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# Fuzzy Logic Control of a Roof Crane with Conflicting Rules

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## ABSTRACT

**In controlling a system having many variables to control and multi objectives to satisfy such as a roof crane system, it is often difficult to obtain fuzzy If-Then rules in usual ways. As an alternative, we can more easely obtain rules in such a manner that we obtain each independent group of rules using partial variables for a partial objective. In this case, obtained rules can be conflicting with each other and conventional inference methods cannot handle such rules effectively. In this paper, we propose a roof crane controller with optimal velocity profile generator and a fuzzy logic controller with an inference method suitable for such conflicting rules.**

## I. Introduction

The roof crane has been widely used for transporting an object hanging on a rope to a desired position. During transportation, the swing of the load hanging on the rope can occur, which in turn takes more time to settle and may lead to a dangerous situation. Therefore, the basic requirement for the motion of the crane is that the load should reach to the final position safely with minimum swing and as fast as possible.

So far, there have been reported several works[1]-[3] for controlling the roof crane. However, the controllers proposed in [1][2] depend on the mathematical model, and not surprisingly, the system is sensitive to disturbances and system modeling error. The work proposed in [3] makes use of a fuzzy logic controller(FLC) and resolves the difficulties in [1][2]. However, they are not capable of reflecting the operators' control strategies in a suitable manner. In their method, variables related only to swing are utilized and thus, exact positioning is not considered. Note that utilizing too many variables can result in too complicated rules. To obtain rules more easily, we make two independent groups of rules. Each group of rules uses partial variables and satisfies single objective. However, obtained groups of rules are conflicting with each other and conventional inference methods are not suitable for such conflicting rules because fat shape fuzzy sets, which can often be considered to be more uncertain than slim shape fuzzy sets, are more influential in aggregating the consequents of the rules.

In this paper, we propose a hybrid controller with optimal velocity profile generator to make the roof crane more fast and also with a new type of FLC to handle such conflicting rules.

## II Design of Roof Crane Controller

*a. Structure of Roof crane controller*

Figure 1 shows the experimental apparatus. The trolley is driven by the AC motor controlled by the inverter. The trolley can move along the rail and the load is hanged by the rope. Two encoders are used for measuring the position of the trolley and the swing angle. The IBM-PC 486 computer with A/D and D/A converters is used as a host computer. The specification of the model roof crane system is shown in Table 1.

The roof crane controller is divided into two parts: the velocity profile generator and the FLC. The velocity profile generator produces the time optimal trajectory from an initial position to a final desired position. if the initial swing is zero and there is no disturbance, the trajectory is designed to cause no swing at the final position. During the whole traversing period, the reference position of the trolley is produced by the optimal velocity generator. The FLC is added to the velocity profile generator to compensate for the swing caused by disturbance or the initial swing. The objectives of the FLC are two fold: (i) To maintain the swing as small as possible. (ii) To make the crane to follow the desired trajectory. The operation for the objective(i) is performed at the constant speed period and stop period of the velocity profile generator.

In order to make rules to follow up the above two objects in usual ways, we usually should utilize four variables such as angle, change of angle, position and change of position. It is very difficult to make rules with four

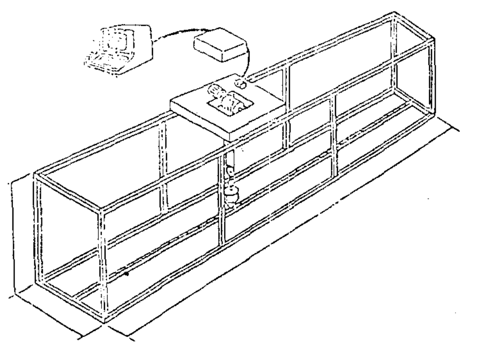

Fig.1. Experimental apparatus.

| Δθ \ θ | NB | NM | NS | ZE | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | AZ | AZ | AZ | NB | AZ | AZ | AZ |
| NM | AZ | AZ | AZ | NM | AZ | AZ | AZ |
| NS | AZ | AZ | AZ | NS | AZ | AZ | AZ |
| ZE | AZ | AZ | AZ | ZE | AZ | AZ | AZ |
| PS | AZ | AZ | AZ | PS | AZ | AZ | AZ |
| PM | AZ | AZ | AZ | PM | AZ | AZ | AZ |
| PB | AZ | AZ | AZ | PB | AZ | AZ | AZ |

(a) Rule table for anti-swing.

| Δx \ x | NB | NM | NS | ZE | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | PM | PLS | PLS | PM | AZ | AZ | AZ |
| NM | PLS | PLS | PNB | PS | AZ | AZ | AZ |
| NS | PLS | PNB | PNB | PVS | AZ | AZ | AZ |
| ZE | PB | PLS | PNB | ZE | NNB | MNS | NB |
| PS | PS | AZ | AZ | NVS | NNB | NNB | MNS |
| PM | AZ | AZ | AZ | NS | NNB | MNS | MNS |
| PB | AZ | AZ | AZ | NB | NNB | MNS | NB |

(b) Rule table for positioning.

Fig.2. Used rules.

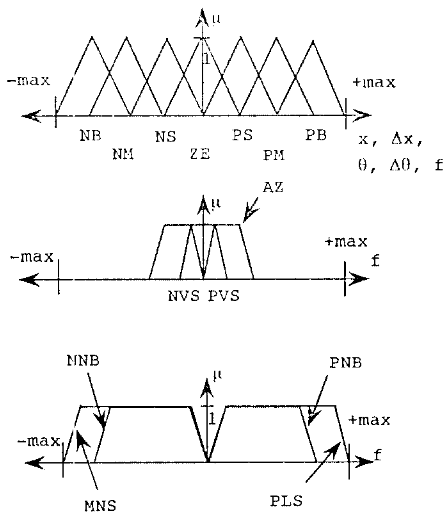


Fig.3. Used membership functions.

variables because we should make too many number of rules. Therefore, we independently make two groups of rules. The one is the group of rules utilizing two variables such as angle and change of angle to follow-up the first objective of reducing the swing. The other is the group of rules utilizing two variables such as position and change of position to follow-up the second objective of making the trolley to follow the desired trajectory. We apply the two groups of rules simultaneously. Rules and membership functions used in the rules are shown in Figure 2 and Figure 3, respectively. Because two groups of rules are independently designed, two rules from two groups of rules

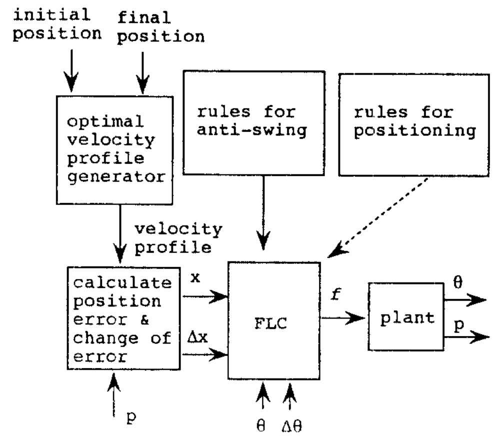


Fig.4. Structure of the controller.

can yield different conclusions at the same time, we may say that two rules in the whole rules can be conflicting with each other. We design an inference method suitable for such conflicting rules. Figure 4 shows the structure of the roof crane controller.

*b. Time optimal velocity profile generator*

The velocity profile is designed in view of the anti-swing control. The velocity profile generator makes the velocity plan to be used as a reference position for the FLC. To generate the velocity profile, the work of crane is divided into acceleration period, constant traveling period and deceleration period. The state model of the crane can be represented as follows:

$$\dot{z}(t) = Az(t) + bu(t)$$

$$A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -\frac{g}{l} & 0 \end{bmatrix} \qquad b = \begin{bmatrix} 1 \\ 0 \\ \frac{1}{l} \end{bmatrix}$$

$$z = \begin{bmatrix} \dot{X} & \theta & \dot{\theta} \end{bmatrix}^T$$

where

$\theta$ : the angle of swing
$X$ : horizontal position of the trolley
$l$ : length of the rope
$g$ : gravity constant

During the acceleration period, there are two boundary conditions:

$$z(t_0) = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T$$

$$z(t_f) = \begin{bmatrix} \dot{X}_{max} & 0 & 0 \end{bmatrix}^T$$

where $t_0$ is the initial time and $t_f$ is the final time.

To solve the velocity profile by the optimal control theory, the following are assumed:

1. The acceleration and deceleration velocity profile is monotone.
2. The velocity of the trolley is bounded.
3. The trolley of the crane can reach its maximum velocity within its period of swing($T$).

The performance index for the minimum time is defined as

$$J = \int_{t_0}^{t_f} dt$$

Then, Hamiltonian is

$$H(z(t),u(t),p(t),t) = 1+p(t)(Az(t)+bu(t))$$

where $p(t)$ is Lagrange multiplier.

The following relations hold by Minimum principle.

$$\dot{p}^*(t) = -\frac{\partial H}{\partial z}(z^*(t),\ u^*(t),\ p^*(t),\ t)$$

$$H(z^*(t),\ u^*(t),\ p^*(t),\ t) \leq H(z^*(t),\ u(t),\ p^*(t),\ t)$$

The optimal solution $u^*(t)$ should satisfy

$$p^{*T}(t)bu^*(t) \leq p^{*T}(t)bu(t)$$

From the above constraints, the optimal control input $u^*(t)$ must be a bang bang control and the problem is to determine the switching time. By the boundary condition, the transient time is less than the time $T$. Thus, switching occurs within two times ($\zeta \to \eta \to \zeta^*$) and the parameters for the switching time of the optimal solution $u^*$ can be obtained as follows:

1. $\zeta = \zeta^*$.
2. $2a_{max}\frac{\zeta}{\omega} = \dot{X}_{max}$.
3. $\frac{\eta}{2} = \tan^{-1}(\frac{\sin\zeta}{1-\cos\zeta})$.

Figure 5 shows the obtained velocity profile $u^*$.

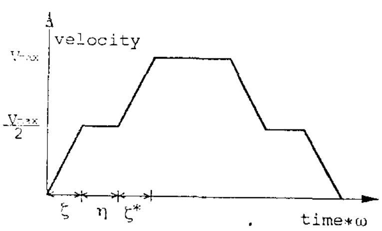


Fig.5. velocity profile.

Table 1. Characteristics of the pilot crane system.

| | |
|---|---|
| Size [mm] | 600*1600*5100 |
| Power | 1.5 Kw |
| Controller | VVVF controller |
| Encoder | 2000[pul./rev.] |
| Max. Velocity | 430[mm/sec] |
| Max. accel. | 400[mm/sec$^2$] |
| Length of rope | 1420[mm] |

### *c. An inference method suitable for conflicting rules*

Because we apply two groups of rules designed independently for the single FLC, two rules from each group of rules can yield different conclusions. We may say that such two rules are conflicting with each other. Conventional inference methods have the difficulty to handle such conflicting rules. To be specific, consider the rule R1 which is belong to rules for anti-swing and the rule R2 which is belong to rules for positioning which read as follows:

R1: If (angle is PS) and (change of angle is ZE) Then (output is AZ)

R2: If (position error is ZE) and (change of position error is NS) Then (output is PVS).

The rule R1 says that the output should be AZ(*almost zero*) for the objective for the anti-swing objective when the angle is PS(*positive small*) and the change of angle is ZE(*zero*). The rule R2 says that any output value near the value of zero is possible for the objective for positioning when the position error is ZE and the change of position error is NS(*negative small*). In the above case, it is our common understanding that both objectives are well satisfied if the output is PVS(*positive very small*). However, when the well known direct method of Mamdani's min-max inference method[4] is employed, the output value of the FLC is dominantly influenced by the fat shape fuzzy set AZ(*almost zero*). This is because conventional FLC has the phenomenon that rules having fatter shape consequent fuzzy sets are more influential.

Here, we propose a new type of inference method to overcome the difficulty. First, we define the measure of certainty. Let $X \subset R^1$ be the universe of discourse and $F_X$ be the family of fuzzy sets on $X$.
Let the width of a fuzzy set $W(\tilde{A})$: $F_X \to R^1$ be defined as:

$W(\tilde{A})=0$, if $\max\{\mu_{\tilde{A}}(x)\} = 0$

$W(\tilde{A}) = \int_X \mu_{\tilde{A}}(x)dx\ /\ \max\{\mu_{\tilde{A}}(x)\}$ otherwise

and let the width-certainty $C_w$: $R^1 \to R^1$ be defined as:

$C_w(x) = 1$ for $0 \leq x < p_1$

$C_w(x) = (p_2 - x)\ /\ (p_2 - p_1)$ for $p_1 \leq x < p_2$

$C_w(x) = 0$ for $p_2 \leq x$

where $p_1$ and $p_2$ are user's choice positive constants satisfying $p_1 < p_2$,

and let the height-certainty $C_h$: $F_X \to R^1$ be defined as:

$C_h(\tilde{A}) = \max\{\mu_A(x)\}$ for $x \in X$.

The measure of certainty $M_c(\tilde{A})$ is defined as:

$M_c(\tilde{A}) = \min\{\ C_w(W(\tilde{A})),\ C_h(\tilde{A})\}$

where $\mu_{\tilde{A}}(x)$ is the membership function of $\tilde{A} \in F_X$. Secondly, we also define the distance $\rho_f(\tilde{A},\tilde{B})$ between two fuzzy sets as:

$$\rho_f(\tilde{A},\tilde{B}) = |p_{\tilde{A}} - p_{\tilde{B}}|$$

where $p_A$ and $p_B$ are the centroid of the membership functions of $\tilde{A}$ and $\tilde{B}$, respectively. Then we consider the problem of Generalized Modus Ponens(GMP)[8] with multiple implicants:

Implicants:

$R_1$: IF ($x_1$ is $\tilde{A}_{11}$) and $\cdot\cdot$ ($x_m$ is $\tilde{A}_{1m}$) THEN (Y is $\tilde{O}_1$)

$R_2$: IF ($x_1$ is $\tilde{A}_{21}$) and $\cdot\cdot$ ($x_m$ is $\tilde{A}_{2m}$) THEN (Y is $\tilde{O}_2$)

$\cdots$

$\cdots$

$R_n$: IF ($x_1$ is $\tilde{A}_{n1}$) and $\cdot\cdot$ ($x_m$ is $\tilde{A}_{nm}$) THEN (Y is $\tilde{O}_n$)

Observation: $x_1$ is $u_1$, $x_2$ is $u_2$, $\cdots$ $x_m$ is $u_m$

---

Conclusion: Y is $\tilde{C}_f$

where $x_1 \sim x_m$ are m inputs and $\tilde{A}_{i1} \sim \tilde{A}_{im}$ are fuzzy sets for antecedent linguistic terms such as *big, small* or *any* used in the i-th rule. As is often the case in conflicting rules, if the i-th rule does not refer to the condition of $x_j$, we consider $\tilde{A}_{ij}$ as the fuzzy set *any* whose membership function $\mu_{any}(x)$ is constant unity for all x in the universe of discourse. The fuzzy sets $\tilde{O}_1 \sim \tilde{O}_n$ represent the consequent linguistic terms.

The problem is to find the centroid of the conclusion fuzzy set $\tilde{C}_f$ when the rules are given as the above and the inputs of FLC $x_1 \sim x_m$ are given as $u_1 \sim u_m$, respectively. we define compatibility of the i-th rule as

$$W_i = \min\{\mu_{\tilde{A}_{i1}}(u_1), \mu_{\tilde{A}_{i2}}(u_2), \cdots \mu_{\tilde{A}_{im}}(u_m)\} \quad \text{for} \quad i = 1, 2, \cdots, n.$$

We define the conclusion Y of the above GMP as the fuzzy set $\tilde{C}_f$ minimizing

$$J = \sum_{i=1}^{n} W_i \cdot M_c(\tilde{O}_i) \cdot \rho_f^2(\tilde{O}_i, \tilde{C}_f)$$

where n is the number of rules.

By a simple calculation, the centroid of the final conclusion $\tilde{C}_f$ can be written as

$$p_{\tilde{C}_f} = \sum_{i=1}^{n} p_{\tilde{O}_i} \cdot W_i \cdot M_c(\tilde{O}_i) \,/\, \sum_{i=1}^{n} W_i \cdot M_c(\tilde{O}_i) \qquad (1)$$

Therefore, the final conclusion $\tilde{C}_f$ is the fuzzy set whose centroid is given by the above. The output value of the FLC is the centroid of the $\tilde{C}_f$.

## IV. Experimental Results

The proposed scheme is applied to the model roof crane system. The response without an initial swing is shown in Figure 6. The figure shows the fuzzy control regulates both the swing and the position at the arrival. The results for the case of the initial swing is shown in Figure 7. Due to the initial swing, the oscillation occurs when the trolley reaches its maximum velocity. However, the swing does not occur at the arrival position because the FLC eliminates the swing. Moreover, in spite of the anti-swing operation changing the velocity profile, the trolley can reache its final position by the operation of the rules for positioning.

## VI. Conclusion

We proposed the controller for the roof crane using the optimal velocity profile generator and the FLC with the inference method suitable for conflicting rules.

The previous works[3] could not compensate for the deviation of the position caused by the anti-swing operation because rules become too complicated if we make rules in consideration of the regulation of both the swing and the position. To solve the difficulty, we obtained rules in such a manner that we used all the rules available even if the rules seemed conflicting and we proposed the inference method suitable for such conflicting rules.

The proposed controller performed fast transportation by the operation of the optimal velocity generator and also compensated for both the swing of the load and the deviation of the position successfully by the operation of the FLC. The experimental results showed that the hybrid controller was effectively applicable to the automation of a roof crane.

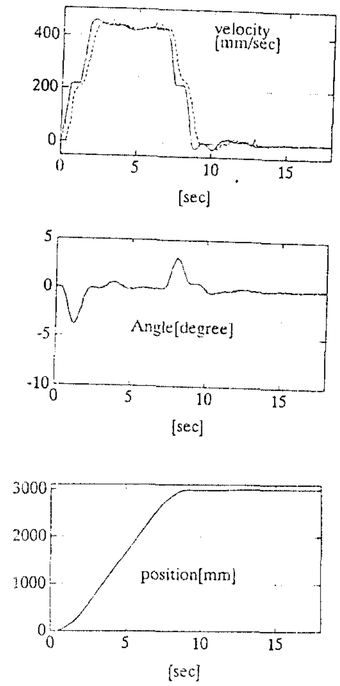


Fig.6. Experimental result : without initial swing.

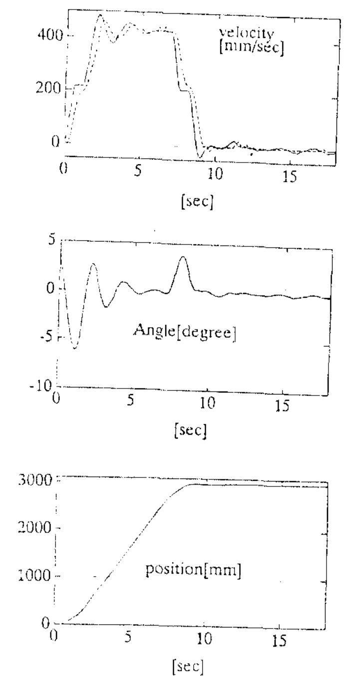


Fig.7. Experimental result : with initial swing.

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