ZESZYTY NAUKOWE POLITECHNIKI ŚLĄSKIEJ 1981

Seria: AUTOMATYKA z. 61 Nr kol. 701

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APPROACH TO AN ADAPTIVE METHOD OF FUZZY CONTROL SYSTEMS

Summary. From the point of view of the control theory a great amount of papers on fuzzy controllers have been concerned with one-level structure of the controller.

In the paper a two-level structure of fuzzy controller is being proposed and discussed, where the first one consists of a fuzzy logic controller and the second one has two components: an Identification Block and Fuzzy Optimizer, which makes it possible to tune the controller in a formal way.

1. Introduction

In many works on fuzzy control systems in the application area, a fuzzy logic controller containing a set of control rules of a complex, ill-defined process, forms a precise, formal description of the actions of a human operator. [1], [2], [3]. From the point of view of the control theory a great amount of papers have been concerned with one-level structure of the controller (fig. 1). Because of the ease of computation, fuzzy control algorithms are implemented mainly on real time minicomputers. Fuzzy control rules, their structure, the definition of basic sets of error, change of error, control etc. are defined at the design stage of controller. Attempts have been made to improve such kind of algorithms, modifying properly the control rules discussing their influence on the dynamical characteristics (e.g. unit step response, rise time, damping factor of the process) [1]. Self-organizing, adaptive algorithms have been discussed, too [2], [3]. The way of obtaining the final proper conditions of a fuzzy controller is in its main idea rather heuristic.

In this paper a two-level structure of fuzzy controller is being proposed. The first one consists of a fuzzy logic controller, the second one which consists of a Fuzzy Optimizer and an Identification Block, makes it possible to tune the controller in a formal way. Thus the second level enables us to analyse the properties of the controlled process, as well.

A similar two-level structure of fuzzy controller, i.e. a self-organizing controller has been described by Procyk and Mamdari [3], where the second level consists of two blocks: a performance measure and a incremental model, which according to assumption, is more precise than a fuzzy

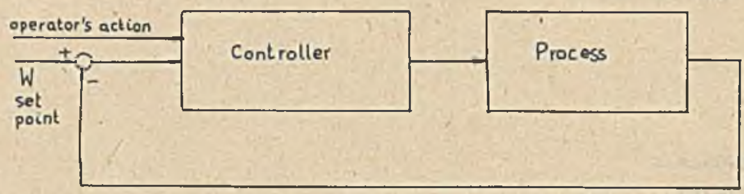

Fig. 1. One-level structure of a fuzzy logic controller

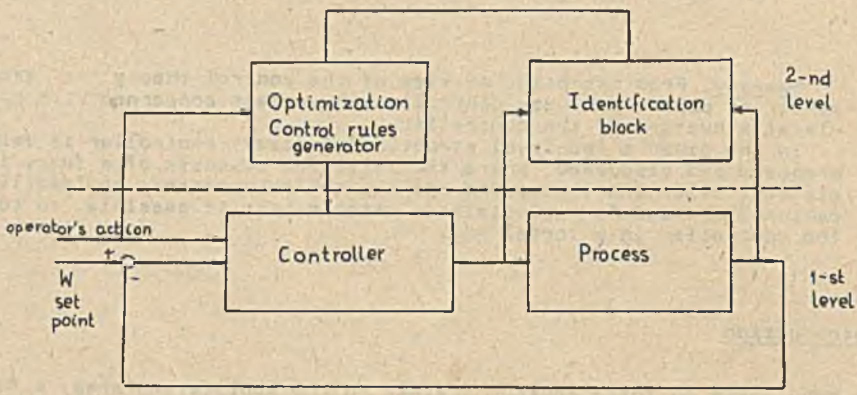

Fig. 2. Two-level structure of a fuzzy logic controller

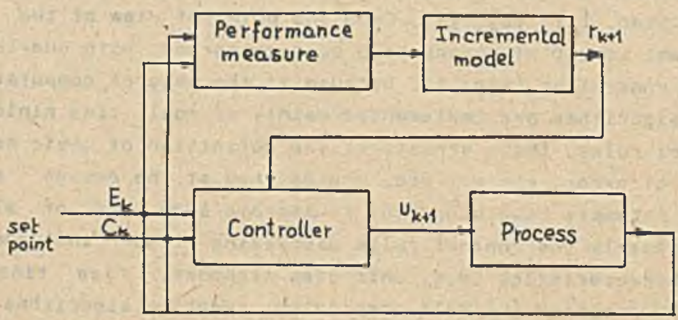

Fig. 3. General structure of a self-organizing controller

logic controller. When the concrete values of error and change of error are given, the incremental value r_{k+1} of control is computed as follows

$$U'_{k+1} = U_{k+1} + r_{k+1} \tag{1}$$

where U_{k+1} denotes the value of control computed by means of maxmin operation of input fuzzy sets and the controller s matrix. Fuzzy sets E_k, C_k, U_{k+1}, U'_{k+1} are created by means of fuzzification [6]:

$$E_k = F(e_k)$$
$$C_k = F(c_k)$$
$$U_{k+1} = F(u_{k+1})$$
$$U'_{k+1} = F(u'_{k+1})$$

The control rules of the controller in the form:

- if error is equal to E_k
  else
  if change of error is equal to C_k,
  then
  control is equal to U_{k+1}.

(R'_k)

should be replaced by the following implication:

- if error is equal to E_k
  else
  if change of error is equal to C_k
  then
  control is equal to U'_{k+1}

(R''_k)

Thus the replacement might be expressed as follows:
The matrix R_{k+1} of the controller should contain the rule R''_k but not the rule R'_k, i.e.

$$R_{k+1} = (R_k \wedge \overline{R}'_k) \vee R''_k \tag{3}$$

The method is an effective one, under the assumption that the incremental model is an adequate one, and in the case. when the input variables i.e. error and change of error are measurable, so that a hierarchical model can be constructed in an analytical form.

We present the method of fuzzy process identification and the algorithm of generation of control rules with respect to the performance index. For further discussion we assume that all the spaces in which fuzzy sets of state or error, and control are defined, have a finite number of elements i.e.:

$$\begin{aligned} \mathrm{card}(\mathbb{X}) &= n \\ \mathrm{card}(\mathbb{U}) &= m \end{aligned} \tag{4}$$

where $\mathbb{X}$ stands for state space and $\mathbb{U}$ denotes the control space.

2. Identification of a fuzzy system

We take into account a relational descriptio n of the process:

$$X_{k+1} = X_k \circ U_k \circ R \tag{5}$$

where X_k, X_{k+1} are fuzzy sets of the space of process in discrete time moments, U_k is a fuzzy control and R denotes a fuzzy relation describing the connections in the process

$$X_k, X_{k+1} \in \mathcal{F}(\mathbb{X}),\ U_k \in \mathcal{F}(\mathbb{U}),\ R \in \mathcal{F}(\mathbb{X} \times \mathbb{X} \times \mathbb{U})$$

where $\mathcal{F}(\cdot)$ denotes a family of fuzzy sets defined in the spaces $\mathbb{X}$ and $\mathbb{U}$ respectively [4] . $\circ$ stands for maxmin operation. Eq (5) could be rewritten in the following equivalent form:

$$\mu_{X_{k+1}}(x_i) = \bigvee_{l=1}^{m} \left\{ \mu_U(u_l) \wedge \left[\bigvee_{j=1}^{n} (\mu_{X_k}(y_j) \wedge \mu_R(x_i, y_j, u_l)) \right] \right. \tag{6}$$

$$\vee \equiv \max \qquad x_i, y_j \in \mathbb{X} = \{x_1, x_2, \dots, x_n\}$$
$$\wedge \equiv \min \qquad u_l \in \mathbb{U} = \{u_1, u_2, \dots, u_m\}$$

Our task is to estimate the unknown process relation, where a collection of "measurements" is given. Before describing the process idenfification let us introduce some useful definitions.

Def. 1 Fuzzy set $X \in \mathcal{F}(\mathbb{X})$ is called an i-normal fuzzy set if $\mu_X(x_i)=1$.

Def. 2 i-normal and j-normal fuzzy sets $X, Y \in \mathcal{F}(\mathbb{X})$ are called independent if $i \neq j$.

Generally fuzzy sets $A_1, A_2, \dots, A_n$ are called mutually independent if $i_1 \neq i_2 \neq i_3 \neq \dots = i_n$ where $\max\limits_{x_j \in \mathbb{X}} \mu_{A_i}(x_j) = \mu_{A_i}(x_{i_j})$

Def. 3 Degree of fuzziness of fuzzy set X is a nonnegative real number φ_X:

$$\varphi_X = \frac{1}{\max\limits_{x_i \in X} \mu_X(x_i)} \sum_{i=1}^{n} \mu_X(x_i) \tag{7}$$

Def. 4 An extension of fuzzy relation G induced by the fuzzy singleton $\{u_l\}$ we call a fuzzy relation $\text{Ext}\ G \in \mathcal{F}(\mathbb{X} \times \mathbb{X} \times \mathbb{U})$ defined as follows:

$$\mu_{ExtG}(x,y,u) = \begin{cases} \mu_G(x,y), u=u_i \\ 0, \text{ otherwise} \end{cases}$$

We discuss and identification method, basing on an active experiment, so the following eq.

$$Y_k = X_k \circ U_i \circ R \tag{8}$$

holds. For every degenerate control U_i, where $\mu_{U_i}(u_j) = \delta_{u_i,u_j}$, a collection of fuzzy input and output sets is given:

$$\{X_{ji}\} \quad \{Y_{ji}\} \qquad j = 1,2,\dots,n$$

where $\{X_{ji}\}$ forms a family of mutually independent normal fuzzy sets. As a the result of identification we take a fuzzy relation $\hat{R}$ computed as:

$$\hat{R} = \bigcup_{i=1}^{m} \text{Ext}\left[\bigcap_{j=1}^{n} X_{ji} \circledalpha Y_{ji}\right] \tag{9}$$

where $\circledalpha$ stands for α-operator defined as [5]:

$$T = X_{ji} \circledalpha Y_{ji} \in \mathcal{F}(X \times X)$$

$$\mu_T(x_r, y_s) \overset{\text{def}}{=} \begin{cases} 1, & \text{if } \mu_{X_{ji}}(x_r) \leq \mu_{Y_{ji}}(y_s) \\ \mu_{Y_{ji}}(y_s), & \text{if } \mu_{X_{ji}}(x_r) > \mu_{Y_{ji}}(y_s) \end{cases} \tag{10}$$

An active experiment as defined above enables us to identify accurately an unknown fuzzy relation. Otherwise if identified fuzzy sets are not chosen as described above, having a higher value of degree of fuzziness, the performance index of identification expressed as the Hamming distance ρ_H betwen R and $\hat{R}$ has a non-zero value.

3. Generation of the rules of fuzzy logic controller

The task of generating the rules of a fuzzy logic controller might to stated as follows. The local performance index of the control

$$Q(U_k, X_k) = \rho_H(X_{opt}, X_{k+1}) + \alpha\rho_H(U_{opt}, U_k) \quad \alpha \geq 0 \tag{11}$$

and a set of fuzzy sets $X^1, X^2, \dots, X^N$ (specified e.g. by the human operator of a controlled process) are given.

The procedure of generating a fuzzy control U^i for each $X^1, X^2, \dots, X^N$ deals with the computation of the membership function in the following way For each $X^i, i=1,2,\dots,N$ we compute a value of the performance index $Q(X^i, U_j)$ for a control equal to:

$$U_j = \{u_j\} \qquad j=1,2,\dots,m$$

i.e. $Q(X^i, u_j)$

Thus the fuzzy control U^i has a membership function:

$$\mu_{U^i}(u_j) = 1 - \frac{Q(X^i, u_j)}{\max\limits_{1 \le j \le m} Q(X^i, u_j)} \tag{12}$$

Repeating this procedura for each X^i, we generate a collection of rules of a fuzzy controller:

$$\begin{aligned} X^1 &\to U^1 \\ X^2 &\to U^2 \\ &\vdots \\ X^N &\to U^N \end{aligned} \tag{13}$$

In the case when $\mu_{U_{opt}}(u) = \delta_{u,u_{opt}}$ and $\mu_{U^i}(u) = \delta_{u,u_i}$, the Hamming distance in eq. 11 is equal to:

$$\rho_H(U_k, U_{opt}) = \frac{|u_i - u_{opt}|}{\max\limits_{u_j \in U} u_j} \tag{14}$$

The matrix of a fuzzy controller is formed as a logical sum of each of the rules i.e.

$$G = \bigcup_{i=1}^{N} (X^i \times U^i). \tag{15}$$

with the membership function:

$$\mu_G(x_j, u_l) = \max_{1 \le i \le N} \left[\min(\mu_{X^i}(x_j), \mu_{U^i}(u_l))\right] \tag{16}$$

The method described above may be generalized, if some different competitive criteria are discussed, i.e.:

$$Q^{I}, Q^{II}, Q^{III}, \dots, Q^{M} \tag{17}$$

with a slight modification, that G is created in a different way:

$$G = \bigcap_{p=1}^{M} \left[\bigcup_{i=1}^{N} X^{ip} \times U^{ip} \right] \tag{18}$$

where X^{ip}, U^{ip} stand for i-th fuzzy set of state and control respectively discussed from the point of view of p-th criterion.

4. Conclusions

A two-level structure of a fuzzy controller permits to identify an unknown process and to generate the control rules analytically, minimizing the performance index. The fuzzy relation obtained by the identification procedure might be useful for the solution of another problem as well, i.e. the prediction of the state of the process. The control rules generated according to the method described in the paper, can form the matrix of a fuzzy controller and be compared with those given by a human operator making it possible to try to estimate (at least approximately) the performance index (i.e. its general feature) using a human beinig in the control procedure. The structure of the controller defines also the structure of the computer system and its working mode, so the optimization and identification may be worked out off-line and the control algorithm can be implemented on on-line minicomputer.

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Złożono w redakcji 4.12.79 r. Recenzent
W formie ostatecznej 30.05.80 r. Doc. dr hab. inż. Andrzej Tylikowski

METODA ADAPTACJI W ROZMYTYCH SYSTEMACH STEROWANIA

S t r e s z c z e n i e

Z punktu widzenia teorii sterowania większość prac dotycząca regulatorów rozmytych rozpatruje je jako struktury jednopoziomowe. W niniejszej pracy zaproponowano i przedyskutowano strukturę dwupoziomową, gdzie regulator rozmyty znajduje się na pierwszym poziomie, zaś drugi, złożony z Bloku Identyfikacyjnego i Optymalizacyjnego, pozwala na nastrojenie regulatora.

МЕТОД АДАПТАЦИИ В РАСПЛЫВЧАТЫХ СИСТЕМАХ УПРАВЛЕНИЯ

Р е з ю м е

С точки зрения теории управления большинство работ посвященых расплывчатым регуляторам рассматривает их как одноуровенные структуры (не иерархические). В данной работе предложено и оговорено двухуровенную структуру, в которой расплывчатый регулятор находится на первом уровне. Второй регулятор состоящий из Блока идентификации и Блока оптимизации даёт возможность настройки регулятора.