Control Engineering Practice 76 (2018) 123–132

Contents lists available at ScienceDirect

Control Engineering Practice

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

Nonlinear control for underactuated multi-rope cranes: Modeling, theoretical design and hardware experiments☆

Biao Lu, Yongchun Fang *, Ning Sun

Institute of Robotics and Automatic Information System, Nankai University, Tianjin 300353, China

ARTICLE INFO

Keywords:
Underactuated systems
Multi-rope cranes
Modeling
Nonlinear control
Lyapunov methods

ABSTRACT

Researches on overhead cranes are mainly aimed at single-rope ones. However, to guarantee safety and increase the transportation efficiency, many overhead cranes tend to use more ropes to suspend the payload during the actual operation, which results in severe gap between theory and practice. The study on multi-rope cranes has achieved little progress in the past years, and no precise model has been proposed for such systems. So far, existing results for multi-rope cranes are usually based on linearizations or approximations, whose performance can be hardly guaranteed in many cases. Motivated to solve this problem, a dynamic model for multi-rope cranes is first set up in this paper by utilizing Lagrangian modeling method. Based on that, a nonlinear controller is further proposed, which incorporates more swing-related information into the control law, so as to enhance the robustness and swing suppression performance of the closed-loop system. The asymptotic stability of the desired equilibrium point is rigorously guaranteed by Lyapunov techniques and LaSalle's invariance theorem. Finally, to demonstrate the feasibility and efficiency of the designed controller, hardware experimental results are provided as a convincing validation.

1. Introduction

Overhead cranes, which are known as typical underactuated systems (Do, 2016; Lu, Fang, & Sun, 2018a, b; Lu, Fang, Sun, & Wang, 2018; Pucci, Romano, & Nori, 2015; Xu & Ye, 2016), are now widely used in many fields to transport cargoes from one destination to another. However, the seemingly easy task is actually very difficult in practice. On the one hand, one needs to accurately deliver a cargo to the desired location as soon as possible. On the other hand, the payload swing must be suppressed within a very small range throughout the transportation process and zero residual swing should be guaranteed, so as to ensure operation safety. However, due to the underactuated nature of overhead cranes, these two objectives may conflict with each other. Currently, most industrial overhead cranes are manually operated, which usually presents the drawbacks of poor positioning accuracy, low efficiency, high risk of accidents, and so on. Motivated to solve these problems, many researchers have put much of their effort on the automatic control of overhead cranes.

Until now, plenty of remarkable results for overhead cranes have been published in the literature (Chwa, 2009; Ermidoro, Cologni, Formentin, & Previdi, 2016; Lee, Huang, Ku, Yang, & Chang, 2014; Park, Chwa, & Eom, 2014; Sun, Fang, Chen, Fu, & Lu, 2017; Sun, Wu, Fang, & Chen, 2017; Zhang et al., 2016). Among them, some control strategies have proven to be efficient and are thus widely employed for the control of overhead cranes. Specifically, energy-based methods (Hoang, Lee, Kim, & Kim, 2014; Hua & Shing, 2007; Lu et al., 2018a, b; Wu & He, 2017) are very popular because they can avoid direct analysis on the complex dynamic equations. Sliding mode control methods (Chen & Saif, 2008; Lu, Fang, & Sun, 2017; Tuan, Lee, Ko, & Nho, 2015) achieve satisfactory results in dealing with various disturbances. Input shaping methods (Singhose, Kim, & Kenison, 2008; Sorensen & Singhose, 2008) have very simple structures and they do not need any feedback signals. As a result, they have now been successfully employed in practical systems when there is not too much requirement for control performance. Flatness-based methods (Delaleau & Rudolph, 1998; Fliess, Levine, Martin, & Rouchon, 1995; Kolar, Rams, & Schlacher, 2017), which allow rapid transitions between equilibrium points, are also extensively utilized for the control of overhead cranes, and have proven to be very efficient. More recently, intelligent control methods, which do not require exact model knowledge, are also applied to the control of overhead cranes and show promising prospects for

☆ This work is supported by the National Natural Science Foundation of China under Grant of 61633012, and also in part by the Natural Science Foundation of Tianjin under Grant 16JCZDJC30300.

* Corresponding author.
E-mail addresses: lubiao@mail.nankai.edu.cn (B. Lu), fangyc@nankai.edu.cn (Y. Fang), sunn@nankai.edu.cn (N. Sun).

https://doi.org/10.1016/j.conengprac.2018.04.005
Received 5 November 2017; Received in revised form 26 March 2018; Accepted 10 April 2018

practical applications (Solihin, Wahyudi, & Legowo, 2010; Yu, Moreno-Armendariz, & Rodriguez, 2011; Zhao & Gao, 2012).

Though great efforts have been made on the control of overhead cranes, a lot of challenging problems still remain to be solved. Specifically, most of current researches are aimed at single-rope cranes. However, in practice, more ropes are often utilized to suspend payloads for the sake of safety and efficiency, especially for payloads with large size. For example, container cranes usually utilize more than four ropes for payload suspension. These ropes are attached to different sites of the container and suspended from different points of the trolley. Under such circumstances, the payload can no longer be regarded as a mass point, and the corresponding swing process is also much more complicated. Therefore, existing results obtained for single-rope cranes are no longer applicable, which makes the control of multi-rope cranes a pretty open problem.

Compared with the study of single-rope cranes, much fewer results have been reported for multi-rope cranes. One of the main reasons is that precise modeling, and further the corresponding problem analysis for multi-rope cranes are much more difficult. Particularly, because of the special configuration of multi-rope cranes (see Figs. 1–2), more variables, including some non-independent variables, are required to precisely describe their dynamic characteristics. The proper process of these variables is actually a very challenging issue for both modeling and problem analysis. Furthermore, the dynamics of multi-rope cranes present much stronger internal couplings and more nonlinearities, which are very cumbersome to analyze. In fact, till now, *no* precise model for multi-rope cranes has been proposed in the literature, and the existing results for multi-rope cranes are usually based on linearization or approximation techniques. For example, in Park, Chwa, and Hong (2005), multi-rope container cranes are simply regarded as single-rope cranes, which is also the current mainstream approach for the study of multi-rope cranes (Kim & Hong, 2009; Ngo & Hong, 2012; Shah & Hong, 2014), even though there is no theoretical guarantee for this simplification. In Ref. Xu, Gu, Shen, Chu, and Niu (2011), an anti-swing control scheme with fuzzy uncertainty compensation is proposed for an eight-link lifting container crane by simplifying it as an inverted-triangle link mechanism. Motivated by the idea that *a controller based on a more accurate model generally results in improved response*, Masoud and Nayfeh (2003) develop a more precise double-pendulum-like model for multi-rope cranes, based on which a delayed feedback controller is further constructed. Unfortunately, these results are still based on a series of linearizations, which decreases the accuracy of the model. To solve this problem, Lu, Fang, and Sun (2015a) propose a new modeling technique, which establishes a precise model for a four-rope crane. Based on that, an adaptive tracking controller is further designed to successfully stabilize the system in Lu, Fang, and Sun (2015b). However, these two works do not consider more complicated situations, where the cranes have more than four hoisting ropes and different suspension mechanisms. Besides, the designed controller has little swing feedback, which may fail to achieve good swing suppression performance in practice. Finally, only simulation results are present as validation, which might not be sufficient for practical application. There are also some researchers who focus on the study of cable-suspended parallel mechanisms (Tang, Tang, Jiang, & Gosselin, 2015), which presents similar research challenges with that of multi-rope cranes in the sense of dynamic modeling, nonlinear control and trajectory planning, *etc.* Specifically, in Jiang and Gosselin (2016), a new s–$\dot{s}$ plane method, which always guarantee a positive and continuous cable tensions, is proposed to address the dynamic trajectory planning problem of a spatial cable-suspended parallel robot. In Zhang, Shang, and Cong (2017), the authors present another efficient dynamic point-to-point trajectory planning method for three-degree-of-freedom cable suspended parallel robots, where experimental results on a testbed are also provided as validation.

To solve the aforementioned problems, this paper first extends the modeling technique in the authors' previous works (Lu et al., 2015a, b), and sets up a precise model for multi-rope cranes after carefully analyzing their structures and payload hoisting mechanisms. Based on that, a nonlinear controller is further proposed, which incorporates more swing-related information into the control law, so as to enhance the robustness and swing suppression performance of the closed-loop system. By utilizing Lyapunov techniques and LaSalle's invariance theorem, the asymptotic stability of the desired equilibrium point is rigorously guaranteed, without tuning to linearizations or approximations. Finally, extensive hardware experiments are implemented on the self-built testbed to validate the feasibility and efficiency of the proposed method.

The novelty and contributions of this paper can be summarized as follows:

- Without turning to linearization or approximations, this paper designs an advanced nonlinear controller for the original multi-rope crane dynamics, which guarantees more reliable performance than existing results. Besides, the elaborate analysis method, as indicated by the heavy mathematics in this paper, also provides valuable experience for the control of other similar systems.
- Through a systematic study on the practical multi-rope crane system, this paper helps to narrow the gap between theory and practice. Moreover, instead of simulation results reported in literature, it provides much more convincing hardware experimental results, which strongly verifies the performance of the proposed model/controller for multi-rope cranes.

The rest of this paper is organized as follows. In Section 2, the multi-rope crane system is briefly introduced and the control problem is formulated. In Section 3, a dynamic model for multi-rope cranes is set up by utilizing Lagrangian modeling method. Section 4 details the design process of the nonlinear controller and provides the corresponding stability analysis. Hardware experimental results are provided in Section 5. Finally, some concluding remarks are given Section 6.

2. Problem statement

For multi-rope cranes, there are various ways for payload suspension, where different numbers of hoisting ropes may be utilized. Nevertheless, to guarantee smooth payload swing, as well as to avoid possible risks, nearly all of them are designed to share the following common characteristics: (1) there are two rows of hoisting ropes; (2) for each row, the hoisting ropes lie in the same plane, and are usually evenly distributed. To make the analysis concise and clear, the multi-crane mechanism is illustrated in Fig. 1, where the hoisting ropes are divided into two groups, namely, group A and group B. As indicated in Fig. 1, group A has n hoisting ropes while group B has m ropes. No matter what values m, n may take, and how these ropes are distributed in the plane (for example, they may be parallel or intersecting with each other in the plane), the projection of the crane from the side can always be shown as Fig. 2 (Masoud & Nayfeh, 2003).

In this paper, the payload mass is assumed to be uniformly-distributed.[1] Thus, when the trolley moves along the rail, there will be no movement, either for the payload or the trolley, along the z-axis.[2] Consequently, the dynamic characteristics of multi-rope cranes can be represented by the two-dimensional motion in the x-y plane shown in Fig. 2. As a result, the analysis is mainly focused on Fig. 2 in this paper, and the obtained results are partially applicable to other multi-rope cranes.

[1] Such an assumption is roughly satisfied in most cases, and thus it is widely adopted by other multi-rope crane-related works (Kim & Hong, 2009; Masoud & Nayfeh, 2003; Ngo & Hong, 2012; Park et al., 2005; Shah & Hong, 2014; Xu et al., 2011). The situations where such an assumption is not satisfied will be solved in the future work.

[2] For now, the authors consider only the one-way motion of the trolley. In the future, the control problem of the 3-dimensional case will be studied, which can deal with disturbances perpendicular to the plane shown in Fig. 2.