Command Shaping For Residual Vibration Free Crane Maneuvers

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Gordon G. Parker

Ben Petterson

Clark Dohrmann

Rush D. Robinett

Structural Dynamics and Vibration Control Department
Sandia National Laboratories
Albuquerque, New Mexico
ggparke@sandia.gov

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Abstract

Cranes used in the construction and transportation industries are generally devices with multiple degrees of freedom including variable load-line length, variable jib length (usually via a trolley), and variable boom angles. Point-to-point payload maneuvers using cranes are performed so as not to excite the spherical pendulum modes of their cable and payload assemblies. Typically, these pendulum modes, although time-varying, exhibit low frequencies. Current crane maneuvers are therefore performed slowly contributing to high construction and transportation costs. This investigation details a general method for applying command shaping to various multiple degree of freedom cranes such that the payload moves to a specified point without residual oscillation. A dynamic programming method is used for general command shaping for optimal maneuvers. Computationally, the dynamic programming approach requires order M calculations to arrive at a solution, where M is the number of discretizations of the input commands. This feature is exploited for the crane command shaping problem allowing for rapid calculation of command histories. Fast generation of commands is a necessity for practical use of command shaping for the applications described in this work. These results are compared to near-optimal solutions where the commands are linear combinations of acceleration pulse basis functions. The pulse shape is required due to hardware requirements. The weights on the basis functions are chosen as the solution to a parameter optimization problem solved using a Recursive Quadratic Programming technique. Simulation results and

experimental verification for a variable load-line length rotary crane are presented using both design procedures.

1. Introduction

Construction and transportation cranes can generally be grouped into one of two categories based on their configuration. The first category consists of overhead, gantry cranes. These systems incorporate a trolley which translates in the horizontal plane. Attached to the trolley is a load-line for payload attachment. Typically, they have varying load-line length capabilities. The second category consists of rotary cranes. As the name implies, the load-line attachment point undergoes rotation. Other degrees of freedom may exist such as translation of the load-line attachment point along the jib, variable load-line length, or if the jib is replaced by a boom, the characteristic boom rotational motion, known as luffing¹.

Auernig and Troger [1] consider time optimal payload maneuvers of a gantry crane undergoing trolley translation and load-line length change. The coupled, nonlinear equations of motion and adjoint equations, obtained from the application of Pontryagin's maximum principle, are solved analytically for the cases of constant and variable hoisting speeds. In both cases the maneuvers are developed such that the payload is residual oscillation free. Moustafa and Ebeid [2] demonstrate a state feedback controller for damping load sway for a gantry crane con-

¹ Boom rotational motion, referred to as luffing, causes the tip of the boom to move vertically.

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figured to move along two orthogonal directions in the horizontal plane. This work is expanded on by Ebeid et. al. [3] to incorporate actuator dynamics into the crane model. Fliess et. al. [4] investigate a feedback linearizing controller for a one-dimensional gantry crane. Trolley traversal and load-line length changes are considered. Simulation results indicate the ability of the closed-loop controller to control load sway for relatively slow maneuvers. This same system is examined by Nguyen [5] where simulation and experimental results of a nonlinear state-feedback controller is used. Small motions are assumed about a specified operating point. This allows for decoupled equations of motion and decoupled controller design.

Sakawa and Nakazumi [6] investigate a rotary crane undergoing hub and boom rotation and load hoisting using a combined open and closed-loop approach. The open-loop input to the crane is designed based on a postulated set of functions such that the sway motion of the load is excited minimally. The closed-loop controller is then switched on when the maneuver is near the end, providing significant sway damping. Vaha et. al. [7] generate suboptimal, minimum time inputs for a rotary crane. Tracking is achieved via a state feedback control law. However, radial sway, due to centripetal acceleration of the payload, is not compensated. Souissi and Koivo [8] consider a rotary crane undergoing a boom-rotation-boom maneuver using a proportional-integral-derivative controller similar to Fliess et.al. [4]. The simulation model considers both radial and tangential payload sway, however, the control strategy used results in residual load oscillation.

In this paper a procedure for input command shaping for a rotary jib crane with variable load-line length is introduced. The maneuver of interest is the residual oscillation free, point-to-point movement of a payload. The input angular acceleration to the jib motor is calculated by two methods. The first method uses a dynamic programming algorithm to obtain the general angular acceleration history. The second method uses a parameterized pulse acceleration profile. The initially unknown parameters are determined by solving a constrained optimization problem.

2. Crane Description

The crane considered here consists of a rotatable jib with a variable length load-line attached to the end. A mass, representing a payload, is attached to the end of the load-line. This apparatus is shown in Fig. 1

The $\hat{a}_1, \hat{a}_2, \hat{a}_3$ coordinate system is attached to the jib and rotates about the hub with angular rate $\dot{\gamma}$. The rotation angles θ_1, θ_2 are defined as rotations of the load-line about the $\hat{a}_1, \hat{a}_2$ axes respectively. The attachment point of the load-line to the jib is at a distance x from the center of rotation of the hub. The load-line has time-varying

Figure 1. The Rotary Jib Crane.

length L and the payload has mass m . The two rotations will from now on be referred to as the radial (θ_2) and the tangential (θ_1). The input to this system is the hub rotation trajectory $\gamma(t)$ and the outputs are the rotation angles of the load-line, $\theta_1(t), \theta_2(t)$.

The experimental system uses a constant acceleration, computer controlled, direct-drive, motor. Physical values for x, m are given in Table 1. The maneuver considered consists of a 90° jib rotation where at the end of the jib maneuver, the payload is oscillation free.

Table 1. Physical quantities used for the experimental apparatus.

Parameter	Units	Value
x	m	0.659
m	kg	0.05
L_o	m	1.02
c_1	m	0.096
c_2	m	0.096

3. Equations of Motion

Using the rotating $\hat{a}_1, \hat{a}_2, \hat{a}_3$ coordinate system, the vector from the center of rotation of the hub to the payload is given by

$$\begin{aligned} \underline{p}(t) = & (x - L(t) \cos[\theta_1(t)] \sin[\theta_2(t)]) \hat{a}_1 + \\ & L(t) \sin[\theta_1(t)] \hat{a}_2 - \\ & L(t) \cos[\theta_1(t)] \cos[\theta_2(t)] \hat{a}_3 \end{aligned} \quad (1)$$

Lagrange's equations

$$\frac{d}{dt} \left(\frac{\partial \mathcal{L}}{\partial \dot{\theta}_i} \right) - \frac{\partial \mathcal{L}}{\partial \theta_i} = 0 \quad (2)$$

are applied to this system where the Lagrangian $\mathcal{L}$

$$\mathcal{L} = T - V \quad (3)$$

is the difference between the kinetic energy T and the potential energy V .

With the aid of Fig. 1 and Eq. 1, the kinetic and potential energy expressions can be found and when substituted into Eq. 2 yield the following equations of motion

$$\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + 2 \begin{bmatrix} \frac{L}{L} & -\dot{\gamma} \\ \dot{\gamma} & \frac{L}{L} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} + \begin{bmatrix} \left(\frac{g}{L} - \dot{\gamma}^2 \right) - \left(\dot{\gamma} + 2\dot{\gamma} \frac{L}{L} \right) \\ \dot{\gamma} + 2\dot{\gamma} \frac{L}{L} \quad \left(\frac{g}{L} - \dot{\gamma}^2 \right) \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = -\frac{x}{L} \begin{bmatrix} \ddot{\gamma} \\ \dot{\gamma}^2 \end{bmatrix} \quad (4)$$

where small angle assumptions have been exploited for θ_1, θ_2 and their derivatives.

The load-line length changes during the maneuver as a function of the hub rotation according to

$$L = L_0 - \sqrt{x^2 + c_1^2 + c_2^2 + 2xc_1 \cos \gamma + 2xc_2 \sin \gamma} \quad (5)$$

The values used for L_0 , c_1 , and c_2 are given in Table 1. For these values, and a 90° jib rotation, the load-line length has initial and final values of 0.26 m . During the maneuver, the length decreases symmetrically, about the 45° position, to a minimum length of 0.23 m .

In the following, a numerical solution for the hub rotation $\gamma(t)$ yielding the residual oscillation free motion of the payload, is found relying on the equations of motion of Eq. 4.

4. Maneuver Generation

Two methods for hub angle generation are considered. The first uses a dynamic programming technique where the discretized hub motion is found by minimizing the hub motor effort while simultaneously enforcing the payload oscillation constraints. The second method uses a postulated hub motion which is parameterized by five values. These values are found by solving a parameter optimization problem which minimizes a cost function that penalizes the residual oscillation.

4.1 Dynamic Programming Approach

The dynamic programming optimal control problem for obtaining the hub trajectory $\gamma(t)$ is

$$\text{MINIMIZE:} \quad J = \int_0^{t_f} \ddot{\gamma}^2 dt$$

SUBJECT TO: Eq. 4

CONSTRAINED BY:

$$\theta_1(t_f) = \dot{\theta}_1(t_f) = \theta_2(t_f) = \dot{\theta}_2(t_f) = 0$$

$$\gamma(t_f) = 90^\circ, \dot{\gamma}(t_f) = 0$$

$$t_f = 2.2$$

The implementation of the dynamic programming solution method utilizes a discretization of the hub angular acceleration into 100 zero order hold values, i.e., the input is allowed to change every 0.022 seconds during the maneuver and the dynamic programming algorithm will return the optimal value for each discretized point.

As stated by Dohrmann [9] [10], the dynamic programming method is well suited to input command shaping applications since each iteration requires order M calculations where M is the number of discretizations. In contrast, gradient based sequential quadratic programming methods require order M^3 calculations per iteration.

4.2 Parameter Optimization Approach

The use of this method is motivated by the hardware restrictions of requiring constant acceleration commands for the hub. However, this method illustrates that sub-optimal trajectories, in terms of hub motor effort, exist satisfying the primary objective of residual oscillation free motion.

The hub angular acceleration profile is postulated using the pulse-coast-pulse form shown below. The hub motion is uniquely described by the five parameters A_1 the first pulse magnitude, T_1 the first pulse duration, T_2 the coast time, A_2 the second pulse magnitude, and T_3 the second pulse duration.

The parameter optimization problem for obtaining the hub trajectory $\gamma(t)$ is

Figure 2. Postulated Angular Acceleration Profile

$$\text{MINIMIZE: } J = \int_{t_f}^{t_f + \Delta} (\theta_1^2 + \theta_2^2) dt$$

SUBJECT TO: Eq. 4

CONSTRAINED BY:

$$\dot{\theta}_1(t_f) = \dot{\theta}_2(t_f) = 0$$

$$\gamma(t_f) = 90^\circ, \dot{\gamma}(t_f) = 0$$

$$t_f = \text{Free}$$

In this case the cost function is a measure of the residual oscillation of the payload. A fundamental difference between this approach and the dynamic programming method is that the final time is free. The quantity Δ was chosen as 2.0 seconds, to capture residual oscillation in the cost function.

5. Results

5.1 Simulation

Using the values of Table 1, the trajectory features for residual oscillation free motion using both dynamic programming and parameter optimization are shown in Figure 3 through Figure 6. The values for the parameter optimization method are shown in Table 2 where a recursive quadratic programming [11] method is employed. The initial guess for the parameter optimization method was chosen based on an approximation of the dynamic programming solution to a pulse profile. The resulting maneuver completed in 2.1 seconds compared to the dynamic programming maneuver duration of 2.0 seconds.

Table 2. Values of Optimal Hub Acceleration Pulse Profile Parameters.

Parameter	Units	Value
A_1	r/s^2	1.346
T_1	s	0.903
T_2	s	0.390
A_2	r/s^2	1.346
T_3	s	0.903

5.2 Experimental

As mentioned previously, the experimental hardware requires constant acceleration hub commands, excluding the use of the dynamic programming results for verification. The hub trajectory of the parameter optimization results, however, is implemented on the hardware. The resulting motion is observed to be residual oscillation free with no modification to the optimized solution. This implies excellent ability to model and simulate the physi-

cal system using Eq. 4. Because of the correlation between simulation and experimental results, the simulation plots are used in lieu of measured experimental data.

Figure 3. Hub Acceleration -- Dynamic Programming vs. Parameter Optimization.

Figure 4. Hub Position -- Dynamic Programming vs. Parameter Optimization.

Figure 5. Tangential Oscillation θ_1 -- Dynamic Programming vs. Parameter Optimization.

Figure 6. Radial Oscillation θ_2 -- Dynamic Programming vs. Parameter Optimization.

6. Summary

A dynamic programming method was employed for obtaining the hub angular acceleration history for a variable load-line jib crane producing residual oscillation free payload motion. It was shown that the hub angular acceleration could also be postulated using a bang-coast-bang shape to achieve the desired residual oscillation free behavior. The parameters of this shape were calculated using a recursive quadratic programming numerical optimization code. The time required for a solution of this gradient based approach was dependent on the quality of the initial guess. When the guess was based on an approximation to the results of the dynamic programming approach, the time required for solution was approximately the same as the dynamic programming method. It should be noted, however, that the dynamic programming method requires no initial guess. This feature is particularly useful for systems with time-varying or nonlinear equations of motion where physical insight into the solution is elusive.

The parameter optimization results were verified experimentally using constant acceleration commands to the hub motor. The resulting residual oscillation free motion of the payload was achieved with no "tuning" of the crane simulation indicating the ability to accurately model the system.

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