Mechanical Systems and Signal Processing 102 (2018) 87–101

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

An energy-optimal solution for transportation control of cranes with double pendulum dynamics: Design and experiments

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ARTICLE INFO

Article history:
Received 14 June 2017
Received in revised form 24 August 2017
Accepted 16 September 2017

Keywords:
Underactuated systems
Double pendulum cranes
Energy consumption
Swing elimination

ABSTRACT

Underactuated cranes play an important role in modern industry. Specifically, in most situations of practical applications, crane systems exhibit significant double pendulum characteristics, which makes the control problem quite challenging. Moreover, most existing planners/controllers obtained with standard methods/techniques for double pendulum cranes cannot minimize the energy consumption when fulfilling the transportation tasks. Therefore, from a practical perspective, this paper proposes an energy-optimal solution for transportation control of double pendulum cranes. By applying the presented approach, the transportation objective, including fast trolley positioning and swing elimination, is achieved with minimized energy consumption, and the residual oscillations are suppressed effectively with all the state constrains being satisfied during the entire transportation process. As far as we know, this is the *first* energy-optimal solution for transportation control of underactuated double pendulum cranes with various state and control constraints. Hardware experimental results are included to verify the effectiveness of the proposed approach, whose superior performance is reflected by being experimentally compared with some comparative controllers.

1. Introduction

Mechatronic systems have been widely applied in modern industrial fields, and the issues of dynamic analysis and control for such systems have been studied both theoretically and practically [1–3]. In particular, with numerous merits such as high flexibility, low energy consumption, low production costs, simple mechanical structure, and so on, underactuated mechatronic systems have attracted more interests in academia [4–14]. The fact that the number of independent control inputs is less than the degrees of freedom makes the control problem for underactuated systems still challenging and deserve further studies both theoretically and practically.

Underactuated overhead cranes are now widely used in industrial applications. Over the past decades, many ambitious control strategies for overhead crane systems have been reported in the literature [15–39]. Specifically, Rami et al. present a comprehensive review of crane control strategies in [15] which discusses the latest research works. In [16], a novel nonlinear controller for overhead cranes is presented by combining the partial feedback linearization method and the sliding mode technique. In [17], a Lyapunov-based adaptive controller is designed to suppress the undesirable residual swings of cranes with boundary output constraints. Ref. [18] exploits a robust error tracking control method for overhead crane systems

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http://dx.doi.org/10.1016/j.ymssp.2017.09.027
0888-3270/

which pre-specifies the error trajectories of the trolley and the payload swing. Ref. [19] applies the differential-flatness-based approach to the finite-time regulation controller for underactuated crane systems. Moreover, some sliding-mode-based controller are presented [20–22]. For example, a sliding-mode antiswing controller is proposed for overhead cranes, which guarantees asymptotic stability while keeping all state signals bounded [21]. Refs. [23–25] suggest some energy analysis-based controllers for underactuated crane systems. In addition, some intelligent algorithms are also introduced to enhance the control performance, such as learning control methods [26], fuzzy control methods [27–29], model predictive control methods [30], and neural network based controllers [31,32]. Then, trajectory planning methods are designed based on the coupling behavior existing between the translational movement and the payload swing [33–35]. For example, in [33], Sun et al. propose a phase plane based trajectory planning method, in which a three segment trajectory is obtained by geometric analysis, which can achieve the dual objective of swing suppression and residual swing elimination. Moreover, the input shaping methods are also applied to crane systems in [36–39] which realize residual swing suppression and state tracking. It is worthwhile to mention that, most existing approaches assume the hook and the payload as a mass point. Then the structure of the overhead crane system can be reduced into a single pendulum model, for which the control objective is usually aimed at achieving accurate orientation when transporting the payload. The payload (traditionally heavy cargo) is connected to the trolley through a rope and a hook. Thus, it will be very dangerous if the payload swings back and forth during the transportation process. In most cases, cranes are operated by skilled technicians. However, when cranes are manually manipulated, mistakes are usually unavoidable and payloads often exhibit uncontrolled residual oscillations, which are very likely to trigger serious accidents. Therefore, high performance control of overhead cranes for overhead crane systems has significant importance and is worthy of further studies.

In fact, in most situations, the mass of the hook is large and cannot be neglected. Moreover, the centers of gravity of the hook and the payload do not coincide with each other. This makes the system present significant double pendulum characteristics. On this occasion, the planners/controllers designed based upon traditional single pendulum representation are not suitable. Up to now, the research of double pendulum cranes is still at an early stage and there are many unresolved problems [40–49]. For example, In [40], an adaptive tracking controller for double pendulum cranes subject to parametric uncertainties and external disturbances is proposed, which guarantees that the trolley tracking error is within a prior set of boundary conditions and converges to zero rapidly. The input shaping technology is also applied to double pendulum crane systems [41–45] to suppress the oscillatory dynamics. In [46], one conventional sliding mode controller and one hierarchical sliding mode controller are designed to achieve transportation and anti-swing control objectives for double pendulum crane systems, both of which are discontinuous full state feedback controllers. Several intelligent controllers are proposed and used in [47,48]. More recently, in [49], an amplitude-saturated output feedback antiswing controller is proposed to regulate double pendulum cranes. However, none of the existing planners/controllers for double pendulum cranes take consideration of energy consumption which is an important criterion in modern industry.

To remedy the drawbacks of the state-of-art studies and to realize the energy optimal objective, this paper proposes an off-line energy-optimal trajectory planner for the horizontal motion control of double pendulum crane systems with the consideration of state constraints. In [35], Wu et al. propose an energy-optimal planner to reduce the energy consumption for single pendulum crane systems. In this paper, an energy-optimal solution is *firstly* presented for double pendulum cranes to move the trolley to the desired location and eliminate the double pendulum angle swings while minimizing energy consumption and keeping all the state variables within the given boundaries for safety concern. It is worthwhile to mention that the proposed planner generates the energy-optimal trajectory offline by implementing the optimization algorithm before practical use. Specifically, we first provide the system dynamics by using Lagrange's method. After that, the energy consumption function is constructed based on the dynamics. Then, after the convexification of the energy consumption function (through some transformations and calculations) and the discretization of the overall system (including the system dynamics, the initial/final conditions, the energy consumption function, and the preset state constraints), the control problem is formulated as a quadratic programming (QP) problem. Then the convex optimization technique is applied to solve the presented QP problem. Finally, hardware experiments are implemented on a double pendulum crane testbed to verify the performance of the proposed planner.

Compared with the existing planners/controllers, the merits of the suggested approach can be summarized as follows:

- The presented planner *firstly* solves the energy-optimal control problem for double pendulum cranes.
- System state constraints are taken into consideration to ensure that, all the system state variables are kept within given scopes during the entire process. Meanwhile, theoretically, there is no residual swing when the trolley reaches the destination.
- Hardware experiments are implemented on a double pendulum crane testbed, which are more convincing than merely simulation results provided by most existing works on double pendulum cranes.

The rest of this paper is arranged as follows. Section 2 provides the system dynamics of the double pendulum cranes system. Section 3 states the energy-optimal trajectory planning problem. The problem is formulated with initial/final conditions, energy consumption, and preset state constraints. Section 4 reformulates the energy-optimal trajectory planning issue into a convexity-based QP problem by discretizing the system dynamics. In Section 5, both numerical simulation and hardware experimental results are given to illustrate the satisfactory control performance of the proposed approach. Section 6 summarizes the main results of the paper.