Knowledge-Based Systems 87 (2015) 80–91

Contents lists available at ScienceDirect

Knowledge-Based Systems

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

A novel rule base representation and its inference method using the evidential reasoning approach

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ARTICLE INFO

Article history:
Received 25 October 2014
Received in revised form 15 June 2015
Accepted 24 June 2015
Available online 2 July 2015

Keywords:
Certainty rule base
Representation of knowledge
Similarity measure
Uncertainty inference method
Evidential reasoning approach

ABSTRACT

In this paper, a novel rule base, *Certainty Rule Base* (CeRB), and its inference method are proposed. This rule base is firstly designed with certainty degrees embedded in the antecedent terms as well as in the consequent terms. CeRB is shown to be capable of capturing vagueness, incompleteness, uncertainty, and nonlinear causal relationships in an integrated way. Secondly, the CeRB inference method using the evidential reasoning approach is provided. The overall representation and inference framework offer a further improvement and a great extension of the recently uncertainty inference methods. Namely, the knowledge is represented by CeRB and the evidential reasoning approach is applied to the rule combination. In the end, two case studies including a numerical example and a software defect prediction are provided to illustrate the proposed CeRB representation, generation and inference procedure as well as demonstrate its high performance by comparing with some existing approaches.

1. Introduction

Uncertainty exists in our real-life, there are various objectives or factitious uncertainties in the fields of management science, computer science, system science, information science and some other fields. How to describe the uncertainty? How to model reasoning in uncertain environments? How to solve these models? For decades, uncertainty information is processed by various ways in various uncertainty methods. Uncertainty information is also processed in knowledge systems. In fact, uncertainty can be modeled by probabilities, or fuzziness, or possibilities, or some others. So how to structure the uncertainty reasoning method is a hot spots [1].

The development of uncertainty reasoning framework has received considerable attention in the last three decades. Several frameworks have been proposed for handing uncertain knowledge. There exist numerous uncertainty theories. The most common representing and reasoning frameworks for uncertain knowledge include [2,3]: probability theory, fuzzy set theory and Dempster–Shafer evidence theory (D–S theory) [4,5].

Each of these methods is aimed at a special application environment and has its own features. The first uncertainty reasoning method based on probability theory is the certainty factor model which was proposed by Shortliffe and Buchanan for MYCIN system in 1975 [6]. Another important probability theory was the Bayesian probability theory which was proposed by Dyda for PROSPECTOR [7]. Fuzzy set theory was proposed by Zadeh in 1965 [8], then developed into a case of possibilistic inference method by Dubois and Prade [9–11]. The D–S theory was presented by Dempster in the 1960s [4], extended and progressed by Shafer [5]. The D–S theory provides an appropriate framework to model ignorance whilst fuzziness can be well treated using fuzzy set theory [12]. Although the D–S theory is not originally proposed in relation to artificial intelligence, it has found wide applications in expert systems over the past two decades [13–16]. D–S theory has been widely used in expert system, information fusion, situation analysis, decision making and so on [17,18].

In fact, different kinds of uncertainty may coexist in real systems, for example, fuzzy information may coexist with ignorance. Therefore, it is highly desirable to develop a knowledge representation scheme and inference method to deal with different uncertainty. Some scholars are making studies for the complex uncertainty reasoning method, the most famous are Yager and Yang. Yager [14,15,19–21] suggested a methodology for including

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http://dx.doi.org/10.1016/j.knosys.2015.06.018
0950-7051/

probabilistic uncertainty in the fuzzy systems model and noted the quantification of these simplifying features involves some subjective considerations about the humans preferences, investigate the important features of the considerations associated with an uncertainty profile using D–S theory. There are some disadvantages of D–S theory. D–S theory is a non-polynomial hard problem, it need to take much more time to produce results, and it is not easy to deal with the conflicting evidences.

Yang et al. [2,12,22–25] have researched and given *Belief Rule Base Inference Methodology using the Evidential Reasoning approach* (RIMER). The rule base is designed with belief degrees embedded in the consequent term of rule, called *Belief Rule Base* (BRB), the inference of the belief rule based system is implemented using the *Evidential Reasoning* (ER) approach [26–32] which was also proposed by Yang. RIMER is used to capture fuzziness, random, incompleteness as well as nonlinear causal relationships, and has been widely used in multitudinous areas [33]. Since RIMER was built by Yang [24], the improvements of RIMER approach and ER approach have been given [12,25,30,34]. Both quantitative and qualitative attributes under uncertainty can be modeled and analyzed using ER approach, and RIMER has been widely used in multitudinous areas. There exist three cases for ER approach, one is ER recursive algorithm [24], one is ER analytical algorithm [34], and the other is ER rule with both weight and reliability [25].

RIMER approach has solved the problems of D–S theory, but there are still some defects of RIMER approach. The structure and representation of the basic knowledge based belief rule base and the input information are given [2]. The belief rule base is designed with belief degrees embedded in the consequent term of a rule with the certain antecedent term. A general input from corresponding to all antecedent attributes, and each antecedent attribute value is assigned with a degree of belief, which reflects the uncertainty of the input data. Since the differences between the antecedent attributes of general input and the antecedent attributes of rule in the belief rule base, the input should be transformed. By using the distribution assessment approach [23], a referential value of an attribute may in general be regarded as an evaluation grade, and the input can be transformed to a distribution on the referential values of the attribute using belief degrees.

Liu et al. [30] have given a novel belief rule base representation—*Extended Belief Rule Base* (EBRB) and its inference methodology, as the consequence attribute of BRB, the antecedent attribute and consequent attribute are with the packet referential values. The input should be transformed to a distribution on the referential values of the attribute using belief degrees.

Among many alternative means for knowledge representation, rule seems to be one of the most common forms for expressing various types of knowledge for a number of reasons [2,25,35]. As the knowledge systems (e.g., expert system, knowledge based system and so on) are usually constructed from knowledge in the forms of If-then rules, the knowledge system has become widely used in some scientific areas, such as decision theory, operations research, management science and artificial intelligence [1]. There are two essential parts of knowledge system: knowledge representation and inference engine.

Due to the defects of the existing methods: (i) the consequent attribute and its evaluation grade set are single; (ii) the linguistic value (subjective information) which is given by expert should be converted to belief structure, and there may be information loss in the conversion process. A novel rule base representation and its inference method are proposed in this paper. The knowledge representation is a rule base with certainty factors, named *Certainty Rule Base* (CeRB) [36]. The inference engine is given based on the ER approach. The CeRB and inference engine are used to infer consequents using rules which are established by domain experts or gotten by data mining from domain knowledge. Further, the knowledge system can be applied to support human decision making. Different from the existing representations, there are multi-consequent attributes in each rule, the antecedent attribute values and the consequent attribute values are with the degree of belief (certainty factors) directly. This representation is more in tune with human knowledge and reduces the loss of information.

The rest of this paper is organized as follows. CeRB and its inference framework are proposed in Section 2, including the structure and representation of CeRB and its inference methodology. The proposed rule representation, inference method and its performance are demonstrated in Section 3, with some case studies in numerical example as well as in software defect prediction compared with some existing approaches. Conclusions are drawn in Section 4.

2. Certainty rule base inference method using the evidential reasoning approach

2.1. Certainty rule base

The structure and representation of CeRB are given in this section. The starting point of constructing a rule base is collecting If-then rules from domain experts or through data mining based on domain knowledge. A CeRB and an inference engine are then designed to infer consequents.

In our daily life, we often make inference using uncertain fact and knowledge. In order to make such an inference, the formalization of inference method is given as follows:

Ant 1:	If x is A	(α)	then y is B	(β) with γ
Ant 2:	x is A	(α')		
Con:	y is B	(β')		

In this formalization, Con is obviously reached by combining Ant 1 (rule or knowledge) and Ant 2 (antecedent or fact). In order to get Con and its uncertainty, the uncertainty of Ant 1 and Ant 2 should be fused. First of all, the knowledge and fact with uncertainty should be represented.

Definition 1. A certainty rule base (CeRB) with K rules model can be formally represented as follows:

$$R = \langle (X, A), (Y, C), CF, \Theta, W, F \rangle,$$

where $X = \{X_i | i = 1, 2, \ldots, I\}$ is the set of antecedent attributes. $A_i = \left\{A_{i,l_i} | l_i = 1, 2, \ldots, L_i^A\right\}$ is the set of attribute values for antecedent attribute X_i, let $A = \{A_i | i = 1, 2, \ldots, I\}$, it means the set of antecedent attribute value sets. $Y = \{Y_j | j = 1, 2, \ldots, J\}$ is the set of consequent attributes. $C_j = \left\{C_{j,l_j} | l_j = 1, 2, \ldots, L_j^C\right\}$ is the set of attribute values for consequent attribute Y_j, let $C = \{C_j | j = 1, 2, \ldots, J\}$, it means the set of consequent attribute value sets. $\Theta = \left(\theta^1, \ldots, \theta^k, \ldots, \theta^K\right)$ is the vector of the importance degree (weight) of each rule, θ^k is the weight of the kth rule. $W = (w_1, \ldots, w_i, \ldots, w_I)$ is the vector of the antecedent attribute weights, w_i is the weight of A_i, and $\sum_{i=1}^{I} w_i = 1$. $CF = \{CF(\Delta) | CF(\Delta) \in [0, 1]\}$ is the certainty factor set, $CF(\Delta)$ is the certainty factor of event Δ; $CF(\Delta)$ satisfies that the degree of certainty is more high if $CF(\Delta)$ is more large, $CF(\Delta) = 0$ means completely uncertainty, $CF(\Delta) = 1$ means completely certainty. $(\Delta, CF(\Delta))$ is the certainty factor structure, including event Δ and its certainty factor $CF(\Delta)$. F is a logical function, it reflects the relationship between antecedent and its associated consequent in rule with uncertainty, reasoning method and decision method are decided on F.