A Robust Adaptive Control of Robot Manipulator Based on TMS320C80

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Abstract: We propose a new technique to the design and real-time implementation of an adaptive controller for robotic manipulator based on digital signal processors in this paper. The Texas Instruments DSPs(TMS320C80) chips are used in implementing real-time adaptive control algorithms to provide enhanced motion control performance for dual-arm robotic manipulators. In the proposed scheme, adaptation laws are derived from model reference adaptive control principle based on the improved direct Lyapunov method. The proposed adaptive controller consists of an adaptive feed-forward and feedback controller and time-varying auxiliary controller elements. The proposed control scheme is simple in structure, fast in computation, and suitable for real-time control. Moreover, this scheme does not require any accurate dynamic modeling, nor values of manipulator parameters and payload. Performance of the proposed adaptive controller is illustrated by simulation and experimental results for a dual arm robot consisting of two 4-d.o.f. robots at the joint space and cartesian space.

Keywords: Adaptive Control, DSP(TMS320C80), Dual-Arm Robot, Real Time Control, Real-Time Implementation

1. INTRODUCTION

Currently there are much advanced techniques that are suitable for servo control of a large class of nonlinear systems including robotic manipulators [1-3]. Since the pioneering work of Dubowsky and DesForges [4], the interest in adaptive control of robot manipulators has been growing steadily [5-8]. This growth is largely due to the fact that adaptive control theory is particularly well-suited to robotic manipulators whose dynamic model is highly complex and may contain unknown parameters. However, implementation of these algorithms generally involves intensive numerical computations [9, 10].

Current industrial approaches to the design of robot arm control systems treat each joint of the robot arm as a simple servomechanism. This approach models the time varying dynamics of a manipulator inadequately because it neglects the motion and configuration of the whole arm mechanism. The changes in the parameters of the controlled system are significant enough to render conventional feedback control strategies ineffective. This basic control system enables a manipulator to perform simple positioning tasks such as in the pick-and-place operation. However, joint controllers are severely limited in precise tracking of fast trajectories and sustaining desirable dynamic performance for variations of payload and parameter uncertainties [11, 12]. In many servo control applications the linear control scheme proves unsatisfactory, therefore, a need for nonlinear techniques is increasing.

Digital signal processors (DSP's) are special purpose microprocessors that are particularly suitable for intensive numerical computations involving sums and products of variables. Digital versions of most advanced control algorithms can be defined as sums and products of measured variables, thus can naturally be implemented by DSP's. DSPs allow straightforward implementation of advanced control algorithms that result in improved system control. Single and/or multiple axis control systems can be controlled by a single DSP. Adaptive and optimal multivariable control methods can track system parameter variations. Dual control, learning, neural networks, genetic algorithms and Fuzzy Logic control methodologies are all among the digital controllers implementable by a DSP [13, 14]. In addition, DSP's are as fast in computation as most 32-bit microprocessors and yet at a fraction of their prices. These features make them a viable computational tool for digital implementation of advanced controllers. High performance DSPs with increased levels of integration for functional modules have become the dominant solution for digital control systems. Today's DSPs with performance levels ranging from 5 to 5400 MIPS are on the market with price tags as low as $3 [15, 16]. In order to develop a digital servo controller one must carefully consider the effect of the sample-and-hold operation, the sampling frequency, the computational delay, and that of the quantization error on the stability of a closed-loop system [17]. Moreover, one must also consider the effect of disturbances on the transient variation of the tracking error as well as its steady-state value [18-20].

This paper describes a new approach to the design of adaptive control system and real-time implementation using digital signal processors for robotic manipulators to achieve the improvement of speedness, repeating precision, and tracking performance at the joint and cartesian space. This paper is organized as follows : In Section 2, the dynamic model of the robotic manipulator is derived. Section 3 derives adaptive control laws based on the model reference adaptive control theory using the improved Lyapunov second method. Section 4 presents simulation and experimental results obtained for a dual-arm robot. Finally, Section 5 discusses the findings and draws some conclusions

2. SYSTEM MODELING

The dynamic model of a manipulator-plus-payload is derived and the tracking control problem is stated in this section.

Let us consider a nonredundant joint robotic manipulator in which the $n\times 1$ generalized joint torque vector $\tau(t)$ is related to the $n\times 1$ generalized joint coordinate vector q(t) by the following nonlinear dynamic equation of motion

$$D(q)\,\ddot{q} + N(q,\dot{q}) + G(q) = \tau(t) \tag{1}$$

where $D(q)$ is the $n\times n$ symmetric positive-definite inertia matrix, $N(q,\dot{q})$ is the $n\times 1$ coriolis and centrifugal torque vector, and $G(q)$ is the $n\times 1$ gravitational loading vector.

Equation (1) describes the manipulator dynamics without any payload. Now, let the n×1 vector X represent the end-effector position and orientation coordinates in a fixed task-related cartesian frame of reference. The cartesian position, velocity, and acceleration vectors of the end-effector are related to the joint variables by

$$X(t) = \Phi(q)$$
$$X(t) = J(q)\,\dot{q}(t) \tag{2}$$
$$X(t) = \dot{J}(q,\dot{q})\,\dot{q}(t) + J(q)\,\ddot{q}(t)$$

where Φ(q) is the n×1 vector representing the forward kinematics and J(q) = [∂ Φ(q)/∂q] is the n×n Jacobian matrix of the manipulator.

Let us now consider payload in the manipulator dynamics. Suppose that the manipulator end-effector is firmly grasping a payload represented by the point mass ΔM_p. For the payload to move with acceleration $\ddot{X}(t)$ in the gravity field, the end-effector must apply the n×1 force vector $T(t)$ given by

$$T(t) = \Delta M_p\,[\,\ddot{X}(t) + g\,] \tag{3}$$

where g is the n×1 gravitational acceleration vector.

The end-effector requires the additional joint torque

$$\tau_f(t) = J(q)^T\,T(t) \tag{4}$$

where superscript T denotes transposition. Hence, the total joint torque vector can be obtained by combining equations (1) and (4) as

$$J(q)^T\,T(t) + D(q)\,\ddot{q} + N(q,\dot{q}) + G(q) = \tau(t) \tag{5}$$

Substituting equations (2) and (3) into equation (5) yields

$$\begin{aligned}&\Delta M_p\,J(q)^T[J(q)\,\ddot{q} + \dot{J}(q,\dot{q})\,\dot{q} + g]\\ &+ D(q)\ddot{q} + N(q,\dot{q}) + G(q) = \tau(t)\end{aligned} \tag{6}$$

Equation (6) shows explicity the effect of payload mass ΔM_p on the manipulator dynamics. This equation can be written as

$$\begin{aligned}&[D(q) + \Delta M_p J(q)^T J(q)]\,\ddot{q} + [N(q,\dot{q})\\ &+ \Delta M_p J(q)^T \dot{J}(q,\dot{q})\,\dot{q}] + [G(q) + \Delta M_p J(q)^T g] = \tau(t)\end{aligned} \tag{7}$$

where the modified inertia matrix $[D(q) + \Delta M_p J(q)^T J(q)]$ is symmetric and positive-definite. Equation (7) constitutes a nonlinear mathematical model of the manipulator-plus-payload dynamics.

3. ADAPTIVE CONTROLLER

The manipulator control problem is to develop a control scheme which ensures that the joint angle vector *q*(*t*) tracks any desired reference trajectory $q_r(t)$, where $q_r(t)$ is an n×1 vector of arbitrary time functions. It is reasonable to assume that these functions are twice differentiable, that is, desired angular velocity $\dot{q}_r(t)$ and angular acceleration $\ddot{q}_r(t)$ exist and are directly available without requiring further differentiation of $q_r(t)$. It is desirable for the manipulator control system to achieve trajectory tracking irrespective of payload mass ΔM_p.

The controllers designed by the classical linear control scheme are effective in fine motion control of the manipulator in the neighborhood of a nominal operating point P_o. During the gross motion of the manipulator, operating point P_o and consequently the linearized model parameters vary substantially with time. Thus it is essential to adapt the gains of the feedforward, feedback, and PI controllers to varying operating points and payloads so as to ensure stability and trajectory tracking by the total control laws. The required adaptation laws are developed in this section. Fig. 1 represents the block diagram of adaptive control scheme for robotic manipulator. Nonlinear dynamic equation (7) can be written as

$$\begin{aligned}\tau(t) &= D^*(\Delta M_p, q, \dot{q})\,\ddot{q}(t) + N^*(\Delta M_p, q, \dot{q})\,\dot{q}(t)\\ &+ G^*(\Delta M_p, q, \dot{q})\,q(t)\end{aligned} \tag{8}$$

where D^*, N^*, and G^* are n×n matrices whose elements are highly nonlinear functions of ΔM_p, q, and $\dot{q}$.

In order to cope with changes in operating point, the controller gains are varied with the change of external working condition. This yields the adaptive control law

$$\begin{aligned}\tau(t) &= [P_A(t)\,\ddot{q}_r(t) + P_B(t)\,\dot{q}_r(t) + P_C(t)\,q_r(t)\,]\\ &+ [P_V(t)\,\dot{E}(t) + P_P(t)\,E(t) + P_I(t)\,]\end{aligned} \tag{9}$$

where $P_A(t)$, $P_B(t)$, $P_C(t)$ are feedforward time-varying adaptive gains, and $P_P(t)$ and $P_V(t)$ are the feedback adaptive gains, and $P_I(t)$ is a time-varying control signal corresponding to the nominal operating point term, generated by a feedback controller driven by position tracking error *E*(*t*) defined as $q_r(t) - q(t)$.

Thus, the gains of adaptive control low in equation (9) are defined as follows:

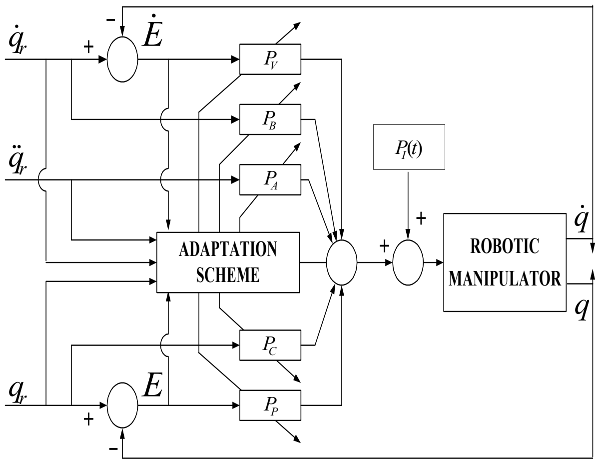

Fig. 1. Adaptive control scheme of Robotic Manipulator with eight joint.

$$P_A(t)=a_1[p_{a1}E+p_{a2}\dot{E}][\ddot{q}_r]^T + a_2\int_0^t [p_{a1}E+p_{a2}\dot{E}][\ddot{q}_r]^T dt + p_a(0) \tag{10}$$

$$P_B(t)=b_1[p_{b1}E+p_{b2}\dot{E}][\dot{q}_r]^T + b_2\int_0^t [p_{b1}E+p_{b2}\dot{E}][\dot{q}_r]^T dt + p_b(0) \tag{11}$$

$$P_C(t)=c_1[p_{c1}E+p_{c2}\dot{E}][q_r]^T + c_2\int_0^t [p_{c1}E+p_{c2}\dot{E}][q_r]^T dt + p_c(0) \tag{12}$$

$$P_I(t)=\lambda_2[p_{i2}E]+\lambda_1\int_0^t [p_{i1}E]^T dt + p_i(0) \tag{13}$$

$$P_P(t)=p_1[p_{p1}E+p_{p2}\dot{E}][E]^T + p_2\int_0^t [p_{p1}E+p_{p2}\dot{E}][E]^T dt + p_p(0) \tag{14}$$

$$P_V(t)=v_1[p_{v1}E+p_{v2}\dot{E}][\dot{E}]^T + v_2\int_0^t [p_{v1}E+p_{v2}\dot{E}][\dot{E}]^T dt + p_v(0) \tag{15}$$

where $[p_{p1}, p_{v1}, p_{c1}, p_{b1}, p_{a1}]$ and $[p_{p2}, p_{v2}, p_{c2}, p_{b2}, p_{a2}]$ are positive and zero/positive scalar adaptation gains, which are chosen by the designer to reflect the relative significance of position and velocity errors E and $\dot{E}$.

4. SIMULATION AND EXPERIMENT

4.1 Simulation

This section represents the simulation results of the position and velocity control of a eight-link robotic manipulator by the proposed adaptive control algorithm, as shown in Fig.2, and discusses the advantages of using joint controller based-on DSPs for motion control of a dual-arm robot. The adaptive scheme developed in this paper will be applied to the control of a dual-arm robot with eight axes. Fig.2 represents link coordinates of the dual-arm robot. Table 1 lists values of link parameters of the robot.

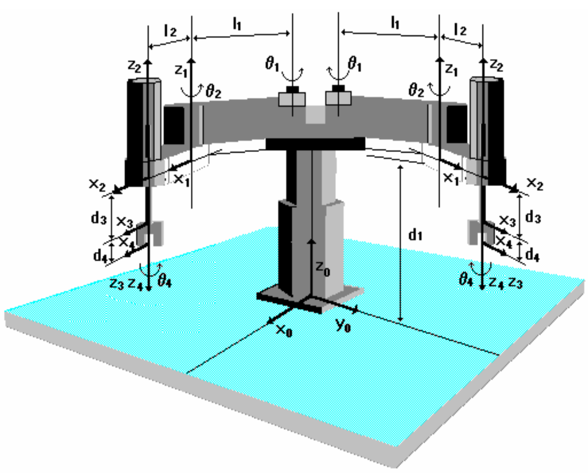

Fig.2. Link coordinates of dual-arm robot.

Table 2 lists motor parameters. Consider the dual-arm robot with the end-effector grasping a payload of mass ΔM_p. The emulation set-up consists of a TMS320 evm DSP board and a Pentium IV personal computer (PC). The TMS320 evm card is an application development tool which is based on the TI's TMS320C80 floating-point DSP chip with 50ns instruction cycle time. The adaptive control algorithm is loaded into the DSP board, while the manipulator, the drive system, and the command generator are simulated in the host computer in C language. The communication between the PC and the DSP board is done via interrupts. These interrupts are managed by an operating system called A shell which is an extension of Windows9x. It is assumed that drive systems are ideal, that is, the actuators are permanent magnet DC motors which provide torques proportional to actuator currents, and that the PWM inverters are able to generate the equivalent of their inputs.

Table 1 Link parameters of robot.

Mass of link(kg)		**Length of link(kg)**		**Inertia of link(kg)**		**Gear ratio of link**	
m1	15.0067	l1	0.35	I1	0.1538	r1	1/100
m2	8.994	l2	0.3	I2	0.0674	r2	1/80
m3	3.0	l3	0.175	I3	0.045	r3	1/200
m4	1.0	l4	0.007	I4	0.0016	r4	1/75
m5	15.067	l5	0.35	I5	0.1538	r5	1/100
m6	8.994	l6	0.3	I6	0.0674	r6	1/80
m7	3.0	l7	0.175	I7	0.045	r7	1/200
m8	1.0	l8	0.007	I8	0.0016	r8	1/75

Table 2 Motor parameters of robot.

Rotor inertia ($kg \cdot m^2$)		**Torque constant (K m/a)**		**Back emf constant (V s/rad)**		**Amaturewinding resistance(ohms)**	
Jm1	5.0031×10^5	Ka1	21.4839×10^2	Kb1	214.8592×10^3	Ra1	1.5
Jm2	1.3734×10^5	Ka2	20.0124×10^2	Kb2	200.5352×10^3	Ra2	4.2
Jm3	0.8829×10^5	Ka3	20.0124×10^2	Kb3	200.5352×10^3	Ra3	9
Jm4	0.2256×10^5	Ka4	17.6580×10^2	Kb4	176.6620×10^3	Ra4	20
Jm5	5.0031×10^5	Ka5	21.4839×10^2	Kb5	214.8592×10^3	Ra5	1.5
Jm6	1.3734×10^5	Ka6	20.0124×10^2	Kb6	200.5352×10^3	Ra6	4.2
Jm7	0.8829×10^5	Ka7	20.0124×10^2	Kb7	200.5352×10^3	Ra7	9
Jm8	0.2256×10^5	Ka8	17.6580×10^2	Kb8	176.6620×10^3	Ra8	20

In all simulations the load is assumed to be unknown. The adaptive control algorithm given in equation (10) and parameter adaptation rules (28) – (33) as are used for the motion control of robot. The parameters associated with adaptation gains are selected by hand turning and iteration as $\lambda_1 = 0.5$, $\lambda_2 = 0.02$, $a_1 = 0.2$, $a_2 = 0.3$, $b_1 = 0.01$, $b_2 = 0.3$, $c_1 = 0.05$, $c_2 = 0.1$, $P_1 = 10$, $P_2 = 20$, $u_1 = 0.1$, $u_2 = 10$, $P_{a1} = 10^{-5}$, $P_{a2} = 10^{-4}$, $P_{b1} = 20$, $P_{b2} = 30$, $P_{c1} = 10$, $P_{c2} = 15$, $P_{p1} = 0.5$, $P_{p2} = 0.4$, $P_{v1} = 0.01$, and $P_{v2} = 0.05$.

It is assumed that $\omega_1 = \omega_2 = 10 rad/\sec$, $\xi_1 = \xi_2 = 1$, and $S_1 = 80I$, $S_2 = 25I$ in the reference model. The sampling time is set as 0.001 sec. Simulations are performed to evaluate the position and velocity control of each joint under the condition of payload variation, inertia parameter uncertainty, and reference trajectory variation. Control performance for the reference trajectory variation is tested for four different position reference trajectories C and velocity reference trajectories D for each joint. As can be seen in Figs. 3 to 4, position reference trajectories C and velocity reference trajectory D consist of four different trajectories for joints 1, 2, 3, and 4.

The performance of DSP-based adaptive controller is evaluated in tracking errors of the position and velocity for the four joints.

The results of trajectory tracking of each joint in the different position cases are shown in Fig.'s 3～4. Fig. 3 shows results of angular position trajectory tracking and parameter uncertainties (6%) for each joint with a 4 kg payload and parameter uncertainties (6%) for reference trajectory C. Fig. 4 shows position trajectory tracking error for each joint with a 4 kg payload and parameter uncertainties (6%) for reference trajectory D. As can be seen from these results, the DSP-based adaptive controller represents extremely good performance with very small tracking error and fast adaptation response under the payload and parameter uncertainties.

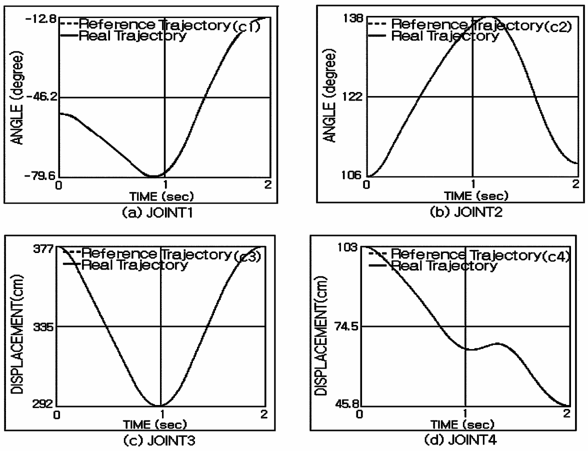

Fig. 3. (a)-(d) Position tracking performance of each joint with 4kg payload and inertia parameter uncertainty (6%) for reference trajectory C.

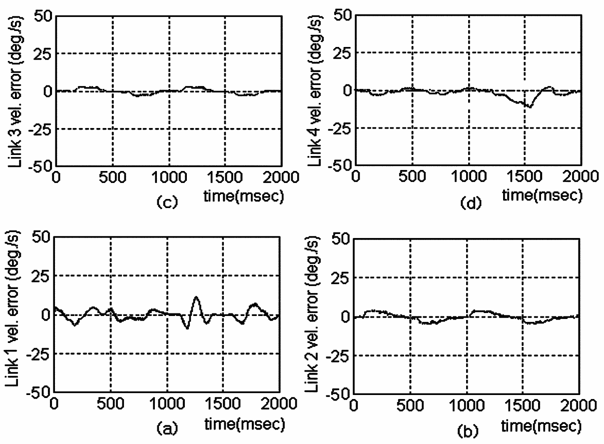

Fig. 4. (a)-(d) Velocity tracking error of each joint with 4kg payload and inertia parameter uncertainty(6%) for reference trajectory D.

4.2 Experiment

Fig. 5. Experimental set-up.

The performance test of the proposed adaptive controller has been performed for the dual-arm robot at the joint space and cartesian space. At the cartesian space, it has been tested for the peg-in-hole tasks, repeating precision tasks, and trajectory tracking for D-shaped reference trajector. At the joint space, it has been tested for the trajectory tracking of angular position and velocity for a dual-arm robot made in Samsung Electronics Company in Korea. Fig. 5 represents the experimental set-up equipment. To implement the proposed adaptive controller, we used our own developed TMS320C80 assembler software. Also, the TMS320C80 emulator has been used in experimental set-up. At each joint of a dual-arm robot, a harmonic drive (with gear reduction ratio of 100 : 1 for joint 1 and 80 : 1 for joint 2) has been used to transfer power from the motor, which has a resolver attached to its shaft for sensing angular velocity with a resolution of 8096 (pulses/rev). Fig. 6 represents the schematic diagram of control system of dual-arm robot. And Fig. 7 represents the block diagram of the interface between the PC, DSP, and dual-arm robot.

The performance test in the joint space is performed to evaluate the position and velocity control performance of the four joints under the condition of payload variation, inertia parameter uncertainty, and change of reference trajectory.

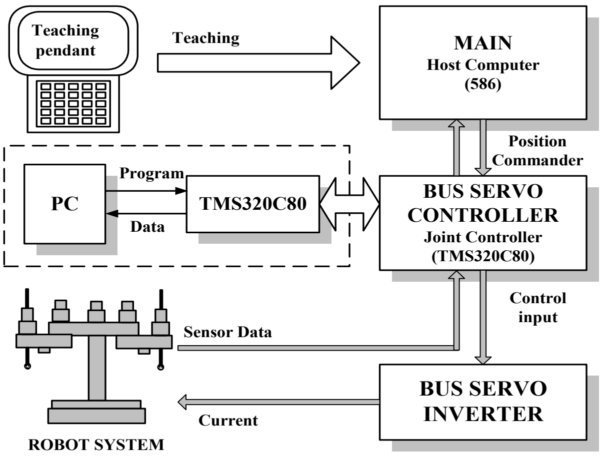

Fig. 6. The block diagram of the interface between the PC, DSP, and dual-arm robot.

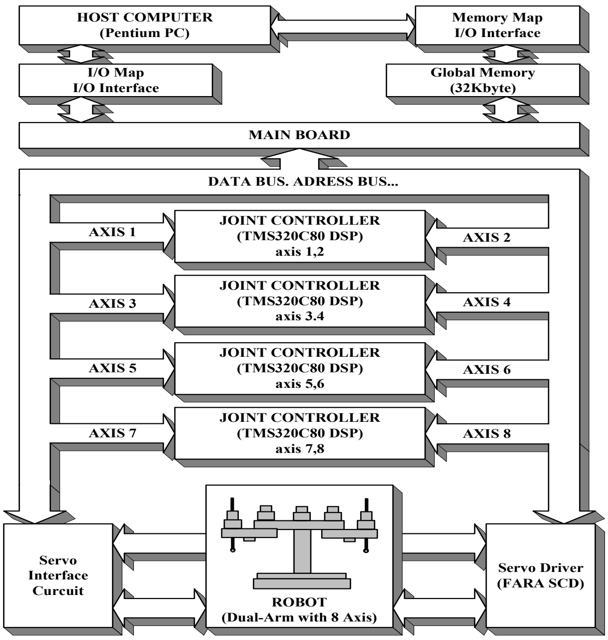

Fig. 7. The schematic diagram control system of dual-arm robot.

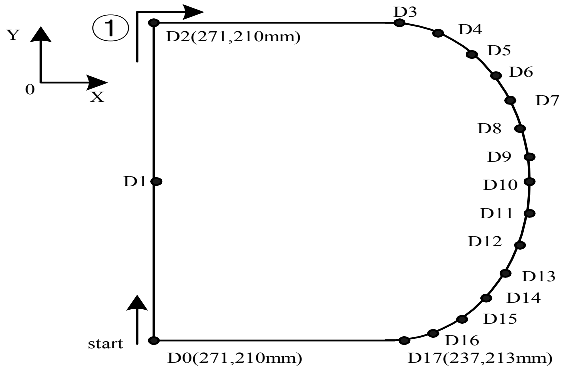

Fig. 8. The D shaped reference trajectory in the cartesian space.

Fig. 8 represents the D-shaped reference trajectory in the cartesian space. Fig. 9 shows the experimental results of the position and velocity control at the first joint with payload 4 kg and the change of reference trajectory. Fig. 10 shows the experimental results for the position and velocity control at the second joint with 4 kg payload. Fig.'s 11 and 12 show the experimental results for the position and velocity control of the PID controller with 4 kg payload. As can be seen from these results, the DSP-based adaptive controller shows extremely good control performance with some external disturbances. It is illustrated that this control scheme shows better control performance than the exiting PID controller, due to small tracking error and fast adaptation for disturbance

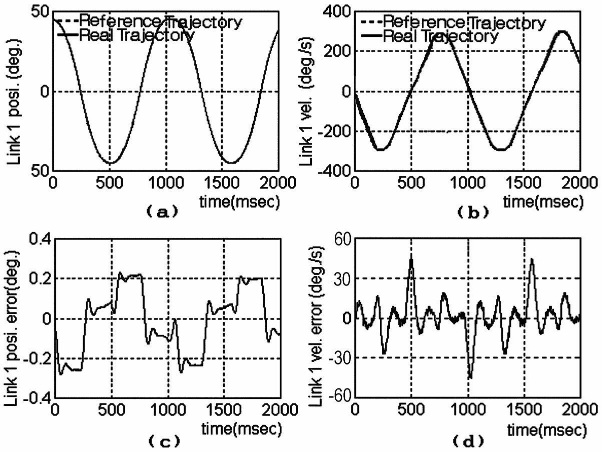

Fig. 9. (a)-(d) Experimental results for the position and velocity tracking of adaptive controller at the first joint with 4kg payload.

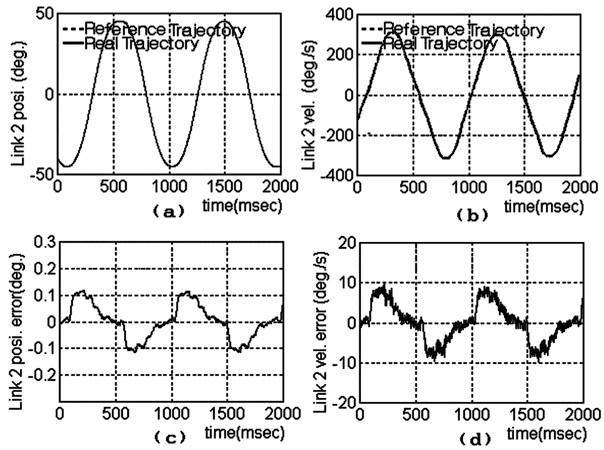

Fig. 10. (a)-(d) Experimental results for the position and velocity tracking of adaptive controller at the second joint with 4kg payload.

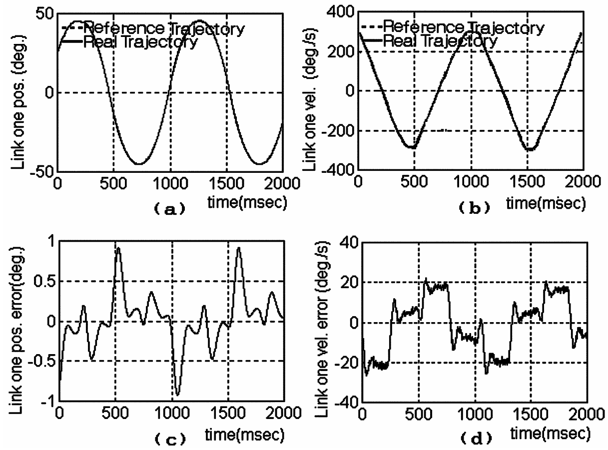

Fig. 11. (a)-(d) Experimental results of PID controller for the position and velocity tracking at the first joint with 4kg payload.

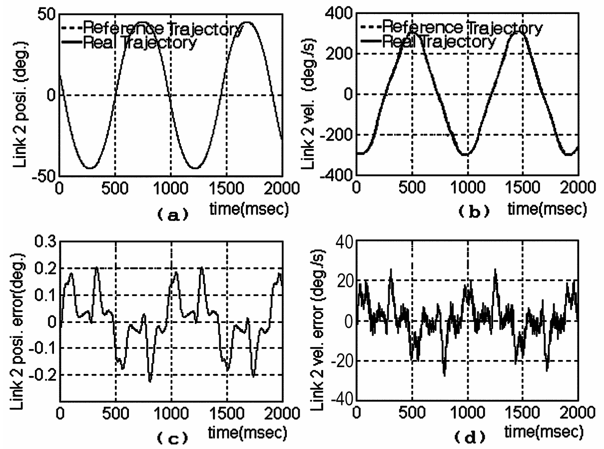

Fig. 12. (a)-(d) Experimental results of PID controller for the position and velocity tracking at the second joint with 4kg payload.

4. CONCLUSIONS

In this paper, a new adaptive digital control scheme is proposed using TMS320C80 for robotic manipulators. The adaptation laws are derived from the direct adaptive technique using the improved Lyapunov second method. The simulation and experimental results show that the proposed DSP-adaptive controller is robust to the payload variation, inertia parameter uncertainty, and change of reference trajectory. This adaptive controller has been found to be suitable to the real-time control of robot system. A novel feature of the proposed scheme is the utilization of an adaptive feedforward controller, an adaptive feedback controller, and a PI type time-varying control signal to the nominal operating point which result in improved tracking performance. Another attractive feature of this control scheme is that, to generate the control action, it neither requires a complex mathematical model of the manipulator dynamics nor any knowledge of the manipulator parameters and payload. The control scheme uses only the information contained in the actual and reference trajectories which are directly available. Futhermore, the adaptation laws generate the controller gains by means of simple arithmetic operations. Hence, the calculation control action is extremely simple and fast. These features are suitable for implementation of on-line real-time control for robotic manipulators with a high sampling rate, particularly when all physical parameters of the manipulator cannot be measured accurately and the mass of the payload can vary substantially.

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