge 0$ is also satisfied by (13). Using these relationships, we can write (21) as follows :

$$\begin{aligned}\dot{V}_2 \le - & B_1\mu_1\left\{\|\varepsilon\|-\frac{\gamma_d}{2\beta_1\mu_1^2}\right\}^2+\frac{\gamma_d^2}{4\beta_1\mu_1} \\ & \beta_2\mu_1\left\{\|f_1+f_2\|_\infty\|\varepsilon\|-\frac{\gamma_m}{2\beta_2\mu_1^2}\right\}^2+\frac{\gamma_m^2}{4\beta_2\mu_1}\end{aligned}$$

$$\beta_3\mu_1\left\{ \| Y\|_m \|\varepsilon\| - \frac{\mu_m\gamma_{\theta 2}}{2\beta_3\mu_1^2} \right\}^2 + \frac{\mu_m^2\gamma_{\theta 2}^2}{4\beta_3\mu_1} \tag{22}$$

where $\dot{V}_2 < 0$ whenever $V_2 > V_{20}$ for some positive constant V_{20}, and thus V_2 is uniformly bounded by some $0 < V_{20} < V_{20} < \overline{V}_{20} < \infty$. This implies that $\varepsilon, \tilde{\theta}$ are also bounded without *a priori* knowledge of unmodeled dynamics, and all other signals in the closed-loop system remain bounded. Hence, there exists a finite time $t_f \geq t_0$ such that $\|\cdot\|_\infty, \|\cdot\|_s, \|\cdot\|_m$ are positive constants for all $t \geq t_f$. Using $-\sigma\tilde{\theta}^T \leq 0$ and the boundedness of all signals, the equation (20) can be rewritten as follows :

$$\dot{V}_2 \leq -\frac{B_m}{2}\|\varepsilon\|^2\left\{\|\varepsilon\| - \frac{\gamma_\mu\Delta_1}{\beta_m^2}\right\}^2 + \frac{\gamma_\mu^2\Delta_1^2}{2\beta_m} \tag{23}$$

where $\gamma_\mu = \max[\gamma_d, \gamma_m, \mu_m]$, and β_m, Δ_1 are positive constants which satisfy the following relationships :

$$\begin{aligned}\beta_m &= \beta_1 + \beta_2\|f_1 + f_2\|_\infty^2 + \beta_3\|Y\|_m^2, \\ \Delta_1 &= \|g_1\|_\infty + \|g_2\|_\infty + \|\mu\|_\infty + 1, \forall t \geq t_f \geq t_0\end{aligned} \tag{24}$$

Integrating both sides of (23) t_f to T , dividing by T, and taking the limit as $T \to \infty$, we obtain the following

$$E = \left\{\varepsilon \mid \lim_{T\to\infty} \sup_T \frac{1}{T}\int_{t_f}^{t_f+T}\|\varepsilon\|^2 dt \leq \frac{\gamma_\mu^2\Delta_1^2}{\beta_m^2}\right\} \tag{25}$$

In (23)-(25), we have shown that unmodeled dynamics, bounded disturbances, manipulator nonlinearity are *normalized* by their upper bounds, and also shown that the average of the tracking error is *normalized* by β_m corresponding to the upper bound of the unmodeled dynamics and manipulator nonlinearity.

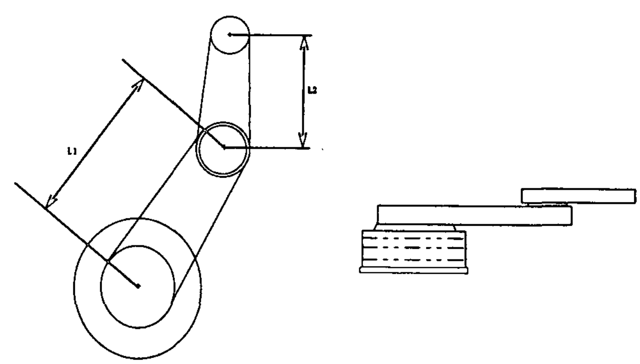
IV. Experimental Result

The adaptive controller proposed in this paper has been tested by the experiment referred to the two-link direct drive planar manipulator manufactured by Control Systems Group in KIST. The schematic drawing of the two-link planar robot manipulator used in the experiment is represented as shown in Fig. 1. The types of motors for link 1 and link 2 are NSK RS-1410 and RS-608, respectively. A detailed specification of the motor is given in [9]. The mechanical parameters of manipulator system are represented in the table 1.

Table 1. The manipulator system parameters

Parameter	Link 1	Link 2
mass	22 Kg	12 Kg
length	0.395 m	0.265 m
rotor inertia	0.2675 $Kg \cdot m^2$	0.0077 $Kg \cdot m^2$
mass of motor	73 Kg	13 Kg

The major part of the motor driving system is CRPWM(current regulated pulse width modulation) inverter for regulation of three phase current. The configuration of the overall control system for the direct drive manipulator is represented as shown in Fig. 2. The main processor is MVME-147 the VME-based 32 bit microprocessor operated by VxWorks[10] the real-time operating system. The control program is coded in C-Language, and compiled in SUN SPARC-I workstation, and downloaded into MVME-147 through the MVME-712 the data transition module, and operated by the multi-task scheduling method allowing in the VxWorks[9]. MACRO-6781 the local I/O bus-based analog output module is used to send the control signals to the motor driving system. HIMV-606A the pulse count module is used to receive the position data from resolvers. The resolution of the resolvers (153,600 counts/rev.) allow numerical differentiation to advantageously replace the velocity sensor. Therefore, in this experiment, we do not use the velocity sensors to reduce the effect of measurement errors of velocities due to phase lag and analog to digital data conversion and low resolution of velocity sensors, etc. The tasks to generate the control signals for each joint execute at every 5 [msec] using timer interrupt service routine, and the total execution time of each task is less than 5 [msec].



(a) Plane Drawing. (b) Elevation Drawing.

Fig. 1. Schematic drawing of a two-link manipulator.

The performance of the proposed adaptive controller, for the two-link direct drive manipulator, is compared to that of the conventional adaptive controller represented in [2]. In this experiment, no load is attached to the second link of the manipulator. The initial values of the parameter estimates are taken to be zero, that is, the parameters of the manipulator system are assumed to be unknown. In the proposed case, the controller gains are chosen as follows: $\Lambda = [20\ 5]^T$, $\beta_1 = 10$, $\beta_2 = 10$, $\beta_3 = 0.5$, $\delta_1 = 0.5$, $\delta_2 = 0.5$, $\delta_3 = 5$. The signals to guarantee the relative boundedness for external disturbance due to unmodeled dynamics are as follows: $f_1(\dot{q}) = \| \dot{q}_1 \| ..+ \| \dot{q}_2 \| .., f_2(q) = \| q_1 \| ..+ \| q_2 \| ..$. The parameter adaptation gains are as follows: $\sigma_0 = 0.01$, $M_0 = 20, \Gamma = diag\{2, 2, 2, 2, 10, 10, \}$. In the conventional case of [2], the controller gains are as follows: $K_D = [10\ 10]^T, \Lambda = [20\ 5]^T$ and the parameter adaptation law is the same as in (12) without switching-σ term. The desired positions are represented in Fig. 3. It can be shown that the position errors in the proposed case are bounded as shown in Figs. 4-5. The norm of the parameter estimates is represented in Fig. 6. In the conventional case, the instability of the closed-loop system was found, and also adequate choices of the controller gains are difficult and important to satisfy the signal boundedness.

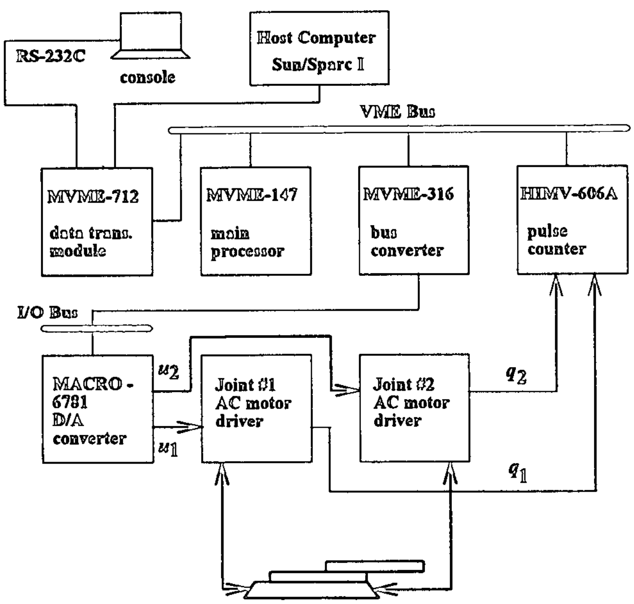


Fig. 2. The configuration of the overall control system.

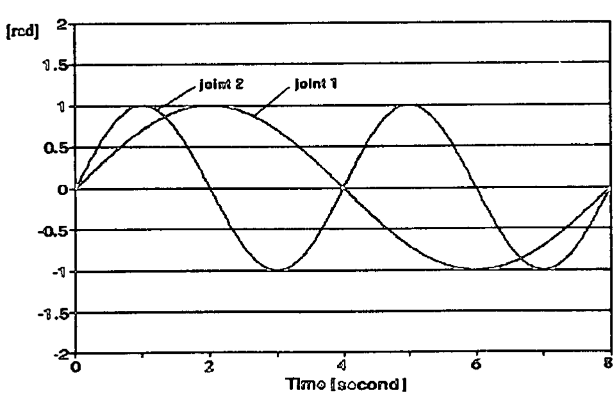


Fig. 3. The desired positions.

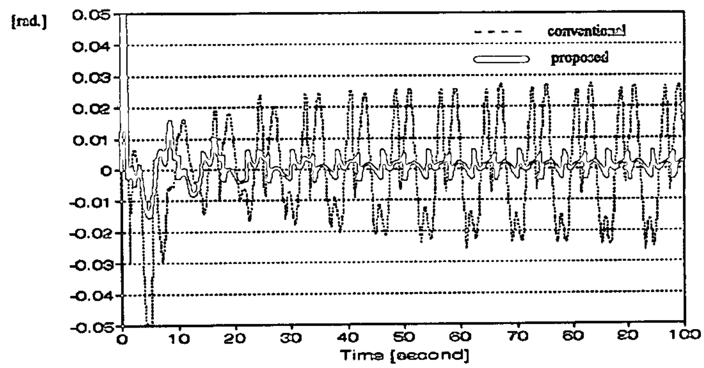


Fig. 4. The position error of joint 1.

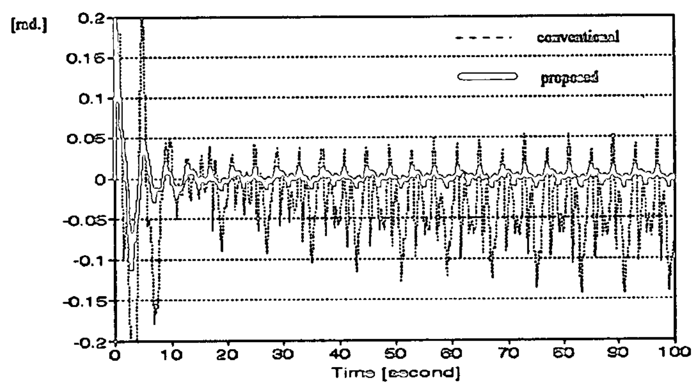


Fig. 5. The position error of joint 2.

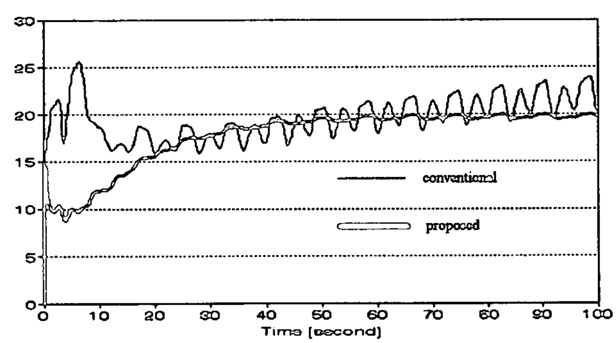


Fig. 6. The parameter estimates norm.

V. Conclusion

In this paper, a robust adaptive controller was proposed for robot manipulators without *a priori* knowledge of the unmodeled dynamics of that manipulator. It was shown that the parameter adaptation law ensures the boundedness of the parameter estimates without data normalization, and shown that the controller with switching action guarantees the uniform stability of the closed-loop system, and also shown that the average of the output tracking error is *normalized* by the proportional constant corresponding to the upper bound of the unmodeled dynamics and manipulator nonlinearity. The proposed adaptive controller was implemented for the two-link direct drive manipulator system manufactured by Control Systems Group in KIST, and the enhanced robustness of that controller was tested via experimental results.

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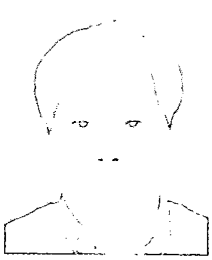

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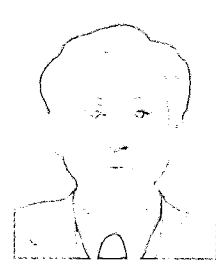

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