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Swing-Free Cranes via Input Shaping of Operator Commands

Kenneth N. Groom, Gordon G. Parker, Rush D. Robinett, Frank Leban
Sandia National Laboratories
P.O. Box 5800, Mail Stop 1003
Albuquerque, NM 87185
kngroom@sandia.gov

1 Abstract

This paper presents an open-loop control method for suppressing payload oscillation or swing caused by operator commanded maneuvers in rotary boom cranes and the method is experimentally verified on a one-sixteenth scale model of a Hagglunds shipboard crane. The crane configuration consists of a payload mass that swings like a spherical pendulum on the end of a lift-line which is attached to a boom capable of hub rotation (slewing) and elevation (luffing). Positioning of the payload is accomplished through the hub and boom angles and the load-line length. Since the configuration of the crane affects the excitation and response of the payload, the swing control scheme must account for the varying geometry of the system. Adaptive forward path command filters are employed to remove components of the command signal which induce payload swing.

2 Introduction

A recent trend for the U.S. Navy is to reduce the number of its auxiliary ships, those used for supply, and instead rely on commercial ships for logistical support. The commercial shipping industry, however, has been moving toward high speed, non-self-sustaining container ships which in general require large cranes to handle its containers. Military operations, as well as disaster relief operations, are often conducted on undeveloped beaches and response time often precludes the construction of port facilities.

The Navy's Container Offloading and Transfer System (COTS) is currently under development to address the problem of offloading container ships and moving supplies ashore in the absence of port facilities. The keystone of the system will be boom cranes mounted on a dedicated ship, which will move cargo from container ships to lighterages, small landing craft, for transport to shore. See Figure 1.

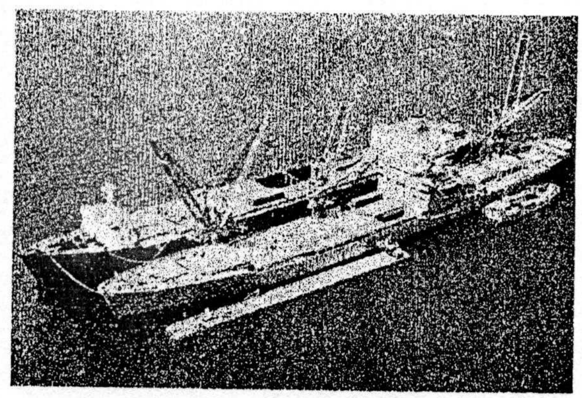

Figure 1: Crane ship transferring cargo from container ship to lighter

Lack of a protective harbor during these operations subjects the crane ships to wave activity which results in undesirable oscillations, or swinging, of the container. Sandia National Labs is currently developing crane control methods to eliminate unwanted payload swing in sea state three like conditions. A critical component of this control system is a filter for preventing swing induced by the operator's commands.

This paper presents an open-loop control method for suppressing payload swing caused by operator commanded maneuvers in rotary boom cranes and the method is experimentally verified on a one-sixteenth scale model of a Hagglunds shipboard crane. Illustrated in Figure 2, the crane configuration consists of a payload mass that swings like a spherical pendulum on the end of a lift-line which is attached to a boom capable of hub rotation (slewing) and elevation (luffing).

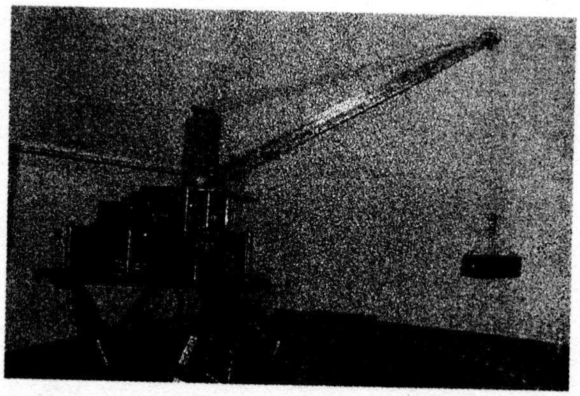

Figure 2: Navy crane testbed

Positioning of the payload is accomplished through slewing, luffing and hoisting (change in load-line length). Since the configuration of the crane affects the excitation and response of the payload, the swing control scheme must account for the varying geometry of the system. Adaptive forward path command filters are employed to remove components of the command signal which induce payload swing. During the experimental verification, a swing sensor, illustrated in Figure 3, will be used to independently measure sway and pendulation of the payload.

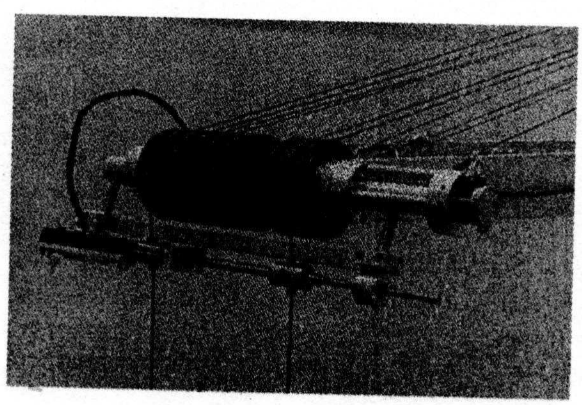

Figure 3: Payload swing sensor

3 Crane Dynamics

The kinematics and kinetics of the crane are developed with the aid of Figure 4. The model has three degrees-of-freedom under direct operator control. Slewing describes the rotation of the boom about the hub of the support column and is measured by α; the slew angle has a value of zero when the boom is positioned in the $\hat{X} - \hat{Y}$ plane. Luffing describes the elevation of the boom and is measured by angle β; the luffing angle is defined as zero when the boom is positioned parallel to the $\hat{X} - \hat{Z}$ plane. Finally, hoist describes the lift-line length and is labeled as L_3.

The remaining two degrees-of-freedom describe the position of the payload as it moves similar to a spherical pendulum. Pendulation, θ_1, defines the angle of payload swing tangential to the hub axis of rotation, $\hat{Y}$. Sway, θ_2 defines the angle of payload swing radial to the hub axis. Both pendulation and sway have zero values when the hoist line is parallel to $\hat{Y}$, which is parallel to the gravitational vector, and there positive directions are shown in the figure.

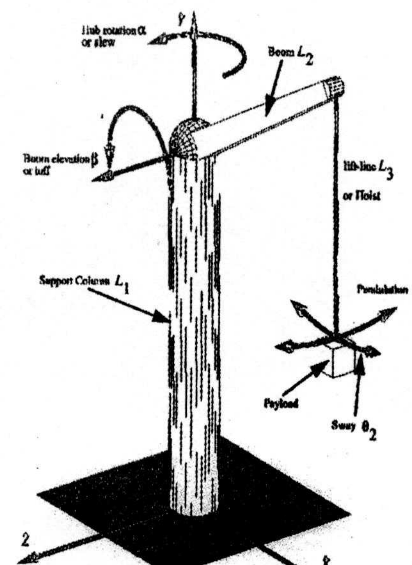

Figure 4: Crane Model.

To make the mathematical model tractable, the following simplifications are made. The hoist line is assumed to always be straight. The support column and boom are perfectly rigid. The payload behaves as a point mass. Finally, the connection of the hoist line to the boom is modeled as a point attachment.

Given these assumptions, the position vector of the payload, in base coordinates, is given as

$$
\begin{aligned}
\mathbf{p}(t) = \; & [L_2\cos(\beta)\cos(\alpha) + L_3\sin(\theta_2)\cos(\alpha) - \\
& L_3\cos(\theta_2)\sin(\theta_1)\sin(\alpha)]\mathbf{i} + \\
& [L_1 + L_2\sin(\beta) - L_3\cos(\theta_2)\cos(\theta_1)]\mathbf{j} + \\
& [-L_2\cos(\beta)\sin(\alpha) - L_3\sin(\theta_2)\sin(\alpha) - \\
& L_3\cos(\theta_2)\sin(\theta_1)\cos(\alpha)]\mathbf{k}.
\end{aligned}
\tag{1}
$$

The equations of motion for the spherical pendulum are derived using Lagrange's energy function

$$\mathcal{L} = T - V \tag{2}$$

where the kinetic energy, T, and the potential energy, V, of the payload are computed using Equation 1. Applying Euler-Lagrange's equations

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}_i}\right) - \frac{\partial \mathcal{L}}{\partial q_i} = F_i, \tag{3}$$

where $q_1 = \theta_1$, $q_2 = \theta_2$ and the applied force along these DOF, F_i, is zero, gives the desired equations of motion. To simplify the equations, small angles of sway, pendulation, and their derivatives were assumed and terms of order two and higher in these angles were eliminated giving

$$
\begin{aligned}
& \tfrac{-L_2\cos(\beta)\ddot{\alpha}}{L_3} + \tfrac{2L_2\sin(\beta)\dot{\alpha}\dot{\beta}}{L_3} = \ddot{\theta}_1 \\
& + \tfrac{2\dot{L}_3}{L_3}\dot{\theta}_1 + \left(-\dot{\alpha}^2 + \tfrac{g}{L_3} - \tfrac{L_2\sin(\beta)\dot{\beta}^2}{L_3} + \tfrac{L_2\cos(\beta)\ddot{\beta}}{L_3}\right)\theta_1 \\
& + 2\dot{\alpha}\dot{\theta}_2 + \left(\ddot{\alpha} + \tfrac{2\dot{\alpha}\dot{L}_3}{L_3}\right)\theta_2
\end{aligned}
\tag{4}
$$

$$
\begin{aligned}
& \tfrac{L_2\cos(\beta)\dot{\alpha}^2}{L_3} + \tfrac{L_2 cos(\beta)\dot{\beta}^2}{L_3} + \tfrac{L_2\sin(\beta)\ddot{\beta}}{L_3} = \ddot{\theta}_2 \\
& + \tfrac{2\dot{L}_3}{L_3}\dot{\theta}_2 + \left(-\dot{\alpha}^2 + \tfrac{g}{L_3} - \tfrac{L_2\sin(\beta)\dot{\beta}^2}{L_3} + \tfrac{L_2\cos(\beta)\ddot{\beta}}{L_3}\right)\theta_2 \\
& - 2\dot{\alpha}\dot{\theta}_1 - \left(\ddot{\alpha} + \tfrac{2\dot{\alpha}\dot{L}_3}{L_3}\right)\theta_1 .
\end{aligned}
\tag{5}
$$

4 Filter Generation

In this section the procedure for designing forward path command filters for slewing, $\dot{\alpha}$, and luffing, $\dot{\beta}$ are described. To simplify the design of the filter, Equations 4 and 5 are further reduced by assuming small velocities and accelerations of the operator inputs α, β, and L_3; a reasonable assumption for the crane under consideration. Retaining terms of order less than two gives the decoupled equations

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} \frac{g}{L_3} & 0 \\ 0 & \frac{g}{L_3} \end{bmatrix}\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} \frac{-L_2\cos(\beta)\ddot{\alpha}}{L_3} \\ \frac{L_2\sin(\beta)\ddot{\beta}}{L_3} \end{bmatrix} \tag{6}$$

or symbolically for each equation

$$\ddot{y}_i + w^2 y_i = u_i. \tag{7}$$

Taking the Laplace transform, the transfer function of the equations of motion are computed as

$$\frac{Y_i(s)}{U_i(s)} = \frac{1}{(s^2 + w^2)}, \tag{8}$$

where $w^2 = \frac{g}{L_3}$ is assumed constant over each finite length sample period. The filter between the commanded modal space input U_i^c and the actual model space input U_i is given as

$$U_i(s) = \frac{a^3(s^2 + w^2)}{w^2(s+a)^3}U_i^c(s) \tag{9}$$

where the filter numerator is designed to notch out the modal frequency and the constant a is chosen to yield constant notch filter characteristics over the full range of lift-line changes. This choice of input shaping filter yields the transfer function

$$\frac{Y_i(s)}{U_i^c(s)} = \frac{a^3}{w^2(s+a)^3}. \tag{10}$$

Solving for operator inputs yields

$$\ddot{\alpha}_{filtered}(s) = \frac{a^3(g + L_3 s^2)}{g(a+s)^3}\ddot{\alpha}_{commanded}(s) \tag{11}$$

$$\ddot{\beta}_{filtered}(s) = \frac{a^3(g + L_3 s^2)}{g(a+s)^3}\ddot{\beta}_{commanded}(s). \tag{12}$$

5 Test Results

Figures 5 through 9 display the results of testing the input shaping filters on the one-sixteenth scale Hagglunds shipboard crane testbed. The test trajectory was provided by an operator through joystick commands. The trajectory was recorded by the control computer and replayed with the digital implementation of the filters both off and on. The speed of the crane motor servo loops, as well as the sample rate of the joystick commands, is 1000Hz. The value of filter parameter a was set to $\sqrt{\frac{g}{L_3}}$.

From Figure 5 one observes that the initial lift-line length of 58 inches was immediately servoed to approximately 30 inches. Length changes to the lift-line after five seconds are the result of the level-luffing capability designed into the boom (as the boom is raised, line is payed out so that the payload remains at approximately the same height). This explains the filtered and unfiltered hoist trajectories even though the lift-line operator commands were unfiltered. Figures 6 and 7 give the luffing and slewing trajectory of the boom for both filtered and unfiltered operator commands. As can be seen in the figures, an effect of the filters is to round off the corners of the operator's commanded trajectory, resulting in the crane being slightly less responsive.

The effect of the input shaping filters on payload swing are illustrated in Figures 8 and 9. From Figure 8, the two degree step in sway during the first second of the trajectory is the result of the sway sensor aligning with the lift-line as the lines became tensioned. The remainder of the figure illustrates a reduction in residual sway from twenty degrees peak-to-peak to two degrees peak-to-peak. Similarly in Figure 9, residual pendulation is reduced from eighteen degrees peak-to-peak, to two degrees peak-to-peak. While these experimental results were not as impressive as the simulated results given by Lewis et al. [1] and Parker et al. [2][3] this cannot be avoided since mechanical factor such as gear cogging, friction, and cable slip on the takeup spools are difficult to eliminate or model.

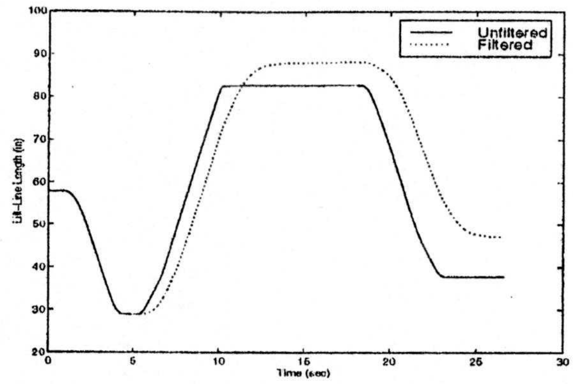

Figure 5: Hoist trajectory

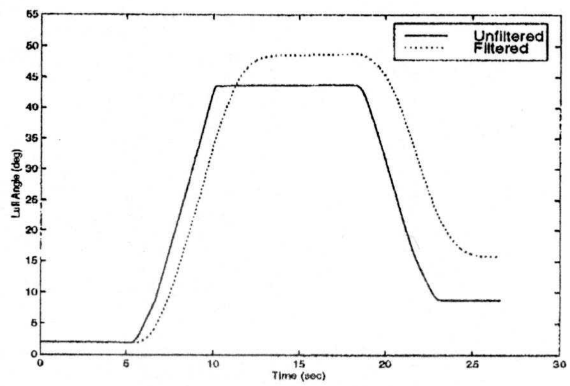

Figure 6: Luff trajectory

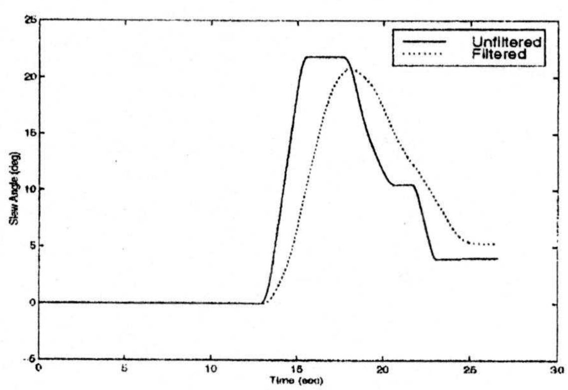

Figure 7: Slew trajectory

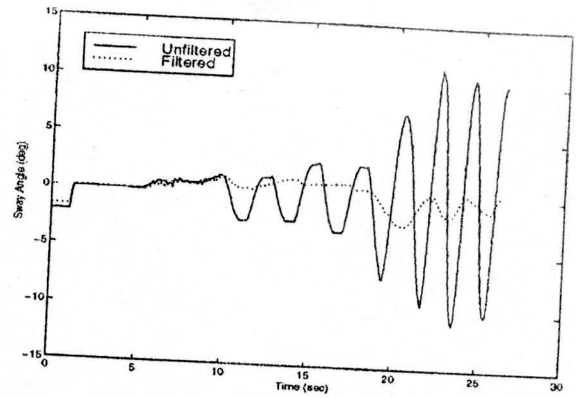

Figure 8: Payload sway

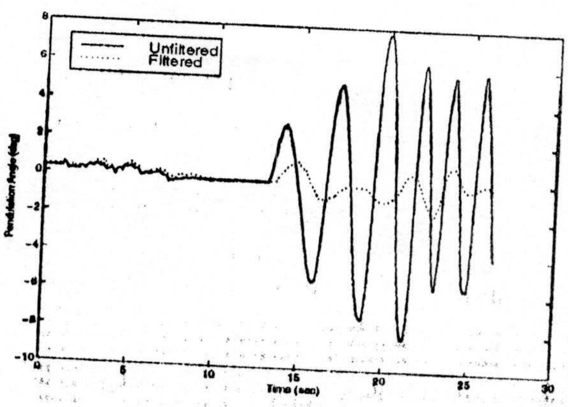

Figure 9: Payload pendulation

6 Summary and Future Work

A method for reducing the residual oscillation of operator in-the-loop point-to-point crane maneuvers was presented. Configuration dependent notch filters were proposed for filtering forward path velocity commands for the slewing and luffing speeds of the boom. Testing was performed using the one-sixteenth scale Hagglunds shipboard crane testbed. Results indicated an approximate 90 percent reduction in peak-to-peak residual oscillations for payload sway and pendulation. Future work will see the development of closed loop controllers for canceling the effect of wave induced ship motion and damping residual payload swing.

7 Acknowledgments

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