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Modeling and advanced sliding mode controls of crawler cranes considering wire rope elasticity and complicated operations

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ABSTRACT

In this study, a new mathematical model of crawler cranes is developed for heavy working conditions, with payload-lifting and boom-hoisting motions simultaneously activated. The system model is built with full consideration of wind disturbances, geometrical nonlinearities, and cable elasticities of cargo lifting and boom luffing. On the basis of this dynamic model, three versions of sliding mode control are analyzed and designed to control five system outputs with only two inputs. When used in complicated operations, the effectiveness of the controllers is analyzed using analytical investigation and numerical simulation. Results indicate the effectiveness of the control algorithms and the proposed dynamic model. The control algorithms asymptotically stabilize the system with finite-time convergences, remaining robust amid disturbances and parametric uncertainties.

1. Introduction

As material handling machines, cranes are utilized to pick up cargoes/materials and transfer them to destinations in restricted areas with repeated actions. Cranes are normally classified into two groups: gantry (bridge) cranes and boom cranes. A crawler crane [1,2] is a boom-type machine equipped with four driving mechanisms to lift and move cargo, namely, payload-lifting, boom-luffing, crane-rotating, and crawler-moving mechanisms. As a heavy industrial machine, crawler cranes (Fig. 1) feature a large lifting capacity and lifting height that varies depending on boom length and boom swing angle. The boom is assembled from compartments of a steel structure; thus, its length can be flexibly modified.

Crane control has been extensively studied for many decades [3]. A large a number of studies focus on controlling gantry (overhead) cranes [4–15], whereas a few other papers pay attention to boom cranes [16–21]. Many control techniques, from classical to modern approaches, have been successfully applied to crane systems. Earlier studies explored linear control [22], feedback linearization [23], and nonlinear control [24], whereas later studies focused on feedforward control, such as command shaping [25,26]; robust controls, such as sliding mode [27] and $\mu-$synthesis [28]; and adaptive controls, such as gain-scheduling [29], model reference adaptive system [30], and optimal control [31]. Modern control approaches, such as fuzzy logic [32,33], neural networks [34], and machine learning [35], have been proposed for boom and gantry cranes in many recent studies.

Classified as a group of mobile cranes, crawler cranes are driven by using cable control systems. Cargo-lifting translation and boom rotation are controlled by pulley wire cable systems, in which wire ropes roll around pulleys mounted on a boom

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1. Hook, 2. Boom, 3 Payload-hoisting cables, 4. Boom-luffing cables,

5. A-shaped frames, 6. Crawler moving mechanism.

Fig. 1. Kobelco CKE-600 [1] crawler crane.

head and A-shaped frames with many loops. The modeling and control of crawler cranes have yet to be comprehensively studied. Considering the case in which only payload-lifting motion is activated, Sun et al. [36] calculated the dynamics of a crawler crane using a finite element model that considered the boom as a Timoshenko beam. In another dynamics analysis [37], the elasticity of crane structures influencing cargo swings was investigated using a finite element method. Recently, Li et al. [38] analyzed kinematics and then proposed an automatic lifting system for the case in which two crawler cranes simultaneously hoist a payload. Beliveau et al. [39] proposed a simple method for reducing the payload motion of a crawler crane by introducing periodic balancing forces to hoisting cables. Aiming to maintain control in practice, Araya et al. [40] constructed a control system for varying the boom swing angle of Kobelco-type crawler cranes. By combining feedback control, feedforward control, and nonlinear compensation with gain scheduling, they developed an adaptive controller with a simple but effective structure. Klosinski [41] created a mathematical model and designed a control algorithm for hydraulic mobile cranes using the pole placement technique to eliminate the swing motions of the boom and the payload.

On the basis of the preceding review, we explore the topic of crawler crane control in terms of other research directions. We develop a new mathematical model of a crawler crane with simultaneous consideration of boom-luffing and cargo-lifting motions. The influences of internal disturbances, such as elasticity of wire ropes and geometrical nonlinearities of A-shaped frames, are also fully considered. Considering the operation characterized by the cooperative motions of cargo and boom, we identify five outputs of the crane system that require control: cargo-lifting motion along the suspending cable, cargo swing, boom rotation, rotation of payload-hoisting drum, and rotation of boom-lifting drum. However, only two actuators composed of payload-lifting and boom-lifting motors are equipped. Next, we design three versions of robust control for crawler cranes: sliding mode control (SMC), terminal SMC, and fast terminal SMC. The controllers simultaneously track the cargo and boom to destinations with high precision while reducing the boom and cargo swings. The simulation is applied to a Kobelco CKE–600 crawler crane [1] to investigate the effectiveness of the proposed control systems. In summary, this study contributes the following key improvements:

(i) A new dynamic model for crawler cranes is developed with a set of fully nonlinear differential equations that describe nearly all physical behaviors of the dynamic system. Such a mathematical model for crawler cranes has not been mentioned in the literature of control and modeling. The system dynamics is established for the complicated operating case, in which the payload-hosting and boom-lifting motions are simultaneously activated.