Control and Cybernetics

vol. 25 (1996) No. 2

Anti-swing fuzzy control of overhead cranes referring a velocity pattern

by

Huiyang Yang*, Yohsuke Kinouchi* and Noboru Sugio**

*Dept. of EE Eng., Faculty of Eng., The University of Tokushima
**Shikoku Co. Ltd.
Japan
E-mail: yang@ee.tokushima-u.ac.jp

Abstract: This study proposes a simple and practical fuzzy control method for overhead cranes. It is composed of two parts, i.e., one is anti-swing fuzzy control which damps the swing during conveyance, and the other is a position control referring to a changeable velocity pattern. Additionally, the membership functions of fuzzy variables are tuned by a steepest decent method. It has been found from computer simulations for various conditions that the automatic fuzzy control has damped load swing effectively and conveyed a load to its target place precisely.

Keywords: fuzzy control, overhead crane, swing control.

1. Introduction

An overhead crane is one of the most important transportation systems in factories and yards, capable of conveying heavy loads flexibly in a three dimensional space. To improve the efficiency and safety of the crane, its automatic control has been looked for over the past years.

The main subject of the automatic control is to operate the crane so as to suppress the load swing. Several methods for the subject have been proposed during the past decades. One of them is the time-optimal pattern control, see Kuntze and Strobel (1975), Beeston (1969), which changes trajectories of swing dynamics at appropriate times. In case of practical cranes with a long rope, this method needs much time for effective control action (more than two swing periods) and is not so controllable for disturbance, hence its application may be restricted. To avoid this, the variable structure control, Zinober (1979), has been proposed. It is, however, somewhat complicated to implement and requires specialist skills for its installation and maintenance in factories. Control strategies using linear feedback, Ridout (1989), have also been devised, in which the response of damping load swing is, however, not good enough. Therefore, such conventional control approaches have a limited potential for their industrial use.

Along with the development on fuzzy theory, it has been applied to crane control. A fuzzy control method shows a great superiority over conventional methods in regard to practical applications because of no need of making a strict mathematical model. A predictive fuzzy control method of an overhead crane has been proposed by Yasunobu (1986), in which a mathematical model of crane dynamics is used for predicting a load swing state. Hence, the method, to be implemented practically, is rather complicated and needs many parameters to be measured. A time-optimal fuzzy control has been also reported in Yamada, and Walasugi (1989), which combines a time-optimal control in transient state with a fuzzy control in stationary state to damp a load swing. The method still has the shortcoming of a time-optimal control described above.

Most overhead cranes used are still controlled manually by a skilful operator rather than by a fuzzy controller, because of some problems mentioned above. The purpose of this study is to propose a simpler fuzzy control method conceived to make its practical use easy, considering feasibility for usual overhead crane. A crane is controlled by a time-varying parallel combination of two control channels, i.e., a velocity pattern control to convey a load through an allowable space and a normalized fuzzy control to damp load swing incessantly. This method may be very similar to that of a human operator. It needs not a mathematical model in it and has small number of parameters. The performance of the fuzzy control is examined by computer simulations.

2. The dynamics of overhead crane

Figure 1 shows a model of usual overhead cranes which can convey a load in three-dimensional space. That is, the trolley of the crane moves along the gantry path in X and Y directions, while it hoists a load up and down in Z direction. Three-dimensional dynamics of the crane is divided into two independent dynamics, i.e., two dimensional dynamics in the $X-Z$ plane and that in the $Y-Z$ plane.

In order to examine basic properties of our method, a two-dimensional system in $X-Y$ plane as shown in Fig. 2 is discussed here. The dynamics of a trolley and a load is expressed by:

$$(M+m)\ddot{x} + D\dot{x} - ml\dot{\theta}^2 \sin\theta + ml\ddot{\theta}\cos\theta = F \tag{1}$$

$$l\ddot{\theta} + g\sin\theta + \ddot{x}\cos\theta = 0 \tag{2}$$

where M and x are the mass and position of the trolley respectively, m, l and θ are the mass, the rope length and the swing angle of the load respectively, D is the coefficient of friction, F is the force applied to the trolley, and g is acceleration of gravity. There are several selections as to a manipulated variable

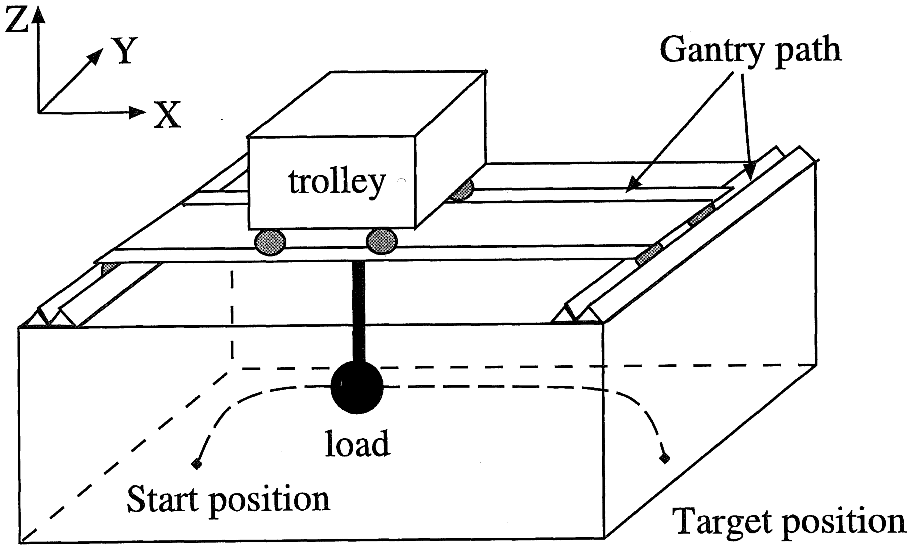

Figure 1. Model of overhead crane

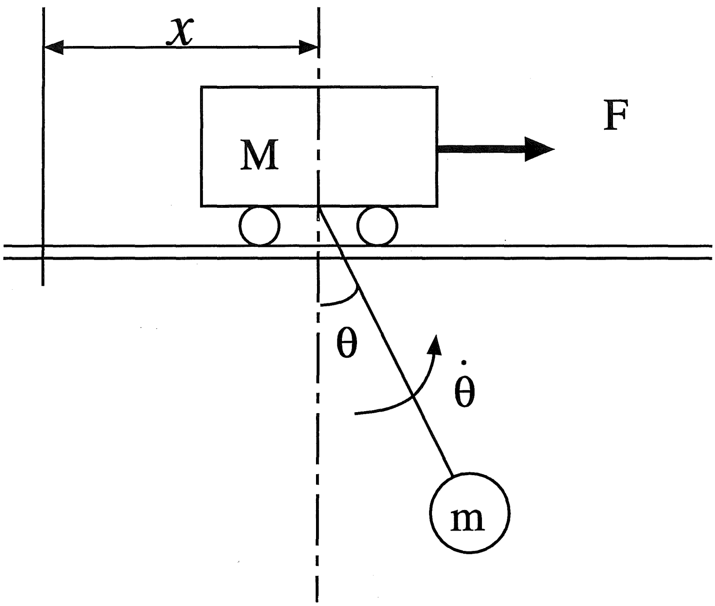

Figure 2. Dynamics of overhead crane

of the trolley, e.g., force F, velocity $\dot{x}$ and acceleration $\ddot{x}$. The acceleration is chosen here because the load swing can be separated from the trolley dynamics as found from (2). It is therefore assumed here that the trolley is controlled by an acceleration servomotor. This makes a crane control system simple.

Let θ_{max} be the maximum swing angle of the load. Then, the free oscillation of the load shown by the linearized (2) gives the maximum swing angle velocity $\dot{\theta}_{max} = \sqrt{g/l}\theta_{max}$ and the maximum swing acceleration $l\ddot{\theta}_{max} = g\theta_{max}$. Using these quantities, θ, $\dot{\theta}$ and $\ddot{x}$ are normalized as follows.

$$\left.\begin{array}{l} \Theta = \theta/\theta_{max} = \alpha\theta \\ \dot{\Theta} = \sqrt{l/g}\dot{\theta}/\theta_{max} = \beta\dot{\theta} \\ \ddot{X} = \ddot{x}/(g\theta_{max}) = \gamma\ddot{x} \end{array}\right\} \tag{3}$$

where $\alpha(= 1/\theta_{max})$, $\beta(= \sqrt{l/g}/\theta_{max})$ and $\gamma(= 1/(g\theta_{max})$ are normalized coefficients. The normalized variables Θ, $\dot{\Theta}$ and $\ddot{X}$ are therefore in the range of $[-1, 1]$.

3. Manual control system of overhead crane

The essential of the fuzzy control is to simulate the mental decision of operators. Therefore, the decision method for manual crane control must necessarily be analyzed. The manual control is considered as a man-machine system, Sutton, Cherrington and Towill (1986), in which the operator performs his task in a skilful manner as a processor.

As shown in Fig. 3, an operator in a crane control system handles two control channels. One of them is related to the conveying state such as the position of a trolley and the distance from a target place, and the other is related to the swing state of a load. The operator estimates visually both states and analyzes them, resulting in that both control channels are brought to a compromise to get a control adjustment suitable for smooth conveyance without load swing. Rough intuitions of operator used for suppressing load swing are as follows:

1. Accelerate when the load moves forward relative to the crane.
2. Decelerate when the load swings backward.
3. Keep the velocity unchanged when the load swing angle is zero or nearly zero.

In order to convey a load to a target place, a position control is also needed. A skilful operator forms a velocity pattern of conveyance in his mind through his experience. Usually, in this pattern a trolley is accelerated first to some high velocity level, and this velocity is kept constant until the trolley arrives at the place near the target. Then, the trolley is decelerated graduately and stopped at the target point. According to this velocity pattern, a load will be conveyed to the target place smoothly.

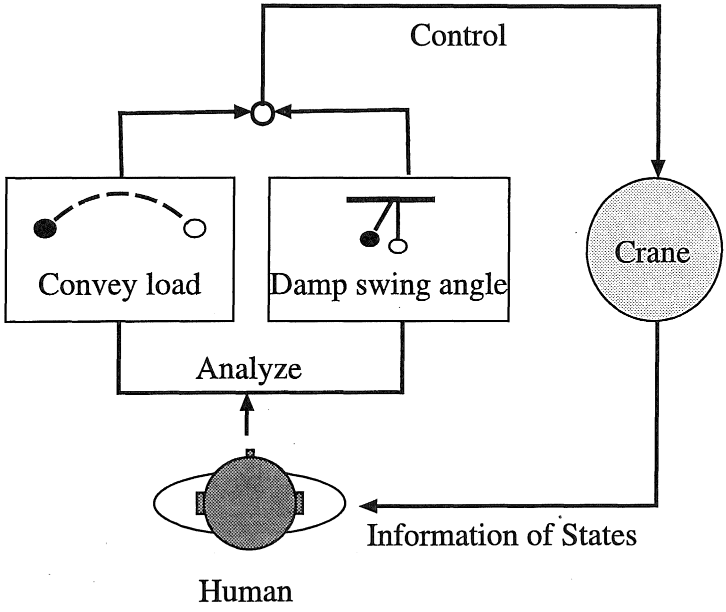

Figure 3. Manual control system

4. Automatic control system

Based on the analyses of the manual operations above, the control system proposed here consists of two control channels corresponding to Fig. 3. One is a velocity pattern control and the other is an anti-swing fuzzy control.

4.1. Velocity pattern control

A velocity pattern is a velocity profile along a path defined from some conveyance requirements, such as conveyance distance, the maximum velocity and the maximum acceleration. In this study, a trapezoid-shaped velocity pattern is used, which ordinarily is presented as a simple pattern of the know-how on a position control of human being. Fig. 4 shows a standard velocity pattern along a path in X direction which will guide the trolley to the target position. Small positive velocity v_0 at the origin is needed to start the trolley. The velocity v_m should be chosen less than the maximum velocity v_{max} of the trolley. The slope K of the velocity pattern should be chosen less than a_{max}/v_{max} where a_{max} is the maximum acceleration of the trolley.

A velocity pattern can be designed arbitrarily if the velocity and acceleration of the trolley are within the specified domain described above. The optimal control theory will give its proper velocity-pattern, which may be difficult to implement because conveyance paths are subject to temporary restrictions and

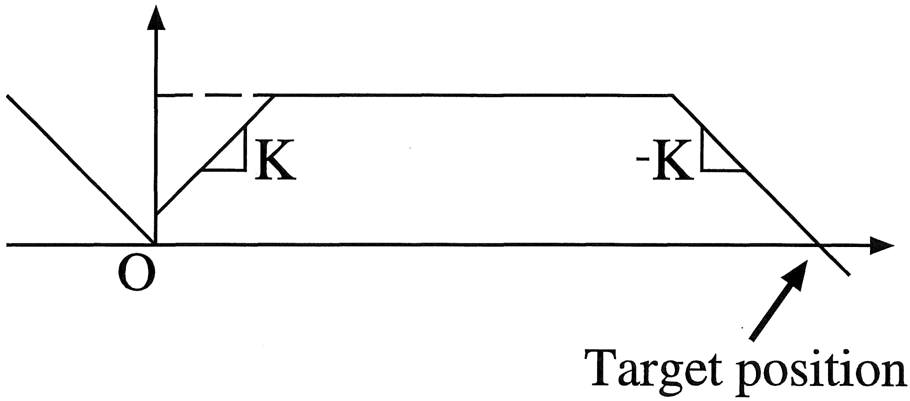

Figure 4. The standard velocity pattern

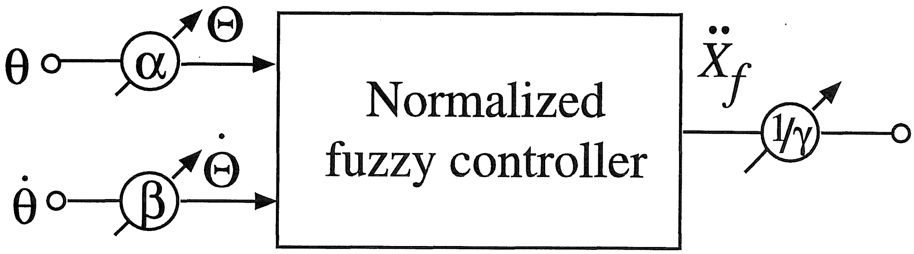

Figure 5. Anti-swing fuzzy controller

change always according to working processes in factories. A velocity pattern is therefore required to be flexible. The method proposed here satisfies this requirement.

The velocity pattern control gives a velocity $\dot{x}$ from the velocity profile at the present position x of the trolley. The acceleration $\ddot{x}_s$ is calculated by

$$\ddot{x}_s = B(v_s - \dot{x}) \tag{4}$$

where B is a positive constant. If the absolute value of $\ddot{x}_s$ exceeds a_{max}, it is limited to a_{max} or $-a_{max}$.

4.2. Anti-swing fuzzy control

Though a velocity pattern control is utilized to convey a load to a target place, it induces also swing of the load. A fuzzy control is used for damping the swing during conveyance. Load swing states are expressed by swing angle θ, swing

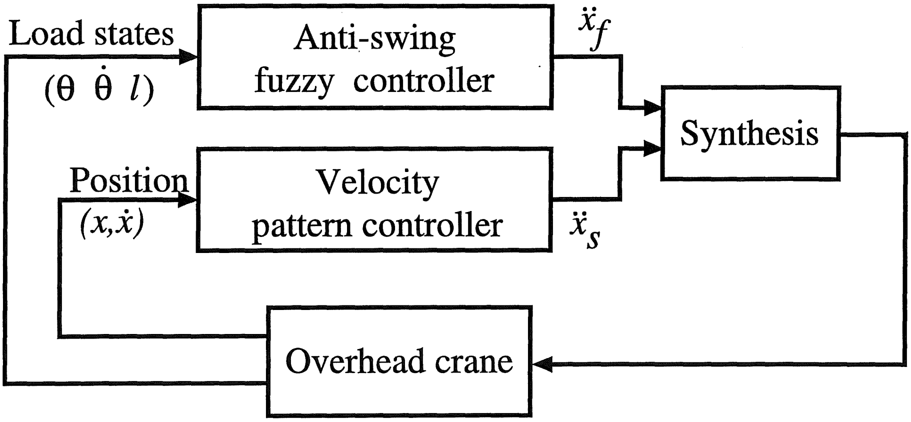

Figure 6. The system structure

angular velocity $\dot{\theta}$ and a rope length l. Since the swing velocity of the load is related to the rope length in terms of $l\dot{\theta}$, the fuzzy controller should suppress the swing stronger for a longer rope length even if $\dot{\theta}$ is the same. Therefore the fuzzy controller needs generally θ, $\dot{\theta}$ and l as its inputs. This may complicate the controller for its practical use. We use here the normalized variables Θ and $\dot{\Theta}$ as inputs, where a rope length is included in a normalizing coefficient β as shown in (3). Thus, a rope length can be excluded from fuzzy rules and the controller becomes much simpler. A normalized acceleration $\ddot{X}_f$ is also used as an output and it is converted easily to an actual acceleration $\ddot{x}_f$ by the coefficient γ. $\ddot{x}_f$ is limited to a_{max} and $-a_{max}$ in the same way as $\ddot{x}_s$. Fig. 5 shows a normalized fuzzy controller, whose details will be discussed later.

Triangle-shaped membership function is widely used in control system because of its simplity and effectiveness. The anti-swing fuzzy controller also uses a triangle-shaped membership function for antecedents but a singleton membership function for a consequent.

4.3. The whole control system

The velocity pattern control and the anti-swing control are combined in parallel as shown in Fig. 6.

The outputs $\ddot{x}_f$ and $\ddot{x}_s$ of each controller are synthesized by the following equation to get the manipulated variable $\ddot{x}$ for the trolley:

$$\ddot{x} = A\ddot{x}_f + (1 - A)\ddot{x}_s \tag{5}$$

A is a weight for anti-swing control and is given by

$$A = A_m tanh\{d(|\Theta| + |\dot{\Theta}|)/\sqrt{2}\} \tag{6}$$

		swing angle Θ				
		NB	*NS*	*ZO*	*PS*	*PB*
swing angular velocity $\dot{\Theta}$	*NB*	NB	NB	NS	NS	ZO
	NS	NB	NS	NS	ZO	PS
	ZO	NS	NS	ZO	PS	PS
	PS	NS	ZO	PS	PS	PB
	PB	ZO	PS	PS	PB	PB

Table 1. Decision table

where A_m and d are constants satisfying $0 \leq A_m \leq 1$ and $d > 0$. Thus, the weight A changes with the load swing states Θ, $\dot{\Theta}$ so that the anti-swing control becomes strong for larger swing. The sensitivity of the effectiveness for A is adjusted by A_m and d according to the priority requirements between conveyance time and anti-swing control precision. Consequently, we can expect to obtain an appropriate acceleration of the trolley at any time for smooth conveyance to the target place like a skilful manual control.

5. The fuzzy rule and tuning

Linguistic anti-swing control experiences of an operator are transformed into a group of fuzzy logic rules like the following.

R^1: **If** swing angle is forward relative to trolley and big (PB), **and** swing angular velocity also tends forward and is big (PB), **then** the acceleration of trolley should be positive big (PB).
R^2: **If** swing angle is backward relative to trolley and big (NB), **and** swing angular velocity also tends backward and is big (NB), **then** the acceleration of trolley should be negative big (NB).
R^3: **If** swing angle is zero (ZO), **and** swing angular velocity is also zero (ZO), **then** the acceleration of trolley should be zero (ZO).
and so on.

These rules are expressed through a decision table. Product-sum-average implication function is used to get the output of the normalized fuzzy controller. To determine the number of levels in a decision table, we have examined anti-swing properties for three, five and seven levels, using together the tuning of parameters described later. As a result, five and seven levels show almost the same properties which are better than those of three levels. Therefore, the decision table with five levels as shown in Table 1 is used here.

There are two tuning methods, one of which is rule-based and the other data-based. The data base approach is used here because of the simplicity of tuning process as described below. Fig. 7 shows an example of membership functions

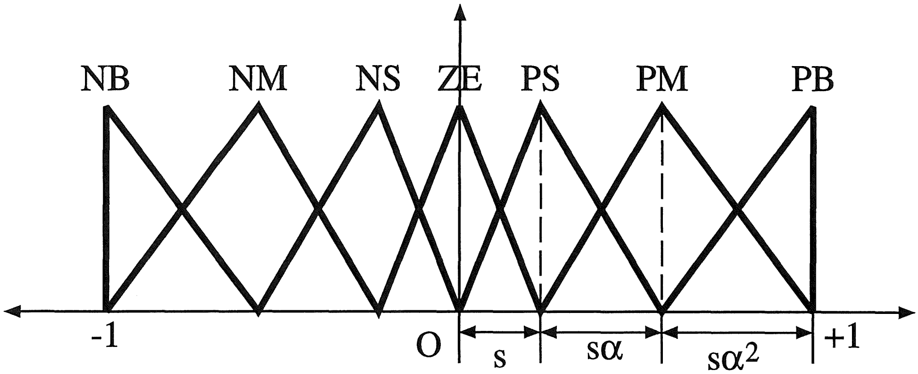

Figure 7. Membership functions

in general. In our problem, the arrangement of the functions between -1 and 1 should be symmetrical with respect to the origin because of symmetrical control for damping swing. We tune the membership functions by such a method that the center positions of the functions varies monotonously as shown in Fig. 7. This adjusts the sensitivities with respect to the magnitude of Θ and $\dot{\Theta}$ to an effective anti-swing control. The monotonous change is characterized by a parameter α in the figure. Let s be a distance between the center of the first positive membership function and the origin. Then, from $s + s\alpha + s\alpha + \cdots + s\alpha^{n-1} = 1$,

$$s = (1 - \alpha)/(1 - \alpha^n) \tag{7}$$

is given, where n is (the number(odd) of levels -1)/2.

Let us define the following error function E:

$$E = \int_O^T (\Theta^2 + \dot{\Theta}^2)dt \tag{8}$$

where $T(= 4\pi\sqrt{l/g})$ is twice the period of load swing. E represents the degree of swing and should be made minimum by adjusting each parameter α of the membership functions relative to Θ, $\dot{\Theta}$ and $\ddot{X}$, i.e., α_Θ , $\alpha_{\dot{\Theta}}$ and $\alpha_{\ddot{X}}$. To do this, a steepest decent method is used here. Increments of α, $\delta\alpha$, are given by

$$\delta\alpha = -\eta(\partial E/\partial\alpha), \quad \alpha = (\alpha_\Theta, \alpha_{\dot{\Theta}}, \alpha_{\ddot{X}})^t \tag{9}$$

where η is a small positive constant. It has been obtained from this tuning that $\alpha_\Theta = 2.71$, $\alpha_{\dot{\Theta}} = 0.56$, $\alpha_{\ddot{X}} = 0.4$ for the decision table in Table 1.

6. Simulations

Computer simulations for various conveyance conditions are performed to confirm the effectiveness of the control method proposed here. At first, a usual conveyance with a standard velocity pattern like Fig. 4 is simulated. The results are shown in Fig. 8, where conveyance distance $= 30m$, $l = 5m$, $\theta_{max} = 10degree$, $v_m = 1.5m/s$, $v_0 = 0.2m/s$, $K = 0.3(m/s)/m$, $a_{max} = 1m/s^2$, $B = 5$, $A_m = 0.5$, $d = 30$ and there is no initial swing. It can be seen from the figure that swing during conveyance is suppressed well and a load has stopped at the target position precisely. The actual velocity $\dot{x}$ almost follows the standard velocity v_s. At the acceleration region in the beginning of the conveyance, large positive acceleration $\ddot{x}_s$ is required to follow the velocity pattern, but it will induce a positive load swing. Hence, negative acceleration $\ddot{x}_f$ appears to suppress the swing. Both accelerations are compromised to give an appropriate acceleration $\ddot{x}$ which damps a load swing to become as small as possible during carrying of the load along the velocity pattern. Opposite accelerations are required at the deceleration region near the target position, though the difference between $\dot{x}$ and v_s is somewhat large. Conveyance time is about 37.3 seconds for the stop gap precision of $1cm$. Conveyance time along the standard velocity v_s is about 41.2 seconds for the same stop gap. Therefore, both conveyance times are almost the same. Simulations for different rope lengths have also given satisfying result, hence the normalized fuzzy control has been found to be effective and useful.

Figure 9 shows another simulation in case when an initial swing ($\theta = 10degree$, which is may be the largest in actual swing) remains. Other parameter values are the same as those in Fig. 8. The load also encounters an unexpected perturbation (a step swing of $10degree$) during conveyance due to some disturbance such as wind, collision and so on. The initial swing and the perturbation are readily suppressed as seen in the figure. This method can therefore deal well with unexpected disturbances.

Fig. 10 shows a simulation for hoisting up a load to avoid an obstacle. The rope length at the middle of the conveyance becomes $2m$, i.e., 40% of the initial or final length as shown in the figure. Other parameter values are the same as those in Fig. 8. This is the case with time-varying rope length. The manipulated variable $\ddot{x}$ changes more during the beginning of hoisting up. Let θ_1 and θ_2 be the maximum swing for rope lengths of l_1 and l_2 ($< l_1$) respectively. Then, $\theta_2 = \sqrt{l_1/l_2}\theta_1 > \theta_1$ for a given swing energy of the linearized (2). Therefore, the swing becomes so large and fast during hoisting up that the rapid change of $\ddot{x}_f$ may be required to damp the swing. Fig. 10 shows, however, that the load moves along the predetermined path for hoisting up and down with less swing, but the acceleration $\ddot{x}$ is a little bigger than that in Fig. 8. Our method has given a good result for such a case owing to the normalized fuzzy control.

We have made a simulation in which a trolley bearing an initial swing is required to go back to its original position without load swing. Equation $v_s =$

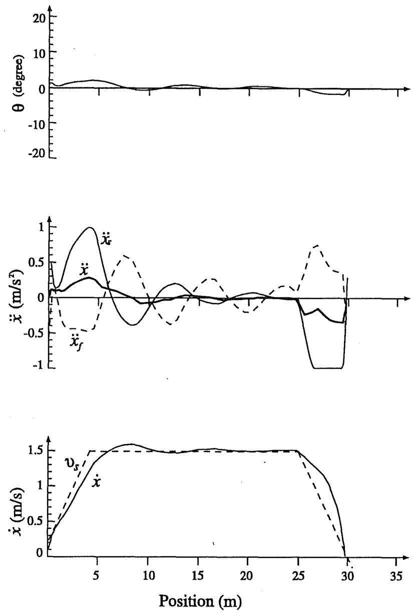

Figure 8. Simulation for usual operation.

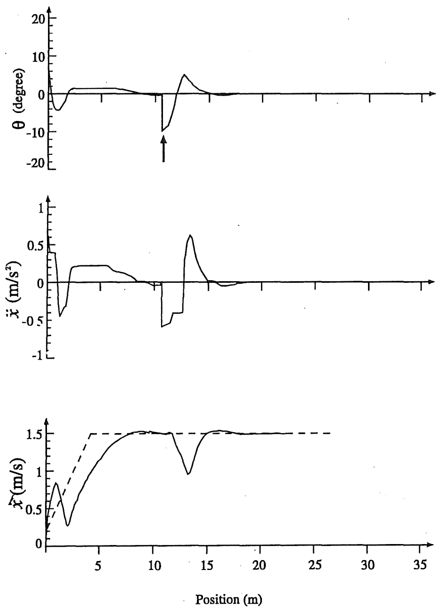

Figure 9. Simulation for initial swing and unexpected disturbance (arrow).

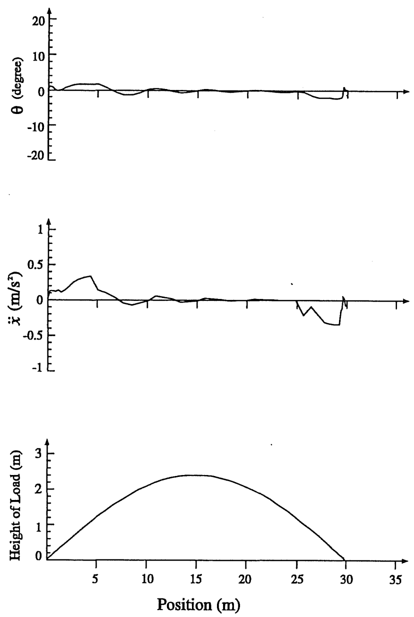

Figure 10. Simulation in case of hoisting up a load to avoid an obstacle. Rope length changes with the position of the trolley.

$-Kx$ can be used as a velocity pattern in this case. This means that a load should stay finally at the designated position for any disturbance. Fig. 11 shows that the trolley moves to damp the initial swing (10*degrees*) and goes back to the origin immediately within a small area moving, where the parameter values are the same as these in Fig. 8 except that $A_m = 0.7$. If the crane is operated by the velocity pattern controller only, the above equation and (4) give the equation $\ddot{x} + B(\dot{x} + Kx) = 0$. The origin $x = 0$ is therefore stable and the equation is overdamped for actual cases because $4K/B < 1$. Consequently, the movement of x to suppress a load swing through the anti-swing fuzzy controller is always pulled back to the origin stably.

It is found from these simulations that the control system can convey smoothly a load in any state along a given path to its target position. This is due to the consistent operation of two control channels weighted by the swing state. Since a velocity pattern can be set arbitrarily within the specified restrictions of trolley movement, a manually controlled velocity can be considered as a velocity pattern. Hence, this system may be also used in combination with a manual control, i.e., as a semi-automatic control.

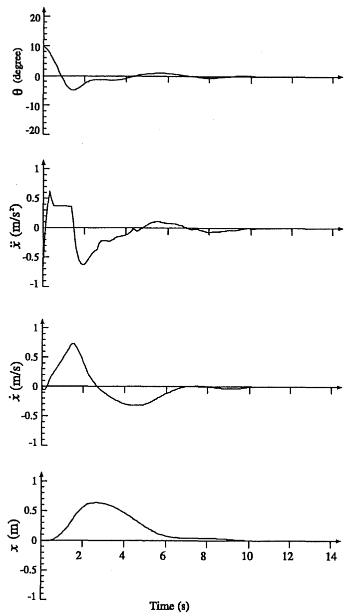

Figure 11. Simulation for anti-swing control to hold the crane at original position.

7. Conclusions

The overhead crane control consists of two control channels, one of which suppresses load swing by fuzzy inferences and the other conveys a load along a velocity pattern. A dominant control channel varies with swing state of a load, e.g., the fuzzy control becomes dominant for large swing. The computer simulations in various situations have shown that the control system is very effective for smooth conveyance of a load. The fuzzy rules have been normalized to have only two antecedents and one consequent. No mathematical model is required in the control system. The velocity pattern can be designed flexibly to convey a load through any path. This simple structure and flexibility will be very convenient for practical applications of the control method.

At the end, authors wish to thank President M.Tomida and Director N. Nagase of Shikoku Measurement Co. Ltd. for their support to this study.

References

BEESTON, J.W. (1969) Cloosed-loop time optimal control of a suspended load. *Proc. 4th IFAC World Congress*, Warsaw, Paper 39.5.

KUNTZE, H.B. and STROBEL, H. (1975) A contribution to adaptive time-optimal crane control. *Proc.6th IFAC World Congress, Boston/Cambrige*, MA, USA, Pt. 3, Paper 4.5.

RIDOUT, A.J. (1989) Anti-swing control of the overhead crane using linear feedback. *IE Aust. & IREE Aust.*, **9**, 17-26.

SUTTON, R., CHERRINGTON, J.E. and TOWILL, D.R. (1986) Manual control of crane system. *Ergonomics*, **29**, 10, 1155-1171.

YAMADA, S. and WALASUGI, Y. (1989) Fuzzy control of the roof crane. *IEEE, Trans. on CH*, **29**, 709-714.

YASUNOBU, S. (1986) Automatic container crane operation based on a predictive fuzzy control. *Trans. of ICE*, **22**, 1066-1073.

ZINOBER, *A.a.T.* (1979) Automatic control of crane operations. *Proc. 5th IFAC Symp. Identification and System Parameter Estimation*, Darmstadt, 1161-7.