Mechanism and Machine Theory 79 (2014) 217–229

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Bending moment-based force control of flexible arm under gravity

Takahiro Endo, Haruhisa Kawasaki

Faculty of Engineering, Gifu University, 1-1 Yanagido, Gifu 501-1193 Japan

A R T I C L E I N F O

Article history:
Received 23 October 2013
Received in revised form 18 April 2014
Accepted 21 April 2014
Available online 16 May 2014

Keywords:
Force control
Flexible arm
Distributed parameter systems

A B S T R A C T

We discuss the force control problem for a constrained one-link flexible arm with the effect of gravity, based on a distributed parameter model. To solve the force control problem, we propose a simple controller constructed using only the bending moment at the root of the flexible arm. Information about the force and rotational angle of the motor is not necessary for implementation of the controller, and thus a force sensor and encoder are not needed. Several numerical simulations were carried out to determine the performance of the proposed controller, and we found that it works well for force control.

1. Introduction

Studies of flexible arms have traditionally focused on vibration or tip position control [1]. However, vibration or tip position control alone does not provide enough control to use a flexible arm for more complex tasks. It is also necessary to control the contact force applied to an object or environment at the contact point [2]. For example, minimally invasive surgery systems use thin and lightweight instruments like a flexible arm, which makes contact inside the patient's body [3,4]. Force control is required when using a flexible arm for such a complex task.

Eppinger and Seering (1986) proposed that link flexibility may contribute to the instability problem in force control [5]. Since then, many researchers have investigated the force control of flexible arms based on a finite-dimensional approximated model [6–11]; this has meant, however, that the findings obtained in these studies are confined to the finite-dimensional approximated model. Because that model is derived by neglecting infinite modes, the following problems arise. The dimension of the controller increases along with an increase in the number of modes provided in the controller design model. Furthermore, spillover, which results from a neglected high-frequency characteristic, makes such systems unstable. For these reasons, it is both desirable and of interest to consider the force control of a flexible arm using the infinite dimensional model.

In contrast to investigations based on the finite-dimensional approximated model, there are only a few studies based on the infinite dimensional model [12–15]. In these studies, the force control problem for a one-link flexible arm was discussed, and an asymptotic stabilizing controller of the closed-loop system was constructed. In a previous study, we also examined the force control of a one-link flexible arm, and proposed an exponential stabilizing controller [16]. However, these controllers require accurate velocity information (e.g., angular velocity of the motor, and time derivative of the bending moment) that is difficult to obtain from the point of view of implementation.

In contrast, for position control of a rigid robot manipulator, controllers that use only position measurements – i.e., that does not need velocity information – have been proposed for many years [17–19]. The controller in [16] consists of the bending moment at the root of the flexible arm and its time derivative (see Eq. (12)).

E-mail address: tendo@gifu-u.ac.jp (T. Endo).

http://dx.doi.org/10.1016/j.mechmachtheory.2014.04.013

In this paper, we use the dynamic compensator (the differentiation filter) proposed in [17–19], and estimate the value of the time derivative of the bending moment. Through this procedure, we propose a controller that accomplishes the force control of a flexible arm using only bending moment information. In particular, we consider the case in which the system is affected by the acceleration of gravity. A large number of publications about the control of flexible link arms are motivated by applications for outer space, where gravity is absent. This paper, in contrast, is written from the perspective of systems that work on earth, such as those designed to perform a minimally invasive surgery. Thus, we consider a system affected by the acceleration of gravity. We also confirm the asymptotic stability of the closed-loop system, and describe our simulations of the controller's performance.

To summarize, this paper improves on our previous controller [16], and presents the following new content: a controller constructed with only the bending moment, a discussion about a system subject to the influence of gravity acceleration, a new asymptotic stability proof, and new simulation results. The advantages of our proposed controller include: (1) it does not require velocity information, and thus does not need a force sensor or encoder for implementation, and (2) it works not only in space applications but also for tasks on earth.

The paper is organized as follows: in the next section, we describe the mathematical model of the constrained one-link flexible arm under gravity. Section 3 presents the proposed controller and proof of the stability of the closed-loop system. In Section 4, we describe several numerical simulations to demonstrate the validity of the proposed controller. Section 5 presents our conclusions.

2. Description of the problem

2.1. Dynamics of a constrained flexible arm under gravity

Fig. 1 illustrates the constrained one-link flexible arm that we consider. One end of the arm is clamped to the motor, and the other end has a concentrated mass m. This tip mass makes contact with the surface of an object. Using the motor, the flexible arm rotates in the vertical plane (XY plane in Fig. 1) and is affected by the acceleration of gravity (g). In Fig. 1, this gravitational force works in the direction opposite to the Y-axis. Note that Fig. 1 is 3D, but that we consider the 2D movement of the flexible arm. The flexible arm, having length (l), uniform linear mass density (ρ), and uniform flexural rigidity (EI), satisfies the Euler–Bernoulli beam hypothesis. In this paper, we assumed the flexible arm to be a slender beam, and thus the Euler–Bernoulli beam hypothesis to be valid. It should be noted that if a non-slender beam were used for the flexible arm, the Euler–Bernoulli beam would have to be replaced by the Timoshenko beam theory.

Let $O-XY$ be a world coordinate system and $O-xy$ a local coordinate system, as shown in Fig. 1. The origin of $O-xy$ is fixed at the rotor of the motor, and $O-xy$ rotates with the rotor. Let J, $\tau_m(t)$, $\theta(t)$, and $w(x,t)$ be the moment of inertia of the rotor of the motor, the torque generated by the motor, the rotational angle of the arm, and the transverse displacement of the flexible arm at time t and at a spatial point x, respectively. Note that $\theta(t)$ and $w(x,t)$ are assumed to be small; this is because, in this paper, we consider the force control of a flexible arm where it makes contact with an object. If we considered a large movement of $\theta(t)$, plastic deformation of the flexible arm could occur, or the flexible arm could generate excessive force at the contact point. These are critical problems, and are not realistic for force control.

Since the tip mass contacts the surface of the object, we obtain a geometric constraint as follows:

$$\Phi \equiv l\theta(t) - w(l,t) = 0. \tag{1}$$

Under the above preparation, we can obtain the equations of motion using the procedure described in [7] as follows:

$$\ddot{w}(x,t) + \frac{EI}{\rho} w''''(x,t) = x\ddot{\theta}(t) - g, \quad 0 < x < l, \quad t > 0, \tag{2}$$

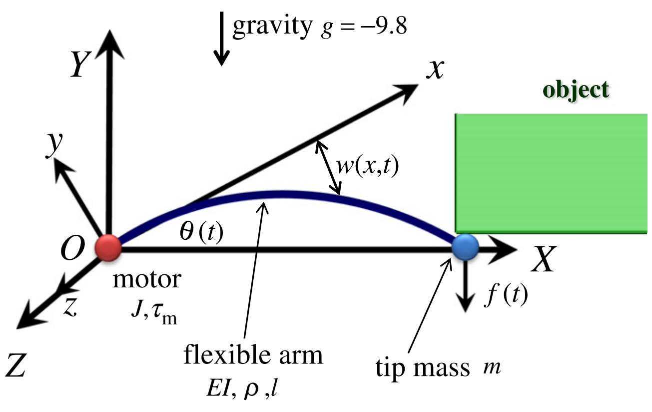

Fig. 1. One-link flexible arm making contact with an object.