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A multi-attribute fusion approach extending Dempster–Shafer theory for combinatorial-type evidences

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ABSTRACT

Human cognition of the world generally begins with attribute perception of things. Knowledge element, which is able to reveal microscopic regularities by attribute network, provides an intelligent support for attribute-based cognition. In the field of emergency management, knowledge element has been widely used in evolution rules, risk analysis and machine learning based on emergency cases. However, since the knowledge of emergency management is multidisciplinary and in addition, limited by diverse cognitive perspectives and language expressions, integrating heterogeneous knowledge from domain experts and data sources for depth mining and decision support seems to be difficult. Especially, with the advent of big data, the problem of developing an efficient multi-attribute fusion method to reorganize complex and massive data in a consensual knowledge framework must be addressed. In this paper, a novel mathematical approach, which extends Dempster–Shafer theory to fuse combinatorial-type evidences, is elaborated to handle multi-attribute integration through the use of knowledge element model. This methodology makes it possible to establish a complete knowledge structure for attribute description of things by implementing new uncertainty measures to determine a degree of belief when combining evidences. It is meaningful to optimize the fusion algorithm in view of reliability and expansibility to some extent. Furthermore, the processing also has the advantage of being effective without any semantic preprocessing. The application of the proposed model is shown in marine disaster monitoring for emergency management. We make an empirical analysis in the attribute fusion of knowledge element "sea".

1. Introduction

Human cognition of the world generally begins with attribute perception of things. People are usually good at using multiple characteristics to describe familiar things, as well as estimating exactly what the thing is just based on a few key features. Knowledge element (KE), which is able to reveal microscopic regularities by attribute-relation description, provides an intelligent support for attribute-based cognition.

With the advent of big data, more opportunities have emerged to improve attribute-based cognition (Felice & Rosalind, 2008; Manyika et al., 2011). Taking full advantage of the volume of big data, complete attribute-based perception with the use of KE is able to realize by integrating large amounts of data from diverse sources. Meanwhile, identifying crucial attributes of things by knowledge discovery is helpful for understanding the real value of big data (Canedo, Canedo, & Betanzos, 2015).

Regardless of focusing on complete attributes or crucial attributes, cognitive representation is always derived from some known causalities and in addition, subjectivity in selecting features, whether by an individual or by a group, should not be ignored. In the matter of emergency management, since the relevant knowledge is multidisciplinary, integrating multi-source heterogeneous knowledge within a unified knowledge framework for depth mining seems to be difficult. Furthermore, limited by diverse cognitive perspectives and language expressions, the problem of developing an efficient multi-attribute fusion method to reorganize domain knowledge from various experts for emergency decision-making must be addressed (Liu, Wang, & Wang, 2007; Nov, Ye, & Kumar, 2012; Scally, Cassimatis, & Uchida, 2012).

Using uncertainty reasoning methodology to implement knowledge fusion is by no means new. There are numerous publications that use Dempster–Shafer theory of evidence (DST), Bayesian theory, fuzzy logic, neural network, etc. for mathematical modeling and optimization of various problems. The pros and cons of these mainstream methods are shown in Table 1. As one of the most popular knowledge fusion methods, DST provides an effective way to fuse uncertain information without any prior probabilities

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Table 1
A comparison of mainstream uncertainty reasoning methods.

Uncertainty reasoning	Advantage	Disadvantage
Evidence theory	No additional assumptions; Treats uncertainty due to imprecision and conflict separately; Quantifies uncertainty with bits of information; Decreases the complexity of knowledge space.	An interval of probabilities of an event; Expert's reliability is not considered.
Bayesian theory	A single value of the probability of an event; Expert's reliability is considered.	Assumptions can affect the results significantly.
Fuzzy logic	Emphasis on membership in the same category; Generation of continuous characteristic function.	Fuzzy subsets of standard and identification target are needed; Larger detection error by membership function; Ineffective under strong stochastic variations.
Neural network	Self-learning and self-adaptive ability; Nonlinear mapping capability; Fault-tolerant ability.	A certain number of training models are needed; Generalization ability is affected by model selection.

(Lin, Liang, & Qian, 2015; Soundappan, Nikolaidis, Haftka, Grandhi, & Canfield, 2004). The outstanding advantage of DST lies in quantifying the degree of uncertainty when small amounts of information are available (Agarwal, Agarwal, Preston, & Padmanabhan, 2004). The existing studies combine the advantages of various uncertainty reasoning approaches to carry out some comprehensive cross research, and have achieved breakthroughs and successful applications in many fields. For instance, Dempster–Shafer based fuzzy set (DFS) was carried out to formulate diagnostic rules in diagnosis support systems (Porebski & Straszecka, 2018), to capture the stochastic disturbance and provide effective inference under strong stochastic uncertainty in wind speed prediction (Li, Wang, & Chen, 2017), etc.

In recent years, DST research on combination rules and model optimizations have given rise to frequent discussion among scholars, focusing on highly conflicting or unreliable evidences (Han, Deng, & Han, 2013; Yager, 1987), basic belief assignment (Zhang, Hu, Chan, Sadiq, & Deng, 2014), fast hybridized algorithms (Shafer, 1976), as well as non-exhaustive frames of discernment (Janez & Appriou, 1998; Schubert, 2012). Although these works use several elicitation techniques, hardly any research has yet been carried out on combinatorial-type evidence fusion in the framework of DST.

In this paper, we propose a multi-attribute fusion approach in the framework of knowledge element model (KEM) from the perspective of establishing a complete knowledge representation system based on attribute- relation of things. This method is regarded as the first attempt at extending evidence theory to fuse combinatorial-type evidences, which means the fusion decision result is multi-attribute description that there may exist some 'total support' or 'partial support' for other evidences. That is, uncertainty measures and combination rules of traditional evidence theory should consider more about the subordinate or intersection relations of evidences. The superiority of this method lies not only in its solution to integrate highly conflicting evidences with different reliabilities, but also in its efficient computing without any preprocessing of complex semantic relations from diverse attribute descriptions.

The remainder of this paper is organized as follows. Section 2 briefly reviews the basic formulation of KEM for knowledge representation of an object. Section 3 elaborates on the multi-attribute fusion model that extends DST to fuse combinatorial-type evidence, together with a special interpretation on some new uncertainty measures. In section 4, a fusion algorithm is designed, primarily for non-exhaustive frames of discernment and computing efficiency. Section 5 illustrates a multi-attribute representation example of knowledge element "sea" in the application of marine disaster monitoring for emergency intelligent support and furthermore, discusses the experimental results of the proposed fusion method. Conclusions are finally drawn in Section 6, along with some future endeavors of this study.

2. Knowledge element model

A unified knowledge representation framework is the basis of multi-attribute fusion. Knowledge element (KE), which has the properties of ontology and epistemology, is regarded as the smallest independent unit with complete knowledge description (Hermann, 2014). As the most primitive element of knowledge discovery and reasoning, KE is able to reveal microscopic regularities by attribute-relation fusion. Nowadays, KE is acknowledged to be a typical method for standardizing knowledge representation, as evidenced by the growing number of publications related to it (Jiang, 2007; Marshall, Chen, & Madhusudan, 2006; Wu, 2004). However, most of these studies confined KE as a text unit, while the primitivity and the objectivity of things have not been revealed thoroughly.

Wang first defined KEM as a triad to identify the attributes of an object (Wang, 2011). Compared with other knowledge representation methods, KEM not only raises advantages of interpreting and mining interdisciplinary knowledge, but also overcomes the ontological challenge in explicit description of conceptual relations (Chen & Xiao, 2013). Moreover, the construction of a KE-based framework provides intelligent support for improving human attribute-based cognition and further exploring universal relations of objects. Especially in the field of emergency management, KEM has been applied widely to the studies of evolution rules (Zhong, Guo, & Wang, 2012), risk analyses of emergencies (Lu & Yu, 2014) as well as machine learning based on emergency cases (Wang, Huang, Zhong, & Wang, 2014), which demonstrate the feasibility and superiority of KEM in knowledge representation and reasoning. Therefore, the proposed multi-attribute fusion method in this paper is based on Wang's KEM.

As Wang described in the six-level cognitive model (Wang, 2011), the universal connexion of things can be delineated based on their explicit or implicit attribute-relations. In this case, the knowledge representation of an object can be defined as a triad:

$$K = (N, A, R) \tag{1}$$

where N denotes the name-set of attributes, A denotes the state-set of attributes, and R denotes the relation–set mapping on $A \times A$. Given that any state-element $a \in A$ may be a qualitative or quantitative description, R should also describe qualitative or quantitative relations. In addition, if the state-element a is describable or measurable, the KE of a can be defined as

$$K_a = (p_a, d_a, f_a) \tag{2}$$

where p_a denotes the measurable type of the state-element a, d_a denotes the probability distribution or the fuzzy number, and f_a is the function describing the change of a. In particular, $a_t = f_a(a_{t-1}, t)$ is expressed if the state-element a is time-varying and discernible. Any $r \in R$ satisfies $r: A_r^I \to A_r^O$ and $A_r^O = f_r(A_r^I)$, where A_r^I denotes the input-attribute set, A_r^O denotes the output-attribute set