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].

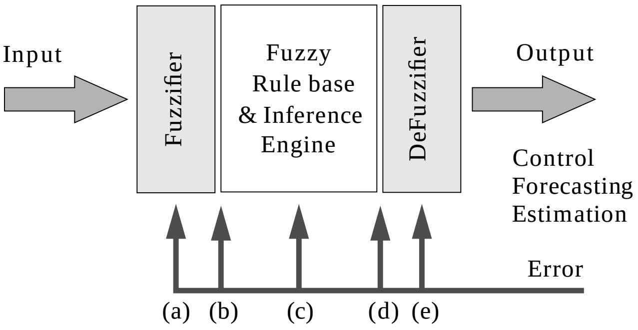

Figure 1: Block diagram of a general fuzzy inference system: The error value from a given performance measure is fed back and used to adapt all or one of the following: (a) Membership function shapes and cardinality (b) & (d) And/Or aggregation operators, (c) The rule base, and (e) The defuzzification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

Define a set

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

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 ν^k, forming activation values ζ:

$$\zeta_{lm}^k = \underset{l,m\in S_k}{T} \left(\mu_1^l(x_1), \mu_2^m(x_2)\right). \tag{2}$$

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 $T^* = T^*(\beta)$

$$w_k = \underset{l,m\in S_k}{T^*} (\zeta_{lm}^k) \tag{3}$$

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:

$$\mu = \sum_{k=1}^{K} w_k \nu^k \tag{4}$$

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

where

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

A_k and c_k are, respectively, the area and centroid of the consequent membership function ν^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:

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

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

$$\Delta\alpha \propto \frac{\partial E}{\partial \alpha}, \tag{8}$$

where

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

where

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

and

$$\frac{\partial \zeta^k_{lm}}{\partial \alpha} = \frac{\partial T}{\partial \alpha}\bigg|_{x\to\mu_1^1(x_1)\; y\to\mu_1^1(x_2)}. \qquad (11)$$

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 $\partial w_k/\partial\zeta^k_{lm}$ 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:

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

Denote:

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

We have:

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

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

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

$$\begin{aligned}\frac{dT_N}{\partial \alpha} &= T_N^{(1)} + \frac{\partial T_N}{\partial T_{N-1}}\left[T_{N-1}^{(1)} + \frac{\partial T_{N-1}}{\partial T_{N-2}}\frac{dT_{N-2}}{\partial \alpha}\right]\\ &= T_N^{(1)} + \frac{\partial T_N}{\partial T_{N-1}}\Bigg[T_{N-1}^{(1)} + \frac{\partial T_{N-1}}{\partial T_{N-2}}\\ &\times \left(T_{N-2}^{(1)} + \frac{\partial T_{N-2}}{\partial T_{N-3}}\frac{dT_{N-3}}{\partial \alpha}\right)\Bigg]\\ &= \cdots \qquad \cdots \qquad \cdots \qquad \frac{dT_0}{\partial \alpha} \qquad (15)\end{aligned}$$

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

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

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 $\nu \to \infty$, the function $w(x;\nu)$, by the central limit theorem, becomes Gaussian in shape (with zero width). Note, when using backpropagation,

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

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.

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