A study on Real-Time Implementation of Robust Control for Horizontal Articulated Arm with Eight Axis

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〈Abstract〉

In this paper, we describe a new approach to perform real-time implementation of an robust controller for robotic manipulator based on digital signal processors in this paper. The Texas Instruments DSPs 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 robot manipulator consisting of dual arm with eight degrees of freedom at the joint space and cartesian space.

Keywords: Robust Control, 8 Axis Robot, Real Time Control, Real-Time Implementation

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1. INTRODUCTION

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. 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 (N. Sadegh et al., 1990; Z. Ma et al., 1995). 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 (P. Bhatti et al., 1997; T. H. Akkermans et al., 2001). 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 (S. A. Bortoff, 1994). Moreover, one must also consider the effect of disturbances on the transient variation of the tracking error as well as its steady-state value (F. Mehdian et al., 1995; S. H. Han et al., 1996).

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

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

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 $\triangle V_p$. 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

$$T(t)=\triangle V_p\left[\ddot{X}(t)+g\right] \tag{3}$$

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

$$\triangle V_p J(q)^T [J(q)\ddot{q} + \dot{J}(q,\dot{q})\dot{q} + g] + D(q)\ddot{q} + N(q,\dot{q}) + G(q) = \tau(t) \quad (6)$$

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

$$[D(q) + \triangle V_p J(q)^T J(q)]\ddot{q} + [N(q,\dot{q}) + \triangle V_p J(q)^T \dot{J}(q,\dot{q})\dot{q}] + [G(q) + \triangle V_p J(q)^T g] = \tau(t) \quad (7)$$

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

3. ROBUST 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×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 $\triangle V_p$.

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 K_0. During the gross motion of the manipulator, operating point K_0 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.

$$\tau(t) = D^*(\triangle V_p, q, \dot{q})\ddot{q}(t) + N^*(\triangle V_p, q, \dot{q})\dot{q}(t) + G^*(\triangle V_p, q, \dot{q})q(t) \quad (8)$$

where D^*, N^* and $G^*$are n×n matrices whose elements are highly nonlinear functions $\triangle V_P, q$ 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

$$\tau(t) = [K_A(t)\ddot{q}_r(t) + K_B(t)\dot{q}_r(t) + K_C q_r(t)] + [K_V(t)\dot{E}(t) + K_p(t)E(t) + K_I(t)] \quad (9)$$

where $K_A(t), K_B(t), K_C(t)$ are feedforward time-varying adaptive gains, and $K_P(t)$ and $K_V(t)$ are the feedback adaptive gains, and $K_I(t)$ 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 $q_r(t) - q(t)$.

The gains of adaptive control low in equation (9) are defined as follows:

$$K_A(t) = a_1[k_{a1}E + k_{a2}\dot{E}][\ddot{q}_r]^T + a_2\int_0^t [k_{a1}E + k_{a2}\dot{E}][\ddot{q}_r]^T dt + k_a(0) \quad (10)$$

$$K_B(t) = b_1[k_{b1}E + k_{b2}\dot{E}][\ddot{q}_r]^T + b_2\int_0^t [k_{b1}E + k_{b2}\dot{E}][\ddot{q}_r]^T dt + k_b(0) \quad (11)$$

$$K_C(t) = c_1[k_{c1}E + k_{c2}\dot{E}][\ddot{q}_r]^T + c_2\int_0^t [k_{c1}E + k_{c2}\dot{E}][\ddot{q}_r]^T dt + k_c(0) \quad (12)$$

$$K_I(t) = \lambda_2[k_{i2}E] + \lambda_1[k_{i1}E]^T dt + k_i(0) \quad (13)$$

Where $[k_{p1}, k_{v1}, k_{c1}, k_{b1}, k_{a1}]$ and $[k_{p2}, k_{v2}, k_{c2}, k_{b2}, k_{a2}]$ 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 four-link robotic manipulator by the proposed adaptive control algorithm, as shown in Fig.1, 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 eighth axes. Fig.1 represents link coordinates of the dual-arm robot.

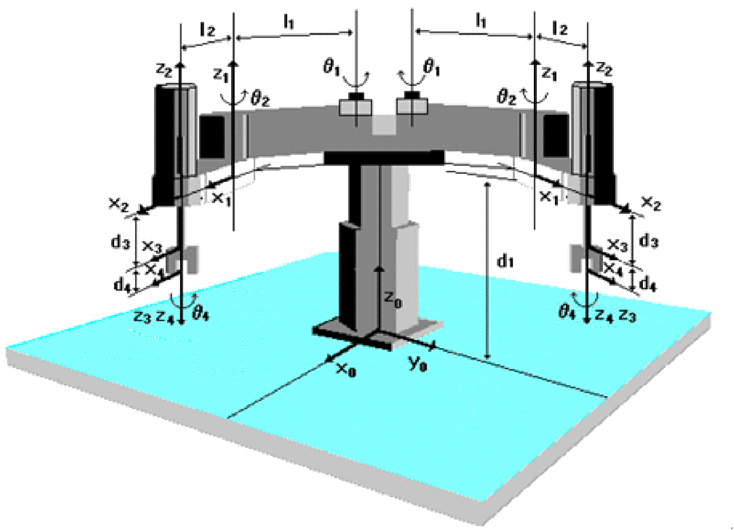

Fig.1. The Coordinates ftame of robotic arm with 8 axis

Table 1 Link parameters

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

Table 2 Motor parameters

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}	Kb 2	200.5352×10^{-3}	Ra2	4.2
Jm3	0.8829×10^{-5}	Ka3	20.0124×10^{-2}	Kb 3	200.5352×10^{-3}	Ra3	9
Jm4	0.2256×10^{-5}	Ka4	17.6580×10^{-2}	Kb 4	176.6620×10^{-3}	Ra4	20
Jm5	5.0031×10^{-5}	Ka5	21.4839×10^{-2}	Kb 5	214.8592×10^{-3}	Ra5	1.5
Jm6	1.3734×10^{-5}	Ka6	20.0124×10^{-2}	Kb 6	200.5352×10^{-3}	Ra6	4.2
Jm7	0.8829×10^{-5}	Ka7	20.0124×10^{-2}	Kb 7	200.5352×10^{-3}	Ra7	9
Jm8	0.2256×10^{-5}	Ka8	17.6580×10^{-2}	Kb 8	176.6620×10^{-3}	Ra8	20

4.2 Experiment

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 B-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. 4 represents the schematic diagram of control system of dual-arm robot. And Fig. 5 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.

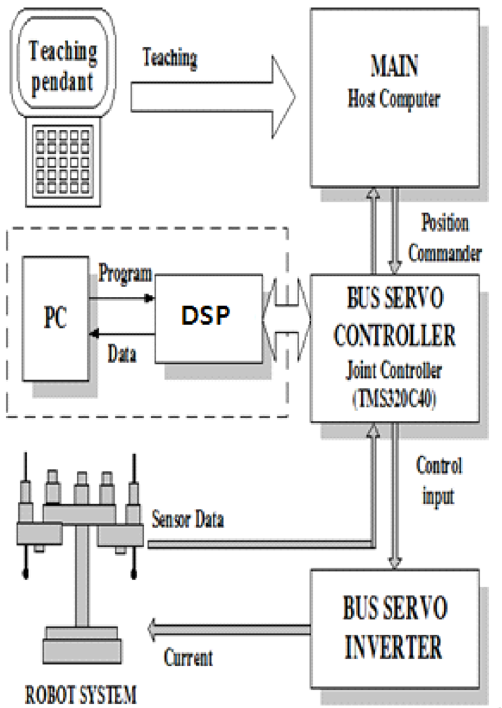

Fig. 4. The block diagram of the interface between the PC. DSP, and dual-arm robot.

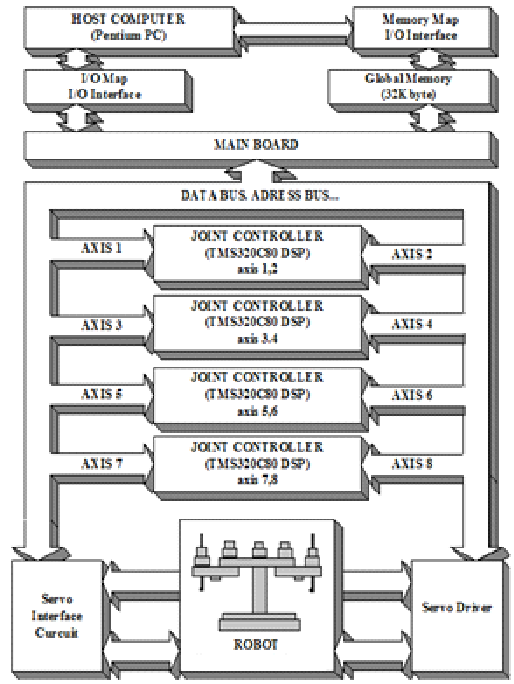

Fig. 5. The schematic diagram control system of dual-arm robot.

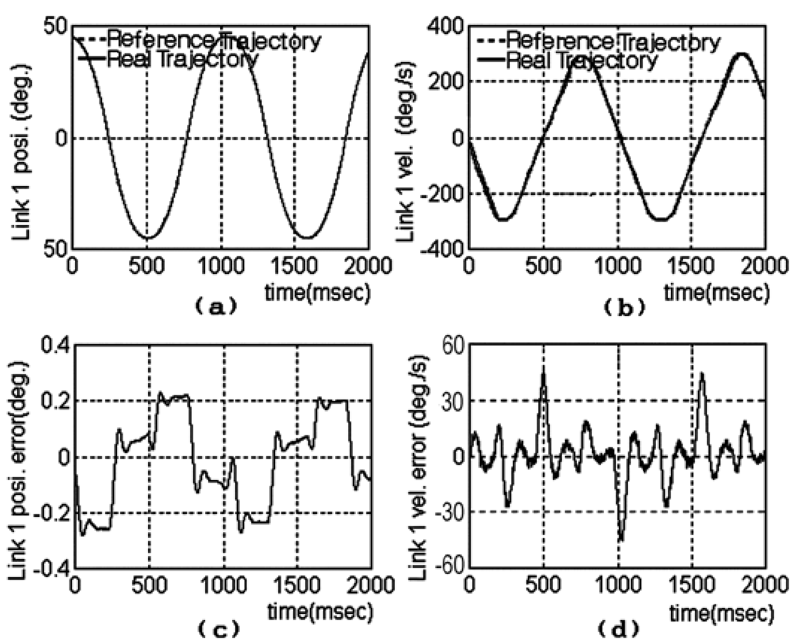

Fig. 6. (a)-(d) Experimental results for the position and velocity tracking of robust controller at the first joint with 3kg payload.

5. CONCLUSIONS

A new adaptive digital control scheme is described in this paper using DSP(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.

The proposed DSP-based adaptive controllers have several advantages over the analog control and the micro-computer based control. This allows instructions and data to be simultaneously fetched for processing. Moreover, most of the DSP instructions, including multiplications, are performed in one instruction cycle. The DSP tremendously increase speed of the controller and reduce computational delay, which allows for faster sampling operation. It is illustrated that DSPs can be used for the implementation of complex digital control algorithms, such as our adaptive control for robot systems.

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