控制与决策
Control and Decision

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引用本文:
陈子聪, 王林, 刘建圻, 等. 带输入饱和的不确定非线性系统自适应模糊触发式补偿控制[J]. 控制与决策, 2021, 36(12): 3007-3014.

在线阅读 View online: https://doi.org/10.13195/j.kzyjc.2020.0907

带输入饱和的不确定非线性系统自适应模糊触发式补偿控制

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摘 要: 针对一类带有输入饱和特性的不确定非线性系统,为了在保证系统跟踪性能的同时最大限度节省系统通讯资源,结合 Backstepping 技术,提出一种自适应模糊触发式补偿控制方法. 由于安全需求或者物理限制等因素,输入饱和特性往往不可避免地存在于实际物理系统中,给系统的控制性能和稳定性造成不利影响. 为有效解决该问题,将光滑的双曲正切函数融入自适应控制设计过程,以实现对系统输入饱和约束的补偿. 此外,由于实际系统模型难以精确建立,系统描述中难免会存在未知不确定部分,对此,利用模糊逻辑系统对系统的未知不确定部分进行逼近处理. 为节省系统的通讯资源,引入一种基于相对阈值的事件触发控制策略,以减小系统传输压力. 通过 Lyapunov 稳定性理论分析,系统的所有信号都是半全局一致最终有界的. 仿真结果验证了所提出方法的有效性.

关键词: 输入饱和；自适应控制；Backstepping 技术；触发式控制；模糊逻辑系统；双曲正切函数

中图分类号: TP273 **文献标志码:** A

DOI: 10.13195/j.kzyjc.2020.0907 **开放科学(资源服务)标识码(OSID):**

引用格式: 陈子聪,王林,刘建圻,等. 带输入饱和的不确定非线性系统自适应模糊触发式补偿控制[J]. 控制与决策, 2021, 36(12): 3007-3014.

Adaptive fuzzy trigger compensation control for uncertain nonlinear system with input saturation

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Abstract: In order to guarantee system tracking performance as well as economize system communication resources effectively, an adaptive fuzzy trigger compensation control method is investigated for the uncertain nonlinear systems with input saturation based on the Backstepping technology. Due to factors such as security requirements or physical limitations, the phenomenon of input saturation often unavoidably exists in the practical physical system, which adversely affects the control performance and stability of the system. Aiming to effectively solve this problem, a smooth hyperbolic tangent function is integrated into the adaptive control design process to realize the compensation of the system input saturation constraint. In addition, the practical system model is often difficult to establish accurately and unknown uncertain parts will inevitably exist in the system description. Therefore, fuzzy logic systems (FLS) are applied to approach the unknown and uncertain parts of the system. Aiming to economize the communication resources, an event-triggered control strategy based on relative threshold is introduced to reduce the transmission pressure of the considered system. Through the theoretical analysis of Lyapunov stability, all signals of the system are semi-globally consistent and ultimately bounded. Simulation results verify the effectiveness of the proposed method.

Keywords: input saturation；adptive control；Backstepping technology；trigger control；fuzzy logic systems；hyperbolic tangent function

0 引 言

在实际应用中,由于安全需求或者物理限制等因素,大部分物理系统都会存在输入饱和现象. 输入饱和特性会给系统带来不利影响,降低系统的性能指标,甚至影响系统的稳定性. 因此,如何更好地处理系统的输入饱和约束问题,对于提升系统控制性能具有重要的意义[1-5]. 文献[6]研究了具有时变输出约束和输入非对称饱和的非线性系统跟踪控制问题. 文

收稿日期: 2020-07-06；**修回日期:** 2020-09-22.

基金项目: 中山市重大科技专项项目(191021082628279)；广东省自然科学基金项目(2016A030312013)；广东省基础与应用基础研究基金项目(2019A1515110995)；广州市科技计划项目(202002030286).

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献[7]通过引入一类辅助系统,同时结合Lyapunov-Krasovskii函数,消除时变延迟和输入饱和对系统产生的不利影响. 针对受输入饱和、全状态约束、运动学耦合、参数不确定性等因素作用下的航天器系统,文献[8]提出了一种6自由度相对运动控制方法. 上述方法可以有效地处理系统输入饱和约束. 然而,这将在控制设计中引入切换函数. 此外,除输入饱和特性,系统往往也会存在未知不确定部分,这些问题给系统控制设计带来了一定的困难.

由于实际系统模型难以精确获取,在控制系统描述中难免会出现未知不确定部分. 如何恰当地对系统的未知不确定部分进行处理,对于系统控制精度影响较大. 神经网络(neural network, NN)[9-12]和模糊逻辑系统(fuzzy logic systems, FLSs)[13-17]常用于逼近系统的未知不确定部分,并取得了较好的效果. 文献[12]利用径向基函数神经网络对系统的未知光滑非线性函数进行逼近,提出了一种基于模型的神经网络控制方法. 文献[16]针对带有状态约束和时变滞后的非线性不确定系统,提出了一种基于FLSs的自适应模糊跟踪控制. 上述方法均可以较好地解决系统未知不确定部分,但没有考虑系统的通讯资源问题. 当同时考虑系统的未知不确定部分和通讯资源问题时,如何平衡系统的跟踪性能与通讯资源约束,这是一个极具挑战性的课题.

当系统控制输入需要快速切换以保证系统性能时,系统传输压力陡增,但是,系统的通讯资源往往是有限的. 周期控制根据系统实际情况设定相应的周期,每个周期内触发一次,更新系统的控制输入,可以在保证系统性能的同时节省系统通讯资源[18-22]. 基于周期控制策略,文献[18]研究了一类组合自适应控制系统的构造问题. 事件触发机制主要是根据控制信号的测量误差来判断是否需要触发,进而更新控制输入信号[23-26]. 相较于周期控制策略,事件触发控制策略更加灵活,节省通讯资源效果更好. 文献[24]研究了带有输入死区的不确定随机非线性系统的事件触发模糊自适应控制问题. 针对一类不确定非线性多智能体系统,文献[25]结合事件触发控制策略,提出了一种自适应分布式事件触发控制方法,有效节省了系统的传输资源.

基于上述分析,本文针对一类带有输入饱和现象的不确定非线性系统的跟踪控制问题,设计一种自适应模糊触发式补偿控制方法. 相较于现有结果,本文采用双曲正切函数对系统的输入饱和特性进行拟合,同时应用FLSs对系统的未知不确定部分进行处理. 在此基础上,引入基于相对阈值的事件触发控制策略. 本文所提出的方法可以很好地保证系统的跟踪性能,同时最大限度节省系统通讯资源,减小系统传输压力.

1 问题描述

1.1 系统模型

考虑如下带输入饱和特性的不确定非线性系统:

$$\begin{cases}\dot{x}_i = x_{i+1} + f_i(\bar{x}_i),\ i = 1,2,\ldots,n-1;\\ \dot{x}_n = u(v) + f_n(\bar{x}_n);\\ y = x_1.\end{cases} \tag{1}$$

其中: $x = [x_1, x_2, \ldots, x_n]^{\mathrm{T}} \in R^n$ 和 $\bar{x}_i = [x_1, x_2, \ldots, x_i]^{\mathrm{T}} \in R^i$ 是系统状态, $y \in R$ 是系统的输出, $f_i\ (i = 1, 2, \ldots, n)$ 是系统未知光滑的非线性函数, $v(t)$ 是实际的控制输入, $u(v)$ 是具有饱和特性的控制输入.

$u(v)$ 可描述为如下形式:

$$u(v) = \mathrm{sat}(v) = \mathrm{sgn}(v)\min(|v|, u_{\max}). \tag{2}$$

其中: $u_{\max} > 0$ 是系统输入饱和特性的阈值, $|u(v)| \leqslant u_{\max}$.

为更好地对系统的饱和特性进行拟合,将光滑的双曲正切函数引入到控制设计中,即

$$p(v) = u_{\max}\tanh\Big(\frac{v}{u_{\max}}\Big) = u_{\max}\frac{\mathrm{e}^{v/u_{\max}} - \mathrm{e}^{v/u_{\max}}}{\mathrm{e}^{v/u_{\max}} + \mathrm{e}^{v/u_{\max}}}. \tag{3}$$

定义 $q(v) = \mathrm{sat}(v) - p(v)$, 则 $q(v)$ 是一个以 E 为界的有界函数, 有

$$|q(v)| = |\mathrm{sat}(v) - p(v)| \leqslant u_{\max}(1 - \tanh(1)) = E. \tag{4}$$

为便于本文的进一步分析设计,给出如下引理.

引理1 [27] 对于 $\varGamma \in R, \sigma > 0$, 如下不等式成立:

$$0 \leqslant \varGamma - \varGamma\tanh(\varGamma/\sigma) \leqslant 0.278\,5\sigma, \tag{5}$$

其中 $-\varGamma\tanh(\varGamma/\sigma) \leqslant 0$.

引理2 [28] 对于 $\forall\upsilon$, 如下不等式成立:

$$\hat{\upsilon}^{\mathrm{T}}\tilde{\upsilon} \leqslant -\frac{1}{2}\tilde{\upsilon}^{\mathrm{T}}\tilde{\upsilon} + \frac{1}{2}\upsilon^{\mathrm{T}}\upsilon. \tag{6}$$

其中: $\tilde{\upsilon}$ 和 $\hat{\upsilon}$ 分别是 υ 的估计和估计误差, $\tilde{\upsilon} = \upsilon - \hat{\upsilon}$.

1.2 模糊逻辑系统研究

本文拟采用模糊逻辑系统对系统的未知不确定性部分 $f_i(\bar{x}_i)$ 进行逼近. 传统的FLSs函数大多采用如下形式:

$$F_i(\bar{x}_i) = \sum_{j=1}^{N_i}\varphi^{\mathrm{T}}\delta_{i,j}(\bar{x}_i). \tag{7}$$

其中: $\delta_{i,j}(\bar{x}_i)$ 为已知的模糊基函数, $\varphi = (\varphi_1, \varphi_2, \ldots, \varphi_N)^{\mathrm{T}}$ 为未知的权重向量.

模糊基函数$\delta_{i,j}(\bar{x}_i)$的定义如下:

$$\delta_{i,j}(\bar{x}_i)=\frac{\prod\limits_{p=1}^{i}\mu_{F_p^{i,j}}(x_p)}{\sum\limits_{j=1}^{N_i}\prod\limits_{p=1}^{i}\mu_{F_p^{i,j}}(x_p)}. \tag{8}$$

其中

$$\mu_{F_p^{i,j}}(x_p)=\psi_p^{i,j}\exp\Big[-\frac{1}{2}\Big(\frac{x_p-\bar{x}_p^{i,j}}{\varpi_p^{i,j}}\Big)^2\Big],$$

$\psi_p^{i,j}$、$\bar{x}_p^{i,j}$和$\varpi_p^{i,j}$均为实值参数.

根据文献[29]可得

$$\sup_{\bar{x}_i\in R^i}|f_i(\bar{x}_i)-\varphi^{\mathrm{T}}\delta_i(\bar{x}_i)|\leqslant\varepsilon_i,\ \forall\varepsilon_i>0, \tag{9}$$

其中$\delta_i(\bar{x}_i)=[\delta_{i,1}(\bar{x}_i),\dots,\delta_{i,N_i}(\bar{x}_i)]^{\mathrm{T}}\in R^{N_i}$. 因此, 式(9)可以转化为

$$f_i(\bar{x}_i)=\varphi^{\mathrm{T}}\delta_i(\bar{x}_i)+d_i(\bar{x}_i), \tag{10}$$

其中$d_i(\bar{x}_i)$为逼近系统的逼近误差,且满足$|d_i(\bar{x}_i)|<\varepsilon_i$.

2 自适应模糊控制设计和分析

2.1 自适应模糊触发式控制设计

首先,为方便后续设计,定义如下的误差系统:

$$\begin{cases}z_1=x_1-r,\\ z_i=x_i-\alpha_{i-1}-r^{(i-1)},\ i=2,3,\dots,n.\end{cases} \tag{11}$$

其中: z_i 是误差变量, $r(t)$是参考信号, α_{i-1}为后续将给出的虚拟控制信号.

详细的设计过程如下.

step 1: 由式(1)和(11)可得

$$\dot{z}_1=z_2+\alpha_1+f_1. \tag{12}$$

定义Lyapunov函数V_1为

$$V_1=\frac{1}{2}z_1^2+\frac{1}{2\lambda_1}\tilde{\varepsilon}_1^{\mathrm{T}}\tilde{\varepsilon}_1, \tag{13}$$

其中λ_1为设计参数.

根据上文对FLSs的研究,给出如下定义:

$$f_1=\varphi^{\mathrm{T}}\delta_1+d_1. \tag{14}$$

对V_1求导可得

$$\dot{V}_1=z_1(z_2+\alpha_1+\varphi^{\mathrm{T}}\delta_1+d_1)-\frac{1}{\lambda_1}\tilde{\varepsilon}_1^{\mathrm{T}}\dot{\hat{\varepsilon}}_1. \tag{15}$$

虚拟控制器α_1和调节函数χ_1定义为

$$\begin{cases}\alpha_1=-c_1z_1-\hat{\varphi}^{\mathrm{T}}\delta_1-\mathrm{sg}_1(z_1)\hat{\varepsilon}_1,\\ \chi_1=z_1\delta_1,\end{cases} \tag{16}$$

其中$c>0$为设计参数.

式(15)可进一步改写为

$$\dot{V}_1=z_1(z_2-c_1z_1-\mathrm{sg}_1(z_1)\hat{\varepsilon}_1+\tilde{\varphi}^{\mathrm{T}}\delta_1+d_1)-\frac{1}{\lambda_1}\tilde{\varepsilon}_1^{\mathrm{T}}\dot{\hat{\varepsilon}}_1. \tag{17}$$

为了方便后续设计,根据文献[30],引入如下一类光滑函数:

$$\mathrm{sg}_i(z_i)=\begin{cases}\dfrac{z_i}{|z_i|},\ |z_i|\geqslant\mu_i;\\ \dfrac{z_i}{(\mu_i^2-z_i^2)^{n-i+2}+|z_i|},\ |z_i|<\mu_i.\end{cases} \tag{18}$$

其中: $\mu_i>0$为设计参数, $i=1,2,\dots,n$.

应用式(18)可得

$$z_1d_1\leqslant z_1\mathrm{sg}_1(z_1)|d_1|\leqslant z_1\mathrm{sg}_1(z_1)\varepsilon_1. \tag{19}$$

设计自适应律$\dot{\hat{\varepsilon}}_1$为

$$\dot{\hat{\varepsilon}}_1=-\lambda_1\rho\hat{\varepsilon}_1+\lambda_1z_1\mathrm{sg}_1(z_1), \tag{20}$$

于是$\dot{V}_1$可以转换成如下形式:

$$\begin{aligned}&\dot{V}_1\leqslant\\&-c_1z_1^2+z_1z_2+\tilde{\varphi}^{\mathrm{T}}\chi_1-z_1\mathrm{sg}_1(z_1)\hat{\varepsilon}_1+\\&z_1d_1-\frac{1}{\lambda_1}\tilde{\varepsilon}_1^{\mathrm{T}}\dot{\hat{\varepsilon}}_1\leqslant\\&-c_1z_1^2+z_1z_2+\tilde{\varphi}^{\mathrm{T}}\chi_1+z_1\mathrm{sg}_1(z_1)\tilde{\varepsilon}_1-\frac{1}{\lambda_1}\tilde{\varepsilon}_1^{\mathrm{T}}\dot{\hat{\varepsilon}}_1\leqslant\\&-c_1z_1^2+z_1z_2+\tilde{\varphi}^{\mathrm{T}}\chi_1+\rho\tilde{\varepsilon}_1^{\mathrm{T}}\hat{\varepsilon}_1.\end{aligned} \tag{21}$$

step 2: 定义Lyapunov函数V_2为

$$V_2=V_1+\frac{1}{2}z_2^2+\frac{1}{2\lambda_2}\tilde{\varepsilon}_2^{\mathrm{T}}\tilde{\varepsilon}_2. \tag{22}$$

对V_2求导可得

$$\begin{aligned}\dot{V}_2=&\dot{V}_1+z_2\dot{z}_2-\frac{1}{\lambda_2}\tilde{\varepsilon}_2^{\mathrm{T}}\dot{\hat{\varepsilon}}_2\leqslant\\&\dot{V}_1+z_2(\dot{x}_2-\dot{\alpha}_1-\ddot{r})-\frac{1}{\lambda_2}\tilde{\varepsilon}_2^{\mathrm{T}}\dot{\hat{\varepsilon}}_2\leqslant\\&\dot{V}_1+z_2(z_3+\alpha_2+f_2-\dot{\alpha}_1)-\frac{1}{\lambda_2}\tilde{\varepsilon}_2^{\mathrm{T}}\dot{\hat{\varepsilon}}_2.\end{aligned} \tag{23}$$

虚拟控制器α_2和调节函数χ_2定义为

$$\begin{cases}\alpha_2=-z_1-c_2z_2+\dfrac{\partial\alpha_1}{\partial x_1}x_2+\dfrac{\partial\alpha_1}{\partial r}\dot{r}-\\ \qquad \mathrm{sg}_2(z_2)\hat{\varepsilon}_2-\hat{\varphi}^{\mathrm{T}}\Big(\delta_2-\frac{\partial\alpha_1}{\partial x_1}\delta_1\Big)+\\ \qquad \dfrac{\partial\alpha_1}{\partial\hat{\varphi}}\lambda(\chi_2-\rho\hat{\varphi}),\\ \chi_2=\chi_1+z_2\Big(\delta_2-\dfrac{\partial\alpha_1}{\partial x_1}\delta_1\Big).\end{cases} \tag{24}$$

根据上文对FLSs的研究,给出如下定义:

$$f_2-\frac{\partial\alpha_1}{\partial x_1}d_1+\frac{\partial\alpha_1}{\partial\hat{\varepsilon}_1}\dot{\hat{\varepsilon}}_1=\varphi^{\mathrm{T}}\delta_2+d_2. \tag{25}$$

通过式(16)可得

$$\dot{\alpha}_1=\frac{\partial\alpha_1}{\partial x_1}\dot{x}_1+\frac{\partial\alpha_1}{\partial r}\dot{r}+\frac{\partial\alpha_1}{\partial\hat{\varphi}}\dot{\hat{\varphi}}+\frac{\partial\alpha_1}{\partial\hat{\varepsilon}_1}\dot{\hat{\varepsilon}}_1. \tag{26}$$

与式(19)类似,可得

$$z_2d_2\leqslant z_2\mathrm{sg}_2(z_2)\varepsilon_2. \tag{27}$$

设计自适应律$\dot{\hat{\varepsilon}}_2$为如下形式:

$$\dot{\hat{\varepsilon}}_2=-\lambda_2\rho\hat{\varepsilon}_2+\lambda_2 z_2\mathrm{sg}_2(z_2). \tag{28}$$

将式(24)～(28)代入(23),可得

$$\begin{aligned}&\dot{V}_2\leqslant\dot{V}_1+z_2(z_3+\alpha_2+f_2-\dot{\alpha}_1)-\frac{1}{\lambda_2}\tilde{\varepsilon}_2^{\mathrm{T}}\dot{\hat{\varepsilon}}_2\leqslant\\&-c_1z_1^2-c_2z_2^2+z_2z_3+\tilde{\varphi}^{\mathrm{T}}\chi_1+\rho\tilde{\varepsilon}_1^{\mathrm{T}}\hat{\varepsilon}_1+\\&z_2\Big(-\tilde{\varphi}^{\mathrm{T}}\frac{\partial\alpha_1}{\partial x_1}\delta_1+\frac{\partial\alpha_1}{\partial\hat{\varphi}}(\lambda\chi_2-\lambda\rho\hat{\varphi}-\dot{\hat{\varphi}})\Big)+\\&z_2\mathrm{sg}_2(z_2)\tilde{\varepsilon}_2-\frac{1}{\lambda_2}\tilde{\varepsilon}_2^{\mathrm{T}}\dot{\hat{\varepsilon}}_2\leqslant\\&-c_1z_1^2-c_2z_2^2+z_2z_3+\rho\tilde{\varepsilon}_1^{\mathrm{T}}\hat{\varepsilon}_1+\rho\tilde{\varepsilon}_2^{\mathrm{T}}\hat{\varepsilon}_2+\\&\tilde{\varphi}^{\mathrm{T}}\Big(\chi_1+z_2\Big(\delta_2-\frac{\partial\alpha_1}{\partial x_1}\delta_1\Big)\Big)+\\&z_2\frac{\partial\alpha_1}{\partial\hat{\varphi}}(\lambda\chi_2-\lambda\rho\hat{\varphi}-\dot{\hat{\varphi}})\leqslant\\&-c_1z_1^2-c_2z_2^2+z_2z_3+\tilde{\varphi}^{\mathrm{T}}\chi_2+\rho\tilde{\varepsilon}_1^{\mathrm{T}}\hat{\varepsilon}_1+\\&\rho\tilde{\varepsilon}_2^{\mathrm{T}}\hat{\varepsilon}_2+z_2\frac{\partial\alpha_1}{\partial\hat{\varphi}}(\lambda\chi_2-\lambda\rho\hat{\varphi}-\dot{\hat{\varphi}}).\end{aligned} \tag{29}$$

step i $(i=3,4,\ldots,n-1)$: 定义Lyapunov函数V_i为

$$V_i=V_{i-1}+\frac{1}{2}z_i^2+\frac{1}{2\lambda_i}\tilde{\varepsilon}_i^{\mathrm{T}}\tilde{\varepsilon}_i,\ i=3,4,\ldots,n-1. \tag{30}$$

对V_i求导可得

$$\dot{V}_i\leqslant\dot{V}_{i-1}+z_i(z_{i+1}+\alpha_i+f_i-\dot{\alpha}_{i-1}). \tag{31}$$

类似于式(26),可得

$$\begin{aligned}\dot{\alpha}_{i-1}=&\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_j}\dot{x}_j+\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial r^{(j-1)}}r^{(j)}+\\&\frac{\partial\alpha_{i-1}}{\partial\hat{\varphi}}\dot{\hat{\varphi}}+\frac{\partial\alpha_{i-1}}{\partial\hat{\varepsilon}_{i-1}}\dot{\hat{\varepsilon}}_{i-1}.\end{aligned} \tag{32}$$

根据上文对FLSs的研究,给出如下定义:

$$f_i-\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_j}d_j+\frac{\partial\alpha_{i-1}}{\partial\hat{\varepsilon}_{i-1}}\dot{\hat{\varepsilon}}_{i-1}=\varphi^{\mathrm{T}}\delta_i+d_i. \tag{33}$$

虚拟控制器α_i和调节函数χ_i定义为

$$\begin{cases}\alpha_i=-z_{i-1}-c_iz_i+\displaystyle\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_j}x_{j+1}-\hat{\varphi}^{\mathrm{T}}\delta_i+\\\quad\displaystyle\frac{\partial\alpha_{i-1}}{\partial\hat{\varphi}}\lambda(\chi_i-\rho\hat{\varphi})+\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial r^{(j-1)}}r^{(j)}+\\\quad\displaystyle\Big(\sum_{j=2}^{i-1}z_j\frac{\partial\alpha_1}{\partial\hat{\varphi}}\Big)\lambda\Big(\delta_i-\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_j}\delta_j\Big)+\\\quad\displaystyle\hat{\varphi}^{\mathrm{T}}\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_j}\delta_j+\mathrm{sg}_i(z_i)\hat{\varepsilon}_i,\\\chi_i=\chi_{i-1}+z_i\Big(\delta_i-\displaystyle\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_j}\delta_j\Big).\end{cases} \tag{34}$$

与式(27)类似,可得

$$z_id_i\leqslant z_i\mathrm{sg}_i(z_i)\varepsilon_i. \tag{35}$$

设计自适应律$\dot{\hat{\varepsilon}}_i$为

$$\dot{\hat{\varepsilon}}_i=-\lambda_i\rho\hat{\varepsilon}_i+\lambda_iz_i\mathrm{sg}_i(z_i). \tag{36}$$

式(31)可以转化为

$$\begin{aligned}\dot{V}_i\leqslant&-\sum_{j=1}^{i}c_jz_j^2-\sum_{j=1}^{i}\rho\tilde{\varepsilon}_j^{\mathrm{T}}\hat{\varepsilon}_j+z_iz_{i+1}+\tilde{\varphi}^{\mathrm{T}}\chi_i+\\&\sum_{j=2}^{i}z_j\frac{\partial\alpha_{i-1}}{\partial\hat{\varphi}}(\lambda\chi_i-\lambda\rho\hat{\varphi}-\dot{\hat{\varphi}}).\end{aligned} \tag{37}$$

step n: 给出如下事件触发机制:

$$\begin{cases}\omega(t)=-(1+\tau)[\alpha_n\tanh(z_n\alpha_n/\beta)+\\\qquad\bar{m}\tanh(z_n\bar{m}/\beta)];\\p(t)=\omega(t_k),\ \forall t\in[t_k,t_{k+1});\\t_{k+1}=\inf\{t\in R||e(t)|\geqslant n|p(t)|+m\}.\end{cases} \tag{38}$$

其中: τ、β、m 为正的设计参数, $\bar{m}>m/\tau$, $e(t)=\omega(t)-p(v)$.

定义Lyapunov函数V_n为

$$V_n=V_{n-1}+\frac{1}{2}z_n^2+\frac{1}{2\lambda_n}\tilde{\varepsilon}_n^{\mathrm{T}}\tilde{\varepsilon}_n+\frac{1}{2\lambda}\tilde{\varphi}_n^{\mathrm{T}}\tilde{\varphi}_n. \tag{39}$$

对V_n求导,可得

$$\begin{aligned}&\dot{V}_n=\\&\dot{V}_{n-1}+z_n\dot{z}_n-\frac{1}{\lambda_n}\tilde{\varepsilon}_n^{\mathrm{T}}\dot{\hat{\varepsilon}}_n-\frac{1}{\lambda}\tilde{\varphi}^{\mathrm{T}}\dot{\hat{\varphi}}\leqslant\\&-\sum_{i=1}^{n-1}c_iz_i^2-\sum_{j=1}^{n-1}\rho\tilde{\varepsilon}_j^{\mathrm{T}}\hat{\varepsilon}_j+z_{n-1}z_n+\tilde{\varphi}^{\mathrm{T}}\chi_{n-1}+\\&\sum_{j=2}^{i}z_j\frac{\partial\alpha_{i-1}}{\partial\hat{\varphi}}(\lambda\chi_i-\lambda\rho\hat{\varphi}-\dot{\hat{\varphi}})-\frac{1}{\lambda}\tilde{\varphi}^{\mathrm{T}}\dot{\hat{\varphi}}+\\&z_n(p(v)+q(v)+f_n-\dot{\alpha}_{n-1}-r^{(n)})-\frac{1}{\lambda_n}\tilde{\varepsilon}_n^{\mathrm{T}}\dot{\hat{\varepsilon}}_n.\end{aligned} \tag{40}$$

自适应律$\dot{\hat{\varphi}}$的设计如下:

$$\dot{\hat{\varphi}}=\lambda\chi_n-\lambda\rho\hat{\varphi}. \tag{41}$$

由式(38)可得

$$\omega(t)=(1+\mu_1(t)\tau)p(v)+\mu_2(t)m. \tag{42}$$

其中: $t\in[t_k,t_{k+1})$; $\mu_1(t)$和$\mu_2(t)$为时变参数,且满足$|\mu_1(t)|<1,|\mu_2(t)|<1$. 进而可得

$$z_n\omega(t)\leqslant 0,\ \frac{z_n\omega(t)}{1+\mu_1(t)\tau}\leqslant\frac{z_nw(t)}{1+\tau},\ \frac{\mu_2(t)m}{1+\mu_1(t)\tau}\leqslant\frac{m}{1+\tau}.$$

结合引理1,可进一步得到

$$\begin{aligned}z_np(v)\leqslant&\frac{z_nw(t)}{1+\tau}+\Big|\frac{z_nm}{1+\tau}\Big|\leqslant\\&-z_n\alpha_n\tanh\Big(\frac{z_n\alpha_n}{\beta}\Big)-\end{aligned}$$

$$
\begin{aligned}
&z_n\bar{m}\tanh\left(\frac{z_n\bar{m}}{\beta}\right)+\left|\frac{z_n m}{1+\tau}\right|\leqslant\\
&z_n\alpha_n+0.557\beta.
\end{aligned}
\tag{43}
$$

虚拟控制器α_n和调节函数χ_n设计为

$$
\begin{cases}
\alpha_n=\\
-z_{n-1}-\left(c_n+\dfrac{1}{2}\right)z_n+\displaystyle\sum_{j=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial x_j}x_{j+1}-\hat{\varphi}^{\mathrm{T}}\delta_n+\\
\hat{\varphi}^{\mathrm{T}}\displaystyle\sum_{j=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial x_j}\delta_j+\frac{\partial\alpha_{n-1}}{\partial\hat{\varphi}}\lambda(\chi_n-\rho\hat{\varphi})+\\
\displaystyle\sum_{j=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial r^{(j-1)}}r^{(j)}-\mathrm{sg}_n(z_n)\hat{\varepsilon}_n+r^{(n)}+\\
\left(\displaystyle\sum_{j=2}^{n-1}z_j\frac{\partial\alpha_1}{\partial\hat{\varphi}}\right)\lambda\left(\delta_n-\displaystyle\sum_{j=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial x_j}\delta_j\right),\\
\chi_n=\chi_{n-1}+z_n\left(\delta_n-\displaystyle\sum_{j=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial x_j}\delta_j\right).
\end{cases}
\tag{44}
$$

根据上文对FLSs的研究,给出如下定义:

$$
f_n-\sum_{j=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial x_j}d_j+\frac{\partial\alpha_{n-1}}{\partial\hat{\varepsilon}_{n-1}}\dot{\hat{\varepsilon}}_{n-1}=\varphi^{\mathrm{T}}\delta_n+d_n.
\tag{45}
$$

对α_{n-1}求导,可得

$$
\begin{aligned}
\dot{\alpha}_{n-1}=&\sum_{i=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial x_i}\dot{x}_j+\sum_{i=1}^{n-1}\frac{\partial\alpha_{n-1}}{\partial r^{(i-1)}}r^{(i)}+\\
&\frac{\partial\alpha_{n-1}}{\partial\hat{\varphi}}\dot{\hat{\varphi}}+\frac{\partial\alpha_{n-1}}{\partial\hat{\varphi}}\dot{\hat{\varphi}}+\frac{\partial\alpha_{n-1}}{\partial\hat{\varepsilon}_{n-1}}\dot{\hat{\varepsilon}}_{n-1}.
\end{aligned}
\tag{46}
$$

与式(35)类似,可得

$$
z_n d_n\leqslant z_n\mathrm{sg}_n(z_n)\varepsilon_n.
\tag{47}
$$

设计自适应律$\dot{\hat{\varepsilon}}_n$为

$$
\dot{\hat{\varepsilon}}_n=-\lambda_n\rho\hat{\varepsilon}_n+\lambda_n z_n\mathrm{sg}_n(z_n).
\tag{48}
$$

将式(41)$\sim$(48)代入(40),可得

$$
\dot{V}_n\leqslant-\sum_{i=1}^{n}c_i z_i^2+\sum_{i=1}^{n}\rho\tilde{\varepsilon}_i^{\mathrm{T}}\hat{\varepsilon}_i+\rho\tilde{\varphi}^{\mathrm{T}}\hat{\varphi}+0.557\beta.
\tag{49}
$$

由引理2可知

$$
\tilde{\varphi}^{\mathrm{T}}\hat{\varphi}\leqslant-\frac{1}{2}\tilde{\varphi}^{\mathrm{T}}\tilde{\varphi}+\frac{1}{2}\varphi^{\mathrm{T}}\varphi;
\tag{50}
$$

$$
\begin{cases}
\tilde{\varepsilon}_1^{\mathrm{T}}\hat{\varepsilon}_1\leqslant-\dfrac{1}{2}\tilde{\varepsilon}_1^{\mathrm{T}}\tilde{\varepsilon}_1+\dfrac{1}{2}\varepsilon_1^{\mathrm{T}}\varepsilon_1,\\
\qquad\vdots\\
\tilde{\varepsilon}_n^{\mathrm{T}}\hat{\varepsilon}_n\leqslant-\dfrac{1}{2}\tilde{\varepsilon}_n^{\mathrm{T}}\tilde{\varepsilon}_n+\dfrac{1}{2}\varepsilon_n^{T}\varepsilon_n.
\end{cases}
\tag{51}
$$

结合式(50)和(51),式(49)可进一步转化为

$$
\begin{aligned}
\dot{V}_n\leqslant&-\sum_{i=1}^{n}c_i z_i^2-\sum_{i=1}^{n}\frac{\rho}{2}\tilde{\varepsilon}_i^{\mathrm{T}}\tilde{\varepsilon}_i+\sum_{i=1}^{n}\frac{\rho}{2}\varepsilon_i^{\mathrm{T}}\varepsilon_i-\\
&-\frac{\rho}{2}\tilde{\varphi}^{\mathrm{T}}\tilde{\varphi}+\frac{\rho}{2}\varphi^{\mathrm{T}}\varphi+0.557\beta\leqslant\\
&-\varsigma\Big(\sum_{i=1}^{n}z_i^2+\sum_{i=1}^{n}\frac{1}{2\lambda_i}\tilde{\varepsilon}_i^{\mathrm{T}}\tilde{\varepsilon}_i+\frac{1}{2\lambda}\tilde{\varphi}^{\mathrm{T}}\tilde{\varphi}\Big)+\\
&\sum_{i=1}^{n}\frac{\rho}{2}\varepsilon_i^{\mathrm{T}}\varepsilon_i+\frac{\rho}{2}\varphi^{\mathrm{T}}\varphi+0.557\beta\leqslant\\
&-\varsigma V_n+K.
\end{aligned}
\tag{52}
$$

其中

$$
\varsigma=\min\{2c_1,2c_2,\dots,2c_n,\rho\lambda,\rho\lambda_1,\rho\lambda_2,\dots,\rho\lambda_n\},
$$

$$
K=\sum_{i=1}^{n}\frac{\rho}{2}\varepsilon_i^{\mathrm{T}}\varepsilon_i+\frac{\rho}{2}\varphi^{\mathrm{T}}\varphi+0.557\beta.
$$

2.2 稳定性分析

基于上述分析,可以得到如下定理.

定理1 给出具有不确定非线性系统的闭环系统(1),虚拟控制律(16)、(24)、(32)、(44),事件触发控制机制(38)和自适应律(20)、(28)、(36)、(41)、(48). 在引理1和引理2的帮助下,可以保证: 1)系统所有信号都是半全局一致最终有界的; 2)所设计的控制器可以避免奇诺现象的发生.

证明 由式(52)可得$\dot{V}_n\leqslant-\varsigma V_n+K$. 根据文献[31]可知,系统所有信号都是半全局一致最终有界的,即

$$
\frac{1}{2}z_1^2\leqslant V(t)\leqslant\mathrm{e}^{-\varsigma t}V(0)+(K/\varsigma)(1-\mathrm{e}^{-\varsigma t}).
$$

然后,z_1^2由一个向紧集$\varOmega=\{z_1|z_1^2\leqslant 2K/\varsigma\}$以$\varsigma$的速率呈指数收敛的函数界定. 在设定$\varsigma$收敛速度时,可以通过减小$\beta$来减小$\varOmega$. 于是

$$
\frac{\mathrm{d}}{\mathrm{d}t}|e|=\frac{\mathrm{d}}{\mathrm{d}t}(e\times e)^{\frac{1}{2}}=\mathrm{sign}(e)\dot{e}\leqslant|\dot{\omega}|.
\tag{53}
$$

其中:$\forall t\in[t_k,t_{k+1}),e(t)=\omega(t)-u(v)$.

$\dot{\omega}(t)$是连续的,因为$f_i(\cdot)$至少是$(n+1-i)\mathrm{th}$阶光滑非线性函数,$r(t)$具有$(n+1)\mathrm{th}$阶分段连续导数. $\dot{\omega}(t)$满足$|\dot{\omega}_1|<\gamma,\gamma>0$为一个设计常数. 因为$e(t_k)=0,\lim\limits_{t\to t_{k+1}}e(t)=m$,所以存在$t^*$满足$t^*\leqslant\dfrac{n|v(t)|+m}{\gamma},\forall k\in z^+,\{t_{k+1}-t_k\}\geqslant t^*$. t^*为执行间隔的下限. 显然,奇诺现象被成功避免了. □

注1 由式(38)给出的事件触发机制可知,具体的触发条件为$|e(t)|\geqslant n|u(t)|+m$. 由该式在笛卡尔坐标系中的范围可知,当$\omega(t)$与$u(t)$的关系一定时,增大$n$、$m$的值,可以获取更长的触发区间,减少系统触发次数.

3 仿真实验

3.1 数值仿真

带输入饱和的非线性不确定系统定义如下:

$$\begin{cases}\dot{x}_1 = x_2 + f_1(\bar{x}_1),\\ \dot{x}_2 = u(v) + f_2(\bar{x}_2),\\ y = x_1.\end{cases}$$

其中:未知光滑非线性函数$f_1(\bar{x}_1)$和$f_2(\bar{x}_1)$定义为$f_1(\bar{x}_1) = \sin x_1, f_2(\bar{x}_2) = \sin x_2$;$x_1$、$x_2$和$y$的初始值分别是$x_1(0) = 0.5, x_2(0) = 0, y(0) = 0.5$. 另外,$r = \sin t$为参考信号.

自适应模糊控制器的隶属度函数为

$$\mu_{i,p}(x_p) = \mathrm{e}^{\frac{1}{2}(x+2-\frac{2}{7}(p-1))^2},\ p = 1, 2, \ldots, 15.$$

虚拟控制器和自适应率的设计如下:

$$\alpha_1 = -c_1 z_1 - \hat{\varphi}^{\mathrm{T}}\delta_1 - \mathrm{sg}_1(z_1)\hat{\varepsilon}_1,$$

$$\chi_1 = z_1\delta_1,$$

$$\chi_2 = \chi_1 + z_2\Big(\delta_2 - \frac{\partial\alpha_1}{\partial x_1}\delta_1\Big),$$

$$\alpha_2 = -z_1 - \Big(c_2 + \frac{1}{2}\Big)z_2 + \frac{\partial\alpha_1}{\partial x_1}x_2 + \frac{\partial\alpha_1}{\partial r}\dot{r} - \mathrm{sg}_2(z_2)\hat{\varepsilon}_2 - \hat{\varphi}^{\mathrm{T}}\Big(\delta_2 - \frac{\partial\alpha_1}{\partial x_1}\delta_1\Big) + \frac{\partial\alpha_1}{\partial\hat{\varphi}}\lambda(\chi_2 - \mu\hat{\varphi}) + r^{(n)}.$$

其中,事件触发机制的参数选择如下:$c_1 = 5.75, c_2 = 1.8, \tau = 0.3, \beta = 0.2, m = 0.2, \rho = 0.2, \lambda = 0.3, n = 0.1, u_{\max} = 4$.

仿真结果如图1～图4所示.

图1为系统输出轨迹和参考信号轨迹. 显然,系统输出可以快速响应参考信号的轨迹,误差较小. 图2为实际控制输入和事件触发控制输入曲线,而图3为系统的饱和输入曲线. 从图2、图3的对比可知,系统遭受输入饱和现象,输入饱和特性的阈值为4,符合初始值的设定. 图4为事件触发的触发执行间隔的保持时间,表1为具体的触发次数. 由仿真结果可以看出,系统触发率仅为6.6%(仿真步长为0.01). 因此,在本文所提出方法的作用下,系统的跟踪性能得到了保证,同时可以大幅度减少控制信号的传输次数,节省系统的通讯资源,从而减小系统传输压力.

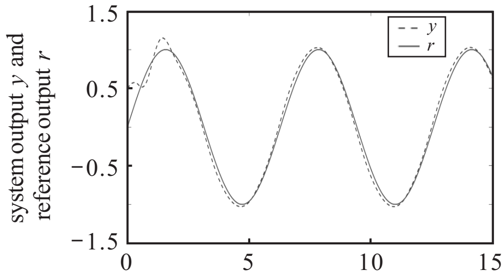

图 1 跟踪轨迹(1)

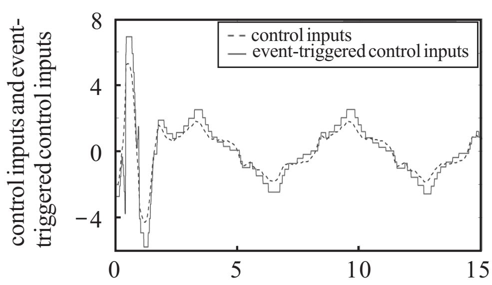

图 2 系统控制输入(1)

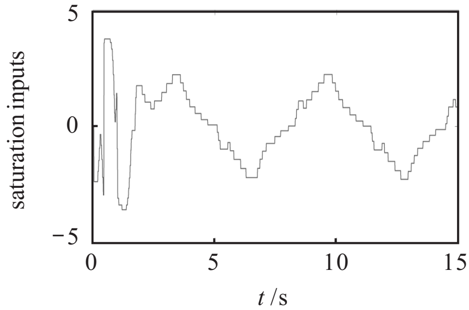

图 3 饱和输入(1)

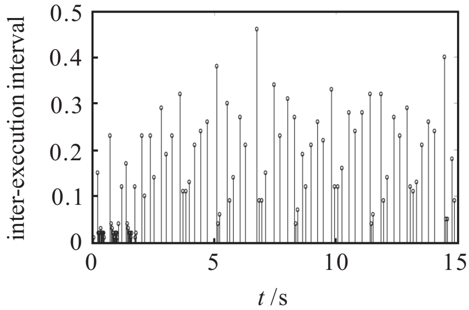

图 4 触发间隔(1)

表 1 触发次数(1)

时间/s	1～3	4～6	7～9	10～12	13～15
次数	40	15	15	14	15

3.2 实际系统仿真

为验证本文所提出方法在实际系统中的控制效果,考虑如下二阶机械臂系统:

$$\begin{cases}\dot{x}_1 = x_2,\\ \dot{x}_2 = \dfrac{1}{J}(u(v) - Bx_2 - \bar{m}gl\sin x_1),\\ y = x_1.\end{cases}$$

其中:$J = 1$为转动惯量,$B = 1$为关节转动的粘性摩擦系数,$\bar{m}$为关节的质量,l为关节的质心与关节的距离,$\bar{m}gl = 1$.

本例子的控制设计与数值仿真例子相同. 参数选取如下:$c_1 = 6, c_2 = 5, \tau = 0.3, \beta = 0.4, m = 0.5, \rho = 0.1, \lambda = 0.3, n = 0.1, u_{\max} = 4$.

仿真结果如图5～图8所示.

图5～图8为二阶机械臂系统的仿真验证结果.

与数值仿真相似,在系统遭受输入饱和现象时,系统输出可以较好地跟踪给定参考轨迹. 从表2可知,系统的触发率为7.7%(仿真步长为0.01). 显然,通过降低控制信号的传输次数,有效节省了系统的通讯资源. 因此,本文所提出的方法在实际二阶机械臂系统中也是切实可行的.

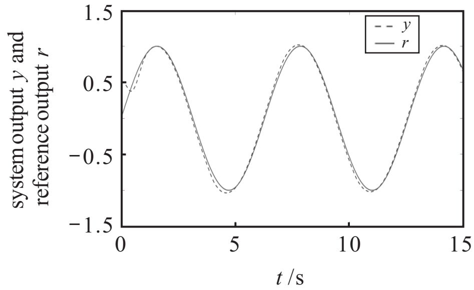

图5 跟踪轨迹(2)

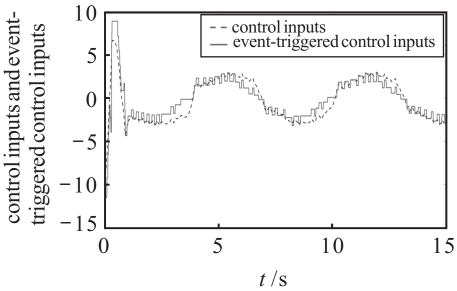

图6 系统控制输入(2)

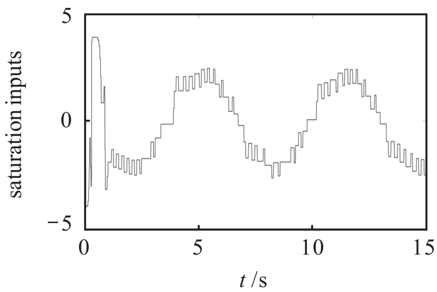

图7 饱和输入(2)

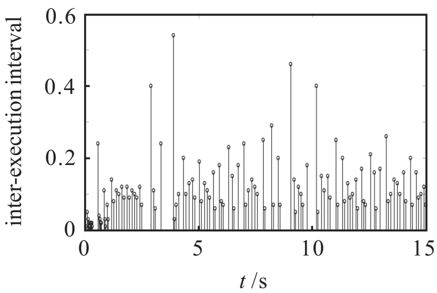

图8 触发间隔(2)

表2 触发次数(2)

时间/s	1～3	4～6	7～9	10～12	13～15
次数	34	21	17	22	22

4 结论

本文研究了带输入饱和的非线性不确定系统的跟踪控制问题,提出了一种自适应模糊触发式补偿控制方法. 为了实现对系统输入饱和约束的有效补偿,将光滑的双曲正切函数融入自适应控制过程以提高系统性能. 同时,利用模糊逻辑系统对实际系统的未知不确定部分进行逼近处理. 此外,本文还引入了基于相对阈值的事件触发控制策略以节省系统通讯资源. 理论分析及仿真实例均验证了所提出方法的有效性. 该方法可以在保证系统跟踪性能的同时最大限度地节省系统通讯资源.

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(责任编辑：李君玲)