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Invited Paper

EVALUATION OF AN AUTOMATIC CONTAINER CRANE OPERATION SYSTEM BASED ON PREDICTIVE FUZZY CONTROL*

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Abstract. This paper presents an application of the predictive fuzzy controller to an automatic container crane operation (ACO) system. This predictive fuzzy controller, which uses rules derived from skilled human operator experiences, selects the most likely control command based on the control result prediction and on the direct evaluation to achieve the control objectives efficiently and effectively.

The proposed fuzzy controller is applied to the ACO system for controlling container cranes with a focus on four principal performance characteristics: the evaluation of safety, stop-gap accuracy, minimum container sway and carrying time. Results of a field experiment using an 18-m-high, half-scale container crane confirm that the crane can be controlled to the same degree as is possible with a skilled operator.

Key Words—Fuzzy set theory, fuzzy control, container crane, automatic crane operation, predictive control.

1. Introduction

In recent years, in line with hardware technology developments such as microcomputers, computer control rather than human operators is being widely used in plants, transportation systems, and so on.

Fuzzy logic control aims at using a fuzzy set, which allows objects to have membership grades of from 0 to 1. Additionally, it is useful for defining the subjective ambiguity of people, and for incorporating human intellectual action into control programs (Zadeh, 1973; Mamdani, 1974). A state evaluate fuzzy controller, which evaluates the system states and decides on a control command, was proposed by Mamdani (1974), and this has been applied to plants, traffic junctions, cement kilns (Holmblad and Ostergaard, 1982), water treatment facilities, and so on.

The authors propose a predictive fuzzy controller which predicts the result and selects the most likely control rule drived from skilled human operator experiences (Yasunobu, Miyamoto and Ihara, 1983). This controller is currently being applied to the automatic train operation system of an actual subway (Yasunobu and Miyamoto, 1985).

Container cranes for handling the cargoes between ships and wharves (Fig. 1) must be operated efficiently and smoothly so as to meet the increasing size and speed of container ships as well as the growing volume of containerized

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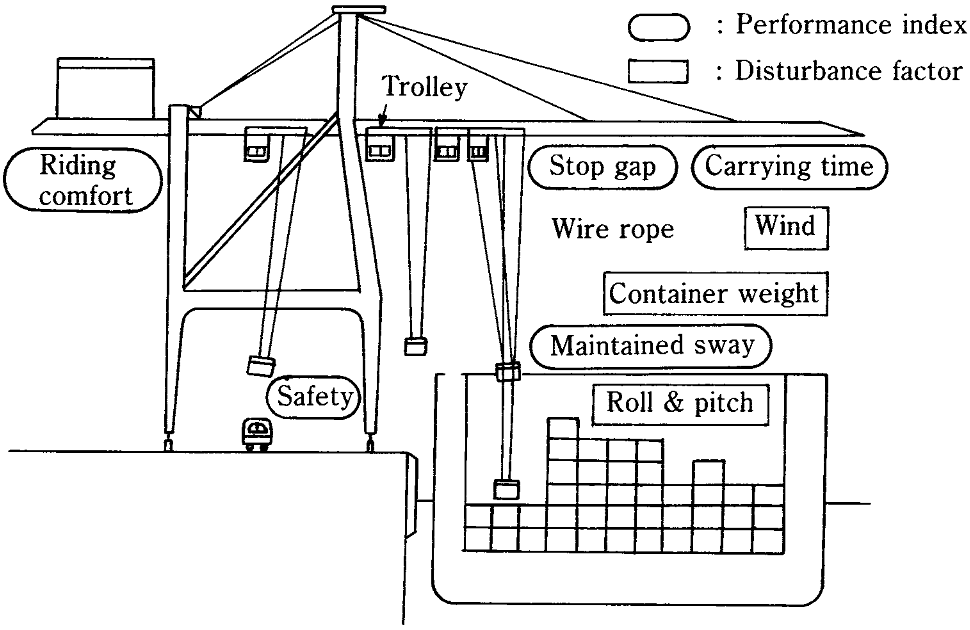


Fig. 1. Container crane operation system.

transportation (Nabeshima, Kiryu and Araki, 1978). At present, most cranes are still operated by skilled human operators. Therefore, an automatic container crane operation (ACO) system is in strong demand. One conventional method proposed is the incorporation of linearized control algorithm with target velocity patterns of the trolley and wire rope on the crane (Sakawa and Shindo, 1982). However, since it is very hard to realize exactly the control of position and sway of a container by using only trolley velocity control, the crane control itself is, in practice, extremely difficult. Such conventional feed-back control methods as the proportional-integral-differential (PID) control and the optimum control using target trolley and wire rope velocity patterns are quite easily disturbed by such factors as wind, time lags of the trolley drive and hoist motors.

This paper explains the predictive fuzzy controller and the ACO controller developed based on the previously reported controller. This controller can realize the level of skilled human operator control by effectively evaluating safety, stop-gap accuracy, minimum container sway and carrying time. Field tests using an experimental 18-m-high, half-scale crane have been conducted to assess the efficiency of the developed controller with that of human crane operation.

2. Predictive fuzzy controller

A skilled human operator has acquired extensive experience through system operation over a long period of time. Furthermore, the operator can achieve a high quality control level satisfying the system objectives.

In order to incorporate this acquired experience into the computer, a predictive fuzzy controller has recently been proposed which decides on the control action, u^*, from an evaluation of the control objectives through control actions (Yasunobu, Miyamoto and Ihara, 1983). In the proposed method,

(i) the control rules $R(R_1, R_2, \cdots, R_n)$ are described as "R_i: if (u is $C_i \rightarrow x$ is A_i and y is B_i), then u is C_i",

(ii) the control rule, R_j, is selected from the predictive results (x, y) indicating the highest likelihood, and

(iii) the control command, C_j, is decided as the controller output.

As one typical example of a train operation rule, "when the control notch is not changed, if the train stops in the predetermined allowance zone, then the controller does not change its notch condition." Figure 2 illustrates this control sequence graphically.

The algorithm of the predictive fuzzy controller is as follows; A fuzzy set, A, on a universe of discourse, U, is characterized by a membership function, μ_A: $U \rightarrow [0,1]$, which associates each element, x, with U with a number, $\mu_A(x)$, in the interval $[0,1]$. A fuzzy set, A, is considered to be the union of its consistent singletons. On this basis, A may be represented in the form of

$$A = \int_U \mu_A(x)/x,$$

where the integral sign means the union of the fuzzy singletons, $\mu_A(x)/x$.

With the predictive fuzzy controller, a control command value is limited to a discrete number, u ($u = c_1, c_2, \cdots, c_n$), and x and y are assumed to be performance indices for control. Evaluations of x and y, for example, "good" or "bad", are defined by fuzzy sets which are characterized by membership functions, $\mu_{A_i}(x)$ and $\mu_{B_i}(y)$. The fuzzy controller periodically evaluates the efficiency of linguistic control rules such as "if the performance index, x, is A_i and index, y, is B_i, when a control command, u, is decided to be C_i at the present time, then this control rule is selected and the control command, C_i, is decided to be the controller output." This linguistic control rule is formulated as

$$R_i\text{: "if } u \text{ is } C_i \rightarrow x \text{ is } A_i \text{ and } y \text{ is } B_i, \text{ then } u \text{ is } C_i."$$

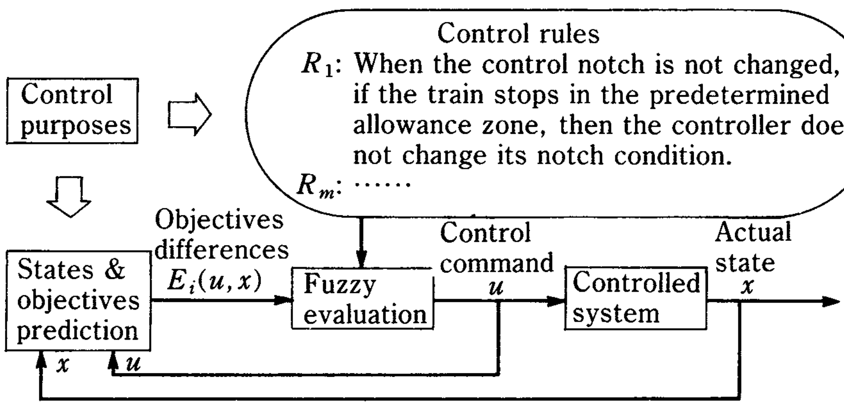


Fig. 2. Predictive fuzzy control sequence.

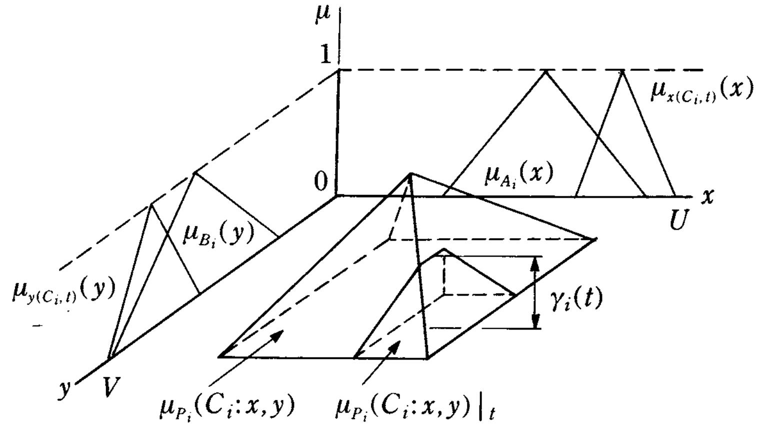


Fig. 3. Evaluation of a fuzzy control rule.

The relation between x and y of the R_i "if" part is defined by the membership function, $\mu_{P_i}(C_i:x,y)$, which is shown by the pyramid in Fig. 3. When u is C_i at the present time, t, the fuzzy sets of performance indices, $X(C_i, t)$ and $Y(C_i, t)$ are predicted by a sub-model of the control system. Therefore, the validity of the control rule derived from the skilled operator experiments is given by

$$P_i\,|_t = (A_i \cap X(C_i, t)) \times (B_i \cap Y(C_i, t)),$$

with its value being

$$r_i(t) = \sup_{x,y \in U \times V} \mu_{P_i}(C_i:x,y)\,|_t.$$

In this way, each control rule is evaluated and the best control rule is selected.

The application process of the fuzzy logic controller involves four steps:

Step 1: Describe human operator strategies for the control system operation;

Step 2: Define the meaning of linguistic performance indices;

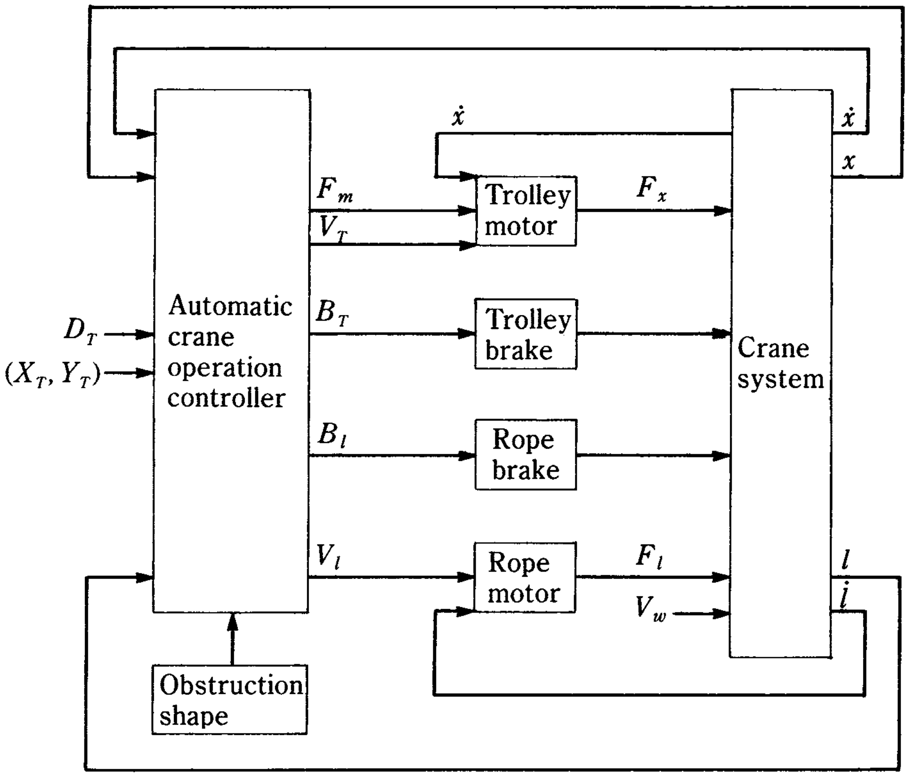
Step 3: Define the models for predicting operation results;

Step 4: Convert the linguistic human operator strategies into the predictive fuzzy control rules.

3. Outline of container crane operation

Recently, almost all container cranes are still operated by skilled human operators. The operations themselves are divided into two simultaneous functions. One is the trolley operation, which commands the trolley target velocity, and moves and stops the trolley at the pre-determined position. The other is the wire rope operation, which commands the container hoisting or lowering target velocity, and regulates the rope length.

As mentioned earlier, the purpose of this paper is to report on an ACO system which realizes crane operation similar to that of a skilled human. As



D_T: Departure signal
F_m: Maximum traction force
V_T: Target velocity of trolley
V_l: Target velocity of rope system
F_x: Tractive force
x: Trolley position
$\dot{x}$: Trolley velocity
(X_T, Y_T): Target position and height
V_w: Window speed
B_T: Brake command of trolley
B_l: Brake command of rope system
F_l: Hoisting force
l: Rope length
$\dot{l}$: Rope velocity

Fig. 4. Block diagram of the automatic crane operation system.

shown in Fig. 1, human experts operate cranes by evaluating various performance indices, such as safety, stop gap, maintained sway and carrying time. Factors affecting operations are the wind, cargo weight, the tide, and so on. Figure 4 shows a block diagram of an ACO system example.

4. Human crane operator strategies

As the first step in applying the fuzzy logic controller to crane operation, actual operations performed by skilled operators coupled with their accumulated knowledge must be studied. Human container crane operation strategies are described below.

4.1 Operation parameter and container course decisions Before carrying a cargo from the start point to the target point, the operator must know the obstruction sections and their heights (danger zone) along the way which the cargo must cross safely, based on the ship body structure and on the state of containers piled on the deck. Such operation parameters as the maximum trolley speed are decided from the traveling distance and the cargo weight.

4.2 Trolley and wire rope operations

4.2.1 Trolley operation Trolley movement is divided into the seven domains of start P_0, acceleration P_1, constant speed control P_2, deceleration P_3, stop P_4, correcting (inching) P_5, and lowering P_6. Furthermore, the operation is divided into two function levels. One is the decision level, in which the present domain of the trolley operation is decided. The other is the activation level, in which the target trolley velocity and the acceleration force are commanded.

(1) Trolley decision level

The timing for switching the domain is affected by the initial sway, the wind and the rope length, which are operated independent of the trolley. These timing changes are given as follows;

(T-1) In the start domain, when the acceleration control is started by an operator under conditions of the present rope length and trolley position, if the trolley is accelerated to a maximum speed in terms of safety and a small maintained sway, then the acceleration control is started. ($P_0 \rightarrow P_1$)

(T-2) When the acceleration control terminates and the trolley speed arrives at the maximum speed, then the operation domain is shifted to the constant speed control domain. ($P_1 \rightarrow P_2$)

(T-3) In the constant speed control domain, when the deceleration control is started by an operator under these trolley speed, trolley position and rope length conditions, if the trolley is stopped beyond the target position at the small maintained sway, then the deceleration control is started. ($P_2 \rightarrow P_3$)

(T-4) When the deceleration control is ended by an operator and the trolley speed arrives at the small speed, then the operation domain is shifted to the stop domain. ($P_3 \rightarrow P_4$ and $P_5 \rightarrow P_4$)

(T-5) After a few seconds in the stop domain, if the trolley stops and the stop gap between the trolley and target position is large, then correction control is started. ($P_4 \rightarrow P_5$)

(T-6) After a few seconds in the stop domain, if the trolley stops near the target position, then lowering control is started. ($P_4 \rightarrow P_6$)

(2) Trolley activation level

The practice function is determined by the trolley decision level mentioned above. At this level, each domain is practiced as follows;

(C-1) In the start domain (P_0), the trolley speed is held at zero.

(C-2) In the acceleration domain (P_1), the method of acceleration control determined at the last start domain (P_0) is performed.

(C-3) In the constant speed control domain (P_2), the trolley speed is held at the maximum trolley speed.

(C-4) In the deceleration domain (P_3), the method of deceleration control determined at the last constant speed control domain (P_2) is performed.

(C-5) In the stop domain (P_4), the trolley speed is held at zero.

(C-6) In the correcting domain (P_5), the trolley is moved toward the target position.

(C-7) In the lowering domain (P_6), the trolley speed is held at zero.

4.2.2 Wire rope operation The wire rope operation is also divided into two function levels. One is the decision level, in which the target rope length is decided. The other is the activation level, in which the target rope velocity is commanded.

(1) Rope decision level

At this level, the hoisting or lowering of cargo is determined by the cargo (trolley) position:

(R-1) Before reaching a danger zone, the cargo is hoisted to a safe rope length which permits the cargo to pass overhead.
(R-2) In the danger zone, the rope length is held at the safe rope length.
(R-3) After passing over the danger zone, the cargo is lowered to a target rope length which is determined by the final target rope length and subsequent obstruction height.
(R-4) The cargo is stopped near the target point and is lowered to the final target height.

(2) Rope activation level

At this level, the target rope velocity is commanded by the present rope length and the determined target rope length, taking the hoist motor capability into consideration.

5. Automatic crane operation system by predictive fuzzy control

5.1 Fuzzy performance index sets In the second applicational step of the fuzzy logic controller, the meaning of linguistic performance indices has to be defined. From the above-mentioned experience rule, such fuzzy performance index sets as (1) safety, (2) stop gap, (3) maintained sway, and (4) carrying time are defined. (Fig. 5)

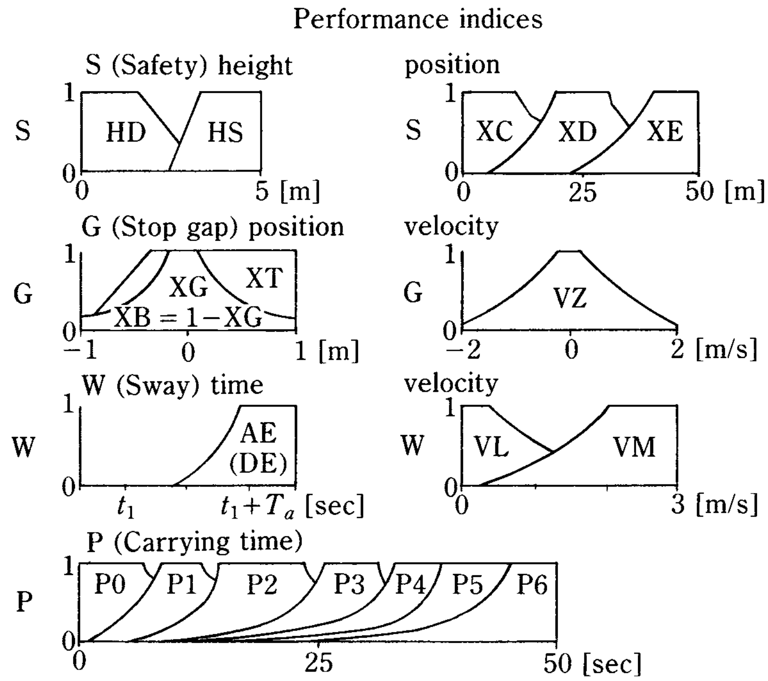


Fig. 5. Membership function of automatic crane operation system.

(1) Safety performance indices (S)

Safety is determined by the height clearances between the cargo trajectory and the body of the ship or the piled containers, and the trolley position. The height clearance is calculated by a predictive model which will be defined later. The safety performance indices (S) are

(a) Height danger (HD), (b) Height safe (HS),
(c) Danger zone (XD), (d) Hoisting zone (XC),
(e) Lowering zone (XE).

(2) Stop-gap performance indices (G)

Stop-gap accuracy is evaluated by the difference between the predicted stop position and the target stop position. Judging of the trolley speed is also important for determining the stop-gap. The stop-gap performance indices are

(a) Beyond-target position (XT), (b) Good stop (XG),
(c) Bad stop (XB), (d) Zero trolley speed (VZ).

(3) Maintained sway performance indices (W)

By accelerating or decelerating between characteristic cycle times determined by the rope length, trolley mass and cargo mass, acceleration or deceleration of a non-swaying load is possible. The acceleration and deceleration and times are ascertained along with the trolley speed. The sway performance indices (W) are

(a) Acceleration end (AE), (b) Deceleration end (DE),
(c) High trolley speed (VM), (d) Low trolley speed (VL).

(4) Carrying time performance indices (P)

The domain presently in action is determined by the departure signal time. The carrying time performance indices (P) are

(a) Start (P0), (b) Acceleration (P1),
(c) Constant speed control (P2), (d) Deceleration (P3),
(e) Stop (P4), (f) Correcting (P5),
(g) Lowering (P6), (h) Before lowering (<P6).

5.2 Predictive model Predictive models for predicting results for index evaluation are defined in the third step. These models enable us to predict (1) the height clearance and (2) stop position.

(1) Height clearance

The height clearance between the trajectory and the ship's body or piled containers is calculated by the acceleration-influenced cargo trajectory which is dependent on both the present trolley position and rope length.

(2) Predicted stop position

The predicted stop position (X_p) is calculated by

$$X_p = X+(V_t T_d)/2,$$

where X is the trolley position, V_t is the trolley velocity and T_d is the deceleration time interval.

5.3 Fuzzy control rules In the final step, the rules of operational experience mentioned previously are converted into fuzzy control rules.

5.3.1 Trolley operation

(1) Trolley fuzzy decision rules

Each phrase of the "experience rule" (T-3) is rewritten as follows;

- In the constant speed control domain $\rightarrow$ P is P2.
- The deceleration control is started by an operator $\rightarrow$ t_3 is t and $t_4 = t + T_d$.
- The trolley is stopped by an operator beyond the target position respectively $\rightarrow$ G is XT.
- In the small maintained sway $\rightarrow$ $F_d = F_m$,

where t_3, t_4 are the start and end times of the deceleration control P_3, t is the present time, F_d is the deceleration force, and F_m is a deceleration or acceleration force of a non-swaying load.

These phrases can be summarized as follows;

(T-3) If P is P2 and ($t_3 = t$ and $t_4 = t + T_d$ and $F_d = F_m \rightarrow$ G is XT), then $t_3 = t$ and $t_4 = t + T_d$ and $F_d = F_m$. The other rules are converted as follows;

(T-1) If P is P0 and ($t_1 = t$ and $t_2 = t + T_a$ and $F_a = F_m \rightarrow$ S is HS), then $t_1 = t$ and $t_2 = t + T_d$ and $F_a = F_m$,

(T-2) If P is P2 and W is AE and W is VM, then $t_2 = t$,

(T-4) If P is P4 and W is DE and W is VL, then $t_4 = t$ and $t_5 = t + 3.0$,

(T-5) If P is P5 and G is VZ and G is XB, then $t_5 = t$,

(T-6) If P is P5 and G is VZ and G is XG, then $t_6 = t$,

where t_1, t_2 are the start and end times of the acceleration control P1, respectively, T_a is the acceleration time interval, F_a is the acceleration force, t_5 is the start time of the correcting control P5, and t_6 is the start time of the lowering control P6.

(2) Trolley fuzzy activation rules

(C-1) If P is P0, then $V_T = 0$,
(C-2) If P is P1, then $V_T = 2V$ and $F = F_a$,
(C-3) If P is P2, then $V_T = V$,
(C-4) If P is P3, then $V_T = -V$ and $F = F_d$,
(C-5) If P is P4, then $V_T = 0$,
(C-6) If P is P5, then $V_T = X_T - X$,
(C-7) If P is P6, then $V_T = 0$,

where V_T is the target trolley velocity, V is the maximum trolley velocity, F is the trolley motor force and X_T is the horizontal target position.

5.3.2 Rope operation

(1) Rope fuzzy decision rules

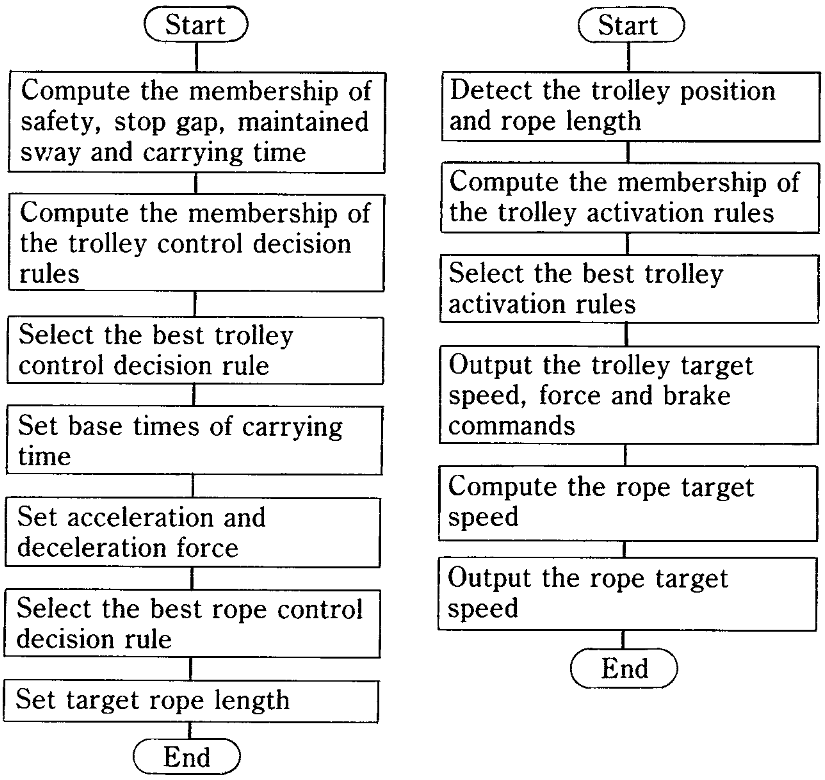
(R-1) If S is XC and P is $<$P6, then $h = L_s$,
(R-2) If S is XD and P is $<$P6, then $h = L_s$,
(R-3) If S is XE and P is $<$P6, then $h = L_n$,
(R-4) If P is P6, then $h = L_b$,

where h is the target rope length, L_s is the minimum rope length, L_n is the safety rope length between X and X_T, and L_b is the target (final) rope length.

(2) Rope activation rules

The target rope velocity is regulated by proportional control, based on target and actual rope length references.

5.4 Realization of fuzzy ACO controller The computation flow charts for realizing the fuzzy controlled ACO with a 16-bit microcomputer (HD68000) are shown in Fig. 6. In the ACO system, the decision level phase is executed at every 100 [ms] following a depart signal, and the activation level phase is executed at every 10 [ms].



(a) Decision level (b) Activation level

Fig. 6. Flow charts of fuzzy-controlled ACO algorithm.

6. Field test of half-scale crane

6.1 Test crane, conditions, and simulation comparison A field test was performed by using an actual crane, as shown in Fig. 7. The crane has a height of 17.8 [m], a span of 50 [m] and is about half the scale of an actual container crane. The specifications are summarized in Table 1. Figure 8 shows the computer

Table 1. Specification of half-scale container crane model

Crane height	:	17.8 [m]
Maximum trolley velocity	:	1.25 [m/s]
Maximum rope velocity	:	0.3 [m/s]
Trolley mass	:	7500 [kg]
Load mass	:	6450 [kg]

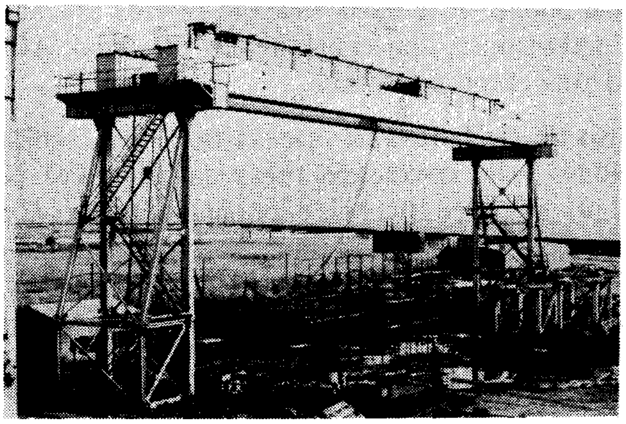


Fig. 7. The half-scale experimental container crane model.

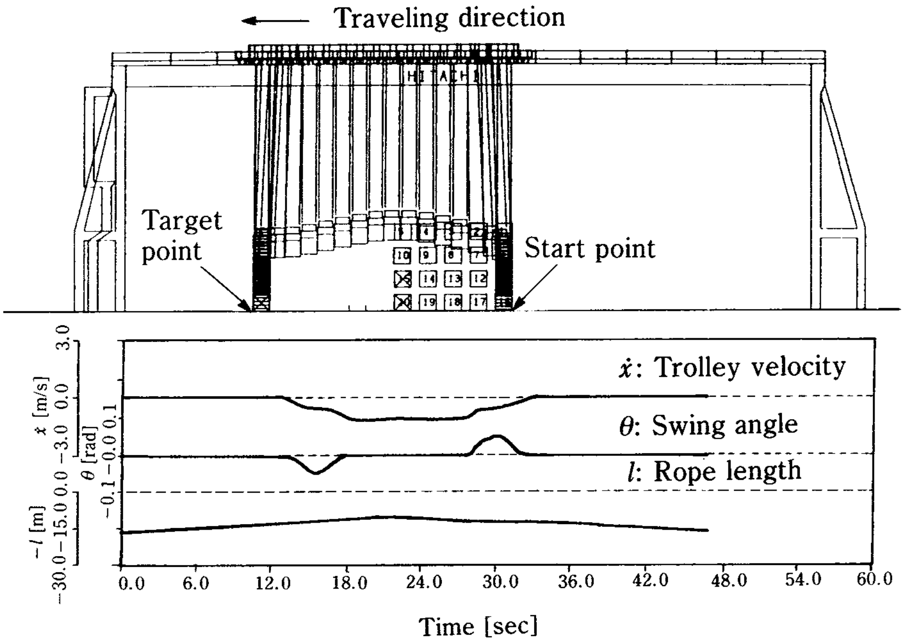


Fig. 8. Field test condition and simulation results of fuzzy control.

simulation results with this field test condition, in which a container (6.45 [ton]) travels 15 [m] across obstructions 5 [m] high.

Figure 9 shows the trolley velocity and the armature current of the field test operation mentioned above. It is clear that the results are almost the same as the simulations. Furthermore, the capability of the fuzzy ACO algorithm was confirmed by the actual crane operation.

6.2 Comparison to skilled human operation To confirm the test crane accuracy and reliability, the developed fuzzy control ACO (Fuzzy-ACO) was compared with results obtained by skilled human operation. Figure 10 summarizes the field test results for carrying time, stop gap and maintained sway for fuzzy control and human operation. Twenty field trials were averaged for each. With respect to carrying time, the Fuzzy-ACO is capable of carrying a cargo at a constant optimum time (the mean is 47 [sec]). In terms of stop-gap accuracy, the Fuzzy-ACO demonstrates the ability to stop the trolley about one third of the distance compared with human operation. Regarding maintained sway, the Fuzzy-ACO proves capable of stopping container sway in about half of the total sway.

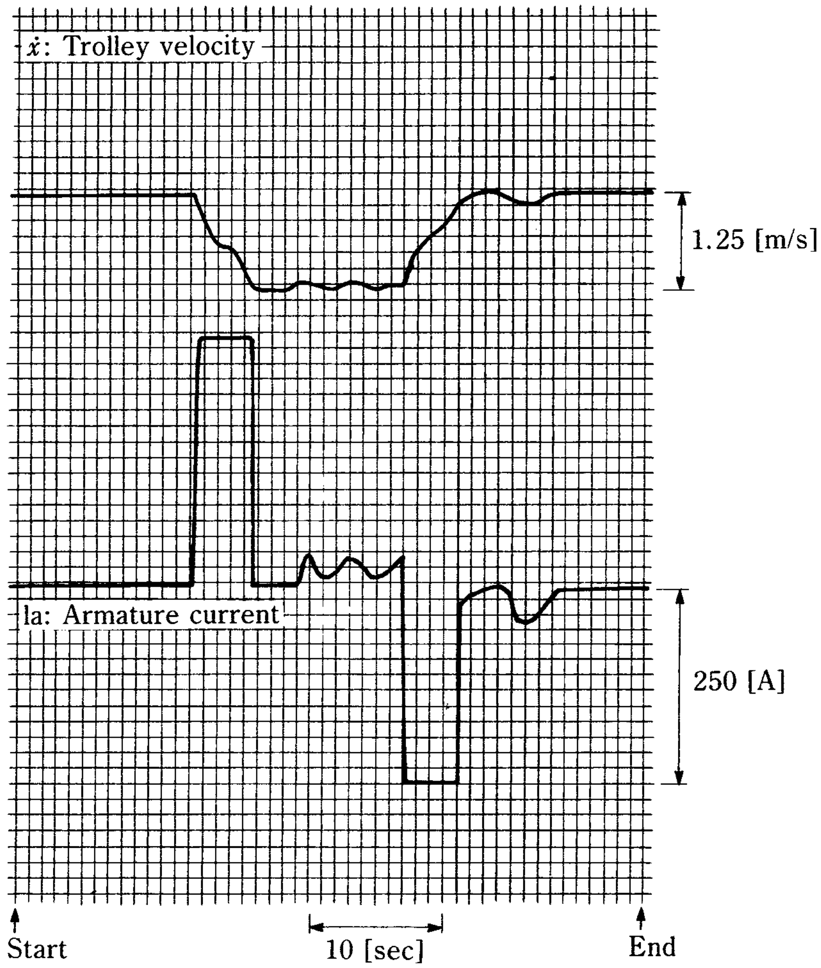


Fig. 9. Field test results.

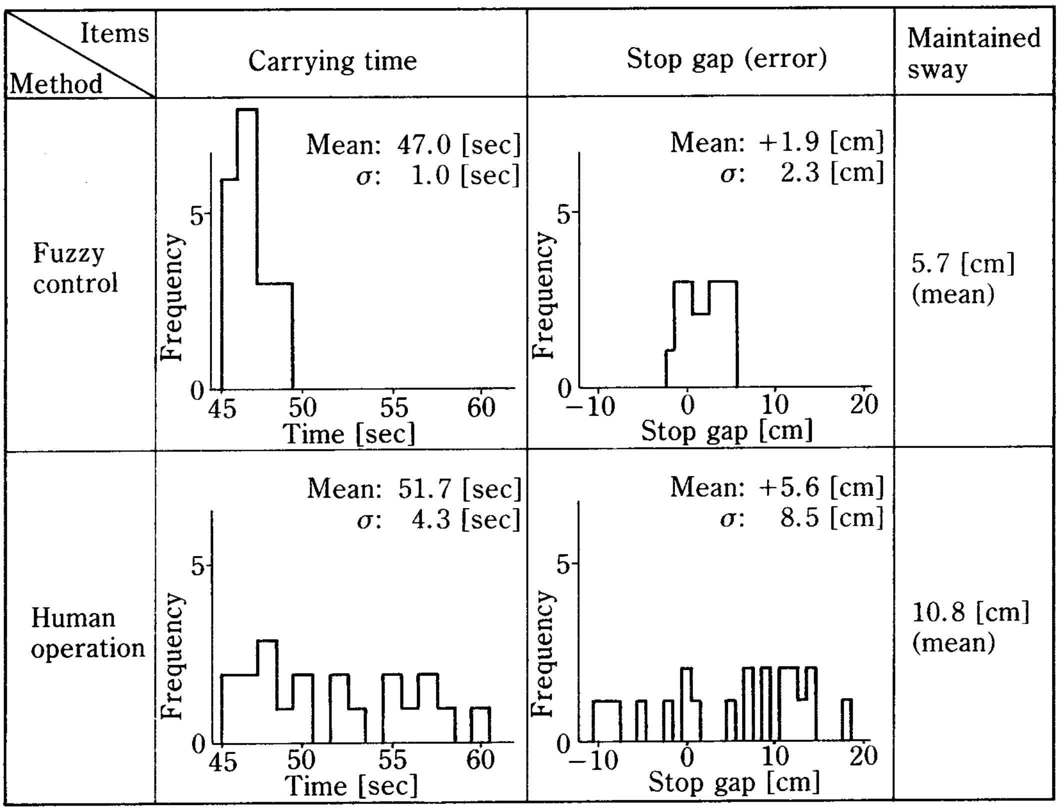


Fig. 10. Summary of field test results.

To summarize the field test results, the human operator is capable of transporting the cargo in an optimum time of 45 [sec], and can stop accurately with no sway. However, the carrying time, stop gap and maintained sway increase greatly, when the timing is missed. With Fuzzy-ACO operation, on the other hand, the controller fully demonstrates its capability of operating the crane as skillfully as any human operator.

7. Conclusions

A predictive fuzzy controller was developed and has been applied to automatic container crane operation (ACO). The proposed Fuzzy-ACO controller was installed in a microcomputer, and field tests were performed by using a half-scale experimental container crane. The field tests indicate two principal results. First, the Fuzzy-ACO controller is fully capable of operating a crane as safely, accurately and skillfully as a skilled human operator. Second, by using the Fuzzy-ACO controller, even an unskilled operator can handle a crane as efficiently as a skillful operator.

Current experiments clearly indicate that the Fuzzy-ACO controller is also being effective, applied to actual automatic container crane operation.

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References

Holmblad, L.P. and J.J. Ostergaard (1982). Control of a cement kiln by fuzzy logic. ed. by M.M. Gupta and E. Sancez. *Fuzzy Information and Decision Processes*, North-Holland, Amsterdum, 389–399.

Mamdani, E.A. (1974). Application of fuzzy algorithms for control of simple dynamic plant. *Proc. IEE*, **121**, 12, 1585–1588.

Nabeshima, Y., T. Kiryu and M. Araki (1978). Hitachi automated container terminal system. *Hitachi Review*, **27**, 6, 295–300.

Sakawa, Y. and Y. Shindo (1982). Optimal control of container crane. *Automatica*, **18**, 3, 257–266.

Yasunobu, S., S. Miyamoto and H. Ihara (1983). Fuzzy control for automatic train operation system. *Proc. of the 4th IFAC/IFIP/IFORS Int. Conf. on Transportation Systems*, Baden-Baden, 39–45.

Yasunobu, S. and S. Miyamoto (1985). Automatic train operation system by predictive fuzzy control. ed. by M. Sugeno, *Industrial Applications of Fuzzy Control*, North-Holland, Amsterdum, 1–18.

Zadeh, L.A. (1973). Outline of a new approach to the analysis of complex systems and decision processes. *IEEE Trans., Systems, Man and Cybernetics*, **SMC-3**, 1, 28–44.