Automatica 50 (2014) 3088–3099

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

A boundary control for motion synchronization of a two-manipulator system with a flexible beam ☆

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ARTICLE INFO

Article history:
Received 25 April 2013
Received in revised form
2 June 2014
Accepted 7 August 2014
Available online 28 October 2014

Keywords:
Motion synchronization
Coupling dynamics
Boundary control
Distributed parameter system
Riesz basis

ABSTRACT

A novel synchronization motion control method is proposed in this paper for the system in which two manipulators are constrained by a flexible beam. Different from the general synchronization control method, the coupling dynamics among various actuators is considered as the shear force, which results from the synchronization errors. Then a simple boundary control is introduced to realize the synchronization motion of actuators by suppressing the shear force. In order to avoid the drawbacks of assumed modes model, the dynamic model of flexible beam is described by a distributed parameter model in this paper. A Riesz basis method is used to prove that the proposed control law can guarantee the synchronization system to be exponential stability. Simulation results demonstrate that the proposed method can effectively improve the performance of synchronization motion compared with other methods.

1. Introduction

In the industrial systems, one often encounters situations, in which a number of individual actuators are combined into one operation. The most familiar examples are the motion synchronization systems. Here, a special motion synchronization system in which the actuators are constrained by a mechanism structure is concerned, such as the synchronized lifting equipment (Li, Mannan, Xu, & Xiao, 2001; Sun & Chiu, 2001, 2002). It is more difficult for this situation to realize the motion synchronization. That is because such constraint results in the force couplings among various actuators. The coupled force may deform or damage the mechanical structure or actuators, for instance, when actuators move at high acceleration. Hence, how to regulate the position errors of individual actuators while avoiding the deformation of mechanical structure is the key to the success of such synchronization motion.

Researches on the synchronization control have traditionally only used position or velocity coupling error to represent the coupling effect. And the coupling error is usually defined by authors. (Lu, Mills, & Sun, 2006a) proposed an adaptive synchronized controller for a planar parallel manipulator. The coupling effects among the sub manipulators are represented by coupling error, which consists of position error of each joint and velocity synchronization error. To reflect the kinematic constraints among the actuated joints and the platform, the forward Jacobian matrix is introduced into the definition of velocity synchronization error. With employment of the control law which is designed based on the coupling error, tracking accuracy of PRR manipulator is improved. Subsequently, Lu, Mills, and Sun (2006b) proposed a convex synchronization controller for a 3-DOF planar parallel manipulator. A new coupling error which consists of position error of each active joint and position synchronization error is defined. In the expression of position synchronization error, position errors of active joints are coupled with each other by a constant gain matrix. Through combining this proposed synchronized control method and convex method, the tracking accuracy of 3-DOF planar parallel manipulator is improved. The cross-coupling method is also a widely used method which makes use of the defined position or velocity coupling error to represent the coupling effect. Sun (2003) proposed an adaptive cross-coupling controller to address position synchronization of multiple motion axes. The position synchronization errors are considered as coupling effects amongst various axes. In the controller design, a coupled error concept which is different from Lu in Lu et al. (2006b) is defined. The integration of

☆ This paper was supported by the National Natural Science Foundation of China (No. 51175014), Program 111 and the National Basic Research Program of China (2014CB046402). The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Yoshihiko Miyasato under the direction of Editor Toshiharu Sugie.

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http://dx.doi.org/10.1016/j.automatica.2014.10.057
0005-1098/

position synchronization error is introduced into the coupled error. Then a controller is designed to make the coupled error and its differential tend to zero. Simulations demonstrate that the proposed controller can guarantee asymptotic convergence to zero of both position and synchronization errors. The cross-coupling approach used in robotics can also be found in Shang, Cong, and Zhang (2009), Sun, Lu, Mills, and Wang (2006), Sun and Mills (2002), Sun, Wang, Shang, and Feng (2009) and Zhao, Li, and Gao (2008). In these methods, the actual force coupling dynamics is not considered. In the situation of this paper, the actuators are constrained by a mechanism structure. Neglecting force coupling dynamics may damage the mechanical structure in some extreme operational situations, for instance, when actuators move at high acceleration. So these methods are not suitable for this paper. In order to avoid the deformation of mechanism structure, effective force coupling characteristics caused by the constraint should be derived at first.

Another group of researchers focused on obtaining the force coupling dynamic characteristics to deal with the coupling effect of synchronization problem. Sun in Sun and Chiu (2002) derived the force coupling dynamics for a dual-cylinder electro-hydraulic (EH) lifting system. Based on the proposed force coupling dynamics, a qualitative feedback theory (QFT) design is used to obtain the decoupling dynamic characteristics. The decoupled dynamics can reduce the complexity of controller from multi-input multi-output (MIMO) to single-input single-output (SISO). But in this force coupling dynamics, only the force due to uneven loading between two cylinders is considered. The force coupling dynamics due to constraint of mechanical structure is not considered. The same issue can be found in Sun and Chiu (2001).

In this paper, a two-manipulator system in which the two tips are constrained by a flexible beam is considered. Under the constraint of flexible beam, that the operation of two manipulators is not synchronous will result in shear force, which can not only deform the flexible beam but also lead to interaction between two manipulators. Based on the shear force couplings, the force coupling dynamics is derived in this paper at first. Then a novel synchronized control method is proposed. There have been many researches on a two-manipulator system handling a flexible beam (Esakki, Bhat, & Su, 2011; Sun & Liu, 2001; Tavasoli, Eghtesad, & Jafarian, 2009). But in these papers, the flexible beam is approximated by finite series of assumed modes, which bring the following problems. On the one hand, the dimension of the controller increases along with an increase in the number of the modes which are provided in the controller design model (Endo, Matsuno, & Kawasaki, 2009). On the other hand, it is very hard to know the actual number of modes that should be retained a priori (Morgul, 1991). For these reasons, the flexible beam is derived in infinite dimensional model by using partial differential equations (PDEs) in this paper. Different from the general synchronization control methods, a boundary control law is used to realize the synchronization motion of two manipulators by suppressing the shear force. A position control law is incorporated into the boundary control to realize the regulation of position errors. A Riesz basis approach is used to prove the whole system with the proposed control law to be exponential stability. The simulation results on the two-manipulator system with a flexible beam demonstrate the effectiveness of the proposed method.

The rest of this paper is organized as follows. Dynamic model is presented in Section 2 followed by the discussion of sync motion control design. The force control is discussed in detail in Section 4 followed by the discussion of compared simulation results. Conclusions are presented in Section 6.

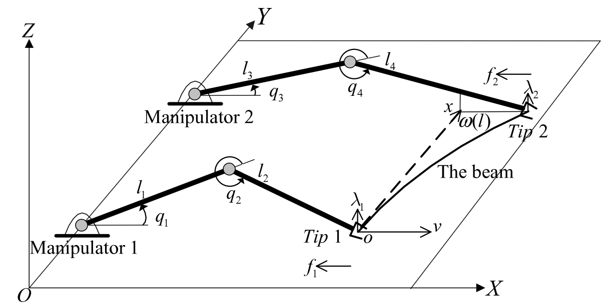

Fig. 1. The synchronization motion system.

2. Dynamic model

2.1. Description of system

The system is illustrated in Fig. 1, which consists of two planar manipulators with two revolute joints and a manipulated flexible beam. And the manipulators can only move on the Z–X plane. For simplicity, assume that the longitudinal deformation of the beam is neglected, and only the transverse deformation along coordinate X occurs. Therefore, an additional constraint control for each manipulator is given to guarantee coordinate Z of each tip to be zero in this paper. The constraint conditions are as follows:

$$\Phi_1 = l_1 \sin(q_1) + l_2 \sin(q_1 + q_2) = 0 \tag{1}$$

$$\Phi_2 = l_3 \sin(q_3) + l_4 \sin(q_3 + q_4) = 0 \tag{2}$$

where q_1 and q_2 are joint coordinates of manipulator 1, q_3 and q_4 are joint coordinates of manipulator 2, l_i $(i = 1, 3)$ is the length of the first link of manipulator i $(i = 1, 2)$, l_i $(i = 2, 4)$ is the length of the second link of manipulator i $(i = 1, 2)$. Under (1) and (2), the tips of two manipulators can only move along coordinate X. The motion control object is to make the tips of two manipulators reach desired positions while maintaining the synchronization motion of the two tips.

2.2. Beam kinematics and dynamics

The beam is considered as an Euler–Bernoulli beam with length l, uniform linear mass density ρ, and uniform flexural rigidity EI. Assume that the deformation of the beam is very small. Thus the motion of the beam can be considered as comprising its rigid motion and elastic deformation. In modeling of the beam, end 1 of the beam is assumed to have no deformation and end 2 of the beam has deformation as in Sun and Liu (2001). According to this assumption, the following boundary conditions of the flexible beam are obtained

$$\omega(0, t) = 0, \qquad \omega'(0, t) = 0, \qquad \omega''(l, t) = 0. \tag{3}$$

And the rigid motion of the beam can be represented by the motion of tip 1 along coordinate X as shown in Fig. 1 (dotted line). To describe the deformation of the beam, a mobile coordinate frame o–xv is attached to the rigid body of the beam, where the origin o is located at the tip 1. The deformation is modeled as relative displacements with respect to the mobile frame o–xv. Thus, the motion of any point on the beam is described as:

$$x_{\text{beam}} = x_1(t) + \omega(x, t) \tag{4}$$

where $x_1(t)$ is the displacement of the tip 1 along coordinate X, $\omega(x, t)$ is the transverse deformation of the beam along coordinate v, $x \in [0, l]$ denotes the spatial coordinate of rigid beam. Define $x_2(t)$ as the displacement of tip 2 along coordinate X. By using Eq. (4), the following constraint relation is obtained

$$x_2(t) = x_1(t) + \omega(l, t). \tag{5}$$