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Z- controller synthesis

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Abstract— In the era of rapid development of artificial intelligence, there are numerous problems in the field of communication technologies, designing controllers, information processing, related to the nature of information. One of the approaches used in the construction of control systems, including controllers, is a knowledge base, expert system. Considering that the construction of fuzzy rules is based on perception, in this case, taking into account the nature of information becomes an urgent problem.

This article proposes an approximate inference approach based on Z-set-based If-Then rules and aimed at building a Z-synthesis controller. The Z-synthesis controller synthesizes control decisions by taking into account both the fuzziness of system variables and the level of reliability of this information through Z-sets.

Z-sets are a natural extension of fuzzy sets and incorporate an additional component that expresses the degree of reliability of information, thereby allowing for the presentation of bimodal information in a unified formal framework.

The main goal of the proposed approach is to create a Z-synthesis controller and update it adaptively based on Z-set-based rules. This update mechanism allows for more accurate and reliable adjustment of the controller's behavior by taking into account the changing uncertainty levels of the input data.

In order to demonstrate the applicability and effectiveness of the proposed method, a numerical example involving seven Z-set-based rules is presented and the approximate inference process of the Z-synthesis controller is analyzed in detail. The results obtained show that the proposed approach provides a promising and effective framework for building intelligent control systems under bimodal uncertainty.

Keywords— Z-number-based inference, Z-synthesis controller, Z-IF-THEN rules, Z-lab software

1. INTRODUCTION

In real-life decision-making and knowledge-based systems, information is often presented in the form of If–Then rules, and both the antecedent and consequent parts of these rules are characterized by uncertainty and imprecision. In many practical applications[1-4], this uncertainty is bimodal in nature, combining both fuzzy and probabilistic aspects. Such information reflects not only the imprecision of linguistic judgments, but also the level of reliability or confidence associated with these judgments.

Existing approaches in the field of approximate inference mainly consider these two types of uncertainty separately. While fuzzy logic-based inference methods allow for effective handling of imprecision and uncertainty, probabilistic approximate inference methods mainly focus on randomness and statistical uncertainty.

However, independent processing of fuzzy and probabilistic uncertainties is not sufficient for modeling complex real systems where these uncertainties exist simultaneously and mutually.

Therefore, there is a serious need to develop unified approximate inference approaches that ensure effective processing of bimodal information in rule-based systems. In [5], the authors have made a comparative analysis of different types of controllers. The results of the analysis show that proportional-integral controllers based on fuzzy information demonstrate higher performance compared to other types of controllers considered in the study.

In [6–13], it is emphasized that fuzzy set theory reflects the essence of control processes more adequately and accurately.

There are numerous studies[14-17] in the scientific literature devoted to the study of fuzzy implications and their various fields of application. Over the past decades, a number of different types of fuzzy implications have been proposed.

However, these implications have limited capabilities in terms of expressing the level of reliability of information. The presented work considers the development of controller synthesis aimed at eliminating the mentioned deficiency.

2. RELATED WORKS

The construction of fuzzy controllers has been widely discussed in the scientific literature. The authors used fuzzy logic in [18] to increase the control accuracy, but in this case the probabilistic nature of the information is ignored and not taken into account. Incorrect information leads to wrong decisions. This seriously affects the reduction of control accuracy.

Today, there is a great need for the development and application of controllers supported by artificial intelligence and new technologies in industrial automation.

In [19] the authors tried to increase the control accuracy by using neural networks, genetic algorithms and fuzzy logic approaches together. In the research conducted over the last 10 years, hybrid approaches have been preferred in the field of fuzzy controller construction and application.

In [20], the authors applied fuzzy logic theory to the traditional PID controller.

The design of a fuzzy controller[21] consisting of 27 rules is considered. It is known that on-chip communication is highly dependent on the bit error of the system implemented on it. The reduction of the bit error rate in on-chip communication is carried out by error detection and correction codes, which also have their own shortcomings. In this paper, a fuzzy controller is designed to select the correct error control scheme. The designed fuzzy controller works with random input data and experiments. As can be seen from this work, both probabilistic and fuzzy information processing are needed in the error control system in chip communication. However, the proposed controller is based only on fuzzy information.

In [22] a fuzzy controller is proposed that allows dynamic adjustment of control parameters in a complex liquid level control problem. They created an artificial intelligence-based control system for liquid level control, that is, a fuzzy logic-based system, and thereby achieved a partial increase in control stability. The authors have proposed a new improved artificial intelligence-based controller for liquid level control that has the ability to respond quickly to changes in liquid levels. Although this approach is considered an effective approach in the design of the control system, the authors did not take into account the probabilistic nature of information. As can be seen, fuzzy controllers are still used as an effective tool. The above proves that there is a need for new approaches in this area. Thus, considering that the mathematical basis of artificial intelligence is based on probability theory, taking into account the probabilistic nature of information is an urgent issue. Various approaches are used in the construction of controllers [20].

One of these approaches is expert systems. The construction of expert systems is based on knowledge obtained from data or knowledge obtained from experts. If this knowledge is obtained using clustering methods, the shortcomings of the method affect the correct compilation of knowledge. If the knowledge is obtained from a human expert, then perception-based information is used (PR). This information has a probabilistic and fuzzy nature. In such a case, when the information is inaccurate, fuzzy logic theory is considered an effective tool for modeling, and when the information is lacking, probability theory is considered.

The development of controllers based on rules that can take into account these two uncertainties is an issue that has been little studied in the scientific literature.

The tool that simultaneously expresses these two uncertainties is the Z-number theory given by Professor Zadeh in 2011 [12]. Until this theory was proposed, fuzzy logic was widely used in the construction of controllers and was considered the most effective tool. This is once again confirmed by the analysis of existing scientific literature.

The Z-number proposed in Zadeh's Z-number theory contains the fuzzy and probabilistic nature of information. Computation with Z-numbers is a complex issue and related problems have been considered in [13].

The issue of constructing a rule based on the information described by Z-numbers has been considered in [16, 23-25]. The input and output information in these rules are Z-numbers Z(A,B). Part A of Z-number represents the subjective assessment, and part B represents the confidence in it. Both A and B are expressed in the form of fuzzy numbers. In this case, logical reasoning based on the established rules is also a complex issue. Here, approaches based on the similarity measure and implications can be used. We will consider the approach related to the first case. Problems related to the second approach have been considered in our previous works. The need to consider an approach based on the similarity method is due to the lack of works related to the second approach in the scientific literature. Z-implication was first proposed by us, and the concept of Z-implication presented in our articles[23,24] is given. Logical inference based on Z-implicatoin covers our previous research.

The Z-reasoning algorithm based on Z-implication is also included in our previous research for the first time. This algorithm can only be applied on the basis of an implication proven as Z-implication. In this algorithm, points of the universe of the B side of the data described in the form of Z numbers are used when performing logical inference.

By selecting these points, the goal programming problem is solved and, as a result, probability distributions are found. During logical inference, the A side of Z (A,B) is determined based on fuzzy logical inference. That is, relation matrices are constructed according to the rules. Their combination is performed by the T-norm operation of the implication. The result is determined using the maxmin composition operation on the obtained matrix.

The calculation of the 2nd side is performed on the basis of cumulative probability distributions and it is based on the copula. This approach is also characterized by computational complexity. However, the introduction of the concept of Z-implication allows for further simplification of this process. The goal is to generate output values using similarity based reasoning method in systems operating with a set of n production rules based on Z-sets, the input parameters are interpreted through logical constructs of the "IF-THEN" type.

3. METHODS

The structure of the knowledge base includes Z-numbers, which act as carriers of hybrid information combining fuzziness and probabilistic uncertainty (degree of confidence).

Despite the evolution of approximate reasoning methods, the amount of research in the field of logical inference based on Z-numbers is limited, which is dictated by the high computational complexity of the algorithms. At the current stage, an effective alternative is the reasoning method based on similarity measures [16].

This approach involves assessing the relevance between current data and rule antecedents, while the formation of the consequent is implemented through a linear combination of weighting coefficients. Such a toolkit is of particular scientific interest, since it allows for the formalization of the synergy of fuzzy and probabilistic uncertainty [25-28].

The definitions we will use in solving the proposed problem are given below.

Definition 1. Z-sets [25]. Z-set is set defined as $Z = (A, B, G)$ in X where $x \in X$,
$A(x) \in [0,1]$,

membership function of probability distributions $P(x)$ is $B(P(x)) \in [0,1]$, $A \subset X$, B is restriction on A, G is probability distributions on P space:

$$G = \{p_Z(x): \int_X p_Z(x)dx = 1, \int_X p_Z(x)A(x)dx \text{ is } B, x \in X\}$$

Definition 2. Z If-Then rules [25].

If X_1 is $Z_{X_1,n} = (A_{X_1,n}, B_{X_1,n})$ and, ..., and X_m is $Z_{X_{m,n}} = (A_{X_{m,n}}, B_{X_{m,n}})$ then Y is $Z_Y = (A_{Y,n}, B_{Y,n})$,

where

$Z_{X_m,n} = (A_{X_m,n}, B_{X_m,n})$ is the Z-sets based inputs and $Z_Y = (A_{Y,n}, B_{Y,n})$ is Z-sets based outputs of the rules, $X_i, i = \overline{1,m}$ is input vector, Y is output vector and n is the number of rules.

Method. Description of the Z-synthesis controller. The structure of the Z-synthesis controller consists of several main functional stages that are sequential and interconnected with each other. These stages provide reception, processing and synthesis of the bimodal uncertain information entering the system.

At the first stage, the input module receives the measured state variables or errors of the system. At this stage, the incoming quantities are subjected to preliminary processing and converted into a form suitable for the next stages.

At the second stage the input variables are represented by Z-sets. Each input variable is expressed in the form of a Z-set consisting of two components: the first component indicates the uncertainty (fuzzy set), and the second component indicates the level of reliability or confidence of this information. Thus, at this stage, bimodal information is modeled in a single formal framework.

At the third stage, there is a Z-set-based rule base. This part consists of If-Then type Z-rules, and each rule contains Z-sets in both the antecedent and the result parts, consequent. The rule base is formed based on expert knowledge.

The fourth stage is the Z-approximate inference mechanism. This mechanism synthesizes the results taking into account the compliance rates of the activated Z-rules and their reliability levels. During the inference process, both the fuzzy compliance and reliability information are processed in parallel.

In the fifth stage, the Z-outputs obtained from the inference stage are combined to form the final control decision. Finally, the information obtained as a result of Z-synthesis is converted into a real-valued control signal and transmitted to the system's executive mechanism.

4.FORMULATION OF THE PROBLEM

The steps and calculated parameters of the algorithm, which refers to the similarity-based reasoning methodology [27], are reflected in the software environment below:

Step 1. Description and semantic identification of linguistic variables in the initial stage, the semantic values of linguistic terms used in both the antecedent and consequent components of the rule structure that forms the knowledge base are determined. This process involves mathematically assigning membership functions to terms through fuzzy sets and specifying the initial input parameters of the model[28].

Statement of the problem is desribed as follow:

1.If e is (negative big, almost sure) =(1.00/-10+0.73/-7+0.34/-3+0.20/0+0.13/3+0.08/7+0.06/10;$0.3/0.7 + 1/0.73 + 0.2/0.75$) THEN u is (negative big, almost sure) =(1.00/-1+0.92/-0.7+0.67/-0.3 +0.50/0+0.37/0.3+ 0.26/0.7 +0.20/1; $0.3/0.7 + 1/0.73 + 0.2/0.75$);

2.If e is (negative medium, sure) =(0.73/-10+1/-7+0.61/-3+0.34/0+0.20/3+ 0.11/7+ 0.08/10; $0.1/0.7 + 1/0.8 + 0.3/0.9$) THEN u is (negative medium, sure) = (0.91/-1+1/-0.7+0.86/-0.3+0.67/0+0.5/0.3+0.34/0.7+0.26/1; $0.1/0.7 + 1/0.8 + 0.3/0.9$);

3.If e is (negative small ,very sure) =(0.34/-10+0.61/-7+1/-3+0.73/0+0.41/3+0.20/7+ 0.13/10; $0.2/0.8 + 1/0.9 + 0.2/1$) THEN u is (negative small, very sure) = (0.61/-1+0.86/-0.7+1/-0.3+0.92/0+0.74/0.3+0.5/0.7+0.37/1; $0.2/0.8 + 1/0.9 + 0.2/1$);

4.If e is (zero, moderately sure) =(0.20/-10+0.34/-7+0.73/-3+1/0+0.73/3+0.34/7+0.20/10; $0.2/0.5 + 1/0.6 + 0.4/0.8$) THEN u is (zero, moderately sure) = (0.50/-1+0.67/-0.7+0.92/-0.3+ +1.00/0+0.92/0.3+ 0.67/0.7+0.50/1; $0.2/0.5 + 1/0.6 + 0.4/0.8$);

5.If e is (positive small, sure) =(0.13/-10+0.20/-7+0.41/-3+0.73/0+1/3+0.61/7+ 0.34/10; $0.1/0.7 + 1/0.8 + 0.3/0.9$) THEN u is (positive small, moderately sure) = (0.37/-1+0.50/-0.7+0.74/-0.3+ 0.92/0+1/0.3+ +0.86/0.7+0.67/1; $0.1/0.7 + 1/0.8 + 0.3/0.9$);

6.If e is (positive medium, very sure) =(0.08/-10+0.11/-7+0.20/-3+0.34/0+0.61/3+1.00/7+0.73/10; $0.2/0.8 + 1/0.9 + 0.2/1$) THEN u is (positive medium, sure) = (0.26/-1+0.34/-0.7+0.50/-0.3+ 0.67/0+0.86/0.3+ +1.00/0.7+0.91/1; $0.1/0.7 + 1/0.8 + 0.3/0.9$);

7.If e is (positive big, moderately sure) =(0.06/-10+0.08/-7+0.13/-3+0.20/0+0.34/3+0.73/7+1.00/10;$0.2/0.5 + 1/0.6 + 0.4/0.8$) THEN u is (positive big, sure) = (0.20/-1+0.26/-0.7+0.37/-0.3+0.50/0+0.67/0.3+ +0.92/0.7+1.00/1;$0.1/0.7 + 1/0.8 + 0.3/0.9$).

The aim of the problem is to define the Z-valued output of $Z_Y^{'}$ using new input $(A'_{X_1}, B'_{X_1}) = \ldots$ $((0.11/-10 + 0.17/-7 + 0.34/-3 + 0.61/0 + 0.96/3 + 0.73/7 + 0.41/10), (0.7,0.8,0.9))$

For comparison, we will solve the same problem using the same rules. It should be noted that the similarity-based reasoning method has the advantages of simplicity [27], no need for predefined rules, and improved results with training; the system evolves as new rules are added, and there is no need to rewrite the algorithm [27].

5. COMPUTER SIMULATION

For the practical implementation of the proposed algorithm and testing of the model, the "Z-lab" software package [26] was used. The "Z-lab" is an integrated development environment based on the principles of the Z-numbers theory introduced by the world-famous scientist, professor Lotfi Zadeh.

This software provides extensive technological opportunities for the mathematical description of high-level uncertainty factors, modeling of complex systems and management of fuzzy information flows.

Since Z-numbers simultaneously take into account both the uncertainty of information and its degree of reliability, they ensure the achievement of more accurate and adequate results in the simulation process.

Step 2. Assume, that similarity measure $S_v = (Z^{'}, Z_j)$:c∈[0,1] [27]and new input is:

Z'=(Z'_{X_1},…, $\mathbf{Z'_{X_m}}$) = $\boldsymbol{Z_E}$= $((0.11/-10 + 0.17/-7 + 0.34/-3 + 0.61/0 + 0.96/3 + 0.73/7 + 0.41/10), (0.7,0.8,0.9))$

Step 3. Calculation of the similarity measure between Z-vectors .

At this step of the algorithm, the general similarity degree between the vector Z' characterizing the current state of the system and the reference vectors Zj previously defined in the knowledge base is determined.

This calculation is based on the principle of the minimum operator (T-norm), which is widely used in fuzzy logic and judgment systems. The mathematical approach is based on a comparison of the individual similarity indicators between the components of both vectors (for example, A linguistic value and B reliability degree).

The overall similarity degree is taken equal to the minimum similarity level between these

components. This methodology increases the reliability of the final result, ensuring the most conservative and cautious approach in the decision-making process of the system[27].

$S_v(Z',Z_j) = min_{i=1,...m} S(Z'_{X_i}, Z'_{X_{i,j}})$ = (0.4031767,

0.45792191, 0.53034279, 0.73020891, 0.86078676,

0.59385703, 0.56392729) = 0.4031767

Step 4. Calculation of interpolation weights.

In this step of the algorithm, interpolation weights are determined for each rule based on the similarity degrees obtained in the previous steps. Obtained weights using software Z-lab are as follow on 7 rules(Table 1):

Table 1. Weights on the rules

	E(error)		**U(action)**	**Weights**
R1	NB, AS	0,403177	NB, AS	0,09738
R2	NM, S	0,457922	NM, S	0,110603
R3	NS, VS	0,530343	NS, VS	0,128095
R4	Z, MS	0,730209	Z, MS	0,17637
R5	PS, S	0,860787	PS, MS	0,207908
R6	PM, VS	0,593857	PS, S	0,143436
R7	PB, MS	0,563927	PB, S	0,136207

Calculate the interpolation weights using formula [27]:

$w_j = \frac{S_v(Z\prime,Z_j)}{\sum S_v(Z\prime,Z_k)}$ = (0.09738047, 0.11060324, 0.12809527, 0.17636953, 0.20790839, 0.14343606, 0.13620704)

This process is a quantitative indicator of the correspondence between the input data and the existing rules in the knowledge base in fuzzy judgment systems.

Step 5. Calculation output Z'_Y using mathematical expression [27]:

$$\mathbf{Z'_Y} = \sum_{j=1}^{n} \omega_j Z_Y, \mathbf{j} = \left(\frac{0.61}{-1}, \frac{0.61}{-0.7}, \frac{0.7825}{-0.3}, \frac{0.9325}{0}, \frac{0.96}{0.32}, \frac{0.895625}{0.7}, \frac{0.862188}{1}; \left\{ \frac{0.1}{0.5}, \frac{1}{0.6}, \frac{0.1}{0.8} \right\} \right)$$

The fuzzy output indicator obtained as a result of the calculations was defuzzified based on the relevant methodology [29,30] and the final quantitative indicator was determined as Y = 0.16.

This value expresses the specific value of the control parameter at the output of the system. The difference of this obtained result from the indicators found in the existing scientific literature emphasizes the uniqueness of the research and the specificity of the applied approach.

Thus, unlike traditional methods, the use of the reliability of information through Z-numbers here created conditions for a more accurate and adequate assessment of the control signal.

This is an important factor that increases the effectiveness of management in dynamic environments where the uncertainty factor is high.

6. DISCUSSION

The work of the created Z-controller was analyzed. Tests were conducted based on the Z-lab package. The effect on the result was investigated by changing the inputs of the rules given in the form of Z-numbers. This process was carried out by changing the type of membership function in the values of linguistic variables and changing the linguistic value. It should be noted that the reaction of the system to these changes was recorded and analyzed in terms of output stability, judgment accuracy and consistency of the control decision. The error value was changed for several scenarios in 7 rules. After several iterations, the result of the controller's rule base and the judgment method used

showed that the result remained stable when the error value was increased and decreased by 8%. The stability of the system was ensured in this interval.

Overall, the sensitivity analysis confirms the practicality and flexibility of the proposed approach and ensures that the designed controller can operate reliably in environments characterized by different degrees of uncertainty and reliability. These results provide a strong foundation for future research and practical application of intelligent systems that require reasoning with both uncertainty and partial reliability of the data. On the other hand, this will allow for the improvement of the mathematical foundations of rapidly developing artificial intelligence, since the shortcomings of binary logic and probability theory are known from the scientific literature.

7. CONCLUSION

In this work, we develop Z-synthesis controller based on IF-THEN rules with Z-set-based antecedents and consequents. The proposed framework provides a systematic methodology for reasoning with Z-rules, enabling a unified treatment of uncertainty that arises in complex real-world systems.

The main advantage of the used approach lies in its ability to operate with a combined representation of fuzzy and probabilistic uncertainties within a single reasoning mechanism.

Traditional reasoning frameworks that treat fuzzy uncertainty and probabilistic uncertainty separately are often unable to preserve the essential properties of the underlying information, particularly in situations where imprecision and randomness coexist and interact.

The proposed approach is capable of processing real-world bimodal information and is characterized by its ability to simultaneously compute both the inaccurate value of a reliability or confidence level.

This dual-output capability enhances the expressiveness and practical relevance of the reasoning process. Due to its generality and flexibility, the proposed approach can be applied across a wide range of real-life domains, particularly in the design and implementation of decision-making and decision support systems, where reliable reasoning under complex uncertainty conditions is essential.

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