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Adaptive neural network sliding mode control of shipboard container cranes considering actuator backlash

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ABSTRACT

Offshore container crane is a highly under-actuated nonlinear system whereas only two control inputs are employed for driving six system outputs. Controlling such a system is not easy since it faces with many challenges composed of actuator backlash, geometrical nonlinearities, seawater viscoelasticity, cable flexibility, strong wave and wind disturbances, and considerable lack of actuators. This article proposes a robust adaptive system for a ship-mounted container crane with the disadvantages mentioned above. The controller structure is constructed using second-order sliding mode control (SOSMC), and a modeling estimator is designed on the basis of radial basis function network (RBFN). While other adaptive control techniques only estimates system parameters, the adaptive RBFN algorithm approximates almost all the structure of a crane model, including system parameters. Simulations and experiments are conducted to verify the superiority of the proposed control system.

1. Introduction

Classified as the heavy-duty machines, cranes [1] are popularly operated in many industrial applications with various types such as, overhead cranes [2–9], tower cranes [10], automobile cranes [11] and so on. In cargo transportation at ports, container cranes are specialized for lifting and transferring the containers. Container transportation occupies large amount of totally cargo penetration at harbors. Global container transport has continuously increased more than 75% from 2005 until recently [12]. Therefore, the number of container cranes severing in the ports is rapidly increasing and the bigger container ships are pressuring on port infrastructure in the recent years. As a result, many river ports with narrow and shallow channels cannot take up large container vessels. For solving this situation, gantry container cranes mounted on ships are applied for transshipping containers from mother vessel to smaller ships. Then, containers are carried to hinterland terminals. Unlike container cranes working at inland port [13–16], container cranes mounted on ship [17–22] suffer from ship excitations due to sea wave disturbances combined with sea wind that easily lead to instability if the high quality control solutions are not equipped. Research on portal container cranes [13–22] have been widely investigated in recent years. These studies are divided into two collections: one focuses container cranes working at harbors attached on rigid fixed foundation [13–16] and the other relates to container cranes mounted ships working offshore [17–22]. A research group [13–15] leaded by

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Nayfeh established a dynamic model for ship-to-shore gantry crane in which container was considered as a rigid body handled on two inelastic cables [13]. Two motions of container composed of center swing and rotation around the center was investigated together the with trolley motion. However, the container hoisting motion was not considered. On the basis of this model, the controllers were respectively analyzed and designed using time-delayed feedback [13,14] and command-shaping technique [15] for reducing the container swing and sway, and tracking the trolley motion. Generally, delayed feedback controller is not compatible with the system having uncertainties and disturbances. This is reason why the studies [13–15] did not consider the influences of wind disturbance to system dynamics and quality of proposed controllers. Furthermore, command-shaping method is classified as feedforward control and it thus cannot guarantee the system robustness when the cranes face with parametric uncertainties. Only focusing on dynamics problem, Arena et al. [16] recently enhanced a dynamic model for 3D motion in which container being a rigid body is suspended on four elastic cables with the action of wind loads. The parameters of practical crane were identified and the dynamic responses were analyzed by both simulation and full-scale experiment. Related to container cranes mounted on vessels, several works [17–22] have been published recently. Ngo [17] developed a mathematical model of container crane with kinematic wave excitation. Then, a fuzzy sliding mode controller was designed for suppressing the payload swing. The control quality was investigated on a laboratory overhead crane mounted on a motion base (that is a parallel robot with 6DOFs). Model predictive control with Kalman filter combined with proposed controller were conducted in experiment. In two papers [18,19], Ngo's model [17] was employed for constructing the control systems. Kim and Park [18] linearized dynamic model [17], identified the modeling parameters, then proposed a linear discrete-time control system with model-predictive method in optimizing the trolley motion. Ismail et al. [19] constituted a sliding mode controller with optimal sliding surface whereas linear quadratic regulator was utilized to optimize the manifold. As a whole, the authors [17–19] proposed the various controllers for regulating the payload swings and tracking the trolley without hoisting motion and without considering the mass and inertial moment of ship. The studies [17,18] considered the influence of kinematic wave excitation while the study [19] supplemented the action of wind on the proposed control systems. Tuan et al. [20,21] improved the crane dynamics by constructing a six DOFs model for ship-crane system. This model considered cable elasticity, viscoelasticity of seawater, physical feature of ship body, hoisting motion, and dynamic excitation of wave. However, the dynamic system including container swing was restricted in 2D motion. On the basis of this dynamic model, three types of control algorithms were designed consisting of nonlinear feedback control [20], sliding mode control [21], back-stepping sliding mode [21]. Container cranes often face with parametric variations, wave and wind disturbances. The proposed controllers based on slide modes [17,19,21] show the robustness better than the others [18,20] when facing with uncertainties. Messineo and Serrani [20] approached the control problem in terms of the other operation scenario. Accordingly, a control scheme was synthesized for reducing the hydrodynamic slamming load acting on a payload when a gantry crane mounted on a pontoon was lifting a payload submerged in seawater environment. The control system includes an adaptive observer, the heave compensation law, and the wave synchronization scheme.

Similar to container cranes, boom cranes can be attached on pontoons for various operating objectives. Ship-mounted boom cranes are more popular than floating container cranes because of their widespread application in offshore construction, shipbuilding, and portal transportation. Meanwhile, the shipboard container crane only specializes in lifting and transshipping containers. For the recent decades, many researchers have addressed the dynamics and control of offshore boom cranes [23–40]. Cha et al. [23] established the 12-DOF nonlinear dynamic model of floating boom cranes and simulated the system responses based on multi-body dynamics. Ellermann et al. [24,25] proposed a dynamic model for boom crane mounted on a pontoon that was moored by two cables and was subjected to periodic waves. The dynamic behaviors of system composed of bifurcations, multiple attractors, resonances, and subharmonic motions were analyzed by using path-following techniques and the method of multiple scales. Meanwhile, the research group of Nayfeh [26–30] utilized a simpler model for analyzing nonlinear dynamics and control. Accordingly, a two-degrees-of-freedom (DOF) model of boom crane with base excitations was used to study primary resonance, principal parametric resonance, and various bifurcations [26,27]. In regard to control, article [28] proposed a delayed position feedback controller to reduce the pendulation of payload by reeling and unreeling the lifting cable while articles [29,30] enhanced this approach for suppressing pendulation of payload by driving the boom-luff angle. Motivated by the findings [26–30] of the Nayfeh's group, a series of other studies on floating boom crane was released. Spathopoulos and Fragopoulos [31] applied linear quadratic Gaussian and predictive control techniques to decrease the payload swing using an anti-swing hydraulic arm instead of luffing the boom. Kimiaghalam et al. [32] proposed a feedforward control strategy by calculating the position of the equilibrium point of the load in space, minimizing the location of the equilibrium point, and then scheduling the control gain. Schaub [33] developed two active control algorithms without knowledge of the position and orientation of the ship. Instead, only translational acceleration and angular rate measured by sensors were supplied. Maczynski and Wojciech [34] stabilized the payload using PID controller with the action of the hoisting motion and an auxiliary mechanical system. Kuchler et al. [35] proposed an active compensation system for lifting the payload that sank into the water when a floating boom crane is employed in offshore installations. Ku et al. [36] applied a tagline mechanism for reducing payload swing where a winch with PD controller was utilized to adjust the tension of the tagline. The research group of Fang [37–39] proposed three various versions of nonlinear control for offshore boom crane on the basis of Lyapunov stability for tracking state outputs according to planed trajectories and reducing cargo swing. Sanfilippo et al. [40] applied genetic algorithms and particle swarm optimization for controlling offshore hydraulic boom crane based on a benchmark framework.

From the review and analysis of the preceding works related to offshore cranes [17–40], especially focusing on floating container cranes [17–22], we realize that the container crane modeling of articles [17–19] mainly dealt with in kinematic