Information Sciences 352–353 (2016) 35–47

Contents lists available at ScienceDirect

Information Sciences

journal homepage: www.elsevier.com/locate/ins

Competitive interaction reasoning: A bio-inspired reasoning method for fuzzy rule based classification systems

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ARTICLE INFO

Article history:
Received 17 June 2013
Revised 27 January 2016
Accepted 25 February 2016
Available online 8 March 2016

Keywords:
Fuzzy classification
Bio-inspired competition
Competitive interaction reasoning

ABSTRACT

In designing fuzzy rule based classification systems (FRBCSs), complex fuzzy rule extraction techniques and tuning membership functions are frequently used to enhance classification accuracy. However, these approaches not only decrease system's transparency which is the hallmark of fizzy design, but also are oftentimes computationally expensive and require multiple parameters to be optimized using a large amount of training data. In this paper, inspired by the so-called competitive behavior of mini-columns in the brain neuronal circuitry, we proposed a new reasoning method for fuzzy classifiers referred to as Competitive Interaction Reasoning (CIR) that employs the cumulative information provided by all fuzzy rules and adjusts the decision boundaries as if the membership functions are directly modified. This mechanism is mathematically implemented by a linear transformation and resembles the competitive interaction observed in brain neuronal columns. Cross-rule competition weights are optimized using Hebbian reinforcement learning. Using a large number of simulations on benchmark data sets, we show that the proposed CIR significantly improves classification accuracy without compromising interpretability of the fuzzy classifier. In addition, CIR can further facilitate formation of the fuzzy rules and incorporation of the expert knowledge by confining the destructive effects of noisy rules or expert inconsistencies. Experiments on 23 well-known benchmark data sets confirm high performance of CIR in comparison with a number of popular classifiers.

1. Introduction

Today, parallel to the advancement of theory of fuzzy rule based classification systems (FRBCSs), their use in various applications is becoming more popular [2,12,13,22,24,28,30,35,38,40,42]. In these systems, fuzzification is exploited to define linguistically meaningful phrases for input features. [31,34,35,43]. This provides human-friendly and understandable knowledge representation that can be utilized in expert knowledge extraction and implementation. Therefore, an important advantage of mapping input-output relations by fuzzy rules lies in their transparency and interpretability. For the same

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http://dx.doi.org/10.1016/j.ins.2016.02.052

reason, FRBCSs provide a valuable platform to incorporate expert's domain knowledge which often further enhances classification accuracy [20,31]. However, in most recent works to enhance performance of fuzzy classifiers, little effort is made to preserve the transparency of fuzzy classification systems [11,43]. These include employing sophisticated membership tuning techniques [36], advanced methods to extract fuzzy 'If-Then' rules from available data [1,19,26,33], and employing hierarchical fuzzy systems [6,27]. These techniques which are based on optimizing one or multiple components of fuzzy classifiers, not only in practice diminish transparency and convenience of incorporating the expert knowledge, but also are often computationally expensive and require a large number of training samples to optimize the parameters. This issue, which is known as accuracy-complexity or accuracy-interpretability trade-off, points out the compromise between interpretability and accuracy in FRBCSs [11,15]. Therefore, keeping number of rules constant, improving classification accuracy in current methods is inevitably accompanied by decreased interpretability.

To address this problem, we propose an indirect approach to enhance the performance of fuzzy classifiers without comprising their transparency. This is achieved by adding a post-processing step to the design of FRBCSs. While quantifying interpretability of a given fuzzy system is still an ongoing research area, it is accepted that lower number of fuzzy rules, smoother structure, and use of simpler membership functions positively contribute to enhance this property [11]. Having this loose relationship in mind, we show that our proposed method improves the accuracy of FRBCSs but does not deteriorate its transparency in the sense that it does not change membership functions, structure, or number of fuzzy rules. On the other hand, because of using conventional fuzzy rule structures and membership functions, our method provides a straightforward algorithm to derive high performance FRBCSs that are also highly transparent.

There are a number of related works on the idea of retaining the transparency of a fuzzy classifier while improving its performance through applying a post-processing technique. The most widely used approach is modification of certainty factors (rule weights) which adjusts the relative firing strength of rules in FRBCSs. Many algorithms have been proposed for learning the rule weights ranging from heuristics to analytical methods [37,44]. However, these algorithms mostly rely on the consequent of the rules with the highest level of associativity and hence miss the information provided by the other rules. A more general framework is suggested in [8] where aggregation is accomplished in such a way that the rules with similar consequents affect one another. Furthermore, a number of other approaches including modification of membership functions after building the rule base, employing adaboost techniques, and fuzzy rule selection have been suggested [16,39,41]. However, in one way or another, they change the main fuzzy rule systems and deteriorate the interpretability by changing the membership function or their relative power [37]. Furthermore, these methods never explore the possibility of exploiting cross-rule interactions to improve fuzzy classification performance. These relations are especially important because fuzzy classifiers are intrinsically local and it is the lack of well-shaped decision areas which underlies misclassification of new samples.

We address these drawbacks in a unified algorithm in which we propose a new post-processing technique to reshape the decision boundaries of a given fuzzy classifier. Our method effectively aggregates the information from all the rules in a FRBCS and, as we will demonstrate throughout this paper, behaves as if the membership functions are directly modified. The proposed method is inspired mainly from two biological observations and is formulated as a reasoning criterion. Biological systems are capable of showing complex behaviors while being made up of simple components. In these systems, oftentimes, the ability to make complicated decisions is attributed to the complex interactions involved [32]. Specifically, competitive behaviors in the nervous system where various neuronal columns compete to lead the firing rate is an interesting example of such interactions and is associated to many cognitive operations [32].

Inspired by the above-mentioned observations, we advocate using typical membership functions and rule types and propose employing an interaction function to enhance the classification performance. With the analogy of fuzzy rules as neuronal assemblies (e.g. neuronal columns), fuzzy rules interact through a competition which takes place in the space spanned by their firing rates. This process is here referred to as Competitive Interaction Reasoning (CIR) and provides a general framework to integrate information represented by all the available fuzzy rules. To classify every new sample, CIR aggregates the firing rates of all the available rules in the knowledge base irrespective of their consequents. This is done mathematically by multiplying a weight matrix containing both positive and negative elements by the vector of firing rates.

The remainder of this paper is organized as follows. Section 2 provides a concise review of the essential biological backgrounds. Methodology is then proposed in Section 3 and consists of a detailed description of CIR and its learning algorithm. Some illustrations on how CIR shapes the decision boundaries are given in this section. In Section 4 the performance of CIR is studied and compared to a number of popular fuzzy and non-fuzzy classification algorithms using large suit of UCI data sets [25]. Finally, Section 5 concludes this paper.

2. Competitive dynamics in neural pools

Nervous system is defined by presence of neurons which are also known as nerve cells [4]. It is widely accepted that it is the acitivity of the neural circuits formed by neurons that determines the organism's perception of the world and its behavior. Generally, neurons in the neural circuits affect one another through electochemical signals and may excite, inhibit, or modulate other neurons. Neuronal response is often quantified by the change in the firing rate. The extent to which receiveing signals may alter the neuron is an intrinsic property of the neuron which is called receptive field. In other words, receptive field of a neuron is defined as the spatiotemporal range of stimuli to which the neuron is responsive. As a rule,