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Adaptive tracking control for double-pendulum overhead cranes subject to tracking error limitation, parametric uncertainties and external disturbances

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ABSTRACT

In a practical application, overhead cranes are usually subjected to system parameter uncertainties, such as uncertain payload masses, cable lengths, frictions, and external disturbances, such as air resistance. Most existing crane control methods treat the payload swing as that of a single-pendulum. However, certain types of payloads and hoisting mechanisms result in double-pendulum dynamics. The double-pendulum effects will make most existing crane control methods fail to work normally. Therefore, an adaptive tracking controller for double-pendulum overhead cranes subject to parametric uncertainties and external disturbances is developed in this paper. The proposed adaptive tracking control method guarantees that the trolley tracking error is always within a prior set of boundary conditions and converges to zero rapidly. The asymptotic stability of the closed-loop system's equilibrium point is assured by Lyapunov techniques and Barbalat's Lemma. Simulation results show that the proposed adaptive tracking control method is robust with respect to system parametric uncertainties and external disturbances.

1. Introduction

In practice, cranes have been widely applied to far-ranging fields, such as harbors, factories, construction sites, manufacturing plants, for handling goods [1–3]. Based on the differences in cranes' mechanical structures, cranes can be roughly classified into three categories as overhead cranes, tower cranes, and boom cranes [4,5]. Regardless of the types of crane, the underactuated characteristic is the fundamental nature of cranes. A mechanical system is called underactuated if the number of independent control inputs is less than its degrees of freedom. Because underactuated mechatronic systems have fewer actuators, their cost is less than that of fully-actuated systems [6]. Yet, compared with fully-actuated mechatronic system, control of underactuated systems is more challenging. Therefore, a considerable amount of studies have been done to address the control problem of underactuated crane systems.

Out of all cranes, overhead cranes are the most widely used ones. As with the other cranes, the control objective of overhead cranes is to transport the payload to the desired position accurately as well as suppress and eliminate the payload swing rapidly. To increase transportation efficiency and decrease payload swing, various control methods have been recently proposed. However, most existing control methods treat the payload swing as that of a single-pendulum. The natural

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frequency of a single-pendulum is related only to the cable length. During the past decades, many methods regarding single-pendulum overhead crane have been developed, including optimal control [7–9], input shaping [10–13], trajectory planning [1,14,15], energy-based control methods [16,17], sliding mode control [18], flatness-based inverse methods [19,20], adaptive control [21], switching-based control [22], fuzzy-model-based control [23–25] and neural network control [26]. However, when the payload size is large or the hook mass is not negligible compared with the payload mass, the payload will rotate around the hook, which results in double-pendulum dynamics. In this case, the performance of existing control methods for single-pendulum overhead cranes degrades seriously. Therefore, investigations into the control of double-pendulum overhead crane systems are both theoretically and practically important.

In recent decades, control problems presented by double-pendulum overhead crane systems have attracted a great deal of interest. Roughly speaking, the control methods for double-pendulum overhead crane systems can be divided into two categories: open-loop control and closed-loop control. For open-loop control, input shaping method is the most well-known scheme. By convolving the human-generated command with a sequence of impulses to drive a crane, input shaping can eliminate expected vibrations of overhead cranes effectively [10,27–30]. The weakness of input shaping is its incapability to handle unexpected vibration from large nonlinearity and parameter variance, and also external disturbances [31]. To solve this issue, several works have been done to combine input shaping with other types of feedback controllers. For example, in the latest works by Singhose et al., input shaping is combined with Model Reference Control to overcome the double-pendulum payload crane nonlinearity and uncertainty [32,33].

In the presence of external disturbances, closed-loop control methods might provide better control results. In [34], by using sliding mode-based control (SMC) techniques and a modified version, two robust controllers (CSMC controller and HSMC controller) are designed for both tracking and anti-swing control of double-pendulum overhead crane systems. In CSMC, a common first-order sliding surface for state variables is determined, and the control input to attract all system states to this surface is generated. In HSMC, by linearizing the crane's nonlinear dynamics around the equilibrium point, a new second-order SMC method is proposed. Because of the underactuated nature, sliding surfaces include different state variables, and it is nontrivial to carry out convergence and stability analyses for the system state on the sliding surface. Because overhead cranes have standard Euler-Lagrange structures, passivity-based frameworks are employed to regulate the overhead crane system by properly shaping their kinetic and potential energy. Guo et al. [35] build the nonlinear dynamic model of the double-pendulum-type overhead crane by using the Lagrangian method, analyze the underactuated nature, passivity, and two natural frequencies of the system, and on this basis, propose a passivity-based control method. Simulation results are used to demonstrate that the passivity-based control method is effective. However, the system parameters must be known in advance, and the passivity-based control method presents a complicated structure and a residual swing.

It is generally known that overhead cranes work in a complex environment. That is, overhead cranes usually suffer from system parameter uncertainties, such as uncertain cable length, payload mass, friction, and external disturbances, such as air resistance, whose exact values are difficult to measure. On the other hand, most of the aforementioned control methods for double-pendulum overhead crane systems mainly focus on the regulation control scheme development while the trajectory planning stage is usually neglected. It is also known that for trajectory planning, many control indexes including physical constraints and working efficiency are incorporated into the trajectory planner, indicating that it is easy to be realized in engineering.

In this paper, to address the control problems mentioned previously, we propose an adaptive tracking control method for double-pendulum overhead cranes subject to tracking error limitation, parametric uncertainties and external disturbances. More precisely, to drive the trolley to the target position smoothly, a novel S-shape smooth trajectory is selected as the trolley's desired trajectory. By using the idea of total energy shaping, a new storage function is constructed, and on this basis, an adaptive tracking control method is derived, which can guarantee that the trolley tracks the selected desired trajectory. Inspired by [36,37], we add a novel additional term into the designed controller to ensure that the tracking error is always within a prior set of boundary conditions and converges to zero rapidly. Lyapunov techniques and Barbalat's Lemma are employed to prove asymptotically stability of the closed-loop system's equilibrium point. Simulation results are provided to demonstrate the designed adaptive tracking control method ensures asymptotic tracking result even in the presence of tracking error limitation, system parameter uncertainties and external disturbances.

In summary, the main contribution of this paper can be listed as follows.

1) To the best of our knowledge, the method proposed in this paper is the first adaptive control method for double-pendulum overhead crane systems.
2) The tracking error of the trolley is always within a prior set of boundary conditions.
3) The adaptive tracking control method admits strong robustness with respect to parametric uncertainties and external disturbances.
4) The designed controller has a simpler structure than most existing control methods for double-pendulum overhead cranes.

The rest of this paper is organized as follows. The dynamic model of double-pendulum overhead cranes is introduced in Section 2. Then, the main results including the selection of the trolley desired trajectory, and the design of the adaptive tracking controller are given in Section 3. In Section 4, stability analysis is presented. Some simulation results are provided in Section 5. Finally, the conclusion of this paper is drawn in Section 6.