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DESIGN OF A CONTROLLER ENABLING PRECISE POSITIONING AND SWAY REDUCTION IN CRANES WITH ON/OFF ACTUATION

Titiloye Stephen Oyediran & Titiloye Yetunde Adebimpe
Department of Electrical Engineering
Federal Polytechnic, Bida.

Abstract

Precise manipulation of payloads is difficult with large cranes. Oscillation can be induced into the lightly damped system by motion of the overhead support point, or from environmental disturbances. A combined feedback and input shaping controller is presented here. The controller uses feedback to detect and compensate for positioning error in the overhead support unit (e.g. the bridge or trolley), and input shaping is used to negate motion-induced oscillation in the payload. The controller is implemented on a 10-ton bridge crane at the Georgia Institute of Technology. The controller generates simple on-off commands, suitable for typical cranes that employ on-off, relay-driven motors. The controller achieves good positioning accuracy, and significant payload sway reduction.

Keywords: Input Shaping, Command Shaping, Crane Control, Automation, Oscillation Control, Anti-Sway

INTRODUCTION

When a human operator attempts to maneuver payloads using a bridge crane, as shown in Figure 1, the oscillations induced into the payload by the motion of the overhead support unit (e.g. the bridge or trolley) can be significant. These oscillations make it difficult to manipulate the payload quickly. Furthermore, when the payload or surrounding obstacles are of a hazardous or fragile nature, the payload oscillations may present a significant safety risk. The ability to successfully negate these detrimental dynamics can result in greater efficiency and improved safety.

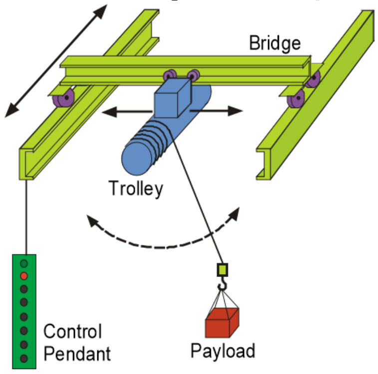


Figure 1: Model of a bridge crane

In many applications, precise positioning of the payload, in addition to minimal payload sway, is desired. At the Hanford Site in Washington State, radiological packages are regularly stacked in tight matrix formations, requiring positioning accuracy greater than 4 cm. Minimizing cable sway during movement of the packages reduces the risk associated with the hazardous content.
This paper describes a controller that has been designed with the desired positioning and oscillation suppression properties. The control uses feedback techniques to position the payload at a desired location, while using input shaping to suppress oscillation. The control has also been designed to produce simple on-off commands, suitable for cranes that use on-off, relay-driven motors.

COMBINED CONTROLLER MOTIVATION

A variety of techniques have been developed for controlling the dynamic response of cranes. Fang et al (2016) proposed to control final trolley position and cable sway through a proportional-derivative type control, in which the coupling between the cable angle and the motion of the trolley is artificially increased. Kim et al (2018) implemented a pole-placement strategy on a real container crane to control cable sway, as well as final positioning. Moustafa (2018) used nonlinear control laws for payload trajectory tracking based on a Lyapunov stability analysis. Finally, Fliess et al (2019) proposed a linearizing feedback control law for a generalized state variable model. The strategies discussed in this literature all use a form of feedback control to mitigate positioning and cable sway errors. The inherent strength of feedback control lays in the fact that it detects errors and responds accordingly. Such a controller is aptly suited for positioning a bridge or trolley. However, the conventional feedback schemes discussed in literature require that the controlled systems are capable of following variable velocity commands. Implementing these types of control schemes on cranes with simple on-off, relay-type motors requires hardware replacement.

Another drawback to conventional feedback control schemes is related to multi-state control. When a feedback controller must minimize cable sway, in addition to positioning a bridge or trolley, the control task becomes much more problematic. Accurate sensing of the payload must be implemented, which is often costly or difficult. Lastly, feedback control schemes are inherently reactive. When, for example, feedback is utilized to control cable sway, cable sway must be present in the system before the control will attempt to eliminate the undesired oscillations.

Another technique used for negating a system's flexible modes is input shaping. Input shaping does not require the feedback mechanisms of closed-loop controllers. Instead, the control reduces oscillations in an anticipatory manner, as opposed to the reactive manner of feedback. Oscillation suppression is accomplished with a reference signal that anticipates the error before it occurs, rather than with a correcting signal that attempts to restore deviations back to a reference signal. In the context of crane control, this means that sensing of the payload sway is not necessary. As a result, input shaping is easier to implement than feedback schemes that require payload sensing. Input shaping is also amenable to systems with bang-bang actuators. Using the proper input shaper, together with suitable baseline commands, input shaping produces on-off, relay-type commands that can be used on unmodified cranes, not fitted with variable velocity compliant hardware. Singer et al ((2017) has demonstrated that input shaping is an effective method for significantly reducing cable sway during crane motion. Lewis et al (2017), Kenison et al (2018) and Singhose et al (2019) all built upon Singer's assertion. Cranes utilizing the input shaping control also exhibited a significant improvement in efficiency and safety (Khalid et al. 2019).

The strength of feedback control to respond to detected error, and the ability of input shaping to negate detrimental dynamics, serve as a motivation for developing a control that uses feedback for crane positioning, and input shaping for sway reduction. Furthermore, input shaping provides a means by which oscillation suppression may be accomplished on standard relay-driven cranes, without hardware replacement.

REVIEW OF INPUT SHAPING

A successful approach to cable sway suppression is to generate a reference command that drives the system to cancel out its own oscillation. One such technique, input shaping, is implemented by convolving a sequence of impulses, known as an input shaper, with a system's reference signal. This shaped command is then used to drive the system. The amplitudes and time locations of the impulses are determined by solving a set of constraint equations that attempt to limit the unwanted system dynamics. All that is needed to solve the equations is an estimate of the system natural frequency and damping ratio.

If the amount of residual oscillation produced by the shaped command is set equal to zero, then a shaper that satisfies the constraint equations is called a Zero Vibration (ZV) shaper (Smith 2016 and Singer et al 2018). If an additional constraint that the magnitude of the shaper's impulses, must equal 1 or −1 is considered in the formulation, then a resulting shaper satisfying constraints is called a Unity Magnitude, Zero Vibration (UM-ZV) shaper (Singhose et al 2018). The input shaping process using a UM-ZV shaper is illustrated in Figure 2. Notice that the resulting shaped command is comprised of the same "on-off" amplitudes as the original step command. It is also important to note that the settling time of the shaped command is increased from the original command by the shaper's duration, Δ.

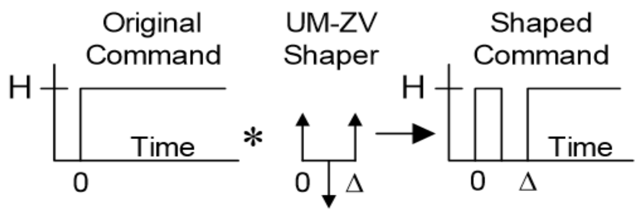


Figure 2: The input shaping process using the UM-ZV shaper

COMBINING FEEDBACK AND INPUT SHAPING

As a first step toward developing a controller enabling precise positioning of the payload, consider a state-space representation of the crane system. This representation relates the states of the payload to the velocity of the overhead support point according to the following equations:

$$\dot{q}_1 = q_2 \qquad (1)$$

$$\dot{q}_2 = -w_n^{\,2} q_1 - 2\zeta w_n + v(t) \qquad (2)$$

The symbols, ω_n, ζ, and $v(t)$, are the natural frequency of the pendulum mode, the damping ratio for cable sway, and the velocity of the overhead support point, respectively. The state, q2, represents the relative horizontal displacement between the overhead support point and the payload. The state, q1, has a less physical meaning; -q1 is a quantity whose derivative yields the relative displacement between the overhead support point and the payload. Computing the eigenvalues of A, we have:

$$\lambda = \zeta\omega_n \pm \omega_n\sqrt{1-\zeta^2 i} \qquad (3)$$

Because the real part of the eigenvalues of A are negative, the states, q1 and q2, are asymptotically stable in the sense of Lyapunov. Therefore, q1 and q2 always approach zero. By this formal treatment of the system's state equations, an obvious fact is emphasized; the payload will always come to rest directly beneath the overhead support point. Therefore, precise positioning of the overhead support point is equivalent to precise positioning of the payload. This fact enables the development of the control to proceed with an easily implementable bridge-position based control rather than with a more difficult payload-position based control.

A block diagram of the controller that guides the payload in the direction of bridge travel is shown in Figure 3; an identical control can be implemented to guide the payload in the direction of trolley travel.

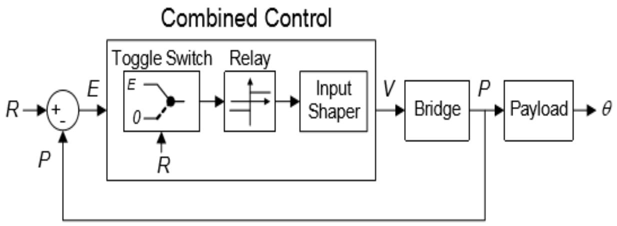


Figure 3: Block diagram of the combined controller

The reference signal, R, is a set point representing a desired final bridge position. A comparison of the set point and the actual bridge position generates an error signal, E. A relay, responding to the error signal, generates an on-off velocity command that drives the crane toward the desired location, positive step (bridge forward), negative step (bridge reverse), or no signal (bridge stationary). A UM-ZV input shaper modifies the relay signals before they are sent to the bridge motors. Like the relay response, the shaped signal is also comprised of simple on-off velocity commands. The bridge responds to the shaped commands with position, P. Finally, the payload responds to the bridge motion in an open loop manner with angle θ.

Ordinarily, a system that uses on-off actuators that are under the guidance of position feedback will exhibit limit cycles around the desired position. To prevent this phenomenon, a toggle switch has been inserted prior to the relay element. This switch toggles between passing the error signal, E, and a signal of 0, when either of the following conditions are met:

$$ToggleSwitch = E, \quad R_0 \neq R \tag{4}$$

$$ToggleSwitch = 0, \quad sign(E_0) \neq sign(E) \tag{5}$$

The "o" subscript indicates the value of the subscripted signal one time step prior to the most recent value of the signal. These toggle conditions allow the crane to come to rest after zero error is detected between the actual and desired bridge positions. The crane resumes motion when a new reference position is issued. To summarize, the combined control uses feedback to drive the bridge toward a desired location; the commanded velocities are shaped to prevent cable sway.

Controller Hardware Implementation

The schematic implementation of the controller was carried out as shown in Figure 4, and tested on Matlab environment.

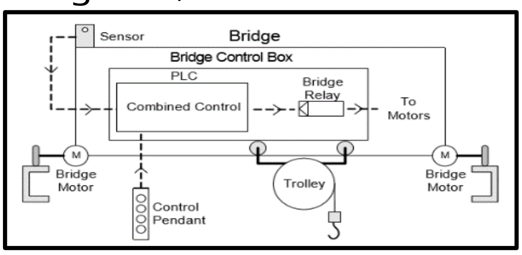


Figure 4: Crane hardware configuration

Experimental Results

The performance of the combined feedback and input shaping controller was experimentally evaluated in the Matlab environment, in two key areas, namely positioning and oscillation suppression. Velocity signals shown in Figure 5 were generated. When the first portion of Figure 5(a) was sent, the relay generated a signal of 0 until a new desired position was detected, and motion began again. The signals generated by the relay were modified by the UM-ZV input shaper before being sent to the motors. The modified velocity commands are shown in Figure 5(b).

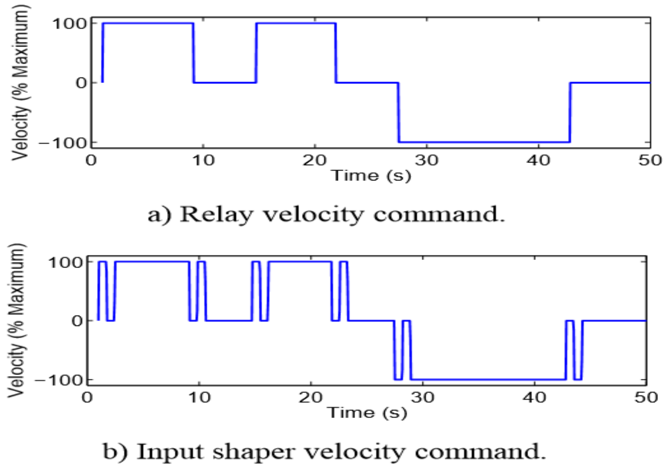


Figure 5: Shaped and unshaped velocity commands

The response of the bridge to the shaped velocity commands is shown in Figure 6(a). The three distinct dashed lines in the figure represent the desired locations issued to the control. The first reference position is at the 2-meter location, the second is at the 4-meter location, and the third is at the 0-meter location. The bridge, initially starting from the 0meter location, traced the position path shown with the solid line. Note that due to delays in the system dynamics, and increased settling times for the shaped commands, the crane overshot each desired location by approximately half of a meter.

Figure 6(b) illustrates the effectiveness of the input shaper in the control. The vertical axis represents the relative displacement between the payload and the bridge. The dashed line shows the payload response when input shaping is not used. The solid line shows the payload response while using the UM-ZV input shaper. For the shaped case, the amplitudes of the oscillations are reduced to less than 20% of the unshaped amplitudes.

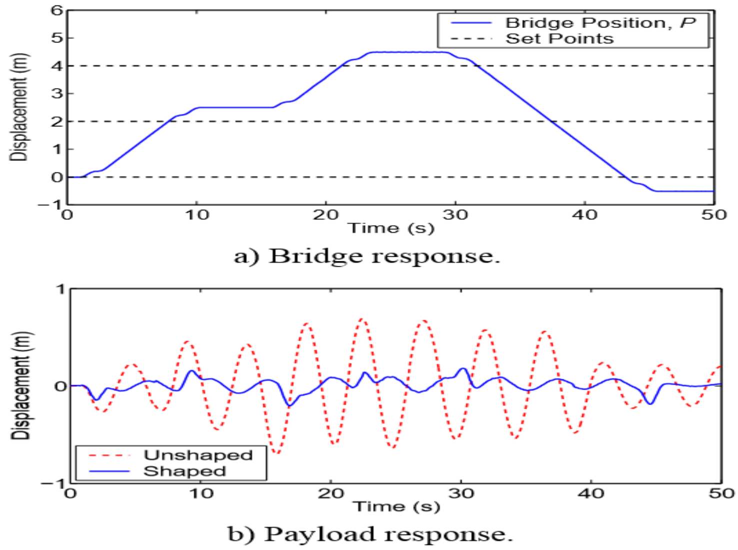


Figure 6: Experimental ridge and payload response

The small amount of residual oscillation exhibited during shaped motion can be largely attributed to nonlinear effects within the crane motors. A more comprehensive understanding of how nonlinear elements degrade the oscillation reducing properties of input shapers was understudied in Sorensen 2018). The data from this experiment indicates that a significant amount of oscillation reduction is possible, even when the control interacts with nonlinear motor elements. The data also show that the added settling time of the shaped commands, coupled with delays in the system dynamics, cause an overshoot of the desired position. If an application of the crane requires positioning accuracy greater than crane's overshoot, this basic version of the combined controller is not suitable.

COMPENSATED FEEDBACK AND COMMAND SHAPING CONTROL

Given the consistency of the crane's overshoot, a modification to the combined controller immediately suggests itself by which the controller triggers the crane to start decelerating prior to reaching a desired position. In this way, a final bridge position may be obtained that is closer to the desired position than would otherwise be achieved.

The compensator works by sending an offset reference position to the controller that precedes the actual reference position by a distance equal to the crane's overshoot. A block diagram of the modified controller is shown in Figure 7.

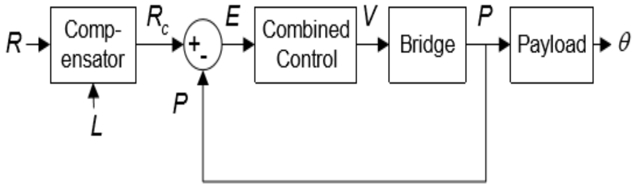


Figure 7: Block diagram of the combined controller

The true reference signal, R, representing the desired final position of the bridge, is intercepted and modified by the compensator. The compensator sends the modified signal, R_c, representing the offset reference position, to the control. At this point, the system performs as expected, triggering the crane to stop after reaching the offset reference position. The amount that the compensator adjusts the actual reference position is a function of L, the distance the bridge overshot the previous reference position. Specifically, the offset reference signal, R_c, is determined from the following:

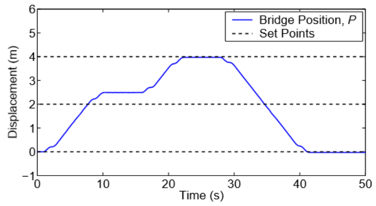
$$(R_c)_i = R_i + O_i \quad (6)$$

$$O_i = (|O_{i-1}| + L_{i-1}) \times \text{sign}(P-R_i) \quad (7)$$

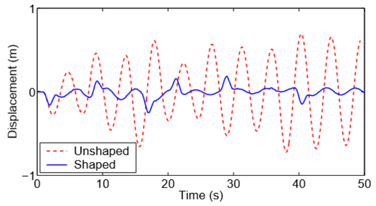
$(R_c)_i$ is the current offset reference signal; R_i is the current true reference signal; O_i is the current offset value; O_{i-1} is the previous offset value; and L_{i-1} is the previous bridge overshoot. This simple algorithm makes use of information gathered during previous bridge motion in order to continually refine the level of signal modification. In this way, the compensator allows the control to be self-calibrating and self-correcting; as the kinetic performance of the crane changes due to time and wear, the controller adapts accordingly.

Modified Controller Experimental Results

Results were also obtained for experiment conducted for modified controller. In order to observe the self-correcting properties of the control, the offset reference signal, R_c, was initially set to be coincident with the true reference signal, R. As shown in Figure 8(a), the bridge position response to the first offset reference signal was nearly identical to bridge response when using the unmodified control, the bridge overshot the first set point by approximately half of a meter. From Figure 8(b), it could be observed that the modified control still significantly reduces cable sway.



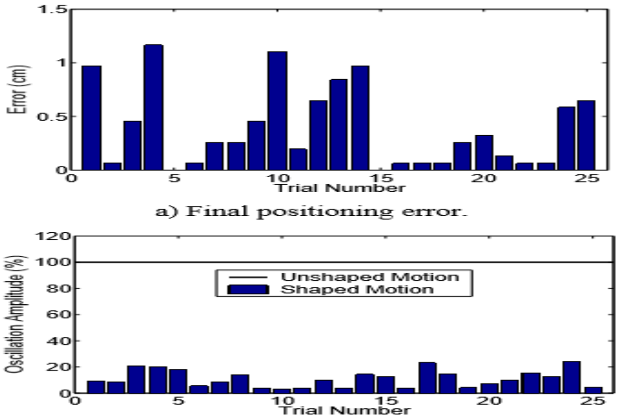
a) Bridge response.



b) Payload response.

Figure 8: Experimental bridge payload response

Figure 9 shows the results obtained for position and oscillation reduction capabilities of the modified control. The vertical axis of Figure 9(a) represents the positioning error between the desired bridge position and the actual final bridge position. And the vertical axis of Figure 9(b) represents the residual peak-to-peak oscillation amplitude of the payload. Notice that this axis has been normalized to the residual peak-to-peak oscillation amplitude for unshaped crane motion.



a) Final positioning error.

b) Residual payload oscillation.

Figure 9: Positioning and oscillation reduction capabilities of the modified control

These figures demonstrate that with the modified control, the crane may be positioned within 1.3 cm of a commanded position, while keeping the oscillations to approximately 20% of the oscillation amplitude normally excited with unshaped motion.

CONCLUSION

The combined feedback and input shaping controller described here takes into account the special properties of cranes, specifically, the predominantly single-mode nature of the dynamics, the known frequency range of the dominant mode, and the common on-off, relay-type motors. The control utilizes the strengths of both feedback control and input shaping to accurately position the crane while limiting cable sway. The input shaper used in the control generates simple on-off, relay-type commands, suitable for use on cranes not fitted with variable velocity compliant hardware. The controller was implemented and tested in the Maatlab environment. Experimental results suggest that the control, when modified to compensate for bridge deceleration time, can significantly reduce cable sway, while enabling precise payload positioning. A positioning accuracy of 1.3 cm was demonstrated. The amplitudes of the payload oscillations resulting from shaped motion were roughly 20% of the oscillation amplitudes caused from unshaped bridge motion.

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