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Brief paper

A global adaptive learning control for robotic manipulators☆

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Abstract

This paper addresses the problem of designing a global adaptive learning control for robotic manipulators with revolute joints and uncertain dynamics. The reference signals to be tracked are assumed to be smooth and periodic with known period. By developing in Fourier series expansion the input reference signals of every joint, an adaptive learning PD control is designed which 'learns' the input reference signals by identifying their Fourier coefficients: global asymptotic and local exponential stability of the tracking error dynamics are obtained when the Fourier series expansion of each input reference signal is finite, while arbitrary small tracking errors are achieved otherwise. The resulting control is not model based and depends only on the period of the reference signals and on some constant bounds on the robot dynamics.

Keywords: Learning control; Adaptive control; Nonlinear systems; PD control; Robotic manipulators

1. Introduction

When the robot dynamics are highly uncertain, adaptive and learning control laws have been developed in order to cope with model uncertainties. Adaptive controls require the assumption that the robot dynamics can be expressed as the product of known functions and unknown parameters (see Slotine and Li (1987)). On the other hand, learning controls require that the reference trajectory is periodic with known period. The key idea is to use the information obtained in the preceding trial to improve the performance in the current one. Under the assumption that the accelerations are measured and a resetting procedure is performed at the beginning of each trial, learning control laws were initially proposed in Arimoto, Kawamura, and Miyazaki (1984), and Bondi, Casalino, and Gambardella (1988). Several learning controls for robot manipulators have been subsequently proposed which do not require joint accelerations (Dixon, Zergeroglu, Dawson, & Costic, 2002; Hamamoto & Sugie, 2002; Kaneko & Horowitz, 1997; Kuc & Han, 2000; Messner, Horowitz, Kao, & Boals, 1991; Tayebi, 2004) and removed (Dixon et al., 2002; Kaneko & Horowitz, 1997; Kuc & Han, 2000; Messner et al., 1991; Tayebi, 2004) the resetting assumption. In Kaneko and Horowitz (1997), and Messner et al. (1991) two adaptive learning controllers are proposed for robot manipulators, achieving local asymptotic tracking under the assumption that the reference input signal (corresponding to the desired output trajectory) is the integral of the product of a known differentiable kernel and an unknown influence function: no robustness analysis is provided for reference inputs which do not belong to such a class. In Kuc and Han (2000) four learning control laws (requiring infinite memory) are applied to a robot arm with revolute joints, which has been linearized along the desired trajectory. In Hamamoto and Sugie (2002) a new type of iterative learning control is proposed which seeks the desired input in an appropriate finite dimensional input subspace. The controller achieves asymptotic tracking using only joint position measurements, provided that an exact resetting is performed at the beginning of each period. In Dixon et al. (2002) a hybrid adaptive/learning control is presented, which, combining the iterative learning and the adaptive control approaches, achieves global asymptotic convergence to zero of the joint errors (exponential convergence is not guaranteed): the proposed controller is characterized by a nonlinear feedback and requires infinite memory. In Tayebi (2004) three adaptive iterative learning controllers are proposed that guarantee asymptotic convergence to zero of the position

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and velocity tracking errors, requiring infinite memory and a resetting procedure at the beginning of each trial. If the exact reset is not guaranteed, then the position error can be made arbitrarily small by increasing the feedback gains. In Norrlöf (2002) an adaptive iterative learning control is proposed and experimentally tested on an industrial robot: each joint is modeled as an independent transfer function to which the iterative control is applied, in parallel with the existing feedback controller.

This paper addresses the problem of designing a global adaptive learning PD control for robotic manipulators with revolute joints and uncertain dynamics. The reference signals to be tracked are assumed to be smooth and periodic with known period. By developing in Fourier series expansion the input reference signals of every joint of the manipulator, an adaptive learning PD control is designed which 'learns' the input reference signals by identifying their Fourier coefficients: global asymptotic tracking and local exponential tracking of both the input and the output reference signals are obtained when the Fourier series expansion of each input reference signal is finite. When the reference input has an infinite Fourier series expansion, the input and output tracking errors converge globally asymptotically and locally exponentially to arbitrarily small residual sets. The resulting control is not model based and depends only on the period of the reference signals and on some constant bounds on the robot dynamics. The control structure consists of a linear part (proportional and derivative) plus a learning part which reconstructs the unknown reference input signal. The structure of the learning part is obtained by adapting to the multi-input multi-output robot model the method already used in Del Vecchio, Marino, and Tomei (2003) for local state feedback control of single-input single-output feedback linearizable systems and in Liuzzo, Marino, and Tomei (2004) for local output feedback control of single-input single-output systems in output feedback form. Preliminary local results for robot control were obtained in Del Vecchio, Marino, and Tomei (2001). The results presented here are global and are based on the choice of a different Lyapunov function proposed in Koditschek (1988), and Tomei (1991).

The idea of developing in Fourier series expansion a periodic reference signal was already considered in the literature (Kempf, Messner, Tomizuka, & Horowitz, 1993; Lee, Lee, & Bien, 1993; Manabe & Miyazaki, 1994; Qin & Cai, 2001; Tang, Cai, & Huang, 2000). In Kempf et al. (1993) the problem of rejecting a periodic disturbance is considered for discrete time linear systems: only disturbances with a finite number of harmonics are considered. In Lee et al. (1993) linear systems are addressed and an application to linearized robot dynamics is also given. The result is local and no robustness analysis is provided. In Manabe and Miyazaki (1994) nonlinear discrete time asymptotically stable systems are studied for which a learning control is obtained, based on local linearization by discrete Fourier transform. An application to robotic manipulators is proposed but the truncation and the linearization errors are not considered in the convergence analysis. In Qin and Cai (2001), and Tang et al. (2000) nonperiodic PD feedback signals are assumed to have a finite Fourier series expansion. No robustness analysis is addressed to take into account signals with an infinite Fourier series expansion.

2. System definition and assumptions

Consider the dynamics of an n-link rigid robot with rotational joints as described by

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + E(q) + F(\dot{q}) = u \tag{1}$$

where: q is the $n \times 1$ vector of the joint coordinates; $H(q)$ is the inertia matrix, which is symmetric and positive definite; $C(q,\dot{q})$ takes into account the Coriolis and centrifugal forces; $F(\dot{q})$ is the friction vector; u is the vector of the applied torques; $E(q)$ is the vector of the gravity forces. We list in the following the properties owned by the robot model (1) and the assumptions under which the control algorithm is designed.

Assumption 2.1. The reference output signal $q_r(t) \in C^N$ (with $N \geq 6$) is periodic with known period T and such that, $\forall t \in [0,T]$, $\|q_r(t)\| \leq B_0$, $\|\dot{q}_r(t)\| \leq B_1$, $\|\ddot{q}_r(t)\| \leq B_2$ with B_0, B_1, B_2 being known positive constant reals.

Property 2.1. *Given a proper definition of $C(q,\dot{q})$ that is not unequivocally defined by the form $C(q,\dot{q})\dot{q}$, the matrix $\mathrm{d}H(q)/\mathrm{d}t - 2C(q,\dot{q})$ is skew-symmetric. One possible definition for the elements of $C(q,\dot{q})$ which leads to the skew-symmetry of $\mathrm{d}H(q)/\mathrm{d}t - 2C(q,\dot{q})$ is*

$$C_{i,j}(q,\dot{q}) = \frac{1}{2}\left[\dot{q}^T\frac{\partial H_{i,j}}{\partial q} + \sum_{k=1}^{n}\left(\frac{\partial H_{i,k}}{\partial q_j} - \frac{\partial H_{j,k}}{\partial q_i}\right)\dot{q}_k\right]$$

which implies that $\mathrm{d}H(q)/\mathrm{d}t = C(q,\dot{q}) + C^T(q,\dot{q})$ and $C(q,x_1)x_2 = C(q,x_2)x_1$, $\forall x_1, x_2 \in \Re^n$.

Property 2.2. *The inertia matrix $H(q)$ is such that, $\forall q, \dot{q}, q_1, q_2 \in \Re^n$, $H_m \leq \|H(q)\| \leq H_M$, $\|H(q_1) - H(q_2)\| \leq k_H \|q_1 - q_2\|$ and $\|\mathrm{d}H(q)/\mathrm{d}t\| \leq H_{DM}\|\dot{q}\|$.*

Property 2.3. *The matrix $C(q,\dot{q})$ is such that, $\forall q, q_1, q_2, \dot{q} \in \Re^n$, $\|C(q,\dot{q})\| \leq C_M\|\dot{q}\|$ and $\|C(q_1,\dot{q}_r) - C(q_2,\dot{q}_r)\| \leq k_C\|q_1 - q_2\|$.*

Property 2.4. *The vector of the gravity forces $E(q)$ is such that, $\forall q, q_1, q_2 \in \Re^n$, $\|E(q)\| \leq E_M$ and $\|E(q_1) - E(q_2)\| \leq k_E\|q_1 - q_2\|$.*

Assumption 2.2. The friction vector $F(\dot{q})$ is such that $F(0) = 0$ and, $\forall \dot{q}_1, \dot{q}_2 \in \Re^n$, $\|F(\dot{q}_1) - F(\dot{q}_2)\| \leq F_M\|\dot{q}_1 - \dot{q}_2\|$.

Assumption 2.3. The bounds H_m, H_M, k_H, C_M, k_C, E_M, k_E, F_M defined in Property 2.2–2.4 and Assumption 2.2 are known positive reals.

The bounded periodic reference input $u_r(t) \in \Re^n$ of period T, corresponding to the reference $q_r(t)$, can be computed as

$$u_r = H(q_r)\ddot{q}_r + C(q_r,\dot{q}_r)\dot{q}_r + E(q_r) + F(\dot{q}_r). \tag{2}$$