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THE ALGORITHM OF DESIGNING FUZZY LOGIC INFERENCE SYSTEMS FOR DIAGNOSTICS OF MACHINE TOOL AND CUTTING PROCESS

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ABSTRACT
The paper presents an algorithm for designing fuzzy logic inference system of Takagi–Sugeno structure. In the first part of the research, the systems designed based on generated data were introduced. Then, Takagi-Sugeno fuzzy logic systems were applied for classifying cutting tool wear during multi-spindle drilling, estimating grinder's thermal deformation and correcting positioning errors. The performed tests served as a base for developement of the algorithm of FL system design. While developing the algorithm, classification and interpolation were taken into consideration.
Keywords: diagnostics of machine tool and cutting process, fuzzy logic systems

1. INTRODUCTION

Fuzzy logic (FL) inference systems have been widely tested for solving different tasks and problems. Also, various approaches for determining parameters of fuzzy logic systems have been suggested (e.g. [4]). However, the robust algorithm for automatic (without human interaction) design of the whole FL system has not been developed, yet. The paper shows the results of research aiming at solving (at least partially) the problem stated above.

The Takagi-Sugeno fuzzy logic system [5] has been applied in the research conducted. Such a system is usually used in last step of diagnostics, i.e. in the reasoning phase. The most important feature of fuzzy logic reasoning is related to possibility of dealing with uncertain and imprecise data. This capability is really valuable while diagnosing different processes and machines. In the paper, diagnostics of machine tool and cutting process is considered as a typical field of application of fuzzy logic inference.

The main goal of the presented research was to develop an algorithm for designing Takagi-Sugeno fuzzy logic system. The structure of the system together with tasks to be solved in the designing stage is shown in Figure 1. The research has been conducted in two steps. In the first step, the systems constructed based on generated data were introduced, i.e. simple "academic tasks" were analysed. During this step, the influence of the type of membership functions on the system performance was emphasised. Also, the analysis of the influence of the number of membership functions and the kind of conclusion on FL system operation was performed.

In the second step, the discussion of fuzzy logic inference systems designed on the basis of problems, which have been already solved in Department of Machine Technology [2], [3], [4] was done. In this case, Takagi-Sugeno fuzzy logic systems were applied for classifying cutting tool wear during multi-spindle drilling and for estimating grinder's thermal deformation. It should be emphasised that the above mentioned tests together with simulations done with generated data served as a base for preliminary formulation of the algorithm of FL system design. While developing the algorithm, classification and interpolation were taken into consideration.

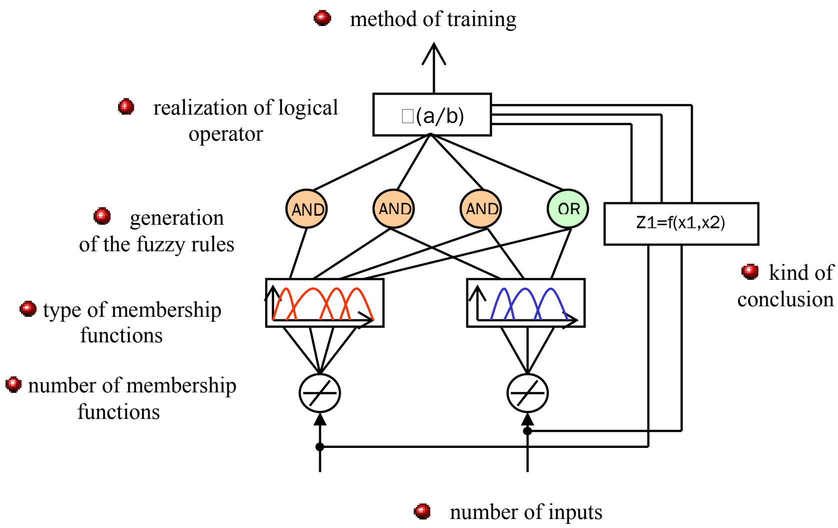

Figure 1. Structure of Takagi-Sugeno fuzzy logic system with partial tasks to be solved while designing such a system

The proposed algorithm was verified with data collected during principal part of the experimental research. Here, the measurement of the accuracy of positioning of numerically controlled feed axis in the function of temperatures measured in the selected points of the machine has been considered. The aim of the conducted research was to decrease errors evoked by thermal deformations. In this way, configuration of a hypothetical system for the position correction based on fuzzy logic inference has been developed. This research allowed introducing some modifications to the algorithm proposed. The algorithm and results of selected simulations are described in the following parts of the paper.

2. THE PROPOSED ALGORITHM

The design of Takagi-Sugeno fuzzy logic systems is performed in several steps that reflect its structure (see Figure 1). The design starts with estimation of number of membership functions. A simple formula (1) expressing relationship between number of membership functions and the number of training vectors has been applied in this case.

$$k \approx \sqrt{\frac{n}{2}} \tag{1}$$

where: n- number of training vectors

In the next step, type of membership functions is to be decided. In our research satisfying results have been obtained while applying Gaussian type of membership function. This function has only 2 parameters that determine its position and width.

$$S = 2 \cdot \frac{Z}{k} \tag{2}$$

where: k – number of membership functions (number of clusters)
Z – input data range

Initialization of membership function parameters is to be done, next. As it was revealed, application of clustering methods is very helpful. Simply, the positions of membership functions equal the centres of clusters. Membership function widths are, then, determined with formula (2).
Initialized membership functions allow designing of fuzzy rule base. The fuzzy rules in the Takagi-Sugeno system have user defined function in the conclusion part (Figure 1). Kind of conclusion is very important, because it affects number of parameters, which are determined during training. Trying to

simplify the FL system design, one can apply constant kind of conclusion or conclusion expressed with linear function. In most cases, the constant kind gives fully satisfying results. However, the tasks with complicated, irregular output hyper-surface require linear kind of conclusion. Since knowledge on output hyper-surface is not available in many cases, we suggest application of linear conclusion while designing FL systems. Finally, clustering is applied again for generating fuzzy rule base. Such an approach has been selected based on several tests of different methods.

In order to determine the parameters of membership functions and parameters of linear conclusions, the FL system training must be performed. The training is done with available data. During this phase two methods available in [1] can be used, namely error back propagation method or the hybrid method that actually bases on error back propagation procedure, as well. The results of the conducted test and simulations uniquely pointed at higher efficiency of the hybrid method. Before training, the condition of training termination must be decided. Obviously, one could suggest to perform training to the possibly smallest error. However, such approach leads to over-fitting and lost of generalisation ability of the system. In other words, the FL system can start learning noise inherent to experimental data. In the presented research, formula (3) for calculating acceptable FL system maximal error has been used. The $B_{FL\ max}$ value depends on the task to be solved. In case of classification task, a user can stop the training when 100% classification performance is reached. The interpolation task is much more difficult in terms of deciding $B_{FL\ max}$ error. Here, a user has to estimate the desired accuracy of FL system in the light of the considered phenomenon, e.g. accuracy of modelling positioning error for sufficient compensation in the CNC system.

$$B_{FL\ \max} > \max_{i=1}^{n} \left| W_i^{obl} - W_i^{wz} \right| \tag{3}$$

where: W_i^{obl} – calculated output value for i-th input vector,
W_i^{wz} – expected output value for i-th input vector

The final step of designing the Takagi-Sugeno fuzzy logic system is related to simplification of fuzzy rule base. The simplification relies on removing or joining similar membership functions. In order to calculate degree of similarity between fuzzy sets A_1 and A_2, formula (4) can be applied.

$$P(A_1, A_2) = \frac{|A_1 \cap A_2|}{|A_1 \cup A_2|} = \frac{\sum_{j=1}^{m} MIN\left[\mu_{A1}(x_j), \mu_{A2}(x_j)\right]}{\sum_{j=1}^{m} MAX\left[\mu_{A1}(x_j), \mu_{A2}(x_j)\right]} \tag{4}$$

3. SUMMARY - VERIFICATION OF PROPOSED ALGORITHM

The summary of the research can be done in two steps. First of all, positive impact of hypothetical application of Takagi-Sugeno fuzzy logic system is depicted. Here, the research that has been conducted on HSM feed drive is recalled. As it was mentioned earlier, during experimental procedure the difference between measured and assumed position of machine tool table (positioning error) was measured. Also, the temperatures of selected elements of feed drive were recorded since the positioning error was caused by thermal deformation, mainly. The FL system was applied to model relationship between the temperatures and positioning error. This model can be applied to correct the real position of the table. In other words, measuring of the temperatures and applying FL system should give values that can be introduced to the CNC system. In Figure 2, the range of measured positioning error for different data sets is shown. Also, the range of error that could be reached while applying Takagi-Sugeno fuzzy logic system is depicted. As it can be clearly seen, application of this system allows substantial decrease of positioning error and potentially allows achieving desired workpiece accuracy.

The second step of research summary is related to verification of the proposed algorithm for Takagi-Sugeno fuzzy logic system design. A representative example of the obtained results is shown in Figure 3. The drill wear classification is considered in this case. Figure 3 presents classification performance achieved during different stages of the research. The range of performance reflects the performance that can be achieved while designing the FL systems with different methods and parameters. Obviously, testing different approaches is time and cost consuming. From other hand, application of the proposed algorithm allows to obtain satisfying results without such testing. Typically, the classification performance is not the best one, but is close to the highest values. Such a conclusion points at a field of application of the proposed algorithm. If knowledge on the way of FL system design is not available, one can use the algorithm considering it as “the second best approach” and expect satisfying results.

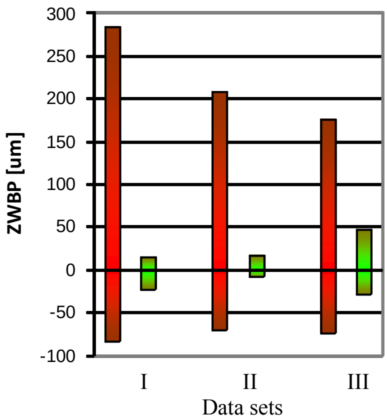

Figure 2. Ranges of positioning error (ZWBP)

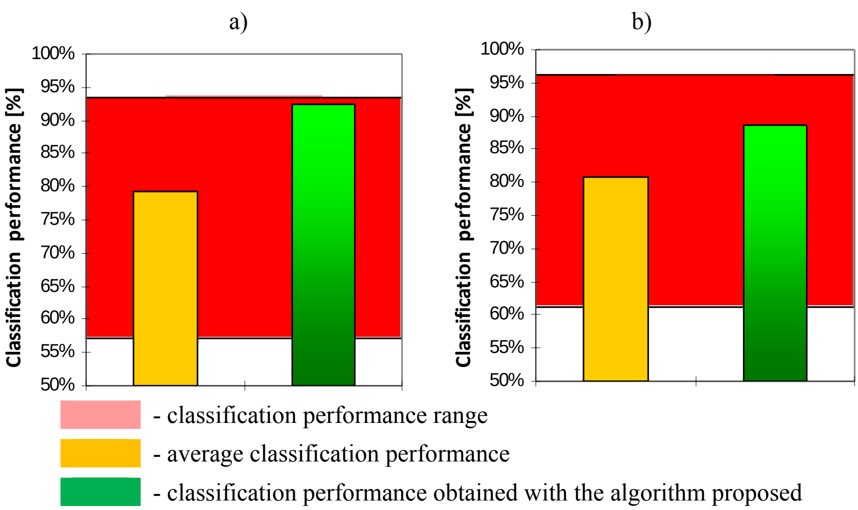

Figure 3. Performance of drill wear classification; a) data selected with weight sum method, b) data selected with weight pruning method

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