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Boundary cooperative control by flexible Timoshenko arms[☆]

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ABSTRACT

This paper discusses a cooperative control problem by two one-link flexible Timoshenko arms. The goal is to control a grasping force to collect an object with the two flexible arms, and to simultaneously suppress the vibrations of the arms. To solve this problem, we propose a boundary controller that is based on a dynamic model represented by a hybrid PDE–ODE model; the exponential stability of the closed-loop system is then proven by the frequency domain method. Finally, several numerical simulations are carried out to investigate the validity of the proposed boundary cooperative controller.

1. Introduction

A flexible arm is a controlled system modeled by partial differential equations (PDEs) to present the dynamics of the elastic links, and ordinary differential equations (ODEs) to present the dynamics of sensors, actuators, and tip loads. The dynamic model of the flexible arm is thus a hybrid PDE–ODE model. The Euler–Bernoulli beam model in particular is widely used to present the dynamics of the elastic links. On the other hand, the Timoshenko beam model is a modified model of the Euler–Bernoulli beam model that includes the effects of shear and rotational inertia. Therefore, the Timoshenko beam model can be used in a wider range of applications than the Euler–Bernoulli beam model (Han, Benaroya, & Wei, 1999; Huang, 1961). Here, the flexible arm, modeled as a Timoshenko beam, is called the flexible Timoshenko arm.

There have been several relevant studies about the flexible Timoshenko arm based on the hybrid PDE–ODE model (Endo, Sasaki, & Matsuno, 2017; Grobbelaar-Van Dalsen, 2010; He, Zhang, & Ge, 2013; Macchelli & Melchiorri, 2004; Morgül, 1992; Muñoz Rivera & Ávila, 2015; Taylor & Yau, 2003; Zhang, Dawson, de Queiroz, & Vedagarbha, 1997; and references therein). However, many of these studies on hybrid PDE–ODE infinite dimensional settings address only the vibration suppression problem. This is insufficient for use of the flexible arm for more complex tasks. In addition to the vibration control, the force control, that is the control of the contact force at the contact point where the flexible arm touches an object or the environment, is necessary for realization of more complex tasks (Hokayem & Spong, 2006; Yoshikawa, 2000). Very few studies, Endo et al. (2017) have investigated the force control problem of the flexible Timoshenko arm.

This paper discusses the cooperative control problem of two one-link flexible Timoshenko arms modeled by hybrid PDE–ODE infinite dimensional model. This problem is a typical applied force control problem. In the cooperative control problem, two one-link flexible Timoshenko arms grasp an object, and the flexible arms control the contact-force at the contact point to achieve the desired grasping force. From the point of view of cooperative control, control of grasping force must consider the following: how to control the internal force applied to the grasped object by the two flexible Timoshenko arms, and how to control the motion of the grasped object. For cooperative control of the flexible arms, it is necessary to suppress vibration in the arms, as well as to control the grasping force. Although there has been little research on the cooperative control of flexible arms, several studies have investigated the

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infinite dimensional settings (Dou & Wang, 2014; Endo, Matsuno, & Kawasaki, 2009; Matsuno & Hayashi, 2000; Morita, Matsuno, Ikeda, Ukai, & Kando, 2003). These studies (Endo et al., 2009; Matsuno & Hayashi, 2000; Morita et al., 2003), discussed the cooperative control by two one-link flexible arms modeled by the Euler–Bernoulli beam model, and proposed asymptotic/exponential stabilizing controllers. Dou and Wang (2014) had a slightly different focus, proposing a cooperative controller for a system in which two rigid arms grasp a flexible object modeled by the Euler–Bernoulli beam. To the best of our knowledge, however, there has been no study of cooperative control by the flexible Timoshenko arms based on the hybrid PDE–ODE infinite dimensional model. As mentioned above, the Timoshenko beam model is a modified model of the Euler–Bernoulli beam model, and its application range is wide. Thus, the cooperative control problem by two one-link flexible Timoshenko arms is a challenging and useful issue.

In this paper, we propose a simple boundary cooperative controller for the cooperative control of two one-link flexible Timoshenko arms. Many boundary controllers have been proposed for various hybrid PDE–ODE infinite dimensional models other than the flexible Timoshenko arm (e.g., Choi, Hong, & Yang, 2004; Curtain & Zwart, 2016; d'Andréa-Novel, Boustany, Conrad, & Rao, 1994; Endo, Matsuno, & Kawasaki, 2014; He, Ge, How, Choo, & Hong, 2011; Krstic & Smyshlyaev, 2008; Littman & Markus, 1988; Luo, Guo, & Morgul, 1999; Matsuno, Ohno, & Orlov, 2002; Nguyen & Hong, 2010; Slemrod, 1989; Yang, Hong, & Matsuno, 2005). In the boundary controller, the control action is at the boundary of the systems. Consideration of the distributed controller of the hybrid PDE–ODE model (e.g. He, Yang, Meng, & Sun, 2016; Hong, 1997) reveals that implementation of the boundary controller is generally easy from a practical point of view. We therefore propose a boundary controller to solve the cooperative control problem by two one-link flexible Timoshenko arms modeled by the hybrid PDE–ODE model. The proposed system consists of two flexible Timoshenko arms installed on a slider. The two arms push an object toward each other from opposite sides using the same force; together they produce a positive internal force and the object is grasped by the flexible arms. In addition, the motion of the grasped object is realized by the motion of the slider. We prove that cooperative control is accomplished; that is, we prove the exponential stability of the closed-loop system by the frequency domain method. In addition, we consider the robustness of the proposed boundary controller with respect to the disturbance at the grasped object and the control input. The paper is organized as follows: in Section 2, we formulate the control problem and propose a simple boundary cooperative controller. Section 3 presents the semigroup setting of the closed-loop system. Exponential stability and the robustness are given in Section 4. The numerical simulation results, which demonstrate the validity of the proposed boundary controller, are presented in Section 5. Finally, Section 6 contains our conclusions.

2. System description and boundary controller

2.1. A controlled system

Fig. 1 illustrates a controlled system. The system consists of two one-link flexible arms and a grasped object. One end of flexible arm i, $i = 1, 2$, is clamped to the rotational motor i, and the other end has a concentrated mass m_i. The mass makes contact with a surface of the grasped object. Two rotational motors are installed on the slider; thus, we used three actuators here. This is because, in the vibration control problem of one-link Timoshenko beam, it is well known that a system with one actuator at the free end is exponentially stable if and only if the two wave speeds are equal (this is a physically impossible condition) (Almeida Júnior, Santos, & Muñoz Rivera, 2013; Soufyane & Wehbe, 2003). To obtain exponential stability while avoiding this physically impossible condition, it is desirable that the effects of two actuators, such as force and torque, act on one beam. Here, we set two rotational motors and one slider to act as the effects of force and torque at each flexible beam. Using these actuators, the flexible arms rotate and translate in the XY plane in Fig. 1, and thus it is not affected by the acceleration of gravity. The flexible arm i, with mass per unit length ρ_i, mass moment of inertial μ_i, flexural rigidity EI_i, cross sectional area A_i, shear modulus G_i, shear coefficient κ_i, and length l, satisfies the Timoshenko beam hypothesis.

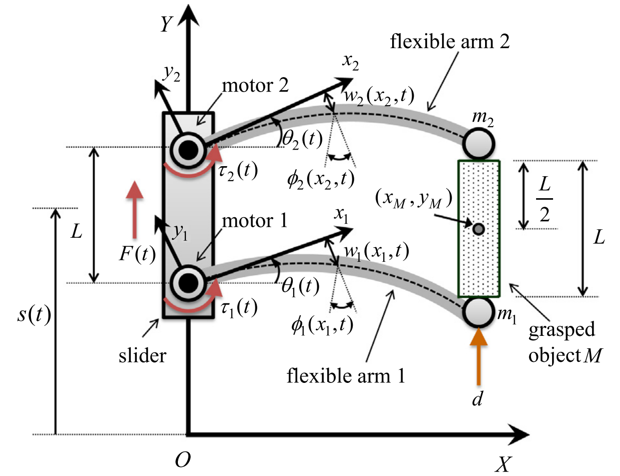

Fig. 1. Grasped object and two flexible Timoshenko arms.

In Fig. 1, XY is an absolute coordinate system, and x_iy_i is a local coordinate system, which rotates with the rotor of the motor i and translates with the slider. Let $w_i(x_i, t)$ and $\phi_i(x_i, t)$ be the transverse displacement and the rotation of the cross section of the flexible arm i, respectively, where x_i is the spatial point on the local coordinate system x_iy_i, and t is a time. In addition, let $\theta_i(t)$, $\tau_i(t)$, J_i, $s(t)$, $F(t)$, and M_s be the angle, torque, and inertial moment of motor i, the position of the slider between O and the center of the slider, the force of the slider, and the mass of the slider, respectively. The disturbance d acts at the grasped object, and the disturbance response is discussed in Section 4.2. For the grasped object, let M and L be the mass and length of the object, respectively, and (x_M, y_M) be the position vector of the center of mass in XY. Note that $w_i(x_i, t)$, $\phi_i(x_i, t)$, $\theta_i(t)$, and $s(t)$ are assumed to be small, and the distance between motors 1 and 2 is L. Here, note that we make the assumption that the distance between motors 1 and 2 is L to derive the homogeneous boundary conditions. If we do not assume this point, we cannot obtain homogeneous boundary conditions such as (4), and we cannot analyze the system. We plan to consider how to eliminate the need for this assumption in future work. In addition, in terms of the contact between the grasped object and flexible Timoshenko arms, we assume the following: the contact is described by a frictional point contact model (Murray, Li, & Sastry, 1994); there is no slippage and no contact break; the positions of contact points on the X-axis are equal to x_M, and these do not change during movement because both flexible Timoshenko arms are equal in length. Therefore, the flexible arms exert force to the grasped object only in the Y direction, and the grasped object is moved only on the Y-axis.

Since the tip mass makes contact with the surface of the grasped object, we obtain the following geometric constraint:

$$\Phi_i := s(t) + l\theta_i(t) + w_i(l, t) - y_M(t) = 0, \quad \text{for } i = 1, 2. \tag{1}$$