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ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

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

Research Article

Robust adaptive antiswing control of underactuated crane systems with two parallel payloads and rail length constraint

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ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form
15 July 2016
Accepted 29 July 2016
This paper was recommended for publication by Jeff Pieper.

Keywords:
Underactuated systems
Rail length limitation
Antiswing control
Parameter uncertainties
Motion analysis

ABSTRACT

The antiswing control and accurate positioning are simultaneously investigated for underactuated crane systems in the presence of two parallel payloads on the trolley and rail length limitation. The equations of motion for the crane system in question are established via the Euler–Lagrange equation. An adaptive control strategy is proposed with the help of system energy function and energy shaping technique. Stability analysis shows that under the designed adaptive controller, the payload swings can be suppressed ultimately and the trolley can be regulated to the destination while not exceeding the pre-specified boundaries. Simulation results are provided to show the satisfactory control performances of the presented control method in terms of working efficiency as well as robustness with respect to external disturbances.

1. Introduction

Over the past decades, the control of underactuated mechanical systems has become an active subject in the nonlinear control community [1–4]. Since underactuated systems have fewer number of independent actuators than degrees of freedom to be controlled, control design for such systems poses a challenge to control engineers. As an important class of underactuated systems, bridge cranes act as an indispensable role in modern industrial process because its widespread application in the real world [5]. To the best of our knowledge, the entire crane work process can be broken into the following three stages: hoisting the payload to a safe location, driving the trolley along the horizontal rail, and lowering the payload to end the transportation task. To avoid severe accidents, it strongly requires that the payload swing should be restrained as a small-amplitude swing in the second phase, and best and completely eliminated in the beginning of the third stage [6,7]. As a consequence, antiswing control for bridge cranes is theoretically and practically crucial, and many endeavors have been devoted to this direction. The early used method is linear approach (see, for example, [8]), which subsequently generates a lot of linear control schemes, such as input shaping [9] and offline position planning [10].

Subsequently, some nonlinear control strategies and fuzzy control methods are reported successively in the literature (see [11,12] and references therein) to meet the higher control objective. It should be mentioned that since the crane system is typically passive, the energy-based control, which belongs to nonlinear control community, receives the most extensive attention during the past ten years (see [13,14] and the references cited therein for an interesting introduction to this quickly expanding area). However, these traditional energy-based methods are always dependent of system parameters, and therefore they are sensitive to parameter variation. An end-effector motion-based approach was designed in [15] such that the control law was in a simpler form independent of plant parameters. Considering the varying rope length and unknown parameters, Sun et al. [16] proposed an adaptive mechanism to handle the system uncertainties, trolley positioning, load hoisting/lowering, and payload swing elimination. Compared with the traditional adaptive mechanism (see e.g., [17,18]), Sun et al. [16] constructed a new adaptive method which can accurately identify the unknown parameter.

The rail length is not considered in the previous works related to bridge cranes. Due to the physical constraints, the trolley must be operated within a specified motion scope. Once the trolley goes beyond the motion range, severe collisions will happen around the boundaries. It is well known that the closed-loop control approaches (e.g., [19–21]) can be used to obtain asymptotic results but the transient control performance cannot be guaranteed. In

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http://dx.doi.org/10.1016/j.isatra.2016.07.014
0019-0578/

Please cite this article as: Zhang Z, et al. Robust adaptive antiswing control of underactuated crane systems with two parallel payloads and rail length constraint. ISA Transactions (2016), http://dx.doi.org/10.1016/j.isatra.2016.07.014

[22], an adaptive control framework was presented by total energy shaping, and symmetric Barrier function term was introduced into the control law to protect the trolley from going out the permitted motion range. However, it requires that the relative distance between the left boundary and the origin of coordinates equals to the relative distance between the right boundary and the origin of coordinates. This requirement is inconvenient to obtain the biggest trolley operating range. Moreover, in order to improve the work efficiency, it is expected that the trolley can hang multiple (more than one) parallel loads.

By considering the aforementioned two points, in this paper, we propose a new adaptive control strategy for underactuated crane systems in the presence of multiple parallel payloads, parametric uncertainties, and rail length limitation. The equidistant boundary condition has been relaxed to the unequal boundary condition from the theoretically viewpoint. The main contributions of this work can be described by the following efforts.

(1) By constructing system energy storage function, the equations of motion for underactuated crane systems with 2 up to n parallel payloads are established by the Euler–Lagrange principle.
(2) Under some milder assumptions, we fabricate a new storage function which consists of the system energy storage function, energy shaping terms, and an asymmetric Barrier function. The Barrier function is inserted with the purpose of preventing the trolley from running out the permitted range. See [23–25] for further details regarding Barrier Lyapunov function.
(3) An adaptive controller is designed to achieve the control aim of simultaneous accurate positioning and swing suppression in presence of rail length constraint and uncertain parameters. Simulation results are provided to illustrate that the proposed adaptive control scheme can achieve satisfactory control performance in terms of working efficiency as well as robustness with respect to external disturbances.

Notations: For function $f(t)$, $t \ge 0$, $\mathcal{L}_2-$norm is defined as $\|f\|_2 = \left(\int_0^\infty \|f(t)\|^2 dt\right)^{1/2}$ and $\mathcal{L}_\infty-$norm is defined as $\|f\|_\infty = \sup_{t\ge 0}\|f(t)\|$. We say that $f \in \mathcal{L}_2$ (or $f \in \mathcal{L}_\infty$) when $\|f\|_2$ (or $\|f\|_\infty$) exists. $I_{k\times k}$ denotes an identity matrix of dimension $k \times k$, and $0_{k\times 1}$ represents an zero column vector of dimension k.

2. Problem statement

In this paper, we study the underactuated crane system with two parallel payloads (see Fig. 1). Let $x(t)$ be the trolley position, $\theta_1(t)$, $\theta_2(t)$ denote the payloads swings, M, m_1, m_2, l_1, l_2 stand for the trolley mass, the payload masses, and the rope lengths, respectively. Suppose that F is the horizontal control force imposed on the trolley, $d_1\dot{\theta}_1$, $d_2\dot{\theta}_2$ represent the pivot friction where $d_1, d_2 > 0$, the bridge friction F_r is of the following classical form [1,15]:

$$F_r = f_{r0}\tanh(\dot{x}/\epsilon) - k_r|\dot{x}|\dot{x} \tag{1}$$

where f_{r0}, k_r, $\epsilon \in \mathbf{R}$ being friction parameters.

The total energy of the system is given by

$$L = \tfrac{1}{2}(M+m_1+m_2)\dot{x}^2 + m_1 l_1 \dot{x}\dot{\theta}_1\cos\theta_1 + m_2 l_2 \dot{x}\dot{\theta}_2\cos\theta_2 + \tfrac{1}{2}m_1 l_1^2\dot{\theta}_1^2 + \tfrac{1}{2}m_2 l_2^2\dot{\theta}_2^2 + m_1 g l_1(1-\cos\theta_1) + m_2 g l_2(1-\cos\theta_2), \tag{2}$$

which is a positive definite function with regard to $x(t)$, $\theta_1(t)$, $\theta_2(t)$ and $\theta_i(t) \in (-\pi, \pi)$ $i = 1, 2$. According to the Euler–Lagrange equations of motion for an underactuated mechanical system [26], one has

$$\begin{cases} \dfrac{d}{dt}\left(\dfrac{\partial L}{\partial \dot{x}}\right) - \dfrac{\partial L}{\partial x} = F - F_r, \\ \dfrac{d}{dt}\left(\dfrac{\partial L}{\partial \dot{\theta}_1}\right) - \dfrac{\partial L}{\partial \theta_1} = -d_1\dot{\theta}_1, \\ \dfrac{d}{dt}\left(\dfrac{\partial L}{\partial \dot{\theta}_2}\right) - \dfrac{\partial L}{\partial \theta_2} = -d_2\dot{\theta}_2, \end{cases} \tag{3}$$

from which, the equations of motion for the investigated crane system can described as

$$M(q)\ddot{q} + H(q,\dot{q})\dot{q} + G(q) = u \tag{4}$$

where $q = [x, \theta_1, \theta_2]^T$, $u = [F - F_r, -d_1\dot{\theta}_1, -d_2\dot{\theta}_2]^T$,

$$M(q) = \begin{bmatrix} M+m_1+m_2 & m_1 l_1\cos\theta_1 & m_2 l_2\cos\theta_2 \\ m_1 l_1\cos\theta_1 & m_1 l_1^2 & 0 \\ m_2 l_2\cos\theta_2 & 0 & m_2 l_2^2 \end{bmatrix},$$

$$H(q,\dot{q}) = \begin{bmatrix} 0 & -m_1 l_1\dot{\theta}_1\sin\theta_1 & -m_2 l_2\dot{\theta}_2\sin\theta_2 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad G(q) = \begin{bmatrix} 0 \\ m_1 g l_1\sin\theta_1 \\ m_2 g l_2\sin\theta_2 \end{bmatrix}.$$

In this paper, the main control objective is simultaneous trolley positioning and antiswing control of the two payloads on the cart, which can be formulated vividly as:

$$\begin{cases} \lim\limits_{t\to\infty} x(t) = x_1 = \dfrac{x_d}{2},\ \lim\limits_{t\to\infty}\dot{x}(t) = 0, \\ \lim\limits_{t\to\infty}\theta_1(t) = 0,\ \lim\limits_{t\to\infty}\dot{\theta}_1(t) = 0, \\ \lim\limits_{t\to\infty}\theta_2(t) = 0,\ \lim\limits_{t\to\infty}\dot{\theta}_2(t) = 0 \end{cases} \tag{5}$$

where x_1 is the destination (see Fig. 1), x_d denotes the distance from the initial trolley position $x_0 = -x_d/2 \in (-\xi_1, 0)$ to its destination $x_1 = x_d/2 \in (0, \xi_2)$. Here, like in [22], we set the initial trolley position as $x_0 = -x_d/2$ since there is only a need to consider the relative distance between the starting point x_0 and the desired location x_1.

Due to physical constraints, the rail length is limited. Considering this practical situation, the trolley must be operated within a safe motion scope in order to avoid the severe collisions happened around the boundaries. To remedy this, in the control process, we should comply with the practical factors presented below:

(1) *The trolley should always move within the range of* $(-\xi_1, \xi_2)$ *where* $\xi_1, \xi_2 > 0$, *that is,*

$$-\xi_1 < x < \xi_2, \quad \forall t \ge 0. \tag{6}$$

(2) *The system and physical parameters* M, m_1, m_2, l_1, l_2, d_1, d_2, f_{r0}, k_r *in model (4) are unknown.*

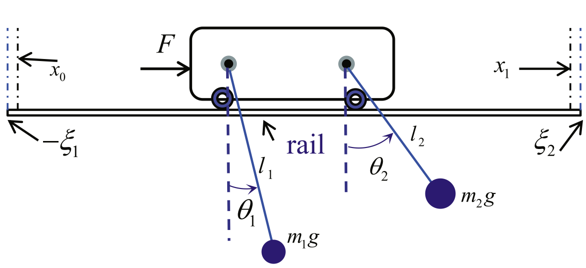

Fig. 1. The crane model with two parallel payloads.