Variant Scheme of Adaptive Tracking Control for Robot Manipulators

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Abstract: This paper develops a variant scheme of adaptive algorithm for tacking control of robot manipulators, which includes the traditional adaptive algorithm as a special case. Asymptotic stability of the resulting closed-loop system is guaranteed. Simulation results show the improved transient performance in respect to the counterpart of the traditional adaptive.

Keywords: adaptive tracking control; robot manipulator; asymptotic stability

0 Introduction

It was shown (Ortega and Tang, 1989 ; Rriedle and Kokotovic, 1984 ; Rohrs *et al.*, 1985) [1-3] that unmodeled dynamics or even a small bounded disturbance could cause most of the adaptive control algorithm to go unstable. Various approach of adaptive control algorithms, such as dead zone, σ-modification, e_1-modification, projection technique, normalization, persistency of excitation, etc., and their combinations, have been developed for counteracting instability as well as improving robustness with respect to bounded disturbance and unmodeled dynamics.

By using sufficient excitation the nominal adaptive system can be made exponentially stable. Since the system is exponentially stable there is some modeling error and some disturbances for which stability will be maintained. It should be noted, however, that sufficient excitation should not be viewed as a panacea that creates robust adaptive controller, the amount of modeling error or disturbance for which the adaptive system can maintain stability may be extremely small. The results of the Krause *et al.*'s analysis (Krause *et al.*, 1983) [4] show that the input must not only be sufficiently exciting to produce parameter convergence in the nominal system, but also be dominantly rich enough to overcome the destabilizing effects. Nevertheless, a drawback of the techniques relying on excitation signals is that the excitation signals introduced in the system should be large enough to predominate over the plant noise, and this may not be feasible or desirable in some practical applications. Furthermore, how the external probing signals are chosen to ensure the persistent excitation and performance has not been completely resolved yet (Feng, 1999) [5].

Some modifications for parameter update law have been proposed to achieve the robustness of the adaptive control system. The basic idea of most of the modification is to prevent the instability by eliminating the pure integral action of the adaptive laws and to guarantee boundedness of all signals in the adaptive loop. Dead zone modification (Petersen and Narendra, 1982; Samson, 1983) [6-7] turns off the algorithm when the identification error is smaller than a certain threshold and hence zero tracking is lost when disturbances are removed. In order to choose an appropriate size of the dead zone, a bound on the disturbance must be known. Another method is adaptive law modification (Kreisselmeier and Narendra, 1982) [8], where adaptation comes into operation only when the norm of the estimated controller parameter exceeds a certain value. In this case, a bound on the norm of the desired unknown controller parameter must be known. The third method is the so-called σ-modification (Ioannou and Kokotovic, 1984) [9], *i.e.*

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an adaptive law is modified with the extra leakage term. This method suffers from the drawback that a bias term is added to the parameter update law, and therefore zero tracking cannot be guaranteed when disturbance is absent. Ioannou (1986) [10] proposed a modified method so that nonzero tracking can be avoided, but an upper bounded on the matching controller parameters must be known.

Many of the modified algorithms require some sort of knowledge on the parameters of the bounding function on the unmodeled dynamics or the knowledge of the norm bound concerning unknown matching controller parameters of plant parameters. It's also possible to add additional refinements to the algorithm. For example, it is possible to constrain the parameter estimates to lie in pre-specified convex regions, and/or to add parameter searches to satisfy additional constraints. Robustness of the adaptive control algorithm can be achieved with only simple projection techniques in parameter estimation (Naik et al., 1992; Wen, 1995; Wen and Hill, 1992) [11-13]. It is particularly important to constrain the estimate in the case of normalization since, unlike the dead zone algorithm, this algorithm does not guarantee boundedness automatically.

A *projection algorithm* (Lozano and Brogliato, 1992; Bridges *et al.*, 1995) [14-15] is used to guarantee the parameter estimate stay within finite known region; hence, the resulting system is stable even though it subjects to some disturbance. Feng (1999) [5] proposed and analyzed a new indirect adaptive control algorithm that does use a dead zone but does not require the knowledge of the parameter of the upper bounding function on the unmodeled dynamics and bounded disturbance. The basic idea of this new approach, which does not necessarily the knowledge of the upper bound *a priori*, is to estimate those unknown bounds with projection and to use the estimated bounds to implement the dead zone technique. However, it is difficult.

In summary, most of the modified approaches to achieving robustness to the bounded disturbance and/or unmodeled dynamics require knowledge of either the upper bound on the disturbances, or the bound on the norm of unknown matching controller parameter, or the parameters of bounding function on the unmodeled dynamics, *etc*. Although the stability problem may be solved via the algorithm proposed by Feng (1999) [5] or *projection algorithm* by Zergeroglu (2000) [16] and Dixon *et al.* (1999) [17], they can't reveal the relationship between stability and error of the estimated region, say what will happen when the true parameters don't belong to this region. Moreover, these algorithms seem to be a little complicated for practice execution on-line.

This paper continues to explore the benefit from adaptive control. A variant scheme of adaptive tracking control is developed for tracking control of robot manipulator. Simulation results demonstrated its effectiveness and the improved transient performance in respect to traditional adaptive schemes.

1 Preliminaries

Throughout this paper, we use $\lambda_m\{\cdot\}$ ($\lambda_M\{\cdot\}$)to denote the minimal (maximal) eigenvalue of matrix. The norm of vector x is defined by $\|x\| = \sqrt{x^T x}$ and norm of matrix M is defined by the corresponding induced norm $\|M\| = \sqrt{\lambda_M\{M^T M\}}$ $|\bullet|$ stands for the absolute value.

In the absence of friction and other disturbances, the dynamics of rigid serial n-link robot manipulator is given in joint space as follows,

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

where q is n-dimensional vector of joint angles, $M(q) \in R^{n\times n}$ is the robot inertial matrix;

$C(q,\dot{q})\dot{q}$, $g(q)$ and $\tau \in R^n$ denote the centrifugal Coriolis force, the gravitational force and control inputs respectively.

A list of useful properties of its dynamic model is given as follows (Canudas de Wit *et al.*, 1997, Santibanez and Kelly, 1999) [18-19].

P1. A suitable definition of $C(q,\dot{q})$ makes the matrix ($\dot{M}-2C$) skew-symmetric, *i.e.*

$$\dot{M}(q) = C(q,\dot{q}) + C^T(q,\dot{q}) \tag{2}$$

P2. The inertial matrix $M(q)$ is a symmetric positive definite matrix that verifies

- $\lambda_m\{M(q)\}I \le M(q) \le \lambda_M\{M(q)\}I$ (3)
- $\|M(q_2) - M(q_1)\| \le \alpha_M \|q_2 - q_1\|$ (4)

for all $q,\ q_1,\ q_2 \in R^n$, α_M is a positive constant.

P3. For all vector $v,\ w,\ x,\ y,\ z \in R^n$, there exist positive constants c_1, c_2 such that

- $\|C(x,y)z\| \le c_1\|y\|\cdot\|z\|$ (5)
- $C(x,y+z)w = C(x,y)w + C(x,z)w$ (6)
- $\|C(x,z)w - C(y,v)w\| \le c_1\|z-v\|\cdot\|w\| + c_2\|x-y\|\cdot\|z\|\cdot\|w\|$ (7)

P4. There exists positive constant c_g such that

$$\|g(x) - g(y)\| \le c_g\|x-y\| \tag{8}$$

for all $x,\ y \in R^n$.

P5. For all $v,\ w \in R^n$, we have

$$M(q)v + C(q,w)w + g(q) = \Phi(v,w,q)\theta + \Lambda(v,w,q,\theta_0) \tag{9}$$

where $\Lambda(v,w,q,\theta_0) = M_0(q)v + C_0(q,w)w + g_0(q)$. $\Lambda(v,w,q)$ is a known vector including the known parameters θ_0; $\Phi(v,w,q) \in R^{n\times l}$ is regressor matrix; $\theta \in R^l$ is a parameter vector containing only the interest or unknown robot parameters.

The control problem is subjected to the following assumptions.

A.1 The desired reference trajectory q_d, $\dot{q}_d$ and $\ddot{q}_d$ are all bounded.

A2. The operating scope $\Omega_{\dot{q}}$ is bounded with respect to angle velocity $\dot{q}$. Namely, for *constant* $\bar{\gamma}_{\dot{q}} > 0$,

$$\Omega_{\dot{q}} = \left\{\dot{q} \in R^n \,\middle|\, \|\dot{q}\| \le \bar{\gamma}_{\dot{q}}\right\} \tag{10}$$

2 The Main Result

The following tracking control laws are proposed as follows,

$$\tau = M_0(q_d)\ddot{q}_d + C_0(q_d,\dot{q}_d)\dot{q}_d + g_0(q_d) - K_p\tilde{q} - K_v\dot{\tilde{q}} + \Phi(\ddot{q}_d,\dot{q}_d,q_d)\cdot\hat{\theta} \tag{11}$$

$$\hat{\theta}(t) = \hat{\theta}(0) - \Gamma\int_0^t exp[-\int_\varsigma^t \lambda(r)dr]\cdot\Phi_d^T(\varsigma)\cdot[\dot{\tilde{q}}(\varsigma) + \alpha\tilde{q}(\varsigma)]d\varsigma \tag{12}$$

where $\tilde{q} = q - q_d$, $\Phi_d := \Phi(\ddot{q}_d,\dot{q}_d,q_d)$, α is strictly positive constant, Γ, K_p, K_v are all positive definite diagonal matrices; $M_0(\cdot),\ C_0(\cdot,\cdot),\ g_0(\cdot)$ are the known dynamics; $exp(\cdot)$ denotes the exponential function; $\lambda(t)$ is time-dependent factor, $0 \le \lambda(t) < \infty$.

Remark 1

Obviously, the parameter update law (12) becomes of the case of the traditional one when $\lambda(t)\equiv 0$. In other words, the traditional adaptive algorithm is the especial case of the proposed adaptive algorithm (11) (12).

For the sake of convenience, let

$$K_p = k_p\boldsymbol{I},\quad K_v = k_v\boldsymbol{I}. \tag{13}$$

Using the property ***P5***, the control law can also be rewritten as

$$\tau = M(q_d)\ddot{q}_d + C(q_d,\dot{q}_d)\dot{q}_d + g(q_d) - K_p\tilde{q} - K_v\dot{\tilde{q}} + \Phi_d\tilde{\theta} \tag{14}$$

where $\tilde{\theta}=\hat{\theta}-\theta$. Then the closed-loop system dynamics is obtained as

$$M(q)\ddot{\tilde{q}} + C(q,\dot{q})\dot{\tilde{q}} - H(\dot{\tilde{q}},\tilde{q}) = -K_p\tilde{q} - K_v\dot{\tilde{q}} + \Phi_d\cdot\tilde{\theta} \tag{15}$$

where $H(\dot{\tilde{q}},\tilde{q}) = [M(q_d)-M(q)]\ddot{q}_d + g(q_d) - g(q) + [C(q_d,\dot{q}_d)-C(q,\dot{q})]\dot{q}_d$

Theorem

Consider the dynamics of robot manipulator (1), the adaptive controller (11)(12) is chosen such that the following conditions are all satisfied

$$(k_p + \alpha k_v)\boldsymbol{I} > \alpha^2 M \tag{16}$$

$$k_v > \alpha\lambda_M\{M\} - c_1\|\dot{q}_d\| - \tfrac{1}{2}[\eta + \alpha c_1(\|\dot{q}_d\| + \bar{\gamma}_{\dot{q}})] \tag{17}$$

$$k_p > \eta - \frac{1}{2\alpha}[\eta + \alpha c_1(\|\dot{q}_d\| + \bar{\gamma}_{\dot{q}})] \tag{18}$$

then the solutions of the closed-loop system, $\tilde{q}(t)$, $\dot{\tilde{q}}(t)$, $\tilde{\theta}(t)$ are all bounded for $t>0$. Where

$$\eta = \alpha_M\|\ddot{q}_d\| + c_2\|\dot{q}_d\|^2 + c_g$$

Moreover, when $\lambda(t)\in L_1(0,T)$ ($0<T\le+\infty$), then

$$\lim_{t\to\infty}\left\|[\dot{\tilde{q}}^T\ \tilde{q}^T]^T\right\| = 0 \tag{19}$$

The proof of the result requires the following lemma.

Lemma (Song, 1995)

Let $V_1: R^n \to R$ and $V_2: R^m \to R$ be non-negative and C^1 time functions defined on $[0,T]$ ($0<T\le+\infty$), satisfying

$$\varepsilon_1\|x\|^2 \le V_1(x) \le \varepsilon_2\|x\|^2,\quad \forall\varepsilon_2\ge\varepsilon_1>0 \tag{20}$$

$$\varepsilon_3\|y\|^2 \le V_2(y) \le \varepsilon_4\|y\|^2,\quad \forall\varepsilon_4\ge\varepsilon_3>0 \tag{21}$$

$$\dot{V}_1 + \dot{V}_2 \le -\delta_1 V_1 - \delta_2 V_2 + \gamma_0(t) \tag{22}$$

where δ_1 is a strictly positive constant, $\delta_2(t)\ge 0$ and $\gamma_0(t)$ is a time function belonging to $L_1(0,T)$, i.e.

$$\int_0^T|\gamma_0|d\tau \le \alpha_0 \le \infty \tag{23}$$

then $x\in L_2\cap L_\infty$ and $y\in L_\infty$. Moreover, if x is a uniformly continuous function of t, $\|x\|\to 0$ as $t\to\infty$.

Proof of Theorem: We complete it by two steps:

Step 1. The globally positive definition of the Lyapunov function candidate.

Consider the Lyapunov function candidate

$$V(\dot{\tilde{q}},\tilde{q},\tilde{\theta})=\tfrac{1}{2}\dot{\tilde{q}}^{T}M(q)\dot{\tilde{q}}+\alpha\dot{\tilde{q}}^{T}M(q)\,\tilde{q}+\tfrac{1}{2}(k_p+\alpha k_v)\tilde{q}^{T}\tilde{q}+\tilde{\theta}^{T}\Gamma^{-1}\tilde{\theta} \tag{24}$$

Fuction (24) is radially unbounded positive definition provided that $V_a(\dot{\tilde{q}},\tilde{q})\geq 0$, where

$$\begin{aligned}V_a&=\tfrac{1}{2}\dot{\tilde{q}}^{T}M\dot{\tilde{q}}+\alpha\dot{\tilde{q}}^{T}M\tilde{q}+\tfrac{1}{2}(k_p+\alpha k_v)\tilde{q}^{T}\tilde{q}\\&=\tfrac{1}{2}(\dot{\tilde{q}}+\alpha\tilde{q})^{T}M(\dot{\tilde{q}}+\alpha\tilde{q})+\tfrac{1}{2}\tilde{q}^{T}[(k_p+\alpha k_v)\boldsymbol{I}-\alpha^{2}M]\tilde{q}\end{aligned} \tag{25}$$

From (16), it is easily to verify that $V_a(\dot{\tilde{q}},\tilde{q})\geq 0$.

Step 2. To prove the negative definition of function $\dot{V}$

The time derivative of function in (42) is

$$\dot{V}=(\dot{\tilde{q}}+\alpha\tilde{q})^{T}M\ddot{\tilde{q}}+\alpha\dot{\tilde{q}}^{T}(\dot{M}\tilde{q}+M\dot{\tilde{q}})+\tfrac{1}{2}\dot{\tilde{q}}^{T}\dot{M}\dot{\tilde{q}}+(k_p+\alpha k_v)\cdot\dot{\tilde{q}}^{T}\tilde{q}+\dot{\tilde{\theta}}^{T}\Gamma^{-1}\tilde{\theta} \tag{26}$$

Substituting (15) and the parameter update law (12) with property ***P1*** into the above equation,

$$\begin{aligned}\dot{V}&=(\dot{\tilde{q}}+\alpha\tilde{q})^{T}[H-C(q,\dot{q})\dot{\tilde{q}}-K_p\tilde{q}-K_v\dot{\tilde{q}}-\Phi(\ddot{q}_d\dot{q}_d,q_d)\cdot\tilde{\theta}]\\&\quad+\alpha\dot{\tilde{q}}^{T}(\dot{M}\tilde{q}+M\dot{\tilde{q}})+\tfrac{1}{2}\dot{\tilde{q}}^{T}\dot{M}\dot{\tilde{q}}+(k_p+\alpha k_v)\dot{\tilde{q}}^{T}\tilde{q}+\dot{\tilde{\theta}}^{T}\Gamma^{-1}\tilde{\theta}\end{aligned} \tag{27}$$

According to (12), it verified that

$$\dot{\tilde{\theta}}=\dot{\hat{\theta}}=-\lambda(t)\tilde{\theta}+\lambda(t)[\hat{\theta}(0)-\theta]-\Gamma\Phi_d^{T}\cdot(\dot{\tilde{q}}+\alpha\tilde{q}) \tag{28}$$

we obtain

$$\begin{aligned}\dot{V}&=\alpha\dot{\tilde{q}}^{T}[C^{T}\cdot\tilde{q}+M\dot{\tilde{q}}]+(k_p+\alpha k_v)\dot{\tilde{q}}^{T}\tilde{q}-\lambda(t)\cdot\tilde{\theta}\\&\quad+[\dot{\tilde{q}}+\alpha\tilde{q}]^{T}[H-k_p\tilde{q}-k_v\dot{\tilde{q}}]+\lambda(t)\Gamma^{-1}[\hat{\theta}(0)-\theta]\end{aligned}$$

From assumption ***A.2*** and (5) in ***P2,*** it yields

$$\tilde{q}^{T}C(q,\dot{q})\dot{\tilde{q}}\leq c_1\bar{\gamma}_{\dot{q}}\cdot\|\quad\|\cdot\|\tilde{q}\| \tag{29}$$

Make use of (4), (6), (7) and (8),

$$(\dot{\tilde{q}}+\alpha\tilde{q})^{T}H(\dot{\tilde{q}},\tilde{q})\leq[\|\dot{\tilde{q}}\|+\alpha\|\tilde{q}\|]\cdot\{\eta\cdot\|\tilde{q}\|+c_1\|\dot{q}_d\|\cdot\|\dot{\tilde{q}}\|\} \tag{30}$$

therefore,

$$\begin{aligned}\dot{V}&\leq-\{k_v-[\alpha\lambda_M\{M\}+c_1\|\dot{q}_d\|]\}\cdot\dot{\tilde{q}}^{T}\dot{\tilde{q}}-\lambda(t)\cdot\tilde{\theta}^{T}\tilde{\theta}+[\eta+\alpha c_1(\|\dot{q}_d\|+\bar{\gamma}_{\dot{q}})]\\&\quad\|\dot{\tilde{q}}\|\cdot\|\tilde{q}\|-\alpha(k_p-\eta)\tilde{q}^{T}\tilde{q}+\lambda(t)\cdot\tilde{\theta}^{T}\cdot\Gamma^{-1}\cdot[\hat{\theta}(0)-\theta]\end{aligned}$$

Note that

$$xy\leq\tfrac{1}{2}(x^{2}+y^{2}) \tag{31}$$

for all $x,y\in R$. It yields

$$\dot{V}\leq-\lambda_1\|\quad\|^{2}-\lambda_2\|\tilde{q}\|^{2}-\lambda(t)\cdot\tilde{\theta}^{T}\Gamma^{-1}\tilde{\theta}+\lambda(t)\cdot\tilde{\theta}^{T}\cdot\Gamma^{-1}\cdot[\hat{\theta}(0)-\theta] \tag{32}$$

where

$$\lambda_1=k_v-\alpha\lambda_M\{M\}-c_1\|\dot{q}_d\|-\tfrac{1}{2}[\eta+\alpha c_1(\|\dot{q}_d\|+\bar{\gamma}_{\dot{q}})]$$

$$\lambda_2=\alpha(k_p-\eta)-\tfrac{1}{2}[\eta+\alpha c_1(\|\dot{q}_d\|+\bar{\gamma}_{\dot{q}})]$$

When $\tilde{\theta}$ is within some region *viz.* $\Omega_{\tilde{\theta}}$, where

$$\Omega_{\tilde{\theta}}=\left\{\,z\;\middle|\;\lambda_m\{\Gamma^{-1}\}\cdot\|z\|\geq\lambda_M\{\Gamma^{-1}\}\cdot\|\hat{\theta}(0)-\theta\|\right\} \tag{33}$$

inequality (48) indicates that there always exists some positive constant μ such that

$$-\lambda_1 \left\|\dot{\tilde{q}}\right\|^2 - \lambda_2 \left\|\tilde{q}\right\|^2 - \lambda(t)\cdot\tilde{\theta}^T\Gamma^{-1}\tilde{\theta} + \lambda(t)\cdot\tilde{\theta}^T\cdot\Gamma^{-1}\cdot[\hat{\theta}(0)-\theta] \le -\mu V \tag{34}$$

and hence

$$\dot{V} \le -\mu V \tag{35}$$

That's the proof of the boundedness of $\tilde{q}(t)$, $\dot{\tilde{q}}(t)$, $\tilde{\theta}(t)$.

Because

$$\lambda(t)\cdot\tilde{\theta}^T\Gamma^{-1}[\hat{\theta}(0)-\theta] \le \lambda(t)\cdot\lambda_M\{\Gamma^{-1}\}\cdot\left\|\tilde{\theta}\right\|\cdot\left\|\hat{\theta}(0)-\theta\right\|$$

the boundedness of $\tilde{\theta}$ with $\lambda(t)\in L_1(0,T)$ implies that

$$\lambda(t)\cdot\tilde{\theta}^T\cdot\Gamma^{-1}\cdot[\hat{\theta}(0)-\theta]\in L_1(0,T) \tag{36}$$

On the basis of inequality (32) and the aforementioned *Lamma* by *Song*, it leads to the asymptotic results. The proof is completed.

Remark 2

i) In order to guarantee an asymptotic tacking result, the time-dependent factor $\lambda(t)$ should be chosen as

$$\int_0^T \lambda(\tau)d\tau \le \alpha_0 \le \infty$$

It is interesting to note that there are many possible choices for such $\lambda(t)$, e.g.

$$\lambda(t) = \frac{1}{(t+1)^{a_1}},\ a_1 > 1 \ \text{ or } \ \lambda(t) = e^{-a_2 t},\ a_2 > 0$$

ii) According to inequality (32), it shows that the closed-loop system is equivalent to an exponential stable system with the addition of the some disturbance that is depended on $\lambda(t)\cdot\tilde{\theta}^T\Gamma^{-1}[\hat{\theta}(0)-\theta]$. It's well-known that the exponential stable system has good robustness and convergence rate, so the resulting system adaptive algorithm (11)(12) results in robustness improvement as well as quicker convergence rate than the traditional adaptive accordingly.

3 Numeric Example

As the sine-cosine (*amplitude* denotes A (*rad*), *frequency* denotes f =1 (*Hz*)) trajectory-tracking task for a weighting-lifting operation is considered, the two-link manipulator described in *Fig.1* has parameters:

link mass $m_1 = 1\,(kg)$, $m_2 = 10\ (kg)$

link length $l_1 = 1\,(m)$, $l_2 = 1\,(m)$

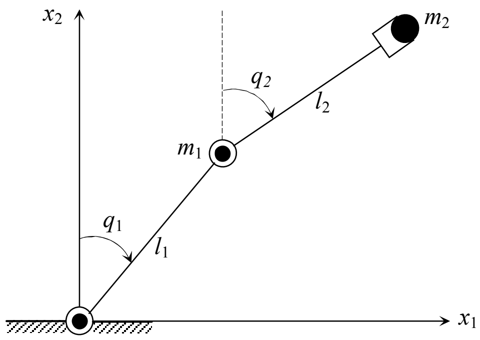

Fig.1 The two-link robot manipulator

Using SIMULINK™ in MATLAB™, simulation results demonstrate the effectiveness of the robust-adaptive algorithm when the robot system subjects to uncertain parameter m_2, while other parameters are known exactly. So we have

$$\Lambda(\ddot{q},\dot{q},q,\theta_0)=m_1(l_1^2\ddot{q}_1-l_2 g\sin q_1)$$

$$\Phi_d=\begin{bmatrix} l_1^2\ddot{q}_{d1}+l_1l_2c_{21}\ddot{q}_{d2}-l_2s_{21}\ddot{q}_{d2}^2-g\sin q_{d1} \\ l_1l_2c_{21}\ddot{q}_{d1}+l_2^2\ddot{q}_{d2}-l_2s_{21}\ddot{q}_{d1}^2-g\sin q_{d2} \end{bmatrix}$$

where $c_{21}=\cos(q_{d2}-q_{d1})$, $s_{21}=\sin(q_{d2}-q_{d1})$.

The initial states are $\hat{m}_2(0)=7\ (kg)$

$$q(0)=[1\ \ 0.1]^T(rad),\quad \dot{q}(0)=[0\ \ 0]^T\ (rad/s)$$

The controller parameters are selected as follows,

$$\alpha=8,\ k_p=100,\ k_v=100,\ \Gamma=2\times\boldsymbol{I},\ \lambda(t)=20e^{-t}$$

Simulations is to take a comparison between the fast-adaptive and the traditional algorithm that include the tracking error and the parameter convergence.

From the comparison of tacking error in *Fig.2*, it shows the better transient performance of the fast-adaptive than that of the traditional adaptive. And from *Fig.3*, the former has the quicker parameter convergence rate than the latter.

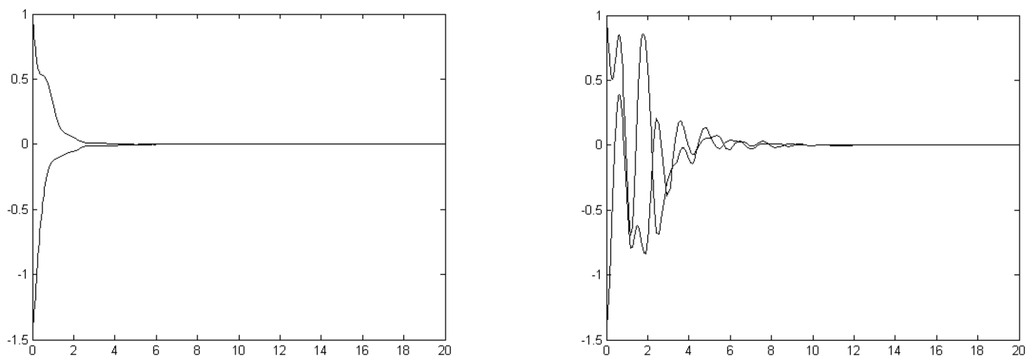

Fig. 2(a) The case of the fast-adaptive Fig.2(b) The case of traditional adaptive

Fig. 2 Comparison of the angle tacking error

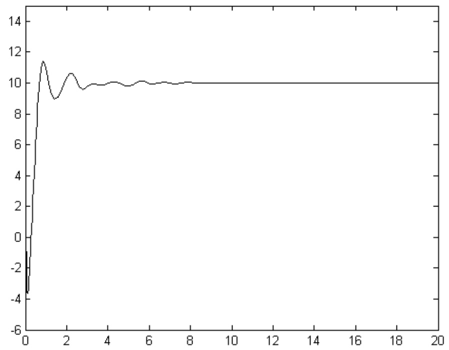

Fig.3(a) The case of the fast-adaptive

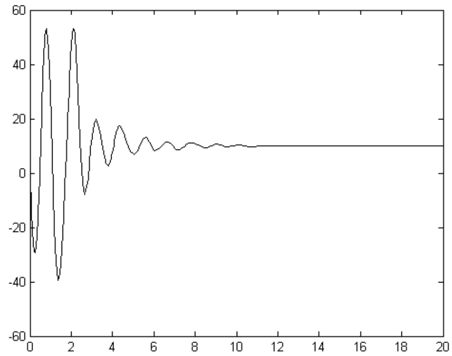

Fig. 3(b) The case of traditional adaptive

Fig. 3 Comparison of the parameter convergence rate

4 Conclusion

In this paper, a variant scheme of adaptive tracking control for robot manipulators is proposed. The traditional adaptive is the special case of this proposed adaptive algorithm. It shows the asymptotic stability of the resulting closed-loop system and the improved transient performance of the proposed scheme than the former as well.

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操作机器人的一种变形自适应跟踪控制算法

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摘要：本文提出了一种操作机器人跟踪控制变形自适应算法，常规的自适应算法是其特例，并保证了闭环系统的渐进稳定。仿真结果表明，相对于常规的自适应算法，本文的算法在瞬态性能方面得到了很大的改善。

关键词：自适应跟踪控制；操作机器人；渐进稳定

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