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Adaptive robust tracking control for an offshore ship-mounted crane subject to unmatched sea wave disturbances

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ABSTRACT

An offshore ship-mounted crane consisting of a trolley, a wire, and a payload, is a typical nonlinear underactuated system, which suffers from unmatched disturbances mainly caused by sea waves and currents. Besides, unknown or uncertain parameters may cause vertical positioning errors or make accurate gravity compensation impossible, which may induce various risks during the transportation process. In terms of the aforementioned problems, this paper studies the adaptive robust tracking control problem for an offshore ship-mounted crane. In particular, a new adaptive robust coupling control approach, with adaptive laws included to deal with unknown parameters, and robust terms included to handle unknown disturbances, especially unmatched disturbances, is constructed in this paper, which achieves simultaneous load swing suppression and disturbances elimination. Without any approximation to the original nonlinear model, it is rigorously proven that the proposed method can ensure the stability of the overall crane system's equilibrium point, as supported by Lyapunov techniques. Finally, some contrast simulations and experimental results are collected to verify the superior performance of the proposed controller.

1. Introduction

Offshore ship-mounted cranes are in common use to transfer freights/cargos between a ship and a harbor, or between two ships under marine environment, which can be applied to heavy industry to carry out numerous difficult transportation tasks. As a typical representative, offshore cranes are playing a very important role mainly for their merits of high payload capacity, good operational flexibility, less energy consumption, etc. In particular, an offshore ship-mounted crane, consisting of a trolley, a wire and a payload, similar to an overhead crane, is also a typical nonlinear underactuated mechatronic system, which has less number of actuators than its degrees of freedom (DOFs). Apart from the challenging underactuated property, an offshore crane system also suffers from persistent disturbances, such as sea winds and sea waves. Therefore, the trolley can be caused to move repeatedly and the payload is affected to swing back and forth, which then brings plenty of difficulties for dynamics analysis and controller design. As it inevitably suffers from more complex unmatched disturbances,[2] which do not satisfy the so-called matching condition [1], the control problem for an offshore crane is fairly different from those of

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[2] Unmatched disturbance: the disturbances that appear in the unactuated dynamics and there is no direct control input to address them.

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traditional land-fixed crane systems. Additionally, for an offshore ship-mounted crane with a trolley flexibly moving along the boom, in most cases, tracking control has more important theoretical and practical merits than regulation control.

In general, the primary transport objective for an offshore ship-mounted crane is fast and precise payload positioning with efficient disturbances rejection. During the transportation process, noticing that the payload's swing is inevitably affected by the complex movement of the ship induced by sea breezes, ocean currents, or sea waves, especially under harsh sea conditions, it is of great significance to construct an accurate dynamic model and design an efficient tracking controller for an offshore ship-mounted crane.

During past decades, many researches regarding modeling and dynamics analysis of offshore cranes have been developed. To be more specific, in [2], after analyzing the ship motions induced by random currents or sea waves, a dynamic model of a container crane, called as mobile harbor, is investigated by Hong et al. Moreover, the Discrete Euler-Lagrange equation is successfully applied to construct a model for the multi-body system in [3]. To set up the model of a rigid-flexible multibody crane system, He et al. implement dynamics analysis for an offshore crane in [4]. Besides, in [5], Fang et al. propose a high-performance nonlinear controller based on rigorous dynamics analysis for an offshore boom crane.

It should be noted that, when modeling the dynamics of a ship-mounted crane, it is crucial to carefully consider the dynamics caused by sea waves/currents. This problem has recently received some attention. For instance, to explore the sea wave response of floating cranes, in [6], Čorić et al. establish a linearized dynamic model by using the wave spectrum theory, while in [7], Hannan et al. investigate the nonlinear hydrodynamic responses of a submerged payload barge in waves. Unfortunately, the aforementioned results mainly focus on a part of the system without considering its full dynamics. Therefore, it is still an unsolved problem to set up a synthetic dynamic model which successfully describes the exact motions of system states under complicated oceanic conditions.

On the other hand, compared with land-fixed crane systems, controller design for a ship-mounted crane is still a fairly open problem, which has received much less attention. For example, in contrast with numerous control strategies applied to overhead crane systems, such as slew/translation positioning control for tower cranes [8], input-shaped model reference control [9], visual feedback method [10], energy-based controllers [11–13], predictive control [14], adaptive approaches [15–18], output feedback control [19], as well as trajectory planning methods for overhead cranes [20–22], and so on [23–27], the researches dealing with the control problem of offshore cranes include a repetitive learning control [28], a robust boundary control [29], sliding mode controllers [30,31], an anti-swing control for the offshore boom crane [32], and so on [33]. Moreover, for more floating based control systems, such as an accommodation vessel, an artificial potential based adaptive H_∞ control method is proposed by Wen et al. in [34], while for a free-floating space manipulator, in [35], an eye-in-hand tracking controller is designed to cope with the uncertain dynamics and the unknown 3-D motion of the target. However, for those control methods proposed for offshore cranes, either *a priori* system parameters or over-simplified models are required to construct the controllers, which are lack of robustness and adaptability.

Additionally, apart from those factors, tracking control problem for an offshore ship-mounted crane encounters more difficulties than that of regulation control, mainly due to state coupling of such a complex nonlinear system and unexpected multi-dimensional ship motions, and so forth. Different from numerous regulation control methods for land-fixed crane systems, such as adaptive sliding-mode regulation control for an overhead crane [36], end-effector motion-based control approach [37], backstepping sliding-mode motion control [38], prediction controller [39], etc., few results have been reported so far for tracking control of offshore ship-mounted crane systems.

As an efficient control method, adaptive control has been widely utilized in numerous practical systems. For instance, some high performance adaptive-robust tracking controllers for a class of Euler–Lagrange systems are proposed by Roy et al. in [40–43], in which such barriers for the requirements of parametric knowledge or model knowledge have been almost removed. In [44–46], adaptive control techniques are properly suggested by Mobayen et al. for the tracking control of uncertain and nonlinear time-varying systems, while in [47], the composite nonlinear feedback robust control of uncertain linear systems is also presented. Particularly, for crane systems, Qian et al. take advantage of the adaptive strategy and propose an adaptive learning controller in [28], while for an tower crane with parametric uncertainties, in [8], an adaptive positioning control is designed. In [29], He et al. propose a robust adaptive boundary controller for a flexible marine riser with vessel dynamics. Besides, numerous adaptive approaches are taken into account in various crane systems in [16,17,34,36], and so on [48,49]. Among which, for overhead cranes, Sun et al. utilize the adaptive approach to deal with the problems of load hoisting/lowering with unknown parameters in [16], while in [34], an artificial potential-based adaptive h_∞ synchronized tracking controller is proposed by Ngo et al. for accommodation vessels.

To the best of the authors' knowledge, very little attempts have been made to design an adaptive robust controller (ARC) for nonlinear offshore ship-mounted crane systems with external disturbances. Through the literature review of related works above, it can be seen that high-performance control for an offshore ship-mounted crane is still an open problem. In this paper, we study the modeling and tracking control problem for an offshore ship-mounted crane, with the unmatched sea wave interferences specifically considered. Firstly, through applying the Lagrangian equation to an attached frame fixed on the ship, a detailed dynamic model of an offshore ship-mounted crane [50], which considers the roll motion and the heave motion of the ship induced by sea waves, is accomplished. Secondly, considering uncertainties of system parameters such as load mass and friction parameters, as well as external sea wave disturbances, an adaptive robust tracking controller is proposed for an offshore ship-mounted crane, which can guarantee the stability of the closed-loop system's equilibrium point during the entire transportation process. Lyapunov analysis is implemented to support the theoretical derivations, while comparative experimental results are provided to demonstrate the effectiveness of the proposed control method.