Available online at www.sciencedirect.com
ScienceDirect
automatica
Automatica 42 (2006) 1761 – 1767
www.elsevier.com/locate/automatica

Brief paper

A fully adaptive decentralized control of robot manipulators☆

Su-Hau Hsu[a], Li-Chen Fu[a,b,*]

[a]Department of Electrical Engineering, National Taiwan University, Taiwan, ROC
[b]Computer Science & Information Engineering, National Taiwan University, Taiwan, ROC

Received 9 February 2004; received in revised form 2 May 2006; accepted 10 May 2006
Available online 31 July 2006

Abstract

In this paper, we develop a fully adaptive decentralized controller of robot manipulators for trajectory tracking. With high-order and adaptive variable-structure compensations, the proposed scheme makes both position and velocity tracking errors of robot manipulators globally converge to zero asymptotically while allowing all signals in closed-loop systems to be bounded, even without any prior knowledge of robot manipulators. Thus this control scheme is claimed to be fully adaptive. Even when the proposed scheme is modified to avoid the possible chattering in actual implementations, the overall performance will remain appealing. Finally, numerical results are provided to verify the effectiveness of the proposed schemes at the end.

Keywords: Decentralized control; Adaptive control; Robot manipulators

1. Introduction

The control of robotic manipulators is especially challenging due to the inherent high non-linearity in its dynamics. In a practical situation, the inevitable uncertainty in the underlying manipulator model, say, payload change, adds additional difficulty into the control task. Although significant achievements, marked by the development of adaptive and robust centralized control schemes, have been made to improve the tracking performance of robots (Slotine & Li, 1987; Spong, Thorp, & Kleinwaks, 1987), the decentralized controller structure is still adopted by the majority of modern robots in favor of its computation simplicity and low-cost hardware setup. As a result, how to best improve the tracking performance of robots through decentralized control is still an interesting research topic that attracts great attention from robotic community.

The adaptive decentralized control approaches for linear and linear-dominant systems have been well developed, for example, by Gavel and Šiljak (1989), Ioannou (1986), Shi and Singh (1992) and Wen and Soh (1999). Specifically, for a set of linear-dominant subsystems whose interconnections are nonlinear but linearly bounded by the norms of the overall system states, the approaches proposed by Gavel and Šiljak (1989) and Ioannou (1986) guarantee the exponential convergence of tracking errors and parameter estimation error to a bounded residual set. Shi and Singh (1992) use nonlinear feedback to handle the interconnections bounded by a higher-order polynomial of the system-state norms. Moreover, Wen and Soh (1999) develop a decentralized model reference adaptive control without restriction on subsystem relative degrees.

For manipulator tracking tasks, decentralized approaches are not that straightforward since the overall system cannot be decomposed into subsystems whose states and control inputs are totally decoupled from one another because of the inherent coupling such as moment of inertia and Coriolis force. In recent years, several attempts, e.g. by Fu (1992), Liu (1999), and Tang, Tomizuka, Guerrero, and Montemayor (2000), have been made for the adaptive independent-joint control (IJC) or the so-called adaptive decentralized control such that a separate actuator taking feedback only from that particular joint is responsible for the joint control. Although those schemes result in asymptotical convergence of tracking errors, prior estimation of gains is necessary, that is inconvenient in applying. In order to

☆ This paper was not presented in any IFAC meeting. This paper was recommended for publication in revised form by Associate editor Yong-Yau Cao under the direction of Editor Mituhiko Araki.
* Corresponding author. Department of Electrical Engineering, National Taiwan University, Taiwan, ROC. Tel.: +886 223 622209; fax: +886 223654267.
E-mail address: lichen@ntu.edu.tw (L.-C. Fu).

0005-1098/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.automatica.2006.05.012

resolve this problem, a novel adaptive decentralized control law is proposed here such that the desired tracking performance is achieved without any prior determination of gains.

This paper is originated as follows: Tracking problem of robot manipulators is introduced in Section 2. And then a novel adaptive decentralized control scheme is proposed in Section 3. In order to demonstrate the performance of the proposed scheme, a numerical study is provided in Section 4. Finally, a conclusion is given in Section 5.

2. Problem statement

For general n-link rigid manipulators, the dynamic model can be derived by using the Euler–Lagrangian approach and expressed in joint space as:

$$M[q(t)]\ddot{q}(t) + C[q(t), \dot{q}(t)]\dot{q}(t) + g[q(t)] = \tau(t) + d[t, q(t), \dot{q}(t)], \tag{1}$$

where $t \geqslant 0$ denotes time; $q(t) = [q_1(t), \ldots, q_n(t)]^{\mathrm{T}} \in R^n$ and $\dot{q}(t) = [\dot{q}_1(t), \ldots, \dot{q}_n(t)]^{\mathrm{T}} \in R^n$ are the vectors of joint position and velocity, respectively; $\tau(t) = [\tau_1(t), \ldots, \tau_n(t)]^{\mathrm{T}} \in R^n$ is the control input; M: $R^n \rightarrow R^{n\times n}$ such that $M[q(t)]$ is the inertia matrix; C: $R^n \times R^n \rightarrow R^{n\times n}$ such that $C[q(t), \dot{q}(t)]\dot{q}(t)$ is the vector of centrifugal and Coriolis force, g: $R^n \rightarrow R^n$ such that $g[q(t)]$ is the vector of gravitational force, and finally d: $[0, \infty) \times R^n \times R^n \rightarrow R^n$ such that $d[t, q(t), \dot{q}(t)]$ is the vector of friction input. This dynamic model has the following properties that will be used in controller design (Spong & Vidyasagar, 1989; Fu, 1992):

- (P1) The matrix $M(y)$ is a symmetric and positive-definite matrix and satisfies $\mu_m I \leqslant M(y) \leqslant \mu_M I$ for some constants μ_m, $\mu_M > 0$, where $y \in R^n$.
- (P2) The matrix $C(y, z)$ satisfies $||C(y, z)||_2 \leqslant \mu_C ||z||_2$ for some constant $\mu_C > 0$, where y, $z \in R^n$.
- (P3) The vector $g(y)$ satisfies $||g(y)||_2 \leqslant \mu_G$ for some constant $\mu_G > 0$, where $y \in R^n$.
- (P4) Time-varying matrix $\mathrm{d}/\mathrm{d}t\, M[y(t)] - 2C[y(t), \dot{y}(t)]$, is always skew-symmetric for all $t \geqslant 0$, where differentiable signals y: $[0, \infty) \rightarrow R^n$.

If an adaptive decentralized control scheme achieves the desired tracking performance without any prior knowledge of plants, it is called a fully adaptive decentralized control scheme. In this paper, such a control scheme is proposed for robot manipulators such that all signals of closed-loop systems are bounded as well as both position and velocity tracking errors globally converge to zero asymptotically. Global convergence here means convergence from any initial position and velocity tracking errors in joint space.

3. Controller design

In this section, a novel control scheme is proposed for the tracking control of general n-link rigid manipulators. Let q_d: $[0, \infty) \rightarrow R^n$ such that $q_d(t)$ for all $t \geqslant 0$ means the desired position trajectory of robot manipulators and is generally chosen twice differentiable to guarantee smoothness of the motion. Define the position tracing error $e(\cdot)$ as $e(t) = [e_1(t), \ldots, e_n(t)]^{\mathrm{T}} \in R^n$ where $e(t) \equiv q(t) - q_d(t)$ and auxiliary signal $s(\cdot)$ as $s(t) = [s_1(t), \ldots, s_n(t)]^{\mathrm{T}} \in R^n$ where $s(t) \equiv \dot{e}(t) + \Lambda e(t)$ with $\Lambda \in R^{n\times n}$ being a feedback-gain matrix. Now the dynamics defined by the signals $e(\cdot)$ and $s(\cdot)$ is derived as

$$\dot{e}(t) = -\Lambda e(t) + s(t), \tag{2a}$$

$$M[q(t)]\dot{s}(t) = -C[q(t), \dot{q}(t)]s(t) + \tau(t) - v[t, q(t), \dot{q}(t)], \tag{2b}$$

where

$$\begin{aligned} v[t, q(t), \dot{q}(t)] = {} & M[q(t)][\ddot{q}_d(t) + \Lambda \dot{e}(t)] \\ & + C[q(t), \dot{q}(t)][\dot{q}_d(t) + \Lambda e(t)] \\ & + g[q(t)] - d[t, q(t), \dot{q}(t)], \end{aligned} \tag{3}$$

behaves as the disturbance. Without loss of generality, several technical assumptions are made to pose the problem in a tractable manner.

- (A1) The feedback-gain matrix Λ is constant, diagonal and positive-definite; that is, $\Lambda = \mathrm{diag}(\lambda_1, \ldots, \lambda_n) > 0$ for any constant $\lambda_i > 0$, $i \in \{1, \ldots, n\}$.
- (A2) The desired joint position trajectory $q_d(t)$ and the time derivatives $\dot{q}_d(t)$ and $\ddot{q}_d(t)$ are bounded signals.
- (A3) Let d_i: $[0, \infty) \times R \times R \rightarrow R$, $i \in \{1, \ldots, n\}$, satisfy that $|d_i(t, y, z)| \leqslant d_{i\_1} + d_{i\_2}|y| + d_{i\_3}|z|$ for all $t \geqslant 0$ for some constant $d_{i\_j} \geqslant 0$, $i \in \{1 \ldots, n\}$ and $j \in \{1, 2, 3\}$, where y, $z \in R$, such that the friction input considered in (1) is assumed as $d[t, q(t), \dot{q}(t)] = [d_1[t, q_1(t), \dot{q}_1(t)], \ldots, d_n[t, q_n(t), \dot{q}_n(t)]]^{\mathrm{T}}$.

Remark 1. From properties (P1)–(P3) and assumptions (A1)–(A3), it is guaranteed that along the trajectory of robot manipulators the disturbance (3) satisfies the following:

$$\begin{aligned} \|v[t, q(t), \dot{q}(t)]\|_2 \leqslant {} & \eta_1 + \eta_2\|e(t)\|_2 + \eta_3\|\dot{e}(t)\|_2 \\ & + \eta_4\|e(t)\|_2\|\dot{e}(t)\|_2, \end{aligned} \tag{4}$$

with some positive constants η_1–η_4, which only depend on the desired trajectory and parameters in (1).

Before designing the claimed decentralized control law, one useful lemma should be derived first. Here we start with adopting the norm of vector-valued signals as follows: For vector-valued signals x: $[0, \infty) \rightarrow R^n$, $||x||_T$, the norm of $x(\cdot)$ for $T > 0$, is defined as $||x||_T \equiv \sup_{t\in[0,T]} ||x(t)||_2$. The following lemma will obtain another bound estimation of the disturbance (3), which is useful in control design.

Lemma 1. *Under assumptions (A1)–(A3), if there is a constant* $T > 0$ such that $||s||_T$ *exists, then there are positive constants* $\beta1$, $\beta2$ *and* $\beta3$ *such that along the trajectory of robot manipulators it is satisfied that*

$$\|v[t, q(t), \dot{q}(t)]\|_2 \leqslant \beta_1 + \beta_2\|s\|_T + \beta_3(\|s\|_T)^2, \tag{5}$$