Anti-sway and Position 3D Control of the Nonlinear Crane System using Fuzzy Algorithm

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ABSTRACT

The crane operation used for transporting heavy loads causes a swinging motion with the loads due to the crane's acceleration and deceleration. This sway causes the suspension ropes to leave their grooves and can cause serious damage. Ideally, the purpose of a crane system is to transport loads to a goal position as soon as possible without any oscillation of the rope. Currently, cranes are generally operated based on expert knowledge alone, accordingly, the development of a satisfactory control method that can efficiently suppress object sway during transport is essential. The dynamic behavior of a crane shows nonlinear characteristics. When the length of the rope is changed, a crane becomes a time-varying system thus the design of an anti-sway controller is very difficult. In this paper, a nonlinear dynamic model is derived for an industrial overhead crane whose girder, trolley, and hoister move simultaneously. Furthermore, a fuzzy logic controller, based on expert experiments during acceleration, constant velocity, deceleration, and stop position periods is proposed to suppress the swing motion and control the position of the crane. Computer simulation is then used to test the performance of the fuzzy controller with the nonlinear crane model.

Keywords: Anti-sway Controller, Overhead Crane, Fuzzy Control, Position Controller, Nonlinear System

1. Introduction

The most significant problem in transporting heavy objects using an overhead crane is the sway of the rope. This sway induces an undesirable swinging of the suspended objects and can lead to serious damage plus lost work time. Accordingly, the development of an effective anti-sway control is essential..

Until now, this sway has generally been controlled by skilled operators, however, there is a current demand for automatic control.. As a result, there has been a lot of recent research on controlling the sway of crane ropes, yet most of the resulting proposals have too many restrictions for practical application.

Ridout[1] proposed a control strategy for a linearized crane model using a feedback algorithm based on the velocity of the trolley. Sakawa and Shindo [2] proposed an optimal control strategy for a rotary crane. Auernig Troger[3] and Mita[4] proposed time optimal control methods for a crane which only allows travel motion. An adaptive control method for a linearized model was proposed by F. Boustany and B. d'Andrea-Novel[5], however, this crane model is limited as it only involves the swing in a plane motion, plus the linearized model contains many assumptions.

A nonlinear model for the control of a rotary crane was developed by Sakawa[2]. They also developed a control strategy comprised of both open-loop and closed schemes. Their goal was to achieve a zero swing at the end of the transport, however, the swing during transport can also be too large.

For a crane with only a moving trolley, Sakumoto and Hayashi[6] were successful in controling the linearized crane system using a fuzzy inference method, yet the industrial application of a crane that only moves in one direction is very limited.

Most industrial cranes require simultaneous travel and traverse motions. Moustafa and Ebeid[7] derived a nonlinear model of an overhead crane in the case of simultaneous travel and traverse motions with the assumption of a constant rope length. They linearized the nonlinear crane model and proposed a mathematical control strategy using the pole-placement method.

There are two problems in this method: first, the controller is designed for a linearized crane model and can not be applied to a nonlinear crane, and second, the controller can only use the swinging angle to control the crane system, whereas the stopped position of a trolley and the residual swing angle of a rope also need to be controlled. The purpose of this research is to derive a dynamic model of an overhead crane which allows for simultaneous travel, traverse, and hoisting motions and develop a non-mathematical control strategy. In plane motions, travel and transport motions induce both swing and oscillations as determined by the ropes and vertical axis through the suspension point about an equilibrium position. The hoisting motions vary the length of the rope, and as a result the system exhibits time-varying characteristics.

An anti-sway control system needs to be developed that can transport an object along a specified route in such a way that the aforementioned swing-angle and oscillations of the object are suppressed quickly.

The most important point is that the dynamics of a container crane are nonlinear and time-varying. Since it is difficult to control using a mathematical control strategy, a non-mathematical control algorithm is needed. Accordingly, fuzzy control was introduced to transport the load safely, correctly, and rapidly and stop at the exact unloading position quickly without swinging. Fuzzy control is a technique which can realize the skill of human operators.

Therefore, fuzzy rules based on the characteristics of the various periods were designed. In the accelerating and decelerating period, the controller depresses the swing angle of the rope, whereas in the constant velocity period, it depresses the swing angle of the rope and the velocity of the trolley.

In the stop position control period, the fuzzy controller controls the swing angle of the rope, the position of trolley, plus the length of the rope. The developed fuzzy control scheme was simulated on a PC. The results indicate the usefulness of the derived model and prove the efficiency of a feedback control scheme.

2. Modeling of Nonlinear Crane System

2.1 Simulation(Times New Roman 10pt)

An overhead crane system is considered as shown in Fig. 1. An object with mass M and center of mass G is Suspended from point 0, and is assumed to be a rigid body symmetric about its axial axis.

The position vector of the point of suspension with respect to the fixed axes coordinate system is

$$R_0 = xi + yj + zk \tag{1}$$

where, $x = x_0 + r_1\theta_1$, $y = y_0 + r_2\theta_2$, $z = z_0 + r_3\theta_3$.

x_0 y_0 are the initial positions of the girder and trolley, respectively. and l_0 is the initial length of the rope. l is the length of the suspended rope, and θ_1, θ_2 θ_3 are the rotating angles of the girder, trolley, and hoister motor, respectively.

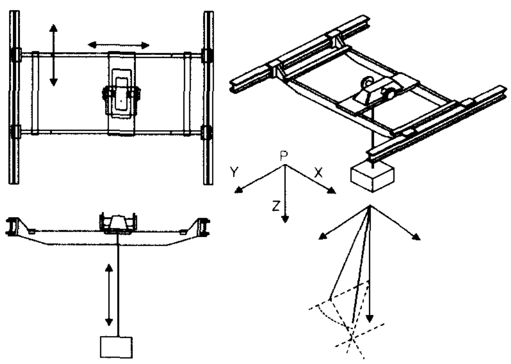


Fig. 1 Overhead Crane System

Note that θ is the inclined angle of the rope from the downward vertical, and ψ is the rotating angle of the rope in Fig. 1. An object can move in the directions x, y, and z and rotates together. Thus, the potential energy of the crane system and the kinetic energy is

$$V = \frac{1}{2} p\Phi^2 - Mgl\cos\theta \tag{2}$$

$$T=\frac{1}{2}M(\dot{x}_G^2+\dot{y}_G^2+\dot{z}_G^2)+\frac{1}{2}m_1\dot{x}^2+\frac{1}{2}m_2(\dot{x}^2+\dot{y}^2)$$
$$+\frac{1}{2}I_a\dot{\psi}^2\cos\theta+\frac{1}{2}I_t(\dot{\theta}^2+\dot{\psi}^2\sin^2\theta)$$
$$+\frac{1}{2}I_1(\frac{\dot{x}}{r_1})^2+\frac{1}{2}I_2(\frac{\dot{y}}{r_2})^2+\frac{1}{2}I_3(\frac{\dot{z}}{r_3})^2 \qquad (3)$$

The nonlinear dynamic equations of the crane system can be derived utilizing the Lagrangian equation. Equations (4)~(9) represent the nonlinear dynamic model of the overhead crane.

$$\frac{\ddot{l}}{l}+\frac{Mr_3^2}{(Mr_3^2+I_3)l}\sin\theta(\ddot{x}\sin\psi+\ddot{y}\cos\psi)$$
$$-\frac{Mr_3^2}{(Mr_3^2+I_3)}(\dot{\theta}^2+\dot{\psi}^2\sin^2\theta)-\frac{Mr_3^2}{(Mr_3^2+I_3)l} \qquad (4)$$
$$g\cos\theta=\frac{T_3r_3}{(Mr_3^2+I_3)l}+D_z\frac{\dot{l}}{l}$$

$$\frac{\ddot{x}}{l}+(\delta_1\sin\theta\cos\theta)\ddot{\psi}+(\delta_1\cos\theta\sin\psi)\ddot{\theta}$$
$$-(\delta_1\sin\theta\sin\psi)(\dot{\theta}^2+\dot{\psi}^2) \qquad (5)$$
$$+2(\delta_1\cos\theta\cos\psi)\dot{\theta}\dot{\psi}=U_1-D_1\frac{\dot{x}}{l}$$

$$\frac{\ddot{y}}{l}-(\delta_2\sin\theta\sin\psi)\ddot{\psi}+(\delta_2\cos\theta\cos\psi)\ddot{\theta}$$
$$-(\delta_2\sin\theta\cos\psi(\dot{\theta}^2+\dot{\psi}^2))-(2\delta_2\cos\theta\sin\psi) \qquad (6)$$
$$\dot{\theta}\dot{\psi}=U_2-D_2\frac{\dot{y}}{l}$$

$$(M+\frac{I_t}{l^2})\ddot{\theta}+\frac{2M\dot{l}\dot{\theta}}{l}+\frac{Mg\sin\theta}{l}$$
$$-(M+\frac{I_t-I_a}{l^2})\dot{\psi}^2\cos\theta\sin\theta \qquad (7)$$
$$=-M(\frac{\ddot{x}}{l}\sin\psi+\frac{\ddot{y}}{l}\cos\psi)\cos\theta$$

$$((M+\frac{I_t}{l^2})\sin^2\theta+\frac{I_a}{l^2}\cos^2\theta)\ddot{\psi}+\frac{2M\dot{l}\dot{\psi}\sin^2\theta}{l}$$
$$+2(M+\frac{I_t-I_a}{l^2})\dot{\theta}\dot{\psi}\sin\theta\cos\theta+(\frac{p\dot{\phi}}{l^2}) \qquad (8)$$
$$\cos\theta=-M(\frac{\ddot{x}}{l}\cos\psi-\frac{\ddot{y}}{l}\sin\psi)\sin\theta$$

$$\dot{\phi}-\dot{\psi}\cos\theta=0 \qquad (9)$$

where $\delta_1,\delta_2,\delta_3,D_1,D_2,D_3,U_1,U_2,U_3$ represent

$$\delta_1=\frac{Mr_1^2}{J_1},\quad \delta_2=\frac{Mr_2^2}{J_2},\quad \delta_3=\frac{Mr_3^2}{J_3}$$
$$D_1=C_x\frac{r_1^2}{J_1},\quad D_2=C_y\frac{r_2^2}{J_2}\quad D_3=C_z\frac{r_3^2}{J_3}$$
$$U_1=\frac{T_1r_1}{J_1},\quad U_2=\frac{T_2r_2}{J_2}\quad U_3=\frac{T_3r_3}{J_3}$$
$$J_1=(M+m_1+m_2)r_1^2+I_1,$$
$$J_2=(M+m_1+m_2)r_2^2+I_2 \qquad (10)$$
$$J_3=(Mr_3^2+I_3)$$

C_x,C_y,C_z are the equivalent viscous damping coefficients associated with the motions in the x, y, and z directions, respectively. T_1,T_2,T_3 the torque of input to the girder , trolley, and hoister motors, respectively, and U_1,U_2,U_3 are the control inputs implied for the girder, trolley and hoister motor, respectively.

3. Fuzzy Control System

3.1 Open-loop Control

In open-loop control, a reference torque is applied to the system. The reference torque is calculated on the basis of the equilibrium state and desired velocity profile. Figures 2 and 3 are the reference velocity profiles of the trolley, girder and hoister. The reference values vary with the period. Figure 4 is block diagram of the open-loop control. To reduce the occurrence of rope sway during the acceleration period, several patterns of velocity profiles, including notch and step type velocity profiles, are generally used.

However, this gives rise to a delay in the acceleration time and the efficiency of the work is reduced. Accordingly, for the efficient control of the crane system in the deceleration period, the control method needs to be designed to reflect the characteristics of the moving velocity period. In this paper, equilibrium state values of θ and ψ are obtained for acceleration, constant velocity, and deceleration motions.

The first aim for controlling the system is to make each state variable converge at an equilibrium state value. The equilibrium state of constant acceleration ($\ddot{x}(t)=\ddot{x}_i$, $\ddot{y}(t)=\ddot{y}_i$ can be obtained by substituting $\dot{\theta}(t)=\ddot{\theta}(t)=0$

$\ddot{\psi}(t) = \dot{\psi}(t) = 0, \phi(t) = 0$.)

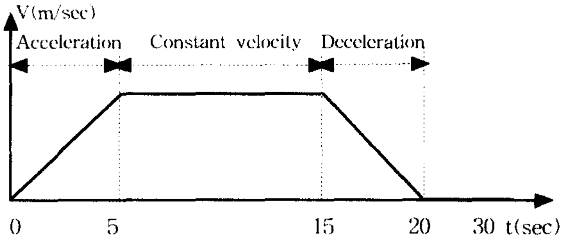


Fig. 2 Reference Velocity Profile of Girder and Trolley

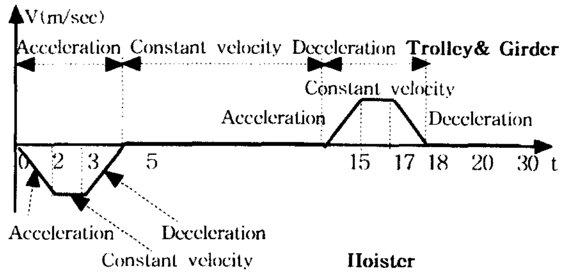


Fig. 3 Reference Velocity Profile of Rope (Hoisting Motion)

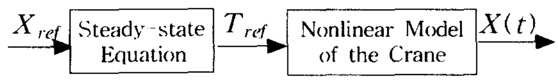


Fig. 4 Block Diagram of the Open-loop Control

Especially in the case when the acceleration of a crane is very large relative to the gravitational acceleration, this equation has an approximate solution as follows

$$\theta_i = \ddot{a}_i / g \qquad \psi_i = -\tan^{-1}(\ddot{x}_i / \ddot{y}_i) \tag{11}$$

when the velocity of a crane is constant, its acceleration is

$$a_i = \sqrt{\ddot{x}_i^2 + \ddot{y}_i^2} = 0, \quad \theta_i = \psi_i = 0 \tag{12}$$

the system variables can, therefore, be defined as equation (13). The reference input X_{ref} is calculated based on the velocity scheme. the equilibrium state X_i.

$$X(t) = [\theta, \dot{\theta}, \psi, \dot{\psi}, x, \dot{x}, y, \dot{y}, l, \dot{l}] \tag{13}$$

Since there is no feedback in open-loop control, the reference torque input T_{ref} calculated by the equilibrium state value, is used to obtain the desired $X(t)$. After conducting acceleration, constant velocity, deceleration motions as outlined in the velocity profile of Fig. 2, the crane will stop at the desired unloading position.

3.2. Design of Fuzzy Controller

If there is an error between the desired trolley position velocity and the real position velocity, this error needs to be corrected. There are many feedback algorithms, however, the mathematical models are complex and the gain matrices very difficult to solve. Accordingly, a non-mathematical anti-sway algorithm is proposed. A fuzzy algorithm is characterized by a human knowledge-based inference. Fig. 5 is a block diagram of fuzzy control.

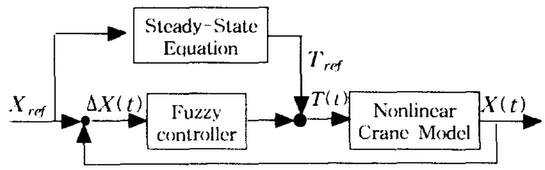


Fig. 5 Block Diagram of Fuzzy Control

This is a block diagram of an anti-sway control system that can suppress the swing of the rope occurring during open-loop control. The change of the torque $T(t)$ is used as the control input.

$T(t)$ is obtained by summing the reference torque T_{ref} and output of the fuzzy controller, $\Delta T(t)$. $\Delta T(t)$ is calculated by the fuzzy controller based on the operator's knowledge and the state of system, $\Delta X(t)$. $\Delta X(t)$ is defined as the difference between the reference variables, $T(t)$

$$\Delta X(t) = X(t) - X_{ref} \tag{14}$$

$$T(t) = T_{ref} + \Delta T(t) \tag{15}$$

as a result, the input of the fuzzy controller is $\Delta X(t) = [\Delta\theta, \Delta\dot{\theta}, \Delta x, \Delta\dot{x}, \Delta y, \Delta\dot{y}, \Delta l, \Delta\dot{l}]$ **and the output of the fuzzy** controller is the change of the torque, $\Delta T(t)$. The summation of the reference torque T_{ref} and the change of torque $\Delta T(t)$ is implied to the crane system, $T(t)$.

The membership functions of the input and output variables are shown in Fig. 6. There are many kinds of membership functions including triangular, bell shaped, and trapezoidal etc. In this paper, triangular membership functions were selected to divide the input and output variable space, where NB means Negative Big, NM is Negative Medium, NS is Negative Small, ZR is Zero, PS is Positive Small, PM is Positive Medium, and PB is Positive Big. Seven membership functions are used to divide the fuzzy output variables. The input variables are converted into output variables by forward inference using fuzzy rules. These variables are then converted into fuzzy values using the fuzzification method. The suitability(α) is calculated by modus ponens using a Max-min composition.10)

The output of the inference process thus far is a fuzzy set, therefore the fuzzy control action inferred from the fuzzy control algorithm must be defuzzified.

The defuzzification method used in this paper is the COA10)(center of area) method. This method is generally used in deffuzifying and the output variable can be easily calculated.

3.3. Anti-sway Control During Acceleration and Deceleration Period

The constant torque applied to a crane system induces the swing of the rope (Fig. 9). The velocity of the trolley and girder is varied by this sway of the rope. If the theta error is positive, this means that the moving acceleration is too high so the torque of the trolley and girder must be decreased to decrease the acceleration.

ΔT_{12} and $\Delta T_{1/2}$ are defined as equation (16),(17) and $\Delta T_1, \Delta T_2$ can be easily calculated from this equation.

$$\Delta T_{12} = \sqrt{\Delta T_1^2 + \Delta T_2^2} \tag{16}$$

$$\Delta T_{1/2} = \Delta T_1 + \Delta T_2 \tag{17}$$

If the psi error is not zero, this means that the acceleration ratio is incorrect. A positive psi error means that the acceleration of the girder is higher so the

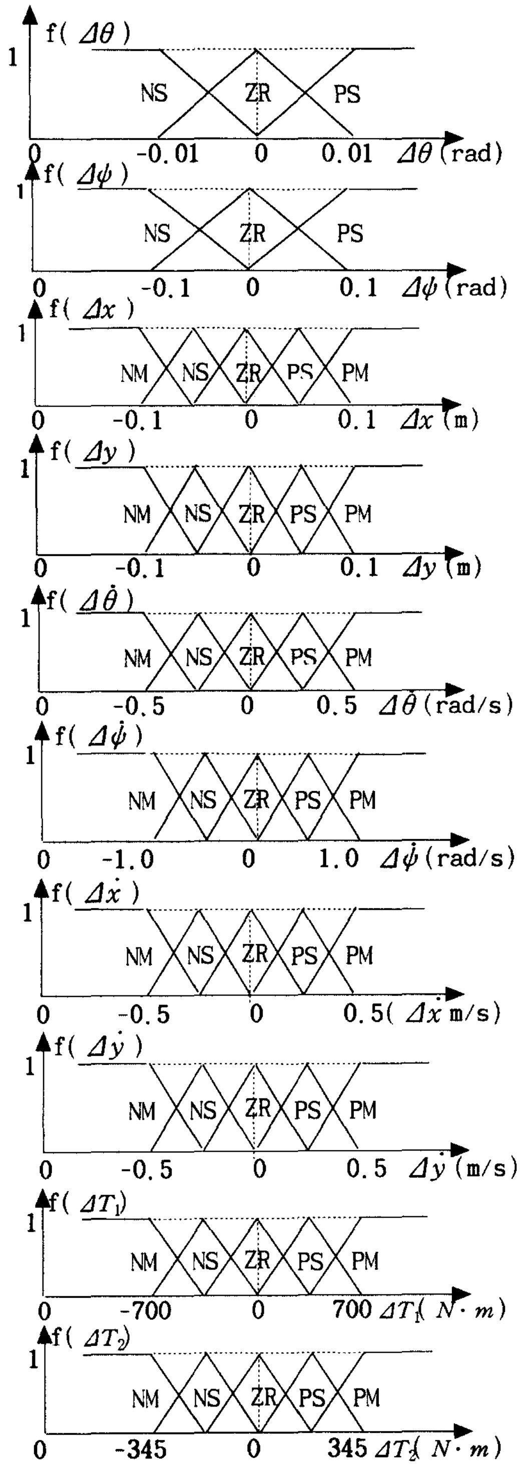


Fig. 6 Fuzzy Membership Functions for Input& Output Variables

acceleration ratio must be decreased. This means that $\Delta T_{1/2}$ must be controlled to make the psi error zero.

Fuzzy control rules can be obtained from dynamic characteristics based on expert knowledge. The fuzzy control rules, outlined in Table. 1, were obtained based on the general characteristics mentioned above and experimental knowledge.

Table. 1 Fuzzy Rules for Anti-sway Control during Acceleration & Deceleration

Rule Number	Input variables				Output variables	
	$\Delta\theta$	$\Delta\dot{\theta}$	$\Delta\psi$	$\Delta\dot{\psi}$	ΔT_{12}	$\Delta T_{1/2}$
Rule 1	NS	NS			PM	
Rule 2	NS	ZR			PS	
Rule 3	NS	PS			ZR	
Rule 4	ZR	NM			PM	
Rule 5	ZR	NS			PS	
Rule 6	ZR	ZR			ZR	
Rule 7	ZR	PS			NS	
Rule 8	ZR	PM			NM	
Rule 9	PS	NS			ZR	
Rule10	PS	ZR			NS	
Rule11	PS	PS			NM	
Rule12			NS	NS		PM
Rule13			NS	ZR		PS
Rule14			NS	PS		ZR
Rule15			ZR	NM		PM
Rule16			ZR	NS		PS
Rule17			ZR	ZR		ZR
Rule18			ZR	PS		NS
Rule19			ZR	PM		NM
Rule20			PS	NS		ZR
Rule21			PS	ZR		NS
Rule22			PS	PS		NM

The reference input during acceleration and deceleration can be calculated using the equilibrium state equation (11). The reference input X_{ref} varies directly with the magnitude of the acceleration of the trolley and girder. In the acceleration period, the fuzzy rules that can suppress the swinging angle of the spreader are based on the operator's experience, as in Table 1. Their meaning is as follows (for example) :

Rule 1 means that if the error of swing angle is Zero and the error of angular velocity is Negative Medium then make torque magnitude Positive Medium

Table 2 Fuzzy Rules for Velocity Control

Rule Number	Input variables				Output variables	
	$\Delta\theta$	$\Delta\dot{\theta}$	$\Delta\dot{x}$	$\Delta\dot{y}$	ΔT_1	ΔT_2
Rule 1	NS	NS			PB	PB
Rule 2	PS	PS			NB	NB
Rule 3	ZR	ZR	ZR		ZR	ZR
Rule 4	NS				PS	PS
Rule 5	PS				NS	NS
Rule 6		PS			NM	NM
Rule 7		NS			PM	PM
Rule 8			PS		NM	
Rule 9			NS		PM	
Rule10			PM		NB	
Rule11			NM		PB	
Rule12				PS		NM
Rule13				NS		PM
Rule14				PM		NB
Rule15				NM		PB

3.4. Velocity Control in Constant Velocity Period

During the constant velocity mode, it should be noted that the psi error can be controlled. however, it is sufficient to force the theta error to zero to suppress the object swing. In this case, the velocity of the trolley and girder must be kept as a maximum velocity 0.525 m/sec. in order for the swing angle of the rope to be suppressed. The reference input is X_{ref} = $\theta,\dot{\theta},\Psi,\dot{\psi}$. Since the velocity of the girder and trolley is 0, the reference angle can be calculated, plus the reference angles θ_{ref} and Ψ_{ref} are 0 based on the equilibrium state equation (11). If $\theta(t)$ converges to zero, the reference angles θ_{ref} , the inclined angle of the rope $\psi(t)$, is naturally zero. Therefore, the first aim of anti-sway control is a zero. $\theta(t)$, accordingly, the velocity of the girder, $\Delta\dot{x}$, the velocity of the trolley, $\Delta\dot{y}$ and the swing angle and the angular velocity of the rope, $\Delta\theta,\Delta\dot{\theta}$, respectively, were chosen as the fuzzy input variables. The fuzzy control rules were constructed in the same method outlined in Table 2.

3.5. Stop Position Control for Unloading

There are several problems in unloading. Since the rope is inclined in the trolley-moving direction due to the deceleration at the stop position, the rope is swinging with a constant frequency when the crane stops. In addition, another problem is the difficulty in finding the exact unloading position. The crane deceleration and velocity will vary during the deceleration period because of the feedback control. therefore, the stop position of the trolley varies each time. Accordingly, an algorithm that can control the swinging angle and position of the trolley is needed. and another control rule needs to be added for position control. The input variables of the fuzzy controller are $\Delta\theta, \Delta\dot{\theta}, \Delta x, \Delta\dot{x}, \Delta y, \Delta\dot{y}$ $\Delta l, \Delta\dot{l}$ and fuzzy control rules are constructed based on the expert knowledge.

3.6. Velocity and Length Control of the Rope

In this paper, the length of the rope during the traversing motion changes. To prevent the drop of the load due to the gravity, a constant torque was applied to the hoister motor. A large torque will wind the rope and a small torque will lower the load.

The reference velocity profile of the rope length is included in Fig. 3. The length of the rope will change with the time. At the lowering position the length of rope must be constant. However, in the case of open loop control, the length of the rope increases continuously after the trolley and girder stop at the unloading position(Fig. 11(m)). This is because the rope has a remaining velocity after the crane stops, plus a remaining velocity due to the swinging and acceleration of the load. As a result, a compensator is necessary. Fuzzy rules to control the rope length and velocity were obtained based on these characteristics.

4. Computer Simulation

4.1. System Parameters

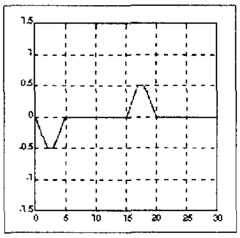
The parameters of the system are in Table. 2.

The nonlinear differential equations are solved using the Runge-Kutta method. The simulation was condicted using a PC with 0.1 second steps. The equivalent moment of inertia of the trolley and girder motor, I_1, I_2 were neglected. The damping effects of the frictions were also neglected. The maximum transporting velocity of the trolley and girder was $V_x = V_y = 0.525m/\sec$ the accelerating time was 5 sec, and the acceleration was $0.105m/\sec^2$

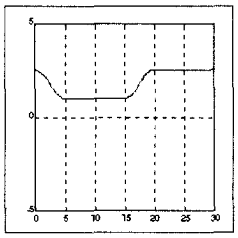
Table 3 System Parameters

Parameter names	Values
Mass of the Girder m_1	9,500 Kg
mass of the trolley m_2	1,150 Kg
mass of the load M	8,000 Kg
torsional stiffness of rope p	0.1 N · m/rad
mass moment of inertia about the traverse axis I_a	11,835 Kg · m2
mass moment of inertia about the axial axis I_t	1,120 Kg · m2
radius of motor pinion r_1 (trolley, hoister, girder)	0.3 m

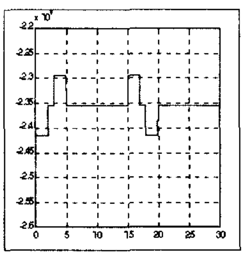
4.2. Dynamic Characteristic of the System



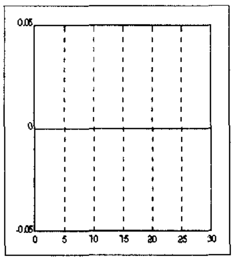
(a) Velocity of Rope dL(m/s)



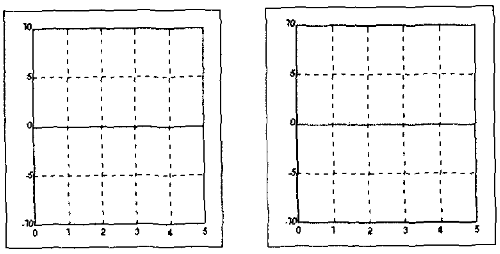
(b) Length of the Rope L(m)



(c) Torque of Hoister $T_3(N \cdot m)$



(d) Swing Angle of the Rope θ(rad)



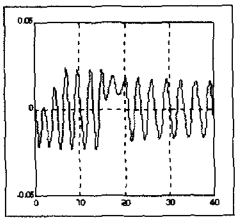
(e) Position of the Trolley y(m) (f) Position of the girder x(m)

Fig. 7 Open-loop Control of the Rope Length

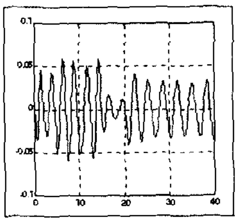
Fig. 7 is the dynamic response of the crane system when the specific reference torque is applied to the hoister. The reference torque obtained using the reference velocity, load, and radius of the pinion was applied to prevent the drop of the load due to gravity. The constant torque calculated based on the load and the radius of the hoister pinion was also applied. The length of rope was successfully controlled, however, in this case it was noticed that the trolley did not move. In the situation where traversing and hoisting motions occur simultaneously, the response may be different.

4.3. Result of Open-loop Controlled System

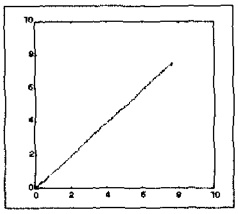
Fig. 8 is the result of the open-loop control. The torque input implied to the trolley motor was $\pm 345 N \cdot m$, and the torque applied to the girder motor was $\pm 703 N \cdot m$. This was calculated according to the equilibrium state equation (15) based on Fig. 2. A constant torque was implied in the acceleration and deceleration periods and no torque was implied in the constant velocity period. In Fig. 8(a) the rope swung during the acceleration, constant velocity, and deceleration periods. After the crane stopped the rope continued to swing and the swinging fluctuated the velocity of the trolley and the girder. In Figs. 8 (e) and (g), the velocity of the girder and trolley fluctuated with a constant period caused by the swing of the object. The velocity of the girder fluctuated less than that of the trolley. This was because the mass of the girder was greater than that of the trolley. Because the acceleration of the trolley made the load a resistance to the hoister motor, the hoister motor had residual velocity. Accordingly, in Fig. 8(j) the length of the rope increased at the unloading position.



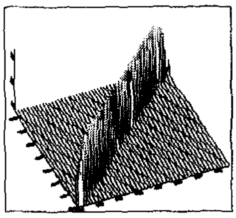
(a) Swing Angle of the Rope θ (rad)



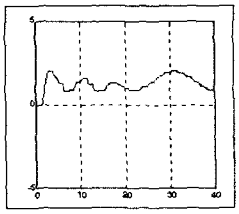
(b) Angular Velocity $\dot{\theta}$ (rad/s)



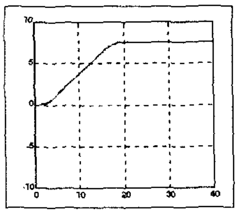
(c) Trajectory x-y (m/m)



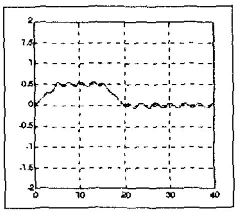
(d) 3D Trajectory of the Loads



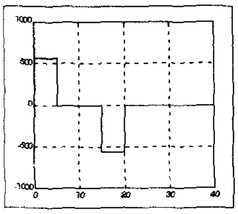
(e) Rotational Angle of the Rope ψ (rad)



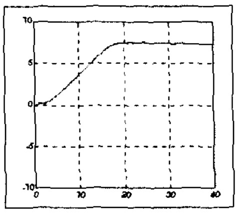
(f) Position of the Girder x(m)



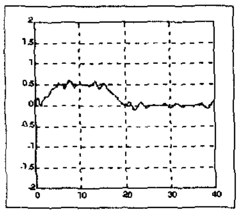
(g) Velocity of the Girder $\dot{x}$ (m/s)



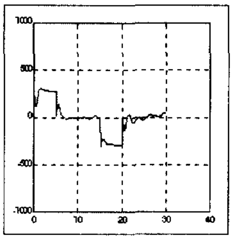
(h) Torque of Hoister $T_1 (N \cdot m)$



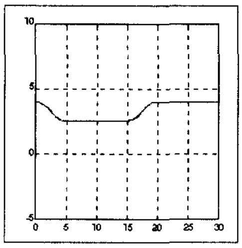
(i) Position of the Trolley y(m)



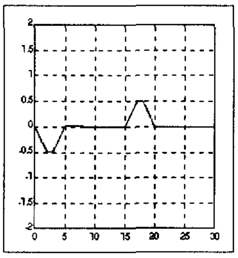
(j) Velocity of the Trolley $\dot{y}$ (m/s)



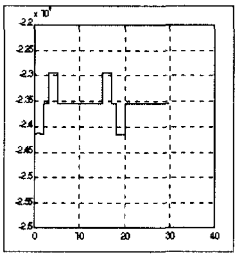
(k) Torque of the Trolley $T_2(N \cdot m)$



(l) Length of the Rope L(m)



(m) Velocity of the Rope Length L(m/s)



(n) Torque of the Hoister $T_3(N \cdot m)$

Fig. 8 Response of the Open-loop Control

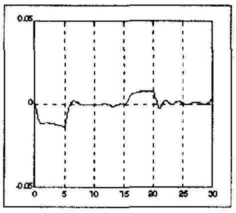
4.4. Simulation of Fuzzy Controlled System

Fig. 9 is the simulation result of the fuzzy controlled crane system. The torque input $\Delta T(t)$ was calculated based on the fuzzy control rules. $T(t)$ is the summation of the reference torque input T_{ref} in the open-looped control and $\Delta T(t)$.

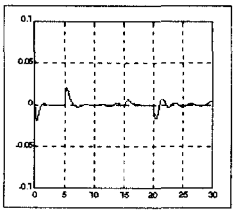
In Fig. 9(a) θ converged to 0.01513rad during the acceleration period, 0 rad during the constant velocity period, -0.01513 rad during the deceleration period.

After deceleration, the swing angle of the rope was 0.01513 rad, however the fuzzy controller was able to make the swing angle converge to 0 rad, the velocity of the trolley and girder to 0, and the position error of the trolley and girder to 0. The start position of the trolley and girder was $0m$, and the desired unloading position of the trolley and girder was $8m$.

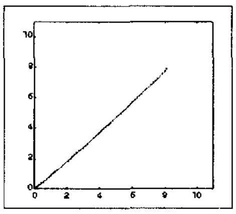
In Fig. 9(k) the trolley and girder moved past the desired unloading position, however, the fuzzy controller controled the position error to converge to 0. The length of the rope did not increase anymore.



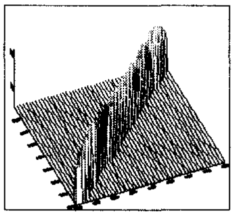
(a) Swing Angle of the Rope θ (rad)



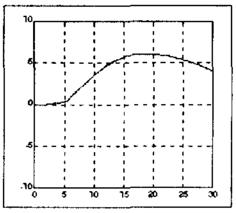
(b) Angular Velocity $\dot{\theta}$ (rad/s)



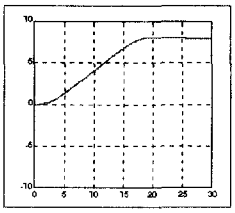
(c) Trajectory x-y (m/m)



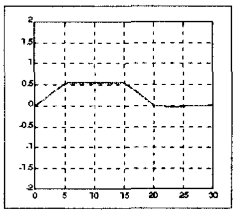
(d) 3D Trajectory of the Loads



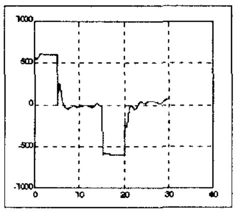
(e) Rotational Angle of the Rope ψ (rad)



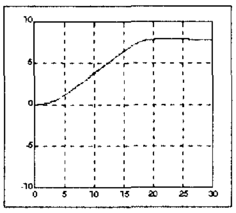
(f) Position of the Girder x(m)



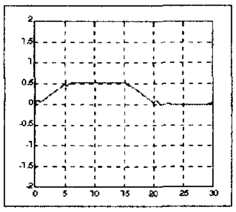
(g) Velocity of the Girder $\dot{x}$ (m/s)



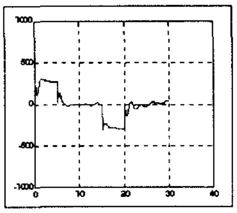
(h) Torque of the Girder $T_1(N \cdot m)$



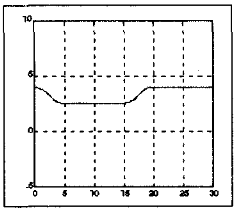
(i) Position of the Trolley y(m)



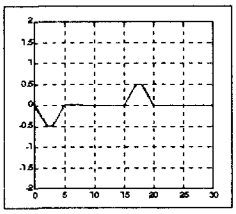
(j) Velocity of the Trolley $\dot{y}$ (m/s)



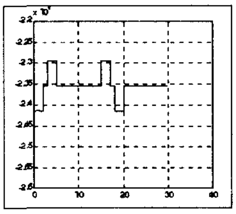
(k) Torque of the Trolley $T_2(N \cdot m)$



(l) Length of the Rope L(m)



(m) Velocity of the Rope Length L(m/s)



(n) Torque of the Hoister $T_3(N \cdot m)$

Fig. 9 Response of the Fuzzy Control

5. Conclusions

The aim in developing an antiθ Ψ as quickly as possible so as to save on the transporting and waiting time for unloading an object and thereby prevent the possibility of the accident. and -sway control system is to suppress the swing angles

In this research, a nonlinear model of a crane system was designed with a girder and trolley that moved at the same time. The velocity profile consisted of an acceleration period, constant velocity period, deceleration period, and stop position control period. The crane was operated with reference to this scheme.

A fuzzy controller based on dynamic characteristics and experimental knowledge was developed for a nonlinear model of an overhead crane. The response of the fuzzy controled system was then simulated on a personal computer.

During the acceleration period, the velocity of the trolley and girder increased constantly, however, the maximum overshoot of the rope angle θ did not exceed $-1°$. Furthermore, the constant velocity period, the velocity of the trolley, was controlled as a constant and the angle of the rope was controlled at $0°$.

The swing angle of the rope due to deceleration was successfully controlled within $1°$.

After stopping at the unloading position, the position of the girder and trolley was located within 0.05m in 5 seconds and the residual swing angle of the rope was successfully controlled within $0.1°$.

References

1. A. J.Ridout, "Anti-swing Control of the Overhead crane using linear feedback," IE Aust., Vol. 9. No. 1/2. pp. 17~26, 1989.
2. Sakawa. Y., and Shindo. Y., "Optimal Control of a Rotary Crane," J. Optimize. Theory Appl., Vol. 35, pp. 535~557, 1981.
3. J.W. Auernig, and H. Troger, " Time Optimal Control of the Overhead Cranes with Hoisting of the Load," International Federation of the Automatic control. Automatica, Vol. 23, No. 4, pp. 437~447, 1987.
4. Tsutomu Mita, and Takashi Kanai, "Optimal Control of the Crane system Using the Maximum Speed of the Trolley," Japan the 21th Automatic control conference.
5. F. Boustany, and B. d'Andrea-Novel, "Adaptive control of an overhead crane using dynamic feedback linearization and estimation design," IEEE. International Conference on Robotics and Automation, 1992.
6. Masakazu Sakumoto, and Toru Hayashi "Fuzzy control of container crane applied to the anti-sway control," Japanese society of Mechanical Engineering. The 58th 550. 1992-6.
7. Moustafa. K. A., and Ebeid. A. M., "Nonlinear Modeling and Control of Overhead Crane Load Sway," ASME Journal of Dynamic Systems, Measurement & Control, Vol. 110, pp. 266~271, 1988.
8. Tae-Young Lee, and Sang Ryong Lee, "Anti-sway Control of the Nonlinear Overhead Crane Using Fuzzy Control Algorithm," Transactions of the KSME Vol. 23, No. 1. pp. 357~366, 1999.