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Tracking and anti-sway control for boom cranes

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A B S T R A C T

This paper presents an anti-sway and tracking control for harbor mobile cranes. The control objective is the sway-free transportation of the crane's load taking the commands of the crane operator into account. Based on the mathematical model linearizing and stabilizing control laws for the slewing and luffing motion are derived using the input/output linearization approach. The operator's commands are smoothened online by a trajectory generator accounting for input and state constraints. The resulting optimal control problem is solved using the model predictive control approach. The efficiency of the control concept is illustrated with experiments on an industrial harbor mobile crane.

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1. Introduction

The continuously growing amount of world trade leads to an increase in cargo, which has to be shipped and handled in harbors by special equipment such as cranes. Common crane systems are gantry and boom cranes. Boom cranes such as the LIEBHERR harbor mobile crane (Fig. 1) are powerful and flexible handling systems. Compared to gantry cranes, boom cranes have less throughput but the type of cargo handled (bulk/container/unit cargo) and the crane's position with respect to the ship can be changed quickly. In order to make the application of boom cranes and hence the transshipment process more efficient, the cycle time of loading and unloading has to be reduced. In crane operation the most time-consuming maneuver is the accurate positioning of the hook or payload at a target position. A characteristic of boom cranes is that the load tends to oscillate spherically due to arbitrary crane maneuvers. Up to now the load sway has to be suppressed by the crane operator. But with the increasing requirements on the operator's skills and the decreasing cycle times demanded, supporting control systems become more and more important.

The major control objectives for the proposed control strategy are damping of the load sway and tracking of a reference trajectory based on the operator's hand lever signals. The main challenges for the realization of such a control concept are the measurement of the rope angles, the coupling of the moving axes due to centrifugal forces, and parameter variations.

Because of the mentioned challenges, there are only a few control concepts in the literature which have proven applicable in practice. Nevertheless, numerous approaches dealing with the sway-free transportation of crane loads were proposed. The focus in the past was mainly on gantry and overhead cranes. Currently, anti-sway systems for gantry cranes are state of the art. For rotary or boom cranes the anti-sway and trajectory tracking problem is treated only in theory. The implementations of these control concepts have never exceeded experimental setups in model scales. An overview of crane control concepts for gantry, rotary, and boom cranes was presented by Abdel-Rahman, Nayfeh, and Masoud (2003). The control strategies proposed in the literature can be divided into open- and closed-loop techniques.

A typical open-loop technique, namely command shaping, was utilized by Lewis, Parker, Driessen, and Robinett (1998) in order to remove components from the operator's command which induce load oscillations. The filter is adapted to the varying length of the cable in order to cancel excitations at the current natural frequency. The control system reduces residual oscillations. However, during the maneuver significant pendulations occur. Other researchers such as Parker, Groom, Hurtado, Robinett, and Leban (1999) and Glossiotis and Antoniadis (2003) further developed this control strategy by using a roll-off coefficient in the notch filter or by utilizing finite impulse response (FIR) filters to shape the operator's commands. A multi-mode input shaper was presented by Singhose and Kim (2007) in order to control double-pendulum load dynamics. Additionally, for robustness reasons, they used a specified insensitivity (SI) shaper. With this approach, a frequency range can be specified over which the oscillations should be suppressed.

Other open-loop techniques are optimal control strategies. Sakawa, Shindo, and Hashimoto (1981) proposed an optimally

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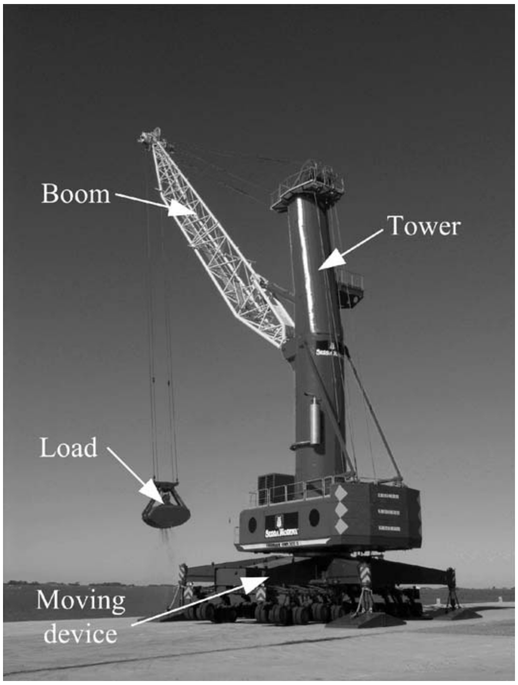

Fig. 1. LIEBHERR Harbour Mobile Crane LHM 400.

controlled rotary crane considering rotation and hoisting. An optimal torque profile was generated offline to transfer the payload along a pre-defined path while the payload's pendulations are minimized. Here luffing movement is not considered. Golafshani and Aplevich (1995) calculated time-optimal acceleration profiles for the jib rotation, the trolley movement, and the rope length. The offline generation of multi axis point to point crane maneuvers accounting for nonideal actuator dynamics was proposed by Agostini et al. (2001) and Agostini, Parker, Schaub, Groom, and Robinett (2003). Another open-loop control strategy for sway-free point to point motions of a payload was presented by Terashima, Shen, and Yano (2007) and Shen, Yano, and Terashima (2002). A straight-line transformation in combination with a time-optimal control technique was used to transfer the load between two points along a straight line in minimum time. Zameroski, Starr, Wood, and Lumia (2008) discussed the utilization of dynamic programming for a sway-free transfer of rope suspended payloads. With the dynamic programming method, the complex nonlinear model of the crane can be used. Arnold, Sawodny, Hildebrandt, and Schneider (2003) formulated the anti-sway problem as a nonlinear constrained optimal control problem. The optimal control functions for slewing and luffing were generated based on a nonlinear model of the crane taking the actuator dynamics into account.

Furthermore, a wide range of closed-loop techniques can be found in the literature. For instance, Souissi and Koivo (1992) proposed a control concept with two controllers to diminish sway for rotary cranes. A PID controller regulates the motor torques so that the slewing, luffing and hoisting motions follow the specified trajectories of the crane load. Another PD controller suppresses the load sway. Both controllers are not adapted to parameter changes such as varying rope length, which limits the control performance. Tabata, Ichise, Ouchi, and Liu (2002) presented a nonlinear controller for pure rotational movement of a boom crane. The controller is based on the LQR technique. Another anti-sway control strategy was proposed by Kondo and Shimahara (2004). They used a switching control method based on two linearized models of the two dimensional crane configurations. Omar and Nayfeh (2004) derived a control law for tower cranes whereby the feedback gains are calculated depending on system parameters such as the load mass and the rope length. Control strategies for rotary cranes using fuzzy logic were proposed by Takeuchi, Fujikawa, and Yamada (1988) and Al-mousa, Nayfeh, and Kachroo (2003).

Besides the contribution of open- or closed-loop control strategies, there are contributions which focus on the modeling, simulation, and analysis of rotary or boom cranes. Kiss, Levine, and Müllhaupt (1999) for instance investigated the flatness property for a class of cranes. They used Lagrange multipliers associated with geometric constraints between generalized coordinates in order to obtain dynamical models and to show differential flatness. Jerman, Podrzaj, and Kramar (2004) considered the dynamics of a rotary crane during slewing motion. They derived a complex nonlinear mathematical model of the load sway and the crane structure. Afterwards, the dynamical model was verified using an experimental setup.

Each of the proposed control strategies neglect important properties and influences which have to be accounted for to obtain an acceptable control performance in practice. The lifting and lowering of the load results in a varying rope length and hence in a varying natural frequency of the load sway. In order to obtain good control performance for all crane configurations, parameter variations have to be considered in the design. Furthermore, various contributions neglect the actuator dynamics. This assumption does not hold for most application cases.

The question of how to generate feasible inputs for the control system is rarely focused on. However, it is important for the performance of the control system. Typical approaches parameterize the output and its derivative profiles by stage-wise low-order polynomials. The coefficients of the polynomials are determined by the boundary values and constraints of the variables, see e.g. Panahi and Toiyat (2006). This can be interpreted as an approximate solution of a suitable optimal control problem. Because of the necessary increasing degree of the polynomials, this approach is limited to lower order derivatives of the output. Graichen and Zeitz (2008) formulate the transition problem between two operating points as a two-point boundary value problem that can be solved by a standard numerical method. Input and output constraints are taken into account by suitable saturation terms in the determination of ansatz functions. Recently developed nonlinear trajectory generation methods formulate the trajectory generation problem as a constrained optimal control problem for the nonlinear system. The control variables and some state variables are parameterized in terms of the output and its time derivatives, see e.g. Faiz, Agrawal, and Murray (2001) and Milam, Mushambi, and Murray (2000). This allows for a reduction of the system order and an efficient numerical solution, especially for differentially flat systems. Feedback control is applied for stabilizing the system around the generated reference trajectory.

The control concept proposed in this paper has to meet all the mentioned requirements for a successful implementation. The nonlinear behavior of the system is therefore simplified applying exact linearization and input/output linearization. The resulting linearized system is stabilized using asymptotic output regulation in order to gain robustness against disturbances. Additionally, the system's reliability is increased by utilizing a linearizing feedforward part and a stabilizing feedback part. To obtain high positioning accuracy and small residual sway the rope angles are reconstructed by observers. The proposed control concept is based on a mathematical model of the boom crane. The controllers and observers are designed analytically. Therefore, it is possible to adapt the control concept to various crane types just

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