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高阶耦合机器人的自适应模糊滑模分散控制*

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摘要　针对一类存在模型不确定性和未知非线性扰动的机器人系统，考虑其不确定项和未知扰动项的上界是关于系统状态的普通高阶多项式，结合模糊系统的逼近能力，提出了一种基于滑模控制原理的自适应模糊分散控制方法. 该方法不仅能够使得关节之间相互耦合的机器人各关节的控制器仅由本关节的信息就能完全确定，而且消除了现存文献在设计机器人分散控制器时要求模型不确定项和未知扰动项的上界是常数或系统状态的一阶多项式等相关限定性假设条件. Lyapunov 稳定理论分析证明了闭环系统半全局一致终结有界，跟踪误差收敛到零. 二自由度机器人的仿真证明了该方法的有效性.

关键词　高阶耦合机器人，　自适应控制，　分散控制

引言

机器人是具有强耦合的多输入多输出非线性系统，传统的集中控制方法[1-5]使得机器人某关节的控制律不仅与本关节的所有状态有关，而且还与其他关节的状态有关，这种相互耦合的控制结构不仅使得控制器设计和控制算法复杂化，不利于故障检测和排除，而且鲁棒性、可靠性也降低. 因此，研究机器人的分散控制[6-10]，对机器人各关节进行独立控制，使得机器人各关节的控制器仅由本关节的信息就能完全确定，设计出具有鲁棒性强 、可靠性高且结构简单便于实现的分散控制器就显得尤为重要. 但是，文献[6-10]的分散控制都是在假设机器人的子系统在未知参数是线性的基础上得到的，而且文献[6-9]假设机器人的互联项为特殊的一阶多项式. 显然，文献[6-10]的分散控制对于含有高阶互联项且具有高度非线性的机器人并不适用.

本文在上述文献的基础上，基于滑模控制原理，结合模糊系统的逼近能力，针对具有高度非线性的复杂机器人系统，在考虑其不确定项和未知扰动项的上界是具有实际意义的关于系统状态的普通高阶多项式的基础上，提出了一种新的自适应模糊分散控制方法. 该方法不仅取消了现存文献在设计机器人分散控制器时要求模型不确定项和未知扰动项的

上界是常数或系统状态的一阶多项式等相关限定性条件，而且能够使得关节之间相互耦合的机器人各关节的控制器仅由本关节的信息就能完全确定，实现了机器人各关节的独立控制. Lyapunov 稳定理论分析证明了闭环系统半全局一致终结有界，跟踪误差收敛到零，二自由度机器人的仿真证明了该方法的有效性.

1　问题描述与基本假设

考虑具有 n 个旋转关节的刚性臂机器人，其动力学模型如下：

$$M(\underline{q})\ddot{\underline{q}}+C(\underline{q},\dot{\underline{q}})\dot{\underline{q}}+G(\underline{q})+F\dot{\underline{q}}+\Phi(\underline{q},\dot{\underline{q}},t)=\underline{u} \tag{1}$$

其中：$\underline{q},\dot{\underline{q}},\ddot{\underline{q}}$分别表示机械臂角位置矢量、速度矢量和加速度矢量；$M(\underline{q})\in R^{n\times n}$为机械臂惯性矩阵；$C(\underline{q},\dot{\underline{q}})\dot{\underline{q}}\in R^n$ 表示离心力和哥氏力；$G(\underline{q})\in R^n$ 为重力项；$F\in R^{n\times n}$为对角正定的摩擦因数矩阵；$\Phi(\underline{q},\dot{\underline{q}},t)\in R^n$ 为外部未知非线性扰动，$\underline{u}\in R^n$ 是控制输入. 控制目标是要求$\underline{q}$尽可能地跟踪指定的轨迹$\underline{q}_d=(q_{1d},q_{2d},\cdots,q_{nd})^T$. 另外机器人系统具有如下的固有结构特性：

特性 1：惯性矩阵 $M(\underline{q})$是对称正定矩阵.

记　$\underline{x}_1=(x_{11},x_{21},\cdots,x_{n1})^T=\underline{q}=(q_1,q_2,\cdots,q_n)^T$，

$\underline{x}_2=(x_{12},x_{22},\cdots,x_{n2})^T=\dot{\underline{q}}=(\dot{q}_1,\dot{q}_2,\cdots,\dot{q}_n)^T$，

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$$(e_{11},\cdots,e_{n1})^T=(x_{11}-q_{1d},\cdots,x_{n1}-q_{nd})^T,$$
$$(e_{12},\cdots,e_{n2})^T=(x_{12}-\dot q_{1d},\cdots,x_{n2}-\dot q_{nd})^T,$$
$$\underline{u}=(u_1,u_2,\cdots,u_n)^T$$

则系统(1)可以改写为：

$$\begin{cases}\dot{\underline{x}}_1=\underline{x}_2\\ \dot{\underline{x}}_2=M^{-1}(\underline{x}_1)\underline{u}+\underline{\Delta}(\underline{x}_1,\underline{x}_2,t)\end{cases}\tag{2}$$

其中，$\underline{\Delta}(\underline{x}_1,\underline{x}_2,t)=(\Delta_1,\Delta_2,\cdots,\Delta_n)^T=-M^{-1}(\underline{x}_1)(C(\underline{x}_1,\underline{x}_2)\underline{x}_2+G(\underline{x}_1)+F\,\underline{x}_2+\Phi(\underline{x}_1,\underline{x}_2,t))$

$$M^{-1}(\underline{x}_1)=\begin{pmatrix}m_{11}(\underline{x}_1)&\cdots&m_{1n}(\underline{x}_1)\\ \cdots&\cdots&\cdots\\ m_{n1}(\underline{x}_1)&\cdots&m_{nn}(\underline{x}_1)\end{pmatrix}$$

由(2)式，机器人第 $i(i=1,\cdots\cdots,n)$ 个旋转关节的动力学模型可表示为：

$$\begin{cases}\dot x_{i1}=x_{i2}\\ \dot x_{i2}=m_{i1}u_1+\cdots+m_{ii}u_i+\cdots+m_{in}u_n+\Delta_i\end{cases}\tag{3}$$

记 $s_i=(\frac{\mathrm{d}}{\mathrm{d}t}+\lambda_i)^1e_{i1}=\lambda_i+\dot e_{i1}=\lambda_ie_{i1}+e_{i2}$，$\lambda_i>0$ 是设计参数，$S=(s_1,s_2,\cdots,s_n)^T$，则

$$\dot s_i=\lambda_ix_{i2}+m_{i1}u_1+\cdots+m_{ii}u_i+\cdots+m_{in}u_n+\Delta_i-\lambda_iq_{id}-\dot q_{id}\tag{4}$$

$$\dot S=M^{-1}(\underline{x}_1)\begin{pmatrix}u_1\\u_2\\\vdots\\u_n\end{pmatrix}+\begin{pmatrix}\Delta_1+\lambda_1x_{12}-\lambda_1q_{1d}-\dot q_{1d}\\ \Delta_2+\lambda_2x_{22}-\lambda_2q_{2d}-\dot q_{2d}\\ \vdots\\ \Delta_n+\lambda_nx_{n2}-\lambda_nq_{nd}-\dot q_{nd}\end{pmatrix}\tag{5}$$

2 分散控制器的设计及稳定性分析

定理 1：对于满足下文所给假设 1，2 的机器人大系统(1)，选择如下(6)、(7a)、(7b)式的分散控制器和相应的参数自适应律，则闭环系统半全局一致终结有界，跟踪误差收敛到零.

$$u_i=-\frac{s_i}{2}-\mathrm{sgn}(s_i)(\hat{\underline{\theta}}_i^T\,\underline{\xi}_i(x_{i1},x_{i2})+\hat\varepsilon)\tag{6}$$

$$\dot{\hat{\underline{\theta}}}_i=\begin{cases}r_i\,\underline{\xi}_i(x_{i1},x_{i2})|s_i|,\text{当}\ \|\hat{\underline{\theta}}_i\|<M_1\ \text{或}\\ \qquad\|\hat{\underline{\theta}}_i\|=M_1,\text{且}\ r_i\,\hat{\underline{\theta}}\underline{\xi}_i(x_{i1},x_{i2})|s_i|\leqslant0\ \text{时}\\ r_i\,\underline{\xi}_i(x_{i1},x_{i2})|s_i|-r_i\dfrac{\hat{\underline{\theta}}_i\,\hat{\underline{\theta}}_i^T}{\|\hat{\underline{\theta}}_i\|^2}|s_i|,\text{当}\\ \qquad\|\hat{\underline{\theta}}_i\|=M_1,\text{且}\ r_i\,\hat{\underline{\theta}}\underline{\xi}_i(x_{i1},x_{i2})|s_i|>0\ \text{时}\end{cases}\tag{7a}$$

$$\dot{\hat\varepsilon}_i=\begin{cases}\tau_i|s_i|,\text{当}\,|\dot{\hat\varepsilon}_i|<M_2\ \text{或}\,|\dot{\hat\varepsilon}_i|=M_2\ \text{且}\,\dot{\hat\varepsilon}_i\leqslant0\ \text{时}\\ 0,\text{当}\,|\dot{\hat\varepsilon}_i|=M_2\ \text{且}\,\dot{\hat\varepsilon}_i>0\ \text{时}\end{cases}\tag{7b}$$

其中，$r_i,\tau_i>0$ 是参数自适应率，$\hat{\underline{\theta}}_i,\hat\varepsilon_i$ 分别是$\underline{\theta}_i^*,\varepsilon_i$ 的估计值，$M_1,M_2>0$ 是设计参数，且记$\tilde{\underline{\theta}}_i=\underline{\theta}_i^*-\hat{\underline{\theta}}_i,\tilde\varepsilon_i=\varepsilon_i-\hat\varepsilon_i$.

证明：假设闭环系统无界，即对 $\forall\,\varepsilon>0$，成立

$$|s_j|\geqslant2\varepsilon+1>1(j=1\cdots N)\tag{8}$$

取

$$V=\frac12S^TMS+\sum_{i=1}^n\frac{1}{2r_i}\tilde{\underline{\theta}}_i^T\,\tilde{\underline{\theta}}_i+\sum_{i=1}^n\frac{1}{2\tau_i}\tilde\varepsilon_i^2\tag{9}$$

由(4)(5)式可得：

$$\dot V=\frac12\dot S^TMS+\frac12S^TM\dot S-\sum_{i=1}^n\frac{1}{r_i}\tilde{\underline{\theta}}_i^T\,\dot{\hat{\underline{\theta}}}_i-\sum_{i=1}^n\frac{1}{\tau_i}\tilde\varepsilon_i\dot{\hat\varepsilon}_i=$$
$$S^T\,\underline{u}+S^TM\begin{pmatrix}\Delta_1+\lambda_1x_{12}-\lambda_1q_{1d}-\dot q_{1d}\\ \Delta_2+\lambda_2x_{22}-\lambda_2q_{2d}-\dot q_{2d}\\ \vdots\\ \Delta_n+\lambda_nx_{n2}-\lambda_nq_{nd}-\dot q_{nd}\end{pmatrix}-$$
$$\sum_{i=1}^n\frac{1}{r_i}\tilde{\underline{\theta}}_i^T\,\dot{\hat{\underline{\theta}}}_i-\sum_{i=1}^n\frac{1}{\tau_i}\tilde\varepsilon_i\dot{\hat\varepsilon}_i\leqslant S^T\,\underline{u}+\frac12\|S\|^2+$$
$$\frac12\|Y\|^2-\sum_{i=1}^n\frac{1}{r_i}\tilde{\underline{\theta}}_i^T\,\dot{\hat{\underline{\theta}}}_i-\sum_{i=1}^n\frac{1}{\tau_i}\tilde\varepsilon_i\dot{\hat\varepsilon}_i\tag{10}$$

其中，

$$Y=\begin{pmatrix}y_1\\y_2\\\vdots\\y_n\end{pmatrix}=M\begin{pmatrix}\Delta_1+\lambda_1x_{12}-\lambda_1q_{1d}-\dot q_{1d}\\ \Delta_2+\lambda_2x_{22}-\lambda_2q_{2d}-\dot q_{2d}\\ \vdots\\ \Delta_n+\lambda_nx_{n2}-\lambda_nq_{nd}-\dot q_{nd}\end{pmatrix}\ \|Y\|^2=\frac12(y_1^2+y_2^2+\cdots+y_n^2)$$

为设计稳定的控制器，对系统做如下假设：

假设 1： 期望轨迹$\underline{q}_d=(q_{1d},q_{2d},\cdots,q_{nd})^T$ 及$\dot{\underline{q}}_d=(\dot q_{1d},\dot q_{2d},\cdots,\dot q_{nd})^T$ 连续有界

假设 2： $y_i\leqslant\sum_{k=1}^P\sum_{j=1}^n(c_{ijk}(|x_{j1}|^k+|x_{j2}|^k))$，其中，$c_{ijk}$ 是未知非负常数，$j=1,\cdots,n,k=0,1,\cdots,P$.

注 1： 文献[6－9]不仅认为子系统的未知参数是线性的而且假设机器人的互联项为特殊的一阶多项式，假设 2 不仅考虑了未知参数的非线性因素，而且假设机器人的互联项为状态向量的高阶多项式，从而比文献[6－9]更具一般性.

记 $f_{ijk}(x_{j1},x_{j2})=c_{ijk}^2(|x_{j1}|^k+|x_{j2}|^k)^2$，由假设 2，柯西不等式及(8)式可得：

$$\begin{aligned}\|Y\|^2&=\frac{1}{2}\sum_{i=1}^{n}\sum_{k=0}^{P}\sum_{j=1}^{n}(c_{ijk}^2(|x_{j1}|^k+|x_{j2}|^k))^2\leqslant\\&\frac{n(p+1)^2}{2}\sum_{i=1}^{n}\sum_{k=0}^{P}\sum_{j=1}^{n}c_{ijk}^2(|x_{j1}|^k+|x_{j2}|^k)^2<\\&\frac{n(p+1)^2}{2}\sum_{i=1}^{n}\sum_{k=0}^{P}\sum_{j=1}^{n}|s_j|c_{ijk}^2(|x_{j1}|^k+|x_{j2}|^k)^2<\\&\frac{n(p+1)^2}{2}\sum_{i=1}^{n}\sum_{k=0}^{P}\sum_{j=1}^{n}|s_j|f_{ijk}\end{aligned}\tag{11}$$

则,由(6)式及(10-11)式可得:

$$\begin{aligned}\dot V&<S^T\underline{u}+\frac{1}{2}\|S\|^2+\frac{n(p+1)^2}{4}\sum_{i=1}^{n}\sum_{k=0}^{P}\sum_{j=1}^{n}|s_j|f_{ijk}-\\&\sum_{i=1}^{n}\frac{1}{r_i}\underline{\tilde\theta}_i^T\,\underline{\dot{\hat\theta}}_i-\sum_{i=1}^{n}\frac{1}{\tau_i}\tilde\varepsilon_i\dot{\hat\varepsilon}_i<-\frac{1}{2}\|S\|^2-\\&\sum_{i=1}^{n}|s_i|(\underline{\hat\theta}_i^T\,\underline{\xi}_i+\hat\varepsilon_i)+\frac{1}{2}\|S\|^2+\\&\frac{n(p+1)^2}{4}\sum_{i=1}^{n}|s_i|\sum_{k=0}^{P}(f_{1ik}+\cdots+f_{Nik})-\\&\sum_{i=1}^{n}\frac{1}{r_i}\underline{\tilde\theta}_i^T\,\underline{\dot{\hat\theta}}_i-\sum_{i=1}^{n}\frac{1}{\tau_i}\tilde\varepsilon_i\dot{\hat\varepsilon}_i<\sum_{i=1}^{n}|s_i|(\underline{\hat\theta}_i^T\,\underline{\xi}_i+\hat\varepsilon_i)+\\&\sum_{i=1}^{n}|s_i|d_i(x_{i1},x_{i2})-\sum_{i=1}^{n}\frac{1}{r_i}\underline{\tilde\theta}_i^T\,\underline{\dot{\hat\theta}}_i-\sum_{i=1}^{n}\frac{1}{\tau_i}\tilde\varepsilon_i\dot{\hat\varepsilon}_i\end{aligned}\tag{12}$$

其中,$d_i(x_{i1},x_{i2})=\dfrac{n(P+1)^2\sum_{k=0}^{P}(f_{1ik}+\cdots+f_{Nik})}{4}$

因为 $d_i(x_{i1},x_{i2})$ 是光滑函数,由模糊逻辑系统的万能逼近性质,$d_i(x_{i1},x_{i2})$ 可以用一个模糊逻辑系统逼近,采用的模糊逻辑系统 *IF - THEN* 规则为:R_l: if x_{i1} F_1^l and x_{i2} is F_2^l then $y_i=B^l$,其中,$F_i^l(l=1,2,\cdots,M;i=1,2,\cdots,n)$,$B^l$ 是模糊集合. 模糊系统的输出可以表示为:$y_i=\dfrac{\sum_{l=1}^{M}c^l(\prod_{j=1}^{2}\mu^{F_j^l}(X_j))}{\sum_{l=1}^{M}(\prod_{j=1}^{2}\mu^{F_j^l}(X_j))}=\underline{\theta}_i^T\xi_i(X)$,其中,$c^l$ 是使 $\mu_{B^l}(c^l)=1$ 的点,$\mu^{F_j^l}(X_j)$ 是模糊变量的隶属度函数,$X=[X_1,X_2]^T=[x_{i1},x_{i2}]^T$ 是子系统的状态向量,$\xi_i=[\xi_{i1},\xi_{i2},\cdots,\xi_{iM}]^T$ 是模糊基向量,$\underline{\theta}_i^T=[c^1,c^2,\cdots,c^M]$ 是可调参数,$\xi_{il}(X)=\dfrac{\prod_{j=1}^{2}\mu^{F_j^l}(X_j)}{\sum_{l=1}^{M}(\prod_{j=1}^{2}\mu^{F_j^l}(X_j))}$,则:

$$d_i(x_{i1},x_{i2})-\underline{\theta}_i^{*T}\xi_i(x_{i1},x_{i2})\leqslant\varepsilon_i(x_{i1},x_{i2})\tag{13}$$

其中,$\underline{\theta}_i^*$ 是最优逼近参数,$\varepsilon_i(x_{i1},x_{i2})$ 是逼近误差,且满足 $|\varepsilon_i(x_{i1},x_{i2})|\leqslant\varepsilon_i,\varepsilon_i>0$.

把(13)代入(12),并由(7-1,7-2)可得:

$$\begin{aligned}\dot V&<-\sum_{i=1}^{n}|s_i|(\underline{\hat\theta}_i^T\,\underline{\xi}_i+\hat\varepsilon_i)+\sum_{i=1}^{n}|s_i|(\underline{\theta}_i^{*T}\xi_i+\varepsilon_i)-\\&\sum_{i=1}^{n}\frac{1}{r_i}\underline{\tilde\theta}_i^T\,\underline{\dot{\hat\theta}}_i-\sum_{i=1}^{n}\frac{1}{\tau_i}\tilde\varepsilon_i\dot{\hat\varepsilon}_i<\sum_{i=1}^{n}|s_i|(\underline{\theta}_i^{*T}\xi_i-\\&\underline{\hat\theta}_i^T\,\underline{\xi}_i)+\sum_{i=1}^{n}|s_i|\tilde\varepsilon_i-\sum_{i=1}^{n}\frac{1}{r_i}\underline{\tilde\theta}_i^T\,\underline{\dot{\hat\theta}}_i-\sum_{i=1}^{n}\frac{1}{\tau_i}\tilde\varepsilon_i\dot{\hat\varepsilon}_i<\\&\sum_{i=1}^{n}|s_i|\underline{\tilde\theta}_i^T\xi_i+\sum_{i=1}^{n}|s_i|\tilde\varepsilon_i-\sum_{i=1}^{n}\frac{1}{r_i}\underline{\tilde\theta}_i^T\,\underline{\dot{\hat\theta}}_i-\\&\sum_{i=1}^{n}\frac{1}{\tau_i}\tilde\varepsilon_i\dot{\hat\varepsilon}_i<0\end{aligned}\tag{14}$$

所以闭环系统半全局一致终结有界.

3　仿真

二自由度旋转机器人的动力学模型如式(1)所示,其中,

$C_{11}=-m_2l_1l_2\sin(q_2)\dot q_1,C_{21}=0$,

$C_{12}=-2m_2l_1l_2\sin(q_2)\dot q_1,C_{22}=m_2l_1l_2\sin(q_2)\dot q_2$,

$M_{11}=(m_1+m_2)l_1^2+m_2l_2^2+2m_2l_1l_2\cos(q_2)+J_1$,

$M_{12}(M_{21})=m_2l_2^2+m_2l_1l_2\cos(q_2)$,

$M_{22}=J_2+m_2l_2^2$,

$\phi_1=\dot q_1\sin t,\phi_2=\dot q_2\cos t$,

$G_1=g((m_1+m_2)l_1\cos(q_2)+m_2l_2\cos(q_1+q_2))$

$G_2=gm_2l_2\cos(q_1+q_2),F=\mathrm{diag}(2,2)$

则式(1)可转化为:

$$\begin{cases}\dot x_{12}=\dfrac{1}{M_{11}M_{22}-M_{12}M_{21}}[M_{22}u_1-M_{12}u_2-(C_{11}M_{22}-\\\quad C_{21}M_{12}+F_{11}M_{22}-F_{21}M_{12})x_{12}-(C_{12}M_{22}-\\\quad C_{22}M_{12}+F_{12}M_{22}-F_{22}M_{12})x_{22}-G_1M_{22}+\\\quad G_2M_{12}-M_{22}\phi_1+M_{12}\phi_2]\\\dot x_{22}=\dfrac{1}{M_{11}M_{22}-M_{12}M_{21}}[M_{11}u_2-M_{21}u_1-(M_{11}C_{21}-\\\quad M_{21}C_{11}+M_{11}F_{21}-M_{21}F_{11})x_{12}-(M_{11}C_{22}-\\\quad M_{21}C_{12}+M_{11}F_{22}-M_{21}F_{12})x_{22}-M_{11}G_2+\\\quad M_{21}G_1-M_{11}\phi_2+M_{21}\phi_1]\end{cases}\tag{15}$$

系统参数选择:

$m_1=0.5\text{kg},m_2=1.5\text{kg},l_1=1\text{m},l_2=0.8\text{m},J_1=J_2=5\text{kg}\cdot\text{m},r_1=r_2=0.9,\tau_1=\tau_2=0.9,\lambda_1=\lambda_2=10,M_1=M_2=0.01$.

系统初始状态:

$(q_1,q_2)^T=(\dot q_1,\dot q_2)^T=(0.5,0.5)^T$,

期望轨迹为:

$q_{d1} = q_{d2} = 0.1\sin t$,

控制律为:

$$u_1 = -\frac{s_1}{2} - \text{sgn}(s_1)(\underline{\hat{\theta}}_i^T \underline{\xi}_1(x_{11}, x_{12}) + \hat{\varepsilon}_1),$$

$$u_2 = -\frac{s_2}{2} - \text{sgn}(s_2)(\underline{\hat{\theta}}_i^T \underline{\xi}_2(x_{21}, x_{22}) + \hat{\varepsilon}_2)$$

仿真结果如下图 1,2:

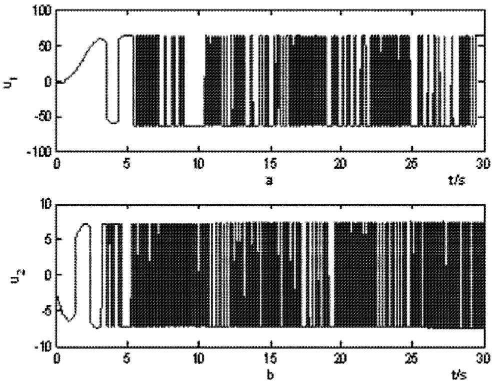
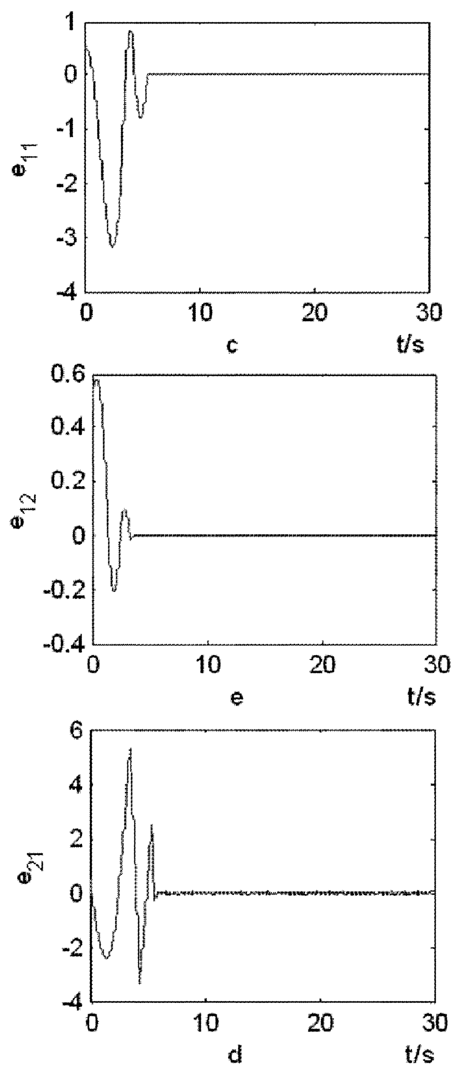


图 1 子关节的控制律 u_1, u_2

Fig. 1 every joint' s controller u_1, u_2



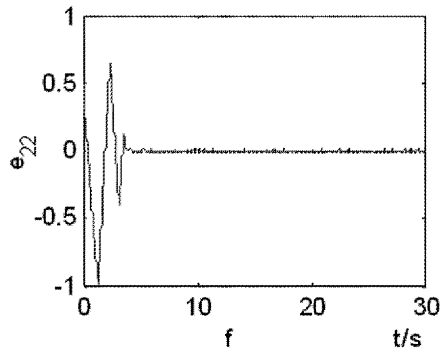


图 2 跟踪误差 $e_{11}, e_{12}, e_{21}, e_{22}$

Fig. 2 tracking errors $e_{11}, e_{12}, e_{21}, e_{22}$

4 结论

本文基于模糊理论和滑模控制原理,针对一类高阶关联机器人系统,给出了一种全新的分散控制方法. 该方法在取消一些限定性前提假设的基础上实现机器人的分散控制,使得关节之间相互耦合的机器人各关节的控制器仅由本关节的信息完全确定. Lyapunov 稳定理论分析证明了闭环半全局系统一致终结有界,跟踪误差收敛到零. 二自由度机器人的仿真证明了该方法的有效性.

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ADAPTIVE FUZZY SLIDING MODE DECENTRALIZED CONTROL OF HIGHER-ORDER COUPLING ROBOT SYSTEMS *

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Abstract For a robot system with model uncertainties and unknown nonlinear perturbations, an adaptive fuzzy sliding mode decentralized control method was put forward by considering the upper bound of the uncertainties and unknown disturbances to be ordinary high order polynomials about the system states, and combined with the approximation ability of fuzzy systems. This method can not only make every joint's controller of robot systems with mutual coupling between the joints completely determined only by the information of itself, but also eliminate the related assumptions which the extant literatures in the design of robot decentralized controller requires modeling uncertainties and the upper bound of the unknown disturbances to be a constant or first-order polynomial about system states. Lyapunov stability theory analysis shows the closed-loop system is semi-globally uniformly ultimately bounded with tracking error converges to zero. Simulation results of two degrees robot systems prove the effectiveness of this method.

Key words higher-order coupling robot, adaptive control, decentralized control

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