A New Fuzzy-Logic Anti-Swing Control for Industrial Three-Dimensional Overhead Cranes

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Abstract
In this paper, a new fuzzy anti-swing control scheme is proposed for a three-dimensional overhead crane. The proposed control consists of a position servo control and a fuzzy-logic control. The position servo control is used to control crane position and rope length, and the fuzzy-logic control is used to suppress load swing. The proposed control guarantees accurate control of crane position and rope length as well as prompt suppression of load swing for simultaneous travel, traverse, and hoisting motions of the crane. Furthermore, the proposed control provides practical gain tuning criteria for easy implementation. The effectiveness of the proposed control is demonstrated by experiments with a three-dimensional prototype overhead crane.

1 Introduction
Overhead cranes are widely used in industry for moving heavy objects. However, the overhead cranes have serious problems; the crane acceleration, required for motion, always induces undesirable load swing, which is frequently aggravated by load hoisting. Such load swing usually degrades work efficiency and sometimes causes load damages and even safety accidents. From a dynamics point of view, the overhead cranes are underactuated mechanical systems; that is, the overhead cranes have fewer control inputs than the degrees of freedom, which complicates the related control problems.

Various attempts have been made to solve the problems of load swing. Mita and Kanai¹ solved a minimum-time control problem for swing-free velocity profiles, which resulted in an open loop control. Ohnishi et al.[2] proposed a feedback control scheme based on load swing dynamics. Ridout[3] designed a linear feedback control using the root locus method. Yu et al.[4] proposed a nonlinear control based on the singular perturbation method. Lee et al.[5] designed a high performance control based on the loop shaping and root locus methods. Singhose et al. [6] applied the input shaping method to the control of gantry cranes with load hoisting. All these researchers have treated the load swing only for a two-dimensional overhead crane that allows only two-dimensional motions for its loads.

Moustafa and Ebied[7] proposed an anti-swing control for a three-dimensional overhead crane. Their control addresses the suppression of load swing; consequently, their control may result in considerable position errors in crane motion and load hoisting. In our previous study[8], a new nonlinear dynamic model was derived based on a newly defined two-degree-of-freedom swing angle, and a practical decoupled anti-swing control was proposed, for a three-dimensional overhead crane, where high performance control was experimentally demonstrated for simultaneous travel, traverse, and slow hoisting motions of a crane.

In this study, a new fuzzy-logic anti-swing control is proposed for a three-dimensional overhead crane. This study presents a practical solution for the anti-swing control of three-dimensional overhead cranes, where practical gain tuning criteria are provided for easy application. The proposed control consists of a fuzzy-logic control and a position servo control. The position servo control is designed based on an experimental model of the velocity servo dynamics of the crane. The fuzzy-logic control is designed based on the control rules of experienced crane operators. The proposed control guarantees not only prompt damping of load swing but also accurate control of crane position and rope length for simultaneous travel, traverse, and hoisting motions of the crane.

The remainder of this paper is organized as follows. In Section 2, a two-degree-of-freedom swing angle and
a linearized dynamic model are described, and then
the velocity servo dynamics of the crane is modeled
based on experiments. In Section 3, a position servo
control and a fuzzy anti-swing control are designed
to constitute a new anti-swing control system. In
Section 4, the proposed control is evaluated through
experiments. Finally, in Section 5, conclusions are
drawn for this study.

2 Dynamic modeling
In this section, a two-degree-of-freedom swing angle
and a linearized dynamic model will be described for
a three-dimensional overhead crane. Then the velo-
city servo dynamics of the crane will be modeled based
on experimental data.

2.1 Definition of a spatial swing angle
Figure 1 shows the coordinate systems of a three-
dimensional overhead crane and its load. XYZ is the
inertial coordinate system and XTYZ is the trolley
coordinate system attached to the trolley, whose
origin is (x, y, 0) in the inertial coordinate system. The
YT axis is defined on and along the girder which is not
shown in the figure. The trolley moves on the girder
in the YT direction and the girder (YT axis) moves in
the XT direction. θ is the swing angle of the load in
a space and has two components θx and θy; θx is the
swing angle projected on the XTZ plane and θy is the
swing angle measured from the XTZ plane.

Then the position of the load (x_m, y_m, z_m) in the
inertial coordinate system is given as

\[ x_m = x + l \sin \theta_x \cos \theta_y, \]
\[ y_m = y + l \sin \theta_y, \]  \hspace{1cm} (1)
\[ z_m = -l \cos \theta_x \cos \theta_y, \]

where l denotes the rope length.

2.2 Dynamic modeling of a crane
In practice, load swing is suppressed as much as pos-
sible for safety considerations. This study considers
this practical case of small load swing around the
stable equilibrium. Then, for the generalized coordi-
ates x, θx, y, θy, and l, the following linearized
dynamic model can be derived[8]:

\[ (M_x + m) \ddot{x} + D_x \dot{x} + m \ddot{\theta}_x = f_x, \]  \hspace{1cm} (2)
\[ l \ddot{\theta}_x + \dot{x} + g \dot{\theta}_x = 0, \]  \hspace{1cm} (3)
\[ (M_y + m) \ddot{y} + D_y \dot{y} + m \ddot{\theta}_y = f_y, \]  \hspace{1cm} (4)
\[ l \ddot{\theta}_y + \dot{y} + g \dot{\theta}_y = 0, \]  \hspace{1cm} (5)
\[ (M_l + m) \ddot{l} + D_l \dot{l} - mg = f_l. \]  \hspace{1cm} (6)

where m is the load mass; M_x, M_y, and M_l are the
x (traveling), y (traversing), and l (hoisting down)
components of the crane mass including the moment-
of-inertia of the gear train and motors, respectively;
D_x, D_y, and D_l denote the viscous damping coeffi-
cients of the crane in the x, y, and l directions,
respectively; f_x, f_y, and f_l are the force inputs
to the crane in the x, y, and l directions, respecti-
vely; g denotes the gravitational acceleration.

In the derivation of the dynamic model, the load was
considered as a point mass, and the mass and stiffness
of the rope were neglected. Refer to our previous
study[8] for the detailed derivation of a nonlinear dy-
namic model and its linearization around the stable
equilibrium.

The linearized dynamic model consists of the travel
dynamics (2) and (3), the traverse dynamics (4) and
(5), and the load hoisting dynamics (6). The travel
and traverse dynamics are decoupled and symmetric.
Hence, in this study, an anti-swing control scheme
will be designed based on the travel dynamics and
will be used for the control of both the travel and
traverse motions.

In practice, the cranes are normally driven by electric
motors that are controlled by motor controllers, the
dynamics of which are in general a hundred times
faster than those of the cranes. Consequently, the
dynamics of the motor controllers can be considered
as constant gains. That is, for the travel motor,

\[ f_x = K_{tx} i_k = K_x u_k, \]  \hspace{1cm} (7)

where K_{tx} and K_x are crane-dependent gains; i_k and
u_k are motor current and motor controller input,
respectively.

Then the travel dynamics (2) and (3) and the load
hoisting dynamics (6) can be rewritten as

\[ M_x \ddot{x} + D_x \dot{x} - mg \dot{\theta}_x = K_x u_k, \]  \hspace{1cm} (8)
\[ l\ddot{x} + \ddot{x} + g\theta_x = 0, \quad (9) \]
\[ (M_t + m)\dddot{l} + D\dot{l} - mg = K_iu_i, \quad (10) \]

where \( K_i \) and \( u_i \) are the crane-dependent gain and motor controller input for the hoisting motor, respectively.

### 2.3 Modeling of velocity servo system

In practice, high-gear-reduction motors are normally used as crane actuators. In this case, load mass can be assumed to be much smaller than the effective crane mass and hence the \( m \) terms in the dynamic model can be safely neglected [2, 3]. Then the travel and hoisting dynamics can be rewritten as

\[ M_x\ddot{x} + D_x\dot{x} = K_xu_x, \quad (11) \]
\[ M_l\dddot{l} + D_l\dot{l} = K_lu_l. \quad (12) \]

The structures of the travel and load hoisting dynamics are the same; hence the travel, traverse, and hoisting motions can be controlled by using the same control algorithm. Consequently, the subscripts \( x \), \( y \), and \( l \) will be omitted hereafter.

In this study, a three-dimensional prototype overhead crane has been built; as in practical cases, the crane is driven by geared motors whose angular velocities are controlled by velocity servo controllers. In this study, the velocity servo dynamics \( G_v(s) \) is modeled based on experiments, where \( s \) denotes the independent complex variable. A step reference is inputted to the velocity servo controller, and then the velocity of the crane is measured as the output. Then, from the input and output relations, the velocity servo dynamics \( G_v(s) \) can be modeled as

\[ G_v(s) \equiv \frac{V}{V_r} = \frac{k_i\omega^2}{s^2 + 2\omega s + \omega^2} \quad (13) \]

where \( V \) and \( V_r \) denote the velocity output \((m/s)\) and velocity reference \((V)\) of the crane, respectively; \( \omega \) and \( k_i \) are the natural frequency and low frequency gain of the velocity servo dynamics, respectively.

### 3 Control Design

In this section, a position servo controller and a fuzzy anti-swing controller will be designed to constitute a new anti-swing control system for three-dimensional overhead cranes.

#### 3.1 Design of a position servo control

Figure 2 shows the position servo control system, which consists of a position servo controller \( K_p(s) \) and the experimental velocity servo dynamics \( G_v(s) \), where the integrator \( 1/s \) is used to convert velocity to position. In the figure, \( X_r \), \( X \), and \( D_v \) denote the

**Figure 2**: Schematic diagram of the position servo system

- position reference, position output, and disturbance, respectively.

In this study, the position servo controller \( K_p(s) \) is designed by using the loop shaping method [9]. That is, first, the open loop transfer function \( G_{x\circ}(s) = \frac{G_p(s)G_v(s)}{s} \) is designed based on the loop shaping performance criteria:

\[ G_{x\circ}(s) = \frac{k_{pp}s + k_{pi}}{s^2 + 2\omega_0s + \omega_0^2} \frac{1}{s}, \quad (14) \]

where \( k_{pp} \) and \( k_{pi} \) are some positive control gains satisfying \( k_{pi}/k_{pp} \ll k_{pp} \ll \omega_0 \). In this case, \( k_{pp} \), the crossover frequency of \( G_{x\circ}(s) \), can be considered as the bandwidth of the position servo control system.

Then, from the definition of the open loop transfer function, the servo controller \( K_p(s) \) is obtained as

\[ K_p(s) = \frac{s \cdot G_{x\circ}(s)}{G_v(s)} = \frac{k_{pp}(s + k_{pi})}{s}, \quad (15) \]

The resulting position servo control system \( G_x(s) \) is then computed as

\[ G_x(s) = \frac{X}{X_r} = \frac{G_{x\circ}(s)}{1 + G_{x\circ}(s)}, \quad (16) \]

Note that the travel, traverse, and hoist motions of the crane can be independently controlled using the position servo controller (15).

#### 3.2 Proposed anti-swing control

Figure 3 shows the schematic diagram of the proposed anti-swing control system. It consists of the position servo control system \( G_x(s) \), the fuzzy-logic controller, and the load swing dynamics \( G_l(s) \) transformed from Eq. (9), where \( \Theta(s) \) is the Laplace transform of \( \Theta(t) \) and \( u_q \) is the output of the fuzzy-logic controller.

The fuzzy-logic controller is adopted as an anti-swing controller. The fuzzy control consists of input fuzzification, fuzzy control rules, fuzzy inference, and output defuzzification.

For input fuzzification, the fuzzy sets shown in Fig. 4 are defined, where each of NB, NM, NS, ZR, PS,
PM, and PB represents the fuzzy set and its membership function for the input $w$ which represents each of the swing angle $\theta$, the swing angle change $\Delta \theta$, and the control action $u$; $w_{\text{max}}$ will be set later based on practical gain tuning criteria.

In most cases, the performance of fuzzy control is influenced little by the shapes of membership functions, but mainly by the characteristics of control rules. Accordingly, the triangular membership functions were adopted in this study for simplicity. In addition, a large number of fuzzy sets were used for improvement in control performance; however, practical gain tuning criteria will be also provided in the sequel to simplify the tuning procedures in application.

The proposed fuzzy control rules for constant rope length are shown in Table 1, where all the entries are the fuzzy sets of the swing angle, the swing angle change for one sampling period, and the control action (the velocity reference of the crane for anti-swing control). The control rules have been designed based on those of experienced crane operators; for example, when the swing angle is PB and the swing angle change is NB, ZR control action is required since the swing angle of itself is rapidly decreasing. The control rules clearly show the non-minimum phase characteristics of the crane dynamics.

For fuzzy inference, Mamdani’s Min-Max method is adopted; that is, the fuzzy control output $U_o(u)$ for the inputs $\theta$, $\Delta \theta$, and $U_i$ is computed as

$$U_o(u) = \bigcup_{i=1}^{n} [\Theta_i(\theta) \land \Delta \Theta_i(\Delta \theta) \land U_i(u)],$$

where $\bigcup$ and $\land$ denote the union and minimum operators, respectively; $n$ (= 49) is the number of rules; $\Theta_i$, $\Delta \Theta_i$, and $U_i$ denote the membership functions for the fuzzy sets of the swing angle, swing angle change, and control action, respectively.

For the defuzzification of the fuzzy control output $U_o(u)$, the center of gravity method is used; that is, the control output $u_o$ is computed as

$$u_o = \frac{\int U_o(u) u du}{\int U_o(u) du}.$$ 

Finally, the anti-swing control $u_o$ (the velocity reference of the crane) is set proportional to $\sqrt{t}$ and $u_o$ to cope with the change of rope length due to load hoisting:

$$u_o = \sqrt{t} u_a.$$ 

For justification, see the load swing dynamics (9), which guarantees that for any constant rope length $t$ the load swing can be effectively damped out by the following anti-swing control:

$$\dot{x} = 2\zeta \sqrt{gl} \theta,$$

where $\zeta$ denotes the damping ratio.

### Table 1: Fuzzy control rules for constant rope length

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<tr>
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### Figure 4: Definition of fuzzy sets and membership functions

| NS: Negative Small | PB: Positive Big |
| PS: Positive Small | PM: Positive Medium |
| NB: Negative Big  | PM: Positive Medium |
| ZR: Zero          | PM: Positive Medium |

### 3.3 3-dimensional anti-swing control

As stated, the travel and traverse dynamics are decoupled and symmetric; consequently, the travel and traverse motions will be independently controlled by
the anti-swing control system shown in Fig. 3. In addition, the rope length will be controlled by the position servo control system shown in Fig. 2.

For the design of the three-dimensional anti-swing control system, the following velocity servo dynamics have been obtained based on experiments:

\[ G_{vx}(s) = \frac{0.0567 \cdot 484}{s^2 + 32.6s + 484} \]  \hspace{1cm} (21)

\[ G_{vy}(s) = \frac{0.0329 \cdot 4761}{s^2 + 74.52s + 4761} \]  \hspace{1cm} (22)

\[ G_{vz}(s) = \frac{0.0119 \cdot 4489}{s^2 + 120.6s + 4489} \]  \hspace{1cm} (23)

where \( G_{vx}, G_{vy}, \) and \( G_{vz} \) denote the velocity servo dynamics defined in Eq. (13) for the travel, traverse, and hoisting motions, respectively.

4 Experimental results

Figure 5 shows the schematic diagram of a three-dimensional prototype overhead crane, where the girder moves in the travel \((x)\) direction, the trolley on the girder moves in the traverse \((y)\) direction, and the hoisting motor hoists the load up and down. The prototype crane is about 5.5 meters long, 3.5 meters wide, and 2 meters high.

The crane is driven by AC servo motors which are controlled by velocity servo controllers, whose input ranges are \( \pm 10 \) V. Two position sensors have been built for accurate measurements of two-dimensional crane positions in spite of the slip of crane wheels. A precision angle sensor has been also built for the measurement of the two-degree-of-freedom swing angle defined in Fig. 1.

The real-time controller has been integrated by using VMEbus computer systems: MC68040 CPU, analogue-to-digital, digital-to-analogue, and digital input-output boards. A commercial real-time operating system is used for the controller. A UNIX workstation is used as a development host, which is connected to the real-time controller.

The proposed control has been evaluated by controlling simultaneous travel, traverse, and hoisting motions of the crane. The proposed control has been implemented through the real-time controller with 10 ms sampling period.

The position servo gains have been tuned based on the criterion \( k_{pi} / k_{pp} \ll k_{pp} k_s \ll \omega \) described in Section 3.1. The resulting gains for the travel, traverse, and hoisting motions are \( k_{pp} = 20.0 \) and \( k_{pi} = 1.0 \), \( k_{pp} = 30.0 \) and \( k_{pi} = 1.5 \), and \( k_{pp} = 40.0 \) and \( k_{pi} = 2.0 \), respectively.

The fuzzy-logic controller has been tuned based on the following criteria. The linearized dynamic model (2) to (6) has been derived under the constraints of \( \beta_x \ll 1 \) and \( \beta_y \ll 1 \). As a consequence, the angle input \( \theta \) was saturated at \( \pm 5^\circ \) by setting \( \theta_{max} = 5^\circ \) in the fuzzy sets defined in Fig. 4 to prevent the deterioration of control performance by excessive anti-swing control due to large swing angle.

The anti-swing control (20) implies that the anti-swing control should be proportional to \( \theta \). Consequently, the effects of \( \theta \) on the anti-swing control was set much smaller than those of \( \theta \) by setting
\( \Delta \theta_{\text{max}} = \alpha \Delta t \theta_{\text{max}} \) in the fuzzy sets, where \( \alpha \) is a weighting factor much larger than unity and \( \Delta t \) denotes the sampling period. In this study, \( \alpha \) was set to be 10 so that \( \Delta \theta_{\text{max}} = 0.5^\circ \).

The maximum output of the fuzzy anti-swing controller was limited to a certain portion of the maximum motor controller input by setting \( u_{\text{max}} = 4 \) V in the fuzzy sets. In this way, the deterioration of control performance due to excessive anti-swing control can be prevented.

Figures 6 and 7 show the experimental results with small and large initial load swings, respectively, where \( x \) and \( y \) denote the crane position and load swing in the travel and traverse directions, respectively, and \( l \) denotes the rope length. The load mass is 20 Kg. The rope length was decreased from 1.5 m to 1.1 m while the crane was accelerating, and was increased from 1.1 m to 1.5 m while the crane was decelerating, which simulates a typical crane operation. The crane position references were computed by integrating the swing-free velocity profiles\(^1\) for the average rope length.

Figures 6 and 7 show that the initial load swing influences the crane motions only for the first four seconds. In spite of the large initial load swing, the control performance is excellent for the simultaneous travel, traverse, and hoisting motions of the crane. The steady state position errors are all zero and the load swing completely disappears about 2 seconds after the crane reaches desired positions.

5 Conclusions

In this paper, a new fuzzy anti-swing control scheme has been designed for three-dimensional overhead cranes, and the robustness and effectiveness of the proposed control have been demonstrated by experiments. The experimental results have shown that the proposed control guarantees both accurate position control and prompt damping of load swing for the simultaneous travel, traverse, and hoisting motions of the crane.

The stability and performance of the proposed control are guaranteed in spite of large initial swing. In addition, the proposed control provides practical gain tuning criteria for easy implementation. Consequently, it can be concluded that the proposed control has a great potential for high-performance anti-swing control of industrial three-dimensional overhead cranes.

References


