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Disturbance Attenuation in Robot Control

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Abstract— **In this paper, we propose a model based disturbance attenuator (MBDA) with the conventional PD controller for robot manipulators. It is a generalization of MBDA structure in [1] and is applied to a robot manipulator which is nonlinear. This method does not require an accurate model of a robot manipulator and takes care of disturbances or modeling errors so that the plant output remains relatively unaffected by them. The output error due to the gravity or constant disturbance can be completely eliminated by this method in the same way as PID controllers. In addition, this can be easily implemented at a moderate computational cost. We apply this to a two-link robot manipulator and compare its performance with PD and PID controllers. Simulation results show that the proposed method is very effective in controlling robot manipulators.**

Keywords— **Robot manipulators, MBDA, position control, Lyapunov function, stability.**

I. Introduction

To achieve high performance in controlling robots, much research has been conducted under the assumption that the dynamics of robot systems are exactly known. But this assumption is not usually satisfied because it is very difficult to obtain an exact robot model due to its nonlinear dynamic structure and modeling uncertainties.

To cope with these problems, many researchers have studied robust and adaptive control schemes extensively. A good survey on this topic can be found in [2]. Some of these researchers have proposed neural network models which adaptively compute the inverse model of the plant [3]-[7]. Though powerful in controlling robot manipulators with parametric uncertainties, these are by nature slow in updating weights and requires high computational efforts.

Regarding robust controller designs [8] [9], quite a few algorithms rely on the linear-multivariable or the feedback-linearization approach [10] where the inverse dynamics of the robot is used in order to globally linearize and decouple the robot dynamic equations. In doing so, strict uncertainty bounds on modeling error and disturbances must be satisfied, but these restrictions can sometimes be difficult to meet in real robot systems.

On the other hand, the conventional PD or PID controllers are very easy to implement and there is little need to know the dynamics of the robot. Thus, most robots employed in industry are controlled by these algorithms independently acting on each joint. It has long been proven that PD control with gravity compensation can be used to achieve global asymptotic stability for any positive values of the control gains [11]. However, it requires knowledge of the gravitational torque, which is not easy to measure. To overcome uncertainties on the gravitational torque, adaptive schemes have been devised [12] [13], but these require the system parameters such as masses and lengths of the robot to satisfy complex inequalities.

In regard to PID controllers, their capability of disturbance elimination motivated many researchers to prove its stability [14]-[16]. Arimoto and Miazaki [14] proposed a proof for the stability of PID controller but the integral gain of the feedback loop must be so small that it actually falls on PD control scheme [15]. Rocco [15] also proved local stability of the PID controller based on a Lyapunov function. Recently, Kelly [16] proved the global stability of a PID like controller by imposing a nonlinear integral action in addition to the PD controller. Even if the PID controller be globally stable, it usually exhibits overshoot and oscillation because robot dynamics behaves in a somewhat similar manner to a second order linear system.

In this paper, we propose a new method for controlling robot manipulators. The proposed method is easy to implement and very robust in regard to modeling errors and disturbances. It consists of a model in parallel with the plant. In the presence of disturbances, this method attenuates the disturbance significantly, thus we call it a "model based disturbance attenuator". MBDA was first proposed by Choi et. al. for a CNC machining center with the stability analysis on linear systems [1] [17]. Here, we generalize the structure of MBDA slightly, and apply it to robot systems whose dynamics are nonlinear. This MBDA controller has both the advantage of a PD controller in that it is globally asymptotically stable and the advantage of a PID controller which can eliminate steady state errors due to modeling errors or disturbances.

The paper is organized as follows: In Section II, we review some properties of robot manipulators. In Section III, we propose the MBDA controller, and give conditions of stability. In Section IV, simulation results are presented showing the merits of MBDA. Conclusions are presented in Section V.

II. Robot Dynamics

In this section, we provide a brief introduction to robot dynamics together with some of its properties. In the

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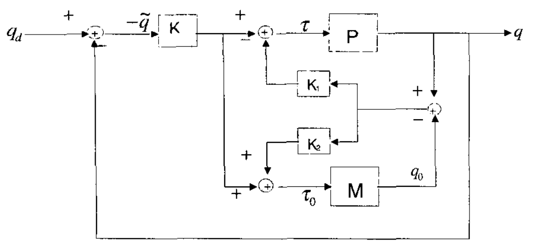


Fig. 1. MBDA Controller

absence of friction and disturbances, the dynamics of an n degree of freedom robot manipulator is given by the Lagrange-Euler vector equation:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau \qquad (1)$$

where $q, \dot{q}, \ddot{q} \in \Re^n$ are the vectors of generalized position, velocity, and acceleration respectively, of n links, $M(q) \in \Re^{n\times n}$ is the inertia matrix which is positive definite and symmetric, $C(q,\dot{q}) \in \Re^{n\times n}$ accounts for the centrifugal and Coriolis terms, $g(q) \in \Re^n$ is the gravity term, and $\tau \in \Re^n$ is the generalized torque acting on the links.

The equation of motion (1) has the following properties [16] [19].

Property 1 : Skew symmetry: The matrix $N(q,\dot{q}) = \dot{M}(q) - 2C(q,\dot{q})$is skew symmetric. Thus,

$$\dot{M}(q) = C(q,\dot{q}) + C^T(q,\dot{q}).$$

Property 2 : Boundedness of centrifugal and Coriolis terms: There exists a positive constants k_c such that

$$||C(q,\dot{q})|| \le k_c||\dot{q}||, \qquad \forall q, \dot{q} \in \Re^n.$$

Property 3 : Boundedness of gravitational torque: There exists a positive constant k_g satisfying

$$\left|\left|\frac{\partial g(q)}{\partial q}\right|\right| < k_g, \qquad \forall q \in \Re^n$$

and

$$||g(x) - g(y)|| \le k_g||x - y||, \qquad \forall x, y \in \Re^n.$$

III. The MBDA Controller and its Stability

Now we propose the MBDA controller to control robot manipulators described above and give a stability analysis. Fig.1 shows the structure of MBDA, where P is a plant, M is a model for the plant. $q, q_0, q_d \in \Re^n$ are a position vector of the plant, a position vector of the model, and a desired position vector respectively, $\tau, \tau_0 \in \Re^n$ are input torques for plant and model. In the figure, K, K_1, and K_2 are feedback gain matrices of appropriate dimensions. The conventional PD gains are used for K and K_1, and only D gains are used for K_2. If $K_2 = 0$, it is the same structure as in [1] [17]. The dynamics of a model is

$$M_0(q_0)\ddot{q}_0 + C_0(q_0,\dot{q}_0)\dot{q}_0 = \tau_0 \qquad (2)$$

where the subscript "0" is used to represent terms related to the model. Note that we omit the gravity term in the model dynamics. Then the inputs become

$$\begin{aligned} \tau &= -K_p\tilde{q} - K_d\dot{\tilde{q}} - K_{p1}(q - q_0) - K_{d1}(\dot{q} - \dot{q}_0) \\ \tau_0 &= -K_p\tilde{q} - K_d\dot{\tilde{q}} + K_{d2}(\dot{q} - \dot{q}_0) \qquad (3) \\ &\text{where} \qquad \tilde{q} = q - q_d \end{aligned}$$

Here, the diagonal matrices K_p (K_{p1}) and K_d (K_{d1}) are P and D gains of K (K_1), and the diagonal matrix K_{d2} is D gain of K_2.

Let $\boldsymbol{q} \triangleq [q^T, \quad (q_0 - K_{p1}^{-1}g(q_d))^T]^T$, $\tilde{\boldsymbol{q}} \triangleq [\tilde{q}^T, \quad (\tilde{q}_0 - K_{p1}^{-1}g(q_d))^T]^T$, and $\boldsymbol{\tau} \triangleq [(\tau - g(q_d))^T, \quad \tau_0^T]^T$, and rewrite (1), (2) and (3) with these augmented position vectors for $\dot{q}_d(t) = 0, t > 0$ which corresponds to a constant input vector.

$$\begin{aligned} \boldsymbol{\tau} &= -\begin{bmatrix} K_p + K_{p1} & -K_{p1} \\ K_p & 0 \end{bmatrix} \begin{bmatrix} \tilde{q} \\ \tilde{q}_0 - K_{p1}^{-1}g(q_d) \end{bmatrix} \\ &\quad - \begin{bmatrix} K_d + K_{d1} & -K_{d1} \\ K_d - K_{d2} & K_{d2} \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{q}_0 \end{bmatrix} \\ &= -\boldsymbol{K_p}\tilde{\boldsymbol{q}} - \boldsymbol{K_d}\dot{\boldsymbol{q}} \qquad (4) \end{aligned}$$

$$\begin{aligned} &\begin{bmatrix} M(q) & 0 \\ 0 & M_0(q_0) \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \ddot{q}_0 \end{bmatrix} + \begin{bmatrix} C(q,\dot{q}) & 0 \\ 0 & C_0(q_0,\dot{q}_0) \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{q}_0 \end{bmatrix} \\ &+ \begin{bmatrix} g(q) - g(q_d) \\ 0 \end{bmatrix} \\ &= \boldsymbol{M(q)}\ddot{\boldsymbol{q}} + \boldsymbol{C(q,\dot{q})}\dot{\boldsymbol{q}} + \boldsymbol{g(q,q_d)} = \begin{bmatrix} \tau - g(q_d) \\ \tau_0 \end{bmatrix} = \boldsymbol{\tau}. \qquad (5) \end{aligned}$$

Here, $\boldsymbol{K_p}$, $\boldsymbol{K_d}$, $\boldsymbol{M(q)}$, $\boldsymbol{C(q,\dot{q})}$, and $\boldsymbol{g(q,q_d)}$ are appropriately defined. To carry out the stability analysis, we consider the following Lyapunov function candidate:

$$V = \frac{1}{2}(\tilde{\boldsymbol{q}}^T\boldsymbol{K}\tilde{\boldsymbol{q}} + \dot{\boldsymbol{q}}^T\boldsymbol{M}\dot{\boldsymbol{q}}) + \frac{1}{\gamma}\tilde{\boldsymbol{q}}^T\boldsymbol{M}\dot{\boldsymbol{q}} \qquad (6)$$

where $\boldsymbol{K}$ is a symmetric positive definite constant matrix and γ is a positive constant.

Lemma: If the following condition holds

$$a_1\gamma > 1, \quad \boldsymbol{K} - \frac{a_1}{\gamma}\boldsymbol{M} > 0 \qquad (7)$$

for an arbitrary positive constant a_1, then

$$V \ge \frac{1}{2}\tilde{\boldsymbol{q}}^T(\boldsymbol{K} - \frac{a_1}{\gamma}\boldsymbol{M})\tilde{\boldsymbol{q}} + \frac{1}{2}(1 - \frac{1}{a_1\gamma})\dot{\boldsymbol{q}}^T\boldsymbol{M}\dot{\boldsymbol{q}}$$

Therefore V is positive definite function [18].

□

Using this Lyapunov function and the the properties of robot dynamics described in the previous section, we can give conditions of stability.

Theorem: Let $K_p = K_{p1}$, $\quad K_d = K_{d1} + K_{d2}$ and

$$\boldsymbol{K} = \begin{bmatrix} 2K_p + \frac{1}{\gamma}(K_d + K_{d1}) & -K_p + \frac{1}{\gamma}(K_d - K_{d2}) \\ -K_p + \frac{1}{\gamma}(K_d - K_{d2}) & \frac{1}{\gamma}K_{d2} \end{bmatrix}.$$

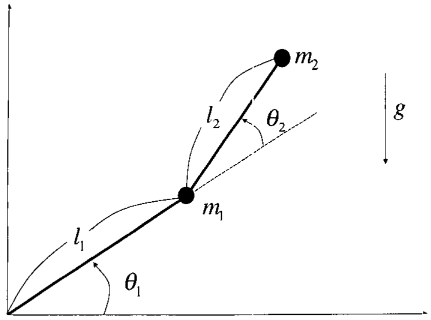


Fig. 2. Two-link manipulator

For a constant input q_d in the control system of Fig.1, $(\tilde{q}, \dot{q}) = (0,0)$ is a globally asymptotically stable equilibrium point when the following condition is satisfied.

$$K_d + K_{d1} - \frac{1}{\gamma}M - \frac{k_c||\tilde{q}||}{\gamma}I_n - \frac{a_3 k_g}{2}I_n > 0$$
$$K_{d2} - \frac{1}{\gamma}M_0 - \frac{k_{c0}||\tilde{q_m}||}{\gamma}I_n - a_2 E > 0$$
$$2K_p - k_g I_n - \frac{\gamma}{a_2}E - \frac{\gamma k_g}{2\omega}I_n > 0 \quad (8)$$

Here a_2 and a_3 are arbitrary positive constants and the elements of matrix E is given as

$$E_{ij} = \begin{cases} |-K_{pij} + \frac{1}{\gamma}K_{d1ij}| & \text{if} \quad i = j \\ 0 & \text{if} \quad i \neq j \end{cases}$$

□

The proof is omitted because of space limitation. Although the conditions in (8) seem hard to be satisfied, these conditions can be easily met if K_p, K_{d1}, and K_{d2} can be set sufficiently large. In section IV we will study this in more detail.

(Remark) At the equilibrium point, the position error of the plant $\tilde{q} = 0$, but the position error of the model $\tilde{q_0} = K_{p1}^{-1}g(q_d)$. The gravitational force $g(q)$, which is a disturbance, is compensated by the model's position error and do not affect the plant output in the steady state.

IV. Simulation Results

In this section, the MBDA controller is applied to a two-link manipulator and its performance is compared with those of conventional PD and PID controllers. The two-link robot manipulator is assumed to be a rigid body with point masses at each end of the link and moves under the gravity as shown in Fig.2 with the initial condition $(\theta_1(0), \theta_2(0)) = (0,0)$.

For this plant, the manipulator dynamics in vector form is as follows [19].

$$\begin{bmatrix} M_{11} M_{12} \\ M_{21} M_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta_1} \\ \ddot{\theta_2} \end{bmatrix} + \begin{bmatrix} C_{11} C_{12} \\ C_{21} C_{22} \end{bmatrix} \begin{bmatrix} \dot{\theta_1} \\ \dot{\theta_2} \end{bmatrix} + \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (9)$$

TABLE I

Gains for 2-link manipulator

		P gain	D gain	I gain
MBDA	K	1000	300	-
	K1	1000	100	-
	K2	-	200	-
PID		1000	300	1000
PD		1000	300	-

where

$$M_{11} = (m_1 + m_2)l_1^2 + m_2 l_2^2 + 2m_2 l_1 l_2 \cos\theta_2$$
$$M_{12} = M_{21} = m_2 l_2^2 + m_2 l_1 l_2 \cos\theta_2$$
$$M_{22} = m_2 l_2^2,$$

$$C_{11} = -m_2 l_1 l_2 \dot{\theta_2} \sin\theta_2$$
$$C_{12} = -m_2 l_1 l_2 (\dot{\theta_1} + \dot{\theta_2}) \sin\theta_2$$
$$C_{21} = m_2 l_1 l_2 \dot{\theta_1} \sin\theta_2$$
$$C_{22} = 0$$

and

$$g_1 = (m_1 + m_2) g l_1 \cos\theta_1 + m_2 g a_2 \cos(\theta_1 + \theta_2)$$
$$g_2 = m_2 g a_2 \cos(\theta_1 + \theta_2).$$

For this manipulator, the lengths are $l_1 = l_2 = 0.5(m)$ and masses are $m_1 = m_2 = 5(kg)$, and the gravitational acceleration is $9.8(m/\sec^2)$.

The feedback gain for each joint is set to be equal as shown in Table I. For the MBDA controller, the feedback loop gain matrix K is the same as that of PD and the gain matrices K_1 and K_2 are set as $K_p = K_{p1}$ and $K_d = K_{d1} + K_{d2}$.

For these feedback gains and manipulator parameters, we will check the conditions (7) and (8). In computing the norms in (8), we will use 1-norm for ease of computation.

In (9), $C^T\dot{q}$ becomes

$$C(q, \dot{q})^T \dot{q} = \begin{bmatrix} 0 \\ -m_2 l_1 l_2 (\dot{\theta_1}^2 + \dot{\theta_1}\dot{\theta_2}) \sin\theta_2 \end{bmatrix}.$$

Now the upper bounds of Coriolis and centrifugal forces and gravity terms become

$$||C^T\dot{q}|| = |m_2 l_1 l_2 (\dot{\theta_1}^2 + \dot{\theta_1}\dot{\theta_2}) \sin\theta_2|$$
$$\leq m_2 l_1 l_2 (|\dot{\theta_1}| + |\dot{\theta_2}|)^2 = k_c ||\dot{q}||^2$$

where $k_c = m_2 l_1 l_2$, and

$$||g(q)|| = |(m_1 + m_2) g a_1 \cos\theta_1 + m_2 g l_2 \cos(\theta_1 + \theta_2)|$$
$$+ |m_2 g a_2 \cos(\theta_1 + \theta_2)|$$
$$\leq (m_1 + m_2) g a_1 + 2 m_2 g a_2 = k_g$$

Using these results, we can set $k_c = 1.25$ and $k_g = 98$ for our manipulator. For simplicity, we set $\gamma = 0.1$ to make matrix E in (8) zero, and we set $a_2 = a_3 = 0.1$. Then the first condition in (8) becomes

$$
\begin{aligned}
&K_d + K_{d1} - \frac{1}{\gamma}M - \frac{k_c||\tilde{q}||}{\gamma}I_n - \frac{a_3 k_g}{2}I_n \\
&= \begin{bmatrix} 357.6 - 25\cos\theta_2 - 12.5||\tilde{q}|| & -12.5 - 12.5\cos\theta_2 \\ -12.5 - 12.5\cos\theta_2 & 382.6 - 12.5||\tilde{q}|| \end{bmatrix} \\
&\geq 0,
\end{aligned}
$$

because $||\tilde{q}|| < 2\pi$.

When the model is exactly the same as the plant with the exception of the gravity term ($M_0 = M, C_0 = C$), the second condition in (8) becomes

$$
\begin{aligned}
&K_{d2} - \frac{1}{\gamma}M_0 - \frac{k_{c0}||\tilde{q_m}||}{\gamma}I_n - a_2 E \\
&= \begin{bmatrix} 162.5 - 25\cos\theta_2 - 12.5||\tilde{q_m}|| & -12.5 - 12.5\cos\theta_2 \\ -12.5 - 12.5\cos\theta_2 & 187.5 - 12.5||\tilde{q_m}|| \end{bmatrix} \\
&\geq 0,
\end{aligned}
$$

because $||\tilde{q_m}|| \leq ||\tilde{q_0}|| + ||K_{p1}^{-1}g(q_d)|| < 2\pi + 0.2$.

And the third condition in (8) is

$$
\begin{aligned}
&2K_p - k_g I_n - \frac{\gamma}{a_2}E - \frac{\gamma k_g}{2\omega}I_n \\
&= \begin{bmatrix} 2000 & 0 \\ 0 & 2000 \end{bmatrix} - \begin{bmatrix} 150 & 0 \\ 0 & 150 \end{bmatrix} = \begin{bmatrix} 1850 & 0 \\ 0 & 1850 \end{bmatrix} > 0.
\end{aligned}
$$

Now let $a_1 \triangleq \frac{1}{\gamma} + \epsilon$. Then,

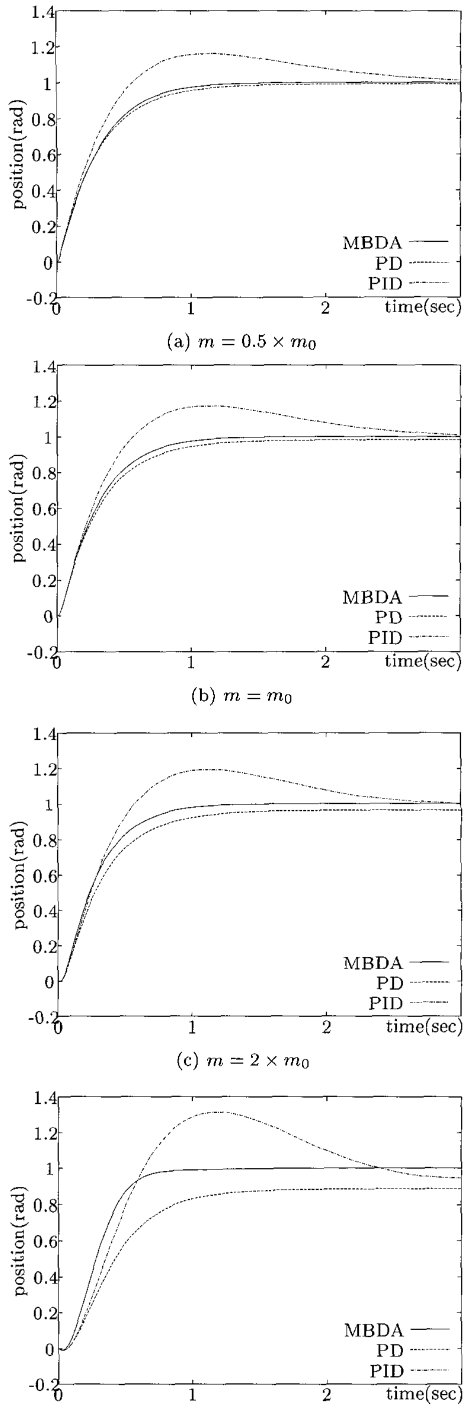
$$
\begin{aligned}
&\boldsymbol{K} - \frac{a_1}{\gamma}\boldsymbol{M} \\
&= \begin{bmatrix} 2K_p + \frac{1}{\gamma}(K_{d1} + K_{d2}) & -K_p + \frac{1}{\gamma}K_{d1} \\ -K_p + \frac{1}{\gamma}K_{d1} & \frac{1}{\gamma}K_{d2} \end{bmatrix} - \frac{1+\gamma\epsilon}{\gamma^2}\begin{bmatrix} M & 0 \\ 0 & M_0 \end{bmatrix} \\
&= \begin{bmatrix} 2K_p + \frac{1}{\gamma}(K_{d1} + K_{d2}) - \frac{1+\gamma\epsilon}{\gamma^2}M & 0 \\ 0 & \frac{1}{\gamma}(K_{d2} - \frac{1+\gamma\epsilon}{\gamma}M_0) \end{bmatrix}
\end{aligned}
$$

and we can always find $\epsilon > 0$ such that $\boldsymbol{K} - \frac{a_1}{\gamma}\boldsymbol{M} > 0$ by (8).

The robot manipulator is moved from the initial position $(\theta_1(0), \theta_2(0)) = (0, 0)$ to the desired position $(\theta_{1d}, \theta_{2d}) = (1, 1)$ where the units are in radian. Fig.3 and Fig.4 show the step responses of the MBDA, PID, and PD controllers for various modeling errors in the masses.

The MBDA controller has little overshoot and little oscillation compare to the PID controller, because it does not include an integrator. Also it shows no steady state positioning error which is not the case for the PD controller. Moreover the results shows the MBDA controller is quite robust with respect to large modeling errors. This property is very useful for robot manipulators with varying masses in grasping action where the masses change drastically before and after grasping.

Fig.5 shows the responses when a constant disturbance is applied at $t = 1.0(sec)$ to the first joint. The MBDA controller attenuates the disturbance very quickly compare to the PID controller while there is a steady state error for



(a) $m = 0.5 \times m_0$

(b) $m = m_0$

(c) $m = 2 \times m_0$

(d) $m = 5 \times m_0$

Fig. 3. Unit step responses of MBDA, PID and PD controllers (θ_1)

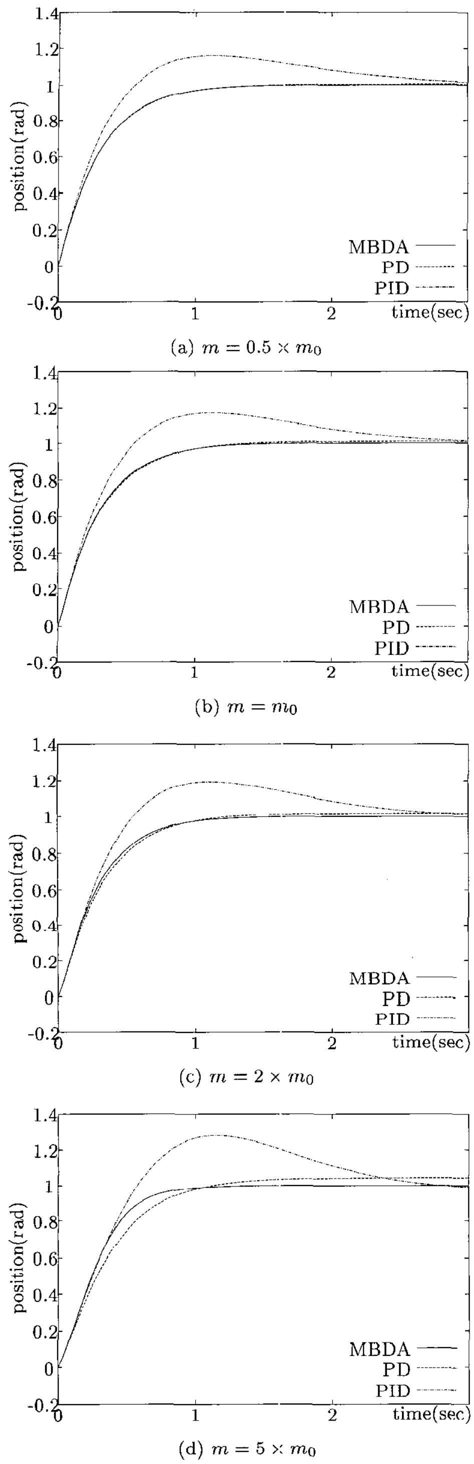


Fig. 4. Unit step responses of MBDA, PID and PD controllers (θ_2)

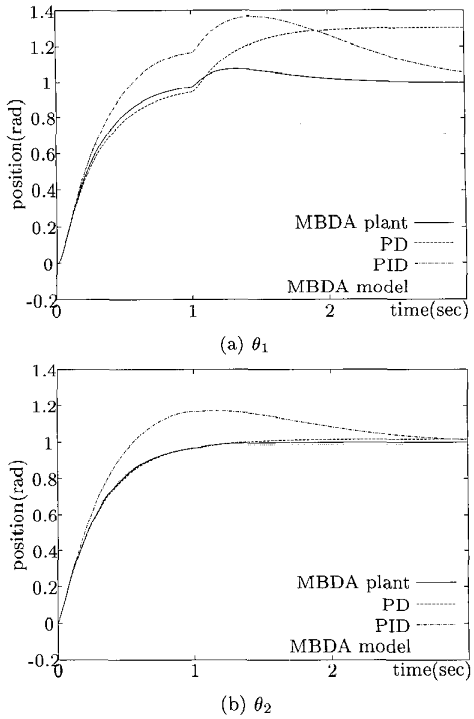


Fig. 5. Unit step responses of MBDA, PID and PD controllers when the disturbance is presented at $t = 1$.

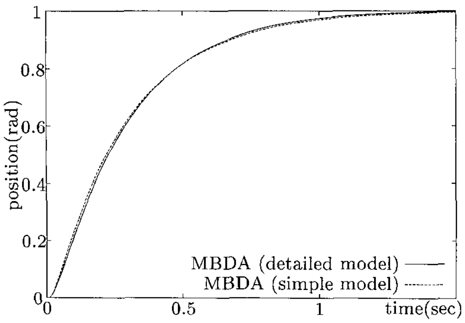
the PD controller. This shows that the MBDA controller is very efficient in disturbance attenuation compare to the PID. In the figure, the dotted line shows the output of the model. Note that its behavior is almost opposite to that of the output produced by the PD controller. This output of the model cancels the disturbance effectively so that there is no steady state error in the plant output.

Fig.6 is a comparison of a plant output with perfect model and that with a simple model which has only diagonal constant terms in its Jacobian matrix, i.e.,

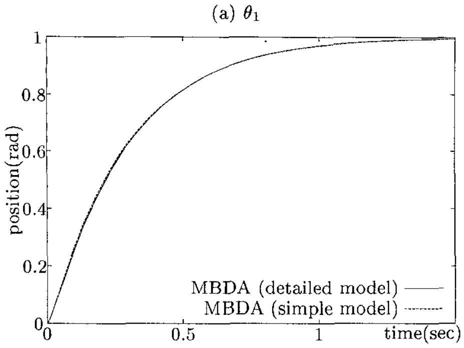
$$M_0 = \begin{bmatrix} (m_1 + m_2)l_1^2 + m_2 l_2^2 & 0 \\ 0 & m_2 l_2^2 \end{bmatrix}, \quad C_0 = 0$$

From (9) one can see that all the terms involving θ_1 and θ_2 are eliminated. The figure shows that there is little difference between the output produced with a perfect model and that produced with a simple one. This result indicates that the modeling process can be simplified significantly by using the MBDA controller without compromising the performance of a robot manipulator. We may discard the terms like C_0 and off-diagonal elements in M_0 in addition to gravity terms. This elimination also eases the stability condition (8) because k_{c0} and all the off-diagonal terms in M_0 become zeros. In addition, though not presented here, the computational burden of the MBDA controller with the simple model does not increase significantly as the number of links increases.

Also, a simulation for a robot with three links was done,



(a) θ_1



(b) θ_2

Fig. 6. Unit step responses of MBDA controllers with detailed and simple models

and similar results were obtained.

V. Conclusions

In this paper, we have proposed a new control method, the MBDA controller, for robot manipulators. The structure of MBDA is a generalization of [1], [17] and its usage had been extended to nonlinear robot systems. We can garantee the global asymptotic stability of the proposed method under certain conditions. The proposed method is robust with respect to modeling errors, very effective in disturbance attenuation, and gives no steady state error caused by either gravity or constant disturbance.

Unlike other controllers which require an exact robot model, a simple model may be sufficient for the MBDA controller. By using simple models, the computational burden for the MBDA does not increase rapidly as the number of links increases, which is very important for robot with many links. The MBDA controller is also well suited for industrial robots whose masses change during operations. Due to these advantages, the MBDA controller is expected to find widespread applications in industrial robot manipulators.

Acknowledgments

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