

Adaptation of Fuzzy Inferencing: A Survey

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Abstract—Fuzzy inference has numerous applications, ranging from control to forecasting. A number of researchers have suggested how such systems can be tuned during application to enhance inference performance. Inference parameters that can be tuned include the central tendency and dispersion of the input and output fuzzy membership functions, the rule base, the cardinality of the fuzzy membership function sets, the shapes of the membership functions and the parameters of the fuzzy AND and OR operations. In this paper, an overview of these tuning procedures is given. An extensive bibliography is provided of recent literature on the topic.

I. INTRODUCTION

A general fuzzy inference system consists of three parts (see Fig. 1). A crisp input is fuzzified by input membership functions and processed by a fuzzy logic interpretation of a set of fuzzy rules. This is followed by the defuzzification stage resulting in a crisp output. The rule base is typically crafted by an expert; though self organizing procedures have been suggested [8, 135, 147, 146, 145, 156, 214, 217, 220, 231].

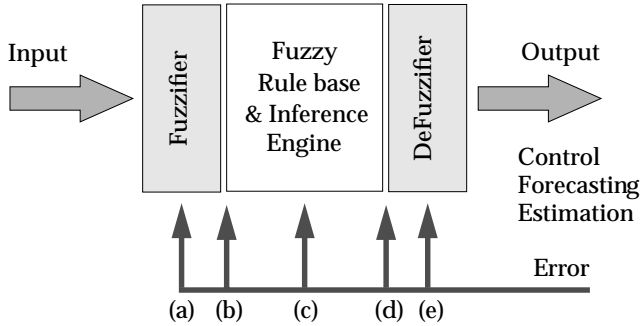


Figure 1: Block diagram of a general fuzzy inference system: The error value from a given performance measure is fed back and used to adapt all or one of the following: (a) Membership function shapes and cardinality (b) & (d) And/Or aggregation operators, (c) The rule base, and (e) The defuzzification technique.

There are a number of different ways to implement the fuzzy inference engine. Among the very first such proposed techniques is that due to Mamdani [156], which describes the inference engine in terms of a fuzzy relation matrix and uses the compositional rule of inference to arrive at the output fuzzy set for a given input fuzzy set. The output fuzzy set is subsequently defuzzified to arrive at a crisp control action. Other techniques include sum-product and threshold inferencing. A review of

these is given by Kosko [131]. The inference methodology we employ here is discussed in [159]. An overview is presented below to motivate our discussion of adaptation of And/Or operators in section A.

Let the input variables be x_p for $1 \leq p \leq P$. The i^{th} membership function in the fuzzifier corresponding to the p^{th} input is $\{\mu_p^i \mid 1 \leq i \leq N_p\}$. We denote the single output by f , with corresponding defuzzification membership functions $\{v^k \mid 1 \leq k \leq K\}$. Generalization of inference and adaptation techniques to more than one output is straightforward.

In the following analysis, for purposes of simplicity, we consider the case $P = 2$ without loss of generality. Defining $N_p = N$ for $p = 1$, and $N_p = M$ for $p = 2$, for a given output membership function v^k , the rules are of the form:

If x_1 is μ_1^i and x_2 is μ_2^j OR If x_1 is μ_1^l and x_2 is μ_2^m OR ...

Then ... f is v^k .

Define a set

$$S_k = \{l, m \mid \mu_1^l \text{ and } \mu_2^m \text{ are antecedents of a rule with consequent } v^k\} \quad (1)$$

The familiar operations to arrive at the output are as follows.

1. Perform a pairwise fuzzy intersection T , on each of the membership values of x_1 and x_2 in μ_1^l and μ_2^m for every rule with consequent v^k , forming activation values ζ :

$$\zeta_{lm}^k = T_{l,m \in S_k}(\mu_1^l(x_1), \mu_2^m(x_2)). \quad (2)$$

Let us assume that the (T -norm) operator T itself is parameterized by α , i.e., $T = T(\alpha)$.

2. Collect activation values for like output membership functions and perform a fuzzy union T^* , where $T^* = T^*(\beta)$

$$w_k = T_{l,m \in S_k}^*(\zeta_{lm}^k) \quad (3)$$

3. These values are defuzzified to generate the output estimated value, $f(x_1, x_2)$, by computing the centroid of the composite membership function μ :

$$\mu = \sum_{k=1}^K w_k v^k \quad (4)$$

$$y(x_1, x_2) = \frac{\sum_{k=1}^K w_k c_k A_k}{\sum_{k=1}^K w_k A_k}, \quad (5)$$

where

$$A_k = \int v^k(x) dx, \quad c_k = \frac{\int x v^k(x) dx}{\int v^k(x) dx}. \quad (6)$$

A_k and c_k are, respectively, the area and centroid of the consequent membership function v^k .

II. ADAPTATION IN FUZZY INFERENCE SYSTEMS

All of the stages of the fuzzy inference system are affected by the choice of certain parameters. A list follows.

A. The Fuzzifier

The fuzzifier in Fig. 1 maps the input onto the possibility domain and has the following parameters:

1. The number of membership functions.
2. The shape of the membership functions (*e.g.* triangle, Gaussian, etc.)
3. The Central tendency (*e.g.* center of mass) and dispersion (*e.g.* standard deviation, bandwidth, or range) of the membership function.

B. The Inference Engine

The inference engine is the system “decision maker” and determines how the system interprets the fuzzy linguistics. Its parameters are those of the aggregation operators, which provide interpretation of connectives “AND” and “Or”.

C. The Defuzzifier

The defuzzification stage maps fuzzy consequents into crisp output values. Its design requires choice of

1. The number of membership functions.
2. The shape of membership functions.
3. The definition of fuzzy implication, *i.e.*, how the value of the consequents from the inference engine impact the output membership functions prior to defuzzification.
4. A measure of central tendency of the consequent altered output membership functions. The center of mass is typically used, although use of medians and modes can also be used to arrive at the crisp output.

It is thus seen that both the fuzzification and defuzzification stages require choices of cardinality, position and shape of membership functions. The defuzzification operation itself can be parameterized, and the inference engine requires choices to be made among numerous fuzzy aggregation operators, which could be parameterized.

All of these parameters can be adaptively adjusted by monitoring a certain target performance measure in a supervised learning environment. Over the years numerous techniques for adaptation of fuzzy membership functions, rule bases, and aggregation operators have been proposed. These techniques include but are not limited to:

- Procyk and Mamdani’s self-organizing process controller [177] which considered the issue of rule generation and adaptation.
- Numerous methods involving the performing of steepest descent on the centroid and dispersion parameters of input and output membership functions [76, 110, 140, 159, 169,

218]. Other algorithms such as random search and conjugate gradient descent can be used in tuning such parameters as well.

- Pruning the number of input and output membership functions, [194, 220].
- Adapting the shape of membership functions (see section IV).
- Adaptation of And/Or aggregation operators. This could occur when the expert designing the rule base is satisfied with both the cardinality and shape of membership functions, as well as the setting up of rules.

As part of the last two categories, we present a technique for adapting the shape of membership functions, as well as a broad methodology for tuning generalized aggregation operators in a fuzzy inference system. For details of other similar techniques, the reader is referred to the extensive bibliography which includes works in the area of adaptive fuzzy inferencing performed over the past few years.

III. ADAPTATION OF GENERALIZED AGGREGATION OPERATORS

Ever since the advent of fuzzy sets [239] and fuzzy control [240, 156], evaluation of fuzzy rules has been widely performed using the MIN and MAX operators for fuzzy intersection and union. Other operators for performing fuzzy intersection and union exist [129]. They fall in the general class of T -norms (for intersection) and T -conorms (for union). A good overview of the theory of such operators is presented by Gupta [63]. Design of fuzzy controllers based on such operators is considered in [64] where it is shown, through simulation studies, that the performance of a fuzzy controller very much depends on the choice of the T -operators for a specific problem. The nature of this dependence however, is not clear due to the complexity of the fuzzy controller, arriving at an analytic solution to this problem appears to be very difficult. Nonetheless, for a given choice of parameterized T -operators, we will show here that obtaining an optimum solution for the value of these parameters is possible. This in turn means that we can arrive at the best representation for a given set of union and intersection operators in a fuzzy inference system, for a given problem.

The process of gradual fine tuning of the values of the parameters of parameterized T -operators involves performing gradient descent on such parameters in a supervised learning environment. We will use techniques analogous to membership function tuning to update the values of the parameters of union and intersection operators.

A. Backward Adjustment

The steps to adapt the fuzzy union and intersection operators within a supervised learning environment, are as follows.

We first form the error function by taking the squared difference between the estimated output f , and the desired target value t :

$$E = \frac{1}{2}(f - t)^2 \quad (7)$$

Assume now that we wish to update parameter α of the intersection operator T by an amount $\Delta\alpha$. We have:

$$\Delta\alpha \propto \frac{\partial E}{\partial \alpha}, \quad (8)$$

where

$$\begin{aligned}
\frac{\partial E}{\partial \alpha} &= \frac{\partial E}{\partial f} \frac{\partial f}{\partial \alpha} \\
&= (f-t) \sum_{k=1}^K \left(\frac{\partial f}{\partial w_k} \frac{\partial w_k}{\partial \alpha} \right) \\
&= (f-t) \sum_{k=1}^K \left(\frac{\partial f}{\partial w_k} \sum_{l,m \in S_k} \left(\frac{\partial w_k}{\partial \zeta_{lm}^k} \frac{\partial \zeta_{lm}^k}{\partial \alpha} \right) \right) \quad (9)
\end{aligned}$$

where

$$\frac{\partial f}{\partial w_k} = \frac{A_k \sum_{p=1}^K w_p A_p (c_k - c_p)}{(\sum_{p=1}^K w_p c_p)^2} \quad (10)$$

and

$$\frac{\partial \zeta_{lm}^k}{\partial \alpha} = \frac{\partial T}{\partial \alpha} \Big|_{x \rightarrow \mu_1^l(x_1) \ y \rightarrow \mu_1^m(x_2)} \quad (11)$$

The operators T and T^* are usually defined for two input variables. This poses no problem in determining $\partial T / \partial \alpha$ as in our problem T is only a function of two input variables. However to determine $\partial w_k / \partial \zeta_{lm}^k$ we need to extend the definition of T^* to N input variables. This can be done using the *associativity* property of fuzzy unions and intersections. For instance, given four input variables x_1, x_2, x_3, x_4 , we perform a fuzzy union T^* on them, in the following way: $T^*\{T^*[T^*(x_1, x_2), x_3], x_4\}$.

Denote a general T -operator by T . The above extension can be written as:

$$\begin{aligned}
&T_0(\alpha, x_1, x_2) \\
&T_1(\alpha, T_0, x_3) \\
&T_2(\alpha, T_2, x_4) \\
&\vdots \\
&T_N(\alpha, T_{N-1}, x_{N+2})
\end{aligned} \quad (12)$$

Denote:

$$T_N^{(1)}(\alpha, T_{N-1}, x_{N+2}) = \frac{\partial T(\alpha, T_{N-1}, x_{N+2})}{\partial \alpha} \quad (13)$$

We have:

$$\begin{aligned}
\frac{dT_N}{d\alpha} &= T_N^{(1)} + \frac{\partial T_N}{\partial T_{N-1}} \frac{dT_{N-1}}{d\alpha} + \frac{\partial T_N}{\partial x_{N+2}} \frac{\partial x_{N+2}}{\partial \alpha} \\
&= T_N^{(1)} + \frac{\partial T_N}{\partial T_{N-1}} \frac{dT_{N-1}}{d\alpha} \quad (14)
\end{aligned}$$

since $\partial x_{N+2} / \partial \alpha = 0$

This can in turn be written in the following recursive way:

$$\frac{dT_N}{d\alpha} = T_N^{(1)} + \frac{\partial T_N}{\partial T_{N-1}} \left[T_{N-1}^{(1)} + \frac{\partial T_{N-1}}{\partial T_{N-2}} \frac{dT_{N-2}}{d\alpha} \right]$$

$$\begin{aligned}
&= T_N^{(1)} + \frac{\partial T_N}{\partial T_{N-1}} \left[T_{N-1}^{(1)} + \frac{\partial T_{N-1}}{\partial T_{N-2}} \right. \\
&\quad \left. \times \left(T_{N-2}^{(1)} + \frac{\partial T_{N-2}}{\partial T_{N-3}} \frac{dT_{N-3}}{d\alpha} \right) \right] \\
&= \dots \quad \dots \quad \dots \quad \frac{dT_0}{d\alpha} \quad (15)
\end{aligned}$$

The incremental update $\Delta \alpha$ to the parameter α can now be computed via Eq. 8.

IV. ADAPTATION OF THE SHAPE OF MEMBERSHIP FUNCTIONS

As a simple example of adaptation of the shape of a membership function, consider the membership function

$$w(x; \nu) = (1 - |x|)^\nu \Pi(x/2) \quad (16)$$

where $\Pi(x/2) = 1$ for $|x| \leq 1$ and is zero otherwise. For $\nu = 1$, Equation 16 is the familiar triangle function while, for $\nu = 0$, it is a rectangular (crisp) membership function. As $\nu \rightarrow \infty$, the function $w(x; \nu)$, by the central limit theorem, becomes Gaussian in shape (with zero width). Note, when using backpropagation,

$$\frac{\partial w(x; \nu)}{\partial \nu} = -\frac{w \ln w}{\nu} \text{sgn}(x) \Pi(x/2)$$

Other examples of shape adaptation have, to the best of our knowledge, not been published.

V. CONCLUSIONS

Performance of fuzzy inference systems can be improved by adaptively tuning a subset of its large number of parameters. The error value formed by comparing actual performance to target performance is used in the adaptation process. The subset choice resulting in the best performance improvement remains unclear. The error value can be fed back as additional input also, though this could have implications for the stability of the system.

REFERENCES

- [1] Aldridge-J. Automated tuning and generation of fuzzy control systems. *ISA Transactions*. vol.31, no.4, pages 15-17, 1992.
- [2] Arabshahi-P, Choi-J-J, Marks-R-J-II, and Caudell-T-P. Fuzzy control of backpropagation. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 967-72, 1992.
- [3] Araki-S, Nomura-H, Hayashi-I, and Wakami-N. A self-generating method of fuzzy inference rules. In *Fuzzy Engineering Toward Human Friendly Systems, Yokohama, Japan, 13-15 Nov. 1991*, pages 1047-58. IOS Press: Amsterdam, Netherlands, 1992.
- [4] Ashida-H and Ichihashi-H. Fuzzy learning control of a biped locomotive robot. In *Fuzzy Engineering Toward Human Friendly Systems, Yokohama, Japan, 13-15 Nov. 1991*, pages 1013-23. IOS Press: Amsterdam, Netherlands, 1992.
- [5] Astrom-K-J. Directions in intelligent control. In Devanathan-R., editor, *Intelligent Tuning and Adaptive Control: Selected Papers from the IFAC Symposium, Singapore*, pages 1-9. Pergamon Press: Oxford, UK, 1991.
- [6] Batur-C and Kasparian-V. Application of a self tuner using fuzzy control techniques. In *Proc. 2nd International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems, IEA/AIE - 89, Tullahoma, TN, USA*, pages 235-44, 1989.
- [7] Batur-C and Kasparian-V. A real time fuzzy self tuning control. In *Proc. 1989 American Control Conference, Pittsburgh, PA, USA*, pages 1810-15, 1989.
- [8] Batur-C and Kasparian-V. Self-organizing model based expert controller. In *Proc. IEEE International Conference on Systems Engineering, Fairborn, OH, USA*, pages 411-14, 1989.

- [9] Batur-C and Kasparian-V. Adaptive expert control. *International Journal of Control*. vol.54, no.4, pages 867–81, 1991.
- [10] Batur-C and Kasparian-V. Model based fuzzy control. *Mathematical and Computer Modelling*. vol.15, no.12, pages 3–14, 1991.
- [11] Batur-C and Kasparian-V. Fuzzy adaptive control. *International Journal of Systems Science*. vol.24, no.2, pages 301–14, 1993.
- [12] Berenji-H. Neural networks and fuzzy logic in intelligent control. In *Proc. 5th IEEE International Symposium on Intelligent Control*. Philadelphia, PA, USA., pages 916–20, 1990.
- [13] Berenji-H-R. On the integration of reinforcement learning and approximate reasoning for control. In *Proc. 30th IEEE Conference on Decision and Control*, Brighton, UK, pages 1900–4, 1991.
- [14] Berenji-H-R. A reinforcement learning-based architecture for fuzzy logic control. *International Journal of Approximate Reasoning*. vol.6, no.2, pages 267–92, 1992.
- [15] Berenji-H-R and Khedkar-P. Learning and tuning fuzzy logic controllers through reinforcements. *IEEE Transactions on Neural Networks*. vol.3, no.5, pages 724–40, 1992.
- [16] Bersini-H, Nordvik-J-P, and Bonarini-A. A simple direct adaptive fuzzy controller derived from its neural equivalent. In *Proc. 2nd IEEE International Conference on Fuzzy Systems*, San Francisco, CA, USA, pages 345–50, 1993.
- [17] Bezdek-J-C. A note on generalized self-organizing network algorithms. In *Proc. SPIE*, vol. 1293, pt.1: *Applications of Artificial Intelligence VIII*, Orlando, FL, USA, pages 260–7, 1990.
- [18] Bezdek-J-C, Tsao-E-C-K, and Pal-N-R. Fuzzy kohonen clustering networks. In *Proc. 1st IEEE International Conference on Fuzzy Systems*, San Diego, CA, USA, pages 1035–43, 1992.
- [19] Blishun-A-F. Fuzzy inductive training models in expert systems. *Tekhnicheskaya Kibernetika: Soviet Journal of Computer and Systems Sciences*. vol.28, no.2, pages 94–104, 1990.
- [20] Boscolo-A and Drius-F. Computer aided tuning tool for fuzzy controllers. In *Proc. 2nd IEEE International Conference on Fuzzy Systems*, San Francisco, CA, USA, pages 291–96, 1993.
- [21] Botta-M, Giordana-A, and Saitta-L. Learning fuzzy concept definitions. In *Proc. 2nd IEEE International Conference on Fuzzy Systems*, San Francisco, CA, USA, pages 18–22, 1993.
- [22] Brown-M, Fraser-R, Harris-C-J, and Moore-C-G. Intelligent self-organising controllers for autonomous guided vehicles: comparative aspects of fuzzy logic and neural nets. In *Proc. International Conference on Control '91 (IEE)*, Edinburgh, UK. vol. 1, pages 134–9, 1991.
- [23] Brown-M and Harris-C-J. A nonlinear adaptive controller: a comparison between fuzzy logic control and neurocontrol. *IMA Journal of Mathematical Control and Information*. vol.8, no.3, pages 239–65, 1991.
- [24] Burkhardt-D-G and Bonissone-P-P. Automated fuzzy knowledge base generation and tuning. In *Proc. 1st IEEE International Conference on Fuzzy Systems*, San Diego, CA, USA, pages 179–88, 1992.
- [25] Chand-S. On-line, self-monitoring tuner for proportional integral derivative controllers. In *Proc. 30th IEEE Conference on Decision and Control*. Brighton, UK, vol.2, pages 1905–16, 1991.
- [26] Chang-Goo-Lee and Sung-Joong-Kim. A study on the rule-based auto-tuning pid controller. *Transactions of the Korean Institute of Electrical Engineers*. vol.40, no.11, pages 1161–8, 1991.
- [27] Chen-Y-Y and Lin-K-Z. Learning behavior of fuzzy controllers with neuron adaptive elements. In *Proc. 1992 American Control Conference (IEEE)*, Chicago, IL, USA, vol.3, pages 1878–82, 1992.
- [28] Chen-Y-Y, Lin-K-Z, and Hsu-S-T. A self-learning fuzzy controller. In *Proc. 1st IEEE International Conference on Fuzzy Systems*, San Diego, CA, USA, pages 189–96, 1992.
- [29] Chi-Cheng-Jou. A fuzzy cerebellar model articulation controller. In *Proc. 1st IEEE International Conference on Fuzzy Systems*, San Diego, CA, USA, pages 1171–8, 1992.
- [30] Chuen-Chien-Lee. A self-learning rule-based controller employing approximate reasoning and neural net concepts. *International Journal of Intelligent Systems*. vol.6, no.1, pages 71–93, 1991.
- [31] Daley-S and Gill-K-F. Comparison of a fuzzy logic controller with a P+D control law. *Transactions of the ASME: Journal of Dynamic Systems, Measurement and Control*. vol.111, no.2, pages 128–37, 1989.
- [32] Dasarathy-B-V. Flute: fuzzy learning in unfamiliar teacher environments. In *Proc. 1st IEEE International Conference on Fuzzy Systems*, San Diego, CA, USA, pages 1070–7, 1992.
- [33] Dasarathy-B-V. Fuzzy learning in vicissitudinous environments. In *Proc. 11th IAPR International Conference on Pattern Recognition*. vol.II. Conference B: *Pattern Recognition Methodology and Systems*, The Hague, Netherlands, pages 500–3, 1992.
- [34] Daugherty-W-C, Rathakrishnan-B, and Yen-J. Performance evaluation of a self-tuning fuzzy controller. In *Proc. 1st IEEE International Confer-*
- [35] Valente de Oliveira-J and Lemos-J-M. System modelling and fuzzy relational identification. In *Proc. 2nd IEEE International Conference on Fuzzy Systems*, San Francisco, CA, USA, pages 1074–78, 1993.
- [36] de Silva-C-W. Fuzzy adaptation and control of a class of dynamic systems. In *Proc. 5th IEEE International Symposium on Intelligent Control 1990*, Philadelphia, PA, USA vol.1, pages 304–9, 1990.
- [37] de Silva-C-W. A two-level servo structure with knowledge-based tuning. *Engineering Applications of Artificial Intelligence*. vol.3, no.3, pages 180–5, 1990.
- [38] Dote-Y, Suyitno-A, and Strefezza-M. Fuzzy learning grasping force controller for manipulator hand. In *Proc. 29th IEEE Conference on Decision and Control*, Honolulu, HI, USA vol.5, pages 2646–7, 1990.
- [39] Dote-Y, Suyitno-A, and Strefezza-M. Fuzzy learning grasping force controller for manipulator hand. In *Intelligent Motion Control: Proc. IEEE International Workshop*, Istanbul, Turkey, vol.1, pages 87–93, 1990.
- [40] Dote-Y, Suyitno-A, and Strefezza-M. Fuzzy learning grasping force controller for manipulator hand. In *Proc. IECON '90: 16th Annual Conference of IEEE Industrial Electronics Society*, Pacific Grove, CA, USA, pages 1259–65, 1990.
- [41] Esogbue-A and Murrell-J-A. A fuzzy adaptive controller using reinforcement learning neural networks. In *Proc. 2nd IEEE International Conference on Fuzzy Systems*, San Francisco, CA, USA, pages 178–83, 1993.
- [42] Fei-J and Isik-C. Adaptive fuzzy control via modification of linguistic variables. In *Proc. 1st IEEE International Conference on Fuzzy Systems*, San Diego, CA, USA, pages 399–406, 1992.
- [43] Feldkamp-L-A and Puskorius-G-V. Trainable fuzzy and neural-fuzzy systems for idle-speed control. In *Proc. 2nd IEEE International Conference on Fuzzy Systems*, San Francisco, CA, USA, pages 45–51, 1993.
- [44] Feng-Hongjuan and Wang-Shoujue. On self-organizing fuzzy control algorithm with regulating the control rules directly. *Acta Electronica Sinica*. vol.20, no.2, pages 10–16, 1992.
- [45] Filev-D-P and Yager-R-R. A generalized defuzzification method via BAD distributions. *International Journal of Intelligent Systems*. vol.6, no.7, pages 687–97, 1991.
- [46] Fu-L-M. Connectionism for fuzzy learning in rule-based expert systems. In *Industrial and Engineering Applications of Artificial Intelligence and Expert Systems: 5th International Conference*, IEA/AIE-92, Paderborn, Germany, pages 337–40, 1992.
- [47] Fukuda-T and Shibata-T. Neural network applications for robotic motion control. In *Intelligent Motion Control: Proc. IEEE International Workshop*, Istanbul, Turkey, vol.1, pages SL31–6, 1990.
- [48] Fukuda-T and Shibata-T. Hierarchical intelligent control for robotic motion by using fuzzy, artificial intelligence, and neural network. In *Proc. IJCNN International Joint Conference on Neural Networks*, Baltimore, MD, USA, vol.1, pages 269–74, 1992.
- [49] Fukuda-T and Shibata-T. Theory and applications of neural networks for industrial control systems. *IEEE Transactions on Industrial Electronics*. vol.39, no.6, pages 472–89, 1992.
- [50] Fukuda-T, Shibata-T, Tokita-M, and Mitsuoka-T. Adaptation and learning by neural network and fuzzy set theory for robotic manipulator. In *Artificial Intelligence in the Pacific Rim: Proc. Pacific Rim International Conference on Artificial Intelligence*, Nagoya, Japan, pages 853–8, 1990.
- [51] Fukuda-T, Shibata-T, Tokita-M, and Mitsuoka-T. Adaptation and learning for robotic manipulator by neural network. In *Proc. 29th IEEE Conference on Decision and Control*, Honolulu, HI, USA, vol.6, pages 3283–8, 1990.
- [52] Fukuda-T, Shibata-T, Tokita-M, and Mitsuoka-T. Neuromorphic control: adaptation and learning. *IEEE Transactions on Industrial Electronics*. vol.39, no.6, pages 497–503, 1992.
- [53] Funabashi-M, Aoki-I, Yahiro-M, and Inoue-H. A fuzzy model based control scheme and its application to a road tunnel ventilation system. In *Proc. IECON '91: 1991 International Conference on Industrial Electronics, Control and Instrumentation*, Kobe, Japan, vol.2 (IEEE), pages 1596–601, 1991.
- [54] Furuhashi-T, Horikawa-S, and Uchikawa-Y. An application of fuzzy neural networks to a stability analysis of fuzzy control systems. In *Proc. 2nd IEEE International Conference on Fuzzy Systems*, San Francisco, CA, USA, pages 369–74, 1993.
- [55] Furuta-H, Umamo-M, Kawakami-K, Ohtani-H, and Shiraishi-N. A fuzzy expert system for durability assessment of bridge decks. In *Proc. First International Symposium on Uncertainty Modeling and Analysis*, College Park, MD, USA, (IEEE), pages 522–7, 1990.
- [56] Gader-P-D. Template generation for pattern classification. In *Proc. SPIE*, vol.1769: *Image Algebra and Morphological Image Processing III*, San Diego, CA, USA, pages 72–81, 1992.
- [57] Graham-B-P and Newell-R-B. Fuzzy adaptive control of a first-order

- process. *Fuzzy Sets and Systems*. vol.31, no.1, pages 47–65, 1989.
- [58] Guang-Geng and Dexter-A-L. Fuzzy gain scheduling control of a nonlinear hvac system. In *Proc. 28th Annual Allerton Conference on Communication, Control and Computing, Monticello, IL, USA*, pages 1044–52, 1990.
- [59] Guély-F and Siarry-P. Gradient descent method for optimizing various fuzzy rule bases. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 1241–46, 1993.
- [60] Guo-P, Ni-X-Z, and Zheng-J. Polymer extrusion production control using active recognition and adaptive control system. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 779–84, 1993.
- [61] Gupta-M-M. Fuzzy neural computing systems. In *Proc. SPIE, vol.1710: Science of Artificial Neural Networks. Orlando, FL, USA, pt.1. vol.2*, pages 489–99, 1992.
- [62] Gupta-M-M and Gorzalczy-M-B. Fuzzy neuro-computational technique and its application to modelling and control. In *Proc. 1991 IEEE International Joint Conference on Neural Networks, Singapore, vol.2*, pages 1454–7, 1991.
- [63] M.M. Gupta and J. Qi, “Theory of T-norms and Fuzzy inference Methods,” *Fuzzy Sets and Systems*, Vol. 40, pp. 431–450, 1991.
- [64] M.M. Gupta and J. Qi, “Design of Fuzzy Logic Controllers Based on Generalized T-operators,” *Fuzzy Sets and Systems*, Vol. 40, pp. 473–489, 1991.
- [65] Gutierrez-E-A, Rosa-L-C, and Lopez-J-R-A. Direct digital and self-organizing controller for a servo-system using fuzzy algorithms. In *Proc. IASTED International Symposium Artificial Intelligence Application and Neural Networks - AINN '90, Zurich, Switzerland*, pages 114–17, 1990.
- [66] Hall-L-O and Romaniuk-S-G. A hybrid connectionist, symbolic learning system. In *AAAI-90: Proc. 8th National Conference on Artificial Intelligence, Boston, MA, USA, vol.2*, pages 783–8, 1990.
- [67] Harris-C-J and Brown-M. Intelligent control for autonomous guided vehicles. In *Proc. IEE Colloquium on “Intelligent Control” (Digest No.044), London, UK*, pages 3/1–4, 1991.
- [68] Harris-C-J and Moore-C. Real time fuzzy based self-learning predictors and controllers. In *Automatic Control World Congress 1990, “In the Service of Mankind”: Proc. 11th Triennial World Congress of the International Federation of Automatic Control. Tallin, USSR, vol.4*, pages 193–8, 1990.
- [69] Harris-C-J and Moore-C-G. Intelligent identification and control for autonomous guided vehicles using adaptive fuzzy-based algorithms. *Engineering Applications of Artificial Intelligence. vol.2, no.4*, pages 267–85, 1989.
- [70] Harris-C-J and Read-A-B. Knowledge based fuzzy motion control of autonomous vehicles. In *Artificial Intelligence in Real-Time Control: Proc. IFAC Workshop, Swansea, UK*, pages 139–44, 1988.
- [71] Hassan-M-A-M, Malik-O-P, and Hope-G-S. A fuzzy logic based self-tuned power system stabilizer. In *3rd International Conference on Power System Monitoring and Control (Conf. Publ. No.336), London, UK, (IEE)*, pages 146–51, 1991.
- [72] Hayashi-I, Naito-E, and Wakami-N. A proposal of fuzzy connective with learning function and its application to fuzzy information retrieval. In *Fuzzy Engineering Toward Human Friendly Systems, Yokohama, Japan, 13-15 Nov. 1991*, pages 446–55. IOS Press: Amsterdam, Netherlands, 1992.
- [73] Hayashi-I, Nomura-H, and Wakami-N. Neural-network-driven fuzzy reasoning model. In *SICE '89: Proc. 28th SICE Annual Conference, (IEEE)*, pages 1343–6, 1989.
- [74] Hayashi-I, Nomura-H, Yamasaki-H, and Wakami-N. Construction of fuzzy inference rules by ndf and ndfl. *International Journal of Approximate Reasoning. vol.6, no.2*, pages 241–6, 1992.
- [75] Hayashi-Y, Buckley-J-J, and Czogala-E. Systems engineering applications of fuzzy neural networks. *Journal of Systems Engineering. vol.2, no.4*, pages 232–6, 1992.
- [76] Y. Hayashi, E. Czogala, and J.J. Buckley, “Fuzzy Neural Controller,” *Proc. First IEEE Int. Conf. Fuzzy Systems*, San Diego, CA, March 8-12, 1992.
- [77] He-S-Z, Tan-H, Xu-F-L, and Wang-P-Z. Pid self-tuning control using a fuzzy adaptive mechanism. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 708–13, 1993.
- [78] He-S-Z, Tan-S-H., Hang-C-C, and Wang-P-Z. Design of an online rule-adaptive fuzzy control system. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 83–91, 1992.
- [79] Hirota-K. Viewpoints of application of extended fuzzy control to processes. *Instrumentation and Control Engineering. vol.32, no.8*, pages 6–8, 1989.
- [80] Ho-J-M and Lin-S-R. A learning algorithm for fuzzy self-organizing controller. In *Intelligent Motion Control: Proc. IEEE International Workshop, Istanbul, Turkey, vol.1*, pages 55–60, 1990.
- [81] Homaifar-A and McCormick-E. Full design of fuzzy controllers using genetic algorithms. In *Proc. SPIE, vol.1766: Neural and Stochastic Methods in Image and Signal Processing, San Diego, CA, USA*, pages 393–404, 1992.
- [82] Hong-Tae-Jun. Realization of a fuzzy neural controller. *Proc. Korean Institute of Electrical Engineers. vol.40, no.4*, pages 59–65, 1991.
- [83] Hong-Tae-Jun. A neuro-fuzzy control system. *Korea Information Science Society Review. vol.10, no.1*, pages 73–80, 1992.
- [84] Hong-Yao-Xu, Baird-C-R, and Riordan-D. Intelligent tuning control for systems with uncertainties. In *Proc. ISMM International Symposium Computer Applications in Design, Simulation and Analysis, MIMI '90, New Orleans, LA, USA*, pages 305–9, 1990.
- [85] Horikawa-S, Furuhashi-T, Okuma-S, and Uchikawa-Y. Composition methods of fuzzy neural networks. In *Proc. IECON '90: 16th Annual Conference of IEEE Industrial Electronics Society, Pacific Grove, CA, USA, vol.2*, pages 1253–8, 1990.
- [86] Horikawa-S, Furuhashi-T, Okuma-S, and Uchikawa-Y. A learning fuzzy controller using a neural network. *Transactions of the Society of Instrument and Control Engineers. vol.27, no.2*, pages 208–15, 1991.
- [87] Horikawa-S, Furuhashi-T, and Uchikawa-Y. On identification of structures in premises of a fuzzy model using a fuzzy neural network. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 661–66, 1993.
- [88] Horikawa-S, Furuhashi-T, Uchikawa-Y, and Tagawa-T. A study on fuzzy modeling using fuzzy neural networks. In *Fuzzy Engineering Toward Human Friendly Systems, Yokohama, Japan, 13-15 Nov. 1991*, pages 562–73. IOS Press: Amsterdam, Netherlands, 1992.
- [89] Horikawa-S-i, Furuhashi-T, and Uchikawa-Y. On fuzzy modeling using fuzzy neural networks with the back-propagation algorithm. *IEEE Transactions on Neural Networks. vol.3, no.5*, pages 801–6, 1992.
- [90] Hsu-L-S, Teh-H-H, Wang-P-Z, Chan-S-C, and Loe-K-F. Fuzzy neural-logic system. In *Proc. IJCNN International Joint Conference on Neural Networks, Baltimore, MD, USA, vol.1*, pages 245–50, 1992.
- [91] Hu-B and Ding-G. Cell state space algorithm and neural network based fuzzy logic controller. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 247–50, 1993.
- [92] Hu-Shaohua and Liu-Shaomin. On the method of self-generating and self-tuning control rule model. *Acta Automatica Sinica. vol.17, no.5*, pages 606–10, 1991.
- [93] Hung-C-C and R-B-Fernández. Minimizing rules of fuzzy logic system by using a systematic approach. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 38–44, 1993.
- [94] Hunt-B-R, Qi-Y-Y, and DeKruger-D. A generalization method for back-propagation using fuzzy sets. In *Proc. 3rd Australian Conference on Neural Networks (ACNN '92), Canberra, ACT, Australia*, pages 12–16, 1992.
- [95] Jun ichi Tanji and Konoshita-M. A self-organizing fuzzy controller for multivariable cooperative control system. *Transactions of the Society of Instrument and Control Engineers. vol.26, no.8*, pages 964–71, 1990.
- [96] Ikebuchi-S and Kojiri-T. Real-time drought control of storage reservoir by combining middle and long-term weather forecast and fuzzy inference. In *Proc. Applications of Artificial Intelligence in Engineering VI. Oxford, UK*, pages 665–81, 1991.
- [97] Ikeda-K-S and Tulunay-E. Fuzzy controller and examples concerning the automatic start up of the fluidized bed combustor. In *Intelligent Motion Control: Proc. IEEE International Workshop, Istanbul, Turkey, vol.1*, pages 95–101, 1990.
- [98] Imasaki-N, Kiji-J, and Arai-M. Framework for fuzzy neural networks. In *Proc. SPIE, vol.1710, pt.1, vol.2: Science of Artificial Neural Networks. Orlando, FL, USA*, pages 535–46, 1992.
- [99] Isaka-S and Sebald-A-V. An adaptive fuzzy controller for blood pressure regulation. In *Images of the Twenty-First Century: Proc. Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Seattle, WA, USA, vol.6*, pages 1763–4, 1989.
- [100] Isaka-S, Sebald-A-V, Karimi-A, Smith-N-T, and Quinn-M-L. On the design and performance evaluation of adaptive fuzzy controllers. In *Proc. 27th IEEE Conference on Decision and Control. Austin, TX, USA, vol.2*, pages 1068–9, 1988.
- [101] Ishibuchi-H, Nozaki-K, and Tanaka-H. Empirical study on learning in fuzzy systems. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 606–11, 1993.
- [102] Ishibuchi-H, Nozaki-K, and Yamamoto-N. Selecting fuzzy rules by genetic algorithm for classification problems. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 1119–24, 1993.

- [103] Ishibuchi-H, Tanaka-H, Tanaka-R, Tamura-R, and Fujioka-R. Identification of membership functions by neural networks. *Transactions of the Institute of Electronics, Information and Communication Engineers D-II*. vol.J73D-II, no.8, pages 1227–32, 1990.
- [104] Ito-O. Direction of effective utilization of fuzzy adaptive control using hierarchical control rules. *Instrumentation and Control Engineering*. vol.32, no.8, pages 9–13, 1989.
- [105] Iwasaki-T and Morita-A. Auto-tuning of servo motors. *Mitsubishi Denki Gihō*. vol.66, no.7, pages 27–30, 1992.
- [106] Iwata-T, Machida-K, and Toda-Y. Fuzzy control using neural network techniques. In *Proc. IJCNN International Joint Conference on Neural Networks, San Diego, CA, USA*, vol.3. (IEEE), pages 365–70, 1990.
- [107] Jager-R, Krijgsman-A-J, Verbruggen-H-B, and Bruijn-P-M. Rule-based controller using fuzzy logic. In *Proc. Engineering Systems with Intelligence: Concepts, Tools and Applications, Corfu, Greece*, pages 423–30, 1991.
- [108] Jager-R, Verbruggen-H-B, Bruijn-P-M, and Krijgsman-A-J. Real-time fuzzy expert control. In *Proc. International Conference on Control '91 (Conf. Publ. No.332), Edinburgh, UK, (IEE)*, vol.2, pages 966–70, 1991.
- [109] Jamshidi-M, Baugh-S, Barak-D, and Vadiie-N. A comparison of an expert and an adaptive fuzzy control approach. In *Proc. 30th IEEE Conference on Decision and Control, Brighton, UK* vol.2, pages 1907–8, 1991.
- [110] Jang-J-S-R. Fuzzy controller design without domain experts. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 289–96, 1992.
- [111] Jang-J-S-R. Self-learning fuzzy controllers based on temporal backpropagation. *IEEE Transactions on Neural Networks*. vol.3, no.5, pages 714–23, 1992.
- [112] Jang-J-S-R and Sun-C-T. Functional equivalence between radial basis function networks and fuzzy inference systems. *IEEE Transactions on Neural Networks*. vol.4, no.1, pages 156–9, 1993.
- [113] Jeong-Jun-Song and Sunwon-Park. A fuzzy dynamic learning controller for chemical process control. *Fuzzy Sets and Systems*. vol.54, no.2, pages 121–33, 1993.
- [114] Jong-Soo-Kim, Hong-Gi-Lee, and Hong-Tae-Jeon. Position control of the robot manipulator using fuzzy logic and multi-layer neural network. *Journal of the Korean Institute of Telematics and Electronics*. vol.28B, no.11, pages 83–9, 1991.
- [115] Jou-C-C. Supervised learning in fuzzy systems: algorithms and computational capabilities. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 1–6, 1993.
- [116] Kajitani-Y, Kuwata-K, Katayama-R, and Nishida-Y. An automatic fuzzy modeling with constraints of membership functions and a model determination of neuro and fuzzy model by plural performance indices. In *Fuzzy Engineering Toward Human Friendly Systems, Yokohama, Japan, 13-15 Nov. 1991*, pages 586–97. IOS Press: Amsterdam, Netherlands, 1992.
- [117] Kang-H and Vachtsevanos-G. Adaptive fuzzy logic control. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 407–14, 1992.
- [118] Karimi-A, Sebald-A-V, and Isaka-S. Use of simulated annealing in design of very high dimensioned minimax adaptive controllers. In *Conference Record: 23rd Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA*, vol.1 (IEEE), pages 116–18, 1989.
- [119] Karr-C-L, Freeman-L-M, and Meredith-D-L. Improved fuzzy process control of spacecraft autonomous rendezvous using a genetic algorithm. In *Proc. SPIE*, vol.1196: *Intelligent Control and Adaptive Systems, Philadelphia, PA, USA*, pages 274–88, 1989.
- [120] Katoh-A and Kubota-H. A variable step gain algorithm with fuzzy control. *Transactions of the Institute of Electronics, Information and Communication Engineers A*. vol.J73A, no.11, pages 1844–50, 1990.
- [121] Katoh-A and Kubota-H. A variable step gain algorithm with fuzzy control. *Electronics and Communications in Japan, Part 3 (Fundamental Electronic Science)*. vol.74, no.7, pages 58–66, 1991.
- [122] Keller-J-M, Krishnapuram-R, and Rhee-F-C-H. Evidence aggregation networks for fuzzy logic inference. *IEEE Transactions on Neural Networks*. vol.3, no.5, pages 761–9, 1992.
- [123] Keller-J-M and Tahani-H. Backpropagation neural networks for fuzzy logic. *Information Sciences*. vol.62, no.3, pages 205–21, 1992.
- [124] Keller-J-M and Yager-R-R. Fuzzy logic inference neural networks. In *Proc. SPIE*, vol.1192, pt.2: *Intelligent Robots and Computer Vision VIII: Algorithms and Techniques, Philadelphia, PA, USA*, pages 582–91, 1989.
- [125] Keller-J-M, Yager-R-R., and Tahani-H. Neural network implementation of fuzzy logic. *Fuzzy Sets and Systems*. vol.45, no.1, pages 1–12, 1992.
- [126] Khan-E and Venkatapuram-P. Neufuz: Neural network based fuzzy logic design algorithms. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 647–54, 1993.
- [127] Kim-C-J and Russell-B-D. A structure of fuzzy decision-making system on Fuzzy Systems, San Francisco, CA, USA, pages 998–1003, 1993.
- [128] King-K-H. The status and future development of fuzzy logic control system. In *Control 92: Enhancing Australia's Productivity Through Automation, Control and Instrumentation, Preprints of Papers, Perth, WA, Australia*, pages 59–67, 1992.
- [129] George Klir and Tina Folger, **Fuzzy sets, uncertainty, and information**. Englewood Cliffs, N.J.: Prentice Hall, 1988.
- [130] Komori-Y, Waibel-A-H, and Sagayama-S. A neural fuzzy training approach for improving speech recognition. *Transactions of the Institute of Electronics, Information and Communication Engineers D-II*. vol.J75D-II, no.7, pages 1101–10, 1992.
- [131] B. Kosko, *Neural Networks and Fuzzy Systems: A Dynamical Approach to Machine Intelligence*. Englewood Cliffs, New Jersey: Prentice Hall, 1990.
- [132] Kong-S-G and Kosko-B. Adaptive fuzzy systems for backing up a truck-and-trailer. *IEEE Transactions on Neural Networks*. vol.3, no.2, pages 211–23, 1992.
- [133] Krishnapuram-R-J and Joonwhoan-Lee. Propagation of uncertainty using neural networks. In *Proc. of the SPIE*, vol.1002: *Intelligent Robots and Computer Vision*. Cambridge, MA, USA, pages 377–83, 1988.
- [134] Kubota-H. Adaptive algorithm. iv. *Journal of the Institute of Electronics, Information and Communication Engineers*. vol.74, no.8, pages 841–6, 1991.
- [135] Langari-G and Tomizuka-M. Self organizing fuzzy linguistic control with application to arc welding. In *Proc. IROS '90: IEEE International Workshop on Intelligent Robots and Systems '90, Towards a New Frontier of Applications, Ibaraki, Japan*, vol.2, pages 1007–14, 1990.
- [136] Lee-M-A and Takagi-H. Integrating design stages of fuzzy systems using genetic algorithms. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 612–17, 1993.
- [137] Lee-S-J, Chen-S-S., and Kao-M. A neural network approach to self-organizing controller design. In *Proc. ISMM International Symposium Computer Applications in Design, Simulation and Analysis, MIMI '90, New Orleans, LA, USA*, pages 273–6, 1990.
- [138] Li-C-J and Tzou-J-C. A new learning fuzzy controller based on the p-integrator concept. *Fuzzy Sets and Systems*. vol.48, no.3, pages 297–303, 1992.
- [139] Li-Shiyong, Sheng-Andong, and Hu-Hengzhang. The application of system simulation in artificial intelligent control. In *Proc. Beijing International Conference on System Simulation and Scientific Computing, Beijing, China*, vol.2, pages 704–6, 1989.
- [140] Lin-C-T and Lee-C-S-G. Neural-network-based fuzzy logic control and decision system. *IEEE Transactions on Computers*. vol.40, no.12, pages 1320–36, 1991.
- [141] Lin-C-T and Lee-C-S-G. Real-time supervised structure/ parameter learning for fuzzy neural network. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 1283–91, 1992.
- [142] Lin-C-T and Shen-Z. Reinforcement structure/parameter learning for neural-network based fuzzy logic control systems. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 88–93, 1993.
- [143] Ling-K-V, Dexter-A-L, Geng-G, and Haves-P. Self-tuning control with fuzzy rule-based supervision for hvac applications. In *Intelligent Tuning and Adaptive Control: Selected Papers from the IFAC Symposium (IEEE)*, Singapore, pages 205–9, 1991.
- [144] Linkens-D-A. Intelligent control in anaesthesia. *Asia-Pacific Engineering Journal, Part A (Electrical Engineering)*. vol.2, no.1, pages 31–46, 1992.
- [145] Linkens-D-A and Abbod-M-F. Fast, self-organizing control for industrial processes. In *Algorithms and Architectures for Real-Time Control: Proc. IFAC Workshop, Bangor, UK*, pages 153–7, 1991.
- [146] Linkens-D-A and Abbod-M-F. On-line self-organizing fuzzy logic controller with patient simulators. In *Proc. IEE Colloquium on Knowledge-Based Control: Principles and Applications (Digest No.091)*, London, UK, pages 4/1–5, 1991.
- [147] Linkens-D-A and Abbod-M-F. Self-organizing fuzzy logic control for real-time processes. In *Proc. International Conference on Control '91 (Conf. Publ. No.332), Edinburgh, UK, (IEE)*, vol.2, pages 971–6, 1991.
- [148] Linkens-D-A and Hasnain-S-B. Self-organising fuzzy logic control and application to muscle relaxant anaesthesia. *IEE Proc. D (Control Theory and Applications)*. vol.138, no.3, pages 274–84, 1991.
- [149] Linkens-D-A and Junhong-Nie. Constructing rule-bases for multivariable fuzzy control by self-learning. 1. system structure and learning algorithms. *International Journal of Systems Science*. vol.24, no.1, pages 111–27, 1993.
- [150] Linkens-D-A, Mahfouf-M, and Abbod-M. Self-adaptive and self-

- organising control applied to nonlinear multivariable anaesthesia: a comparative model-based study. *IEE Proc. D (Control Theory and Applications)*. vol.139, no.4, pages 381–94, 1992.
- [151] Linkens-D-A and Nie-J. Constructing rule-bases for multivariable fuzzy control by self-learning. 2. rule-base formation and blood pressure control application. *International Journal of Systems Science*. vol.24, no.1, pages 129–57, 1993.
- [152] Liu-Xihui, Sun-Baocheng, and Feng-Wenyuan. Fuzzy reasoning with engineering applications using neural networks. In *Proc. Artificial Intelligence and Structural Engineering*, Oxford, UK, pages 279–84, 1991.
- [153] Maeda-A, Ichimori-T, and Funabashi-M. Flip-net: A network representation of fuzzy inference procedure and its application to fuzzy rule structure analysis. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 391–95, 1993.
- [154] Maeda-M and Murakami-S. A self-tuning fuzzy controller. *Fuzzy Sets and Systems*. vol.51, no.1, pages 29–40, 1992.
- [155] Mallampati-D and Shenoi-S. Self-organizing fuzzy logic control. In *Knowledge-Based Systems and Neural Networks: Techniques and Applications*, Stillwater, OK, USA, pages 271–82, 1990.
- [156] E.H. Mamdani and S. Assilian, “An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller,” *Int. J. Man-Mach. Stud.*, vol. 7, pp. 1-13, 1974.
- [157] Mao-Zongyuan and Di-Zheng. Industrial boiler combustion process controlled by a fuzzy controller with self-tuning scaling factors. *Acta Automatica Sinica: Chinese Journal of Automation*. vol.3, no.4, pages 347–51, 1991.
- [158] March-Leuba-C, Abdalla-M, Ford-C-E, and Guimaraes-L. A hybrid fuzzy-pi adaptive control for u-tube steam generators. *Control Theory and Advanced Technology*. vol.8, no.3, pages 567–75, 1992.
- [159] Marks-R-J-II, Oh-S, Arabshahi-P, Caudell-T-P, Choi-J-J and Song-B-J, “Steepest Descent Adaptation of Min-Max Fuzzy If-Then Rules”, *Proc. Int. Joint Conf. Neural Networks*, Beijing, China, November 3-6, 1992 (IEEE Press).
- [160] Matsui-T, Ishimoto-E, and Takawaki-M. Learning position control of a pneumatic cylinder using fuzzy reasoning. *Journal of Fluid Control*. vol.20, no.3, pages 7–29, 1990.
- [161] Miyoshi-T, Tano-S, Kato-Y, and Arnould-T. Operator tuning in fuzzy production rules using neural networks. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 641–46, 1993.
- [162] Moore-C-G and Harris-C-J. Indirect adaptive fuzzy control. *International Journal of Control*. vol.56, no.2, pages 441–68, 1992.
- [163] Morita-A. A neural-network type fuzzy model. *Mitsubishi Electric Advances*. vol.51, pages 12–14, 1990.
- [164] Muiakami-S and Waeda-M. Methodology of fuzzy control. *Journal of the Society of Instrument and Control Engineers*. vol.28, no.11, pages 953–8, 1989.
- [165] Nakayama-S, Shin ichi Horikawa, Furujashi-T, and Uchikawa-Y. Knowledge acquisition of control strategy using a fuzzy neural network. *Transactions of the Society of Instrument and Control Engineers*. vol.28, no.7, pages 899–901, 1992.
- [166] Nie-J and Linkens-D-A. A fuzzified cmac self-learning controller. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 500–05, 1993.
- [167] Nishimori-K, Hirakawa-S, and Tokutaka-H. Fuzzification of control timing in driving control of a model car. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 297–302, 1993.
- [168] Nomoto-K and Kondo-M. An auto-tuning controller using recursive fuzzy reasoning. *Transactions of the Society of Instrument and Control Engineers*. vol.25, no.10, pages 1126–33, 1989.
- [169] Nomura-H, Hayashi-I, and Wakami-N. A learning method of fuzzy inference rules by descent method. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 203–10, 1992.
- [170] Nowe-A. A self-tuning robust fuzzy controller. *Microprocessing & Microprogramming*. vol.35, no.1-5, pages 719–26, 1992.
- [171] Ollero-A and Garcia-Cerezo-A-J. Direct digital control, auto-tuning and supervision using fuzzy logic. *Fuzzy Sets and Systems*. vol.30, no.2, pages 135–53, 1989.
- [172] Pacini-P-J and Kosko-B. Adaptive fuzzy systems for target tracking. *Intelligent Systems Engineering*. vol.1, no.1, pages 3–21, 1992.
- [173] Pal-S-K and Mitra-S. Multilayer perceptron, fuzzy sets, and classification. *IEEE Transactions on Neural Networks*. vol.3, no.5, pages 683–97, 1992.
- [174] Patrikar-A and Provence-J. A self-organizing controller for dynamic processes using neural networks. In *Proc. IJCNN International Joint Conference on Neural Networks, San Diego, CA, USA, vol.3, (IEEE)*, pages 359–64, 1991.
- [175] Pavel-L and Chelaru-M. Neural fuzzy architecture for adaptive control. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA, (IEEE)*, pages 1115–22, 1990.
- [176] Peters-L, Beck-K, and Camposano-R. Adaptive fuzzy controller improves comfort. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 512–15, 1993.
- [177] T.J. Procyk and E.H. Mamdani, “A Linguistic Self-Organizing Process Controller,” *Automatica*, vol. 15, pp. 15-30, 1979.
- [178] Raju-G-V-S and Zhou-J. Fuzzy logic adaptive algorithm to improve robustness in a steam generator level controller. *Control Theory and Advanced Technology*. vol.8, no.3, pages 479–93, 1992.
- [179] Romaniuk-S. Learning fuzzy control with hybrid symbolic, connectionist networks. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 241–46, 1993.
- [180] Romaniuk-S-G and Hall-L-O. Learning fuzzy information in a hybrid connectionist, symbolic model. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 305–12, 1992.
- [181] Rovatti-R, Guerrieri-R, and Baccarani-G. Fuzzy rules optimization and logic synthesis. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 1247–52, 1993.
- [182] Schneider-D-E and Wang-P-P and. Togai-M. Design of a fuzzy logic controller for a target tracking system. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 1131–8, 1992.
- [183] Sebag-M, Schoenauer-M, and Jablot-J-M. A machine learning application to computer-aided engineering. In *Proc. First International Symposium on Uncertainty Modeling and Analysis, College Park, MD, USA, (IEEE)*, pages 19–24, 1990.
- [184] Seung-Woo-Kim and Mignon-Park. Fuzzy compliance robot control. In *Proc. IROS '91: IEEE/RSJ International Workshop on Intelligent Robots and Systems '91: Intelligence for Mechanical Systems, Osaka, Japan*, pages 1628–31, 1991.
- [185] Seung-Woo-Kim and Mignon-Park. Fuzzy compliance robot control using multi rule-base. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 1343–8, 1992.
- [186] Shi-Zhong-He, Shaohua-Tan, and Chang-Chieh-Hang. Pei-Zhuang-Wang. Control of dynamical processes using an on-line rule-adaptive fuzzy control system. *Fuzzy Sets and Systems*. vol.54, no.1, pages 11–22, 1993.
- [187] Shieh-C-Y and Nair-S-S. A new self tuning fuzzy controller design and experiments. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 309–14, 1993.
- [188] Shimizu-K and Morisue-T. Efficient control strategies for bioreactor systems. In *Proc. SICE '89: Proc. 28th SICE Annual Conference Vol.II. Matsuyama, Japan*, pages 1159–62, 1989.
- [189] Sin-S-K and deFigueiredo R-J-P. Optimization of fuzzy systems by approximation of fuzzy relations. In *Proc. IJCNN International Joint Conference on Neural Networks, Baltimore, MD, USA, vol.1 (IEEE)*, pages 257–62, 1992.
- [190] Sing-Chai-Chan and Fui-Hoon-Nah. Fuzzy neural logic network and its learning algorithms. In *Proc. 24th Annual Hawaii International Conference on System Sciences, Kauai, HI, USA, (IEEE)*, pages 476–85, 1991.
- [191] Smith-S-M and Comer-D-J. Self-tuning of a fuzzy logic controller using a cell state space algorithm. In *Proc. 1990 IEEE International Conference on Systems, Man and Cybernetics Conference, Los Angeles, CA, USA*, pages 445–50, 1990.
- [192] Smith-S-M and Comer-D-J. Automated calibration of a fuzzy logic controller using a cell state space algorithm. *IEEE Control Systems Magazine*. vol.11, no.5, pages 18–28, 1991.
- [193] Someya-R, Maeda-A, and Kosaka-M. Incorporation of fuzzy inference in expert systems and a fuzzy knowledge base building tool. In *Fuzzy Engineering Toward Human Friendly Systems, Yokohama, Japan, 13-15 Nov. 1991*, pages 494–502. IOS Press: Amsterdam, Netherlands., 1992.
- [194] Song-B-G., Marks-R-J-II, Oh-S, Arabshahi-P and Caudell-T-P. Adaptive membership function fusion and annihilation in fuzzy if-then rules. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 961–67, 1993.
- [195] Stipanicev-D. Digital control of complex systems by adaptive nonlinear pid controllers. *Elektrotehnika*. vol.34, no.3-4, pages 153–61, 1991.
- [196] Stipanicev-D, De-Neyer-M, and Goretz-R. Self-tuning self-organizing fuzzy robot control. In *Robot Control 1991 (SYROCO '91): Selected Papers from the 3rd IFAC/IFIP/IMACS Symposium, Vienna, Austria*, pages 171–6. Pergamon. Oxford, UK., 1992.
- [197] Strefezza-M and Dote-Y. Fuzzy and neural networks controller. In *Proc. IECON '91: 1991 International Conference on Industrial Electronics, Control and Instrumentation Kobe, Japan, vol.2, (IEEE)*, pages 1437–42, 1991.

- [198] Sun-C-T and Jang-J-S. Fuzzy modeling based on generalized neural networks and fuzzy clustering objective functions. In *Proc. 30th IEEE Conference on Decision and Control, Brighton, UK, vol.3*, pages 2924–9, 1991.
- [199] Sun-C-T and Jang-J-S. A neuro-fuzzy classifier and its applications. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 94–8, 1993.
- [200] Sutton-R and Jess-I-M. Real-time application of a self-organising autopilot to warship yaw control. In *International Conference on Control '91 (Conf. Publ. No.332), Edinburgh, UK, (IEE) vol.2*, pages 827–32, 1991.
- [201] Sutton-R, Roberts-G-N, and Dearden-S-R. A rule-based approach to the ship roll stabilisation problem. In *Proc. IEE Colloquium on "Exploiting the Knowledge Base: Applications of Rule Based Control" (Digest no.89), London, UK*, pages 6/1–4, 1989.
- [202] Takagi-H and Hayashi-I. Nn-driven fuzzy reasoning. *International Journal of Approximate Reasoning. vol.5, no.3*, pages 191–212, 1991.
- [203] Takagi-T, Nakanishi-S, Unehara-K, and Gotoh-Y. Construction of self-organizing fuzzy controllers by neural networks. *Transactions of the Society of Instrument and Control Engineers. vol.26, no.8*, pages 862–9, 1990.
- [204] Takahashi-H. Automatic speed control device using self-tuning fuzzy logic. In *1988 IEEE Workshop on Automotive Applications of Electronics Dearborn, MI, USA*, pages 65–71, 1988.
- [205] Tanaka-Y and Hosaka-S. Fuzzy control using automatic learning technique for telecommunication networks. *Transactions of the Institute of Electronics, Information and Communication Engineers B-I. vol.J76B-I, no.2*, pages 91–9, 1993.
- [206] Torasso-P. Supervising the heuristic learning in a diagnostic expert system. *Fuzzy Sets and Systems. vol.44, no.3*, pages 357–72, 1991.
- [207] Tzes-A and Kyriakides-K. Adaptive fuzzy-control for flexible-link manipulators: a hybrid frequency-time domain scheme. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 122–27, 1993.
- [208] Uehara-K and Fujise-M. Learning algorithm for multi-stage fuzzy inference by back-propagating error information. In *Fuzzy Engineering Toward Human Friendly Systems, Yokohama, Japan*, pages 1035–46. IOS Press: Amsterdam, Netherlands, 1992.
- [209] Uehara-K and Fujise-M. Multistage fuzzy inference formulated as linguistic-truth-value propagation and its learning algorithm based on back-propagating error information. *IEEE Transactions on Fuzzy Systems, vol.1, no.3*, pages 205–221, 1993.
- [210] Ueno-F, Inoue-T, Baloch-B u H, and Yamamoto-T. An automatic adjustment method of backpropagation learning parameters, using fuzzy inference. In *Proc. 22nd International Symposium on Multiple-Valued Logic, Sendai, Japan, (IEEE)*, pages 410–14, 1992.
- [211] Valenzuela-Rendon-M. The fuzzy classifier system: motivations and first results. In *Proc. PPSN 1: Parallel Problem Solving from Nature, 1st Workshop, Dortmund, Germany, (IEEE)*, pages 338–42, 1990.
- [212] van-der Rhee-F, van Nauta-Lemke-H-R, and Dijkman-J-G. Knowledge based fuzzy control of systems. *IEEE Transactions on Automatic Control. vol.35, no.2*, pages 148–55, 1990.
- [213] Velasco-J-R, Fernandez-G, and Magdalena-L. Inductive learning applied to fossil power plants control optimization. In *Control of Power Plants and Power Systems: Selected Papers from the IFAC Symposium, Munich, Germany*, pages 205–10, 1992.
- [214] Vjeh-N. Self organizing fuzzy logic control of a level control rig. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 303–08, 1993.
- [215] Viljamaa-P and Koivo-H-N. Tuning of multivariable fuzzy logic controller. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 697–701, 1993.
- [216] Wang-L-X. Training of fuzzy logic systems using nearest neighbor clustering. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 13–7, 1993.
- [217] Wang-L-X and Mendel-J-M. Generating fuzzy rules by learning from examples. In *Proc. 1991 IEEE International Symposium on Intelligent Control, Arlington, VA, USA*, pages 263–8, 1991.
- [218] Wang-L-X and Mendel-J-M. Back-propagation fuzzy system as nonlinear dynamic system identifiers. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 1409–18, 1992.
- [219] Wang-L-X and Mendel-J-M. Fuzzy basis functions, universal approximation, and orthogonal least-squares learning. *IEEE Transactions on Neural Networks. vol.3, no.5*, pages 807–14, 1992.
- [220] Wang-L-X and Mendel-J-M. Generating fuzzy rules by learning from examples. *IEEE Transactions on Systems, Man and Cybernetics. vol.22, no.6*, pages 1414–27, 1992.
- [221] Wang-L-X and Mendel-J-M. An rls fuzzy adaptive filter, with application to nonlinear channel equalization. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 895–900, 1993.
- [222] Wang-L-X and Mendel-J-M. Fuzzy adaptive filters, with application to nonlinear channel equalization. *IEEE Transactions on Fuzzy Systems. vol.1, no.3*, pages 161–170, 1993.
- [223] Ward-T-L, Ralston-P-A-S, and Davis-J-A. Fuzzy logic control of aggregate production planning. *Computers & Industrial Engineering. vol.23*, pages 137–40, 1992.
- [224] Werbos-P-J. Neurocontrol and fuzzy logic: connections and designs. *International Journal of Approximate Reasoning. vol.6, no.2*, pages 185–219, 1992.
- [225] Whalen-T and Schott-B. Lexicographic tuning of a fuzzy controller using box's "complex" algorithm. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 285–90, 1993.
- [226] Wu-K, Outangoun-S, and Nair-S-S. Modeling and experiments in fuzzy control. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 725–31, 1992.
- [227] Wu-Zhi-Qiao, Wang-Pei-Zhuang, Teh-Hoon-Heng, and Song-Shou-Shan. A rule self-regulating fuzzy controller. *Fuzzy Sets and Systems. vol.47, no.1*, pages 13–21, 1992.
- [228] Xu-H-Y, Wang-G-Z, and Baird-C-B. A fuzzy neural networks technique with fast backpropagation learning. In *Proc. IJCNN International Joint Conference on Neural Networks, Baltimore, MD, USA, vol.1*, pages 214–19, 1992.
- [229] Yager-R-R. Application of neural networks to fuzzy expert control. In *INNC 90 Paris. International Neural Network Conference, Paris, France, vol.1*, page 455, 1990.
- [230] Yager-R-R. Implementing fuzzy logic controllers using a neural network framework. *Fuzzy Sets and Systems. vol.48, no. 1*, pages 53–64, 1992.
- [231] Yamaguchi-T, Takagi-T, and Mita-T. Self-organizing control using fuzzy neural networks. *International Journal of Control. vol.56, no.2*, pages 415–39, 1992.
- [232] Yamaguchi-T, Tanabe-M, Kuriyama-K, and Mita-T. Fuzzy adaptive control with an associative memory system. In *Proc. International Conference on Control '91 (Conf. Publ. No.332), Edinburgh, UK, (IEE) vol.2*, pages 944–9, 1991.
- [233] Yamaguchi-T, Tanabe-M, Murakami-J, and Goto-K. An adaptive control with fuzzy associative memory system. *Transactions of the Institute of Electrical Engineers of Japan, Part C. vol.111-C, no.1*, pages 40–6, 1991.
- [234] Yamaguchi-T, Tanabe-M, and Takagi-T. Fuzzy associative memory applications to control. In *Artificial Neural Networks: Proc. 1991 International Conference, ICANN-91, Espoo, Finland, vol.2*, pages 1249–52, 1991.
- [235] Yamakawa-T and Furukawa-M. A design algorithm of membership functions for a fuzzy neuron using example-based learning. In *Proc. 1st IEEE International Conference on Fuzzy Systems, San Diego, CA, USA*, pages 75–82, 1992.
- [236] Yano-A, Higuchi-M, and Takuma-M. On the improvement of working accuracy by fuzzy control. *Journal of the Japan Society of Precision Engineering. vol.57, no.7*, pages 1283–8, 1991.
- [237] Yu-Lan-Zhou and Zhengyue-Qiu. An expert self-learning fuzzy controller. In *Artificial Intelligence in Real-Time Control 1989: Proc. IFAC Workshop, Shenyang, China*, pages 69–73, 1989.
- [238] Yuan-F, Davis-L-I-Jr, Puskorius-G-V, and Feldkamp-L-A. Design and training of hybrid neural-fuzzy systems. In *Southcon '92 Conference Record (IEEE), Orlando, FL, USA*, pages 253–8, 1992.
- [239] L.A. Zadeh, "Fuzzy Sets," *Inform. Contr.*, vol. 8, pp. 338-353, 1965.
- [240] L.A. Zadeh, "Outline of a New Approach to the Analysis of Complex Systems and Decision Processes," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-3, pp. 28-44, 1973.
- [241] Zhang-B-S and Edmunds-J-M. Self-organising fuzzy logic controller. *IEE Proc. D (Control Theory and Applications). vol.139, no.5*, pages 460–4, 1992.
- [242] Zhang-Huaguang, Chen-Laijiu, and Xu-Zhigao. A kind of fuzzy self-tuning regulator and its application to temperature process control in boiler-turbine unit. *Proc. of the CSEE. vol.12, no.1*, pages 46–52, 1992.
- [243] Zhang-Qinxun and Hou-Boyuan. Application of adaptive-fuzzy control to power systems. *Automation of Electric Power Systems. vol.13, no.3*, pages 27–31, 1989.
- [244] Zhao-H and Fan-L-T. Self-generation of fuzzy if-then rules. In *Proc. International Conference on Systems Science and Engineering (ICSSE'88), Beijing, China*, pages 336–42. Pergamon Press: Oxford, UK, 1988.
- [245] Zheng-L. A practical computer aided tuning technique for fuzzy control. In *Proc. 2nd IEEE International Conference on Fuzzy Systems, San Francisco, CA, USA*, pages 702–07, 1993.
- [246] Zheng-Tang, Ishizuka-O, and Matsumoto-H. An adaptive fuzzy network.

