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Brief paper

Cooperative control of a nonuniform gantry crane with constrained tension ☆

Wei He [a], Shuzhi Sam Ge [b,c]

[a] School of Automation and Electrical Engineering, University of Science and Technology Beijing, Beijing 100083, China

[b] Department of Electrical & Computer Engineering, National University of Singapore, Singapore 117576, Singapore

[c] Center for Robotics, University of Electronic Science and Technology of China, Chengdu 611731, China

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ABSTRACT

In this paper, the control problem is addressed for a hybrid PDE–ODE system that describes a nonuniform gantry crane system with constrained tension. A bottom payload hangs from the top gantry by connecting a flexible cable. The flexible cable is nonuniform due to the spatiotemporally varying tension applied to the system. The control objectives are: (i) to position the payload to the desired setpoint, (ii) to regulate the transverse deflection of the flexible cable, and (iii) to keep the tension values remaining in the constrained space. Cooperative control laws are proposed and the integral-barrier Lyapunov functions are employed for stability analysis of the closed-loop system. Adaption laws are developed for handling parametric uncertainties. The bounded stability is guaranteed through rigorous analysis without any simplification of the dynamics. In the end, numerical simulations are displayed to illustrate the performance of the proposed cooperative control.

1. Introduction

Overhead cranes (d'Andrea Novel, Boustany, Conrad, & Rao, 1994; d'Andrea Novel & Coron, 2000; Fang, Dixon, Dawson, & Zergeroglu, 2003; Ngo & Hong, 2012) are widely used to move the large/heavy objects horizontally for either manufacturing or maintenance applications in many industrial environments, such as ocean engineering, nuclear industries, and airports, etc. In Fang, Ma, Wang, and Zhang (2012), a novel planning-based adaptive control method is proposed for the underactuated overhead crane system. A typical gantry crane system consists of a top trolley, a flexible cable, and a bottom payload as shown in Fig. 1. During the transport of the payload to the desired setpoint, the payload swings freely which makes accurate positioning more difficult. In addition, the flexible property of the cable and the external disturbances exerted on the flexible structures, would cause large vibrations. The large vibrations lead to the fluctuating forces stressed on the cable which will result in the fatigue failure, lead to limited productivity and degrade the performance of system. Therefore, the vibration control for a gantry crane system is an important engineering problem (Fang, Wang, Sun, & Zhang, 2014; Rahn, Zhang, Joshi, & Dawson, 1999).

Various flexible structures (Bhikkaji, Moheimani, & Petersen, 2012; Bobasu, Danciu, Popescu, & Rasvan, 2012; Do & Pan, 2008; He, Ge, & Zhang, 2011; Jin & Guo, 2015; Krstic, 2009; Krstic, Guo, Balogh, & Smyshlyaev, 2008; Nguyen & Hong, 2012; Paranjape, Guan, Chung, & Krstic, 2013; Yang, Hong, & Matsuno, 2005a), represented by coupled partial differential equations (PDEs)-ordinary differential equations (ODEs), are ubiquitous in industry. In literature, many control techniques have been used for various distributed parameter systems (Bernard & Krstic, 2014; Christofides & Armaou, 2000; Guo & Jin, 2015; Ren, Wang, & Krstic, 2013; Wang, Ren, & Krstic, 2012; Wu, Wang, & Li, 2012, 2014; Yang, Hong, & Matsuno, 2005b). Among those methods, boundary control is regarded as a relatively more practical method. Due to the large applications in industry, the control problem for string-based structures has received much attention. Boundary control is designed in Rahn et al. (1999) for a cable with a gantry crane modeled by a string structure, and the experiment is implemented to verify the control performance. The vibration of a

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E-mail addresses: hewei.ac@gmail.com (W. He), samge@nus.edu.sg (S.S. Ge).

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flexible string system is suppressed by using the robust adaptive boundary control in He and Ge (2012), where the stability of the closed-loop system is discussed via Lyapunov's direct method. However, a constant axial tension is assumed in papers mentioned above. From a practical point of view, many string systems do not have to be uniform and it could have a varying tension. The control design for nonuniform flexible structures has also made a great deal of progress. The transverse vibrations of a moving string with a varying tension are regulated in Yang, Hong, and Matsuno (2004) by developing a robust adaptive boundary control. In Nguyen and Hong (2010), an axially moving string with nonlinear behavior is investigated by using a robust adaptive boundary control, where a hydraulic actuator equipped with a damper is used at the right boundary of the string. By using state feedback, the vibration problem of a moving string is addressed by employing the boundary control design in Fung and Tseng (1999), where the asymptotic and exponential stability is achieved. For the system with uncertain parameters, the adaptive control method is usually employed. The adaptive control is studied in Liu and Tong (2015) and Liu, Tang, Tong, and Chen (2015) for nonlinear discrete-time systems with dead-zones by constructing adaptive neural network controller and the originality of approach lies in that an adaptive dead-zone compensatory term is framed to overcome the effect of dead-zones. In Liu, Gao, Tong, and Chen (2016), a more general scheme is designed for nonlinear discrete-time systems with nonlinear dead-zone input and unknown discrete-time control direction by using discrete-time Nussbaum gain technique.

Tension is the pulling force exerted by a cable trying to restore its original when it is deformed. The large tension will make the cable broken especially at the connection point, as the boundaries of a cable tend to fray readily. Therefore, keeping the tension values remaining in the constrained space may effectively avoid serious hazards. The vibration of the flexible cable is known to be the main cause of the swing of the payload, which can result in the unprecise positioning. Hamilton's principle is applied to model the dynamics of the gantry crane system. The mechanical energy of the system is used to construct the Lyapunov candidate functions (He et al., 2011; He, He, & Ge, 2014; Queiroz, Dawson, Nagarkatti, & Zhang, 2000; Zhang, He, & Ge, 2012) for the control design and the stability analysis. Due to the strain resulting from the transverse displacement of the cable, the gantry crane system is modeled to have a varying tension which is given as a nonlinear spatiotemporally varying function. Since the varying tension is a function of the state variable, with the barrier Lyapunov function (Tee, Ren, & Ge, 2011), the tension constraint satisfaction is achieved by ensuring that the state variables remain in the given space. In recent years, the barrier Lyapunov function is widely used for both the ODE systems (Liu & Tong, 2016) and PDE systems (He & Ge, 2015; He, Zhang, & Ge, 2014a).

In this paper, through the dynamical models and Lyapunov's method, in order to position the payload to the desired position D, to suppress the transverse vibrations of the flexible cable, and to keep the tension values remaining in the constrained space, two boundary control laws (act on the trolley and payload, respectively) are needed to be cooperatively designed for the gantry crane system. Therefore, we define them as cooperative control law. All the signals in the proposed control depend on the boundary displacement and slope measurements of the flexible cable, making the control laws implementable. The control of the infinite-dimensional crane system is achieved by using two single-point control inputs.

2. Problem formulation and preliminaries

As shown in Fig. 1, a bottom payload hangs from the top of the gantry (trolley) by connecting a flexible cable. In this paper, we consider the transverse deflection of the cable only. Frame x_bOy_b is the fixed inertia frame, and frame x_aOy_a is the local reference frame fixed along the vertical direction of the cable. Let $y(x, t)$ be the position of the flexible cable with respect to frame x_bOy_b at the position x for time t, $y_0(t)$ denote the position of the gantry, and $w(x, t)$ represent the elastic transverse reflection with respect to frame x_aOy_a at the position x for time t. From Fig. 1, we have $y(x, t) := y_0(t) + w(x, t)$.

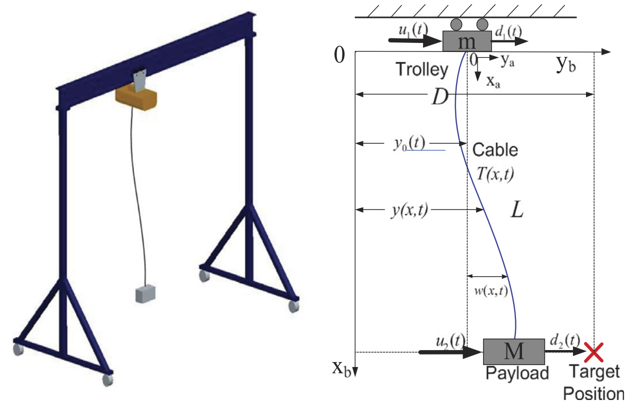

Fig. 1. A gantry crane with flexible cable.

Remark 1. Notations $(\cdot)' := \frac{\partial(\cdot)}{\partial x}$ and $\dot{(\cdot)} := \frac{\partial(\cdot)}{\partial t}$ are used throughout of this paper.

Remark 2. Due to the connection between the trolley and the top boundary of the flexible cable, i.e., $w(0, t) = 0$, then, $y(0, t) := y_0(t)$, $\dot{y}(0, t) := \dot{y}_0(t)$ and $\ddot{y}(0, t) := \ddot{y}_0(t)$ are the position, velocity and acceleration of the trolley respectively. $y(L, t)$, $\dot{y}(L, t)$ and $\ddot{y}(L, t)$ are the displacement, velocity and acceleration of the payload respectively.

2.1. Dynamics of the nonuniform gantry crane system

In this paper, we consider the spatiotemporally varying tension $T(x, t)$ and the nonuniform mass per unit length $\rho(x)$ of the flexible cable. Dynamic equations of the nonuniform gantry crane system in Fig. 1 can be derived by using Hamilton's principle (Goldstein, 1951). The kinetic energy of the nonuniform gantry crane system $E_k(t)$ can be represented as

$$E_k(t) = \frac{M}{2}[\dot{y}(L, t)]^2 + \frac{m}{2}[\dot{y}(0, t)]^2 + \frac{1}{2}\int_0^L \rho(x)[\dot{y}(x, t)]^2 dx, \quad (1)$$

where x and t represent the independent spatial and time variables respectively, L is the length of the flexible cable, m is the mass of the trolley, and M is the mass of the payload.

The potential energy $E_p(t)$ due to a spatiotemporally varying tension $T(x, t)$ can be obtained from

$$\begin{aligned} E_p(t) &= \frac{1}{2}\int_0^L T(x, t)\left[w'(x, t)\right]^2 dx \\ &= \frac{1}{2}\int_0^L T(x, t)\left[y'(x, t)\right]^2 dx, \end{aligned} \quad (2)$$

where the cable tension $T(x, t)$ can be expressed as

$$\begin{aligned} T(x, t) &= T_0(x) + \lambda(x)[w'(x, t)]^2 \\ &= T_0(x) + \lambda(x)[y'(x, t)]^2, \end{aligned} \quad (3)$$

where $T_0(x) > 0$ is the initial tension, and $\lambda(x) \geq 0$ is the nonlinear elastic modulus (Qu, 2001).