

基于边界层的不确定机器人自适应迭代学习控制

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摘要: 针对不确定的多连杆机械手的跟踪控制问题, 提出一种基于边界层的自适应迭代学习控制方法. 自适应控制用来估计系统的未知参数的上界, 本文主要特征是基于边界层设计自适应迭代学习控制器, 避免了传统方法设计控制器的不连续性, 削弱抖振现象的同时也提高系统的鲁棒性. 理论证明系统所有信号有界, 系统误差渐进收敛到边界层邻域内. 仿真表明了算法的有效性.

关键词: 边界层; 迭代学习控制; 自适应控制; 滑模变结构控制

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Adaptive iterative learning control for uncertain robot based on boundary layer

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Abstract: An adaptive iterative learning control algorithm based on boundary layer is proposed for trajectory tracking of uncertain robot systems. Sliding mode variable structure control is used to improve the robustness to disturbance and perturbation, and boundary layer is used to eliminate the chattering of sliding mode control. In the iterative domain, the unknown parameters are tuned and used as part of the controller. We analyze the stability and convergence of this algorithm by using the Lyapunov-like methodology. The simulation results show that the expected control purpose can be achieved using the proposed algorithm.

Key words: boundary layer; iterative learning control; adaptive control; sliding mode variable structure control

1 引言(Introduction)

迭代学习控制适合于具有重复运动性质的被控对象, 实际应用过程中, 不需已经被控对象的精确数学模型, 仅要求知道系统输入输出信号, 经过一定次数的学习后能够在有限时间内实现对目标轨迹的完全跟踪. 这种控制技术通过不断学习期望轨迹的过程, 为具有快速运动特点的机器人系统轨迹跟踪控制提供了有效方法. 因此迭代学习控制方法自提出以来就被广泛的应用到机器人系统轨迹跟踪控制上. 由于传统迭代学习控制方法的限制, 在过去的十几年, 一种新型的迭代学习控制方法——自适应迭代学习控制方法得到广泛研究^[1-4]. 其主要特征是在迭代域上对于不确定参数进行估计, 并将其作为当前控制输入的一部分, 通过对参数的不断学习达到系统理想的控制效果. 但传统自适应迭代学习控制器中往往含有不连续项, 使得控制输入产生高频抖振现象^[5]. 为消除高频抖振现象, 文献[6]中针对不确定线性系统, 提出了一种基于系统状态范数的边界层厚度在线调整算法. 文献[7]提出一种新型动态滑

模控制, 采用饱和函数方法, 通过设计非线性切换函数, 消除了滑模到达阶段的抖振, 实现了全局鲁棒滑模控制, 有效的解决了一类非线性机械系统的控制抖振问题. 本文采用滑模变结构控制来提高控制器对系统干扰和摄动的鲁棒性, 在自适应迭代学习控制方法的基础上, 结合边界层方法设计控制器, 保证了控制器的连续性, 提高系统对参数变化和外界扰动的鲁棒性的同时, 平滑了控制输入项, 消除了滑模控制中的抖振现象. 该方法不仅提高了系统对外界干扰的鲁棒性, 而且保证了系统的全局稳定性.

2 问题的描述(Problem formulation)

考虑不确定机器人系统在第 k 次运行时, 其动力学方程为

$$M(\mathbf{q}_k)\ddot{\mathbf{q}}_k + C(\mathbf{q}_k, \dot{\mathbf{q}}_k)\dot{\mathbf{q}}_k + G(\mathbf{q}_k) = \boldsymbol{\tau}_k + \mathbf{d}_k, \quad (1)$$

式中: $\mathbf{q}_k, \dot{\mathbf{q}}_k, \ddot{\mathbf{q}}_k \in \mathbb{R}^n$ 表示机械手关节的位置、速度、加速度, $M(\mathbf{q}_k) \in \mathbb{R}^{n \times n}$ 为正定有界惯量矩阵, $C(\mathbf{q}_k, \dot{\mathbf{q}}_k) \in \mathbb{R}^{n \times n}$ 表示离心力和哥氏力, $G(\mathbf{q}_k) \in \mathbb{R}^n$ 表示重力项矢量, $\boldsymbol{\tau}_k \in \mathbb{R}^n$ 表示输入控制力矩, $\mathbf{d}_k \in$

\mathbb{R}^n 表示外部干扰力矩. 为了导出本文的控制策略, 作如下假设:

假设 1 对于 $\forall t \in [0, T]$, 参考轨迹 $\mathbf{q}_d, \dot{\mathbf{q}}_d, \ddot{\mathbf{q}}_d$ 和干扰项 \mathbf{d}_k 有界.

假设 2 系统初始状态满足 $\dot{\mathbf{q}}_d(0) - \dot{\mathbf{q}}_k(0) = \mathbf{q}_d(0) - \mathbf{q}_k(0) = 0$.

在本文的理论证明中, 用到以下机器人动力学结构特性:

P1) $M(\mathbf{q}_k) \in \mathbb{R}^{n \times n}$ 对称正定且有界;

P2) 对适当选定的哥氏力矩阵 $C(\mathbf{q}_k, \dot{\mathbf{q}}_k)$, 有

$$\mathbf{x}^T [M(\dot{\mathbf{q}}_k) - 2C(\mathbf{q}_k, \dot{\mathbf{q}}_k)] \mathbf{x} = 0, \forall \mathbf{x} \in \mathbb{R}^n;$$

P3) $\|C(\mathbf{q}_k, \dot{\mathbf{q}}_k)\| \leq k_c \|\dot{\mathbf{q}}_k\|$, $\|G(\mathbf{q}_k)\| < k_g$, $\|\mathbf{d}_k(t)\| \leq k_d, k_c, k_g$ 和 k_d 为正实数.

3 自适应迭代学习控制器设计(Adaptive iterative learning control design)

定义如下跟踪误差:

$$\tilde{\mathbf{q}}_k(t) = \mathbf{q}_d(t) - \mathbf{q}_k(t), \quad \dot{\tilde{\mathbf{q}}}_k(t) = \dot{\mathbf{q}}_d(t) - \dot{\mathbf{q}}_k(t).$$

设计滑模面函数为

$$\mathbf{s}_k(t) = \dot{\tilde{\mathbf{q}}}_k(t) + \alpha \tilde{\mathbf{q}}_k(t). \quad (2)$$

引入误差函数

$$\mathbf{s}_{\varphi k}(t) = \mathbf{s}_k(t) - \varphi \text{sat}(\mathbf{s}_k(t)/\varphi). \quad (3)$$

饱和函数定义为

$$\text{sat}(\mathbf{s}_k(t)/\varphi) = (\text{sat}(s_k^1(t)/\varphi), \dots, \text{sat}(s_k^n(t)/\varphi))^T,$$

$$\text{sat}(s_k^i(t)/\varphi) = \begin{cases} s_k^i(t)/\varphi, & |s_k^i(t)| \leq \varphi, \\ \text{sgn}(s_k^i(t)), & |s_k^i(t)| > \varphi. \end{cases}$$

考虑函数

$$V_k = \frac{1}{2} \mathbf{s}_{\varphi k}^T M(\mathbf{q}_k) \mathbf{s}_{\varphi k}, \quad (4)$$

求导得到

$$\begin{aligned} \dot{V}_k &= \mathbf{s}_{\varphi k}^T M(\mathbf{q}_k) \dot{\mathbf{s}}_{\varphi k} + \frac{1}{2} \mathbf{s}_{\varphi k}^T \dot{M}(\mathbf{q}_k) \mathbf{s}_{\varphi k} = \\ & \mathbf{s}_{\varphi k}^T (M(\mathbf{q}_k)(\ddot{\mathbf{q}}_d + \alpha \dot{\tilde{\mathbf{q}}}_k) + G(\mathbf{q}_k) - \mathbf{d}_k - \\ & \boldsymbol{\tau}_k - C(\mathbf{q}_k, \dot{\mathbf{q}}_k) \mathbf{s}_k + \mathbf{s}_{\varphi k}^T C(\mathbf{q}_k, \dot{\mathbf{q}}_k) \mathbf{s}_{\varphi k} + \\ & C(\mathbf{q}_k, \dot{\mathbf{q}}_k)(\dot{\mathbf{q}}_d + \alpha \tilde{\mathbf{q}}_k)) = \\ & \mathbf{s}_{\varphi k}^T (M(\mathbf{q}_k)(\ddot{\mathbf{q}}_d + \alpha \dot{\tilde{\mathbf{q}}}_k) + G(\mathbf{q}_k) - \boldsymbol{\tau}_k - \mathbf{d}_k + \\ & C(\mathbf{q}_k, \dot{\mathbf{q}}_k)(\dot{\mathbf{q}}_d + \alpha \tilde{\mathbf{q}}_k) - C(\mathbf{q}_k, \dot{\mathbf{q}}_k) \varphi \text{sat}(\mathbf{s}_k/\varphi)). \end{aligned} \quad (5)$$

由性质P1)P3)可以推得存在正常数 θ_i ($i = 1, 2, 3, 4, 5$)满足

$$\begin{aligned} \|M(\mathbf{q}_k) \ddot{\mathbf{q}}_d - \mathbf{d}_k + G(\mathbf{q}_k)\| &\leq \theta_1, \\ \|C(\mathbf{q}_k, \dot{\mathbf{q}}_k) \dot{\mathbf{q}}_d\| &\leq \theta_2 (1 + \|\dot{\tilde{\mathbf{q}}}_k\|), \\ \|\alpha M(\mathbf{q}_k) \dot{\tilde{\mathbf{q}}}_k\| &\leq \theta_3 \|\dot{\tilde{\mathbf{q}}}_k\|, \end{aligned}$$

$$\|\alpha C(\mathbf{q}_k, \dot{\mathbf{q}}_k) \tilde{\mathbf{q}}_k\| \leq \theta_4 (1 + \|\dot{\tilde{\mathbf{q}}}_k\|) \|\tilde{\mathbf{q}}_k\|,$$

$$C(\mathbf{q}_k, \dot{\mathbf{q}}_k) \varphi \text{sat}(\mathbf{s}_k(t)/\varphi) \leq \theta_5 (1 + \|\dot{\tilde{\mathbf{q}}}_k\|).$$

因此

$$\begin{aligned} \dot{V}_k &= \\ & \mathbf{s}_{\varphi k}^T (M(\mathbf{q}_k) \ddot{\mathbf{q}}_d + G(\mathbf{q}_k) - \mathbf{d}_k + \alpha M(\mathbf{q}_k) \dot{\tilde{\mathbf{q}}}_k + \\ & \alpha C(\mathbf{q}_k, \dot{\mathbf{q}}_k) \tilde{\mathbf{q}}_k + C(\mathbf{q}_k, \dot{\mathbf{q}}_k) \dot{\mathbf{q}}_d - \boldsymbol{\tau}_k) \leq \\ & \|\mathbf{s}_{\varphi k}\| (\theta_1 + \theta_2 + \theta_5 + (\theta_2 + \theta_3 + \theta_5) \|\dot{\tilde{\mathbf{q}}}_k\| + \\ & \theta_4 \|\tilde{\mathbf{q}}_k\| + \theta_4 \|\dot{\tilde{\mathbf{q}}}_k\| \|\tilde{\mathbf{q}}_k\|) - \mathbf{q}_{\varphi k}^T \boldsymbol{\tau}_k \leq \\ & \|\mathbf{s}_{\varphi k}\| \theta (1 + \|\dot{\tilde{\mathbf{q}}}_k\| + \|\tilde{\mathbf{q}}_k\| + \|\dot{\tilde{\mathbf{q}}}_k\| \|\tilde{\mathbf{q}}_k\|) - \mathbf{s}_{\varphi k}^T \boldsymbol{\tau}_k = \\ & \|\mathbf{s}_{\varphi k}\| \eta(\tilde{\mathbf{q}}_k, \dot{\tilde{\mathbf{q}}}_k) \theta - \mathbf{s}_{\varphi k}^T \boldsymbol{\tau}_k, \end{aligned} \quad (6)$$

其中:

$$\begin{aligned} \eta(\tilde{\mathbf{q}}_k, \dot{\tilde{\mathbf{q}}}_k) &= 1 + \|\dot{\tilde{\mathbf{q}}}_k\| + \|\tilde{\mathbf{q}}_k\| + \|\dot{\tilde{\mathbf{q}}}_k\| \|\tilde{\mathbf{q}}_k\|, \\ \theta &= \max\{\theta_1 + \theta_2 + \theta_5, \theta_2 + \theta_3 + \theta_5, \theta_4\}. \end{aligned}$$

因此, 本文设计控制律如下:

$$\boldsymbol{\tau}_k(t) = K \mathbf{s}_k + \text{sat}(\mathbf{s}_k/\varphi) \eta(\tilde{\mathbf{q}}_k, \dot{\tilde{\mathbf{q}}}_k) \hat{\theta}_k(t). \quad (7)$$

参数迭代学习律为

$$\hat{\theta}_k(t) = \hat{\theta}_{k-1}(t) + \beta \|\mathbf{s}_{\varphi k}(t)\| \eta(\tilde{\mathbf{q}}_k, \dot{\tilde{\mathbf{q}}}_k), \quad (8)$$

其中: $\hat{\theta}_{-1}(t) = 0$, $K \in \mathbb{R}^{n \times n}$ 是对称正定矩阵, $\beta > 0$.

4 稳定性和收敛性分析(Stability and convergence analysis)

定理 1 考虑机器人系统(1)在满足性质P1) P2)P3)和假设1-2下, 应用控制律(7)和参数自适应律(8)对系统进行控制, 则系统满足

1) $\mathbf{s}_{\varphi k}(t), \mathbf{s}_k(t), \tilde{\mathbf{q}}_k(t), \theta_k(t), \boldsymbol{\tau}_k(t)$ 有界, 对于 $\forall t \in [0, T]$.

2) $\lim_{k \rightarrow \infty} \|\mathbf{s}_{\varphi k}(t)\| = 0, \lim_{k \rightarrow \infty} \|\mathbf{s}_k(t)\| \leq \varphi$, 对 $\forall t \in [0, T]$.

证 考虑如下Lyapunov-like函数:

$$E_k(t) = V_k(t) + \frac{1}{2\beta} \int_0^t \tilde{\theta}_k^2(\tau) d\tau, \quad (9)$$

其中: $\tilde{\theta}_k(t) = \theta(t) - \hat{\theta}_k(t)$, $\hat{\theta}_k(t)$ 是 $\theta(t)$ 的估计值, 则第 k 次迭代时能量差为

$$\begin{aligned} \Delta E_k &= E_k - E_{k-1} = \\ & V_k - V_{k-1} + \frac{1}{2} \int_0^t (\tilde{\theta}_k^2 - \tilde{\theta}_{k-1}^2) d\tau = \\ & V_k - V_{k-1} - \frac{1}{2} \int_0^t (\bar{\theta}_k^2 + 2\tilde{\theta}_k \bar{\theta}_k) d\tau, \end{aligned} \quad (10)$$

其中: $\bar{\theta}_k = \hat{\theta}_k - \hat{\theta}_{k-1}$,

$$\begin{aligned} V_k(t) &= V_k(0) + \int_0^t \dot{V}_k(\tau) d\tau = \\ & V_k(0) + C(\mathbf{q}_k, \dot{\mathbf{q}}_k)(\dot{\mathbf{q}}_d + \alpha \tilde{\mathbf{q}}_k) - \boldsymbol{\tau}_k + \\ & \int_0^t \mathbf{s}_{\varphi k}^T(\tau) (M(\mathbf{q}_k)(\ddot{\mathbf{q}}_d + \alpha \dot{\tilde{\mathbf{q}}}_k) + G(\mathbf{q}_k) - \\ & \mathbf{d}_k - C(\mathbf{q}_k, \dot{\mathbf{q}}_k) \varphi \text{sat}(\mathbf{s}_k(t)/\varphi)) d\tau. \end{aligned} \quad (11)$$

将控制律式(7)代入式(11)得到

$$V_k(t) \leq V_k(0) + \int_0^t (\|s_{\varphi k}\| \eta(\tilde{q}_k, \dot{\tilde{q}}_k) \tilde{\theta}_k(\tau) - s_{\varphi k}^T K s_{\varphi k} - \varphi \lambda_{\min}(K) \|s_{\varphi k}\|) d\tau. \quad (12)$$

由假设2知 $V_k(0) = 0$, 将式(8)和式(12)代入到式(10), 得到

$$\Delta E_k = -V_{k-1} - \frac{1}{2} \int_0^t (\tilde{\theta}_k^2 + 2s_{\varphi k}^T K s_{\varphi k}) d\tau \leq 0. \quad (13)$$

因此, E_k 是非递增序列. 如果 E_0 有界, 那么可以得到 E_k 是有界的, 下面证明 E_0 有界. 由式(6)知

$$\dot{E}_0 \leq s_{\varphi 0}^T (\text{sat}(s_0/\varphi) \eta(\tilde{q}_0, \dot{\tilde{q}}_0) \theta - \tau_0) + \frac{1}{2\beta} \tilde{\theta}_0^2 \leq \|s_{\varphi 0}\| \eta(\tilde{q}_0, \dot{\tilde{q}}_0) \tilde{\theta}_0 - s_{\varphi 0}^T K s_{\varphi 0} + \frac{1}{2\beta} \tilde{\theta}_0^2. \quad (14)$$

由 $\hat{\theta}_{-1}(t) = 0, \hat{\theta}_0(t) = \beta \eta(\tilde{q}_0, \dot{\tilde{q}}_0) \|s_{\varphi 0}\|$, 因此

$$\dot{E}_0 \leq -s_{\varphi 0}^T K s_{\varphi 0} + \frac{(\theta_0 - \tilde{\theta}_0) \tilde{\theta}_0}{\beta} + \frac{1}{2\beta} \tilde{\theta}_0^2 = -s_{\varphi 0}^T K s_{\varphi 0} + \frac{\theta_0 \tilde{\theta}_0}{\beta} - \frac{\tilde{\theta}_0^2}{\beta} + \frac{1}{2\beta} \tilde{\theta}_0^2. \quad (15)$$

由于 $a^2 + b^2 \geq 2ab$, 则

$$\frac{\theta_0 \tilde{\theta}_0}{\beta} \leq \frac{\theta_0^2 + \tilde{\theta}_0^2}{2\beta}. \quad (16)$$

因此

$$\dot{E}_0 \leq -k_1 \|s_{\varphi 0}\| + \frac{\theta_0^2}{2\beta},$$

其中 $k_1 = \lambda_{\min}(K)$, 是 K 的最小特征值. 即 $\dot{E}_0 \leq \frac{\theta_0^2}{2\beta}$. 又由

$$E_0(t) = E_0(0) + \int_0^t \dot{E}_0(\tau) d\tau, \quad (17)$$

由于 $E_0(0) = 0, \dot{E}_0$ 有界, 所以 $E_0(t)$ 是有界的. 下面证明 $E_k(t)$ 的连续性和有界性,

$$E_k(t) = E_0(t) + \sum_{i=1}^k \Delta E_i(t), \quad (18)$$

由式(13)得

$$E_k(t) \leq E_0(t) - \sum_{i=1}^k V_i(t) \leq$$

$$E_0(t) - \frac{1}{2} \sum_{i=1}^k s_{\varphi(i-1)}^T M(q_{i-1}) s_{\varphi(i-1)}(t), \quad (19)$$

则有

$$\sum_{i=1}^k s_{\varphi(i-1)}^T M(q_{i-1}) s_{\varphi(i-1)}(t) \leq 2(E_0(t) - E_k(t)) \leq 2E_0(t). \quad (20)$$

所以 $E_k(t)$ 有界, 从而 $s_{\varphi k}(t), s_k(t), \tilde{q}_k(t), \theta_k(t)$ 有界, 所以对于 $\forall t \in [0, T]$, 有 $\lim_{k \rightarrow \infty} \|s_{\varphi k}(t)\| = 0$, 又由 $s_{\varphi k}(t)$ 的定义, 可得 $\|s_k(t)\| \leq \varphi$, 当 $k \rightarrow \infty$.

5 仿真实例(Simulation examples)

以二关节机器人为例, 动力学方程如式(1),

$$M = [m_{ij}]_{2 \times 2}, C = [c_{ij}]_{2 \times 2}, G = [G_1 \ G_2]^T, \\ m_{11} = m_1 l_{c1}^2 + m_2 (l_1^2 + l_{c2}^2 + 2l_1 l_{c2} \cos q_2) + I_1 + I_2, \\ m_{12} = m_{21} = m_2 (l_{c2}^2 + l_1 l_{c2} \cos q_2) + I_2, \\ m_{22} = m_2 l_{c2}^2 + I_2 c_{11} = -m_2 l_1 l_{c2} \dot{q}_2 \sin q_2, \\ c_{11} = -m_2 l_1 l_{c2} \dot{q}_2 \sin q_2, c_{21} = m_2 l_1 l_{c2} \dot{q}_1 \sin q_2, \\ c_{12} = -m_2 l_1 l_{c2} (\dot{q}_1 + \dot{q}_2) \sin q_2, c_{22} = 0, \\ G_1 = (m_1 l_{c1} + m_2 l_1) g \cos q_1 + m_2 l_{c2} g \cos(q_1 + q_2), \\ G_2 = m_2 l_{c2} g \cos(q_1 + q_2).$$

干扰项 $d_k(t) = (d_m \sin t, d_m \sin t)^T$ 是幅值为1的随机信号. 系统参数为 $m_1 = m_2 = 1, l_1 = l_2 = 0.5, l_{c1} = l_{c2} = 0.25, I_1 = I_2 = 0.1, g = 9.81$.

期望参考轨迹为 $q_{1d} = \sin(\pi t), q_{2d} = \sin(\pi t)$. 控制器参数 $K = \text{diag}\{10, 10\}, \beta = 10$. 边界层宽度取 $\varphi = 0.05$, 每次迭代时间为4s. 仿真结果如图1-5所示.

仿真结果表明, 随着迭代次数的增加, 系统轨迹跟踪误差逐渐减少, 经过5次迭代学习之后, 系统可以达到理想的跟踪期望轨迹的目的. 由图4和图5对比可以看出, 未采用边界层时对系统进行控制器设计, 此时的控制输入抖阵明显, 而采用边界层时对系统进行控制, 此时的控制输入的抖振明显减弱, 达到理想效果.

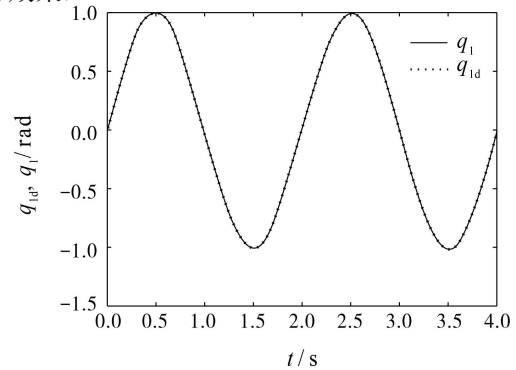


图1 关节1的轨迹跟踪

Fig. 1 Trajectory tracking of joint 1

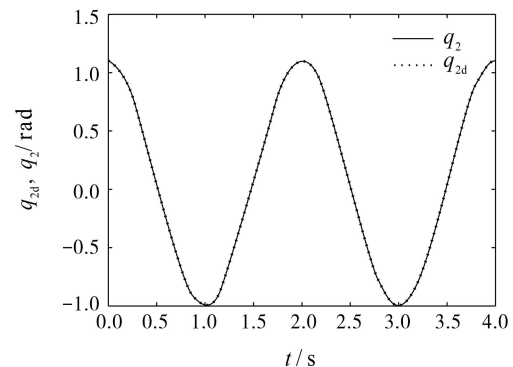


图2 关节2的轨迹跟踪

Fig. 2 Trajectory tracking of joint 2

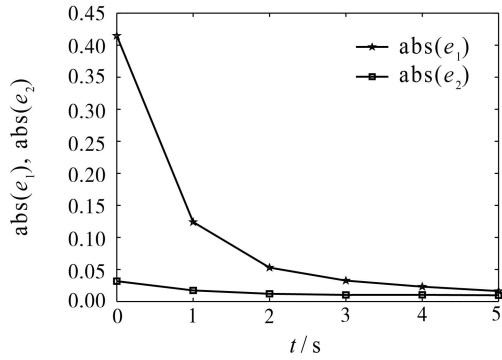


图 3 位置跟踪误差收敛过程

Fig. 3 Position tracking error convergence process

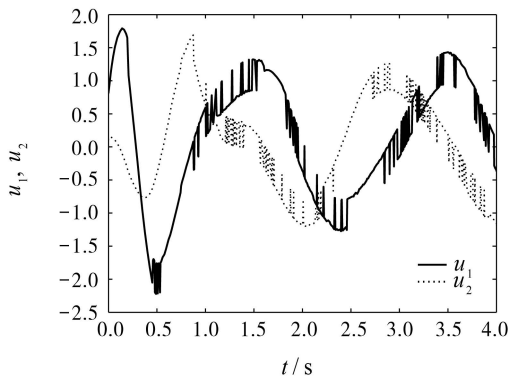


图 4 未加边界层的第5次控制输入

Fig. 4 The 5th control input without a boundary layer

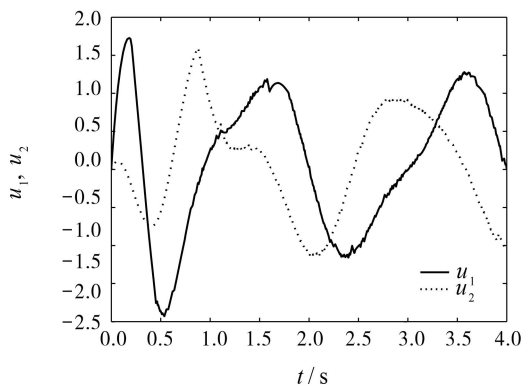


图 5 加入边界层的第5次控制输入

Fig. 5 The 5th control input with a boundary layer

6 结论(Conclusions)

本文提出一种基于边界层的机器人自适应迭代学习控制算法. 基于Lyapunove-like方法分析, 系统未知参数通过在迭代域内不断自适应调节达到更好的学习性能, 自适应律保证了迭代学习控制的稳定性和收敛性. 随着迭代次数增加, 系统跟踪误差渐进收敛到边界层的邻域内, 并保证了所有信号的有界性, 同时满足了平滑控制量的要求.

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