Proceedings of the 2009 IEEE
International Conference on Mechatronics and Automation
August 9 - 12, Changchun, China

Techniques of Anti-sway and Input Tracking Control of a Gantry Crane System

Mohd Ashraf Ahmad, Ahmad Nor Kasruddin Nasir, Haszuraidah Ishak

Faculty of Electrical and Electronics Engineering
Universiti Malaysia Pahang,
Lebuhraya Tun Razak, 26300, Kuantan, Pahang, Malaysia
{mashraf, kasruddin & haszuraidah}@ump.edu.my

***Abstract* - This paper presents investigations into the development of control schemes for anti-swaying and input tracking control of a gantry crane system. A nonlinear overhead gantry crane system is considered and the dynamic model of the system is derived using the Euler-Lagrange formulation. To study the effectiveness of the controllers, initially a collocated PD control is developed for cart position control of gantry crane. This is then extended to incorporate a non-collocated PID and an input shaper control schemes for anti-swaying control of the system. The positive input shapers with the derivative effects are designed based on the properties of the system. Simulation results of the response of the gantry crane with the controllers are presented in time and frequency domains. The performances of the control schemes are examined in terms of level of input tracking capability, swing angle reduction and time response specifications in comparison to the PD control. Finally, a comparative assessment of the control techniques is presented and discussed.**

Index Terms* – *Gantry crane, non-collocated PID, input shaping.

I. INTRODUCTION

The main purpose of controlling a gantry crane is transporting the load as fast as possible without causing any excessive swing at the final position. However, most of the common gantry crane results in a swing motion when payload is suddenly stopped after a fast motion [1]. The swing motion can be reduced but will be time consuming. Moreover, the gantry crane needs a skilful operator to control manually based on his or her experiences to stop the swing immediately at the right position. The failure of controlling crane also might cause accident and may harm people and the surrounding.

Various attempts in controlling gantry cranes system based on open loop system were proposed. For example, open loop time optimal strategies were applied to the crane by many researchers such as discussed in [2,3]. They came out with poor results because open loop strategy is sensitive to the system parameters (e.g. rope length) and could not compensate for wind disturbances. Another open loop control strategies is input shaping [4,5,6]. Input shaping is implemented in real time by convolving the command signal with an impulse sequence. The process has the effect of placing zeros at the locations of the flexible poles of the original system. An IIR filtering technique related to input shaping has been proposed for controlling suspended payloads [7]. Input shaping has been shown to be effective for controlling oscillation of gantry cranes when the load does not undergo hoisting [8, 9]. Experimental results also indicate that shaped commands can be of benefit when the load is hoisted during the motion [10].

On the other hand, feedback control which is well known to be less sensitive to disturbances and parameter variations [11] is also adopted for controlling the gantry crane system. Recent work on gantry crane control system was presented by Omar [1]. The author had proposed proportional-derivative PD controllers for both position and anti-swing controls. Furthermore, a fuzzy-based intelligent gantry crane system has been proposed [12]. The proposed fuzzy logic controllers consist of position as well as anti-sway controllers. However, most of the feedback control system proposed needs sensors for measuring the cart position as well as the load swing angle. In addition, designing the swing angle measurement of the real gantry crane system, in particular, is not an easy task since there is a hoisting mechanism.

This paper presents investigations into the development of techniques for anti-swaying and input tracking of a gantry crane system. Control strategies based on input shaper with PD controller and with combined non-collocated PID and PD controllers are investigated. For non-collocated control, sway angle feedback through a PID control configuration whereas positive input shaper is utilised as a feedforward scheme for reducing a sway effect. A simulation environment is developed within Simulink and Matlab for evaluation of performance of the control schemes. Simulation results of the response of the gantry crane with the controllers are presented in time and frequency domains. The performances of the control schemes are examined in terms of level of input tracking capability, swing angle reduction and time response specifications in comparison to the PD control. Finally, a comparative assessment of the control techniques is presented and discussed.

II. THE GANTRY CRANE SYSTEM

The two-dimensional gantry crane system with its payload considered in this work is shown in Fig. 1, where x is the horizontal position of the cart, l is the length of the rope, θ is the swing angle of the rope, M and m is the mass of the cart and payload respectively. In this simulation, the cart and payload can be considered as point masses and are

978-1-4244-2693-5/09/$25.00 ©2009 IEEE

assumed to move in two-dimensional, x-y plane. The tension force that may cause the hoisting rope elongate is also ignored. In this study the length of the cart, $l = 1.00$ m, $M = 2.49$ kg, $m = 1.00$ kg and $g = 9.81$ m/s^2 is considered.

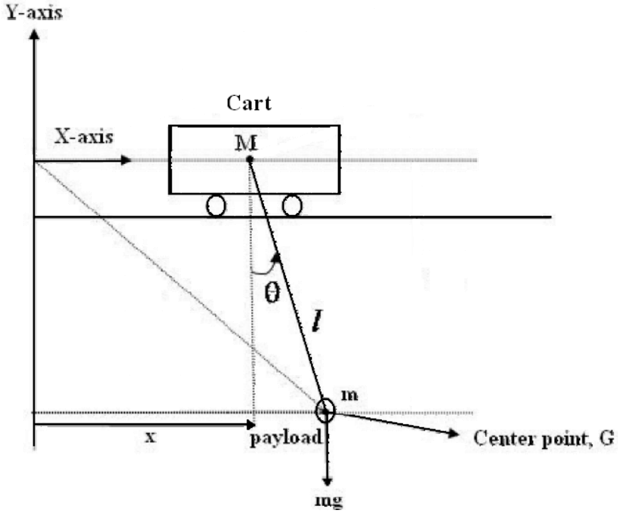

Fig. 1 Description of the gantry crane system.

III. DYNAMIC MODELING OF THE GANTRY CRANE

This section provides a brief description on the modelling of the gantry crane system, as a basis of a simulation environment for development and assessment of the input shaping control techniques. The Euler-Lagrange formulation is considered in characterizing the dynamic behaviour of the crane system incorporating payload.

Considering the motion of the gantry crane system on a two-dimensional plane, the kinetic energy of the system can thus be formulated as

$$T = \frac{1}{2}M\dot{x}^2 + \frac{1}{2}m(\dot{x}^2 + \dot{l}^2 + l^2\dot{\theta}^2 + 2\dot{x}\dot{l}\sin\theta + 2\dot{x}l\dot{\theta}\cos\theta) \quad (1)$$

The potential energy of the beam can be formulated as

$$U = -mgl\cos\theta \quad (2)$$

To obtain a closed-form dynamic model of the gantry crane, the energy expressions in (1) and (2) are used to formulate the Lagrangian $L = T - U$. Let the generalized forces corresponding to the generalized displacements $\overline{q} = \{x, \theta\}$ be $\overline{F} = \{F_x, 0\}$. Using Lagrangian's equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = F_j \qquad j = 1,2 \quad (3)$$

the equation of motion is obtained as below,

$$F_x = (M+m)\ddot{x} + ml(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta) + 2m\dot{l}\dot{\theta}\cos\theta + m\ddot{l}\sin\theta \quad (4)$$

$$l\ddot{\theta} + 2\dot{l}\dot{\theta} + \ddot{x}\cos\theta + g\sin\theta = 0 \quad (5)$$

IV. CONTROL SCHEMES

In this section, control schemes for rigid body motion control of the cart and swaying angle reduction of hoisting rope are proposed. Initially, a PD controller is designed. Then a non-collocated PID control and input shaper control are incorporated in the closed-loop system for control of swaying angle of the hoisting rope.

A. PD controller

A common strategy in the control of manipulator systems involves the utilization of PD feedback of collocated sensor signals. In this work, such a strategy is adopted at this stage. A block diagram of the PD controller is shown in Fig. 2, where K_p and K_d are proportional and derivative gains, respectively, x and $\dot{x}$ represent horizontal position and velocity of the cart, respectively, θ and $\dot{\theta}$ represent swing angle and swing velocity, respectively R_f is the reference horizontal position.

The control signal *u(t)* in Fig. 2 can be written as,

$$u(t) = K_p(R_f(t) - x(t)) + K_d\frac{d}{dt}(R_f(t) - x(t)) \quad (6)$$

In this study, the Ziegler-Nichols approach is utilized to design the PD controller. The value of proportional and derivative gain, K_p and K_d were chosen heuristically to achieve a satisfactory set of time domain parameters. These values were recorded as, $K_p = 150$ and $K_d = 80$.

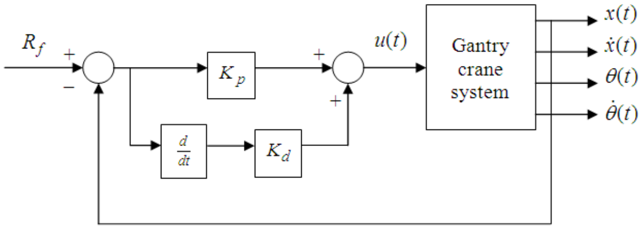

Fig. 2 The PD control structure.

B. PD with non-collocated PID controller

A combination of PD and non-collocated PID control scheme for control of rigid body motion of the cart and swaying angle reduction of the system is presented in this section. The use of a non-collocated control system, where the swing angle of the hoisting rope is controlled, can be applied to improve the overall performance, as more reliable output measurement is obtained. The control structure comprises two feedback loops: (1) The cart position feedback as input to compensate the control gain for rigid body motion control. (2) The swing angle of hoisting rope as input to a separate non-collocated control law for swaying angle suppression. A block diagram of the control scheme is shown in Fig. 3 where θ represents the swing angle of the hoisting rope, r_θ represents swing angle reference input, which is set to zero as the control objective is to have zero swing angle during movement of the gantry crane.

For rigid body motion control, the PD control strategy developed in the previous section is adopted whereas for the sway angle control loop, the swing angle of the hoisting rope feedback through a PID control scheme is utilized. The PID controller parameters were tuned using the Ziegler-Nichols method using a closed-loop technique, where the proportional gain K_p was initially tuned and the integral gain K_i and derivative gain K_d were then calculated [13]. Accordingly, the PID parameters K_p, K_i and K_d were deduced as 1.3, 0.8 and 0.01 respectively. To decouple the swing angle measurement from the rigid body motion of the gantry crane's cart, a third-order infinite impulse response (IIR) Butterworth High-pass filter was utilised. In this investigation, a High-pass filter with cut-off frequency of 1.5 Hz was designed.

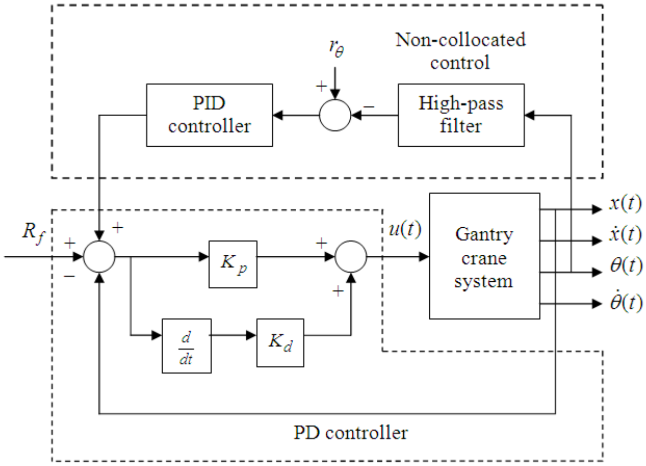

Fig. 3 The PD and non-collocated PID control structure.

C. *PD with input shaping control*

A control structure for control of rigid body motion and swing angle reduction of the gantry crane system based on PD and input shaping control is proposed in this section. The positive input shapers are proposed and designed based on the properties of the system. In this study, the input shaping control scheme is developed using a Zero-Vibration-Derivative-Derivative (ZVDD) input shaping technique [14]. Previous experimental study with a flexible manipulator has shown that significant vibration reduction and robustness is achieved using a ZVDD technique [15]. A block diagram of the PD with input shaping control technique is shown in Fig. 4.

The input shaping method involves convolving a desired command with a sequence of impulses known as input shaper. The design objectives are to determine the amplitude and time location of the impulses based on the natural frequencies and damping ratios of the system. The positive input shapers have been used in most input shaping schemes. The requirement of positive amplitude for the impulses is to avoid the problem of large amplitude impulses. In this case, each individual impulse must be less than one to satisfy the unity magnitude constraint. In addition, the robustness of the input shaper to errors in natural frequencies of the system can be increased by solving the derivatives of the system vibration equation. This yields a positive ZVDD shaper with parameter as

$$\begin{aligned} & t_1 = 0, t_2 = \frac{\pi}{\omega_d}, t_3 = \frac{2\pi}{\omega_d}, t_4 = \frac{3\pi}{\omega_d} \\ & A_1 = \frac{1}{1+3H+3H^2+H^3}, A_2 = \frac{3H}{1+3H+3H^2+H^3} \\ & A_3 = \frac{3H^2}{1+3H+3H^2+H^3}, A_4 = \frac{H^3}{1+3H+3H^2+H^3} \end{aligned} \tag{7}$$

where

$$H = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}}, \quad \omega_d = \omega_n\sqrt{1-\zeta^2}$$

where ω_n and ζ representing the natural frequency and damping ratio respectively. For the impulses, t_j and A_j are the time location and amplitude of impulse j respectively.

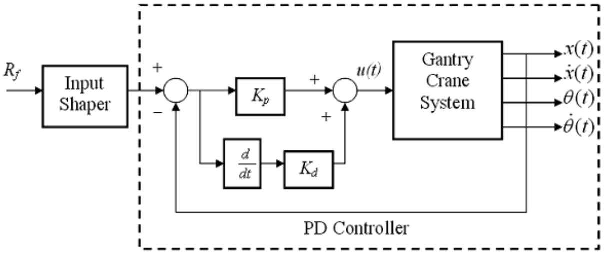

Fig. 4 The PD and input shaping control structure.

V. IMPLEMENTATION AND RESULTS

In this section, the proposed control schemes are implemented and tested within the simulation environment of the gantry crane system and the corresponding results are presented. The cart of the gantry crane is required to follow a trajectory position within the range of 4 ± m. System responses namely the horizontal position of the cart and swing angle of the hoisting rope are observed. To investigate the swing angle effect in the frequency domain, power spectral density (PSD) of the swing angle response is obtained. The performances of the control schemes are assessed in terms of swing angle suppression, input tracking and time response specifications. Finally, a comparative assessment of the performance of the control schemes is presented and discussed.

Figs. 5-7 show the responses of the gantry crane system to the reference input trajectory using PD controller in time-domain and frequency domain (PSD). These results were considered as the system response under rigid body motion control and will be used to evaluate the performance of the non-collocated PID and input shaping control. The steady-state cart position trajectory of +4 m for the gantry crane was achieved within the rise and settling times and overshoot of 1.292 s, 2.002 s and 1.375 % respectively. It is noted that the cart reaches the required position from +4 m to -4 m within 3 s, with little overshoot. However, a noticeable amount of swing angle occurs during movement of the cart. It is noted from the swing angle response with a maximum residual of ±1.3 rad. Moreover, from the PSD of the swing angle response the swaying frequencies are dominated by the first three modes, which are obtained as 0.3925 Hz, 1.276 Hz and 2.06 Hz with magnitude of 32.02 dB, -9.01 dB and -26.19 dB respectively.

The horizontal cart position trajectory, swing angle of the hoisting rope and power spectral density responses of the gantry crane system using PD with non-collocated PID (PD-PID) and input shaping (PD-IS) control are shown in Figs. 5-7 respectively. It is noted that the proposed control schemes are capable of reducing the system sway effect while maintaining the input tracking performance of the gantry crane. Similar cart position trajectory, swing angle and power spectral density of swing angle responses were observed as compared to the PD controller.

Table 1 summarizes the levels of sway effect reduction of the system responses at the first three modes in comparison to the PD control. In overall, higher levels of sway effect reduction for the first three modes were obtained using PD-IS as compared to PD-PID. However, the system response using PD-PID is faster than the case of PD-IS. It is noted with the input shaping controller, the impulses sequence in input shaper increase the delay in the system response. The corresponding rise time, setting time and overshoot of the cart position trajectory response using PD-IS and PD-PID is depicted in Table 1. Moreover, as demonstrated in the cart position trajectory response with PD-PID control, the minimum phase behaviour of the gantry crane is unaffected. A significant amount of swing angle amplitude suppression was demonstrated with both control schemes. With the PD-PID control, the maximum swing angle is ±1.2 rad while with the PD-IS control is ±0.16 rad. Hence, it is noted that the magnitude of oscillation was significantly reduced by using PD with input shaping control as compared to the case of PD with non-collocated PID control. In overall, the performance of the control schemes at input tracking capability is maintained as the PD control.

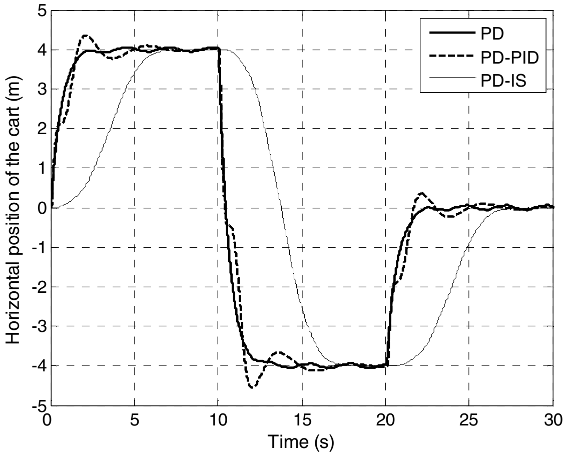

Fig. 5 Horizontal position of the cart using PD, PD-PID and PD-IS.

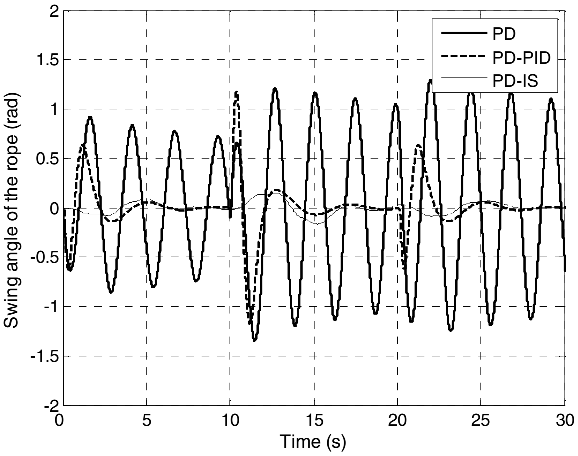

Fig. 6 Swing angle of the rope using PD, PD-PID and PD-IS.

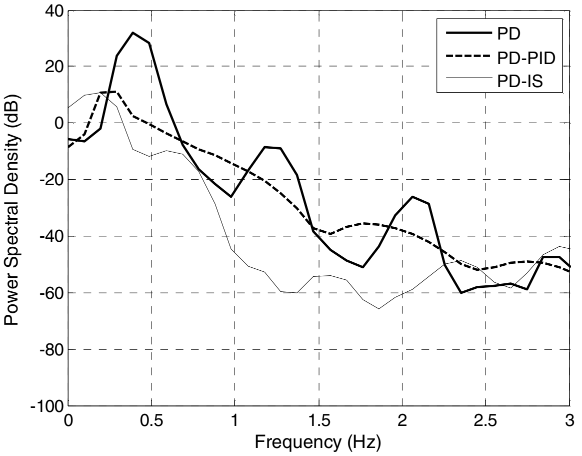

Fig. 7 PSD response using PD, PD-PID and PD-IS.

TABLE I

LEVEL OF SWING ANGLE REDUCTION OF THE ROPE AND SPECIFICATIONS OF THE CART TRAJECTORY FOR PD-PID AND PD-IS CONTROL SCHEMES

Controller	Attenuation (dB) of swing angle of the rope			Specification of cart trajectory response		
	Mode 1	Mode 2	Mode 3	Rise time (s)	Settling time (s)	Overshoot (%)
PD-PID	29.53	11.89	13.03	1.323	6.183	8.73
PD-IS	41.32	50.68	32.74	3.516	6.366	0.03

The simulation results show that the performance of PD-IS control scheme is better than PD-PID schemes in swing angle suppression of the gantry crane. This is further evidenced in Fig. 8 that demonstrates the level of sway effect reduction at the resonance modes of the PD with non-collocated and input shaping control respectively as compared to the PD controller. It is noted that higher swing angle reduction is achieved with PD-IS at the first three modes of sway effect. Almost onefold, threefold and twofold improvement in the sway effect reduction at the first, second and three resonance mode respectively were observed with PD-IS as compared to PD-PID. Moreover, implementation of PD with input shaping control is easier than PD with non-collocated PID control as a large amount of design effort is required to determine the best PID parameters. Note that a properly tuned PID could produce better results. However, as demonstrated in the cart position trajectory response, slightly slower response is obtained using PD with input shaping control as compared to the PD with non-collocated control.

Further comparisons of the specifications of the cart position trajectory responses are summarized in Fig. 9 for the rise and settling times. The work thus developed and reported in this paper forms the basis of design and development of hybrid control schemes for input tracking and sway effect suppression of three-dimensional gantry crane systems and can be extended to and adopted in practical applications.

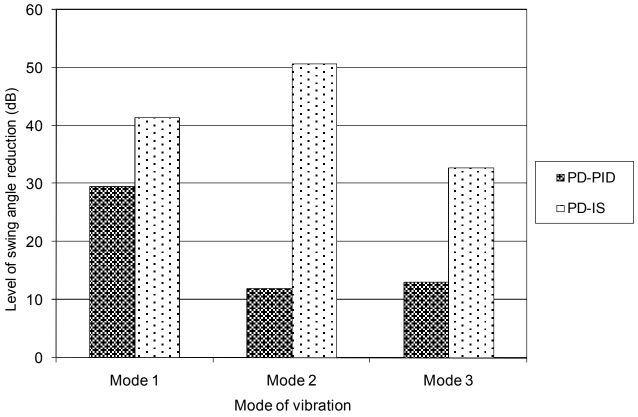

Fig. 8 Level of swing angle reduction using PD-PID and PD-IS.

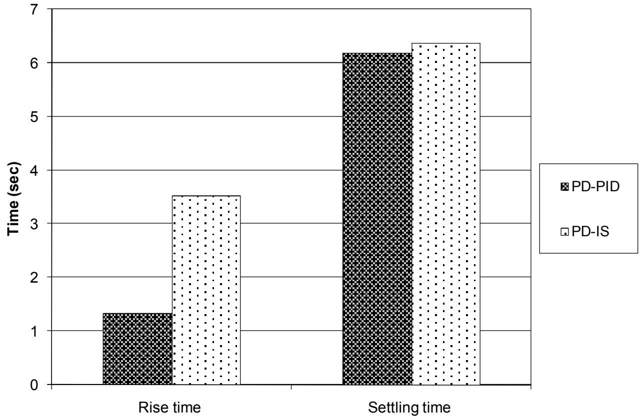

Fig. 9 Rise and settling time of the cart trajectory using PD-PID and PD-IS.

VI. CONCLUSION

The development of techniques for anti-sway and input tracking of the gantry crane system has been presented. The control schemes have been developed based on PD with non-collocated PID control and PD with input shaper technique. The proposed control schemes have been implemented and tested within simulation environment of a non-linear gantry crane. The performances of the control schemes have been evaluated in terms of residual sway angle suppression and input tracking capability at the resonance modes of the gantry crane. Acceptable performance in sway angle suppression and input tracking control has been achieved with proposed control strategies. A comparative assessment of the control schemes has shown that the PD control with input shaping performs better than the PD with non-collocated PID control in respect of swing angle reduction of the hoisting rope. However, the speed of the response is slightly improved at the expenses of decrease in the level of swing angle reduction by using the PD with non-collocated PID control. It is concluded that the proposed controllers are capable of reducing the system sway effect while maintaining the input tracking performance of the gantry crane.

ACKNOWLEDGMENT

This work was supported by Faculty of Electrical & Electronics Engineering, Universiti Malaysia Pahang, especially Control & Instrumentation (COINS) Research Group.

REFERENCES

[1] Omar, H.M, Control of gantry and tower cranes. Ph.D. Thesis, M.S. Virginia Tech, 2003.

[2] Manson, G.A., “Time-optimal control of and overhead crane model”, *Optimal Control Applications & Methods*, Vol. 3, No. 2, 1992, pp. 115-120.

[3] Auernig, J. and Troger, H. “Time optimal control of overhead cranes with hoisting of the load”, *Automatica*, Vol. 23, No. 4, 1987, pp. 437-447.

[4] Karnopp, B H., Fisher, F.E., and Yoon, B.O., "A strategy for moving mass from one point to another", *Journal of the Franklin Institute*, Vol. 329, 1992, pp. 881-892.

[5] Teo, C.L., Ong, C. J. and Xu, M. “Pulse input sequences for residual vibration reduction”, *Journal of Sound and Vibration*, Vol. 211, No. 2, 1998, pp. 157-177.

[6] Singhose, W.E., Porter L.J. and Seering, W., "Input shaped of a planar gantry crane with hoisting", *Proc. of the American Control Conference*, 1997, pp. 97-100.

[7] Feddema, J.T., “Digital Filter Control of Remotely Operated Flexible Robotic Structures,” *American Control Conference*, San Francisco, CA, Vol. 3, pp. 2710-2715, 1993.

[8] Noakes, M.W. and J.F. Jansen, “Generalized Inputs for Damped-Vibration Control of Suspended Payloads,” *Robotics and Autonomous Systems*, 10(2): p. 199-205, 1992.

[9] Singer, N., W. Singhose, and E. Kriikku, “An Input Shaping Controller Enabling Cranes to Move Without Sway,” *ANS 7th Topical Meeting on Robotics and Remote Systems, Augusta*, GA, 1997.

[10] Kress, R.L., J.F. Jansen, and M.W. Noakes, “Experimental Implementation of a Robust Damped-Oscillation Control Algorithm on a Full Sized, Two-DOF, AC Induction Motor- Driven Crane,” *5th ISRAM*, Maui, HA, pp. 585-92, 1994.

[11] Belanger, N.M., Control Engineering: A Modern Approach, Saunders College Publishing, 1995.

[12] Wahyudi and Jalani, J., “Design and implementation of fuzzy logic controller for an intelligent gantry crane system”, *Proceedings of the 2nd International Conference on Mechatronics*, 2005, pp. 345- 351.

[13] Warwick, K. Control systems: an introduction, Prentice Hall, London, 1989.

[14] Mohamed, Z. and Ahmad, M.A., “Hybrid Input Shaping and Feedback Control Schemes of a Flexible Robot Manipulator”, *Proceedings of the 17th World Congress The International Federation of Automatic Control*, Seoul, Korea, July 6-11, 2008, pp. 11714-11719.

[15] Mohamed, Z. and Tokhi, M.O. “Vibration control of a single-link flexible manipulator using command shaping techniques”, *Proceedings IMechE-I: Journal of Systems and Control Engineering*, 216, 191-210, 2002.