Application of Fuzzy Theory to PTP Control of a Robot Manipulator

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Application of Fuzzy Theory to PTP Control of a Robot Manipulator

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This research is concerned with the application of fuzzy theory to PTP(Point to Point) control of a redundant manipulator. On PTP control, an inverse kinematics problem which is to determine each joint angles when the position of an end-effector is given, is unsolvable because its solution is not always unique owing to its redundancy. In this study, the self-controlled manipulator for PTP control can be realized using the fuzzy theory.

The basic structure and uses of the fuzzy controller are developed with an on-line computer aid, by which the manipulator can reach at any prescribed position. The fuzzy inference is proceeded on nine fuzzy rules with respect to output angles for each joints using "product-sum-gravity method" and "simplified method". Two types of output membership functions are proposed and the effectiveness is discussed through simulation studies. By experiments using Rhino robot, it is ascertained that the proposed fuzzy controller is valid to PTP control of the real manipulator.

1. Introduction

In an inverse kinematics problem[1)] which is to determine

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each joint angles when the end-effector position is given, it is generally difficult to obtain analytical solutions with respect to the structure of the manipulator. Also, even if analytical solutions are obtained utilizing the characteristics of each mechanisms, the desired configurations can not be determined uniquely due to having multiple solutions. Therefore, the control of a manipulator has been performed for the most part by a teaching/playback method.[2] However, the operator may control, by some reason or other, even for control systems which analytical solutions can not be explored. A lot of researches and products have been published which introduced such methods of the operator into a computer controlled system by fuzzy theory.[3][4]

In this research, the manipulating method of the operator may be described using fuzzy theory and applied to PTP control[2] of a manipulator with 3-link and 4 degrees of freedom. By this method, the self-controlled manipulator can be realized which does not depend on the teaching/playback method. The inputs to fuzzy inference portion are both metric and height errors which are obtained as differences between the present and desired co-ordinates of an end-effector. For these error inputs, a fuzzy domain is defined with three membership functions; NL (negative large), ZR (zero) and PL (positive large), in which the input fuzzy space is set up with nine sections by their combinations. Corresponding fuzzy rules of experimental formula to each sections, five output membership functions are defined as NL (Negative large), NS (Negative small), ZR (zero), PS (positive small) and PL (positive large). Using both "product-sum-gravity method" and "simplified method"[6] as a fuzzy inference, the command angles to each joints are given. The input and output membership functions in the inference are regulated by simulation experiments. Furthermore, from practical experiments, it can be shown that the self-controlled PTP manipulator due to the application of fuzzy theory has practical use as the software servo mechanism.[2]

2. Outline of Experimental Device

2.1 Structure The experiments are, as shown in Fig.1, performed by use of Rhino manipulator.[7] This manipulator is composed of the arm drive(XR-3) and six axes controller(Mark III controller). This six axes controller is a separate one aided through a signal circuit(RS 232C) by a host computer(NEC PC-9801), in which each arm can be controlled with a chain drive by DC servomotor. This system is constituted by a local closed-loop system with 1-input and 1-output at each joints. This servo system can be controlled by a DC servomotor, in which the rotating angle (steps number) is measured by an optical rotating encorder at each joints and the difference between this value and the desired steps number is detected as a feedback signal. The error register values of this difference are measured through RS-232C circuit on a host computer. The relations between steps number and each joint angles are given as 0.11°/step at each joints C, D and E and 0.23°/step at joint F in Fig.1.

2.2 PTP controller The six axes controller of this manipulator is constructed only by a fundamental command. In order to perform a high level control of the manipulator, it is necessary to support the controller with a software servo system. Then, the new PTP controller has been prepared by constituting the control algorithm with the possibility of real time processing on the host computer. This control algorithm has two functions; (1) calculation and memory of

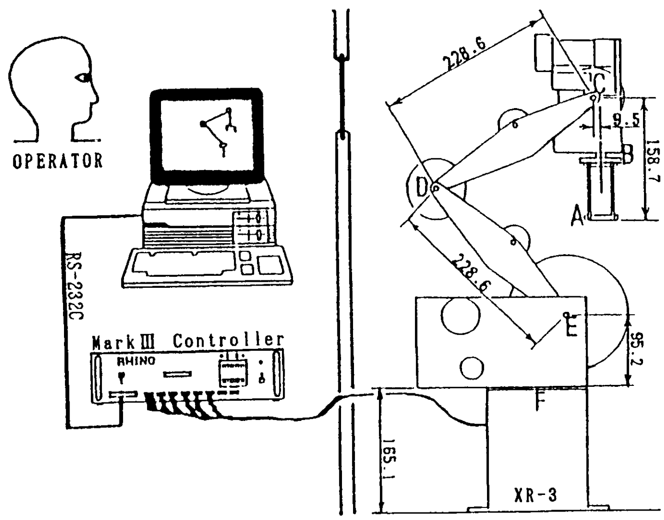


Fig. 1 Construction of Manipulator Control System

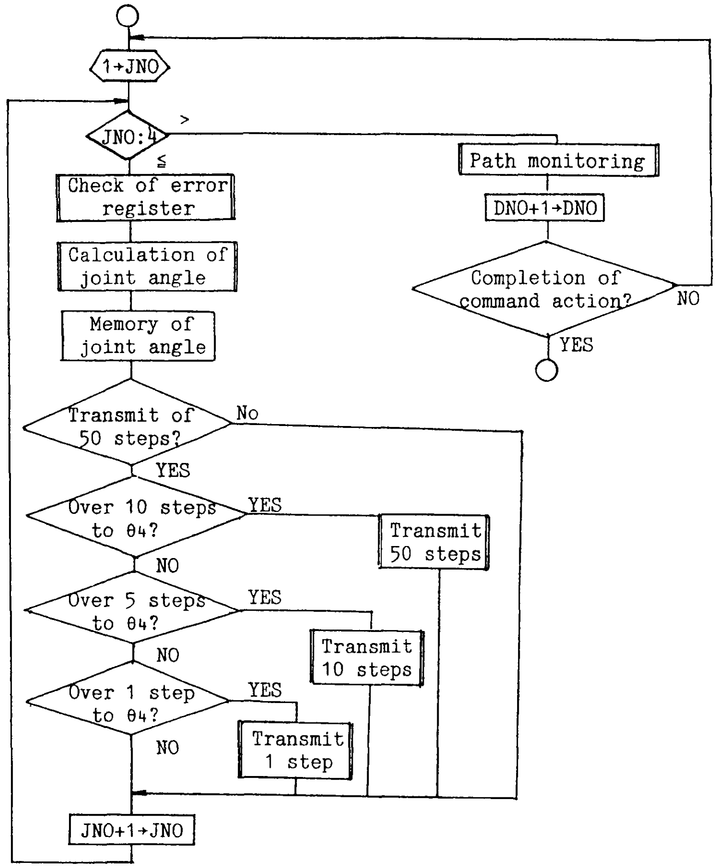


Fig.2 Outline of PTP Control Algorithm

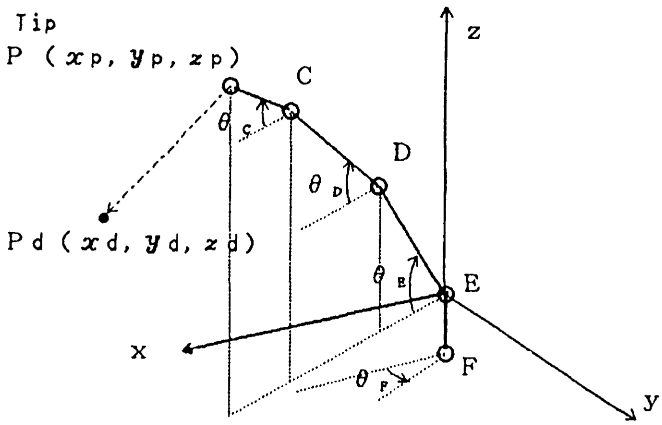


Fig.3 Work Space Coordinates and Each Joint Angle

each joint angles and (2) trajectory monitoring processing, by combining fundamental commands of PTP controller for joint angle inputs. That is, this algorithm is composed of three parts; (1) calculation and memory of each joint angle, (2) trajectory monitoring and (3) their unified PTP controller. The experiments have been performed using this new controller.

3. Fuzzy PTP Control Strategy

3.1 Fuzzy input As the work space of a manipulator, we consider the coordinate which a joint E is, as shown in Fig.3, the origin. Now, let the initial position of an end-effector be at some point $\mathbf{P}(x_p, y_p, z_p)$ on the work space. Then, the task is how to bring the end-effector from a point $\mathbf{P}(x_p, y_p, z_p)$ to a desired point $\mathbf{P_d}(x_d, y_d, z_d)$. In this case, the angular movement θ_F at a joint F is, from values of (x_d, y_d), obtained as an analytical solution. Therefore, in order to shift an end-effector to the target $\mathbf{P_d}$, the manipulated angles θ_C, θ_D and θ_F must be explored using the fuzzy inference.

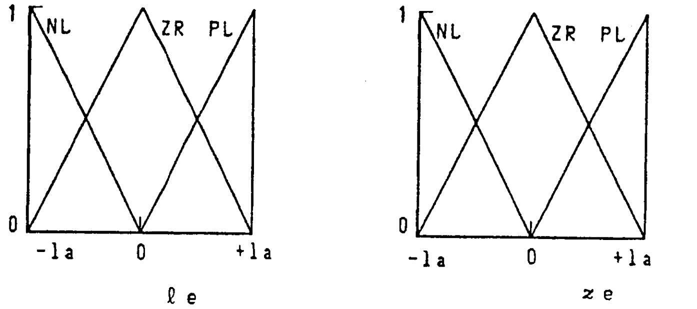
To this end, let distances from the origin (joint E) to points $\mathbf{P}$ and $\mathbf{P_d}$ be ℓ and ℓ_d, and heights from the origin to $\mathbf{P}$ and $\mathbf{P_d}$ be z_p and z_d, respectively. Then, errors relating to the distance and height are respectively defined as

$$\ell_e = \ell - \ell_d \quad \text{(distance error)} \tag{1}$$

$$z_e = z_p - z_d \quad \text{(height error)} \tag{2}$$

Two error variables ℓ_e and z_e are used as fuzzy inputs. Corresponding to each error inputs, three fuzzy domains are defined as NL (negative large), ZR (zero) and PL (positive large), which are represented by membership functions as shown in Fig. 4. By a combination of these error variables, fuzzy input spaces from ① to ⑨ are, in the 2-dimensional space, set as shown in Fig. 5.

3.2 Fuzzy inference approach For each case of nine sections (① ∿ ⑨) in the fuzzy input space, how to determine each manipulated angle θ_C, θ_D and θ_E has been shown in Table 1, based on experience/knowledge. The output membership functions of NL, NS (negative small), ZR, PS (positive small) and PL shown in Table 1 are given as shown in Fig. 6, which are selected best in trial and error through simulation experiments. In Fig. 6, the M_a indicates the maximum



la: maximum error; ($la = l_C + l_D + l_E$)

Fig. 4 Membership Functions of ℓ_e and z_e

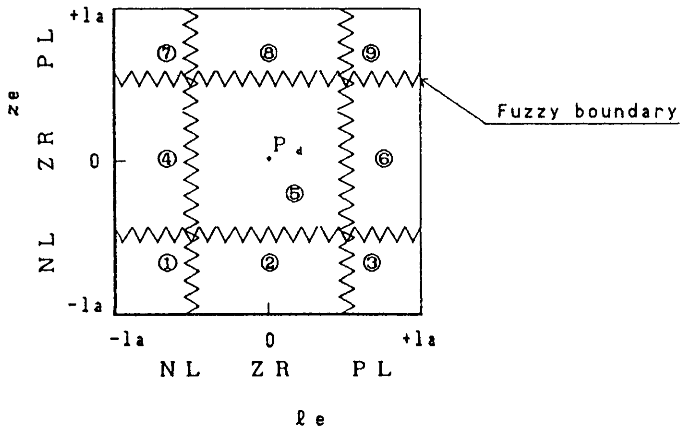


Fig. 5 Fuzzy Input Space

Table 1 Fuzzy Rule in Manipulator Control

Rule No.	Output Value: θ		
	θ C	θ D	θ E
if ① then	PL	PL	PL
if ② then	ZR	ZR	PL
if ③ then	NL	NL	PL
if ④ then	PL	PL	NS
if ⑤ then	ZR	ZR	ZR
if ⑥ then	NL	NL	PS
if ⑦ then	PL	PL	NL
if ⑧ then	ZR	ZR	NL
if ⑨ then	NL	NL	NL

NL: Negative Large
NS: Negative Small
ZR: Zero
PS: Positive Small
PL: Positive Large

manipulated angle. This value is an output gain which gives the maximum value when the fuzzy controller ordered to move large. In this study, the M_a is adjusted as 120°, 110° and 100° at joints C, D and E, respectively.

Based on the fuzzy rule and membership functions described above, the fuzzy inference is achieved using "product-sum-gravity" and "simplified method".[6]

Next, we'll explain how the fuzzy inference is carried out for real inputs. Supposed that both the desired point $\mathbf{P_d}$ and the present point $\mathbf{P}$ are given in PTP control, the distance error ℓ_e and the height error z_e are obtained from the coordinates of these two points. Now, let be ℓ_e=100mm and z_e=50mm. Then, among nine fuzzy rules in Table 1, the rules ⑤, ⑥, ⑧ and ⑨ hold, which indicate

(1) if ⑤, then θ_C=ZR, θ_D=ZR, θ_E=ZR,

(2) if ⑥, then θ_C=NL, θ_D=NL, θ_E=PS,

(3) if ⑧, then θ_C=ZR, θ_D=ZR, θ_E=NL,

and

(4) if ⑨, then θ_C=NL, θ_D=NL, θ_E=NL.

Concerning with each fuzzy rule described above, the following deduction is fulfilled. This fuzzy inference process is, taking cases of ⑤ and ⑨ as an example, illustrated as shown in Figs. 7 and 8. The procedure is as follows;

(1) From each input membership functions of ℓ_e and z_e, the grades of membership are found which both ℓ_e and z_e satisfy in each fuzzy rules. (pre-conditioning part in Figs. 7 and 8)

(2) Taking the algebraic product between the lower grade of ℓ_e and z_e (by minimum calculus: $\wedge$) and the output membership function is condensed by simplified method. (after-conditioning part in Figs. 7 and 8)

(3) For every rules established, composing the condensed membership functions obtained from the result of (2) by the summation and centering them by the gravity method (defuzzification), the output variables are found. (Fig. 9)

According to the procedure mentioned above, the output controlled variables (manipulated angles) are, as shown in Fig. 9, calculated as θ_C=-20°, θ_D=-15° and θ_E=-10°, and transmitted to a fuzzy controller. In the following, until

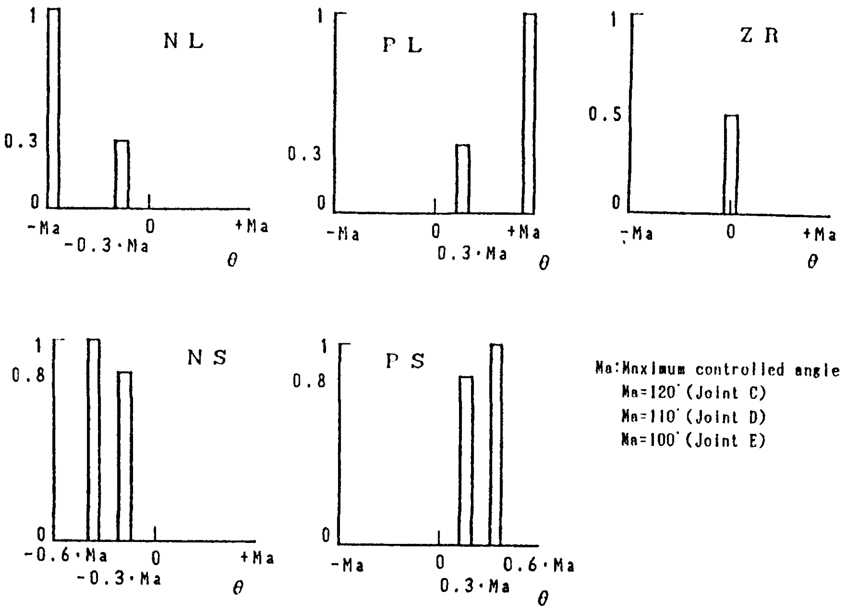


Fig. 6 Output Membership Functions

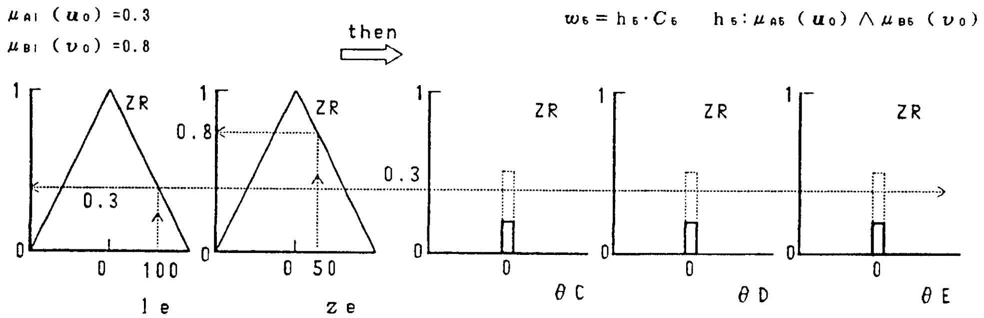


Fig. 7 Inference Process of Fuzzy Rule ⑤

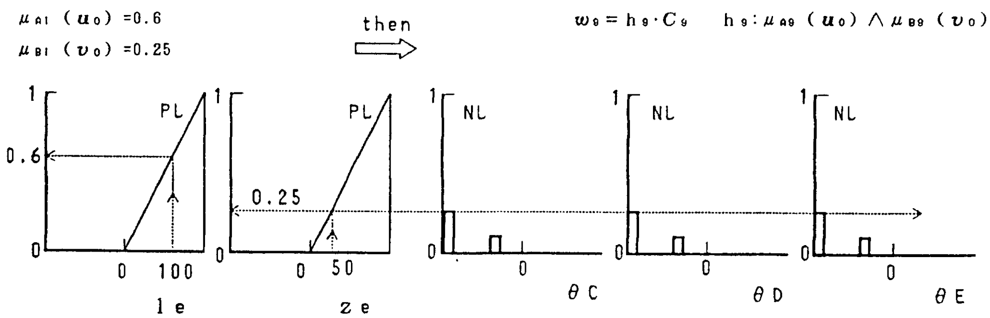


Fig. 8 Inference Process of Fuzzy Rule ⑨

the end-effector reaches to the desired point $\mathbf{P_d}$, the fuzzy inference is repeated in the same way.

3.3 Adjustment of output membership function The effect of outcome membership functions in the fuzzy reasoning shall be considered with respect to ZR, NL and PL. Two kinds of output membership functions, I and II are chosen as shown in Figs.10 and 11, from which four different fuzzy inferences are composed by their combination. Based on these fuzzy reasoning, simulation experiments have been implemented.

Let initial joint angles be $\theta_C=\theta_D=\theta_E=\theta_F=90°$, that is, the

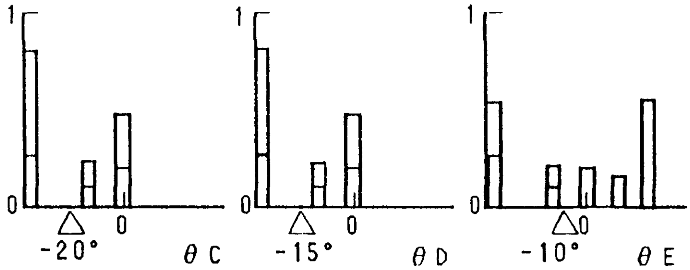


Fig. 9 Union of Output Membership Functions

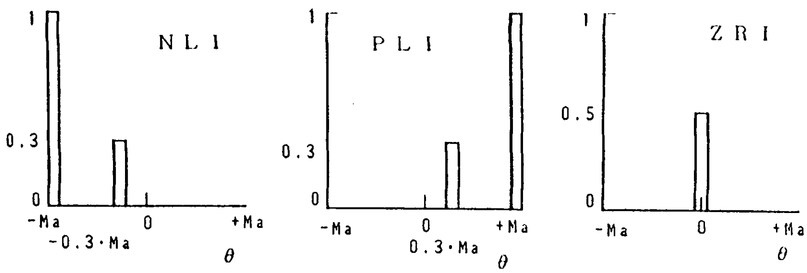


Fig.10, Output Membership Function [Type I]

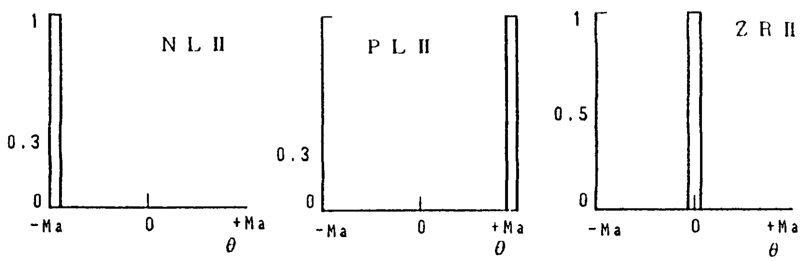
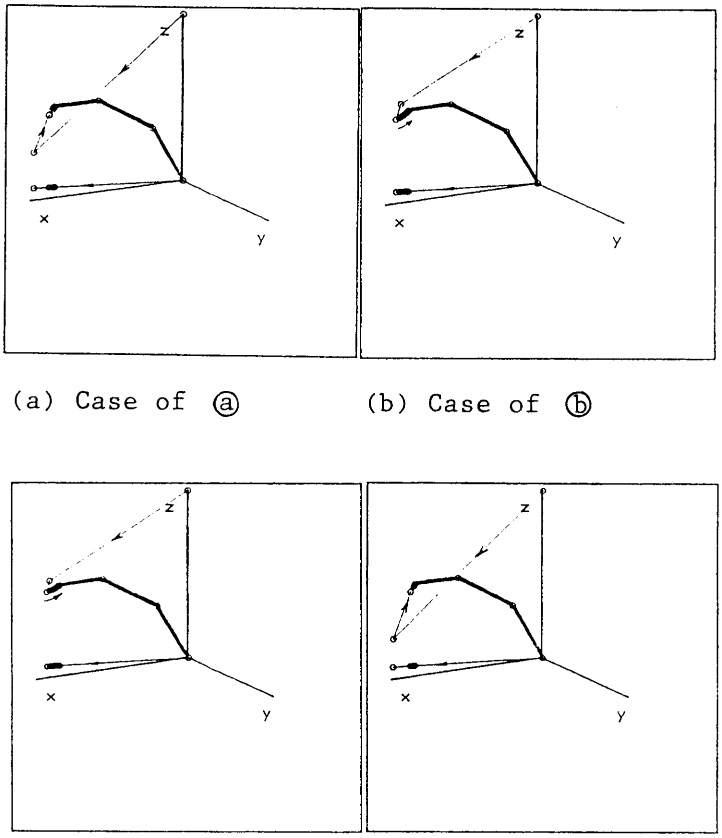


Fig.11 Output Membership Function [Type II]



(a) Case of ⓐ (b) Case of ⓑ

(c) Case of ⓒ (d) Case of ⓓ

Fig.12 Simulation Experiments: $\mathbf{P_d}$(+450.0,-125.0,+300.0)

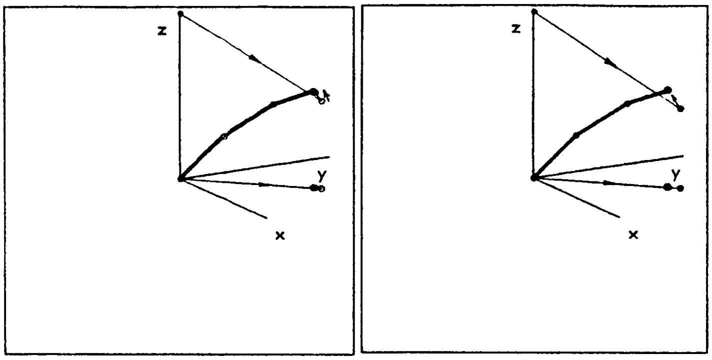
Table 2 Comparison of Simulation Experiments-I

No.	Output type		Settling time		Steady-state error (mm)	
	ZR	NL PL	Session Number	time (s)	ℓe	$z e$
ⓐ	I	I	11	18.9	0.00	-0.49
ⓑ	II	I	29	48.0	+0.84	-3.40
ⓒ	II	II	30	49.6	+1.30	-3.72
ⓓ	I	II	10	17.4	+0.00	-0.57

present point **P**(0, 0, 615.9)(mm). Also, the desired point $\mathbf{P_d}$ is given as an input by (+450.0, -125.0, +300.0). Then, through the inference processes ⓐ, ⓑ, ⓒ and ⓓ as shown in Table 2, how the results of reasoning gives effect to the dynamics of a manipulator has been examined by simulation experiments. Figure 12 (a), (b), (c) and (d) show the results of simulation experiments, which represent the trajectory of a manipulator drawn the action commands at each sessions with a straight line and its projection to the x-y plane. Also the bold line represents the arm of a manipulator. Here, the "session" implies the process until the action angle issues an order by one fuzzy reasoning and the manipulator completes its command action of each joint. In other words, the action of PTP control is composed of combinations of these sessions and approaches gradually to the desired point $\mathbf{P_d}$. The experimental results can be arranged in Table 2.

Table 2 evaluates the settling time (session number) which is the time till the sum of absolute value of the error for reasoning (manipulated angle) at each joint is less than 0.05°, and the steady-state error of both the distance and the height. Furthermore, taking the transient response and the overshoot into consideration, it was judged that ⓐ and ⓓ are optimal as a membership function. Next, in order to certify whether the output membership function is effective to the case the desired point $\mathbf{P_d}$ is changed, the similar simulation experiments have been carried out corresponding to fuzzy reasoning processes ⓐ and ⓓ. The desired point was assigned as $\mathbf{P_d}$(+340.0,+350.0,+360.0). The results are shown in Fig.13 (a) and (b) and Table 3, in which the settling time becomes worse.

Thus, even if the desirable action is obtained for some motion, it is not assured that the selected membership functions are optimal parameters for every motions. Accordingly, for various kinds of membership functions and desired points, simulation experiments have been repeated and then the optimal membership function explored by trial and error. At result, the output membership function has been determined as shown in Fig. 6. As standards of judgement, transient response form, settling time (sessions number), overshoot and the steady state error were adopted and then



(a) Case of ⓐ (b) Case of ⓓ

Fig.13 Simulation Experiments: $\mathbf{P_d}$(+340.0,-350.0,+360.0)

Table 3 Comparison of Simulation Experiments-II

No	Output type		Settling time		Steady-state error (mm)	
	ZR	NL PL	Session Number	time (s)	ℓe	$z e$
ⓐ	I	I	17	28.5	-0.48	+0.45
ⓓ	I	II	23	38.1	-0.55	-0.92

putting these various results together the optimal membership function has been selected.

3.4 Application to real model It has been developed that the established fuzzy rule was applied to a real manipulator. Transmitting the action command angle to PTP controller from a host computer, which is generated by the fuzzy inference controller, the motion experiments of a manipulator have been performed. Comparing these results with simulation experiments, the same desired point $\mathbf{P_d}$ is assigned as (+450.0,-125.0,+300.0). The result of a real experiment is demonstrated in Photo 1, which shows the trajectory monitoring. Also, Fig.14 shows the time movement of each joint angle.

In this experiment, it takes 24.5 seconds for a manipulator to reach the desired point $\mathbf{P_d}$, through the fuzzy reasoning of 7 times. However, if the human beings do the same task, it takes 3 minutes 25 seconds even by the skillful worker.

From results of real experiments of self-controlled PTP

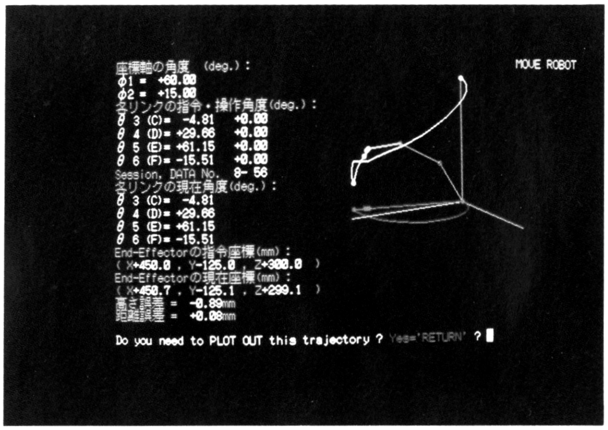


Photo 1 Trajectory Monitoring in Real Experiment

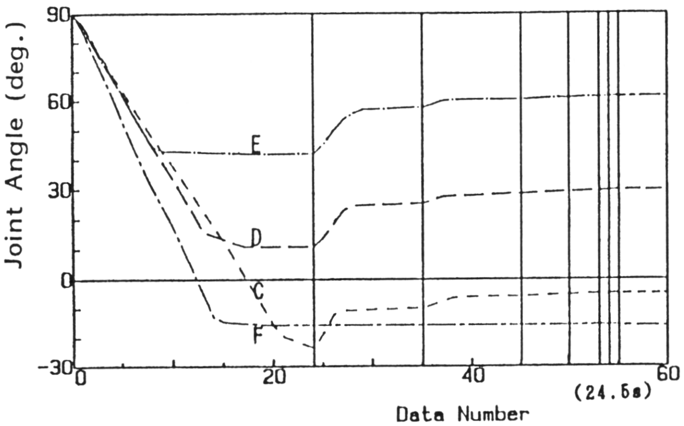


Fig.14 Movement of Joint Angle in Real Experiment

control using fuzzy theory, it is certified that the good response motion is realized, similar to the case of simulation experiments.

4. Conclusion

This paper developed an application of fuzzy inference control to a manipulator with 3-link and 4 degrees of freedom. By incorporating linguistic control rules and the fuzzy set theory, we can manipulate fuzziness and achieve control objects. The fuzzy inference controller has been, using personal computer, established as a software servo system. This control algorithms were evaluated by experiments using

Rhino robot manipulator. From experiments, the following points are clarified.

(1) Using fuzzy set theory, it is possible to realize a self-controlled PTP manipulator, which does not depend on teaching/playback method.

(2) As the input information is only the present values of co-ordinates in an end-effecter, it is available to every manipulator with a sensor which can detect the coordinates in dynamic control, from a conventional encoder to an image processor.

(3) By addition of fuzzy rules, it is applicable to the obstacle avoidance, the time optimal control and the singular point avoidance etc.

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