Position Control of a Flexible Finger Driven by Piezoelectric Bimorph Cells Using Fuzzy Algorithms

Jae-Chun Ryu*, Chong-Kug Park**

ABSTRACT

This paper dealt with the position control of a flexible miniature finger driven by piezoelectric bimorph cells, cemented on both side of the finger.

Bending moments generated by cells drives the finger, and end-point of the finger is controlled, so as to move in synchrony with fluctuation of target and maintain a constant distance between target surface and finger's tip. The voltage applied for the cell is controlled by tip displacement error and error rate. We proposed a PD-Fuzzy controller under conception of PD control strategy. It brought an advantage which reduce number of rules than that of same type conventional fuzzy system and more correct redponse than PID control results.

I. Introduction

Demands for higher speed, less energy consumption, and higher payload capacity call for lightweight robotic manipulators. To endure high performance of such manipulators, it is necessity to consider the dynamic effects of distributed link mass and flexibility in the design of the control system, and many papers on it have been published during recent years. Cannon and Schmitz[1], Skaar and Tucker[2], Yuh[3], Tahara and Chonan[5] studied the open/close loop endpoint controls of single link flexible manipulators driven by the servomotor located at the shoulder.

As for the multilink flexible finger, Ower and Van De Vegre[6], Fukuda and Arakawa[7], and Chonan and Umeno[8] investigated the position control of two link fingers with distributed flexibility. But, the theoretical and experimental results have been obtained on the performance of the finger with DC servo-motor on the shoulder and the elbow.

The requirements for minimizing the vibration of large space structures or driving the micro flexible finger such as the read/write head in the disk unit system make it a necessity to introduce new actuators other than the ordinary electro-motors. It has drawn much interest in the dynamic behavior of piezoelectric bimorph cells. It is well known that these cells produce a large force compared with their weight and respond rapidly to the variation of the applied voltage. In the early study on piezoelectric cells, attention was directed mainly to their physical properties. More recently, an analysis has been done by Bailey and Hubbard on the control of vibration of cantilevers beam using a layer of piezoelectric polymer bound on one side of the beam. The vibration of signal, after being integrated to give the tip velocity, was then applied to the polymer to control the vibration. Tani[10] determined the optimum length of piezoelectric cells introduced as actuators for the control of vibration of

*Professor of Anyang Technical College
** Professor of Kyung Hee University.

flexible beams.

To our knowledge, it appears that so far no work has been done on the problem of how to drive the piezoelectric bimorph cells as the actuator in the tracking control of a flexible beam system. It is in this paper that the present article will discuss the end-point position control of a flexible finger driven by piezoelectric bimorph cells. A discrete-time formulation is presented for the finger-cell system and applied to the problem of moving the finger tip so that it tracks the fluctuation of target precisely. The tip displacement(versus time) is compared with the target fluctuation and the tip position error is used, together with other estimated system states, as the basis for applying control voltage to the cells. A control strategy to reduce the nonlinear hysteresis of the bimorph cells is presented. It is shown of the theoretical results obtained based on the present mathematical model of the bimorph cell.

Ⅱ. Mathematical modeling of the Problem

Figure 2.1 shows a flexible cantilevers finger of length l with a mass m attached at its free end. A pair of piezoelectric bimorph cells of length a are glued on both sides of the finger in such a way that an applied voltage causes one actuator to expand and the other to contract. As a result, a continuous constant bending moment M_p is produced along $x=0$ to l_1 (Fig. 2.2), which deforms the finger in the horizontal $x-y$ plane. In the following, one investigates the problem of controlling the finger so that the end point moves, keeping a constant distance to the fluctuating target. Considering the equilibrium of moment and forces acting on a small element that is cut out of the finger, one has the equation of motion the finger as

$$[\rho(x)A(x)+m\delta(x-l)]\frac{\partial^2 y}{\partial t^2}+\frac{\partial^2}{\partial x^2}[E(x)I(x)(1+\gamma\frac{\partial}{\partial t^2})\frac{\partial^2 y}{\partial x^2}]=M_p\delta'(x-l_1) \qquad (1)$$

where

$$\begin{aligned} &y(t)=Y(t)+u(t)\\ &\dot{\delta}(x)=d\delta(x)/dx\\ &\rho(x)A(x)=\begin{cases}\rho_b A_b & \text{for } l_1\le x\le l\\ (\rho A)_{bp} & \text{for } 0_1\le x\le l_1,\end{cases}\\ &E(x)I(x)=\begin{cases}E_b I_b & \text{for } l_1\le x\le l\\ (EI)_{bp} & \text{for } 0\le x\le l_1,\end{cases}\end{aligned} \qquad (2)$$

Here, $y(t)$ is the deflection of the finger, $Y(t)$ is movement of generalized coordinates and $u(t)$ is fluctuation, and $\delta()$ is Direc delta function.

Also,

$$\begin{aligned}&(\rho A)_{bp}=\rho_b A_b+2\rho_p A_p\\ &(EI)_{bp}=\frac{bh_b^3E_b}{12}+\frac{b[(h_b+2h_p)^3-h_b^3]E_p}{12}\end{aligned} \qquad (3)$$

In above equation, ρ, A, E, and I are the mass density, cross-section area, Young's modules moment of inertia of the finger, h is thickness, and b is width of finger.

When, the bimorph cells are perfectly bonded on both sides of the finger, the system can be modeled as a stepped beam with three uniform sections, having a laminated structure in part.

The homogeneous solution of equation(1) in the i-th uniform section is then obtained as

$$\begin{aligned}W^i(x)=&A^iS(\zeta^ix)+B^iT(\zeta^ix)+C^iU(\zeta^ix)+D^iV(\zeta^ix)\\ &+\bar{m}l\zeta^iw^i(l)V[\zeta^i(x-l)]H(x-l)\\ i=&I, II\end{aligned} \qquad (4)$$

where, $H()$ is Heviside step function and

$$\begin{aligned}&(\xi^i)^4=k^2\frac{(\rho A)^i}{(EI)^i}\\ &\bar{m}=\frac{m}{\rho A}\end{aligned} \qquad (5)$$

$$S(\zeta x)=\frac{1}{2}[\cosh(\zeta x)+\cos(\zeta x)],$$

$$T(\zeta x)=\frac{1}{2}\ [\sinh(\zeta x)+\sin(\zeta x)],$$
$$U(\zeta x)=\frac{1}{2}\ [\cosh(\zeta x)-\cos(\zeta x)], \tag{6}$$
$$V(\zeta x)=\frac{1}{2}\ [\sinh(\zeta x)+\sin(\zeta x)],$$

Here, the eigenvalues ζ^i and the unknowns, A^i through D^i are determined by substituting equation (4) into the system boundary conditions. With the use of the nth mode function w_n^i and the eigenvalues ζ_n^i, n=1, 2, ..., thus determined, the displacement of the finger driven by the bimorph actuators is written in the form

$$y(x,t)=\sum_{n=1}^{N} W_n(x)f_n(t) \tag{7}$$

where $w_n(x)$ is the nth mode function given by

$$W_n(x)=w_n^i(x) \tag{8}$$

Here, i=1 for the range $0\le x\le l_1$, i=2 for $l_1\le x\le l$.

Substituting equation (7) into equation (1), one has

$$\sum_{n=1}^{\infty}[\rho(x)A(x)+m\delta(x-l)]w_n(x)$$
$$[\frac{d^2f_n(t)}{\partial t^2}+k_n^2\gamma\frac{df_n(t)}{dt}+k_n^2f_n(t)]=M_p\dot{\delta}(x-l_1) \tag{9}$$

where $k_n^2=[\frac{(EI)^i}{(\rho A)^i}](\zeta_n^i)^4$

Multiplying both sides of equation (9) by w_m and integrating from $x=0$ to l, one has, by virtue of the orthogonal property of w_n,

$$\frac{d^2f_n(t)}{dt^2}+k_n^2\gamma\frac{df_n(t)}{dt}+k_n^2f_n(t)=Q_n(t) \tag{10}$$

$$Q_n(t)=[\frac{dw_n(l)}{dx}-\frac{dw_n(l_1)}{dx}]M_p/\psi_n \tag{11}$$

where $Q_n(t)=\beta_nM_p(t)$, and β_n is a constant determined by the physical parameters of the system. In the following analysis, the control input using the measured position error between the tip and the target is introduced to control the moment. One here drives the cells so that the moment produced is given by

$$M_p=G_p[u(t)-y_L(t)]+G_v[u(t)-\dot{y}_L(t)]$$
$$=G_pe-G_v\dot{e} \tag{12}$$

Here $y_L(t)$ and $\dot{y}_L(t)$ are the displacement and velocity of the finger tip, and $u(t)$ and $\dot{u}(t)$ are the demanded position of the target; G_p, G_v are the control gains.

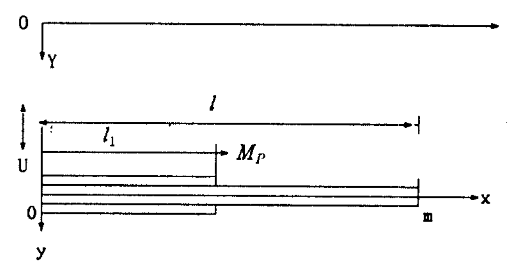


Fig 2.1 Model of Finger

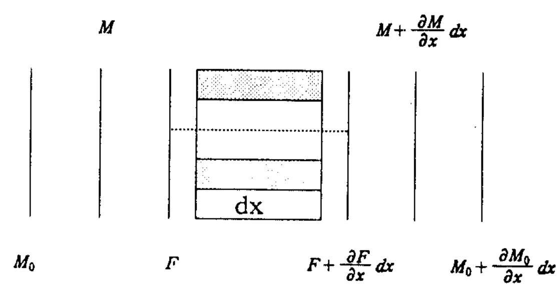


Fig 2.2 Moment Diagram

Ⅲ. Proposed Controller Design

During several years, fuzzy control has emerged as one of the most active areas for research in the application of fuzzy theory. The fuzzy controller is regarded as a set of heuristic decision rules which represents the knowledge of human operators.

It is reported from experiences that fuzzy controller have the following properties. The human intuition and experiences are available, the mathematical model is not required, and it is robust controller. However, it was impossible to realize. Therefore, the determination of control rules, membership function (MSF), and its parameters are very important tasks, and that the closed-loop system is stable. This problem is never easy to solve because fuzzy controller is essentially nonlinear. So we will utilize the conventional PD control scheme for the design of fuzzy controller.

3.1 Properties of PD Control

In order to utilize the knowledge of linear PD controller for the design of fuzzy controller, we must clarify the properties of PD controller. Linear PD controller is represented as follows

$$u = G_p e + G_v \dot{e} \tag{13}$$

where e is the error, $\dot{e}$ is error rate, and G_p, G_v are the gains, respectively. Equation(13) can be written as

$$u = G_v(Ae + \dot{e}) \tag{14}$$

where

$$A = \frac{G_p}{G_v} \tag{15}$$

From equation(14), we have u = 0 if

$$Ae + \dot{e} = 0 \tag{16}$$

Further, a operating point (e_x, $\dot{e}_x$) on the phase plane, the corresponding output u_x is described as

$$u_x = G_v(Ae_x + \dot{e}_x)$$

$$= \begin{cases} G_v\sqrt{(1+A^2)}\,\tau, & Ae_x + \dot{e}_x \geq 0 \\ -G_v\sqrt{(1+A^2)}\,\tau, & Ae_x + \dot{e}_x \leq 0 \end{cases} \tag{17}$$

where

$$\tau = \frac{1}{\sqrt{(1+A^2)}}\,|e_x + A\dot{e}_x| \tag{18}$$

Equation (18) denotes the distance from the line (16). Equation(17) implies that the output of controller is linearly proportional to the distance from the line(16), and has constant value on the line parallel to the line (Fig. 3.1).

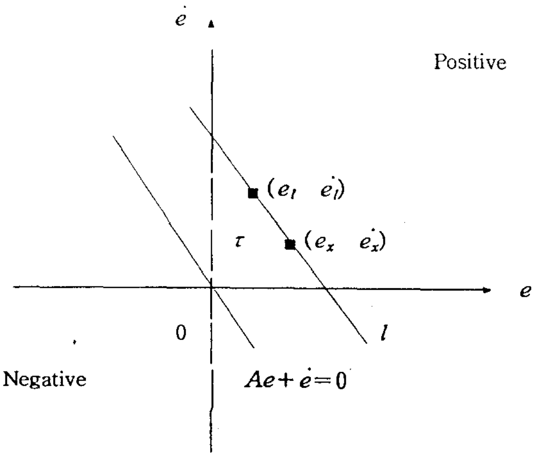


Fig. 3.1 Phase plane of PD controller

Therefore, we get the properties of PD controller as follows

(1) The zero line on which the controller output is equal to zero

(2) The output is positive in upper part of the zero line.

(3) The magnitude of output is linearly proportional to the distance from the zero line.

3.2 Fuzzy Controller of PD type

In this section, we offered a fuzzy controller which is designed based on the PD algorithms.

Letting

$$R = \sqrt{(G_p e)^2 + (G_v \dot{e})^2} \tag{19}$$

Equation (13) reduces to

$$u = \sqrt{2}\,R\cos(\psi - \frac{\pi}{4})$$

$$\cos\psi = \frac{G_p}{R}\,e, \qquad \sin\psi = \frac{G_v}{R}\,\dot{e} \tag{20}$$

Then the following rules may be set

$$\begin{aligned} &R1: If\ \psi\ is\ P\ Then\ y\ is\ Py \\ &R2: If\ \psi\ is\ N\ Then\ y\ is\ Ny \end{aligned} \tag{21}$$

Since the defuzzifier operation is COG, it is convenient to use symmetric MSFs for P and N. Also, we use symmetric singletons for Py and Ny as showed in fig. 3.2(b).

Let the weights of implications be α_i, then we have

$$u_\psi = \frac{\alpha_1 \omega + \alpha_2(-\omega)}{\alpha_1 + \alpha_2} = \omega(2\alpha_1 - 1) \tag{22}$$

In order to determine the MSFs for P and N, we rewrite equation(20) as

$$u = \gamma \sqrt{2}\, G_p [2 \cdot \frac{1}{2} \left\{ \cos(\psi - \frac{\pi}{4}) + 1 \right\} - 1]$$

$$\gamma = \sqrt{e^2 + (\frac{G_v}{G_p} \dot{e})^2} \tag{23}$$

Hence, from (22), we may set the antecedent MSF so that

$$\alpha_i = \frac{1}{2} \left\{ \cos(\psi - \frac{\pi}{4}) + 1 \right\} \tag{24}$$

is satisfied, and is shown in fig. 3.2(a)

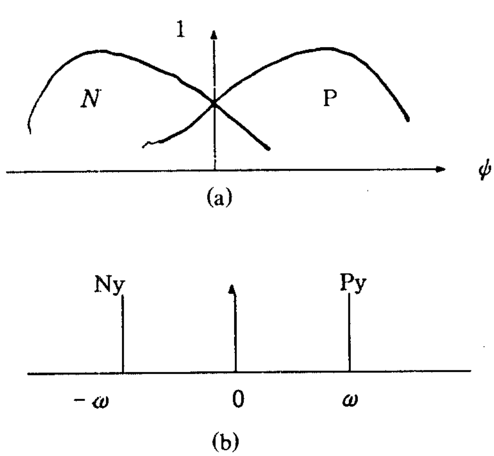


Fig. 3.2 MSF (a) Antecedent (b) Singleton

Also, the parameter of the consequent MSF is determined as

$$\omega = \sqrt{2}\, G_p \tag{25}$$

It follows that a fuzzy controller which is PD controller (13) is given by

$$u = \gamma u_\psi \tag{26}$$

In general, the output of the fuzzy controller for the input is represented by a nonlinear function as

$$u = f(e, \dot{e}) \tag{27}$$

The controller structure is showed fig. 3.3.

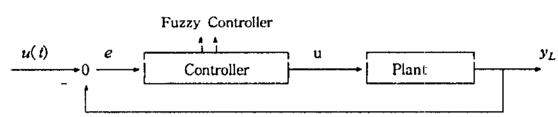


Fig. 3.3 Block Diagram of Proposed controller

Ⅳ. Consideration of the Computer Simulatiom Result

Table 1 is physical parameter using at this simulation. Some results are presented in Figure 4.1, 4.2, 4.3 and 4.4. Figure 4.1 shows the position holding response at initial fluctuation of finger for settling. In fig 4.1(a) is the results of PID control and (b) is fuzzy ones. As shown fig. 4.1 we can see the validity of the proposed controller. Figure 4. 2 show the finger tip displacement y_L following target fluctuation u. Figure 4. show results, which were obtained by taking the first two modes of vibration into account. The natural frequency of the finger was $f_{TH} = 1.7\ Hz$. The target is fluctuating sinusoidal with an amplitude $A_u = 2.15mm$ and frequency $f_u = 1\ Hz$, and the finger tip is following the fluctuation. And fig. 4.4 denote the response of a shock at finger.

Table 1. Physical parameter of flexible finger

	Beam	Piezo Cell
Length(mm)	51.9	33.3
Width(mm)	12.2	12.2
Thickness(mm)	0.3	0.65
Density(Kg/m³)	8670	8300
Young's module(GPa)	102.5	58.03
Damping (s)	4.05×10^{-5}	
Mass of sensor(g)	5.05	
Stiffness(N/m)	2110	

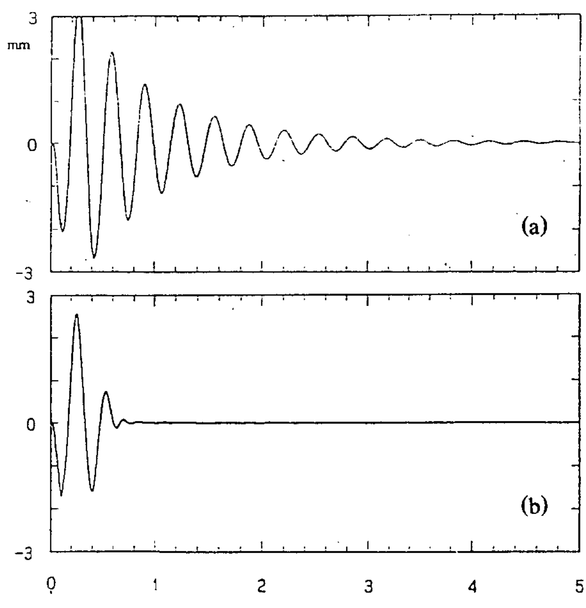
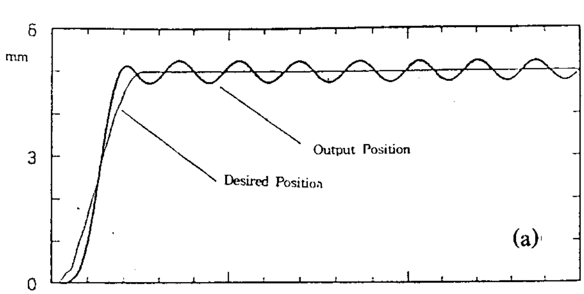


Fig. 4.1 Response of initial fluctuation for settling (a) PID (b) Fuzzy



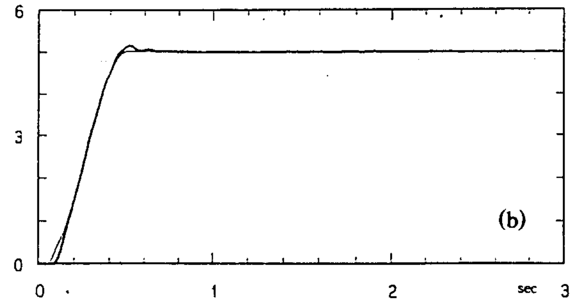
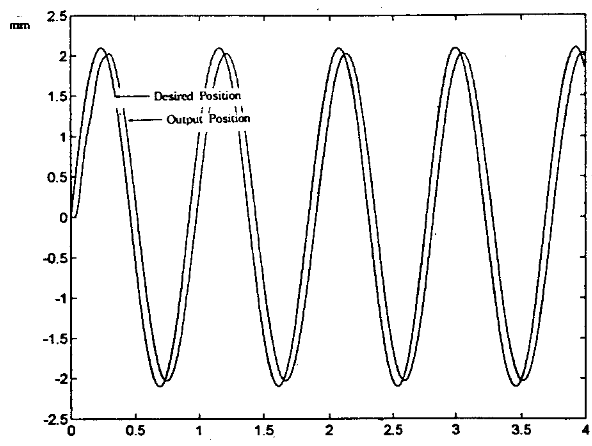
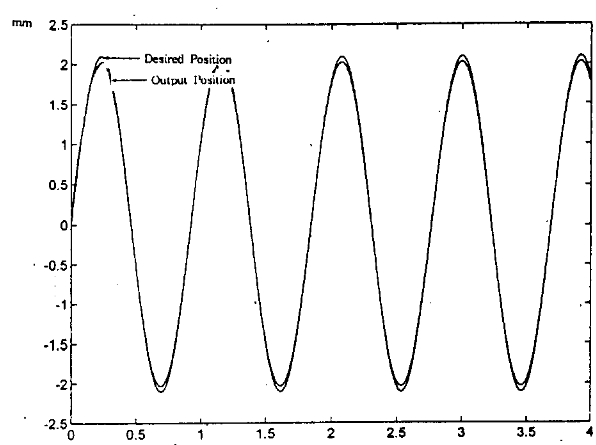


Fig. 4.2 Step fluctuation (a) PID (b) Fuzzy



(a)



(b)

Fig. 4.3 Bounding fluctuation Response (a) PID (b) Fuzzy

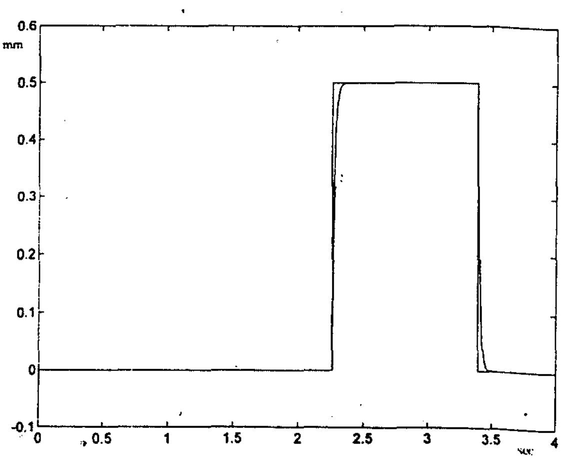


Fig. 4.4 A shock response

V. Conclusion

In this paper, We proposed a theoretical analysis of active position control of slender flexible finger driven by piezoelectric bimorph cells cemented on both side of the finger. Then, we designed PD-Fuzzy controller. This controller designed under conception of PD control strategy. By the computer simulation, we arrived below conclusions.

1. Decrease over-damping of system output which is appeared in Fig. 4.1 and Fig. 4.3.
2. Save the response time when fluctuation is applied.
3. Reducing the number of rules and antecedents of fuzzy inference.
4. Shows the new micro actuator demanding more smaller size and high accuracy control (for robotic finger, moving hard disk head etc.).

Reference

1. Cannon R. H., Jr. and Schmitz, Int. J. Robo Res. 3-3(1984), pp. 62.
2. Skaar, S. B. and Tucker, Trans. ASME. J Appl. Mech 53(1986).
3. Yuh J., J. Robot sys., 4(5) 1987, pp. 621.
4. Yoshida, JSME- C Vol. 54, no. 497, 1988, pp. 201.
5. Dahara, Chonan "Closed loop displacement control..." JSME Int., J. C 31(2) 1988. pp. 409-415.
6. Over, J. C. and Van De Vegta J., IEEE J. Robot Auto., RA-3(5) 1987, pp. 485.
7. Fukuda, Arakawa "Control of flexible robotic arm..." JSME 53(c) 1987, pp. 201-208.
8. Z. W. Jiang, S. Chonan and J. Tani, "Position Control of a Flexible Arm Using Piezoelectric Bimorph Cells", Trans. ASME, Journal of Dynamic System, Measurement, and Control, 113-2(1991), pp. 327-329.
9. S. Chonan, Z. W. Jiang and H. Sato, "End-Point Control of a Miniature Flexible Arm Driven by Piezoelectric Bimorph Cells" The Proceedings of The First Japan-CIS Joint Seminar on Electro-magneto-mechanics in Structures, 1992, pp. 38-41.
10. Jianxin Xu, H. Hashimoto, F. Harashima "Fuzzy Control of Rule Based Dynamic System" 26th SICE Annual Conference, pp. 1237-1240, 1987. 9.
11. F. Hashimoto, Jianxin Xu, "Stability and Controllability of Fuzzy Control System with Energetic Function", 9th SICE Symposium on Dynamical system Theory, 1986. 12, pp. 261-264.
12. Jianxin Xu, H. Hashimoto, F. Harashima, "An Intelligent Learning Control System for Robotic Hands", IEEE International Workshop on Intelligent Robots and Systems, pp. 131-136, 1988. 11.
13. Jaechun Ryu, Chongkug Park "Force Control of a Flexible Robotic Finger With Piezoelectric Actuators using Fuzzy Algorithms" SICE '95 in SAPPORO 1995 pp. 1151-1156.
14. Jaechun Ryu, Chongkug Park "Force Control of a Flexible Robotic Finger." Proceeding of KFIS spring Conference '96, Vol. 6, no. 1.

류 재 춘(Ryu Jae Chun) 정회원
1962년 10월 2일생
1985년 2월 : 경희대학교 전자공학과 (공학사)
1988년 2월 : 경희대학교 전자공학과 (공학석사)
1993년 2월 : 경희대학교 전자공학과 (박사수료)
1992년 3월~현재 : 안양전문대학 전자계산과 조교수
※관심분야 : 퍼지제어, 인공지능, 마이크로 마우스 컴퓨터 네트워크

박 종 국(ChongKug Park) 정회원
한국퍼지 및 지능 시스템학회 논문지 제 6권 3호 참조