Model-Independent Robust Adaptive Tracking Control of Robot Manipulators

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Abstract: This paper proposes a novel model-independent robust adaptive control strategy for trajectory tracking of robot manipulators with uncertainties, in which the only information required in establishing the strategy is the degree-of-freedom (DOF) and output state of the system. It is shown by theories and simulations that uncertain effects such as frictions and external disturbances or unmodelled dynamices can be eliminatated and global exponential stability (GES) or global uniform ultimate boundedness (GUUB) stability can be guaranteed. Furthermore, we also give a measure of the transient tracking error performace.

Key words: robust control; adaptive control; robot; exponential stability; GUUB

1 Introduction

Most of the existing adaptive controllers[1] are model-based, which require very complex computation especially for manipulators with more than two joints and can't warrant global stability in the presence of effects of external disturbances or unmodelled dynamics. Although in recent years some model-independent controllers[2,3] have been presented, they can only achieve global or local UUB and their control structures are also complicated.

In this paper, a novel robust adaptive control strategy consisting of a linear time-invariant PD part and a PD part with adaptive gains is proposed. The only information required in establishing the strategy is the DOF and output state of the system, so it is rather simple and completely model-independent. It is shown by theories and simulations that with this strategy uncertain effects such as frictions and external disturbances or unmodelled dynamics can be effectively compensated and GES or GUUB can be warranted.

2 Structure Properties of Robot Dynamics

Consider the following n-link rigid revolute robot dynamics described by a second order nonlinear differential equation:

$$\begin{aligned} &M(q)\ddot{q} + H(q,\dot{q}) = \tau, \\ &H(q,\dot{q}) = C(q,\dot{q})\dot{q} + G(q) + F_d\dot{q} + F_s(\dot{q}) + \tau_d(q,\dot{q},t) \end{aligned} \tag{1}$$

where τ is an $n \times 1$ vector of applied joint torques, $q(t)$ is an $n \times 1$ joint variables, $M(q)$ is an $n \times n$ symmetric and positive definite inertia matrix, $C(q,\dot{q})\dot{q}$ is an $n \times 1$ vector of centripetal and Coriolis terms, $G(q)$ is an $n \times 1$ vector of gravity terms, F_d is an $n \times n$ diagonal matrix of dynamic friction coefficients, $F_s(\dot{q})$ is an $n \times 1$ vector of static friction terms, and $\tau_d(q,\dot{q},t)$ is

Manuscript received Apr. 21, 1997, revised Dec. 8, 1997.

an $n\times 1$ vector of external disturbances or unmodelled dynamics.

Remark 1 In this paper, we relax the restriction on external distanbances or unmodelled dynamics and follow the assumption of [2], namely

$$\|\tau_d(q,\dot{q},t)\| \leqslant c_0 + c_1\|q\| + c_2\|\dot{q}\| + c_3\|q\|^2 + c_4\|\dot{q}\|^2 \tag{2}$$

where $c_i, i = 0,1,2,3,4$ are unknown positive constants. This assumption contains a broader class of external disturbances or unmodelled dynamics.

The robot dynamics (1) have the following structure properties that are useful in the subsequent theoretical proofs.

Property 1[1] $$x^{\mathrm{T}}[\dot{M}(q) - 2C(q,\dot{q})]x = 0, \quad \forall\, x\in\mathbb{R}^n. \tag{3}$$

Property 2 The dynamic equation(1) can be equivalently expressed as follows

$$\begin{aligned} &M(q)\dot{s} + C(q,\dot{q})s = \tau - \Delta A, \\ &\Delta A = M(q)[\ddot{q}_d - \alpha\dot{e}] + C(q,\dot{q})[\dot{q}_d - \alpha e] + G(q) + F_d\dot{q} + F_s(\dot{q}) + \tau_d(q,\dot{q},t). \end{aligned} \tag{4}$$

where $e = q - q_d, s = \dot{e} + \alpha e$, α is a positive constant, $q_d, \dot{q}_d, \ddot{q}_d$ are given continuous and bounded trajectories, ΔA represents the lumped nonlinearity and uncertainty of the system, it can be shown that

$$\|\Delta A\| \leqslant \xi_0 + \xi_1\|X\| + \xi_2\|X\|^2 \leqslant \xi\rho. \tag{5}$$

where $X = [e^{\mathrm{T}},\dot{e}^{\mathrm{T}}]^{\mathrm{T}}, \rho = 1 + \|X\| + \|X\|^2, \xi = \max(\xi_0,\xi_1,\xi_2), \xi_0,\xi_1,\xi_2$ denote some unknown positive constants, ξ is a concentrated restriction parameter of upper bounding on lumped nonlinearity and uncertainty of robot and ρ is an enveloping function of lumped uncertanties of robot. For the details, see [3].

3 Robust Adaptive Controller Design

Following the same spirit and utilizing a similar framework as [2,3], the controller can be designed as the following:

$$\tau = -k_v\dot{e} - k_p e - k(t)s, \quad \text{where} \quad s = \dot{e} + \alpha e, \quad k_p = \alpha k_v, \tag{6}$$

$$k(t) = \frac{(\hat{\xi}\rho)^2}{\hat{\xi}\rho\|s\| + \varepsilon_1(t)}, \quad \text{where} \quad \dot{\varepsilon}_1 = -\gamma_1\varepsilon_1,\ \varepsilon_1(0) > 0, \tag{7}$$

$$\dot{\hat{\xi}} = -\varepsilon_2(t)\hat{\xi} + \gamma_3\rho\|s\|, \quad \text{where} \quad \dot{\varepsilon}_2 = -\gamma_2\varepsilon_2,\ \varepsilon_2(0) > 0, \tag{8}$$

where $\gamma_1,\gamma_2,\gamma_3,k_v$ and k_p are scalar positive constants, $k(t)$ is a time-varying filtered error feedback gain.

In order to analyze the stability of the proposed control system, we first introduce a Lemma, and then establish a stability theorem of the whole system.

Lemma Let $V(x,t)$ be a Lyapunov function candidate for any given continuous time system with the following properties:

$$\begin{aligned} &\lambda_1\|x\|^2 \leqslant V(x,t) \leqslant \lambda_2\|x\|^2, \quad \forall\,(x,t)\in\mathbb{R}^n\times\mathbb{R}, \\ &\dot{V}(x,t) \leqslant -\lambda_3\|x\|^2 + \varepsilon\exp(-\beta t), \quad \forall\,(x,t)\in\mathbb{R}^n\times\mathbb{R}, \end{aligned} \tag{9}$$

where $\lambda_i (i = 1,2,3)$, ε all are positive constants.

1) If $\beta > 0$, then the system is GES and the state $x(t)$ can be bounded as:

$$\| x \| \leqslant \begin{cases} \left[\frac{\lambda_2}{\lambda_1} \| x(0) \|^2 \exp(-\lambda t) + \frac{\varepsilon t}{\lambda_1} \exp(-\lambda t) \right]^{\frac{1}{2}}, & \lambda = \beta, \\ \left[\frac{\lambda_2}{\lambda_1} \| x(0) \|^2 \exp(-\lambda t) + \frac{\varepsilon}{(\lambda - \beta)\lambda_1} [\exp(-\beta t) - \exp(-\lambda t)] \right]^{\frac{1}{2}}, & \lambda \neq \beta. \end{cases} \tag{10}$$

2) If $\beta = 0$, then the state $x(t)$ is GUUB in the sense that

$$\| x \| \leqslant \left[\frac{\lambda_2}{\lambda_1} \| x(0) \|^2 \exp(-\lambda t) + \frac{\varepsilon}{\lambda \lambda_1} [1 - \exp(-\lambda t)] \right]^{\frac{1}{2}} \tag{11}$$

where $\lambda = \lambda_3 / \lambda_2$, exp( ) denotes the natural logarithm exponential.

Proof Straightforward application of the Theorem 1 of [5] leads to the proof.

Theorem 1 For the robot system described by (1), under the control of (6)～(8), the global exponential stability is guaranteed.

Proof Select the Lyapunov function

$$\begin{cases} V = 0.5 s^{\mathrm{T}} M(q) s + e^{\mathrm{T}} k_p e + 0.5 \gamma_3^{-1} \tilde{\xi}^2 \\ \quad = 0.5 z^{\mathrm{T}} P z, \text{ where } \tilde{\xi} = \xi - \hat{\xi}, z = [e, \dot{e}, \tilde{\xi}]^{\mathrm{T}}, \\ P = \begin{bmatrix} 2k_p I + \alpha^2 M & \alpha M & 0 \\ \alpha M & M & 0 \\ 0 & 0 & \gamma_3^{-1} \end{bmatrix}. \end{cases} \tag{12}$$

By the Rayleigh principle, we have

$$0.5 \lambda_{\min}(P) \| z \|^2 \leqslant V \leqslant 0.5 \lambda_{\max}(P) \| z \|^2. \tag{13}$$

where $\lambda_{\min}(\cdot)$, $\lambda_{\max}(\cdot)$ denotes the operation of taking the minimum eigenvalue or maximum eigenvalue, respectively.

The time derivative of V along the tracking error model (4) is given by

$$\dot{V} \leqslant - k_v \| \dot{e} \|^2 - \alpha k_p \| e \|^2 - k(t) \| s \|^2 + \| s \| \cdot \| \Delta A \| - \gamma_3^{-1} \tilde{\xi} \dot{\hat{\xi}}. \tag{14}$$

Substituting (6)～(8) and making use of Property 2, we have

$$\begin{aligned} \dot{V} &\leqslant - k_v \| \dot{e} \|^2 - \alpha k_p \| e \|^2 - 0.5 \varepsilon_2 \gamma_3^{-1} \tilde{\xi}^2 + 0.5 \varepsilon_2(0) \gamma_3^{-1} \xi^2 \exp(-\gamma_2 t) + \varepsilon_1(0) \exp(-\gamma_1 t) \\ &\leqslant - z^{\mathrm{T}} Q z + 2\varepsilon' \exp(-\gamma' t), \quad \varepsilon' = \max(0.5 \varepsilon_2(0) \gamma_3^{-1} \xi^2, \varepsilon_1(0)), \gamma' = \min(\gamma_1, \gamma_2) \\ &\leqslant - \lambda_{\min}(Q) \| z \|^2 + 2\varepsilon' \exp(-\gamma' t), \quad Q = \mathrm{diag}(\alpha k_p, k_v, 0.5 \varepsilon_2 \gamma_3^{-1}). \end{aligned} \tag{15}$$

Using (13) and lemma, we can show the whole system is globally exponentially stable.

Remark 2 Strictly speaking, Theorem 1 can't conclude that the whole system is exponentially stable, since $\lambda_{\min}(Q) = 0.5 \varepsilon_2(0) \gamma_3^{-1} \exp(-\gamma_2 t) \to 0$ as $t \to \infty$, while we can ensure that the entire system is globally asymptotically stable, i. e. $\| X \| \to 0$ as $t \to \infty$, the details of proof will need theorems of [7], omitted here for brevity. But from the engineering point of view, in a finite interval. the norm of system state $\| z \|$ decays to zero exponentially, in this sense, the whole system is exponentially stable.

Remark 3 The so-called σ-modification[4] used in the adaptation law (8) is to avoid the parameter drift or integral windup due to unmodelled dynamics and disturbances and to enhance the robustness of the system.

Remark 4 If all the parameters of robot dynamics are exactly known, namely, if we may determine the quantity ξ exactly, the adaptation law (8) is not needed. We can substitute the true parameter ξ into control law and the strictly global exponential stablity is warranted. But the bound of ξ calculated by hand is always conservative in general, and the conservatism of control will cause saturation of actuators, by learning this bound on-line, we will obtain relatively satisfactory results.

Furthermore, if the parameters γ_1, γ_2 of (7)(8) are set to zero, we can conclude that the whole system is GUUB with the following theorem.

Theorem 2 For the robot system described by (1), under the control of (6)~(8), and if the control parameters γ_1, γ_2 are set to be zero, the global uniform ultimate boundedness is guaranteed.

Proof Using the same Lyapunov function V as in Theorem 1, and with similar derivation, we have

$$\begin{cases} \dot{V} \leqslant -\lambda_{\min}(Q)\|z\|^2 + \varepsilon', \\ \varepsilon' = 0.5\varepsilon_2(0)\gamma_3^{-1}\xi^2 + \varepsilon_1(0), \quad Q = \operatorname{diag}(\alpha k_p, k_v, 0.5\varepsilon_2(0)\gamma_3^{-1}). \end{cases} \tag{16}$$

By using (13) and lemma, we can conclude that the whole system is globally uniformly unltimatly bounded, and the boundedness is given by

$$\|z\| \leqslant \left[\frac{\lambda_{\max}(P)}{\lambda_{\min}(P)}\|z(0)\|^2\exp(-\lambda t) + \frac{\varepsilon'}{\lambda\lambda_{\min}(P)}[1-\exp(-\lambda t)]\right]^{\frac{1}{2}}, \lambda = 2\lambda_{\min}(Q)/\lambda_{\max}(P). \tag{17}$$

It is clear that the ultimate bound is determined by the ratio $\varepsilon'/(\lambda\lambda_{\min}(P))$ and that the exponential convergence rate of $\|z\|$ to the bound is specifed by λ which may be a measure of tracking error performance.

4 Simulation

A two-degree-of-freedom revolute robotic manipulator is simulated to test the proposed robust adaptive control law. The dynamics model and its parameters can be found in [6].

The joint friction and external disturbances (unmodelled dynamics) can be chosen arbitrarily as

$$F_d = \operatorname{diag}(5,5), \quad F_s(\dot{q}) = 3\operatorname{sgn}(\dot{q}), \quad \tau_d(q_1, \dot{q}_1, t) = [q_1\dot{q}_1\sin t \quad q_2\dot{q}_2\cos t]^{\mathrm{T}}.$$

The desired trajectories are given by

$$q_{d1} = \sin t + 0.1\sin 3t - 0.2\sin 4t, \quad q_{d2} = 0.1\sin 2t - 0.2\sin 3t + 0.1\sin 4t.$$

The initial states of the system are set as

$$q_1(0) = q_2(0) = 0.1, \quad \dot{q}_1(0) = \dot{q}_2(0) = 0, \quad \hat{\xi}(0) = 0.$$

The control parameters are chosen as follows

$$\varepsilon_1(0) = 10. \quad \varepsilon_2(0) = 0.1, \quad \gamma_i = (0.01, 0.01, 100), \quad k_v = 500, \quad \alpha = 10.$$

A four-order Runge-kutta method with a sampling interval 1ms is used to solve the nonlinear differential equations numerically. The simulation results are shown in Fig. 1~4.

Remark 5 In simulation, we find that if the control parameters are not chosen properly, the control torque may be chattering in spite of guaranteeing exponential tracking. From control law (7), we can show when time tends to infinite the control law may become discon-

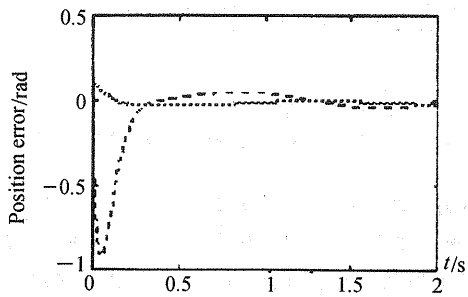

Fig.1 Position tracking error

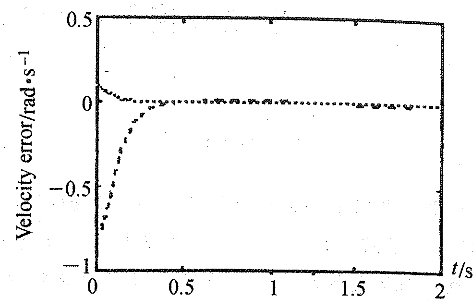

Fig.2 Velocity tracking error

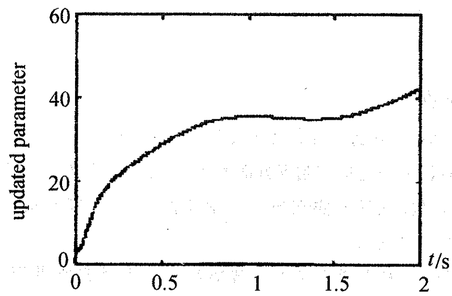

Fig.3 Adaptation of the parameter ξ

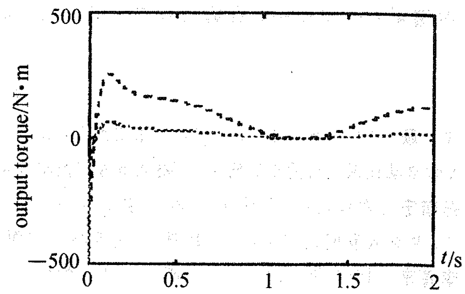

Fig.4 Joint control torque

tinuous. Furthermore the computational accuracy or quantization error may be another reason, so we must choose the control parameters deliberately.

5 Conclusion

A novel robust adaptive controller for trajectory tracking of robot manipulators with uncertainties whose upper bounds are not assumed to be known is proposed, which is model-independent and the only information needed in setting up the control law is the DOF and the output state of system. It is shown by theories and simulations that uncertain effects such as frictions and external disturbances or unmodelled dynamics can be eliminated and GES or GUUB stability can be guaranteed.

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不依赖模型的机器人鲁棒自适应跟踪控制

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摘要:提出了一种新颖的鲁棒自适应控制策略,用于不确定性机器人的轨迹跟踪.它不需要任何模型知识,唯一需了解的是系统的阶数和输出的位置及速度状态.理论和仿真均证明,系统的不确定性诸如摩擦力、外部扰动及未建模动力学带来的不确定性影响,均可被设计的控制律补偿,最后可保证全局指数收敛或全局一致最后有界的结果.另外,本文还给出了跟踪误差的暂态测量.

关键词:鲁棒控制;自适应控制;机器人;指数稳定;一致最后有界

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9月15日、17日晚上分别举行了控制理论专业委员会第一、二次工作会议,参加会议的20多位委员皆出席了会议.在第一次工作会议上,会务组通报了'98中国控制会议的筹备概况,并通过了会议日程安排.在第二次工作会议上,讨论了有关中国自动化学会控制理论专业委员会今后的工作、中国控制会议论文集的出版、中国控制会议的组织、国外个人及团体为关肇直奖的捐款、及2000年、2001年、2002年中国控制会议地点的选定等事宜.

9月18日下午4:00举行'98中国控制会议的《关肇直奖》发奖仪式及闭幕式,会议由专业委员会秘书长张纪峰研究员主持.《关肇直奖》评奖委员会主任黄琳教授宣布本届《关肇直奖》的获奖论文.《关肇直奖》基金委员会副主任秦化淑研究员向获奖作者颁发了获奖证书及奖金.专业委员会副主任郑大钟教授致闭幕词.他说,'98中国控制会议在会务组及与会代表的共同努力下,已经圆满完成了各项议程,本次会议是本世纪内中国控制理论和应用界的最后一次盛会,代表们通过广泛的学术交流加深了对彼此研究工作的了解,加深了对学科领域最新研究进展的了解,也加深了友谊.会议安排的大会报告和专题报告,就控制领域的新技术、新应用、新方法作了综述和介绍,扩大了视野,启发了思路.回顾过去一个世纪中控制科学发展的历程,使我们认识到,控制科学中许多重要的概念和最好的结果,都是在解决当时年代的重大工程和社会发展问题中形成和提出的,因此问题特别是来自重大工程背景和社会背景的问题,始终应当是推动控制科学发展的第一动力.他感谢老一辈科学家对会议的关心和支持,并以广大青年科学家成为会议的中坚力量而自豪,对本届《关肇直奖》的获得者和获得提名者表示祝贺.

'98中国控制会议总体上显示了良好的会风和学风,大多数代表都能全神贯注地投入会议的各种活动中.特别是年长代表,不仅认真严肃地做好学术报告,而且还积极热情地参加各种学术活动,组织专题报告,为年青代表树立了榜样.本次会议上,来自香港地区和海外代表,他们严肃认真,包括精心制作的投影胶片和认真准备的口头演讲,都给我们留下了很深的印象,值得我们借鉴.今后希望能保持和发扬这种良好的会风和学风,使之成为中国控制会议的一个好的传统.

中国自动化学会
控制理论专业委员会
一九九八年九月二十日