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AUTOMATIC TRAIN OPERATION SYSTEM BY PREDICTIVE FUZZY CONTROL

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A predictive fuzzy controller that uses rules based on a skilled human operator's experience has been proposed and applied to Automatic Train Operation (ATO) Systems. The predictive fuzzy controller selects the most likely control command based on a prediction of control results and direct evaluation for the control objectives. The control rules are described as follows; "If (u is C ➛ x is A and y is B) then u is C." The proposed fuzzy controller has been applied to ATO systems which control trains based on the evaluation of safety, riding comfort, traceability of target velocity, accuracy of stop gap, running time and energy consumption.
The simulation results show that the above performance indices of the newly developed Fuzzy ATO are much better than those of conventional PID controlled ATO. Further it is proved by field tests that the Fuzzy ATO can operate trains as skillfully as human experts do.

1. Introduction

In recent years, automatic controllers using a micro-computer instead of a human operator have been developed for plants, transportation systems and so on. In many cases, a computer control gives quick response and accurate control, but inferior quality of control than a skilled human operator. A fuzzy logic[1] control method which can make up an algorithm from control know-how of a skilled human operator by fuzzy sets, is proposed by Mamdani[2] (1973), and applied to a plant[2], a traffic junction[3], a cement kiln[4], a water treatment[5] and so on[6]. By these controllers, operations considering the desired states of a system are difficult.

To solve this problem, we have proposed a predictive fuzzy controller which predicts the result of each candidate control command and selects the most likely control rule based on a skilled human operator's experience. The predictive fuzzy controller is applied to automatic train operation systems, which are referred to as ATO, by which a train can be started, kept to a limited speed and stopped at a target position of a station.[7,8]

ATOs have been applied to develop new transit systems including subway[9], monorail and new public transit systems like PRT.[10,11] In these systems, trains are controlled by a conventional feedback control method such as a PID control. Therefore, it does not take important performance indices for a train operation such as, safety, riding comfort of passengers, accuracy of the stop gap and energy consumption into consideration.

In this paper, the predictive fuzzy control method and an ATO controller developed based on this method are explained. This controller can realize a skilled human operator's control by evaluating safety, riding comfort, traceability of target velocity, energy saving , running time and the accuracy of a stop gap. By computer simulations, the developed fuzzy ATO controller is compared with the conventional PID ATO controller.

2. Conventional Control and Fuzzy Control

2.1 Conventional control and its bounds

An outline of designs for computer control systems is as follows.

(1) Analysis of an actual system
(2) Decisions of a linearized system model, a desired state and an error criterion function
(3) Syntheses of a controller structure and the controller's parameters

In the above-mentioned design, the control parameters are easy decided by a computer aided design system using a criterion function. But it is difficult to define such a function that sufficiently covers the system's purposes.

The conventional controller is able to give accurate control for systems which are matched to the linearized system models and/or the desired state are constant. However, this method cannot provide adequate control for systems which have time-varying parameters, unknown structures and multi-objects for the control. So, the controller is designed using a complex structured algorithm with the designer's knowledge. But re-constructions of the controller, according to the alternation of a sub-system or change of the system structure, devote a designer's effort every time. Fig.1 illustrates graphically the control sequence.

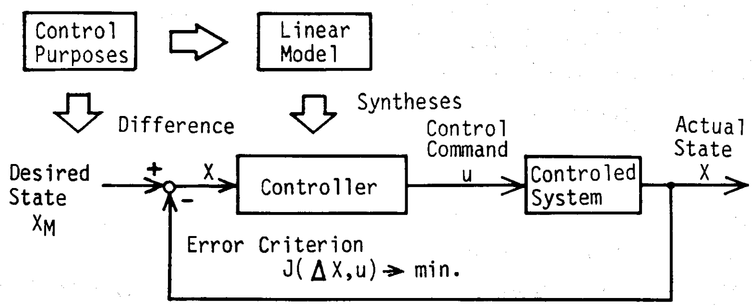


Fig.1 Conventional control sequence

2.2 Application of fuzzy logic to control

2.2.1 States evaluate fuzzy control

The fuzzy control applied to a cement kiln by Holmblad(1982)[4] decides a control action u^* from the set of control rules Ri, which is described as "If x is Ai and Bi, then u is Ui". This fuzzy control evaluates the system state, which is described as "if part: X is A and Y is B", and decides u^* from these values. "If the temperature is high and the pressure is slightly high, then the fuel is decrease." is a typical example of process control rules. Fig.2 illustrates graphically the control sequence.

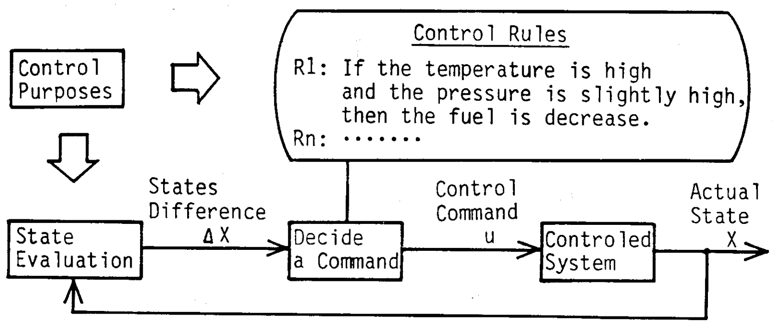


Fig.2 States evaluate Fuzzy control sequence

2.2.2 Predictive (objects evaluation) fuzzy control

A skilled human operator has extensive experience through many experiments with the system's operation. And he can perform high-quality control satisfying the system objectives. However, the above-mentioned fuzzy control cannot evaluate the system objectives.

In order to overcome this problem the predictive fuzzy controller which decides a control action u^* from the objects evaluation of the control results by the control actions has been proposed. In the proposed method,

(i) the control rules **R**(R1,R2···Rn) is described as "Ri: If(u is Ci → x is Ai and y is Bi) then u is Ci",

(ii) the control rule Cj is selected from the predictive results(x,y) that show the highest likelihood.

"When the control notch is not changed, if the train stops in the predetermined allowance zone, then the control notch is not changed." is a typical example of train operation rules. Fig.3 illustrates graphically the control sequence.

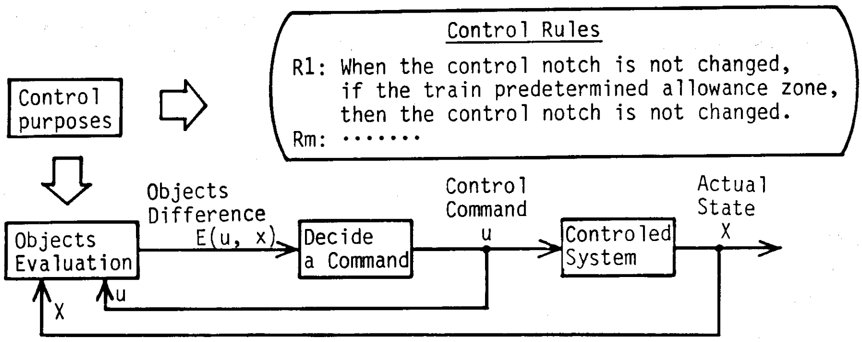


Fig.3 Predictive (objects evaluation) Fuzzy control sequence

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 ϵ(0,1) which associates each element x of U with a number $\mu_A(x)$ in the interval(0,1). A fuzzy set **A** is considered as the union of its constituent singletons. On this basis, **A** may be represented in the form of

$$\mathbf{A} = \int_U \mu A(x)/x$$

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

In the predictive fuzzy controller, a value of control command is limited to a discrete number u (u=c1,c2,..,cn), 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 $\mu Ai(x)$, $\mu Bi(y)$. A fuzzy controller periodically evaluates the efficiency of linguistic control rules such as " If the performance index x is Ai and index y is Bi, when a control command u is decided to be Ci at this time, then this control rule is selected and the control command Ci is decided for output of the controller ". The above linguistic control rule is formulated as follows:

Ri:"If(u is Ci $\rightarrow$ x is Ai and y is Bi) then u is Ci "

The relationship between x and y of Ri's if part is defined by a membership function of $\mu Pi(Ci{:}x,y)$ which is shown as a pyramid of Fig.4.

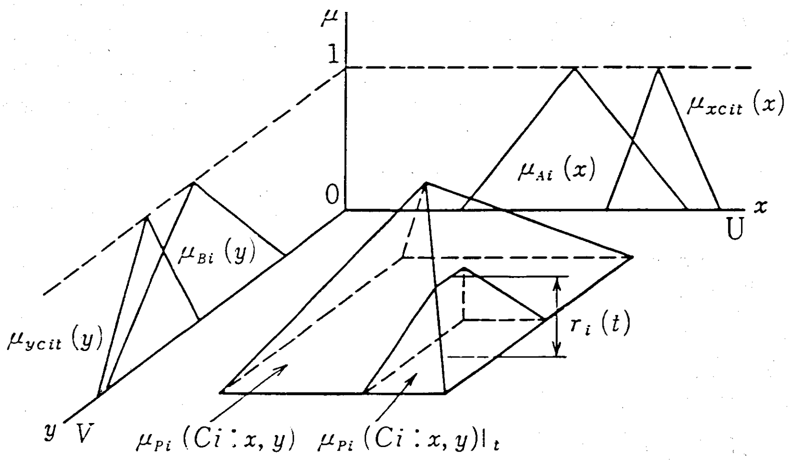


Fig.4 Evaluation of a Fuzzy control rule

When u is Ci at this time t, the fuzzy sets of performance indices X(Ci,t), Y(Ci,t) are predicted by a sub-model of the system. Then, the validity of control rule based on the skilled operator's experiments is given by

$$Pi|t = (Ai \cap X(Ci,t)) \times (Bi \cap Y(Ci,t))$$

and, its value is

$$ri = \sup_{x,y \in U \times V} \mu pi(Ci{:}x,y)|t.$$

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

The process to produce the fuzzy logic controller is as follows.
(step-1) Describe human operator's strategies of the system operation
(step-2) Define the meaning of linguistic performance indices
(step-3) Define models to predict the results of an operation
(step-4) Convert the linguistic human operator's strategies into the predictive fuzzy control rules

3. Automatic Train Operation Control And Modelling

ATO is a sub-system of an automatic train control system(ATC). ATC has two subsystems, namely, ATO and the automatic train protection system(ATP) as shown in Fig.5.

The input data of ATO are distance pulses of a tacho-generator, cab signals of the ATP on-board system, position marker detected signals which show that the train has passed a certain position, and supervisory commands from the automatic train supervision system (ATS). The output data of ATO are powering and braking commands to a traction controller and a brake controller.

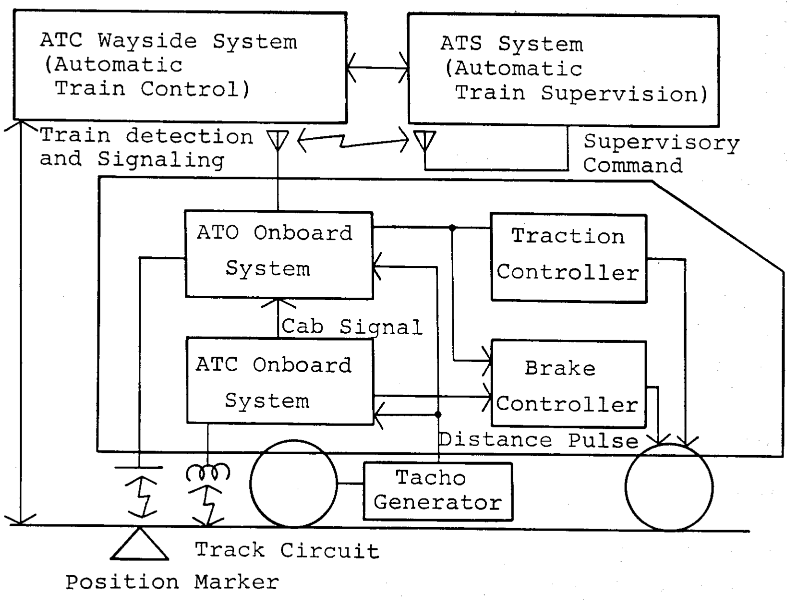


Fig.5 Typical configuration of ATO

A model of the ATO control system is shown in Fig.6. The ATO controller is formulated as follows.

$$\begin{bmatrix} PN(t) \\ BN(t) \end{bmatrix} = A(t,v(t),s(x,t),SPk(t),DT)$$

,where t is time, v is the velocity of train, PN is a power notch (acceleration), BN is a brake notch (deceleration), S is ATP signal, SPk is a point signal of k, and DT is a departure time.

The traction controller and the brake controller are controlled by PN and BN, and these generate the actual power by using those notches.

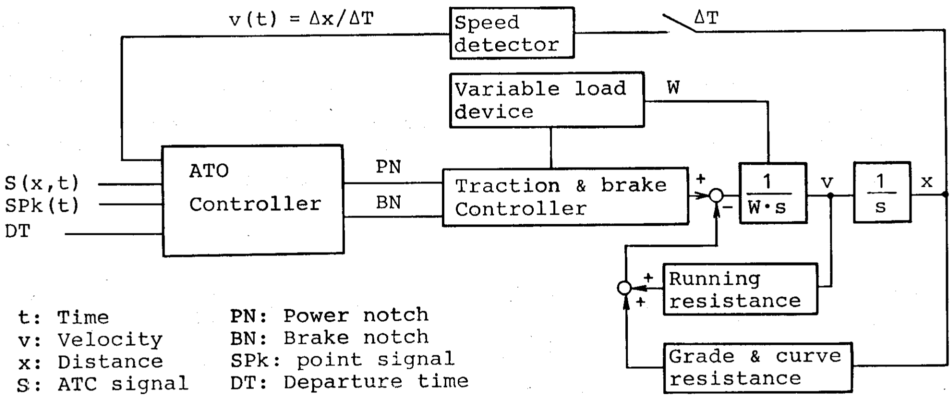


Fig.6 Block diagram of the ATO control system

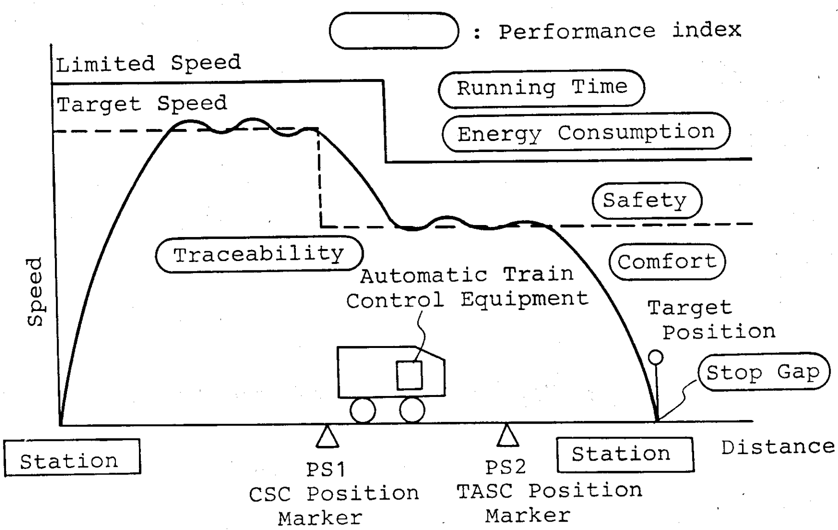


Fig.7 Outline of automatic train operation

4. Human Operator's strategies of Train Operation

The purpose of this paper is to propose an ATO system which realizes train operation similar to a human's operations. As shown in Fig.7, human experts operate trains through evaluating various performance indices such as safety, riding comfort, stop accuracy and so on. The human operator's strategies are divided into two functions. One is the Constant Speed Control (CSC): it starts a train and keeps train speed below the specified one. The other is the Train Automatic Stop Control (TASC) : it regulates a train speed in order to stop the train at a target position of a station. These two functions and a choice of the total control notch are described in the below.

4.1 CSC operation

With the departure command, the operator generates the target speed within the maximum speed limit. If there is a restricted speed track section in front of the train, the target speed is generated at the beginning of this section. In the CSC operation, the control commands are selected by applying experimental control rules in the following way:

(C-1)For safety; if the speed of the train exceeds the speed limit, the maximum brake notch is selected

(C-2)For saving energy; if with coasting the schedule can be kept, coasting is continued.

(C-3)For shortening running time; if the speed is far below the limit, the power notch is selected.

(C-4)For riding comfort; if the train speed is in the predetermined allowance range, the control notch is not changed.

(C-5)For traceability; if the notch is kept constant and the train is about to go out of the allowance range, a $\pm$ n notch is selected so that the target speed way can be traced accurately. In this case, for riding comfort, notch change frequency is considered.

4.2 TASC Operation

An operator starts the TASC operation by detecting the TASC position markers which indicate the distance to the target position of the station. In this control, the control command notch is selected by the following experimental control rules.

(T-1) For riding comfort; when the train is in the TASC zone, and the control notch is not changed, if the train stop predetermined allowance zone, then the control notch is not changed.
(T-2) For minimizing running time and maximizing riding comfort; when the train approaches the TASC zone, the notch is changed from acceleration to a little deceleration by degrees.
(T-3) For the stop gap accuracy; when the train is in the TASC zone, and will not stop within the predetermined allowance zone, a $\pm$ notch is selected so that the train stops accurately at the target position.

4.3 Choice of The Total Control Notch

The traction or brake controller is controlled by the total control notch which is chosen from either the CSC notch or the TASC notch.

5. ATO by Predictive Fuzzy Control

The purpose is to realize an automatic train operation based upon the human operator's experience. Firstly, the fuzzy sets of performance indices such as safety, riding comfort, traceability, energy consump-tion and running time are defined. Secondly, the control rules using these fuzzy sets are described. The symbols which are used below are shown in Table 1.

Table 1 Symbols

t	: time (sec)
$x(t)$	: location of train (m)
$v(t)$	: velocity of train (km/h)
$N(t)$	: control command notch
$X(t)$	: target position of next station (m)
V_t	: target speed (km/h)
T_t	: predicted running time (sec)
X_d	: forward location where the maximum speed limit is lower (m)
t_s	: time to reach X_d point (sec)
X_k	: ending location of coasting (m)
$X_z(v)$	: beginning point of TASC zone (m)
$t_z = (X_z(v)-x(t))/v(t)$	: time to TASC zone (sec)
t_c	: elapsed time from last notch change (sec)
N_c	: degree of last changed notch
N_p	: control command notch to be selected
$V_p(N_p)$	: predicted speed when N_p notch is selected (km/h)
V_e	: velocity allowance range (km/h)
$X_p(N_p)$	: predicted stop position if N_p notch is selected (m)
X_e	: allowance of stop gap (m)

5.1 Fuzzy Sets of Performance Indices

To define the performance indices, the three functions denoted below are used.

$$A(x, a, b) = \begin{cases} b/(a+b-x) & : x < a \\ 1.0 & : a \leqq x \end{cases} \quad (b>0)$$

$$ = \begin{cases} 0.0 & : x < a+2b \\ 1.0+(a-x)/2b & : a+2b \leqq x < a \\ 1.0 & : a \leqq x \end{cases} \quad (b<0)$$

$$B(x, a, b) = A(2a-x, a, b)$$

$$C(x,a_1,b_1,a_2,b_2) = \min.(A(x,a_1,b_1), B(x,a_2,b_2))$$

(1) Safety performance indices (S)

The safety is evaluated by the time for the train to reach to the lower limited speed (danger) zone.

(a) Danger (SD) : μ_{SD}

$$\mu_{SD}(t_S) = B(t_S, 0.0, -T_S)$$

(b) Safe (SS) : μ_{SS}

$$\mu_{SS}(t_S) = A(t_S, -T_S, -T_S)$$

(2) Comfort performance indices (C)

Riding comfort is evaluated by the degree of the last change and the elapsed time from it.

(a) Good comfort (CG) : μ_{CG}

$$\mu_{CG}(t_C, N_C) = A(t_C, N_C, -N_C+C_b)$$

(b) Poor comfort (CB) : μ_{CB}

$$\mu_{CB}(t_C, N_C) = B(t_C, C_b, -N_C+C_b)$$

(3) Energy saving performance indices (E)

Energy saving is evaluated by running time margin.

(a) Energy saved running (ES) : μ_{ES}

$$\mu_{ES} = B(x(t), X_k, -E_x)$$

(b) Not energy saved (consumed) running (EN) : μ_{EN}

$$\mu_{EN} = \mathbf{A}(\ x(t),\ X_k+E_x,\ -E_x)$$

(4) Traceability performance indices (T)

The traceability is evaluated by the difference between the predicted speed and target speed. (Fig.8)

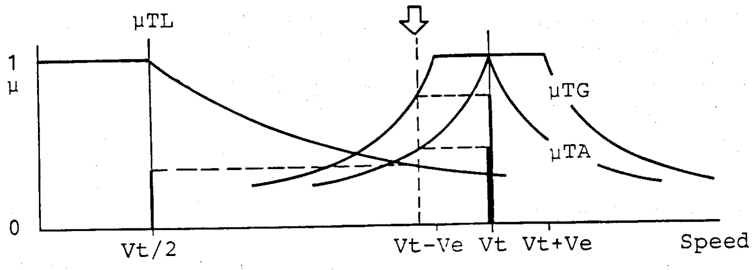


Fig.8 Membership function of the traceability

(a) Good trace (TG) : μ_{TG}

$$\mu_{TG}(V_p(N)) = \mathbf{C}(\ V_p(N),\ V_t-V_e,\ V_e,\ V_t(t)+V_e,\ Ve)$$

(b) Accurate Trace (TA) : μ_{TA}

$$\mu_{TA}(V_p(N)) = \mathbf{C}(\ V_p(N),\ V_t,\ V_e,\ V_t,\ V_e)$$

(c) Low speed (TL) : μ_{TL}

$$\mu_{TL}(V_p(N)) = \mathbf{B}(\ V_p(N),\ V_t/2,\ V_t/4)$$

(5) Running time performance indices (R)

Running time performance is evaluated by a start point for TASC based on the train speed.

(a) In TASC zone (Punctual) (RP) : μ_{RP}

$$\mu_{RP}(t_z) = \mathbf{B}(\ t_z,\ 0.0,\ -R_t)$$

(b) Not in TASC zone (Late) (RF) : μ_{RF}

$$\mu_{RF}(t_z) = \mathbf{A}(\ t_z,\ 2Rt,\ -R_t)$$

(6) Stop gap performance indices (G)

The accuracy of stop gap is evaluated by the difference between the predicted stop position and the target position. (Fig.9)

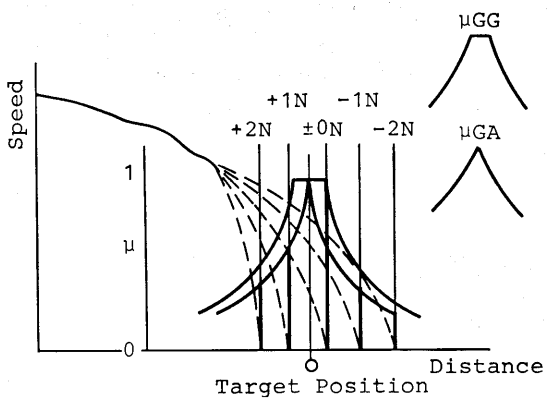


Fig.9 Membership function of the stop accuracy

(a) Good stop (GG) : μ_{GG}

$$\mu_{GG}(X_p(N)) = \mathbf{C}(\ X_p(N),\ X_t - X_e,\ X_e,\ X_t + X_e,\ X_e)$$

(b) Accurate stop (GA) : μ_{GA}

$$\mu_{GA}(X_p(N)) = \mathbf{C}(\ X_p(N),\ X_t,\ X_e,\ X_t,\ X_e)$$

5.2 Predictive Fuzzy Control Rules

The fuzzy control rules have been determined to correspond to the linguistical control rules of human operator's strategies. In the rules, DN is the difference of notches, Pn is the powering notch, and Bn is the braking notch. The maximum members of Pn and Bn are assumed to be 7 and 9.

(1)CSC rules

(C-1)If (N is $(N(t)+B_{max})/2$ → S is SD) Then N is $(N(t)+B_{max})/2$
(C-2)If (N is 0 → S is SS, C is CG and E is ES) Then N is 0
(C-3)If (N is P7 → S is SS, C is CG and T is TL) Then N is P7
(C-4)If (DN is 0 → S is SS and T is TG) Then DN is 0
(C-5)If (DN is n → S is SS, C is CG and T is TA) Then DN is n
(n = ±1, ±2, ±3)

(2) TASC rules

(T-1) If (DN is 0 → R is RP and G is GG) Then DN is 0
(T-2·1) If (N is 0 → R is RF and C is CG) Then N is 0
(T-2·2) If (N is B1 → R is RP and C is CG) Then N is B1
(T-3) If (DN is n → R is RP, C is CG and G is GA)Then DN is n
(n = ±1, ±2, ±3)

6. Realization of the fuzzy ATO controller

The fuzzy ATO control system is incorporated in the simulator for an urban automated guideway transit system (JUMPS; Justified Models for Practical Specification)[12,13]. The JUMPS system calculates the performance of a transit system using graphic display, plotter and printer (Fig.10).

Fig.11 illustrates the structure of the fuzzy ATO algorithm. In the ATO system, the control command is selected by evaluating all of the above-mentioned performance indices rules every 100 ms. An evaluation of the states of the predictive fuzzy controller is displayed on a colour graphic display. Fig.12 is an example of running curves which are drawn by a plotter.

The fuzzy ATO control algorithm (include performance indices and rules) is evaluated by the JUMPS. The algorithm has been built into an on-board controller by a micro-computer(M-6800), as shown in Fig.13.

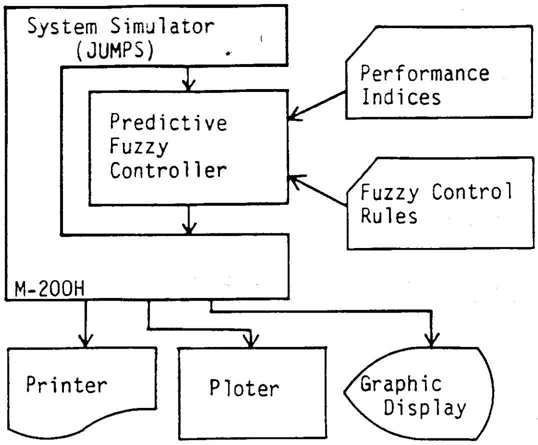


Fig.10 Outline of Fuzzy ATO evaluation system

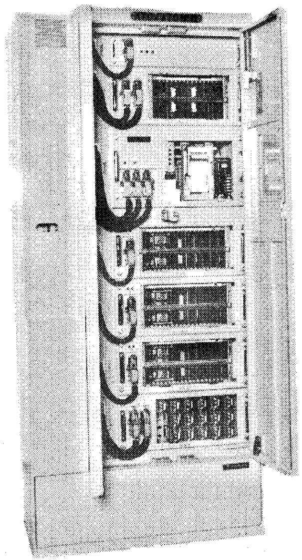


FIG.13 Developed Fuzzy ATO controller

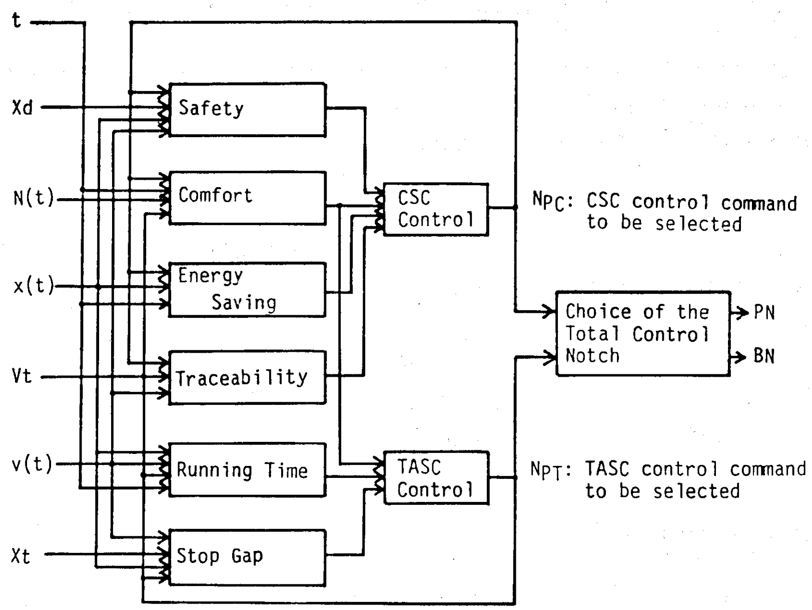


FIg.11 Structure of Fuzzy ATO algorithm

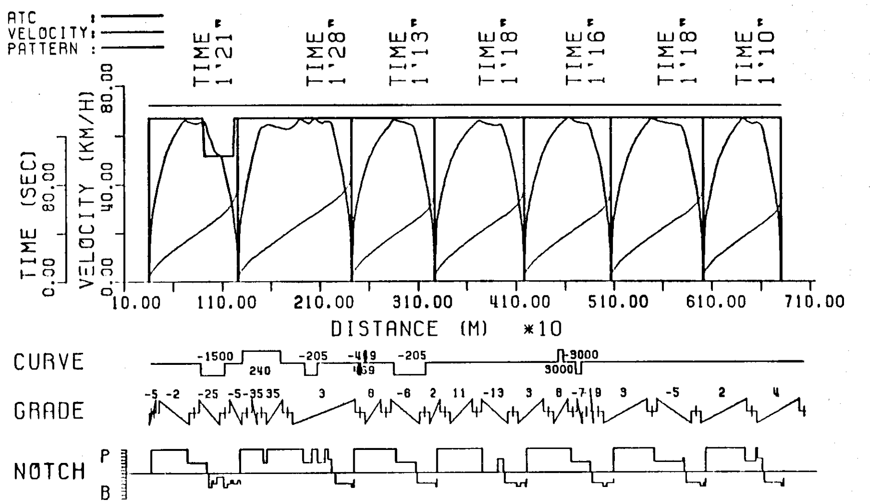


Fig.12 A running curve of the Fuzzy ATO for a subway system by a comuputer simulation

7. Simulations

By the simulation using the JUMPS, the developed predictive fuzzy control ATO (Fuzzy ATO) is compared with the conventional PID control ATO (PID ATO). The parameters used in the simulation are described in Table 2. The simulation results are as follows.

Table 2 Values Used in the Simulation

Train length :	83.5 m
Train weight :	129.0 ton
Running resistance :	
$1.97 + 0.016 * v + 0.00084 * v^2$ kg/ton	
Number of steps of traction:	7 steps
Maximum acceleration of traction:	3.3 km/h·s
Number of steps of brake:	9 steps
Maximum deceleration of brake B_m:	
nominal = 5.14 km/h·s	
minimum = 3.6 km/h·s	
maximum = 6.68 km/h·s	
Dead time of braking system:	0.2 sec
1st order time lag of braking system:	0.6 sec

(a) Riding comfort and stop gap accuracy

Fig.14 shows a summary of simulations for riding comfort and stop gap accuracy. As the results of the simulation, the number of notch changes in the fuzzy ATO is about a half, and the stop gap accuracy is about a third compared

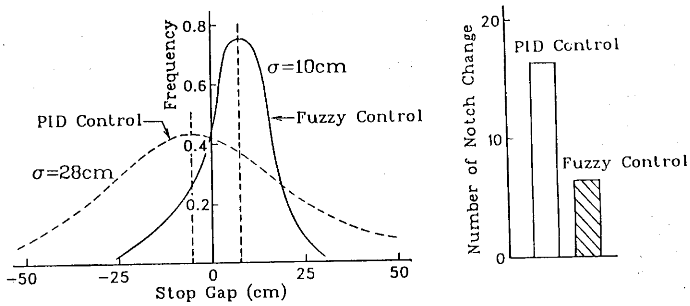
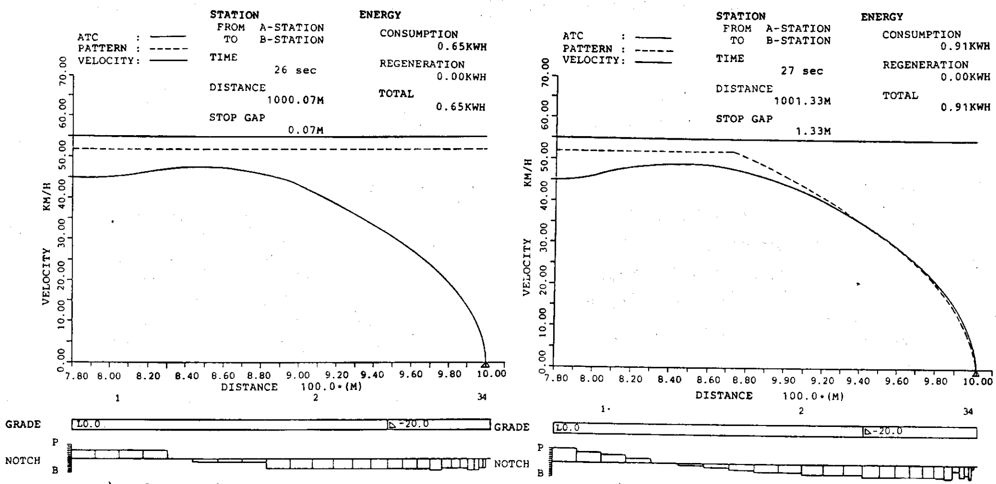


Fig.14 Summary of simulation for riding comfort and stop gap accuracy

- The deceleration to maximum brake notch is 70%, 100% and 130%
- The gradient is $-5^{o}/_{oo}$, $0^{o}/_{oo}$ (level) and $+5^{o}/_{oo}$

with those of the PID ATO. Therefore, the developed fuzzy ATO is able to control a train with good riding comfort and stop gap accuracy.

In the TASC control, the affects of the environment condition, such as track grade and braking ability, are important in controllability. The simulation results, with a grade change just before the station is 0 $^{o}/_{oo}$ to -20 $^{o}/_{oo}$, are shown in Fig.15. The results obtained are that the stop gap of the Fuzzy ATO is 0.03m and the PID ATO is 1.33m. These results show the higher robustness and control accuracy of the Fuzzy ATO.



a) A result by the Fuzzy ATO b) A result of the PID ATO

Fig.15 Simulation for robust control

(b) Energy consumption

The Fig.16 shows a summary of simulation results on running time and energy consumption. As the results of the simulation, the fuzzy ATO is able to control trains over 10% of energy saving and/or shorten a running time compared with the PID ATO.

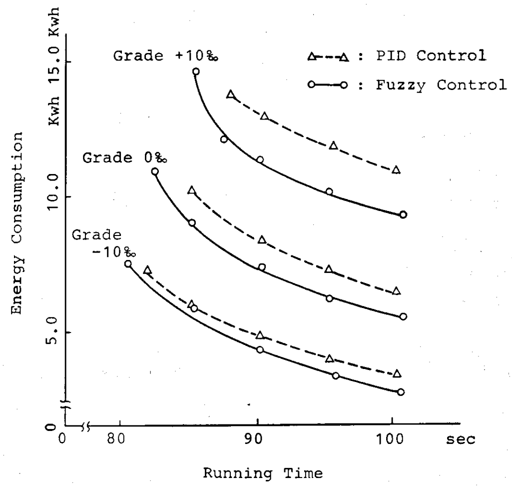


Fig.16 Summary of simulation for energy consumption

- The interval of stations is 1000m
- The gradient is $-10^{o}/_{oo}$, $0^{o}/_{oo}$ (level) and $+10^{o}/_{oo}$

8. Field test for a Subway System

A field test was performed at a subway system. Fig.17 shows a result of the field test. The Fig.12 showed a running curve of a computer simulation for the system, and the results of field test were almost the same as the simulations. The field test shows that the developed Fuzzy ATO controller can operate trains as skillfully as human experts.

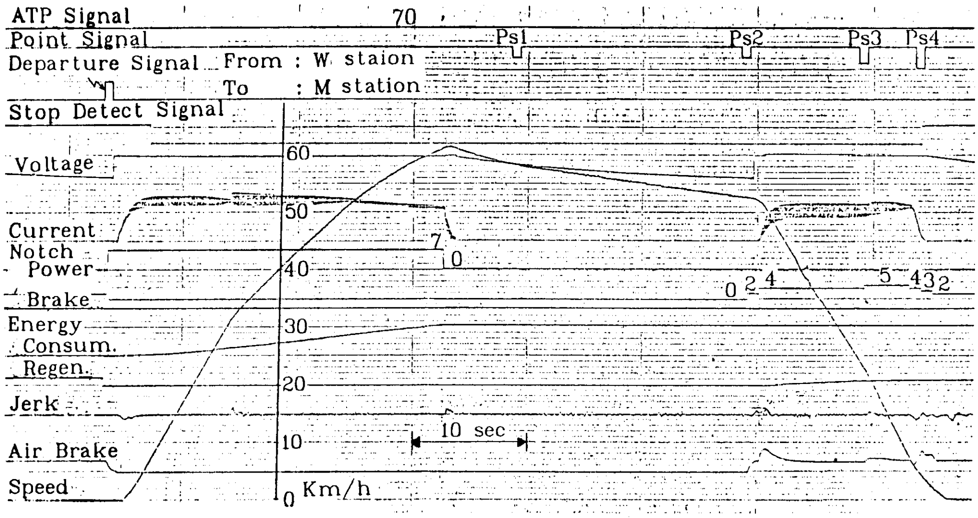


Fig.17 A result of the field tests

9. Conclusions

The predictive fuzzy controller, which selects the most likely control command based on predictions of control results and direct evaluations on the control objectives, has been proposed. This control method has been applied to ATO systems which control trains by evaluating safety, riding comfort, accuracy of stop gap, running time and energy consumption. The simulation studies have revealed that the Fuzzy ATO gives significiant improvements over a conventional PID ATO with respect to the above-mentioned performance indices. Also, it is able to operate robustly under the changing environmental conditions and save over 10% of energy compared with conventional ATO controllers. The proposed Fuzzy ATO algorithm has been built into an on-board controller, and field tests have shown that the developed Fuzzy ATO controller operate trains as skillfully as a human expert. Since control quality is a strong requirement, the proposed predictive fuzzy control is an effective method for overcoming the problems of conventional control systems.

10. Acknowledgements

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