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An adaptive decentralized nonlinear controller for a robot manipulator is presented in this thesis. Based on the adaptive control schemes designed by Seraji [18], Dai [30], and Jiménez [31], we redesigned and further simplified the control algorithm and, as a consequence, we achieved better path tracking performance.

The proposed adaptive controller is made of a PD feedback controller which has time varying gains, a feedforward compensator based on the idea of inverse dynamics, and an auxiliary signal. Due to its adaptive structure, the controller shows robustness against disturbances and unmodeled dynamics. In order to ensure asymptotic tracking we select a Lyapunov function such that the controller forces the negative definiteness of the time derivative of such a Lyapunov function. To do this, the tracking position and velocity error are penalized and used as a part of the adaptive control gain.

The main advantages of this scheme are the comparably faster convergence of tracking error, relatively simpler structure, and smoother control activity. This controller only requires the position and angular speed measurement, it does not require any knowledge about the mathematical model of the robot manipulator. Simulation shows the capacity of this controller and its robustness against disturbances.

A Fast Trajectory Tracking Adaptive Controller for Robot Manipulators

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TABLE OF CONTENTS

LIST OF FIGURES

A Fast Trajectory Tracking Adaptive Controller for
Robot Manipulators

1. INTRODUCTION

Controlling the robot manipulator as a highly nonlinear system has been a very challenging problem for a long time, due to its structural complexity and coupling effects between each of the arms. Controlling a robot manipulator to track a desired trajectory or achieve fast motions are very intensive tasks that require sophisticated control techniques. Early work was an extension of linear control, and worked only for the less demanding tasks. Even now, control techniques such as PID control are widely used in industry. One of the reasons why such a technique can still be used is that by using the high gear ratio between the actuator and joints the gravitational and centripetal forces do not appear drastic. However, for the demands of high performance robots such as precise trajectory tracking or fast motion the linear control technique based on perturbation theory around the nominal trajectory or equilibrium point does not perform satisfactorily. The reason is that the computation of time varying linearized system parameters becomes a very extensive task, and the coupling effects between the joints become more pronounced. Moreover, the recent trend for fast motion demands that robot manipulators have direct drive structures with no gears between the actuators and joints, thus making the nonlinearities of robot manipulators more evident.

To control a robot manipulator under these conditions, many researchers have proposed sophisticated control techniques. One of the techniques which has achieved some degree of success is the computed torque method, which is a model-based technique. This method explicitly utilizes the mathematical model and parameters of the robot manipulator to cancel the nonlinearity. However, due to the requirement of precise knowledge of the system structure and parameters, the computational task is very extensive.

Another technique is called variable structure control [5]. With this, the system states are driven to a switching surface, which is designed to make the states converge to the origin. As the system states cross the switching surface, the states become insensitive to system parameter variations. This method does not require knowledge of exact system parameters, it only requires the possible upper bound of uncertainty. A disadvantage of this method is that due to the discontinuous control activity, it may excite the unmodeled dynamics, and has the possibility of oscillation of control activity called the "chattering problem". Some researchers [2] have proposed the continuous control scheme with the trade off between control band width and tracking precision.

Another technique widely used to control robot manipulators is the adaptive control technique which is a performance-based technique. The well known Lyapunov stability theory is explicitly used many times to discuss system stability or parameter estimator convergence [29]. In this method, no precise information of the mathematical model or parameter values or characteristics are needed. Either system parameters or control laws are adapted to compensate for the uncertainty of system structure, parameters, or unexpected disturbances from the environment. The development of the adaptive control technique arose from the need for controlling complex nonlinear interconnected dynamic systems. The complexity of the system structure and the uncertainty of the critical parameters come from the fact that inertia properties and gravitational loads vary due to the end effector payload which may not be known in advance or which may change unexpectedly.

The brief history of adaptive control will now be discussed. Dubowsky and Deforges [6] were the first to apply the model reference adaptive control technique to the robot manipulator control problem. They developed an adaptation scheme based on linear decoupled models. They state that the theory they developed is valid only if the model parameter change is relatively slower than the adaptation rate. The global stability is not guaranteed in this work. Takegaki and Arimoto [27] developed the model reference adaptive control scheme without a reference model. A desired trajectory is explicitly used instead. Moreover, the stability of adaptive law that ensures the trajectory convergence is first solved by them for a system of linearized dynamics. An adaptive control scheme that takes some of the manipulator dynamics into account was proposed by Horowitz and Tomizuka [9]. In this work, the assumption is made that the manipulator configuration change is small compared to the adaptation time constant in order for the theory to be valid. An adaptive control of a manipulator which uses the full nonlinear dynamic model was introduced by Craig et. al. [3,4]. The global stability of system and parameter convergence are guaranteed by using the Lyapunov's stability theorem. Their method requires the acceleration information to account for the nonlinearity of the manipulator, and the inversion of the matrix. A similar approach is used by Slotine and Li [24], but in their work no acceleration information is needed. However, high complexity of computation is required in order to account for the nonlinear control terms. Johansson [11] made an effort to eliminate the need for inversion of a matrix and for acceleration information with a slightly higher computational complexity. Sadegh and Horowitz [16] proposed another approach of adaptive control. Their scheme explicitly uses the desired joint positions and velocities in the computation of the nonlinearity compensation, but this requires large control gains.

Early work on the decentralized adaptive controller did not take the interconnection between subsystems into consideration. The problem of decentralized adaptive control of interconnected systems with bounded disturbances and interconnection was dealt with by Ioannou [10]. Exponential convergence of the tracking error and parameter estimation error to bounded sets are guaranteed. Oh and Jamshidi [14] introduced a scheme that utilizes the feedforward signal from the desired trajectory, PID feedback, and auxiliary signal. Seraji [17-22] proposed an innovative adaptive control scheme in decentralized fashion. He derived the adaptation law based on the Lyapunov's stability theory to guarantee the global asymptotic convergence of the trajectory to the desired trajectory. However, he assumed that some manipulator parameters are constant even though they are not. Some of the important characteristics of his method are:

1. Because of the decentralized structure it is suitable to parallel signal processor implementation.
2. Being a performance-based control, it does not require the precise model of the plant, manipulator. Thus it is robust to the uncertainty.

In this thesis, we present a decentralized adaptive controller of robot manipulators which is the extension of the one proposed by Seraji [18], Dai [30], and Jiménez [31]. The control scheme we propose is simpler and produces smoother control activity than comparable controllers. This thesis is organized as follows: Chapter 2 discusses briefly manipulator dynamics. In Chapter 3 the controller design is discussed. Chapter 4 contains the controller computer simulation results. In Chapter 5, the control law with time varying inertia is discussed for comparison purposes with the control law proposed in Chapter 3 and 4. Finally, we summarize our conclusions in Chapter 6.

2. DYNAMIC MODEL OF A MANIPULATOR

The dynamic model of a robot manipulator can be constructed by using the Euler-Lagrange equation [15]. An n-joint robot manipulator model in matrix form is:

$$M(\Theta)\ddot{\Theta}+N(\dot{\Theta},\Theta)+G(\Theta)+H(\dot{\Theta})=T(t) \quad (2.1)$$

where

$\Theta(t)$	: joint angle position vector
$M(\Theta)$	: symmetric positive definite inertia matrix
$N(d\Theta/dt,\Theta)$	: coriolis, centripetal force vector
$G(\Theta)$	: gravity loading vector
$H(d\Theta/dt)$	: frictional torque vector.

If the payload is denoted by m_l, these terms can be represented by

$$M \triangleq M_0+m_l J^T J, \quad N \triangleq N_0+m_l J^T \dot{J}\dot{\Theta}, \quad G \triangleq G_0+m_l J^T g \quad (2.2)$$

where J: Jacobian matrix g: gravitational acceleration vector. Furthermore, if we lump the payload, equation (2.1) becomes

$$T=M_0\ddot{\Theta}+N_0+G_0+H_0+m_l J^T[J\ddot{\Theta}+\dot{J}\dot{\Theta}+g] \ . \quad (2.3)$$

This equation says that the relationship between the applied torque and joint angle depends on the payload m_l. Therefore, the controller should be designed to make the whole system insensitive to payload variation.

The system represented by equation (2.1) can be decomposed into n interconnected subsystems, each of which can be represented by

$$m_{ii}(\boldsymbol{\theta})\ddot{\theta}_i(t)+\sum_{\substack{j=1\\ j\neq i}}^{n} m_{ij}\ddot{\theta}_j(t)+N_i(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})+G_i(\boldsymbol{\theta})+H_i(\dot{\boldsymbol{\theta}})=\tau_i. \qquad (2.4)$$

In each subsystem represented by equation (2.4), the summation term represents the interconnection between the ith subsystem and other subsystems.

The idea behind decentralized control is to generate a scalar control signal for each joint independently, instead of generating a vector of control signals for the whole system. To utilize the idea of decentralized control, it is important to view each subsystem separately from other subsystems. Therefore, it is desirable to lump any coupling effect from other subsystems and treat it as a disturbance. In equation (2.4) the disturbances consist of an inertia coupling term, coriolis and centripetal force term, a gravity loading term, and a frictional load term. If we lump these terms in d(t), then each subsystem becomes

$$m_{ii}(\boldsymbol{\theta})\ddot{\theta}_i(t)+d_i(t)=\tau_i(t). \qquad (2.5)$$

As it can be seen, in the absence of any disturbances, this is a simple double integrator system. A block diagram of this subsystem is shown in Figure 2.1. Note that in this figure, the disturbance is added before the plant.

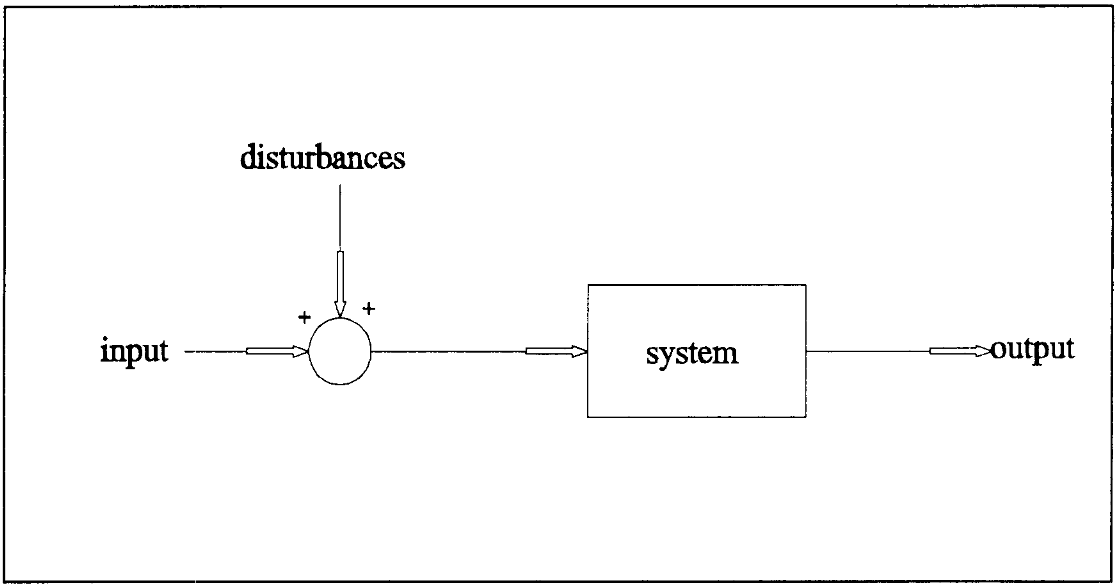

Figure 2.1. Block diagram of ith joint subsystem.

3. CONTROLLER DESIGN

The main objective of the controller design is to control each joint independently in a decentralized fashion and to track the prescribed trajectories. To achieve this objective, the controller should be designed to overcome the effect of unmodeled dynamics and unexpected disturbances.

To achieve this goal, we propose a controller of the form

$$\tau(t) = K_i(t) + K_p(t)e(t) + K_d(t)\dot{e}(t) + K_f\ddot{\theta}_r(t) \qquad (3.1)$$

where $(d^2\theta_r/dt^2)$ is the reference acceleration. The block diagram of the whole system is shown in Figure 3.1. The first term is used to overcome unmodeled disturbances. The second and third terms together form the PD feedback that stabilizes the closed-loop system. The fourth term is the feedforward compensator, which is designed to make the whole system track the time varying trajectory, when no disturbance exists.

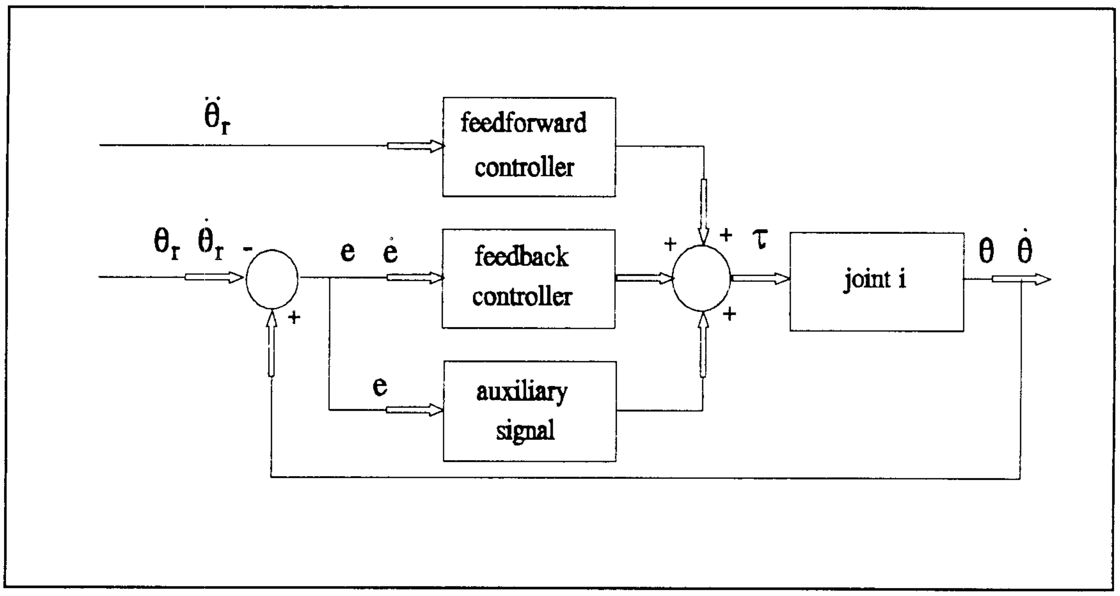

Figure 3.1. An adaptive controller of the ith joint

3.1 Feedforward Compensator

Let us for the time being assume that the system that represents the ith joint is linear and time-invariant. Consider the system in Figure 3.2.

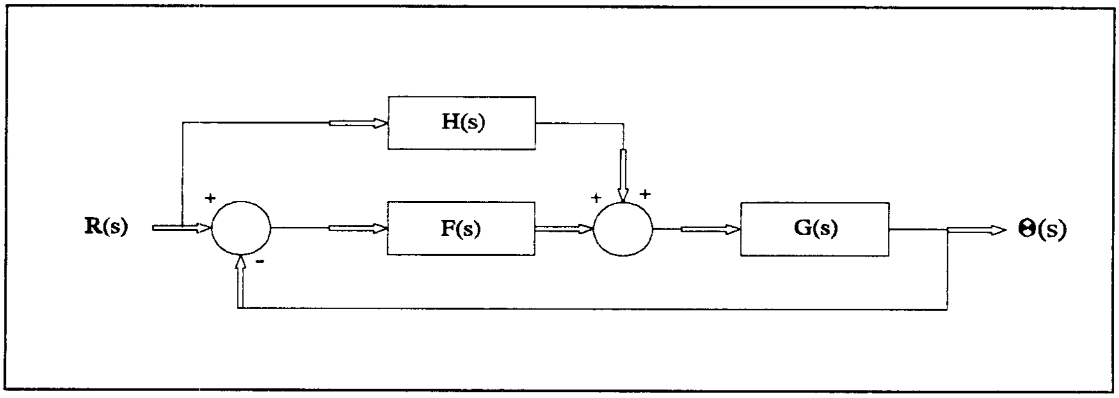

Figure 3.2. A system with feedforward and feedback compensation

where G(s), F(s), and H(s) represent the plant, feedback compensator, and feedforward compensator transfer functions, respectively.

Let these transfer functions be expressed by

$$G(s) = \frac{q(s)}{p(s)}, \quad F(s) = \frac{c(s)}{d(s)}, \quad H(s) = \frac{a(s)}{b(s)}. \qquad (3.2)$$

It is assumed that G(s) is strictly proper and H(s) is proper. The closed-loop transfer function is

$$TF(s) = \frac{\Theta(s)}{R(s)} = \frac{q(s)\,[c(s)b(s) + a(s)d(s)]}{b(s)\,[p(s)d(s) + q(s)c(s)]}. \qquad (3.3)$$

In order for this closed system to be stable, the characteristic equation b(s)(p(s)d(s)+q(s)c(s)) needs to have poles on the left half plane, (i.e., pd+qc needs to be Hurwitz, so does b).

Equation (3.3) can be expressed in terms of the tracking error

$$E(s)=R(s)-\Theta(s),$$

$$q(cb+ad)E+(q(cb+ad)-b(pd+qc))\Theta=0. \qquad (3.4)$$

If we choose b=q, a=p, i.e.,

$$F(s)=\frac{1}{G(s)}, \qquad (3.5)$$

then equation (3.4) becomes

$$q(pd+cq)E=0. \qquad (3.6)$$

As seen in equation (2.5), each subsystem of the robot manipulator is a double integrator system without a disturbance term, thus, the feedforward compensator can be defined by

$$\tau_{FF}=K_f\ddot{\theta}_r. \qquad (3.7)$$

3.2 Feedback Compensator

In this control scheme, a PD compensator is chosen as the feedback compensator. As mentioned above, in the absence of disturbances, the feed-forward controller gives perfect tracking performance, assuming that the closed-loop system is stable. Therefore, the PD compensator should be designed to ensure asymptotic stability of the closed-loop system.

3.3 Auxiliary Compensator

As mentioned before, the feedforward compensator and the PD feedback compensator are used to make the system track the desired path exactly. However, when disturbances exist, as in practical situations, the system output contains an error. For a linear system case as in Figure 3.2, with disturbances denoted as D, the error is given by

$$E(s) = \frac{qd}{pd+qc}D. \tag{3.8}$$

In order to reject this unwanted effect due to disturbances and the effect of unmodeled dynamics, the auxiliary control signal is employed. The actual control structure shall be derived based on the Lyapunov's stability theorem.

3.4 Lyapunov-Based Controller Design

In the previous sections the controller gains K_f, K_p, K_d, and K_i were not derived explicitly. In this thesis, these controller gains are synthesized based on the Lyapunov's stability theory, so that global asymptotic stability can be guaranteed under certain conditions.

Consider each subsystem described by equation (3.1).

$$m\ddot{\theta}+d=\tau . \tag{3.9}$$

Substituting the proposed controller into this equation, we get

$$m\ddot{\theta}+d=K_i+K_p e+K_d\dot{e}+K_f\ddot{\theta}_r. \tag{3.10}$$

Adding the term $m(d^2\theta_r/dt^2)$ to both sides, yields

$$m\ddot{e}+K_d\dot{e}+K_p e=d-K_i-K_f\ddot{\theta}_r+m\ddot{\theta}_r. \tag{3.11}$$

where

$$e=\theta_r-\theta$$

is the tracking error of each joint angle, and

$$\dot{e}=\frac{de}{dt}, \quad \ddot{e}=\frac{d^2e}{dt^2}.$$

Let $x=[e(t)\ de(t)/dt]^T$ be the states of equation (3.11), then the state-space model is given by

$$\dot{X}(t)=\begin{bmatrix}\dot{e}(t)\\ \ddot{e}(t)\end{bmatrix}=\begin{bmatrix}0 & 1\\ \frac{-K_p}{m} & \frac{-K_d}{m}\end{bmatrix}\begin{bmatrix}e(t)\\ \dot{e}(t)\end{bmatrix}+\begin{bmatrix}0\\ \frac{d-K_i}{m}\end{bmatrix}+\begin{bmatrix}0\\ \frac{m-K_f}{m}\end{bmatrix}\ddot{\theta}_r. \tag{3.12}$$

As seen in the literature of model reference adaptive control schemes [3], we define the error model by

$$\dot{x}_m(t)=\begin{bmatrix}\dot{e}_m(t)\\ \ddot{e}_m(t)\end{bmatrix}=\begin{bmatrix}0 & 1\\ -\omega^2 & -2\xi\omega\end{bmatrix}\begin{bmatrix}e_m(t)\\ \dot{e}_m(t)\end{bmatrix}=AX_m(t), \tag{3.13}$$

where ω is the undamped natural frequency, and ξ is the damping factor. The undamped natural frequency and damping factor are chosen such that the second order error model represented by equation (3.13) is asymptotically stable, (the system eigenvalues are located on left half of the complex plane).

Since the error model is designed to show a desired system response in terms of tracking error, it is desirable for the model to have a "zero" tracking error as an initial condition. The error model (3.13) has the simple solution

$$X_m(t)=e^{At}X_m(0)\,. \tag{3.14}$$

With zero initial condition, it has the response

$$X_m(t)=\tilde{0}\,. \tag{3.15}$$

Now, define the tracking error of the error system from the error model by

$$\begin{aligned}\dot{E}(t)&=\dot{X}_m(t)-\dot{X}(t)=\begin{bmatrix}\dot{e}_m(t)-\dot{e}\\ \ddot{e}_m(t)-\ddot{e}\end{bmatrix}\\ &=\begin{bmatrix}0 & 1\\ -\omega^2 & -2\xi\omega\end{bmatrix}E+\begin{bmatrix}0 & 0\\ \dfrac{K_p}{m}-\omega^2 & \dfrac{K_d}{m}-2\xi\omega\end{bmatrix}X\\ &\quad+\begin{bmatrix}0\\ \dfrac{K_i-d}{m}\end{bmatrix}+\begin{bmatrix}0\\ \dfrac{K_f-m}{m}\end{bmatrix}\theta_r\,.\end{aligned} \tag{3.16}$$

To derive the stability condition of this system, we utilize Lyapunov's stability theory. Let us consider the Lyapunov function candidate

$$V(t) = E^T P E + Q_0\left(\frac{K_i - d}{m} - f_o^*\right)^2 + Q_1\left(\frac{K_p}{m} - \omega^2 - f_1^*\right)^2$$
$$+ Q_2\left(\frac{K_d}{m} - 2\xi\omega - f_2^*\right)^2 + Q_3\left(\frac{K_f - m}{m} - f_3^*\right)^2, \tag{3.17}$$

where Q_i,i=0,..,3 are positive constants, and f_i^*,i=0,..,3 are functions yet to be defined. In order for the system to be asymptotically stable, the first time derivative of V needs to be negative definite along the system trajectory. Taking the time derivative of this Lyapunov function candidate (assuming that m and d remain constant over the sampling interval), yields

$$\dot{V}(t) = -E^T Q E + 2\left(\frac{K_i - d}{m}\right)\left[Q_0\left(\frac{\dot{K}_i}{m} - \dot{f}_o^*\right) - r\right] - 2Q_0 f_0^*\left(\frac{\dot{K}_i}{m} - \dot{f}_0^*\right)$$
$$+ 2\left(\frac{K_p}{m} - \omega^2\right)\left[Q_1\left(\frac{\dot{K}_p}{m} - \dot{f}_1^*\right) - re\right] - 2Q_1 f_1^*\left(\frac{\dot{K}_p^*}{m} - \dot{f}_1^*\right)$$
$$+ 2\left(\frac{K_d}{m} - 2\xi\omega\right)\left[Q_2\left(\frac{\dot{K}_d}{m} - \dot{f}_2^*\right) - r\dot{e}\right] - 2Q_2 f_2^*\left(\frac{\dot{K}_d}{m} - \dot{f}_2^*\right) \tag{3.18}$$
$$+ 2\left(\frac{K_f - m}{m}\right)\left[Q_3\left(\frac{\dot{K}_f}{m} - \dot{f}_3^*\right) - r\ddot{\theta}_r\right] - 2Q_3 f_3^*\left(\frac{\dot{K}_f}{m} - \dot{f}_3^*\right),$$

where

$$r = p_2 e + p_3 \dot{e}. \tag{3.19}$$

Since the reference error model is chosen to be an asymptotically stable system, there exists positive definite symmetric constant matrices P and Q such that

$$A^TP+PA=-Q, \tag{3.20}$$

$$P=\begin{bmatrix} p_1 & p_2 \\ p_2 & p_3 \end{bmatrix}, \quad Q=\begin{bmatrix} q_1 & q_2 \\ q_2 & q_3 \end{bmatrix}. \tag{3.21}$$

As stated before, it is assumed in the above derivation that inertia and disturbance terms are relatively slow time varying functions. This assumption can be justified if the sampling speed for the controller is much faster than the variation of the effective inertia and disturbances. Therefore, the time derivatives of these terms may be assumed to be zero. Now, in order for this Lyapunov function time derivative to be negative definite, choose the adaptation law such that

$$\begin{aligned}
&Q_0\left(\frac{\dot{K}_i}{m}-\dot{t}_0^*\right)-r=0 \Rightarrow \dot{K}_i=\left(\frac{r}{Q_0}+\dot{t}_0^*\right)m,\\
&Q_1\left(\frac{\dot{K}_p}{m}-\dot{t}_1^*\right)-re=0 \Rightarrow \dot{K}_p=\left(\frac{re}{Q_1}+\dot{t}_1^*\right)m,\\
&Q_2\left(\frac{\dot{K}_d}{m}-\dot{t}_2^*\right)-r\dot{e}=0 \Rightarrow \dot{K}_d=\left(\frac{r\dot{e}}{Q_2}+\dot{t}_2^*\right)m,\\
&Q_3\left(\frac{\dot{K}_f}{m}-\dot{t}_3^*\right)-r\ddot{\theta}_r=0 \Rightarrow \dot{K}_f=\left(\frac{r\ddot{\theta}_r}{Q_3}+\dot{t}_3^*\right)m.
\end{aligned} \tag{3.22}$$

When these conditions hold, the adaptive gains become

$$K_i=\int_0^t \left(\frac{r}{Q_0}\right) m dt + m f_0^*,$$

$$K_p=\int_0^t \left(\frac{re}{Q_1}\right) m dt + m f_1^*,$$

$$K_d=\int_0^t \left(\frac{r\dot{e}}{Q_2}\right) m dt + m f_2^*, \tag{3.23}$$

$$K_f=\int_0^t \left(\frac{r\boldsymbol{\theta}_r}{Q_3}\right) m dt + m f_3^*.$$

Substituting the time derivative of these gains into equation (3.18), yields

$$\dot{V}(t)=-E^TQE-2\left[f_0^* r + f_1^*(re) + f_2^*(r\dot{e}) + f_3^*(r\boldsymbol{\theta}_r)\right]. \tag{3.24}$$

Furthermore, if we choose the f_i^*'s as follows

$$f_0^*=f_0(t)r,\quad f_1^*=f_1(t)re,$$
$$f_2^*=f_2(t)r\dot{e},\quad f_3^*=f_3(t)r\boldsymbol{\theta}_r, \tag{3.25}$$

where $f_i(t)$,i=0,..,3 are nonnegative time functions or possibly nonnegative constants, then the time derivative of the Lyapunov function candidate becomes

$$\dot{V}(t) = -E^T Q E - 2[f_0(t) r^2 + f_1(t)(re)^2 + f_2(t)(r\dot{e})^2 + f_3(t)(r\dot{\theta}_r)^2]. \qquad (3.26)$$

Since the second term of the right hand side of equation (3.26) is the combination of squared terms multiplied by nonnegative quantities, equation (3.26) is negative definite. Therefore, the choice of controller gains (3.23) yield an asymptotically stable closed-loop system under the assumption that both the disturbance and the effective joint inertia remain relatively costant over the sampling period.

There still remains the task of choosing the nonnegative functions $f_i(t)$. The right hand side of the equation (3.26) needs to be negative definite in order to ensure asymptotic convergence of the tracking error. Since the first term is guaranteed to be negative definite, the second term should be designed to be negative definite. Here we propose penalizing the tracking error and utilizing it as $f_i(t)$ functions. Since the function **r** is defined in such a way that the tracking error and the velocity error are penalized as in equation (3.19), the absolute value of this function **r** will be considered as a possible choice of a nonnegative function.

Let

$$f_0(t) = k_0|r(t)|, \quad k_0 > 0,$$

$$f_1(t) = k_1' \text{ or } k_1|r(t)|, \quad k_1, k_1' \geq 0,$$

$$f_2(t)=k_2' \text{ or } k_2|r(t)|,\quad k_2,k_2'\geq 0, \tag{3.27}$$

$$f_3(t)=k_3' \text{ or } k_3|r(t)|,\quad k_3,k_3'\geq 0,$$

where the choice of $f_i(t)$, i=1,2,3, depends on the application. Since the f_i's are nonnegative and every element of the second term of the right hand side of equation (3.26) is a function of **r**, which is a linear function of the position and the velocity errors, equation (3.26) is guaranteed to be negative definite as long as tracking error exists. Let us modify the adaptive gains as follows

$$K_i=C_0\int_0^t r\,dt+k_0|r|r,$$

$$K_p=C_1\int_0^t re\,dt+f_1(t)\,re,$$

$$K_d=C_2\int_0^t r\dot{e}\,dt+f_2(t)\,r\dot{e}, \tag{3.28}$$

$$K_f=C_3\int_0^t r\boldsymbol{\theta}_r\,dt+f_3(t)\,r\boldsymbol{\theta}_r,$$

where the f_i's are as previously defined, and C_i,i=0,..,3 are constants,(assuming the effective inertia m_{ii} of the ith joint is constant,) defined by

$$C_i = \frac{m_c}{Q_i}, \quad i=0,1,2,3. \qquad (3,29)$$

As it is seen in equation (3.28), the penalized error is utilized as a convergence accelerator, which makes the time derivative of a Lyapunov function negative as long as a tracking error exists. Simulation shows faster tracking error convergence compared to the results from Seraji [18] and Dai [30]. The controller proposed here has the following characteristics:

1) Due to the decentralized structure, each controller has fewer computational tasks.

2) Since no information about the mathematical model of the robot manipulator is used to compute the controller gain, the computation is relatively faster.

3) The adaptive structure of the controller is robust against unmodeled dynamics and disturbances.

4) By using the penalized tracking error as a part of the adaptive gain, faster convergence of the tracking error can be expected.

4. COMPUTER SIMULATION

The performance of the proposed controller is tested via computer simulation by applying it to two joints of the PUMA 560 robot manipulator. This robot manipulator has two revolute joints, as depicted in Figure 4.1.

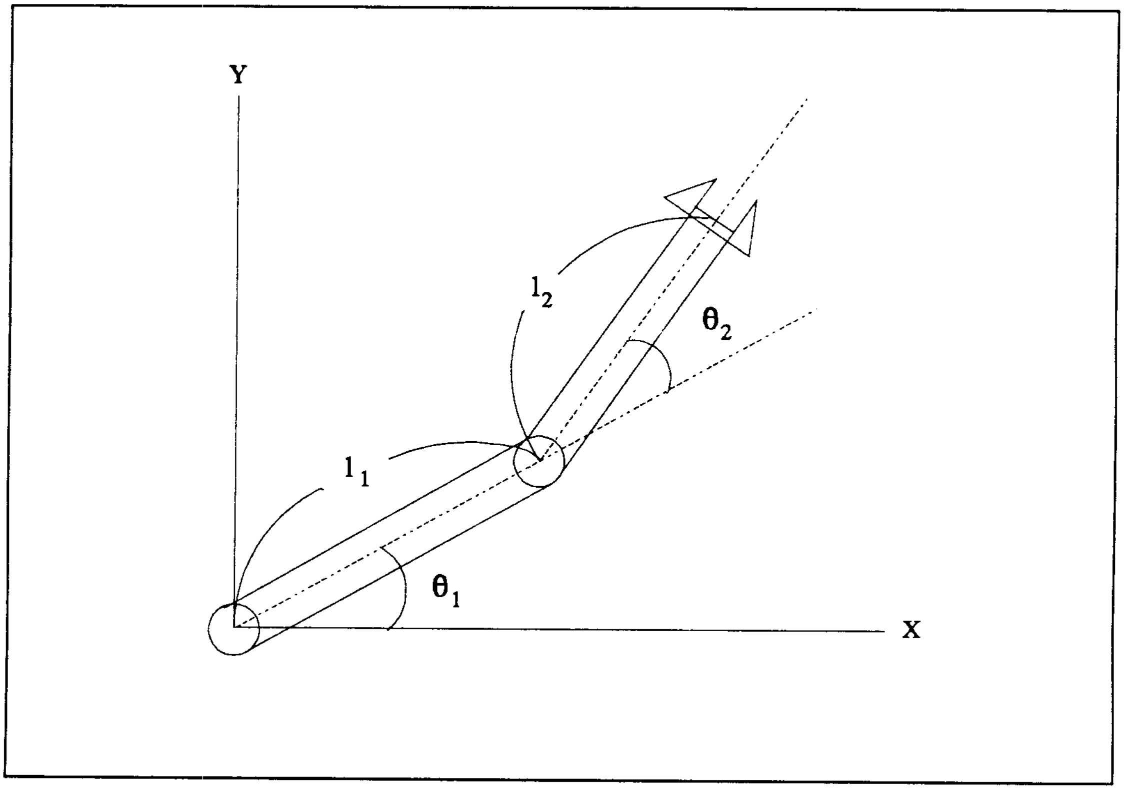

Figure 4.1. Two-joint robot manipulator.

This manipulator is represented mathematically by

$$\tau = M_0(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + N_0(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) + G_0(\boldsymbol{\theta}) + H(\dot{\boldsymbol{\theta}}) + m_l J^T(\boldsymbol{\theta})\,[J(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \dot{J}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})\dot{\boldsymbol{\theta}} + g], \quad (4.1)$$

where

$$M_0=\begin{bmatrix} a_1+a_2C_2 & a_3+\frac{a_2}{2}C_2 \\ a_3+\frac{a_2}{2}C_2 & a_3 \end{bmatrix},$$

$$N_0(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})=\begin{bmatrix} -a_2S_2(\dot{\boldsymbol{\theta}}_1\boldsymbol{\theta}_2+\frac{\dot{\boldsymbol{\theta}}_2^2}{2}) \\ \frac{(a_2S_2)(\dot{\boldsymbol{\theta}}_1^2)}{2} \end{bmatrix},$$

$$G_0(\boldsymbol{\theta})=\begin{bmatrix} a_4C_1+a_5C_{12} \\ a_5C_{12} \end{bmatrix},$$

$$H(\boldsymbol{\theta})=\begin{bmatrix} V_1\dot{\boldsymbol{\theta}}_1+V_2sgn(\dot{\boldsymbol{\theta}}_1) \\ V_3\dot{\boldsymbol{\theta}}_2+V_4sgn(\dot{\boldsymbol{\theta}}_2) \end{bmatrix},$$

$$J(\boldsymbol{\theta})=\begin{bmatrix} -l_1S_1-l_2S_{12} & -l_2S_{12} \\ l_1C_1+l_2C_{12} & l_2C_{12} \end{bmatrix},$$

$$\dot{J}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})=\begin{bmatrix} -l_1\dot{\boldsymbol{\theta}}_1C_1-l_2(\dot{\boldsymbol{\theta}}_1+\dot{\boldsymbol{\theta}}_2)C_{12} & -l_2(\dot{\boldsymbol{\theta}}_1+\dot{\boldsymbol{\theta}}_2)C_{12} \\ -l_1\dot{\boldsymbol{\theta}}_1\dot{S}_1-l_2(\dot{\boldsymbol{\theta}}_1+\dot{\boldsymbol{\theta}}_2)S_{12} & -l_2(\dot{\boldsymbol{\theta}}_1+\dot{\boldsymbol{\theta}}_2)S_{12} \end{bmatrix},$$

$$G=\begin{bmatrix} 0 \\ 9.81 \end{bmatrix},$$

m_1 : *mass of the payload,*

$S_i = \sin(\boldsymbol{\theta}_i)$, $C_i=\cos(\boldsymbol{\theta}_i)$,

$S_{ij} = \sin(\boldsymbol{\theta}_i+\boldsymbol{\theta}_j)$, $c_{ij} = \cos(\boldsymbol{\theta}_i+\boldsymbol{\theta}_j)$.

For each joint the mathematical model is described by

$$\tau_1=[m_{11}+m_l(J_{11}^2+J_{21}^2)]\ddot{\theta}_1+[m_{12}+m_l(J_{11}J_{12}+J_{21}J_{22})]\ddot{\theta}_2$$
$$+N_1+m_l[(J_{11}\dot{J}_{11}+J_{21}\dot{J}_{21})\dot{\theta}_1+(J_{11}\dot{J}_{12}+J_{21}\dot{J}_{22})\dot{\theta}_2$$
$$+G_1+9.81m_lJ_{21}+H_1$$
$$\triangleq\hat{m}_{11}\ddot{\theta}_1+d_1,$$

$$\tau_2=[m_{22}+m_l(J_{12}^2+J_{22}^2)]\ddot{\theta}_2+[m_{12}+m_l(J_{11}J_{12}+J_{21}J_{22})]\ddot{\theta}_1$$
$$+N_2+m_l[(J_{12}\dot{J}_{11}+J_{22}\dot{J}_{21})\dot{\theta}_1+(J_{12}\dot{J}_{12}+J_{22}\dot{J}_{22})\dot{\theta}_2$$
$$+G_2+9.81m_lJ_{22}+H_2$$
$$\triangleq\hat{m}_{22}\ddot{\theta}_2+d_2.$$

The numerical values of the constants are

$$a_1=3.82,\ a_2=2.12,\ a_3=0.71,\ a_4=81.82,\ a_5=24.06,$$
$$l_1=l_2=0.432m,\ V_1=V_2=1N_tm/rad\ S^{-1},\ V_2=V_4=0.5N_tm/rad\ S^{-1}.$$

The controller for each independent joint is generically described by

$$\tau_i(t)=K_i(t)+K_p(t)e(t)+K_d(t)\dot{e}(t)+K_f(t)\ddot{\theta}_r(t). \qquad (4.2)$$

In this simulation, the controller terms have the values

$$r_i(t)=8000e_i+800\dot{e}_i,$$

$$K_{i1}(t)=10\int_0^t r_1dt+0.02|r_1|r_1,$$

$$K_{i2}(t)=10\int_0^t r_2dt+0.005|r_2|r_2,$$

$$K_{p_i}(t)=10\int_0^t (re)_i dt,$$

$$K_{di}(t)=10\int_0^t (r\dot{e})_i dt,$$

$$K_{f1}(t)=\int_0^t (r\ddot{\theta}_r)_1 dt+0.02 r_1 \ddot{\theta}_{r1},$$

$$K_{f2}(t)=\int_0^t (r\ddot{\theta}_r)_2 dt+0.005 r_2 \ddot{\theta}_{r2}.$$

We test the performance of our controller by having the two joints of the robot manipulator track certain desired trajectories. These reference trajectories are prescribed as smooth time functions and they are based on functions introduced by Kane and Levinson in [12], that is,

$$\theta_{ri}(t)=\theta_{ri}(t_0)+\frac{\theta_{ri}(t_p)-\theta_{ri}(t_0)}{2\pi}(\Omega t-\sin(\Omega t)), \qquad (4.3)$$

$$\ddot{\theta}_{ri}=[\frac{\pi}{2p}-\frac{\pi}{2p}\cos(\frac{2\pi t}{p})],$$

$$\Omega=\frac{2\pi}{p} \quad i=1,2 \quad t_0\le t\le t_p,$$

where p is the time period elapsed to trace the whole trajectory, t_o is the initial time, t_p is the final time, $\theta_{ri}(t_o)$ is the initial joint angle, and $\theta_{ri}(t_p)$ is the final joint angle. For joint 1, $\theta_{r1}(t_o) = -90$ and $\theta_{r1}(t_p) = 0$, for joint 2, $\theta_{r2}(t_o)$ $= 0$ and

$\theta_{r2}(t_p) = 90$. Note that the only reference signal used in the proposed control scheme is the reference acceleration

$$\ddot{\theta}_{ri}(t) = \frac{\pi^2}{p^2}\sin\left(\frac{2\pi t}{p}\right).$$

The time period elapsed, p, is set to either 1 or 3 seconds. Note that p = 1 seconds corresponds to the fast motion of the PUMA 560 robot manipulator.

Simulation 1

The proposed controller is applied to the robot arm, which is holding a constant mass of 10 Kg at the end effector of link 2. Figure 4.2 shows the case when time elapsed is 1 second. Figure 4.3 is for p=3 seconds. In both of these cases the control activity and the torque performance are all very smooth. The tracking error is so small that the actual trajectory and the reference trajectory basically coincide with each other.

Simulation 2

In this simulation, the penalized error term in the controller is set to zero, i.e., no convergence accelerator is used to investigate the effect of the convergence accelerator. Note that other controller gain terms are kept at the same values as those in simulation 1. Figures 4.4, 4.5 show the tracking performances for elapsed time 1 and 3 seconds, respectively. As shown in both figures, the torque performance and tracking error both oscillate before they settle down. They show what happens to the convergence of the tracking error when the accelerator component is absent.

Simulation 3

In order to show the robustness of the proposed controller, the payload mass is dropped at t=1.5 seconds. It should be noted that this condition obviously violates the assumption that inertia matrix is time constant. Numerically, for joint 1, the effective inertia changes abruptly about 55%, and 75% for joint 2. Although, the assumption is violated, the tracking performance is still good.

Simulation 4

In this simulation, various disturbances are applied to the robot manipulator to show its robustness. The disturbances are applied as follows: 1) the gravity is artificially halved during robot motion at time t=2.0 seconds, 2) a torque disturbance of 10 N_t.m is applied to each joint over the time period $0.9<t<1.6$ seconds in a random fashion, 3) payload is dropped at t=1.5 seconds.

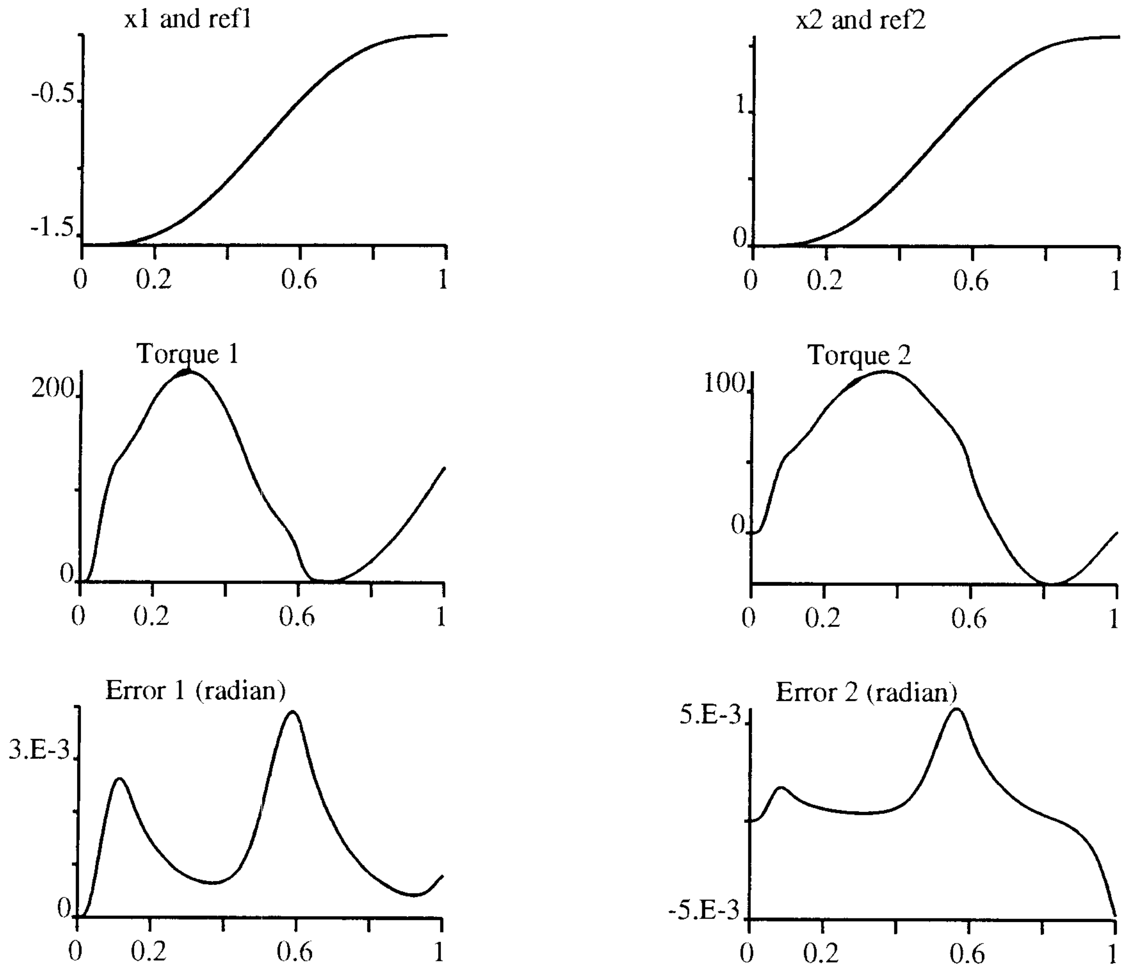

Figure 4.2. Tracking performance when p=1 second.

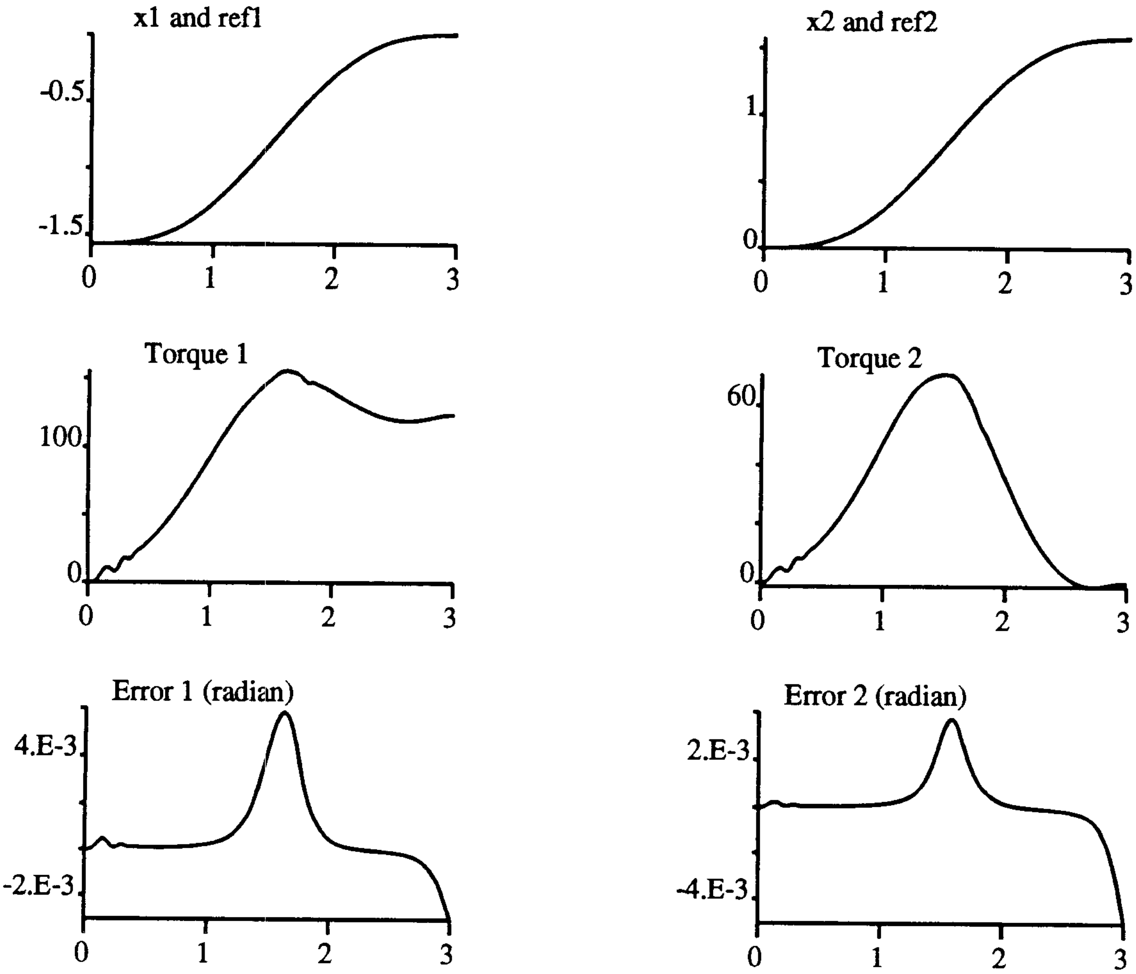

Figure 4.3. Tracking performance when p=3 seconds.

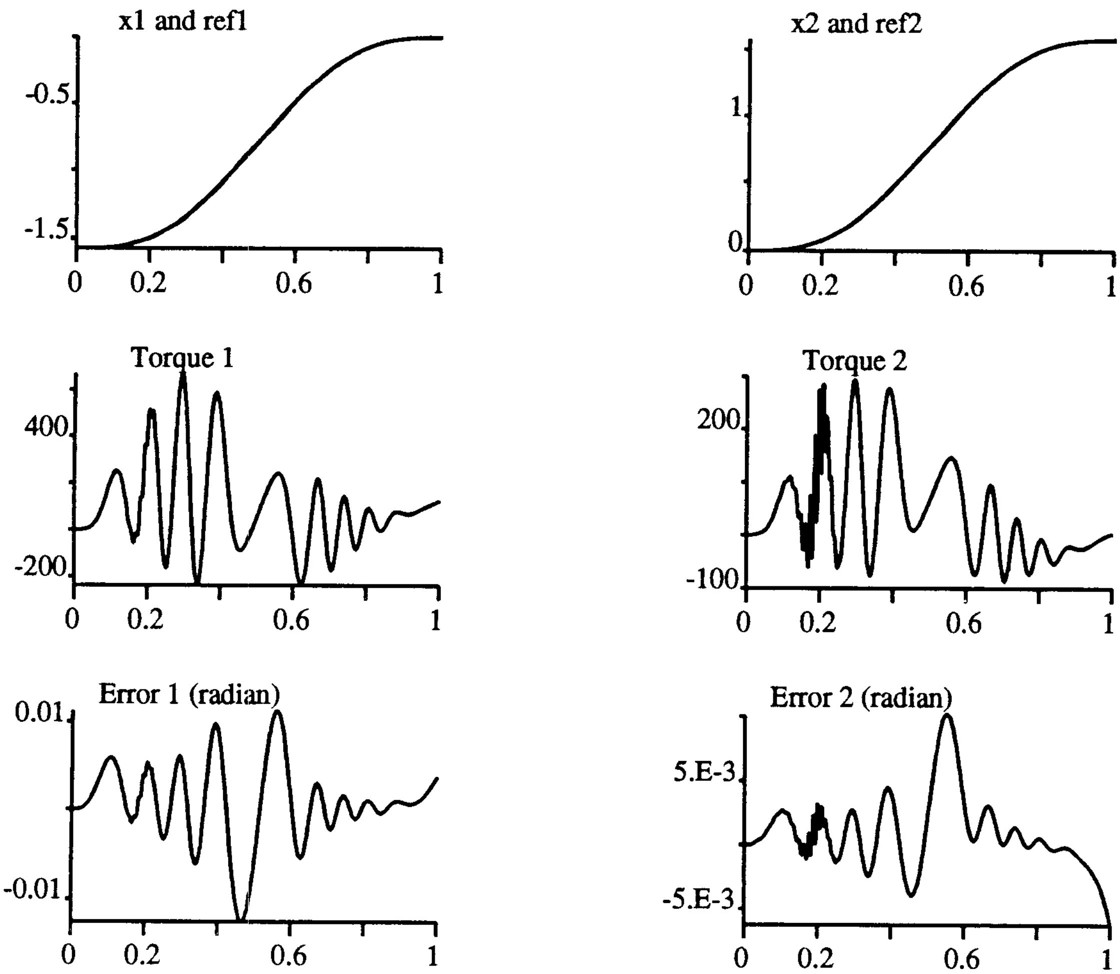

Figure 4.4. Tracking performance when p=1 second without

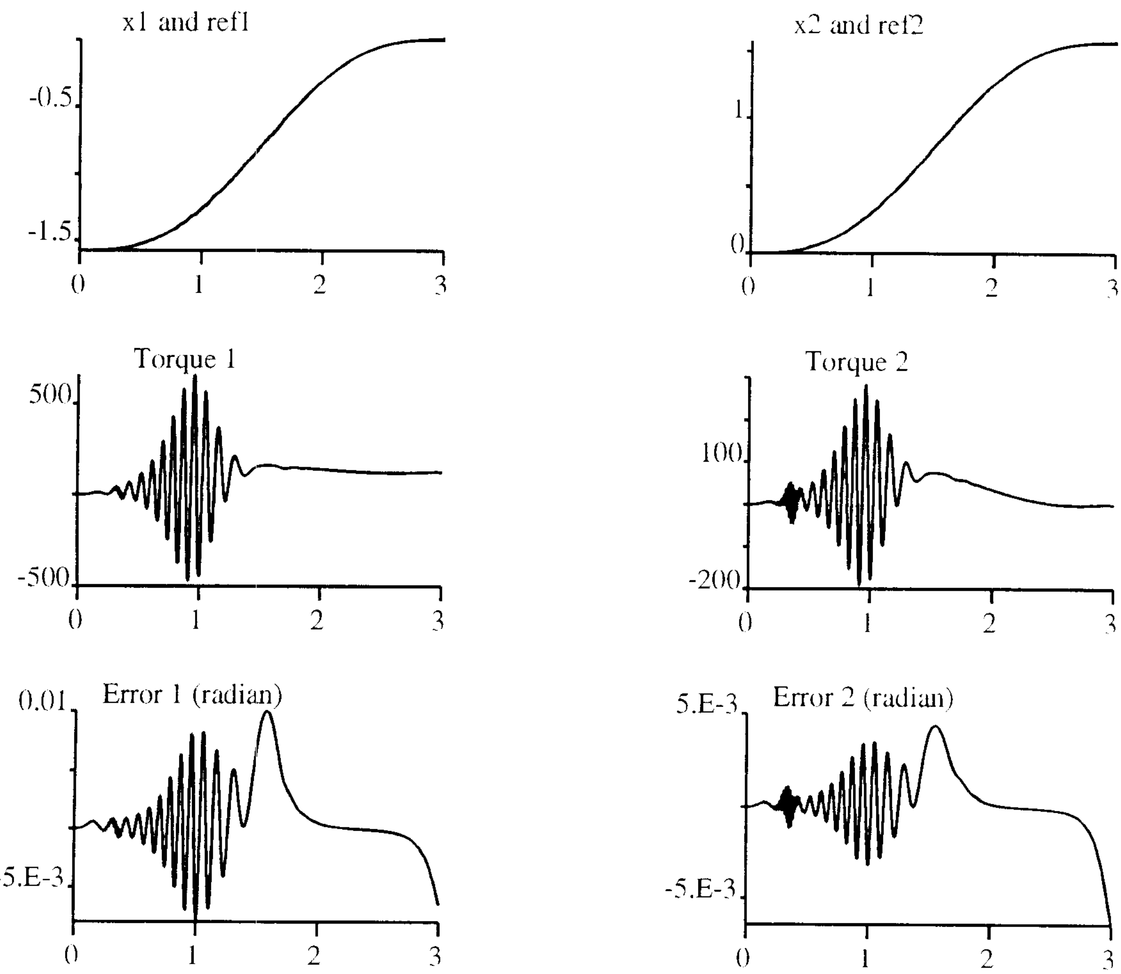

Figure 4.5. Tracking performance when p=3 seconds without convergence accelerator

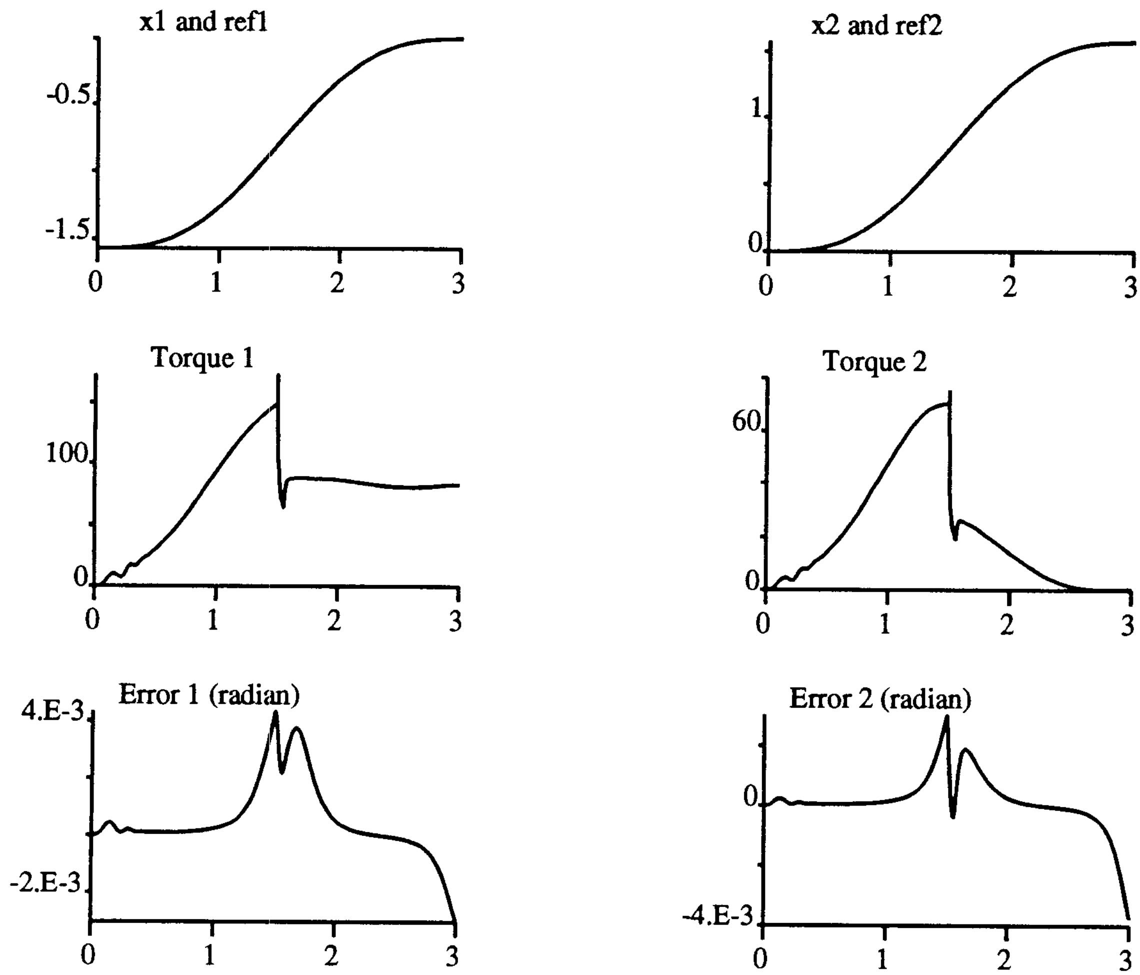

Figure 4.6. Tracking performance when end effector payload is dropped at t=1.5 seconds.

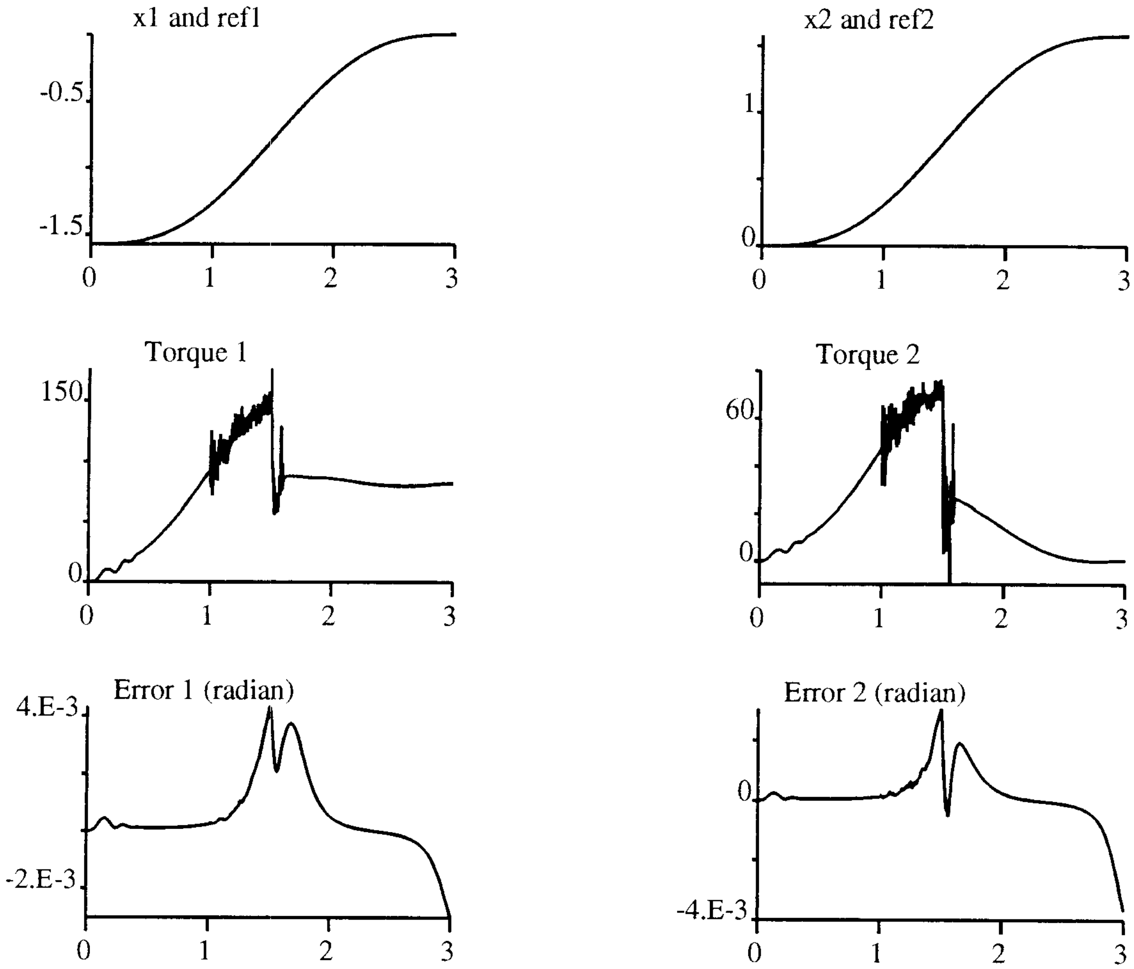

Figure 4.7. Tracking performance when payload is dropped at t=1.5 seconds, the gravity is halved at t=2 seconds, and a random noise is added over 0.9<t<1.6 seconds.

5. CONTROLLER WITH TIME VARYING INERTIA

In Chapter 3, the time varying inertia was assumed to be constant. This is a good approximation only when the sampling speed of the controller is much faster than the variation of the effective inertia. Although the controller with the constant inertia we proposed shows very high performance, it can be expected that utilizing the time-varying inertia in the calculation of controller gains should result in a better controller performance. However, the time varying inertia can not be obtained directly from observations of position and velocity signals. One way of obtaining the effective inertia term is through parameter estimation. However, due to the high nonlinear model of the robot system, this is a very time consuming calculation. Another way is by using a recursive estimate of the theoretical inertia.

In each period, in order to decide the control action, the theoretical inertia calculated from the previous period's information is used. Therefore, the estimated inertia which is used for controller gains is described in a discrete time recursive fashion. We include the estimated inertia when calculating the adaptive control law in order to investigate the possibility of better controller performance.

5.1 Effective Inertia Estimate of Each Joint

The discrete-time estimate of the effective inertia for each joint is

$$\hat{m}_{11}^{j}=a_1+a_2\cos(\theta_2^{j-1})+2m_l l^2(1+\cos(\theta_2^{j-1}))$$
$$\hat{m}_{22}^{j}=a_3+m_l l^2. \qquad (5.1)$$

In equation (5.1), superscripts j and j-1 denote the values of present and previous update times, respectively. Substituting equation (3.25) into equation (3.23), while considering estimated time varying effective inertia, yields a new set of adaptation laws

$$K_i=\int_0^t \left(\frac{r}{Q_0}\right)\hat{m}_{ii}dt+k_0\hat{m}_{ii}|r|r,$$

$$K_p=\int_0^t \left(\frac{re}{Q_1}\right)\hat{m}_{ii}dt+\hat{m}_{ii}f_1(t)re,$$

$$K_d=\int_0^t \left(\frac{r\dot{e}}{Q_2}\right)\hat{m}_{ii}dt+\hat{m}_{ii}f_2(t)r\dot{e},$$

$$K_f=\int_0^t \left(\frac{r\boldsymbol{\theta}_r}{Q_3}\right)\hat{m}_{ii}dt+\hat{m}_{ii}f_3(t)r\boldsymbol{\theta}_r.$$

where

$\hat{m}_{ii}^j$: *estimate of theoretical inertia of joint i at time step* t_j,

$f_i(t)$,i=1,2,3 are fuctions defined in a similar manner as (3,27), and Q_i,i=0,...,3 are positive constants. The numerical values are

$$K_{i1}=\int_0^t \hat{m}_{11} r_1 dt + 0.002\hat{m}_{11}|r_1|r_1,$$

$$K_{i2}=4\int_0^t \hat{m}_{22} r_2 dt + 0.002\hat{m}_{22}|r_2|r_2,$$

$$K_{p1}=\int_0^t \hat{m}_{11} r_1 e_1 dt,$$

$$K_{p2}=4\int_0^t \hat{m}_{22} r_2 e_2 dt,$$

$$K_{d1}=\int_0^t \hat{m}_{11} r_1 \dot{e}_1 dt,$$

$$K_{d2}=4\int_0^t \hat{m}_{22} r_2 \dot{e}_2 dt,$$

$$K_{f1}=0.1\int_0^t \hat{m}_{11} r_1 \boldsymbol{\theta}_{r1} dt + 0.002\hat{m}_{11} r_1 \boldsymbol{\theta}_{r1},$$

$$K_{f2}=0.4\int_0^t \hat{m}_{22} r_2 \boldsymbol{\theta}_{r2} dt + 0.002\hat{m}_{22} r_2 \boldsymbol{\theta}_{r2}.$$

5.2 Simulation with Time Varying Effective Inertia

Figures 5.1 and 5.2 show the tracking performance of the proposed controller with an estimate of the theoretical time varying effective inertia for elapsed time of 1 second and 3 seconds, respectively. In both cases, the difference of the tracking performance from the performance of the controller which does not utilize the time varying inertia is not very obvious. This shows that the rate of change of the inertia is slow enough to be approximated as constant over one sampling period. To investigate more about the effect of the time varying inertia on the control law, the time interval of robot motion is decreased to 0.5 second. It should be noted that this may or may not be a practical situation. Figure 5.3 shows the control performance of the controller

which does not utilize the time varying inertia. Figure 5.4 shows the control performance with the time varying inertia. Both are for the case of 0.5 second elapsed time. In all the cases above, the tracking error of joint 1 is slightly improved with the controller with time varying inertia, while that of joint 2 remains the same. This is because the actual inertia of joint 2 is constant. Therefore, the effect of time varying effective inertia is not significant for joint 2.

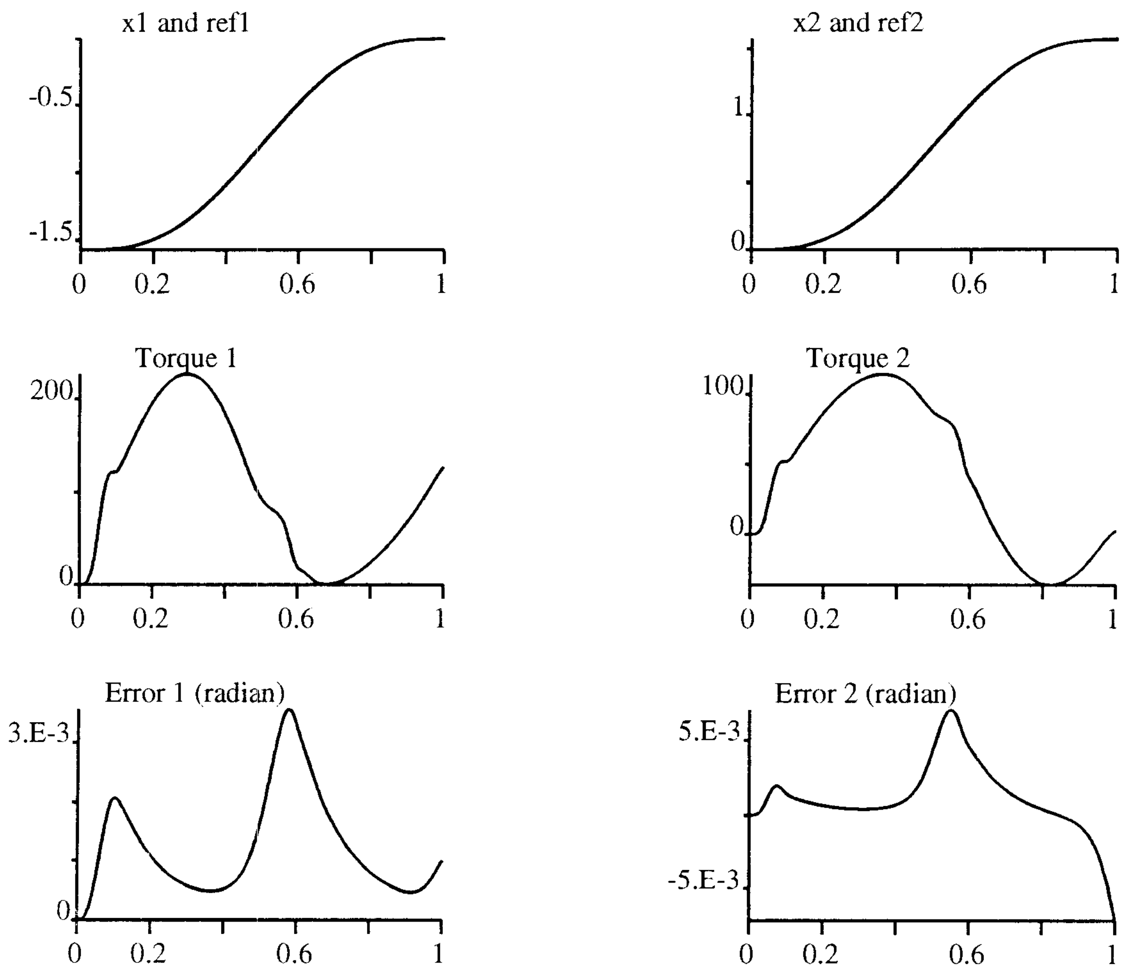

Figure 5.1. Tracking performance when p=1 second with time varying inertia considered.

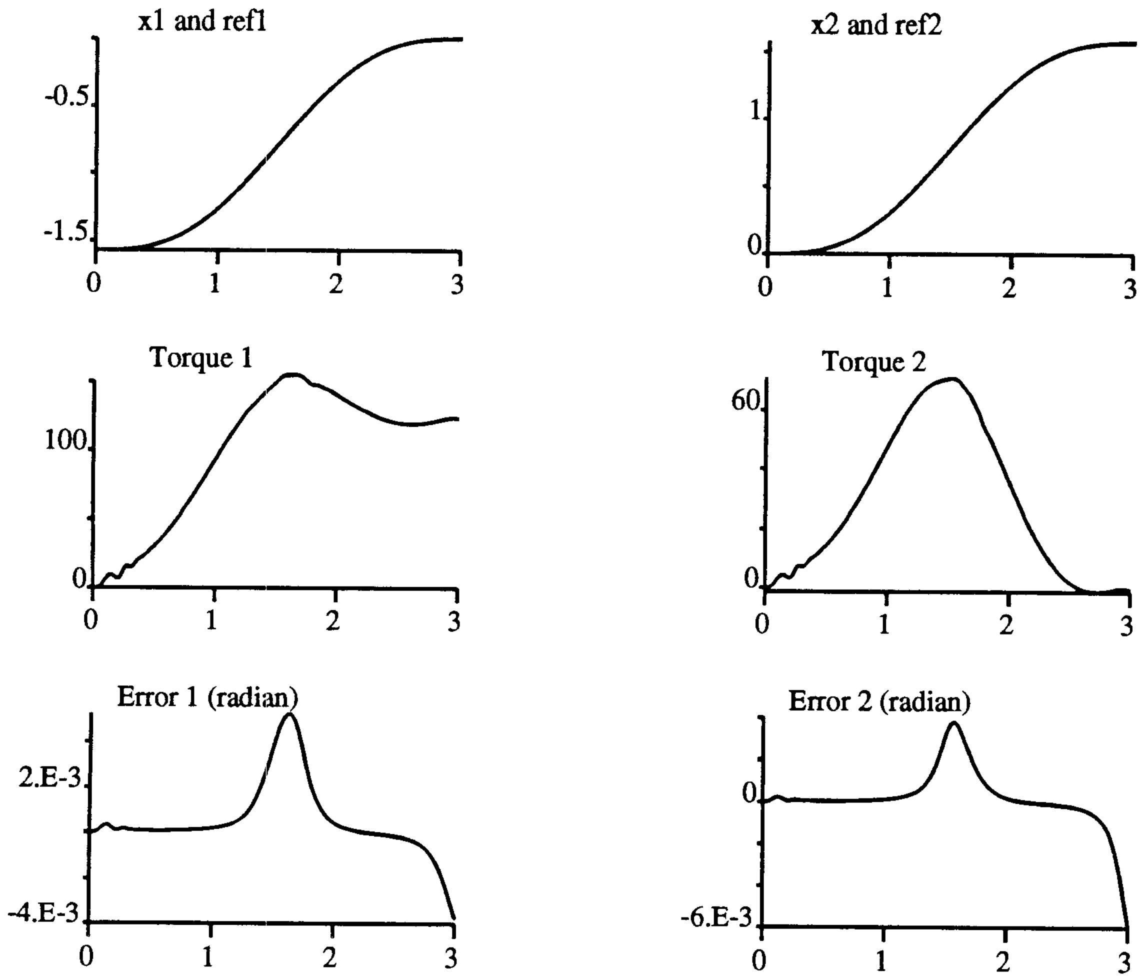

Figure 5.2. Tracking performance when p=3 seconds with time varying inertia considered.

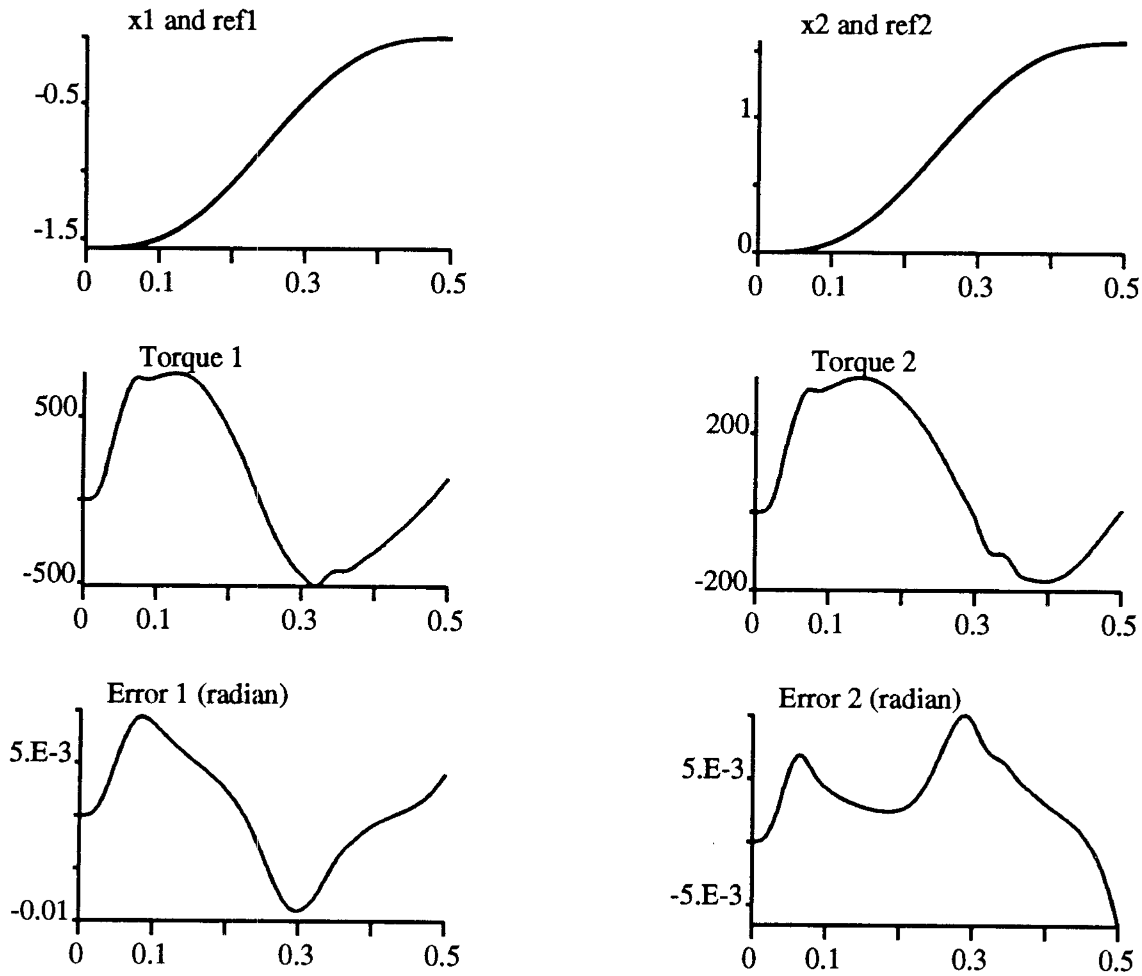

Figure 5.3. Tracking performance when p=0.5 seconds with constant inertia considered.

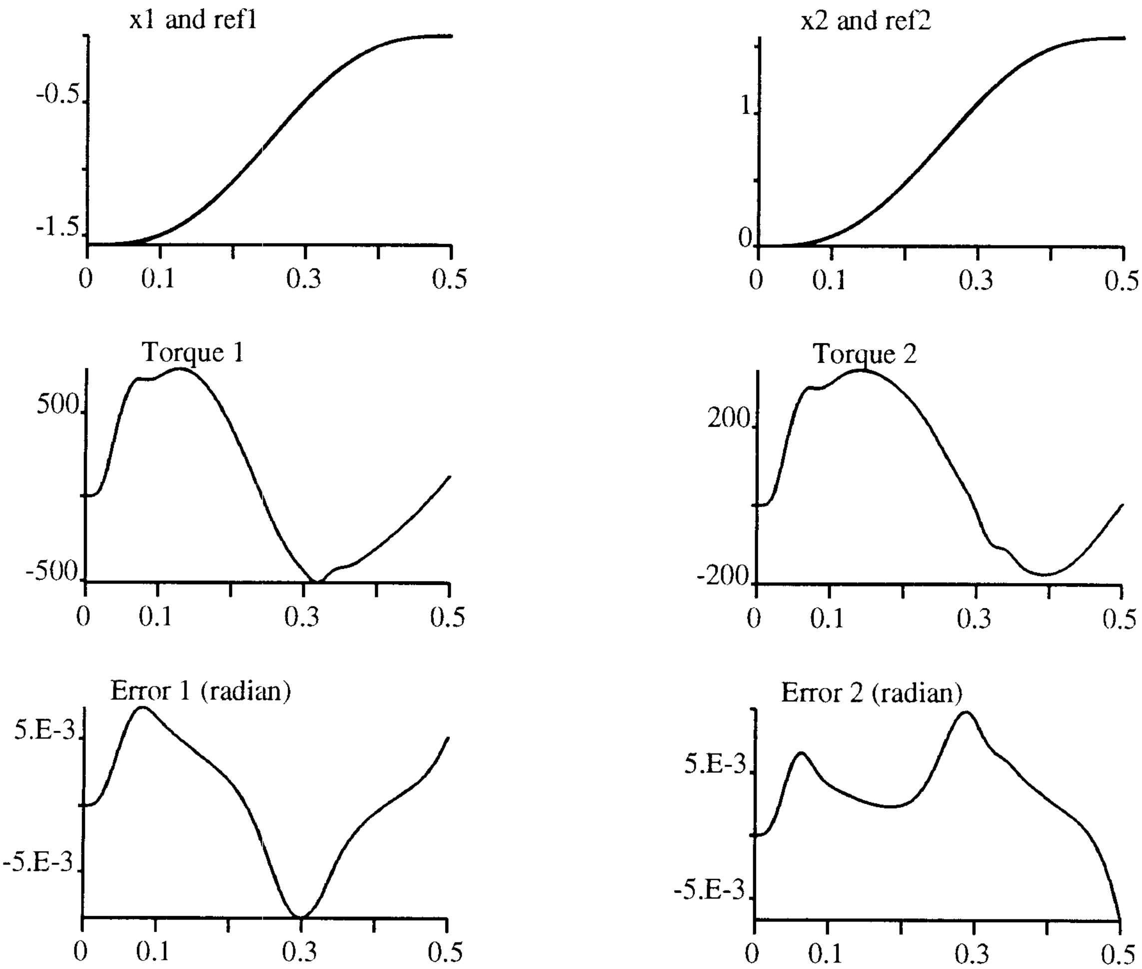

Figure 5.4. Tracking performance when p=0.5 second with time varying inertia considered.

6. CONCLUSION

A decentralized adaptive control scheme for highly nonlinear robot manipulators was designed in this thesis. Its performance was tested on two of the joints of the PUMA 560 industrial robot arm. Due to its decentralized structure, the control scheme only requires position and velocity measurements from the joint to be controlled. The proposed algorithm is characterized by proportional and derivative feedback signals, a feedforward signal derived from the desired trajectory, and an auxiliary signal. Fast convergence of the tracking error as well as smooth control activity was achieved when the tracking error is explicitly utilized as a part of the controller gains.

To evaluate the performance of the proposed controller, we tested it through several computer simulations. The various tests showed the robustness of this control scheme even while violating the assumption that the effective inertia varies much more slowly in time as compared to the sampling period.

The important improvement in performance of our controller over those proposed by Seraji [18], Dai [30], and Jiménez [31] is that with our scheme the tracking error is significantly reduced and much smoother torque activity is attained. The control scheme does not require the desired position and velocity signals. This simplicity helps for faster calculation of the control law, and is more suitable for practical applications. Furthermore, the stability of each joint is ensured, under certain conditions, by explicitly using a Lyapunov function to derive the controller.

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