Chemometrics and Intelligent Laboratory Systems 166 (2017) 61–68

Contents lists available at ScienceDirect

Chemometrics and Intelligent Laboratory Systems

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

Fuzzy decision fusion system for fault classification with analytic hierarchy process approach

Yue Liu, Weite Ni, Zhiqiang Ge *

State Key Laboratory of Industrial Control Technology, Institute of Industrial Process Control, College of Control Science and Engineering, Zhejiang University, Hangzhou 310027, Zhejiang, PR China

ARTICLE INFO

Article history:
Received 6 February 2017
Received in revised form
10 May 2017
Accepted 11 May 2017
Available online 17 May 2017

Keywords:
Decision fusion system
Analytic hierarchy process
Ensemble system
Model evaluation
Fault classification

ABSTRACT

Performance of the most existing fault detection and classification methods can only be guaranteed when each of their own assumptions are met. In other words, a method works well in one condition may not perform well in another. In this paper, a new analytic hierarchy process (AHP) based fuzzy decision fusion system is proposed to tackle the fault classification problem. The AHP approach is introduced to determine the priorities of different classifiers, which are further utilized as the weights in ensemble system. Comparing to conventional equal weighted fusion system, the proposed fuzzy fusion system is able to provide more rational and convincing fault classification result. Effectiveness of the proposed fuzzy fusion system with model evaluation is verified through the Tennessee Eastman (TE) benchmark process.

1. Introduction

Fault detection and classification have become increasingly important in industrial processes. Especially fast detection and accurate classification of faults are extremely significant to ensure the process safety, reduce the economic loss and improve the productivity. Generally, fault detection and classification methods can be divided into three categories [1–4]: model-based methods, knowledge-based methods and data-based methods. Data collection is much easier than before with the wide use of distributed control systems (DCS) in industrial processes, which makes data-based methods become the most popular one in fault detection and classification [5].

Numbers of data-based methods include multivariate statistical methods, signal processing methods and machine learning methods have been proposed for fault detection and classification in industrial processes. Multivariate statistical methods such as principle component analysis (PCA) [6,7], independent component analysis (ICA) and kernel PCA are typically used for fault detection and classification. And Machine learning methods such as Fisher Discriminant Analysis (FDA) [7–9], Support Vector Machines (SVM) [6,8,10,11], k-Nearest Neighbor (kNN) [12,13] and Artificial Neural Networks (ANN) [12,14,15] have been widely used for fault classification in recent years. Although good classification results have been achieved by using those methods, it is difficult to select one perfect method which is applicable to various process conditions, due to different data features of industrial processes. In other words, one method performs well under one assumption may not achieve good performance under another.

Therefore, searching for an effective method for fault classification is extremely important. To solve this problem, ensemble system is used in many research works [16,17]. The main idea of ensemble system is to combine several methods together to deal with the same problem, which can overcome the weakness of single method and simultaneously improve the performance of fault classification. Model diversity and fusion strategy are two key components in the ensemble system. For the former one, diversity can be achieved by using heterogeneous models or using different training datasets. For the latter one, two kinds of fusion approaches have been developed, which are utility-based methods and evidence-based methods. The representative utility-based method is voting-based method [18–20], and the evidence-based methods include Bayesian fusion method [21], Dempster-Shafer method [22], decision templates [23], Borda count [24], etc [25].

Numbers of literature on fault detection and classification are about decision fusion method [21,25–30]. However, most fusion strategies have not considered the performance of each method. Actually, the performance of various methods is different in specific condition, which leads to a significant role of model evaluation in the decision fusion system. Therefore, how to evaluate the performance of each model and give the priority of each model are

* Corresponding author.
E-mail address: gezhiqiang@zju.edu.cn (Z. Ge).

http://dx.doi.org/10.1016/j.chemolab.2017.05.012
0169-7439/

becoming important tasks in constructing decision fusion systems for fault classification.

In this work, an analytic hierarchy process (AHP) based fuzzy fusion system is developed for fault classification in industrial processes. AHP is a decision making method combined with qualitative analysis and quantitative analysis, which was proposed by Thomas L. Saaty in the 1970s [31]. Since then, it has been widely used in various fields, such as economy, management, society, engineering, etc [32]. It provides a multilayer structure includes objective layer, criterion layer and alternative layer to solve the complex multiple objective decision making problem. In order to evaluate the performance of each method in the decision fusion system, the AHP approach is used to determine the priority of each method. After that, a fuzzy decision fusion strategy is developed and applied for fault classification with the use of the priorities achieved by AHP.

The rest of this paper is organized as follows. Section 2 provides a review of analytic hierarchy process (AHP). Due to the length of this paper, detailed knowledge of selected classifiers is ignored, since one can easily find them in many published books and literature. Then, a complete framework of the fuzzy decision fusion system with AHP for fault classification is proposed in Section 3, with selection of multiple classifiers, evaluation of the classifiers by confusion matrix, detailed steps of AHP for model priority calculation, and fuzzy fusion for decision making of the ensemble system. In section 4, the performance of the proposed method is evaluated in the Tennessee Eastman (TE) benchmark process. Finally, conclusions are made.

2. Analytic hierarchy process(AHP)

AHP is a multi-objective decision making method developed by Thomas L. Saaty in the 1970s [31]. Since then, it has been widely used in various fields, such as business, industry, government and so on [32]. Comparing to the other decision making methods, AHP has two advantages. One is that it can decompose the complex system into multiple hierarchy structure, which is easy to understand and analyze, the other one is that it can convert the human knowledge to numerical values, which can be processed over the entire range of the problem. Thus, AHP is known as a systematic and hierarchical method combined with qualitative analysis and quantitative analysis, which is mainly used to provide the priorities. In each hierarchy, the priorities of all elements are derived by comparing them to each other, with respect to their impact on a specific element in the upper hierarchy. And the overall priorities of the alternatives are calculated by synthesizing the priorities in various hierarchies, which are used to make the final decision. Thus, AHP is a synthetic evaluation method, which makes decision making more rational. The typical structure of AHP is shown in Fig. 1.

The detailed steps of the AHP approach are summarized as follows:

(1) Establish the hierarchical structure, which includes the objective hierarchy, the criterion hierarchy and the alternative hierarchy.
(2) Construct the pairwise comparison matrix by comparing the elements pairwise, with respect to a specific element in the upper hierarchy.
(3) Derive the priorities of the elements in each hierarchy based on the pairwise comparison matrix.
(4) Check the consistency of the judgments.

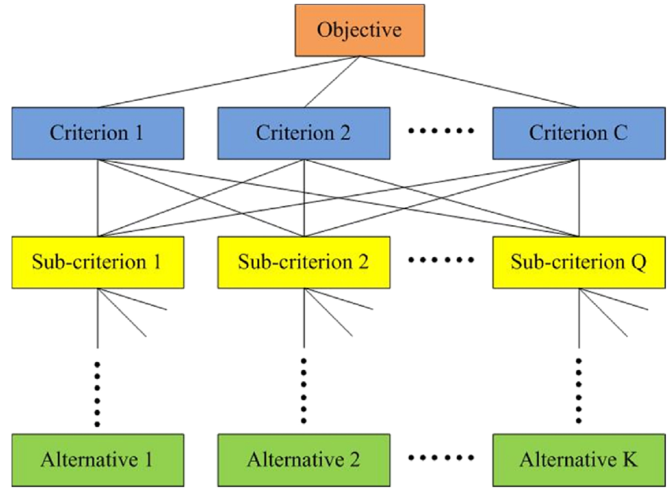

Fig. 1. Typical structure of analytic hierarchy process.

(5) Calculate the overall priorities of the alternatives with respect to the decision objective.

3. Fuzzy decision fusion system with AHP for fault classification

As we know, due to the complexity of process conditions, searching for a method that can work well under different circumstances is difficult. Therefore, a decision fusion system that combines a set of classifiers together and fuses the decision of individual classifier is developed for the purpose of fault classification. In order to make this system more effective, three important issues should be paid attention. The first one is the diversity of the fusion system, the second one is the priority of each classifier, and the last one is the fusion strategy for online fault classification.

Fig. 2 shows the detailed procedures of the proposed system, which consists of both offline model prioritization and online fault classification stages. In particular, there are four main procedures in this system: (1) selection of multiple classifiers, (2) evaluating the performance of classifiers by confusion matrices, (3) AHP for classifier priority calculation, (4) fuzzy fusion system for online fault classification. Detailed illustrations of those four steps are given in the following subsections.

3.1. Selection of multiple classifiers

The diversity of the decision fusion system can be achieved by using different training datasets or heterogeneous classifiers. The latter one is selected for decision fusion system proposed in this paper. Particularly, six commonly used fault classification methods are selected as the base classifiers for decision fusion system, which are: (1) Principle Component Analysis (PCA); (2) Kernel Principle Component Analysis (KPCA); (3) Fisher Discriminant Analysis (FDA); (4) k-Nearest Neighbor (kNN); (5) Support Vector Machines (SVM); (6) Artificial Neural Networks (ANN). In detail, classifier (3)–(6) are general methods for fault classification and classifier (1)–(2) are usually used for fault detection. But PCA and KPCA can also be used for fault classification by defining an index, and the main steps are as follows: