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Adaptive iterative learning control for robot manipulators: Experimental results ☆

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Abstract

In this paper, two adaptive iterative learning control schemes, proposed by A. Tayebi [2004, *Automatica*, *40*(7), 1195–1203], are tested experimentally on a five-degrees-of-freedom (5-DOF) robot manipulator CATALYST5. The control strategy consists of using a classical PD feedback structure plus an additional iteratively updated term designed to cope with the unknown parameters and disturbances. The control implementation is very simple in the sense that the knowledge of the robot parameters is not needed, and the only requirement on the PD and learning gains is the positive definiteness condition. Furthermore, in contrast with classical ILC schemes where the number of iterative variables is generally equal to the number of control inputs, the adaptive control schemes tested in this paper involve just one or two iterative variables.

Keywords: Iterative learning control; Robot manipulators

1. Introduction

It is well known that robot manipulators are generally used in repetitive tasks (e.g., automotive manufacturing industries). Therefore, it is interesting to take advantage of the fact that the reference trajectory is repeated over a given operation time. In this context, iterative learning control (ILC) techniques can be applied in order to enhance the tracking performance from operation to operation. Since the early works of Arimoto et al. (1984), Casalino and Bartolini (1984) and Craig (1984), several ILC schemes for robot manipulators have been proposed in the literature (see for instance Arimoto, 1996; Bondi et al., 1988; Luca et al., 1992; Horowitz, 1993; Kavli, 1992; Kawamura et al., 1988; Moon et al., 1997). These ILC algorithms, whether developed for the linearized model or the nonlinear model, are generally based upon the contraction mapping approach and require a certain a priori knowledge of the system dynamics.

On the other hand, another type of ILC algorithms have been developed using Lyapunov and Lyapunov-like methods. In fact in French and Rogers (2000), a standard Lyapunov design is used to solve ILC problems. The idea consists to use a standard adaptive controller and to start the parameter estimates with their final values obtained at the preceding iteration. In the same spirit, Choi and Lee (2000) proposed an adaptive ILC for uncertain robot manipulators, where the uncertain parameters are estimated along the time horizon whereas the repetitive disturbances are compensated along the iteration horizon. However, as in standard adaptive control design, this technique requires the unknown system parameters to be constant. In Ham et al. (1995), Ham et al. (2000), Kuc et al.

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(1991), Xu (2002), Xu et al. (2000) and Xu and Tan (2001), several ILC algorithms have been proposed based upon the use of a positive-definite Lyapunov-like sequence which is made monotonically decreasing along the iteration axis via a suitable choice of the control input. In contrast with the standard adaptive control, this technique is shown to be able to handle systems with time-varying parameters since the adaptation law in this case is nothing else but a discrete integration along the iteration axis. Based on this approach, Kuc et al. (1991) proposed an ILC scheme for the linearized robot manipulator model, while in (Ham et al., 2000; Xu et al., 2000) nonlinear ILC schemes have been proposed for the nonlinear model. Again these control laws require a certain a priori knowledge of the system dynamics.

In Tayebi (2004), a simple ILC scheme, for the position tracking problem of rigid robot manipulators without any a priori knowledge on the system parameters, has been proposed. The control strategy consists of a PD term plus an additional iterative term introduced to cope with the unknown parameters and disturbances. The proof of convergence is based upon the use of a Lyapunov-like positive definite sequence, which is made monotonically decreasing through an adequate choice of the control law and the iterative adaptation rule. In contrast with classical ILC schemes where the number of iterative variables is generally equal to the number of control inputs, the proposed control strategy uses one or two iterative variables, which is interesting from a practical point of view since it contributes considerably to memory space saving. In this framework, the acceleration measurements and the bounds of the robot parameters are not needed and the only requirement on the control gains is the positive definiteness condition.

In this paper, we present some experimental results on a 5-DOF robot manipulator CATALYST5, confirming the effectiveness of the control strategy proposed in Tayebi (2004).

2. Equations of motion and problem statement

Using the Lagrangian formulation, the equations of motion of a n degrees-of-freedom rigid manipulator may be expressed by

$$M(q_k)\ddot{q}_k + C(q_k, \dot{q}_k)\dot{q}_k + G(q_k) = \tau_k(t) + d_k(t), \tag{1}$$

where $t \in \mathbb{R}_+$ denotes the time and the non-negative integer $k \in \mathbb{Z}_+$ denotes the operation or iteration number. The signals $q_k \in \mathbb{R}^n$, $\dot{q}_k \in \mathbb{R}^n$ and $\ddot{q}_k \in \mathbb{R}^n$ are the joint position, joint velocity and joint acceleration vectors, respectively, at the iteration k. $M(q_k) \in \mathbb{R}^{n\times n}$ is the inertia matrix, $C(q_k, \dot{q}_k)\dot{q}_k \in \mathbb{R}^n$ is a vector resulting from Coriolis and centrifugal forces. $G(q_k) \in \mathbb{R}^n$ is the vector resulting from the gravitational forces. $\tau_k \in \mathbb{R}^n$ is the control input vector containing the torques and forces to be applied at each joint. $d_k(t) \in \mathbb{R}^n$ is the vector containing the unmodeled dynamics and other unknown external disturbances.

Assuming that the joint positions and the joint velocities are available for feedback, our objective is to design a bounded control law $\tau_k(t)$ guaranteeing the boundedness of $q_k(t)$, $\forall t \in [0, T]$ and $\forall k \in \mathbb{Z}_+$, and the convergence of $q_k(t)$ to the desired reference trajectory $q_d(t)$ for all $t \in [0, T]$ when k tends to infinity. Throughout this paper, we will use the $\mathscr{L}_{pe}$ norm defined as follows:

$$\|x(t)\|_{pe} \triangleq \begin{cases} \left(\int_0^t \|x(\tau)\|^p \, d\tau\right)^{1/p} & \text{if } p \in [0, \infty), \\ \sup\limits_{0\leqslant\tau\leqslant t} \|x(\tau)\| & \text{if } p = \infty, \end{cases}$$

where $\|x\|$ denotes any norm of x, and t belongs to the finite interval $[0, T]$. We say that $x \in \mathscr{L}_{pe}$ when $\|x\|_{pe}$ exists (i.e., when $\|x\|_{pe}$ is finite).

We assume that all the system parameters are unknown and we make the following reasonable assumptions:

(A1) The reference trajectory and its first and second time-derivatives, namely $q_d(t)$, $\dot{q}_d(t)$ and $\ddot{q}_d(t)$, as well as the disturbance $d_k(t)$ are bounded $\forall t \in [0, T]$ and $\forall k \in \mathbb{Z}_+$.
(A2) The resetting condition is satisfied, i.e., $\dot{q}_d(0) - \dot{q}_k(0) = q_d(0) - q_k(0) = 0$, $\forall k \in \mathbb{Z}_+$.

We will also make use of the following properties, which are common to robot manipulators

(P1) $M(q_k) \in \mathbb{R}^{n\times n}$ is symmetric, bounded, and positive definite.
(P2) The matrix $\dot{M}(q_k) - 2C(q_k, \dot{q}_k)$ is skew symmetric, hence $x^{\mathrm{T}}(\dot{M}(q_k) - 2C(q_k, \dot{q}_k))x = 0$, $\forall x \in \mathbb{R}^n$.
(P3) $\|C(q_k, \dot{q}_k)\| \leqslant k_c \|\dot{q}_k\|$ and $\|G(q_k)\| < k_g$, $\forall t \in [0, T]$ and $\forall k \in \mathbb{Z}_+$, where k_c and k_g are unknown positive parameters.

3. Adaptive ILC

Let us consider system (1) under the following control law (Fig. 1):

$$\tau_k(t) = K_P\tilde{q}_k(t) + K_D\dot{\tilde{q}}_k(t) + \eta(\dot{\tilde{q}}_k)\hat{\theta}_k(t) \tag{2}$$

with

$$\hat{\theta}_k(t) = \hat{\theta}_{k-1}(t) + \Gamma\eta^{\mathrm{T}}(\dot{\tilde{q}}_k)\dot{\tilde{q}}_k(t), \tag{3}$$

where $\hat{\theta}_{-1}(t) = 0$, $\tilde{q}_k(t) = q_d(t) - q_k(t)$ and $\dot{\tilde{q}}_k(t) = \dot{q}_d(t) - \dot{q}_k(t)$. The matrices $K_P \in \mathbb{R}^{n\times n}$ and $K_D \in \mathbb{R}^{n\times n}$ are symmetric positive definite.