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Design of Fuzzy Controller Based on Fuzzy Model for Container Crane System

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Abstract

The fuzzy control theory is applied to control a container crane, which is a very complicated system and controled manually by experts. As reference velocities of trolley and hoist of the container crane, we use those decided by experts, and express them by fuzzy model. We control the crane to follow the reference velocities by using fuzzy controllers. The fuzzy controllers are designed on the basis of fuzzy models representing the dynamics of the container crane. We made a model container crane and applied the suggested method to it

1. Introduction

Recently, system control theories are applied in many fields. However, systems are getting complicated, and many systems are too complicated to be controled with conventional control theories. Most such systems are controlled by experts. In this paper, the fuzzy control theory is applied to control a container crane, which is a very complicated system and controled by experts.

Container cranes, which carry containers between a container ship and a trailer, are very important equipment for the loading and unloading work in a port. When a ship is loaded or unloaded, minimizing the containers carrying time brings about a large cost saving. Container crane carries containers with trolley moving on rails and hoist rope. Because of nonlinear characteristics and complicated restriction conditions, container cranes are controlled not automatically, but manually by experts.

For the control of container cranes, several methods have been proposed. For example, methods supposing uniform length of hoist rope, optimal conrol method with three predefined motions(vertical motion, horizontal motion, diagonal motion), and predictive fuzzy control can be illustrated. However, such methods could not get so good control results as experts get.

In this paper, as reference velocities of trolley and hoist, we use those decided manually by experts, and control the crane to follow the reference velocities by using fuzzy controllers. The fuzzy controllers are designed on the basis of fuzzy models representing the dynamics of the container crane. We made a model container crane and applied the suggested method to it.

2. Fuzzy Control of Container Crane

Container crane carries containers with trolley moving on rails and hoist rope. Thus, to control a container crane system, we must control a hoist motor and a trolley drive motor. Since a large swing of the container load during the carrying is dangerous, the problem is to carry a container to the desired place as quickly as possible while minimizing the swing of the container. A container crane system is shown in Fig. 1.

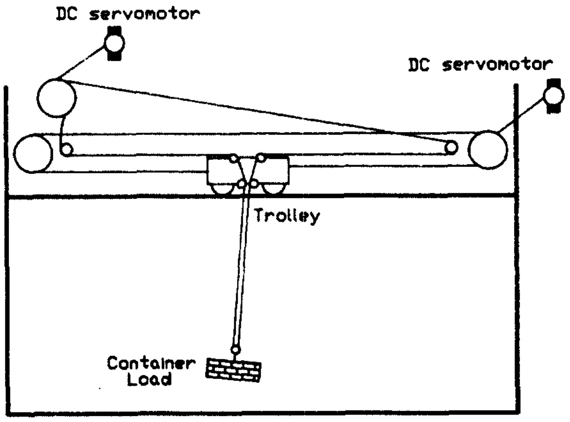


Fig. 1 A container crane system

Because the dynamic equations of conainer crane system are very complicated nonlinear and restriction conditions are very complicated, it is very difficult to apply conventional control theory to the control of container crane.

However, many experts control manually the container crane very well. In this paper, as reference velocities of trolley and hoist we use those decided manually by experts, and control the crane to follow the reference velocities. The overall block diagram of the container crane conrol system is shown in Fig. 2.

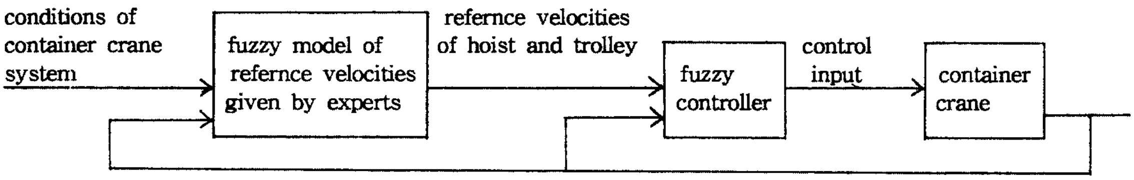


Fig. 2 The overall block diagrm of the container crane control system

The reference velocities of trolley and hoist are expressed as fuzzy models. The fuzzy models of referenc velocities are identified by using the data obtained when an expert operates the container crane manually. In this paper, we use Takagi and Sugeno fuzzy model composed of the following fuzzy implications.

$$L^i : \text{If } x_1 \text{ is } A_1^i,\ x_2 \text{ is } A_2^i,\ \cdots,\ x_n \text{ is } A_n^i \text{ then } y^i = c_o^i + c_1^i x_1 + c_2^i x_2 + \cdots + c_n^i x_n \qquad (1)$$

where, x_j is an input variable, A_j^i is a fuzzy set, c_j^i is a parameter. The output y is infered from the above fuzzy moel as folloows.

$$y = (\sum_i W^i y^i) / \Sigma W^i \qquad (2)$$

$$W^i = \prod_j A_j^i(x_j) \qquad (3)$$

where, $A_j^i(x_j)$ is the membership value of A_j^i at x_j. The algorithm identifing a fuzzy model by using input-output data had been suggested.

When the fuzzy models of reference velocities are made, the container crane is controlled to follow the refernce velocities. At that time, because of the very complicated nonlinear dynamics of the container crane system, we use a fuzzy controller designed on the basis of a fuzzy model representing the dynamics of the container crane. The method designing fuzzy controller is as follows. Let the fuzzy model of dynamics as as follows.

$$L^i : \text{If } z_1 \text{ is } P_1^i,\ z_2 \text{ is } P_2^i,\ \cdots,\ z_m \text{ is } P_m^i \text{ then } x^i(k+1)=a_0^i+a_1^i x(k)+\cdots+a_n^i x(k-n+1) + b^i u(k) \qquad (4)$$

where, P_j^i is a fuzzy set, zj is a premise variable, u(k) is an input.. The fuzzy model (4) can be identified by using the input-output data obtaind by observing the behavior of the container crane system actuated by random inputs. The consequent of the fuzzy implication (4) can be written in the matrix form.

$$X^i(k+1) = A^i X(k) + B^i u(k) + C^i \qquad (5)$$

where, $X(k) = (x(k) \cdots x(k-n+1))^T$, $B^i = (b^i\ 0 \cdots 0)^T$, $C^i = (a_0^i\ 0 \cdots 0)^T$, and A^i is a phase varable canonical form matrix. To design a controller t racking reference inputs, we define a new state variable vector M(k) and input variable v(k).

$$M(k) = \begin{bmatrix} X(k+1) - X(k) \\ x(k) - r \end{bmatrix} \qquad (6)$$

$$v(k) = u(k+1) - u(k) \qquad (7)$$

where, r is a reference input. The state equation using M(k) and v(k) is

$$M(k+1) = \begin{bmatrix} A^i & 0 \\ D & 1 \end{bmatrix} M(k) + \begin{bmatrix} B^i \\ 0 \end{bmatrix} n(k)$$

$$= \Phi^i M(k) + \Gamma^i v(k) \qquad (8)$$

where, $D = (1\ 0 \cdots 0)^T$. The fuzzy model (4) can be rewritten as follows.

$$L^i : \text{If } z_1 \text{ is } P_1^i,\ z_2 \text{ is } P_2^i,\ \cdots,\ z_m \text{ is } P_m^i \text{ then } M^i(k+1) = \Phi^i M(k) + \Gamma^i v(k) \qquad (9)$$

The fuzzy controller designed by using the above fuzzy model is also composed of the same type of fuzzy implications as follows.

$$C^i : \text{If } z_1 \text{ is } P_1^i,\ z_2 \text{ is } P_2^i,\ \cdots,\ z_n \text{ is } P_n^i \text{ then } v^i(k) = G^i M(k) \qquad (10)$$

where, $G^i \in R^{n+1}$ is a state feedback gain. The methods of inferring input v(k) from the fuzzy controller (10) and determining G^i are shown in the next theorem.

Theorem. *Let a desired stable system be,*

$$M(k+1) = \Phi^o M(k) \qquad (11)$$

G^i satisfy,

$$\Phi^o = \Phi^i + \Gamma^i G^i \qquad (12)$$

and the input $v^0(k)$ be infered from the fuzzy controller (10) as follows,

$$n^0(k) = \sum_i (W^i b^i n^i(k)) / \sum_j (W^j n^j(k)) \qquad (13)$$

then the fuzzy system (9) controled by the above input $n^0(k)$ becoms the dsired system (11).

Proof. When $n^0(k)$ is used as an input, the inferred M(k+1) from the fuzzy model (9) becomes

$$\begin{aligned} M(k+1) &= (\Sigma W^i M^i(k)) / \Sigma W^i \\ &= (\Sigma W^i (\Phi^i M(k) + \Gamma^i n^0(k))) / \Sigma W^i \\ &= (\Sigma W^i \Phi^i M(k) + \Sigma W^i \Gamma^i n^0(k)) / \Sigma W^i \end{aligned}$$

Since, $\Sigma W^i \Gamma^i n^0(k) = \Sigma W^i \Gamma^i n^i(k)$ by (13),

$$\begin{aligned} M(k+1) &= (\Sigma W^i \Phi^i M(k) + \Sigma W^i \Gamma^i n^i(k)) / \Sigma W^i \\ &= \Sigma W^i (\Phi^i + \Gamma^i G^i) M(k) / \Sigma W^i \\ &= \Phi^0 M(k) \end{aligned}$$

□

3. Experiment on a Model Container Crane

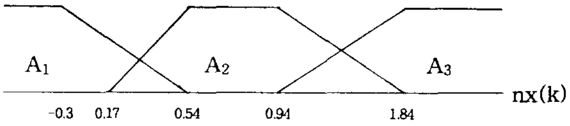
To verify the algorithm suggested above, we made a model conainer crane which has 120cm length and 100cm height. Two 12W DC motors were used for trolley drive and hoist rope, and three encoders were used to sense the position of trolley, the length of rope, and the container swing angle.

3.1 Fuzzy Model of Refernce Velocities

Usually, when an expert operates a container crane, he consider the following facts.

(1) Carry the container precisely in shortest time.
(2) Minimize the swing of container during carrying and the end of carring.
(3) Prevent the container from touching other objects.

Considering the above conditions, we exercised the manual operation of the model container crane until we became experts. Then, two fuzzy models of reference velocities of trolley and hoist were identified by using the data obtained when we operated the model crane. When operating the model crane to obtain the data, we varied the weight of container load 0.5Kg - 1.5 Kg and the carring length 1.0m - 1.1m. The two identified fuzzy models are shown in Fig. 3. In Fig. 3, 'nx' is the position of trolley when start point is 0 and stop point is 1, 'v_t' is the velocity of trolley, 'v_h' is the velocity of hoist, 'le' is the length of hoist rope, 'an' is the swing angle of load, and 'we' is the weight of container load.

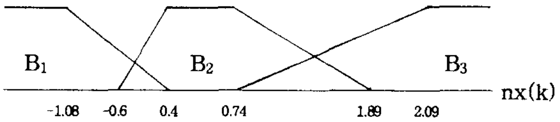


L^1 : If nx(k) is A_1 then $v_t(k+1) = -0.65 + 1.5v_t(k) - 0.068we(k) + 0.007an(k) - 6.87nx(k) + 0.02he(k)$

L^2 : If nx(k) is A_2 then $v_t(k+1) = 2.27 + 0.6v_t(k) - 0.024we(k) - 2.02nx(k) - 0.002he(k)$

L^3 : If nx(k) is A_3 then $v_t(k+1) = 38.6 - 4.06v_t(k) + 0.43we(k) - 0.017an(k) - 41.8nx(k) + 0.02he(k)$

(a) The fuzzy model of trolley refernce velocities.



L^1 : If nx(k) is B_1 then $v_h(k+1) = 0.67 + 2.63v_h(k) - 1.82we(k) + 0.02an(k) + 26.8nx(k) - 0.44he(k)$

L^2 : If nx(k) is B_2 then $v_h(k+1) = 0.18 + 0.72v_h(k) + 0.66we(k) + 0.016an(k) - 1.03nx(k) - 0.042he(k)$

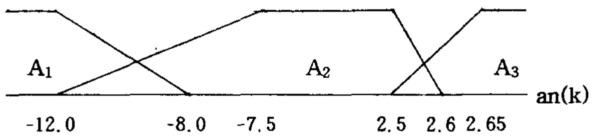
L^3 : If nx(k) is B_3 then $v_h(k+1) = -9.22 + 0.11v_h(k) - 3.03we(k) - 0.07an(k) + 13.4nx(k) - 0.25he(k)$

(b) The fuzzy model of hoist refernce velocities.

Fig. 3 The fuzzy models of refernce velocities

3.2 Fuzzy Controller

To control the model crane so that the velocities of container follow the refernces, two fuzzy controller were designed for hoist motor and trolley drive motor. To design the fuzzy controllers, two fuzzy models representing the dynamics of trolley drive motor and hoist motor were identified and shown in Fig. 4.

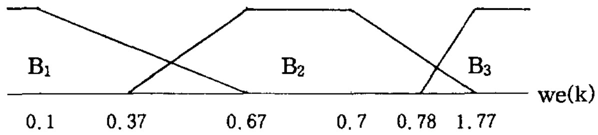


L^1 : If an(k) is A_1 then $v_t(k+1) = -0.3 + 1.03\,v_t(k) - 0.09\,v_t(k-1) + 0.96\,u_t(k)$

L^2 : If an(k) is A_2 then $v_t(k+1) = -4.9 + 0.57\,v_t(k) + 0.01\,v_t(k-1) + 5.44\,u_t(k)$

L^3 : If an(k) is A_3 then $v_t(k+1) = -14.4 + 0.40\,v_t(k) - 0.08\,v_t(k-1) + 12.94\,u_t(k)$

(a) The fuzzy model of trolley drive motor dynamics



L^1 : If we(k) is B_1 then $v_h(k+1) = 1.73 + 1.0\,v_h(k) - 0.37\,v_h(k-1) + 5.70\,u_h(k)$

L^2 : If we(k) is B_2 then $v_h(k+1) = -4.74 + 0.42\,v_h(k) - 0.02\,v_h(k-1) + 12.27\,u_h(k)$

L^3 : If we(k) is B_3 then $v_h(k+1) = -5.84 + 0.45\,v_h(k) - 0.02\,v_h(k-1) + 11.08\,u_h(k)$

(b) The fuzzy model of hoist motor dynamics

Fig. 4. The fuzzy models of the dynamics of motors

We determined the matrix Φ^o so that the eigenvalues are 0.5, 0.3+j0.3, and 0.3-j0.3.

$$\Phi^o = \begin{pmatrix} 0.1 & -0.045 & -0.245 \\ 1 & 0 & 0 \\ 1 & 0 & 1 \end{pmatrix}$$

Then the fuzzy controllers are

C^1 : If an(k) is A_1 then $n_t(k) = (-0.93 \quad 0.04 \quad -0.245)\,M(k)$

C^2 : If an(k) is A_2 then $n_t(k) = (-0.48 \quad -0.055 \quad -0.245)\,M(k)$

C^3 : If an(k) is A_3 then $n_t(k) = (-0.3 \quad 0.003 \quad -0.245)\,M(k)$

(a) The fuzzy controller of trolley drive motor

C^1 : If $we(k)$ is B_1
then $n_h(k) = (-0.9 \quad 0.326 \quad -0.245)\, M(k)$

C^2 : If $we(k)$ is B_2
then $n_h(k) = (-0.32 \quad -0.027 \quad -0.245)\, M(k)$

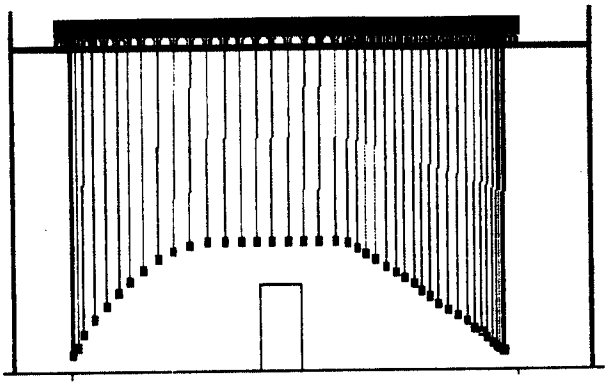
C^3 : If $we(k)$ is B_3
then $n_h(k) = (-0.35 \quad -0.19 \quad -0.245)\, M(k)$

(b) The fuzzy controller of hoist motor

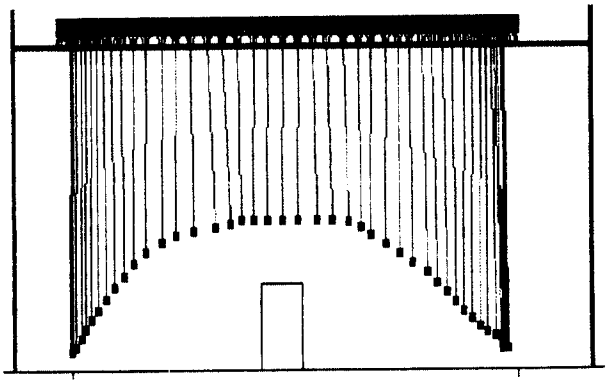
Fig. 4. The fuzzy controllers

3.3 Experiment Results

Control results are shown in Fig. 5. and Fig. 6.

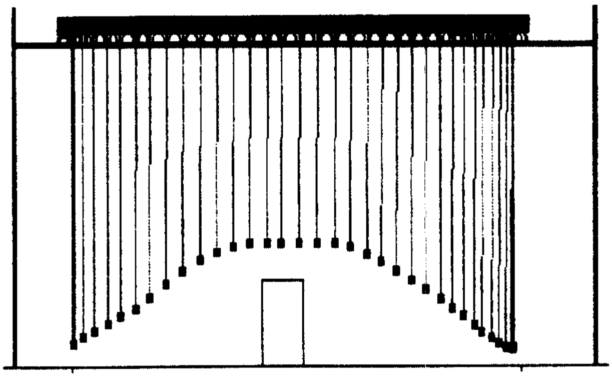


(a) The locus of container controlled by expert

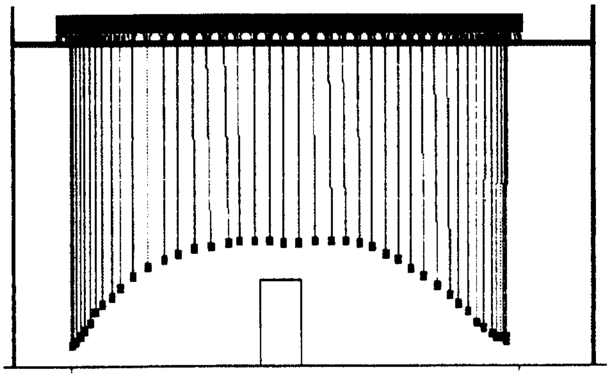


(b) The locus of container controlled by fuzzy controller

Fig. 5. The controll results when the weight of load is 1Kg and the carring length is 107.5cm



(a) The locus of container controlled by expert



(b) The locus of container controlled by fuzzy controller

Fig. 6. The controll results when the weight of load is 0.5Kg and the carring length is 102.5cm

4. Conclusions

We have proposed a new method for controlling container cranes. At present, most container cranes are controlled manually by experts. As reference velocities of trolley and hoist of the container crane, we use those decided manually by experts, and express them by fuzzy model. We control the crane to follow the reference velocities by using fuzzy controllers. The fuzzy controllers are designed on the basis of fuzzy models representing the dynamics of the container crane. We made a model container crane and applied the suggested method to it. The locus of container load controlled by the fuzzy controller were almost the same as those by expert.

Reference

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