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Implementation of Robust Adaptive Control for Robotic Manipulator Using TMS320C30

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A new adaptive digital control scheme for the robotic manipulator is proposed in this paper. Digital signal processors are used in implementing real time adaptive control algorithms to provide an enhanced motion for robotic manipulators. In the proposed scheme, adaptation laws are derived from the improved Lyapunov second stability analysis based on the adaptive model reference control theory. The adaptive controller consists of the adaptive feedforward and feedback controller and PI type time-varying control elements. The control scheme is simple in structure, fast in computation, and suitable for implementation of real-time control. Moreover, this scheme does not require an accurate dynamic modeling, nor values of manipulator parameters and payload. Performance of the adaptive controller is illustrated by simulation and experimental results for a SCARA robot.

Key Words : Model Reference Adaptive Control, Digital Signal Processor

1. Introduction

In these days robotic manipulators utilize independent joint controllers which control joint angles separately through simple position servo loops (Ortega, 1989). This basic control system enables the manipulator to perform simple positioning tasks such as in the pick-and-place operation. However, joint controllers are severely limited in terms of precise tracking of fast trajectories and sustaining desirable dynamic performance for variations of payload and parameter uncertainties. As a consequence, design of a high performance controller for robotic manipulators has been an active topic of research in recent years (Ortega, 1989 ; Tonei, 1991).

The dynamics of manipulators are highly coupled and nonlinear. In many servo control applications the linear control scheme proves unsatisfactory, therefore, a need for nonlinear techniques seems increasing. Today there are many advanced techniques that are suitable for servo control of a large class of nonlinear systems including robotic manipulators (Sadegh, 1990 ; Bortoff, 1994 ; Slotine, 1987). Since the pioneering work of Dubowsky and DesForges (Sadegh, 1990), the interest in adaptive control of robot manipulators has been growing steadily (Ortega, 1989 ; Tonei, 1991 ; Sadegh, 1990 ; Bortoff, 1994). 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.

Digital signal processors (DSPs) are special purpose micro-processors that are particularly suitable for intensive numerical computations involving sums and products of variables (Ahmed, 1991). Digital version of most advanced control algorithms can be defined as sums and products of measured variables, thus can naturally be implemented by DSPs. In addition, DSPs are as fast in computation as most 32-bit micro-processors and yet at a fraction of their prices (Bortoff, 1994 ; Ahmed, 1991). These features make them a viable computational tool for digital

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implementation of advanced controllers.

To develop a digital servo controller for nonlinear systems such as robots, one must carefully consider the effect of the sample and hold operation, sampling frequency, computational delay times, and that of the quantization error on the stability of a closed-loop system (Ahmed, 1991 ; Parks, 1966 ; Dubowsky, 1979 ; Cho, 1986 ; Gavel, 1987). Moreover, one must also consider the effect of disturbances on the transient variation of the tracking error as well as its steady-state value.

This paper presents a new approach to the design of adaptive control system using DSPs (TMS320C30) for robotic manipulators to achieve trajectory tracking by the joint angles. This paper is organized as follows. In Sec. 2, the dynamic modeling of robotic manipulator is derived. In Sec. 3 the adaptive control laws are drived based on the model reference adaptive control theory using the improved Lyapunov second method. In Section 4 the simulation and experimental results obtained for a SCARA robot are presented. Finally, the results are discussed and some conclusions are drawn in Sec. 5.

2. Dynamic 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 $n \times 1$ joint torque vector $\tau(t)$ is related to the $n \times 1$ joint angle 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 $n \times 1$ vector X represent the end-effector position and orientation coordinates in a fixed task-related Cartesian frame of reference. The end-effector Cartesian position, velocity, and acceleration vectors are related to the joint variables by

$$\begin{aligned} X(t) &= \phi(q) \\ \dot{X}(t) &= J(q)\dot{q}(t) \\ \ddot{X}(t) &= \dot{J}(q, \dot{q})\dot{q}(t) + J(q)\ddot{q}(t) \end{aligned} \tag{2}$$

where $\phi(q)$ is the $n \times 1$ vector representing the foreword kinematics and $J(q) = [\partial\lambda(q)/\partial q]$ is the $n \times n$ Jacobian matrix of the manipulator.

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

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

where g is the $n \times 1$ 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 Eqs. (1) and (4) as

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

Substituting Eqs. (2) and (3) into Eq. (5) yields

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

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

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

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

3. Adaptive Control Scheme

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 $n \times 1$ vector of arbitrary time functions. It is reasonable to assume that these functions are twice differentiable, that is, the 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 ΔL.

The controllers designed in the classical linear control scheme are effective in control of fine motion of the manipulator in the neighborhood of 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 so as to ensure stability and trajectory tracking by the total control laws. The required adaptation laws are developed in this section.

Nonlinear dynamic Eq. (7) can be written as

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

where D^*, N^* and G^* are $n \times n$ matrices whose elements are highly nonlinear functions of ΔL, 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

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

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 time varying control signal corresponding to the nominal operating point term, generated by a feedback controller driven by position backing error $E(t)$.

On applying adaptive control law (9) to nonlinear robot model (8) as shown in Fig. 1, the error differential equation can be obtained as

$$\begin{aligned} & D^*\ddot{E}(t) + (N^*+P_V)\,\dot{E}(t) + (G^*-P_P)\,E(t) \\ = & P_I(t) + (D^*-P_A)\,\ddot{q}_r(t) + (N^*-P_B)\,\dot{q}_r(t) \\ & + (G^*-P_C)\,q_r(t) \end{aligned} \tag{10}$$

Defining the $2n \times 1$ position-velocity error vector $\delta(t) = [E(t),\ \dot{E}(t)]^T$, Eq. (10) can be written in the state-space form

$$\begin{aligned}\dot{\delta}(t) = & \begin{pmatrix} 0 & I_n \\ Z_1 & Z_e \end{pmatrix}\delta(t) \\ & + \begin{pmatrix} 0 \\ Z_3 \end{pmatrix} q_r(t) + \begin{pmatrix} 0 \\ Z_4 \end{pmatrix} \dot{q}_r(t) \\ & + \begin{pmatrix} 0 \\ Z_o \end{pmatrix} \ddot{q}_r(t) + \begin{pmatrix} 0 \\ Z_6 \end{pmatrix} \end{aligned} \tag{11}$$

where

$Z_1 = [D^*]^{-1}\,[G^*+P_P]$, $Z_2 = [D^*]^{-1}[N^*+P_V]$

$Z_3 = [D^*]^{-1}[G^*-P_C]$, $Z_4 = [D^*]^{-1}[N^*-P_B]$

$Z_o = [D^*]^{-1}[D^*-P_A]$, $Z_6 = -[D^*]^{-1}[P_I]$.

Equation (11) constitutes an adjustable system in the model reference adaptive control frame-work. We shall now define the reference model which embodies the desired performance of the manipulator in terms of the tracking-error $E(t)$. The desired performance is that each tracking-error $E_i(t) = q_n(t) - q_i(t)$ be decoupled from the others and satisfies a second-order homogeneous differential equation of the form

$$\begin{aligned} & \ddot{E}_i(t) + 2\xi_i\omega_i\dot{E}_i(t) + \omega_i^2 E_i(t) = 0 \\ & (i = 1, \cdots, n) \end{aligned} \tag{12}$$

where ξ_i and ω_i are the damping ratio and the undamped natural frequency specified by the designer. Equation (12) can be written in the vector form.

The desired performance of the system is embodied in the definition of the stable reference model

$$\delta_\gamma(t) = \begin{pmatrix} 0 & I_n \\ -S_1 & -S_2 \end{pmatrix}\delta_\gamma(t) \tag{13}$$

where $S_1 = diag(\omega_i^2)$ and $S_2 = diag(2\xi_i\omega_i)$ are constant $n \times n$ diagonal matrices, $\delta_\gamma(t) = [E_\gamma(t),\ \dot{E}_\gamma(t)]^T$ is the $2n \times 1$ vector of desired position and velocity errors, and the subscript 'γ' denotes the reference model.

We shall now state the adaptation laws which ensure that, for any reference trajectory $\theta_r(t)$, the state of the adjustable system, $\delta(t)=[E(t),\ \dot{E}(t)]^T$ tends to that of the reference model $\delta_\gamma(t)=0$ asymptotically. The controller adaptation laws will be derived using the direct Lyapunov method -based model reference adaptive control technique. The adaptive control problem is to adjust the controller continuously so that, for any $\theta_r(t)$, the system state $\delta(t)$ approaches the reference model state $\delta\gamma(t)$ asymptotically, i.e. $z(t)\longrightarrow z_\gamma(t)$ as $t\longrightarrow\infty$. Let the adaptation error be defined as $\varepsilon(t)=\delta_\gamma(t)-\delta(t)$, and then from Eq. (13), obtain the error differential equation can be obtained as

$$\dot{\varepsilon}=\begin{pmatrix}0 & I_n\\ -S_1 & -S_2\end{pmatrix}\varepsilon+\begin{pmatrix}0 & 0\\ Z_1-S_1 & Z_2-S_2\end{pmatrix}\delta+\begin{pmatrix}0\\ -Z_3\end{pmatrix}q_r+\begin{pmatrix}0\\ -Z_4\end{pmatrix}\dot{q}_r+\begin{pmatrix}0\\ -Z_5\end{pmatrix}\ddot{q}_r+\begin{pmatrix}0\\ -Z_6\end{pmatrix} \tag{14}$$

The controller adaptation laws are now derived by ensuring the stability of error dynamics Eq. (14).

To this end, let us define the scalar positive -definite Lyapunov function can be defined as

$$\begin{aligned}V=\varepsilon^T R\varepsilon&+trace\{[Q_1]^T K_1[Q_1]\}\\&+trace\{[Q_2]^T K_2[Q_2]\}\\&+trace\{[Q_3]^T K_3[Q_3]\}\\&+trace\{[Q_4]^T K_4[Q_4]\}\\&+trace\{[Q_5]^T K_5[Q_5]\}\\&+[Q_6K_6Q_6]^T\end{aligned} \tag{15}$$

where $Q_1=Z_1-S_1-Z_1^*$, $Q_2=Z_2-S_2-Z_2^*$, $Q_3=Z_3-Z_3^*$, $Q_4=Z_4-Z_4^*$, $Q_5=Z_5-Z_5^*$, $q_6=Z_6-Z_6^*$, R is the solution of the Lyapunov equation for the reference model, $[K_1,\ \cdots,\ K_6]$ are arbitrary symmetric positive-definite constant $n\times n$ matrices, and the matrices $[Z_1^*,\ \cdots,\ Z_6^*]$ are functions of time which will be specified later.

Figure 1 represents the block diaram of the proposed adaptive control scheme for robotic manipulator.

From the stability analysis by Lyapunov second method and then simplifying the results, the required adaptive controller gains are obtained as

$$\begin{aligned}P_P(t)&=p_1[P_{p_1}E+P_{p_2}\dot{E}][E]^T\\&+p_2\int_0^t[P_{p_1}E+P_{p_2}\dot{E}][E]^T dt\\&+P_p(0)\end{aligned} \tag{16}$$

$$\begin{aligned}P_V(t)&=v_1[P_{v_1}E+P_{v_2}\dot{E}][\dot{E}]^T\\&+v_2\int_0^t[P_{v_1}E+P_{v_2}\dot{E}][\dot{E}]^T dt\\&+P_v(0)\end{aligned} \tag{17}$$

$$\begin{aligned}P_C(t)&=c_1[P_{c_1}E+P_{c_2}\dot{E}][q_r]^T\\&+c_2\int_0^t[P_{c_1}E+P_{c_2}\dot{E}][q_r]^T dt\\&+P_c(0)\end{aligned} \tag{18}$$

$$\begin{aligned}P_B(t)&=b_1[P_{b_1}E+P_{b_2}\dot{E}][\dot{q}_r]^T\\&+b_2\int_0^t[P_{b_1}E+P_{b_2}\dot{E}][\dot{q}_r]^T dt\\&+P_b(0)\end{aligned} \tag{19}$$

$$\begin{aligned}P_A(t)&=a_1[P_{a_1}E+P_{a_2}\dot{E}][\ddot{q}_r]^T\\&+a_2\int_0^t[P_{a_1}E+P_{a_2}\dot{E}][\ddot{q}_r]^T dt\\&+P_a(0)\end{aligned} \tag{20}$$

$$\begin{aligned}P_I(t)&=\lambda_2[P_{i_2}E]+\lambda_1\int_0^t[P_{t_1}E]^T dt\\&+P_i(0)\end{aligned} \tag{21}$$

where $[\lambda_1,\ p_{p_1},\ p_{v_1},\ p_{c_1},\ p_{b_1},\ p_{a_1}]$ and $[\lambda_2,$

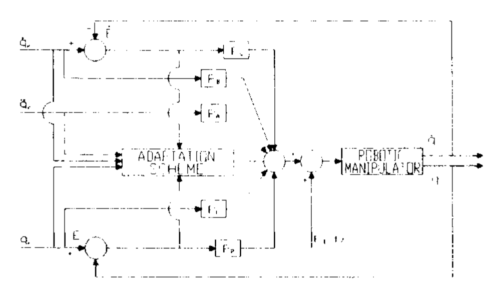

Fig. 1 Block diagram of adaptive control scheme for robotic manipulator.

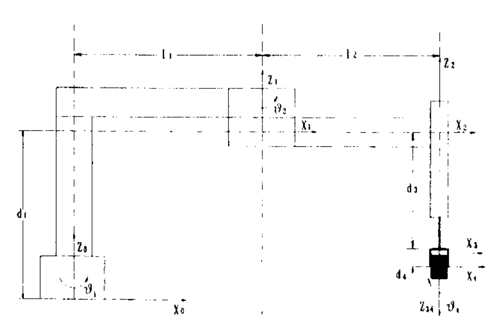

Fig. 2 Link coordinate system of a SCARA robot.

p_{p_2}, p_{v_2}, p_{c_2}, p_{b_2}, p_{a_2}] are positive and zero/positive scalar adaptation gains, and then are chosen by the designer to reflect the relative significance of position and velocity errors $\dot{E}$ and $\dot{E}$.

4. Simulation and Experiment

4.1 Simulation

This section represents the DSPs-based emulation results of the position and velocity control of a four-link robotic manipulator, as shown in Fig. 2, and discusses the advantages of using DSPs for robotic motion control. Thus, the adaptive scheme developed in this paper will now be applied to control the position and velocity of SCARA robot with four axes.

Figure 2 represents link coordinate systems of the SCARA robot. Table 1 lists link coordinate parameters of the robot. Table 2 lists the specification of link parameters of the robot. Table 3 lists motor parameters. Consider the SCARA robot with the end-effector grasping a payload of mass ΔL. The emulation set-up consists of a TMS320 evm DSP board and a 486/33MHz personal computer(PC). The TMS320 evm card is an application development tool which is based on the TI's TMS320C30 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 are done via interrupts. These interrupts are managed by an operating system called Ashell which is an extension of MS-DOS. It is assumed that the drive system is 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 coordinate parameters for a SCARA rovot arm.

Joint	q_i	α_i	a_i	d_i
1	q_1	0	l_1	d_1
2	q_2	0	l_2	0
3	0	180°	0	d_3
4	q_4	0	0	d_4

Dynamic equation of each joint for SCARA robot is expressed as

$$N_{11}\ddot{q}_1+N_{12}\ddot{q}_2+N_{14}\ddot{q}_4+V_{m112}\dot{q}_1\dot{q}_2 + V_{m122}\dot{q}_1\dot{q}_2^2+f_1\dot{q}_1+k_1 sgn(\dot{q}_1)=\tau_1$$

Table 2 Link parameters for a SCARA robot.

Mass of link (kg)		Length of link (m)		Inertia of link (kgm²)		Gear ratio of link	
m_1	15.067	11	0.35	11	0.1538	r_1	1/100
m_2	8.994	12	0.3	12	0.0674	r_2	1/80
m_3	3.0	13	0.175	13	0.045	r_3	1/200
m_4	1.0	14	0.007	14	0.0016	r_4	1/75

Table 3 Motor parameters of a SCARA robot.

Roter inertia(kgm²)		Torque constant(Km/A)		Back emf constant(V · s/rad)		Amature-winding resistance(otms)	
Jm1	5.0031×10^{-5}	Ka1	21.4839×10^{-2}	Kb1	200.5352×10^{-3}	Ra1	15
Jm2	1.3734×10^{-5}	Ka2	20.0124×10^{-2}	Kb2	200.5352×10^{-3}	Ra2	42
Jm3	0.8829×10^{-5}	Ka3	20.0124×10^{-2}	Kb3	200.5352×10^{-3}	Ra3	9
Jm4	0.22563×10^{-5}	Ka4	17.6580×10^{-2}	Kb4	176.6620×10^{-3}	Ra4	20

$$N_{21}\ddot{q}_1+N_{22}\ddot{q}_2+N_{24}\ddot{q}_4+V_{m212}\dot{q}_1\dot{q}_2$$
$$+V_{m221}\dot{q}_1\dot{q}_2+f_2\dot{q}_2+k_2sgn(\dot{q}_2)=\tau_2$$
$$N_{33}\ddot{d}_3+G_3+f_3\dot{d}_3+k_3sgn(\dot{d}_3)=\tau_3$$
$$N_{41}\ddot{q}_4+N_{42}\ddot{q}_2+N_{44}\ddot{q}_4+f_4\dot{q}_4+k_4sgn(\dot{q}_4)$$
$$=\tau_4$$
$$N_{11}=m_1l^2_{c_1}+I_1+m_2(l_1^2+l_{c_2}^2$$
$$+2l_2l_{c_2}\cos q_2)+I_2+(m_3+m_4)(l_1^2$$
$$+l_{c_2}^2+2l_1l_2\cos q_2)+I_4$$
$$N_{12}=N_{21}=m_2(l_{c_2}^2+2l_1l_2\cos q_2)+I_2$$
$$+(m_3+m_4)(l_2^2+2l_1l_2\cos q_2)+I_4$$
$$N_{22}=m_2\ l_{c_2}^2+I_2+m_3l_2^2+m_4\ l_2^2+I_4$$
$$N_{14}=N_{41}=N_{24}=N_{42}=-I_4$$
$$N_{33}=m_3+m_4$$
$$N_{13}=N_{31}=N_{23}=N_{32}=N_{34}=N_{43}=0$$
$$V_{m112}=-2m_2l_1l_{c_2}\sin q_2-2(m_3$$
$$+m_4)l_1l_2\sin q_2$$
$$V_{m122}=-m_2l_1l_{c_2}\sin q_2-(m_3$$
$$+m_4)l_1l_2\sin q_2$$
$$V_{m211}=m_2l_1l_{c_2}\sin q_2+(m_3+m_4)l_1l_2\sin q_2$$
$$V_{m212}=-V_{m221}$$
$$=-0.5(m_2l_1l_{c_2}\sin q_2$$
$$-2(m_3+m_4)l_1l_2\sin q_2)$$
$$G_1=G_2=G_4=0$$
$$G_3=-g(m_3+m_4)$$

$f(\dot{q}_i)$: viscous friction

$ksgn(\dot{q}_i)$: Coulomb friction

q_i : rotation angle of the i-th axis

d_3 : displacement of prismatic motion of the third axis

m_i : mass of the i-th link

l_i : length of the i-th link

l_{ci} : displacement from the i-th coordinate to the center of the i-th link

I_i : rotation inertia moment of i-th link

In all simulations it is assumed that the load, hence the uncertain parameter, is unknown. Adaptive control algorithm given in Eq. (10) together with the parameter adaptation rule, as in Eqs. (18) ~ (23), is used for the motion control of the robot. The parameters associated with adaptation gains are selected as $\lambda_1=0.5$, $\lambda_2=0.02$, $a_1=0.2$, $a_2=0.3$, $b_1=0.01$, $b_2=0.3$, $c_1=0.05$, $c_2=0.1$, $P_1=10$, $P_2=20$, $u_1=0.1$, $u_2=10$, $P_{a_1}=10^{-5}$, $P_{a_2}=10^{-4}$, $P_{b_1}=20$, $P_{b_2}=30$, $P_{c_1}=10$, $P_{c_2}=15$, $P_{p_1}=0.5$, $P_{p_2}=0.4$, $P_{v_1}=0.01$, and $P_{v_2}=0.05$.

It is assumed as $\omega_1=\omega_2=10$ rad/sec, $\xi_1=\xi_2=1$, and $S_1=80I$, $S_2=25I$ in the reference

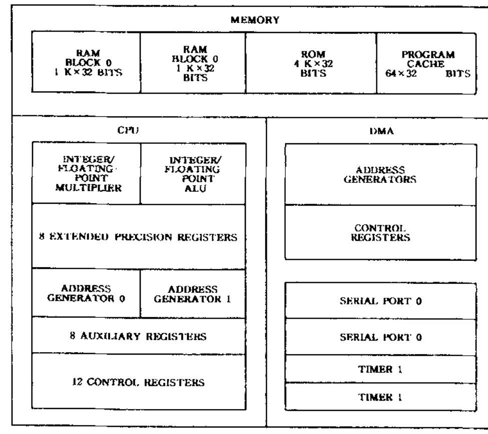

Fig. 3 The Block diagram of TMS320C30.

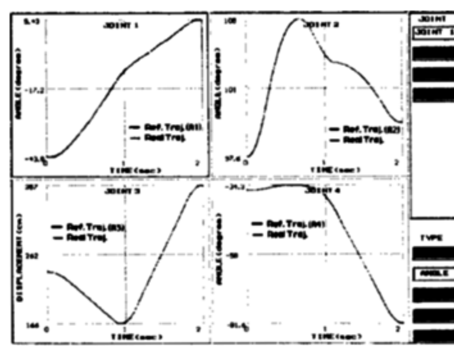

Fig. 4 Position tracking performance of each joint with payload (5kg) for reference trajectory A.

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 to the four reference trajectories A, B, C, and D for each joint. As can be seen in Figs. 4~7, reference trajectory A, B, C, and D consist of four different trajectories for joints 1, 2, 3, and 4.

The performance of DSP(TMS320C30) 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 cases are shown in Figs. 4~7. Figure 4 shows results of angular position trajec-

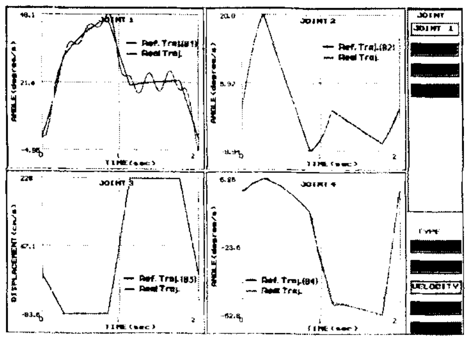

Fig. 5 Velocity tracking performance of each joint with payload (5kg) for the reference trajectory B.

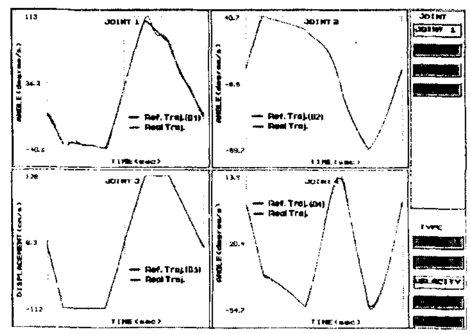

Fig. 7 Velocity tracking performance of each joint with payload (5kg), inertia parameter uncertainties (10%) for reference trajectory D.

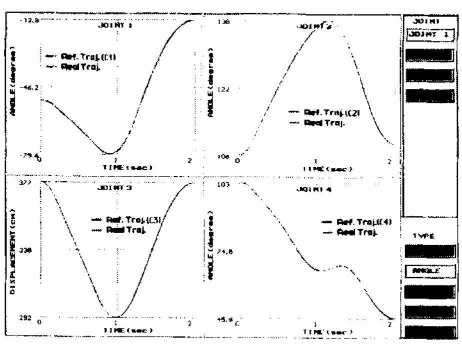

Fig. 6 Position tracking performance of each joint with payload (5kg) and inertia parameter uncertainties (5%) for reference trajectory C.

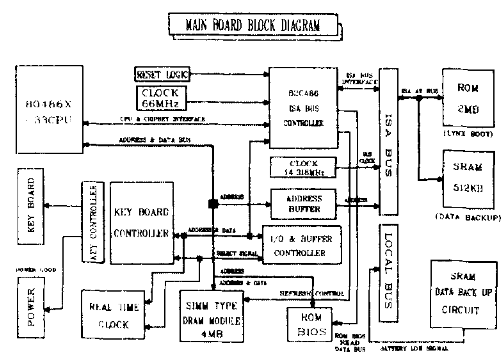

Fig. 8 The main board block diagram of hardware structure of SCARA robot.

tory tracking for each joint with a 5kg payload for reference trajectory A. As can be seen from these results, the DSPs-based adaptive controller represents extremely good performance with very small tracking error and fast adaptation response under the payload.

As can be seen from Figs. 5 and 6, the proposed adaptive controller represents good performance in the position and velocity at each joint for payload variation, inertia parameter uncertainty, and the change of reference trajectory. These simulation results illustrate that this DSPs-based adaptive controller is very robust and suitable to real time control due to its fast adaptation and simple structure. Figure 6 shows results of angular position tracking at each joint with payload (5 kg), parameter uncertainties (5%), and the change of reference trajectory. Figure 7 shows results of angular velocity tracking at each joint with payload (5kg), parameter uncertainties (5%) for reference trajectory D.

4.2 Experiment

The performance experiment of the proposed adaptive controller is performed for two joints of the SCARA robot. To implement the proposed adaptive controller, we used our own developed TMS320C30 assembler software. Also, the TMS320C30 emulator is used in experimental set-up. At each joint, a harmonic drive (with gear reduction ratio of 100 : 1 for joint 1 and 80 : 1 for joint 2) is used to transfer power from the motor, which has a resolver attached to its shaft for sensing angular velocity with a resolution of 8096

Fig. 9 Experimental set-up.

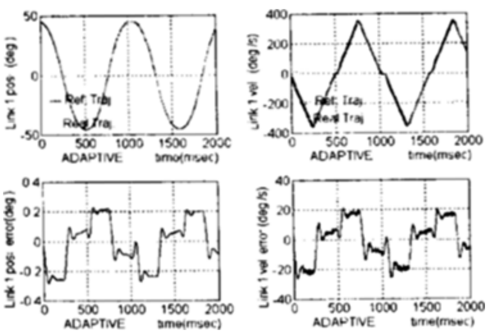

Fig. 10 Experimental results for the position and velocity tracking at the first joint with 5kg payload.

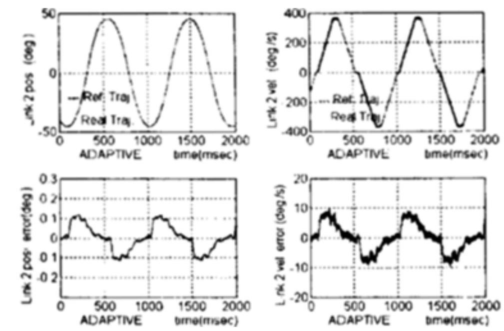

Fig. 11 Experimental results for the position and velocity tracking at the second joint with 5kg payload.

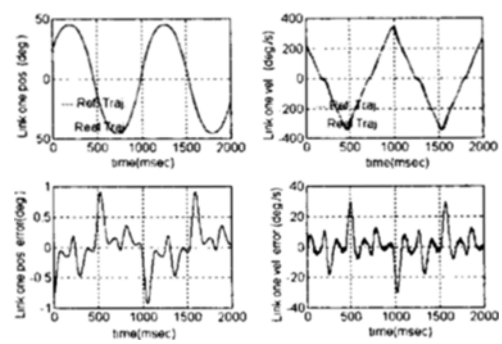

Fig. 12 Experimental result of PID controller for the position and velocity tracking at the first joint with 3kg payload.

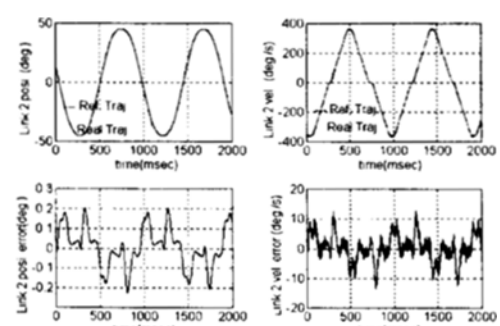

Fig. 13 Experimental result of PID controller for the position and velocity tracking at the second joint with 3kg payload.

pulses/rev. The experiment is performed to emulate the position and velocity control performance of the two joints under the condition of payload variation, inertia parameter uncertainty, and change of reference trajectory. Figure 10 shows the experimental results of the position and velocity control at the first joint with payload 5kg and the change of reference trajectory. Figure 11 shows the experimental results for the position and velocity control at the second joint with 5kg payload. Figs. 12 and 13 show the experimental results for the position and velocity control of the PID controller with 3kg payload. As can be seen from these results, the DSPs-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. Figure 14 shows the experimental results of the position and velocity tracking performance at the first joint with 10kg payload. Figure 15 shows the experimental results of the position and velocity tracking performance at second joint with 10kg payload. From the Fig. 14,

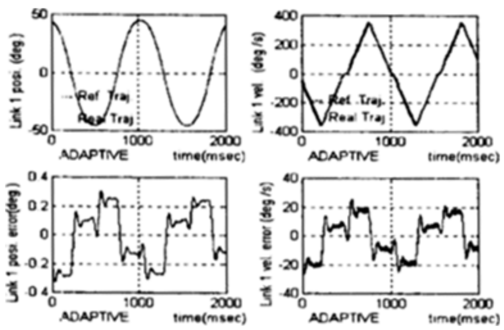

Fig. 14 Experimental results for the position and velocity tracking at the first joint with 10kg payload.

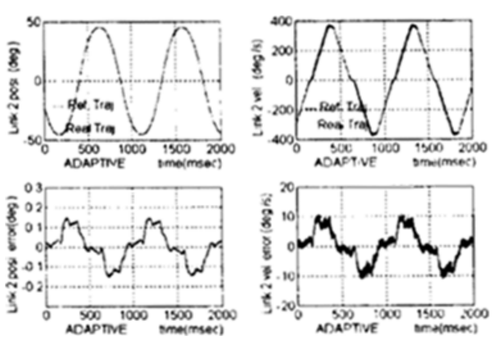

Fig. 15 Experimental results for the position and velocity tracking at the second joint with 10 kg payload.

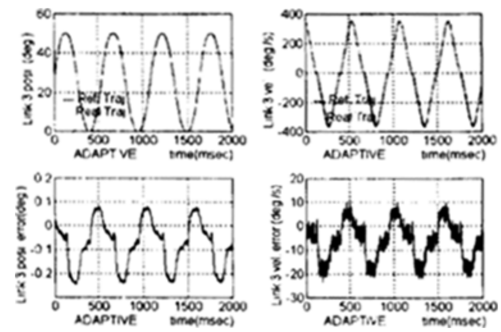

Fig. 16 Experimental results for the position and velocity tracking at the third joint with 5kg payload.

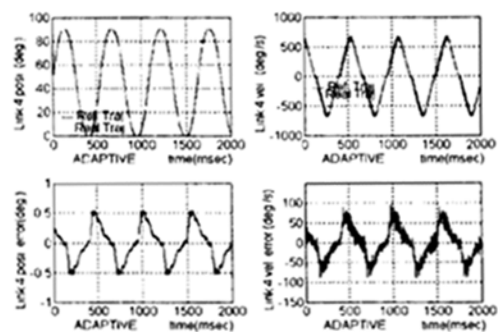

Fig. 17 Experimental results for the position and velocity tracking at the fourth joint with 5kg payload.

it is illustrated that the proposed DSPs-based adaptive controller is very robust and has fast adaptation response to the tracking of the position and velocity at the first joint with external disturbances. Again, as can be seen from the Fig. 15, it is illustrated that this adaptive controller is robust and has fast adaptation in tracking of the position and velocity under the condition of disturbance increasing. Figure 16 shows the experimental results for the position and velocity control at the third joint with 5kg payload. Figure 17 shows the experimental for the position and velocity control at the fourth joint with 5kg payload. As can be seen from above experimental results, it has been illustrated that the proposed adaptive scheme is very robust to the external disturbance, and suitable to real time control of complex nonlinear systems, such as robot systems.

5. Discussion and Conclusions

A new adaptive digital control scheme is described in this paper using DSPs(TMS320C30) for robotic manipulators. The adaptation laws are derived from the model reference adaptive theory using the improved direct Lyapunov method. The simulation and experimental results show that the proposed DSPs-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. The proposed DSPs-based adaptive controllers have several advantages over the analog control and the micro-computer based controls. This allows instructions and data to be simultaneously fetched for processing. Moreover, most of the DSPs instructions, including multiplications, are performed in one instruction cycle. The DSPs tremendously increase speed of the controller and reduce computational delay, which allow for faster sampling operation. It is illustrated that DSPs can be used for the implementation of complex digital control algorithms, such as proposed adaptive control for robot systems.

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