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输入受限机器人的鲁棒自适应输出反馈跟踪控制

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摘 要: 在输入受限的情况下, 通过一个线性一阶滤波器, 实现机器人的鲁棒自适应输出反馈跟踪控制, 解决了自适应控制算法的鲁棒性问题, 即当满足持续激励条件及估计参数域包含参数真实值时, 闭环系统能够实现渐近稳定跟踪 本算法简单有效, 不仅提高了鲁棒性, 改善了控制品质, 同时对于参数域估计误差也具有很强的鲁棒性 仿真算例验证了算法的有效性

关键词: 机器人; 参数不确定; 鲁棒自适应控制; 输入受限; 输出跟踪
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Robust-adaptive output-tracking control of robot manipulators under input constraints

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Abstract: In the presence of input constraints, a output feedback scheme of robust-adaptive tracking control for robot manipulators is proposed based on a linear first-order filter. The robustness problem of conventional adaptive algorithms is resolved in turn. The proposed controller can stabilize the system with some disturbance. When the estimated parameter-region contains the true parameters, asymptotic stability is guaranteed in the case of non-disturbance if the persistency of excitation-condition is satisfied. This robust algorithm is quite simple, and provides further flexibility for adaptive control design as well as better transient performance and robustness to disturbance and error of estimated parameter-region especially. Simulation results demonstrate the effectiveness of the method.

Key words: robot manipulator; parametric uncertainty; robust-adaptive control; input constraints; output-tracking

1 引 言

受物理条件限制, 驱动器的输出力矩是有界的 然而, 几乎所有控制器设计都建立在关节驱动器能产生任意力矩的基础上, 这样的控制器可能会导致控制失败或控制品质的恶化 因此, 输入受限控制器的设计正受到越来越多的关注 目前多数研究是针对线性系统的, 主要集中在输入受限线性系统的特性[1]、可控域和吸引域的准确描述及系统的镇定[2,3]等方面, 少数研究涉及最优[4]和抗干扰设计[5]等问题

对于参数不确定或不可知的机器人控制问题, 基于参数估计的自适应控制是其主要控制策略之一, 即利用机器人动力学方程的线性参数化性质, 通过一个积分运算来估计机器人参数 然而由于积分环节的作用, 在持续干扰条件下, 控制系统不容易稳定 利用映射算法, 将估计参数限制在所规定的范围(包含参数真实值)内, 这在一定程度上提高了自适应控制系统的鲁棒性[6~8]. 但这种算法由 6 个开关组

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成, 略嫌复杂. 另外, 当真实参数不在所规定的范围内时, 它不能给出系统控制品质及鲁棒性等信息. 文献[9]提出一种新颖的状态反馈自适应鲁棒算法, 简单方便地实现了状态反馈的渐近稳定跟踪.

对一般系统而言, 速度测量是通过对位移的微分得到的, 但其精度容易受测量高频噪声的影响. 在考虑输入受限条件下, 本文在鲁棒自适应算法[9]的基础上, 通过一阶线性滤波器, 实现输出反馈的鲁棒自适应跟踪控制, 避免了位移微分的高频噪声不利影响, 同时解决了参数估计自适应控制系统的鲁棒性问题, 改善了控制品质.

在不导致混淆的情况下, 全文将省略参数的变量.

2 预备知识

受篇幅所限, 关于连续可导递增函数向量集 $\mathbf{F}(m, \rho, \epsilon, x)$ 的定义及机器人动力学方程的性质请见文献[9, 10]中相关内容.

假设 1 假设机器人各关节的最大驱动力矩为 $\tau_{i,\max}$, 即

$$|\tau_i| \leq \tau_{i,\max}. \tag{1}$$

3 主要结果

本文的输出反馈跟踪控制律为

$$\tau = -k_p s(\tilde q) - k_v s_\vartheta(\vartheta) + \Phi_d \mathrm{sat}_{\hat\theta}(\hat\theta) + M^*(q_d)\ddot q_d + C^*(q_d, \dot q_d)\dot q_d + G^*(q_d), \tag{2}$$

$$\dot\vartheta = -a\vartheta + b\dot{\tilde q}, \tag{3}$$

$$\hat\theta(t) = \hat\theta(0) + \frac{\alpha}{\delta}\int \Phi_d^{\mathrm T}[(\beta - \gamma k_v)s_\vartheta(\vartheta(\zeta)) - (1 + \gamma k_p)s(\tilde q(\zeta))]\mathrm d\zeta \tag{4}$$

其中: $\Phi_d = \Phi(\ddot q_d, \dot q_d, q_d)$; $\alpha, \beta, \gamma, a, b, k_p, k_v$ 均为正的定常数; $M^*(\cdot), C^*(\cdot, \cdot), G^*(\cdot)$ 为包含已知参数 θ^* 的动力学方程部分; 且

$$s(\cdot) \in \mathbf{F}(m, \rho, \epsilon, x), \tag{5}$$

$$s_\vartheta(\cdot) = \mathbf{F}(m_\vartheta, \rho_\vartheta, \epsilon_\vartheta, \cdot). \tag{6}$$

函数向量 $\mathrm{sat}_{\hat\theta}(\hat\theta)$ 定义为

$$\mathrm{sat}_{\hat\theta}(\hat\theta) = s_{\hat\theta}(\hat\theta - \hat\theta(0)) + \pi, \tag{7}$$

其中

$$s_{\hat\theta}(\cdot) \in \mathbf{F}(m_\theta, \rho_\theta, \epsilon_\theta, \cdot). \tag{8}$$

选择定常 π, 使得 $\mathrm{sat}_{\hat\theta}(\hat\theta)$ 的范围包含参数真实值 θ.

注 1 实际上, 式(3) 是一阶线性滤波器, 即

$$T(s) = \frac{\vartheta_i(s)}{\tilde q_i(s)} = \frac{bs}{s + a}, i = 1, 2, \cdots, n, \tag{9}$$

用于测量关节角误差 $\tilde q$, 从而实现输出反馈控制.

闭环系统的动力学方程为

$$M(q)\ddot{\tilde q} + C(q, \dot q)\dot{\tilde q} - H(\dot{\tilde q}, \tilde q) = -k_p s(\tilde q) - k_v s_\vartheta(\vartheta) + \Phi_d \Psi(\tilde\theta), \tag{10}$$

其中

$$\tilde\theta = \hat\theta - \theta, \Psi(\tilde\theta) = \mathrm{sat}_{\hat\theta}(\hat\theta) - \theta,$$

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

定义正定标量函数 $U_{\tilde q}(\tilde q), U_\vartheta(\vartheta), U_{\tilde\theta}(\tilde\theta)$ 如下:

$$\nabla_\vartheta U_\vartheta(\vartheta) = \frac{1}{b}k_v s_\vartheta(\vartheta), \tag{11}$$

$$\nabla_{\tilde q} U_{\tilde q}(\tilde q) = k_p s(\tilde q), \nabla_{\tilde\theta} U_{\tilde\theta}(\tilde\theta) = \Psi(\tilde\theta). \tag{12}$$

可见, 对于任意 $x \in \mathbf{R}^n$, $j = \tilde q, \vartheta, \tilde\theta$, 总满足

$$U_j(x) > 0 \text{ if } x \neq 0 \text{ 且 } U_j(x) = 0 \text{ if } x = 0. \tag{13}$$

定理 1 考虑无干扰的机器人系统, 假设存在正的常数 $\alpha, \beta, \gamma, \delta, a, b, k_p, k_v$, 定常向量 π 及函数向量 $s(\tilde q), s_\vartheta(\vartheta), \mathrm{sat}_{\hat\theta}(\hat\theta)$ 满足下列条件:

$$k_p > \rho\alpha^2\lambda_M\{M(q)\}, \tag{14}$$

$$k_v > b\rho_\vartheta\alpha^2\beta^2\lambda_M\{M(q)\}, \tag{15}$$

$$\delta > \rho_\theta\alpha^2\gamma^2\lambda_M\{\Phi_d^{\mathrm T}M(q)\Phi_d\}, \tag{16}$$

那么: 1) 当不满足持续激励条件时, 如果 $R_1 > 0$, 则 $t > 0$ 时 $\dot{\tilde q}(t)$ 是有界的; 如果

$$\epsilon m\sqrt{n}\lambda_m\{R_1\} > 2\mu_5\|\Psi(\tilde\theta)\|, \tag{17}$$

则 $t > 0$ 时 $\dot{\tilde q}(t), \tilde q(t), \theta(t)$ 均是有界的.

2) 当满足持续激励条件时, 且

$$R_2 > 0, \tag{18}$$

则

$$\lim_{t\to\infty}\|[\dot{\tilde q}^{\mathrm T} \quad \tilde q^{\mathrm T} \quad \vartheta^{\mathrm T} \quad \tilde\theta^{\mathrm T}]^{\mathrm T}\| = 0. \tag{19}$$

其中

$$R_1 = \begin{bmatrix} 2\mu_1 & -\mu_2 & -\mu_3 \\ -\mu_2 & 2\alpha(k_p - \eta_1) & -\mu_6 \\ -\mu_3 & -\mu_6 & 2\left(\frac{\alpha}{b\rho_\vartheta} - \alpha\beta\right)k_v \end{bmatrix},$$

$$R_2 = \begin{bmatrix} 2\mu_1 & -\mu_2 & -\mu_3 & -\mu_4 \\ -\mu_2 & 2\alpha(k_p - \eta_1) & -\mu_6 & -\mu_5 \\ -\mu_3 & -\mu_6 & 2\left(\frac{\alpha}{b\rho_\vartheta} - \alpha\beta\right)k_v & 0 \\ -\mu_4 & -\mu_5 & 0 & 2\alpha\gamma\lambda_m\{\Phi_d^{\mathrm T}\Phi_d\} \end{bmatrix},$$

$$\eta_1 = \|\ddot q_d\|_M + c_2\|\dot q_d\|_M^2 + 1, \eta_2 = c_1\|\dot q_d\|_M,$$

$$\mu_1 = \alpha\lambda_m\{M(q)(b\beta J_\vartheta - J_{\tilde q})\} - \eta_2 - \alpha c_1[(\rho_\epsilon + \beta\rho_\vartheta\epsilon_\vartheta)\sqrt{n} + 2\gamma\sqrt{p}\,\|\Phi_d\|_M\,\rho_\theta\epsilon_\theta],$$

$$\mu_2 = \eta_1 + \alpha\eta_2 + \alpha^2\gamma(1+\gamma k_p)\cdot\lambda_M\{M\Phi_d J_{\tilde\theta}\Phi_d^{\mathrm T}\}/\delta,$$

$$\mu_3 = \alpha\beta\eta_2 + \alpha a\beta\lambda_M\{MJ_\vartheta\mathrm{diag}\{\vartheta_i/s_{\vartheta,i}(\vartheta)\}\} + \alpha^2\gamma(\gamma k_v - \beta)\cdot\lambda_M\{M\Phi_d J_{\tilde\theta}\Phi_d^{\mathrm T}\}/\delta,$$

$$\mu_4 = (1+\alpha\gamma\eta_2)\|\Phi_d\|_M + \alpha\gamma\lambda_M\{M\dot\Phi_d\},$$

$$\mu_5 = \alpha\gamma\eta_1\|\Phi_d\|_M,\ \mu_6 = \alpha(\beta\eta_1 + |k_v - \beta k_p|),$$

$$J_{\tilde q}(\tilde q) = \frac{\partial s(\tilde q)}{\partial\tilde q^{\mathrm T}},\ J_\vartheta(\vartheta) = \frac{\partial s_\vartheta(\vartheta)}{\partial\vartheta^{\mathrm T}},\ J_{\tilde\theta}(\tilde\theta) = \frac{\partial\Psi(\tilde\theta)}{\partial\tilde\theta^{\mathrm T}}.$$

证明　证明过程分两步:

1) 李雅普诺夫函数正定性的证明

构造李雅普诺夫函数

$$V(x) = \frac{1}{2}\dot{\tilde q}^{\mathrm T}M(q)\dot{\tilde q} + U_{\tilde q}(\tilde q) + \delta U_{\tilde\theta}(\tilde\theta) + U_\vartheta(\vartheta) + \alpha\dot{\tilde q}^{\mathrm T}M(q)[s(\tilde q) - \beta s_\vartheta(\vartheta) - \gamma\Phi_d\Psi(\tilde\theta)], \tag{20}$$

其中 $x^{\mathrm T} = [\dot{\tilde q}^{\mathrm T}\ \ \tilde q^{\mathrm T}\ \ \vartheta^{\mathrm T}\ \ \tilde\theta^{\mathrm T}]$. 式(20) 可写为

$$V = \frac{1}{2}[\dot{\tilde q} + \alpha s(\tilde q)]^{\mathrm T}M[\dot{\tilde q} + \alpha s(\tilde q)] + U_{\tilde q}(\tilde q) + \frac{1}{2}[\dot{\tilde q} - \alpha\beta s_\vartheta(\vartheta)]^{\mathrm T}M[\dot{\tilde q} - \alpha\beta s_\vartheta(\vartheta)] + U_\vartheta(\vartheta) + \frac{1}{2}[\dot{\tilde q} - \alpha\gamma\Phi_d\Psi(\tilde\theta)]^{\mathrm T}M[\dot{\tilde q} - \alpha\gamma\Phi_d\Psi(\tilde\theta)] - \frac{1}{2}\alpha^2 s^{\mathrm T}(\tilde q)M s(\tilde q) - \frac{1}{2}\alpha^2\beta^2 s_\vartheta^{\mathrm T}(\vartheta)M s_\vartheta(\vartheta) - \frac{1}{2}\alpha^2\gamma^2\Psi^{\mathrm T}(\tilde\theta)\Phi_d^{\mathrm T}M\Phi_d\Psi(\tilde\theta) + \delta U_{\tilde\theta}(\tilde\theta), \tag{21}$$

根据

$$U_{\tilde q}(\tilde q) - \frac{1}{2}\alpha^2 s^{\mathrm T}(\tilde q)M(q)s(\tilde q) \geq U_{\tilde q}(\tilde q) - \frac{1}{2}\alpha^2\lambda_M\{M(q)\}s^{\mathrm T}(\tilde q)s(\tilde q) \geq [k_p - \rho\alpha^2\lambda_M\{M(q)\}]\sum_{i=1}^{n}\int s_i(\tilde q_i)\mathrm d\tilde q_i \tag{22}$$

及条件(14), 则

$$U_{\tilde q}(\tilde q) - \frac{1}{2}\alpha^2 s^{\mathrm T}(\tilde q)M(q)s(\tilde q) \geq 0.$$

类似地, 依据条件(15) 和(16), 可以证明

$$U_\vartheta(\vartheta) - \frac{1}{2}\alpha^2\beta^2 s_\vartheta^{\mathrm T}(\vartheta)M(q)s_\vartheta(\vartheta) \geq 0, \tag{23}$$

$$\delta U_{\tilde\theta}(\tilde\theta) - \frac{1}{2}\alpha^2\gamma^2\Psi^{\mathrm T}(\tilde\theta)\Phi_d^{\mathrm T}M(q)\Phi_d\Psi(\tilde\theta) \geq 0. \tag{24}$$

由(13) 可知, $V(x)$ 是正定的, 而且也是径向无界的.

2) 李雅普诺夫函数时间导数负定性的证明.

李雅普诺夫函数的时间导数为

$$\dot V = \{\dot{\tilde q} + \alpha[s(\tilde q) - \beta s_\vartheta(\vartheta) - \gamma\Phi_d\Psi(\tilde\theta)]\}^{\mathrm T}M\ddot{\tilde q} + \alpha\dot{\tilde q}^{\mathrm T}\dot M[s(\tilde q) - \beta s_\vartheta(\vartheta) - \gamma\Phi_d\Psi(\tilde\theta)] + \frac{1}{2}\dot{\tilde q}^{\mathrm T}\dot M\dot{\tilde q} + \alpha\dot{\tilde q}^{\mathrm T}M[\dot s(\tilde q) - \beta\dot s_\vartheta(\vartheta) - \gamma\dot\Phi_d\Psi(\tilde\theta) - \gamma\Phi_d\dot\Psi(\tilde\theta)] + \dot{\tilde q}^{\mathrm T}\nabla_{\tilde q}U_{\tilde q}(\tilde q) + \dot\vartheta^{\mathrm T}\nabla_\vartheta U_\vartheta(\vartheta) + \delta\dot{\tilde\theta}^{\mathrm T}\nabla_{\tilde\theta}U_{\tilde\theta}(\tilde\theta). \tag{25}$$

根据机器人有关性质进行以下两个运算过程:

$$\{\dot{\tilde q} + \alpha[s(\tilde q) - \beta s_\vartheta(\vartheta) - \gamma\Phi_d\Psi(\tilde\theta)]\}^{\mathrm T}H(\dot{\tilde q},\tilde q) \leq \eta_2\|\dot{\tilde q}\|^2 + (\eta_1 + \alpha\eta_2)\|\dot{\tilde q}\|\,\|s(\tilde q)\| + \alpha\beta\eta_2\|\dot{\tilde q}\|\,\|s_\vartheta(\vartheta)\| + \alpha\gamma\eta_2\|\Phi_d\|_M\|\dot{\tilde q}\|\,\|\Psi(\tilde\theta)\| + \alpha\beta\eta_1\|s(\tilde q)\|\,\|s_\vartheta(\vartheta)\| + \alpha\eta_1\|s(\tilde q)\|^2 + \alpha\gamma\eta_2\|\Phi_d\|_M\|s(\tilde q)\|\,\|\Psi(\tilde\theta)\|; \tag{26}$$

$$\dot{\tilde q}^{\mathrm T}M[\dot s(\tilde q) - \beta\dot s_\vartheta(\vartheta) - \gamma\dot\Phi_d\Psi(\tilde\theta) - \gamma\Phi_d\dot\Psi(\tilde\theta)] = \frac{1}{\delta}\alpha\gamma\dot{\tilde q}^{\mathrm T}M\Phi_d J_{\tilde\theta}\Phi_d^{\mathrm T}[(\gamma k_v - \beta)s(\vartheta) + (1+\gamma k_p)s(\tilde q)] + \dot{\tilde q}^{\mathrm T}M\{[J_{\tilde q} - b\beta J_\vartheta]\dot{\tilde q} + \alpha\beta J_\vartheta\vartheta - \gamma\dot\Phi_d\Psi(\tilde\theta)\}. \tag{27}$$

利用下列不等式

$$\|s(\tilde q)\| \leq \rho\epsilon\sqrt{n},\ \|\partial s(\tilde q)/\partial\tilde q^{\mathrm T}\| \leq \rho, \tag{28}$$

$$\|s_\vartheta(\vartheta)\| \leq \rho_\vartheta\epsilon_\vartheta\sqrt{n},\ \|\partial s_\vartheta(\vartheta)/\partial\vartheta^{\mathrm T}\| \leq \rho_\vartheta, \tag{29}$$

$$\|\Psi(\tilde\theta)\| \leq 2\rho_\theta\epsilon_\theta\sqrt{p},\ \|\partial\Psi(\tilde\theta)/\partial\tilde\theta^{\mathrm T}\| \leq \rho_\theta, \tag{30}$$

经运算可得:

① 不满足持续激励条件时, 即

$$\lambda_m\{\Phi_d^{\mathrm T}\Phi_d\} = 0, \tag{31}$$

定义一向量 y, 有

$$y_1^{\mathrm T} = [\ \|\dot{\tilde q}\|\ \ \|s(\tilde q)\|\ \ \|s_\vartheta(\vartheta)\|\ ], \tag{32}$$

则有

$$\dot V \leq -\frac{1}{2}y_1^{\mathrm T}R_1y_1 + \mu_4\|\dot{\tilde q}\|\,\|\Psi(\tilde\theta)\| + \mu_5\|s(\tilde q)\|\,\|\Psi(\tilde\theta)\| \leq -\frac{1}{2}y_1^{\mathrm T}R_1y_1 + 2\mu_4\rho_\theta\epsilon_\theta\sqrt{p}\,\|\dot{\tilde q}\| +$$

$$2\mu_5\rho_\theta\rho_{\epsilon\theta}\epsilon\sqrt{np}. \tag{33}$$

当 $R_1 > 0$ 时, 对于任意 $t > 0$, $\dot{\tilde{q}}(t)$ 是有界的; 另一方面

$$\dot{V} \leq -\frac{1}{2}y_1^{\mathrm{T}}R_1y_1 + \mu_4\|\dot{\tilde{q}}\|\|\Psi(\tilde{\theta})\| + \mu_5\|s(\tilde{q})\|\|\Psi(\tilde{\theta})\| \leq -\frac{1}{2}\lambda_m\{R_1\}[\|\dot{\tilde{q}}\|^2 + \|s(\tilde{q})\|^2 + \|s_\vartheta(\vartheta)\|^2] + \mu_4\|\dot{\tilde{q}}\|\|\Psi(\tilde{\theta})\| + \mu_5\|s(\tilde{q})\|\|\Psi(\tilde{\theta})\|. \tag{34}$$

如果(17) 满足, 那么 $\tilde{q}(t)$ 是有界的; 根据滤波算法(3), 说明 $\theta(t)$ 也是有界的

② 满足持续激励条件时, 即

$$\lambda_m\{\Phi_d^{\mathrm{T}}\Phi_d\} > 0, \tag{35}$$

定义

$$y_2^{\mathrm{T}} = [\|\dot{\tilde{q}}(t)\| \quad \|\tilde{q}(t)\| \quad \|\vartheta(t)\| \quad \|\Psi(\tilde{\theta})\|],$$

则
$$\dot{V} \leq -\frac{1}{2}y_2^{\mathrm{T}}R_2y_2. \tag{36}$$

根据Barbalat 引理, 定理 1 中 2) 得证 □

注 2 有关本算法的鲁棒性分析请参照文献[4].

跟踪控制输入的上界为

$$\bar{\tau}_i = \rho_\epsilon K_{p,i} + \rho_\vartheta\epsilon_\vartheta K_{v,i} + \|\pi_i + (m_\theta)_i(\epsilon_\theta)_i\| \times \|(\Phi_d)_{i\cdot}\|_M + \max_{t>0}\{|\Lambda_i(\ddot{q}_d, \dot{q}_d, q_d, \theta^*)|\}, \tag{37}$$

容易得到如下结果:

定理 2 对于给定的机器人系统, 有最大关节驱动力矩 $\bar{\tau}_i$, 如果满足

$$\tau_{\max,i} \geq \bar{\tau}_i, \tag{38}$$

即

$$\rho_\epsilon K_{p,i} + \rho_\vartheta\epsilon_\vartheta K_{v,i} + \|\pi_i + (m_\theta)_i(\epsilon_\theta)_i\|\|(\Phi_d)_{i\cdot}\|_M + \max_{t>0}\{|\Lambda_i(\ddot{q}_d, \dot{q}_d, q_d, \theta^*)|\} \leq \tau_{i,\max}, \tag{39}$$

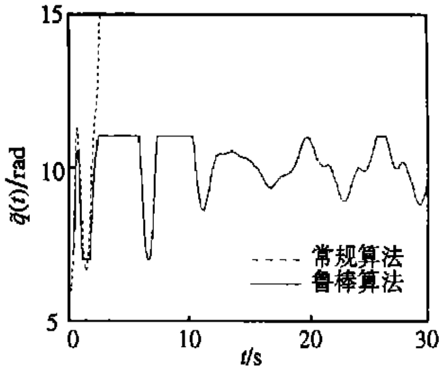
那么控制律(2～ 4) 满足关节驱动力矩受限条件(1), 且该系统能够实现相应的轨迹跟踪

4 仿真算例

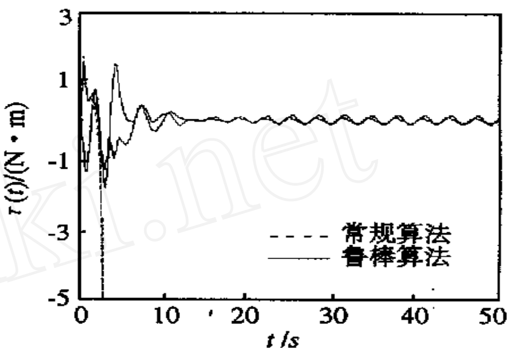
如无特殊说明, 本算例的条件与文献[9] 中的算例是一致的 选取参数为 $k_v = 2, m_\vartheta = \rho_\vartheta = 65, \epsilon_\vartheta = 10/13$, 滤波器方程为

$$T(s) = 5s/(s+1),$$

参数估计器为

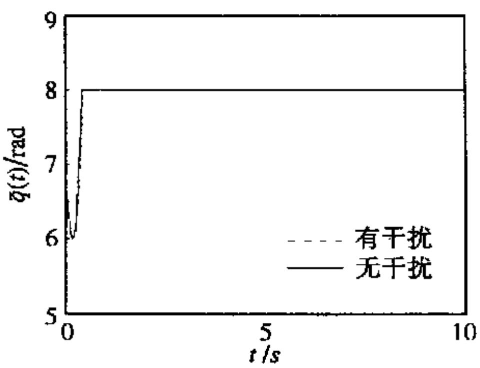


(a) 关节角跟踪误差

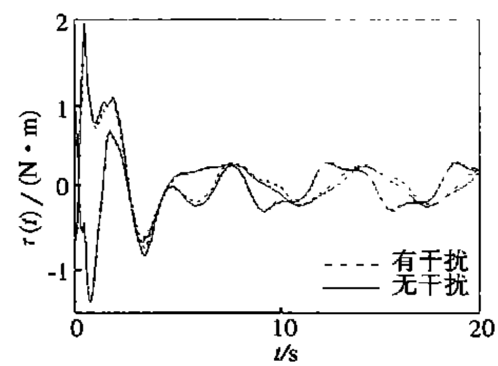


(b) 控制输入力矩

图 1 有干扰 d(t) 时仿真结果的比较



(a) 关节角跟踪误差



(b) 控制输入力矩

图 2 鲁棒自适应控制算法的仿真结果

$$\hat{\theta}(t) = 7 - \int \left[\frac{1}{35} s(\tilde{q}(\zeta)) - \frac{1}{130} s_{\vartheta}(\vartheta(\zeta)) \right] d\zeta$$

当估计参数域包含参数真实值且存在干扰时，图 1（估计参数域 Ω 为 [7, 11]）为两种控制算法仿真结果的比较。显然，输出反馈鲁棒自适应控制系统仍是稳定的，而常规自适应系统则是不稳定的。

当估计参数域不包含真实参数 θ_0 时，图 2（估计参数域为 [0, 8]）验证了鲁棒控制器对参数域估计误差的鲁棒性，包括有干扰和无干扰两种情况。

需要指出的是，控制信号均已进入控制器的饱和区，这说明输入受限的设计起了作用。该算例充分验证了本文算法的鲁棒性和有效性。

5　结　　语

考虑输入受限的情况，在文献 [9] 提出的鲁棒自适应状态反馈跟踪控制的基础上，本文通过一个线性一阶滤波器，实现鲁棒自适应的输出反馈跟踪控制，解决了机器人力矩受限条件下的输出反馈自适应跟踪控制及其鲁棒性的问题，并证明了当满足持续激励条件且估计参数域包含参数真实值时，闭环系统能够实现渐近稳定跟踪。本算法简单有效，提高了控制系统的鲁棒性和控制品质，特别对于参数域估计误差即参数域的估计错误也具有很强的鲁棒性。

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（上接第 564 页）

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