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# A novel neural-network approach of analog fault diagnosis based on kernel discriminant analysis and particle swarm optimization

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ABSTRACT

Kernel principal component analysis (KPCA) and kernel linear discriminant analysis (KLDA) are two commonly used and effective methods for dimensionality reduction and feature extraction. In this paper, we propose a KLDA method based on maximal class separability for extracting the optimal features of analog fault data sets, where the proposed KLDA method is compared with principal component analysis (PCA), linear discriminant analysis (LDA) and KPCA methods. Meanwhile, a novel particle swarm optimization (PSO) based algorithm is developed to tune parameters and structures of neural networks jointly. Our study shows that KLDA is overall superior to PCA, LDA and KPCA in feature extraction performance and the proposed PSO-based algorithm has the properties of convenience of implementation and better training performance than Back-propagation algorithm. The simulation results demonstrate the effectiveness of these methods.



## 1. Introduction

Fault diagnosis plays a very important role in the reliable operation and good maintenance of industrial systems, which guarantees to produce higher quality products, reduce product rejection rates and satisfy increasingly strict safety and environment requirements [1]. Successful implementations of fault diagnosis have been reported in different applications such as rotating machinery [2], electric motor [3,4], pneumatic systems [5], robot manipulators [6] and so on. In recent decades, promoted by the needs of industrial production and rapid progress of modern electronic and computer technologies, a large amount of complex system-on-chip and mixed-signal integrated circuits have been produced. In order to produce high quality chips and develop safe and reliable electronic circuits and systems, it is crucial and necessary to implement fault diagnosis and testing of these circuits. According to collected statistics [7], most part of an electronic system is digital (about 80%), but there are about 80% of the faults which occur in the analog segment. Although the automated techniques for digital circuits' diagnosis and testing have been provided for many years, the diagnosis methods of digitals' circuits are ineffective and inefficient when applied into the analog ones. The reason for this is that analog fault diagnosis is complicated by poor fault models, component tolerances and nonlinearities of analog circuits [8,9], which leads to a slowly evolving process for fault diagnosis on analog and mixed-signal circuits.

Analog diagnosis algorithms are generally classified into two methods [8–10]: the simulation after test method (SAT) and the simulation before test method (SBT). For the SAT approach, fault diagnosis is achieved by calculating the circuit parameters from the measured responses of the circuits under test (CUT), so it needs more computational time than the SBT approach based on generated off-line fault dictionaries. This will increase the time spent on diagnosing systems at production time. In contrast, the SBT method develops a data dictionary and compares the circuit responses associated with the predefined faulty values in the dictionary to locate the faults. The corresponding state of the system is then reported. It turns out that these systems typically require more initial computational costs, but provide faster diagnosis at production time. In this paper, our proposed diagnostic method falls into SBT.

In recent years, fault diagnosis of analog circuits has found a large number of significant diagnosis techniques which have been developed at the system, board and chip levels [7–18]. However, due to the diagnostic difficulties of analog circuits just described above, the process of developing test strategies for analog circuits still heavily relies on the engineer's experience and intuition and is still iterative and time-consuming. Therefore, there is an urgent need to find a systematic approach to automate the fault diagnosis process of these complex circuits.

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Fortunately, the difficulties of analog fault diagnosis make the application of neural networks to this area very attractive since the specific fault models and the comprehensive examination of those adverse effects described above are not required. As a result, various neural networks are extensively used in the field of fault diagnosis of analog circuits [9–18].

From the works presented in these references, we can readily see that the diagnostic performances of these proposed techniques are strongly dependent on the effective feature extraction methods. In [9], the samples of impulse responses of the linear analog circuits are directly fed to a neural network as inputs without any preprocessing. As a result, for even a relatively small circuit, a neural network with a large number of inputs is required for this approach. In [12,13], the authors have taken the simulation program with integrated circuit emphasis (SPICE) model of a faulty circuit and excited it with a narrow pulse to expose its natural frequencies. Then, the response is preprocessed by wavelet transform and principal component analysis (PCA) so as to obtain the optimal features for training neural network. This approach to some extent can reduce the inputs of neural network and improve its performance. In [14], the high frequency details are further added as the inputs of a wavelet network such that the resulting fault diagnostic system can diagnose the faults of analog circuit effectively and achieve higher classification accuracy. In addition, in [18], the authors perform feature extraction in frequency domain using the kurtosis and entropy as a preprocessor, which leads to two fixed features as inputs to neural network. This reduces the number of inputs to a neural network, simplifies the network structure and improves the corresponding diagnostic performance. It is obvious that, in the neural-network-based fault diagnosis system, the smaller features can lead to the dimensionality reduction of input data (inputs of neural network) and the improvement of diagnostic performance.

However, in these works, the choice of neural network structures is based on trial and error process [9,11–15] or individual's experience [18]. Moreover, the Back-propagation (BP) algorithm is usually employed as the training algorithm of these networks. It turns out that the appropriate determination of a neural network including network structure and training algorithm plays an important role in the process of network design [19]. A too large structure can lead to unnecessary interconnected neurons, excessively computational load and over-fitting phenomenon of network; while a too small structure can not provide desired network performance due to its limited information processing capability. Moreover, the BP algorithm based on gradient information usually results in slow convergent rate, gets easily trapped in a local minimum of the error function and is incapable of finding a global minimum in training phase [19,20].

More recently, various particle swarm optimizations (PSO) and improved PSO algorithms as a type of novel evolutionary computation techniques have been developed and applied to a wide range of optimization problems [21–32]. Particularly, in evolving a neural network, a large number of PSO algorithms are proposed to select its structures and tune its weights and biases [21–26]. The PSO algorithm is inspired by the biological and sociological behavior of animal swarms searching for their foods. Compared with genetic algorithm (GA), the PSO algorithm has no complicated evolutionary operators such as crossover and mutation so that it can be computationally efficient and conveniently implemented and has been utilized as a more effective and competitive searching method than GA. In contrast with BP algorithm, the PSO algorithm does not require gradient information of an objective function so that it is insensitive to initial values and can easily achieve global optimum and higher convergent speed. In [21], Kennedy and Eberhart employed the PSO algorithm to train a simple neural network. The results showed that the PSO algorithm tackled effectively the problems of slow convergent rate and being trapped into a local minimum of BP algorithm and displayed strong global search capability. In [22], the authors proposed a hybrid training algorithm combing PSO algorithm with BP algorithm for training weights of a neural network so that the hybrid algorithm obtained better training performance than PSO and BP algorithms. In [23], the improved PSO and discrete PSO algorithms are used to evolve jointly the structure and parameters of a neural network. The experimental results show that the proposed algorithm produces a neural network with good generalization capability. In [24], Liang and Feng proposed an alternative evolutionary method for tuning the structure and parameters of a neural network simultaneously. The results indicate that the proposed method can obtain better performance than existing methods such as BP, GA and traditional PSO in recent references. In [25], the authors proposed a novel technique for the automatic design of neural networks by evolving the network configuration within an architecture space. The experimental results showed that the proposed technique can achieve the optimum or at least near-optimum networks and has a superior generalization capability. In addition, the study of [26] is to propose an adaptive evolutionary radial basis function (RBF) network algorithm to evolve accuracy and connections (centers and weights) of RBF networks simultaneously. The experimental results demonstrate that the proposed approach provides an effective means to solve multi-objective RBF network.

In this paper, in order to reduce computational cost of exploring the structure and weight spaces of a neural network simultaneously and accelerate the convergent speed of PSO toward the global optimum, we propose a PSO-based incremental constructive algorithm of neural network. In such a case, the PSO algorithm is used to tune the parameters of neural network in terms of PSO algorithms described in related Refs. [21–26] and the selection of network structure is implemented in such a way that the number of hidden nodes of neural network is increased from one node until its error goal is achieved [33].

Currently, PCA, kernel principal component analysis (KPCA), linear discriminant analysis (LDA) and kernel linear discriminant analysis (KLDA) are two types of the most popular feature extraction and dimensionality reduction methods, which have aroused considerable interest in the fields of pattern recognition and machine learning [34–46]. The purpose of PCA-based methods such as KPCA is to keep as much information as possible in terms of variance and find directions that have minimal reconstruction error [38]. While LDA-based methods such as KLDA is to optimize the low-dimensional representation of the data and focus on the most discriminant feature extraction [38,39]. Thanks to the capability of acquiring the most discriminant information contained in a data set, LDA-based methods, especially KLDA and its variants have been widely used in many real-world applications [40–46].

However, "small sample size" (SSS) problems in high-dimensional space, where the number of available samples is smaller than the dimensionality of the samples, are frequently encountered by KLDA in real-world applications, which ultimately lead to singularity of corresponding scatter matrix. The SSS problems are divided into two classes [43]: the common SSS problems and the generated SSS problems. For the common SSS problems, the number of samples is less than dimension of the samples in observation space. In generated SSS problems where the kernel-based methods are considered, since the input data in the observation space are transformed implicitly into feature data in high- or infinite-dimensional feature space by kernel, the typical "large sample size" problems where the number of samples is larger than dimension of the samples in observation space, are converted naturally into the so-called generated SSS problems in feature space.

Hence, in order to extract the effective features in a high-dimensional data set, in recent years, many modified LDA and KLDA