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Energy Efficiency of Overhead Cranes

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Abstract: Energy efficiency is firstly considered into the control of overhead cranes. Based on the model of crane system, energy consumption as well as operational safety is formulated in an optimal control problem. The optimal control is used to search optimal trajectories of velocity and acceleration for minimizing energy consumption. Existing related work mainly focused on reducing transportation time and swing, but trajectory in this paper focuses on increasing energy efficiency of transportation while satisfying practical and physical constraints. Model predictive control (MPC) is then proposed to track optimal trajectories in real-time. As a result, the actual trajectories can match the reference trajectories with small errors when external disturbances exist. In the simulation, it can be shown that the proposed control approach can improve energy efficiency of overhead cranes robustly.

Keywords: crane control, motion planning, model predictive control, tracking, energy efficiency.

1. INTRODUCTION

Due to high payload capacity, good operational flexibility and transportation efficiency, overhead cranes have been widely used in many industrial fields, such as sea ports, construction sites, manufacturing plants and factories (Peng et al., 2012; Ngo and Hong, 2012). Regardless of the type of overhead crane, each crane always has a similar fundamental structure that can be described as a trolley-pendulum system, that consists of a trolley, a supporting frame and a rope connecting the trolley with the payload. The crane system has one control input (trolley's actuating force) and two system variables to be controlled (trolley's position and payload's swing angle). It is difficult to control this so-called underactuated mechanical system that has fewer independent control inputs than degrees of freedom. Therefore, the automatic control of crane has attracted much interest from researchers in areas of mechanics and control.

Under the assumption of small payload swing, the nonlinear model of crane can be linearized around its equilibrium points, and then linear control approaches can be used on the simplified linear system. Many linear control methods have been applied to overhead cranes, including feedback control (Hekman and Singhose, 2006), input shaping (feedforward control) (Singhose et al., 2000; Garrido et al., 2008), optimal control (Moon et al., 1996; Piazzi and Visioli, 2002; Terashima et al., 2007). Time efficiency is the main objective of crane control that is usually considered in previous work (Chang and Wijaya Lie, 2012; Sun et al., 2012a). In Moon et al. (1996), time optimal control theory has been evaluated on the bang-bang control system of cranes. In Piazzi and Visioli (2002); Terashima et al. (2007), time optimal trajectories have been designed for continuous system of cranes subject to the swing constraint.

Two important issues have been neglected, i.e., energy efficiency and safety, which turn out to be significantly urgent when a large number of cranes have been equipped in some international industrial fields. To the best of our knowledge, little work has been done to minimize the swing risk while most work only considered the swing as a constraint of the control problem. The total energy consumption, has seldom been optimized in crane control, because the relation between energy consumption and control sequence is still vague. In this paper, energy efficiency as well as safety will be considered in the proposed control approach, that includes trajectory planning and tracking. Optimal trajectories in terms of energy efficiency and safety are planned by the optimal control method. As references, these optimal trajectories will be tracked in real time by model predictive control (MPC).

The reminder of this paper is organized as follows. Section 2 presents the dynamic model of overhead cranes. The discrete-time model is deduced in Section 3. Section 4 illustrates our control approach. Section 5 shows results of numerical simulation. Conclusion is given at last.

2. DYNAMIC MODEL OF OVERHEAD CRANES

The structure of an overhead crane can be illustrated as shown in Figure 1, where the trolley moves on the horizontal bridge and the payload is connected with a constant-length rope. $x(t)$, $\theta(t)$ and $F(t)$ denote the trolley's position, the payload's swing angle and overall force on the trolley respectively. In this paper, air resistance as well as stiffness and mass of the rope is neglected and the load is considered as a point mass. Moreover, as this study only focuses on the control of horizontal transportation, hoisting and lowering of payload are not considered. Then the overhead crane system with constant rope length can be described as follows:

$$(M + m)\,\ddot{x} + ml\cos\theta\ddot{\theta} - ml\sin\theta\dot{\theta}^2 = F, \qquad (1)$$

$$ml^2\ddot{\theta} + ml\cos\theta\ddot{x} + mgl\sin\theta = 0, \tag{2}$$

where M and m denote masses of the trolley and the payload, respectively. l is the length of the rope; g is the gravitational acceleration. The overall force F is composed of the actuating force F_a and the friction F_r as

$$F = F_a - F_r, \tag{3}$$

$$F_r \propto (M+m)g, \tag{4}$$

Motivated by the friction models in Makkar et al. (2007); Sun et al. (2012b), this paper employs the friction model as

$$F_r = (k_{r1}\tanh\dot{x}/\xi + k_{r2}|\dot{x}|\dot{x})(M+m)g, \tag{5}$$

where k_{r1}, k_{r2} and ξ are friction-related coefficients that can be determined by offline regression of historical data.

The crane dynamics consist of the actuated part (Eq. (1)) and the underactuated part (Eq. (2)). The latter part is the system kinematics that defines the coupling behavior between the trolley's acceleration $\ddot{x}(t)$ and the payload's swing angle $\theta(t)$. The main difficulty in controlling the overhead crane lies in handling of the coupling behavior between the swing and horizontal motion. When the swing angle is small enough ($\theta(t) < 5°$), the kinematic equation (2) can be linearized with the approximations of $\cos\theta \simeq 1$ and $sin\theta \simeq \theta$. The approximated linear kinematics can be obtained as

$$l\ddot{\theta} + \ddot{x} + g\theta = 0. \tag{6}$$

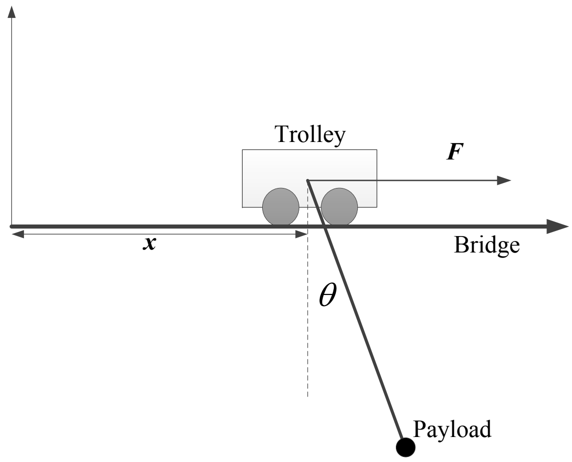

Fig. 1. Two-dimensional overhead crane system

In the evaluated time interval $[0, T]$, the crane is required to arrive at the destination without residual swing. Therefore, several principles must be satisfied according to the physical and practical situations in crane control.

Principle 1: The trolley reaches the desired location p_d at the end of the period. The final states must ensure that the trolley is static with no swing and that it can be lowered immediately as

$$x(T) = p_d, \dot{x}(t) = 0, \theta(T) = 0, \dot{\theta}(T) = 0. \tag{7}$$

Principle 2: During the horizontal transportation, the velocity and acceleration of the trolley must be limited in certain ranges as

$$\begin{cases} 0 \le \dot{x}(t) \le v_m, & t \le T \\ |\ddot{x}(t)| \le a_m, & t \le T \end{cases}, \tag{8}$$

where v_m and a_m are the permitted limits of velocity and acceleration, respectively.

Principle 3: The payload swing during the transportation must be limited within a safe range as

$$|\theta(t)| \le \theta_m, t \le T, \tag{9}$$

where θ_m is the permitted maximum of swing amplitude.

Principle 4: The jerk (defined as the time derivative of acceleration $j(t) = \dddot{x}(t)$) must be limited to a reasonable range to satisfy the mechanical constraint and to prolong the motor's lifetime.

$$|j(t)| \le j_m, t \le T \tag{10}$$

where j_m is the permitted maximal jerk in the horizontal transportation.

3. DISCRETE MODEL OF OVERHEAD CRANES

In our proposed approach, the sequence of control input is $[F_a(1), F_a(2), \ldots, F_a(N)]^T$, where $F_a(n)$ is the actuating force at the nth sampling period and N is the total number of samples in the planning period T. Therefore, the continuous system need be discretized by a sampling period t_0. The discrete model of overhead cranes can be formulated as Eq. (11) and (12).

$$(M+m)\,a(n) + ml\cos\theta(n)\ddot{\theta}(n) - ml\sin\theta(n)\dot{\theta}(n)^2 = F(n), \tag{11}$$

$$l\ddot{\theta}(n) + a(n) + g\theta(n) = 0, \tag{12}$$

where $N = T/t_0$ and $n = 1, \ldots, N$; $a(n)$ and $F(n)$ represent acceleration and overall force at the nth sample respectively. $\theta(n)$, $\dot{\theta}(n)$ and $\ddot{\theta}(n)$ are measured swing angle, swing velocity and swing acceleration at the nth sample. At the period $[n-1, n)$, the overall force $F(n)$ is composed of the actuating force $F_a(n)$ and the friction $F_r(n)$ as

$$F(n) = F_a(n) - F_r(n), \tag{13}$$

where the friction $F_r(n)$ can be formulated similarly with Eq. (5) as

$$F_r = [k_{r1}\tanh\dot{x}(n)/\xi + k_{r2}|\dot{x}(n)|\dot{x}(n)](M+m)g. \tag{14}$$

In this discrete model, we denote the vector of acceleration as $\boldsymbol{a}$ ($a(n) = \Delta^2 x(n)$), and denote the vector of velocity as $\boldsymbol{v}$ ($v(n) = \Delta x(n)$). Suppose that the initial position is $x(0)$, the initial velocity is $v(0)$, the initial acceleration is $a(0)$, the initial swing angle is $\theta(0)$, and the initial swing velocity is $\dot{\theta}(0)$. Given an vector of acceleration $\boldsymbol{a}$, the velocity $\boldsymbol{v}$ and the displacement $\boldsymbol{x}$ can be expressed as

$$\begin{cases} \boldsymbol{v} = \boldsymbol{v}_0 + \boldsymbol{A}\boldsymbol{a}t_0^2 \\ \boldsymbol{x} = \boldsymbol{x}_0 + \boldsymbol{b}v(0)t_0 + \boldsymbol{A}_x\boldsymbol{a}t_0^2 \end{cases}, \tag{15}$$

where

$$\boldsymbol{v}_0 = [\overbrace{v(0), \ldots, v(0)}^{N}]^T, \tag{16}$$

$$\boldsymbol{x}_0 = [x(0), \ldots, x(0)]^T, \tag{17}$$

$$\boldsymbol{b} = [1, 2, \ldots, N]^T, \tag{18}$$