Sensorless Anti-Swing Control Strategy for Automatic Gantry Crane System using Reference Modifier

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***Abstract*— A good control performance of automatic gantry crane system is commonly a chieved by feedback anti-swing control. Hence, sensors are indispensable instrument for feedback signals. However, sensing the payload motion of a real gantry crane, particularly swing motion, is not simple and often costly. Therefore, a sensorless automatic gantry crane control strategy using reference modifier is developed and proposed in this paper. A reference modifier is introduced to produce anti-swing cart motion. An experimental study using lab-scale automatic gantry crane is carried out to evaluate the effectiveness of the proposed control strategy. The results show that the proposed sensorless anti-swing control strategy is effective for suppressing the swing motion since it gives similar performance to that of sensor-based anti-swing control strategy.**

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 cranes result in a swing motion when payload is suddenly stopped after a fast motion [1]. The swing motion can be reduced but it 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 desired position. The failure of controlling cranes might also cause accident and may harm people and the surroundings.

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 importance of open loop strategy is the input shaping introduced by Karnopp [4], Teo [5] and Singhose [6]. However the input shaping method is still an open-loop approach.

On the other hand, feedback control which is well known to be less sensitive to disturbances and parameter variations [7] 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 PD (proportional + derivative) controllers for both position and anti-swing controls. Furthermore, a fuzzy-based intelligent gantry crane system has been proposed [8]. The proposed fuzzy logic controllers consist of position as well as anti-swing controllers. The fuzzy logic controllers were designed based on information of the skillful operators and without the need of crane model and its parameters. The performance of the proposed intelligent gantry crane system had been evaluated experimentally on a lab-scale gantry crane. It was shown that the proposed system has a good positioning performance as well as a good capability to suppress the swing angle in comparison with the crane controlled by the PID (proportional + integral + derivative) controllers [8].

However, most of the feedback control system proposed needs sensors for measuring the cart position as well as the payload 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. Some researches have also focused on control schemes with vision system that is more feasible because the vision sensor is not located at the load side. The drawbacks of the vision system, among those are difficult maintenance and high cost [9].

To overcome this problem, a sensorless anti-swing control strategy using reference modifier is proposed and developed for automatic gantry crane system. The proposed reference modifier basically is used to generate modified reference input to the position control of crane cart so that it moves to the desired position with no excessive swing motion of the payload. In order to evaluate the effectiveness of the proposed method, it is implemented experimentally on a lab-scale gantry crane and it performance is compared that of sensor-based anti-swing control. The experimental results show that the proposed sensorless anti-swing control is effectively used to suppress the payload swing motion since it has similar performance to sensor-based anti-swing control.

II. BASIC CONCEPT OF REFERENCE MODIFIER

Most of automatic gantry crane proposed by researchers use two controllers as shown in Fig. 1, for controlling both cart position and swing of the crane payload. As no-swing motion of the payload is required, the structure of the feedback system for

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automatic gantry crane can be simplified as shown in Fig. 2. In this feedback control system, two sensors are needed to measure the cart position *X(s)* and swing angle *Θ(s)*. The latter is usually installed on the load side. However as discussed previously, swing angle measurement of the real gantry crane system, in particular, is not an easy task since there is a hoisting mechanism.

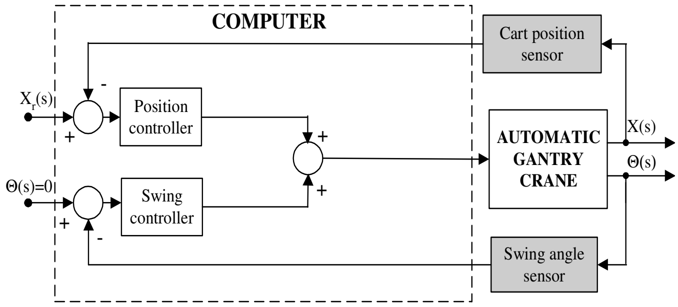

Fig. 1. Diagram of anti-swing feedback control system.

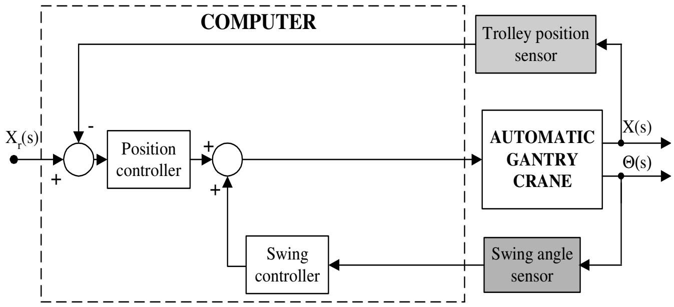

Fig. 2. Simplified diagram of anti-swing feedback control system.

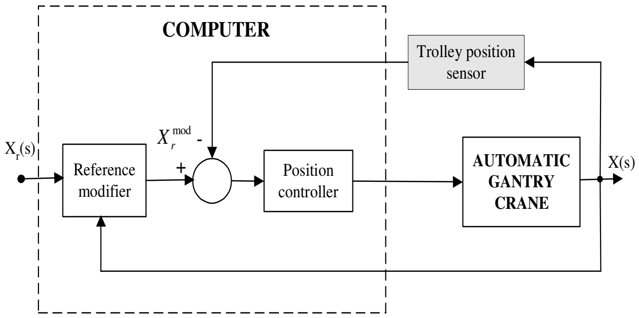

Fig. 3. Proposed sensorless anti-swing control strategy.

To overcome the above-mentioned problem, a reference modifier as shown in Fig. 3 is introduced to realize a sensorless anti-swing control strategy. Basically the reference modifier is used to generate modified reference signal $X_r^{mod}(s)$ based on the desired position $X_r(s)$. The modified reference input $X_r^{mod}(s)$ is developed such that the cart moves from a point to another point without causing an excessive swing motion of the payload. To generate the modified reference input, the mathematical model of the crane system including the characteristic of oscillation is required.

III. Mathematical Model of Gantry Crane

A gantry crane model is required to develop the proposed input reference modifier. Fig. 4 shows a schematic diagram of planar gantry crane system considered in this paper. Due to the fact that only planar motion of crane is considered, there are two independent coordinates namely x and θ to describe the cart position and the swing angle of the payload respectively. The translational position of swinging load suspended by cable with respect to horizontal reference, x_m can be represented as follows:

$$x_m = x + l\sin\theta \tag{1}$$

where l is the rope length. Since the mass of the rope is small enough as compared to the payload mass m_1, it can be assumed as massless. The Lagrange's equation associated with generalized coordinates x and θ are:

$$(m_2 + m_1)\ddot{x} + m_1 l(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta) = F \tag{2}$$

$$l\ddot{\theta} + \ddot{x}\cos\theta + g\sin\theta = 0 \tag{3}$$

By assuming small motion of θ, the following linearized dynamic model of the crane can be obtained:

$$(m_2 + m_1)\ddot{x} + m_1 l\ddot{\theta} = F \tag{4}$$

$$\ddot{x} + l\ddot{\theta} + g\theta = 0 \tag{5}$$

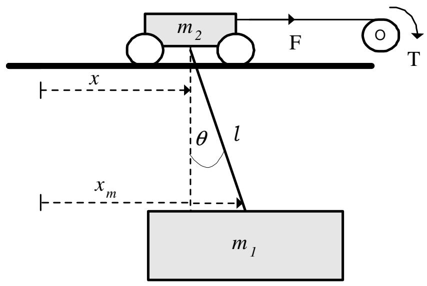

Fig. 4. Gantry Crane Model

The translational motion of cart is driven by DC motor. Therefore, to obtain the entire model of lab-scale gantry crane, the motor dynamic is modeled according to equivalent DC motor circuit. It has armature resistance *R*, inductance *L*, motor inertia *J* and torque constant K_t, input voltage *u*, armature current *i* and viscous friction *b*. The rotational motion is converted to translational motion trough the mechanical part (pulley or gear) with radii of *r*. The dynamic of the DC motor governing the cart can be expressed as follows:

$$u = Ri + L\frac{di}{dt} + K_t\dot{\theta} \tag{6}$$

$$K_t i - b\dot{\theta} - Fr = J\ddot{\theta} \tag{7}$$

Finally, (4)-(7) can be combined in the form of the following transfer functions:

$$\frac{X(s)}{U(s)} = \frac{k_0}{s(a_2 s^2 + a_1 s + 1)} \tag{8}$$

$$\frac{\Theta(s)}{X(s)} = \frac{-s^2}{ls^2 + g} \tag{9}$$

where:

$$k_0 = \frac{K_t r}{Rb} \quad (10.a)$$

$$a_2 = \frac{Lm_2 r^2 + LJ}{Rb} \quad (10.b)$$

$$a_1 = \frac{Rm_2 r^2 + RJ + Lb}{Rb}. \quad (10.c)$$

IV. Development of Sensorless Anti-swing Control Based on Reference Modifier

In the proposed sensorless anti-swing control, it should produce command input that guarantee the positioning performance while canceling the oscillation especially during acceleration/deceleration. This can be achieved by modifying the input reference shown in Fig. 3. In order to develop modified reference input, according to (5), there is linear relationship between swing angle and cart acceleration as follows:

$$l\ddot{\theta} + g\theta = -\ddot{x}. \quad (11)$$

Moreover, by differentiating both sides of (1), the following is obtained:

$$\ddot{x}_m - \ddot{x} = l\ddot{\theta}. \quad (12)$$

Then, (12) is substituted to (11) resulting in the following equation:

$$\ddot{x}_m + \frac{g}{l}x_m - \frac{g}{l}x = 0. \quad (13)$$

By assuming the feedback control system of Fig. 3 has a high bandwidth so that $X(s) = X_r^{mod}(s)$, (13) becomes:

$$X_m(s) = \frac{g/l}{s^2 + g/l} X_r^{mod}(s) \quad (14a)$$

$$X_r^{\mathrm{mod}}(s) = \frac{s^2 + g/l}{g/l} X_m(s) \quad (14b)$$

Let's assume there is no input modifier ($X_r(s) = X_r^{mod}(s)$), (14a) becomes:

$$X_m(s) = \frac{g/l}{s^2 + g/l} X_r(s) \quad (15)$$

Equation (15) shows a second order system without damping which gives an oscillation response of the payload position X_m(s) for any input reference $X_r(s)$. Theoretically, the oscillatory motion can be suppressed by adding enough damping ratio. To add the damping factor to the system, an reference modifier with modifier parameter gain K be inserted to the system so that (15) becomes:

$$X_m(s) = \frac{g/l}{s^2 + Ks + g/l} X_r(s) \quad (16)$$

Equation (14) may be written in standard second order system as follows:

$$X_m(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} X_r(s) \quad (17)$$

Where

$$\omega_n = \sqrt{\frac{g}{l}} \quad (17.a)$$

$$K = 2\zeta\omega_n. \quad (17.b)$$

Then, by combining (14a) and (16), the relationship between the original reference input $X_r(s)$ with the modified reference input $X_r^{mod}(s)$ can be obtained as follows:

$$X_r(s) = X_r^{\mathrm{mod}}(s) + \frac{Ks}{s^2 + g/l} X_r^{\mathrm{mod}}(s). \quad (18)$$

Substituting $X_r^{\mathrm{mod}}(s)$ in the second term of (18) by (14b), yields:

$$X_r(s) = X_r^{\mathrm{mod}}(s) + \frac{Kl}{g} s X_m(s). \quad (19)$$

Finally, by using (11) and (12), (19) is re-written to the following form:

$$X_r^{\mathrm{mod}}(s) = X_r(s) - \left(K \frac{s}{s^2 + g/l}\right) X(s). \quad (20)$$

Fig. 6 shows the diagram of the proposed sensorless anti-swing control developed using (20). The proposed modifier parameter K is obtained based on the added damping ratio ζ and the natural frequency ω_n as shown in (17).

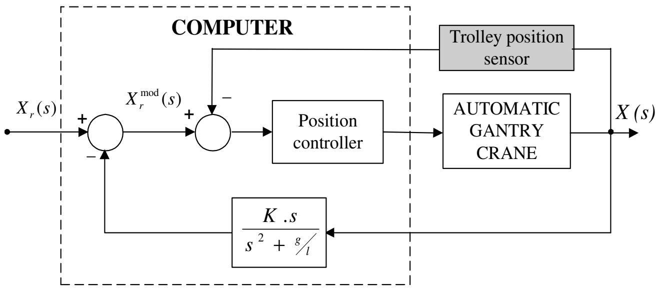

Fig. 4. Proposed Sensorless Anti-swing Control

V. Results

A. System Description

In order to evaluate the performance of the proposed sensorless anti-swing control, the proposed method is implemented to control a lab-scale gantry crane system shown in Fig. 5. The designed lab-scale gantry crane system has four main parts that are cart system, body frame, potentiometers and a DC motor as an actuator. The DC motor and its driver are used to move cart. As the proposed sensorless anti-swing control strategy is based on mathematical model of the crane, a mathematical model of the lab-scale gantry crane was developed and its parameters are identified. The developed dynamics model of the crane is:

$$\frac{X(s)}{U(s)} = \frac{20.12}{0.016s^2 + 0.234s + 1} \tag{21}$$

$$\frac{\Theta(s)}{X(s)} = \frac{-s^2}{60s^2 + 981}\,. \tag{22}$$

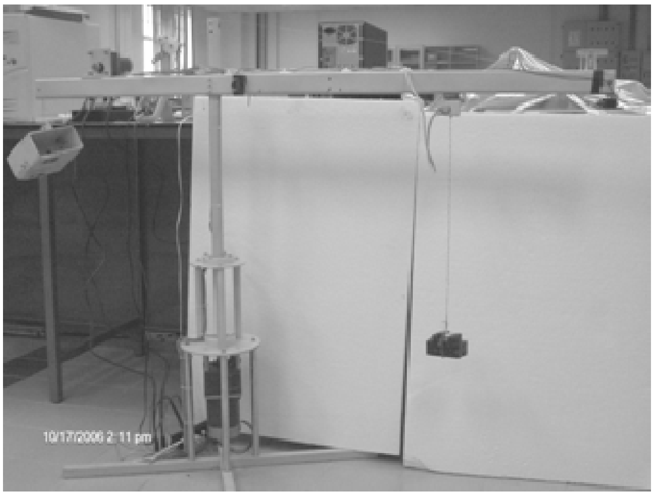

Fig. 5. Lab-scale gantry crane.

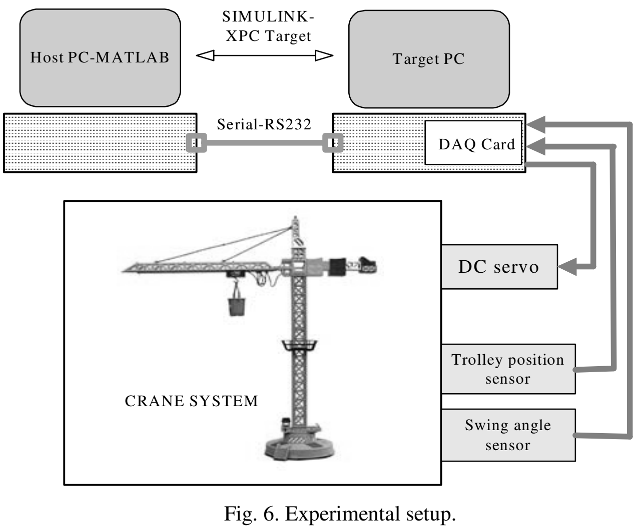

Fig. 6. Experimental setup.

The experimental setup is shown in Fig.6. The DC servo driver circuit operates the motor in the velocity control mode. The input voltage reference between -2.0 volts to 2.0 volts is sent from the PC to drive a 6W, 12V DC motor as control action signal for cart position. To detect cart position and swing angle 10kΩ 10-turns and $^{3}/_{4}$-turns potentiometers are installed respectively. Noise filters are also included to reduce noisy signals from the potentiometers/sensors. This is done by digital filtering in the PC. The proposed method is implemented digitally on a personal computer and is operated with 1 ms sampling time. The MathWork's MATLAB/Simulink is used for real-time controller implementation through RTW and xPC Target. Two potentiometers are used to measure the position and swing angle of the payload.

B. *Controller Design*

Well-known classical PID controllers are designed and used to evaluate the effectiveness of the proposed sensorless anti-swing control. The function of the controller is to control the payload position X(s) so that it moves to the desired position $X_{ref}(s)$ as fast as possible without excessive swing angle Θ(s). Due to its simplicity, a PID controller is adopted to control the cart position, while a PD controller is used for anti-swing controller. The PID controller gains are designed and optimized with simulation model by using *Simulink response optimization library block*. It is a numerical time domain optimizer developed under MATLAB/Simulink environment. Hence the *Simulink response optimization library block* assists in time-domain-based control design by setting the desired overshoot, settling time and steady state error.

In order to realize fast motion with small overshoot, the PID controller is optimized by considering the following desired specifications:

- Overshoot ≤ 2 %
- Settling time ≤ 5 s
- Steady state error ≤ ±1%

Moreover, in order to suppress the swing angle quickly, the PD controller is optimized based on the following desired specifications:

- Settling time ≤ 5 s
- Residual swing ≤ ±0.05 rad.

Table 1 lists the obtained PID controller parameters as the result of optimization prose using *Simulink response optimization library block.*

TABLE I.

PID CONTROLLER PARAMETERS

Gains	Controller	
	Position control	*Anti-swing control*
Proportional, K_p	0.17	13.54
Integral, K_i	$-1.67\text{x}10^{-4}$	-
Derivative, K_d	0.07	-0.33

Moreover, the design parameter *K* of the input reference modifier has to be designed based on the damping ratio added to the system. Whilst the suitable value of design parameter *K* can be evaluated to obtain the best performance, with known parameters of model, l=60cm and g=981cms^{-2}, thus ω_n =4.04. The selection of *K* value theoretically corresponds to the damping ratio which affects the settling time of oscillation to diminish. In this paper an additional damping ratio of ζ = 0.4 is added to the system. Based on

(17b), the parameter K of 3.2 is obtained and used in the proposed system.

C. Performance Evaluation

The performance of the proposed sensorless anti-swing control method is compared with those of sensor-based anti-swing control (Sensor-based). The positioning performances are evaluated in term of overshoot, settling time and steady state error. Whilst swing performances are evaluated based on maximum angle amplitude and settling time.

Fig. 7(a) shows the position responses to a 70 cm step input reference while Table II lists the detail positioning performance comparison. Fig. 7(a) and Table II show that the positioning performance of the both Sensorless and Sensor-based are similar each other since in term of positioning control, the both approaches utilize position sensor to measure the cart movement. However, the use of the input modifier degrades system accuracy since the error of the sensorless system is larger than that of sensor-based system. Further study has to be done to eliminate the negative effect of the input modifier to positioning performance.

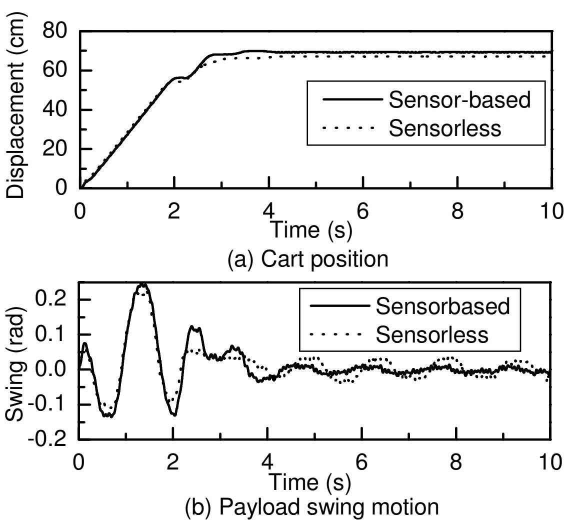

Fig. 7. Experimental Responses to a 70 cm step input reference.

Fig. 7(b) shows the swing angle responses to a 70 cm step input reference while Table III lists the detail anti-swing performance comparison. Fig. 7(b) and Table III show that in general the anti-swing performance of the both Sensorless and Sensor-based are also similar each other. The swing motion can be suppressed by using the proposed method. However, a longer time is needed since the settling time of the sensorless system is longer than that of sensor-based system.

TABLE II.

POSITIONING PERFORMANCE COMPARISON

Performance	Controller	
	Sensor-based	*Sensorless*
Overshoot, %	0	0
Settling time, sec	2.7	4.0
Error, cm	0.77	2.60

TABLE III.

ANTI-SWING PERFORMANCE COMPARISON

Performance	Controller	
	Sensor-based	*Sensorless*
Max. amplitude, rad	0.25	0.23
Settling time, sec	3.9	5.6

VI. CONCLUSIONS

In the real application of gantry crane, the use of sensors on the load side is impractical, particularly swing angle sensor. Therefore, an alternative strategy of anti-swing control is proposed in this paper. A reference modifier is proposed to eliminate real swing angle sensor for automatic gantry crane so that sensorless anti-swing control is realized. The swing motion of the crane is suppressed by modifying the reference input to the position control system. Implementation of the proposed method on a lab-scale gantry crane confirmed the effectiveness of the proposed method. The swing motion of the payload can be suppressed without using sensor for measuring the swing motion.

However, further studies need to be done to improve the performance of the proposed method. Furthermore, the experiment was done using lab-scale gantry prototype in the laboratory under ideal conditions where there were no disturbances such as wind like in the real situations. This subject must be also studied further.

VII. ACKNOWLEDGMENT

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

[8] 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.

[9] Kim, Y.S., Yoshihara, H., Fujioka, N., Kasahara, H., Shim. H., Sul, S.K., "A new vision-sensorless anti-sway control system for container cranes", Industry Applications Conference, 2003..