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Three-dimensional Gabor feature extraction for hyperspectral imagery classification using a memetic framework

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A B S T R A C T

Feature extraction based on three-dimensional (3D) wavelet transform is capable of improving the classification accuracy of hyperspectral imagery data by simultaneously capturing the geometrical and statistical spectral–spatial structure of the data. Nevertheless, the design of wavelets is always proceeded with empirical parameters, which tends to involve a large number of irrelevant and redundant spectral–spatial features and results in suboptimal configuration. This paper proposes a 3D Gabor wavelet feature extraction in a memetic framework, named M3DGFE, for hyperspectral imagery classification. Particularly, the parameter setting of 3D Gabor wavelet feature extraction is optimized using memetic algorithm so that discriminative and parsimonious feature set is acquired for accurate classification. M3DGFE is characterized by an efficient fitness evaluation function and a pruning local search. In the fitness evaluation function, a new concept of redundancy-free relevance based on conditional mutual information is proposed to measure the goodness of the extracted candidate features. The pruning local search is specially designed to eliminate both irrelevant and redundant features without sacrificing the discriminability of the obtained feature subset. M3DGFE is tested on both pixel-level and image-level classification using real-world hyperspectral remote sensing data and hyperspectral face data, respectively. The experimental results show that M3DGFE achieves promising classification accuracy with parsimonious feature subset.

1. Introduction

Hyperspectral imaging captures an image of objects with wavelengths ranging from the visible spectrum to the infrared region. The technology has allowed accurate image classification, object discrimination, and material identification thanks to the availability of rich information on both spectral and spatial distributions of the analyzed targets. However, hyperspectral imagery data usually contain tens and thousands of images simultaneously collected from various spaced spectral bands. When only a limited number of labeled samples are available, it is a great challenge for classification of such data [9]. In addition, noise imposed by sensors and the environment also deteriorates the performance of learning algorithms.

Feature selection and extraction methods have been widely used to address the aforementioned problems. Feature selection [13,19] selects relevant features and removes noisy/redundant ones in the original feature space, so that the

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classification accuracy could be improved or not substantially deteriorated. Feature extraction methods [20] transform the given features into other space to generate a new set of features possessing high information packing properties. The most discriminative information is concentrated to relative small number of selected new features with which superior classification accuracy is permitted.

Principle component analysis (PCA) [36], linear discriminant analysis (LDA) [15], and wavelet transform [17] are among the most commonly used feature extraction methods for hyperspectral imagery classification. PCA identifies a subspace where data variances are maximized by orthogonally transforming possibly correlated features into a smaller set of linearly uncorrelated principal components [1,29]. LDA is related to PCA in that it also tries to find a linear combination of features but explicitly attempts to model the difference between the classes of data [3,5]. Wavelet transform, in a solid and formal mathematical framework, has attracted increasing attention and served as another powerful solution for feature extraction of hyperspectral imagery classification [12,24,26,41,51].

Many feature extraction methods mentioned above have been shown to be effective in improving the hyperspectral imagery classification accuracy. However, most of them consider only the spectral signature of each pixel or an individual spectral band, whereas the important spatial information is ignored. Since hyperspectral imagery is naturally a three-dimensional (3D) data cube containing both spatial and spectral dimensions, it is believed that spectral and spatial structures of hyperspectral data should be considered simultaneously to further improve the classification accuracy. In this regard, feature extraction of hyperspectral imagery data should treat the 3D cube as a whole and a few 3D feature extraction methods have been proposed. For instances, Qian et al. [37,38] proposed a 3D discrete wavelet transform (3D-DWT) to extract spectral–spatial features from hyperspectral remote sensing data. Bau et al. [4] introduced a 3D Gabor filterbank as a tool for extracting spectral–spatial features to represent image regions in hyperspectral region classification. Two authors of this work, i.e., Shen and Jia [45], proposed a 3D Gabor wavelet transform based feature extraction method for hyperspectral imagery classification. Particularly, a set of well-designed Gabor wavelets with different frequencies and orientations was applied to extract signal variances in joint spatial-spectrum domains. We further extended [45] in [46] by introducing a filter-ranking feature selection method based on symmetrical uncertainty and approximate Markov blanket to select discriminative 3D Gabor features. As a result, comparable or better classification accuracy was achieved with much more parsimonious feature set.

On one hand, 3D feature extraction methods have been shown to obtain better classification accuracy than many other state-of-the-art feature selection/extraction methods [4,37,38,45]. On the other hand, 3D feature extraction would generate a larger number of spectral–spatial features, therefore dimension reduction like feature selection is necessarily needed after feature extraction. For example, in [37], a structured sparse logistic regression was applied after the 3D-DWT extraction to select discriminative spectral–spatial features. A stepwise greedy feature selection was adopted in [4] to identify Gabor filters that optimize the discriminability among different classes. A sequential feature selection and fusion process was developed in [45] to identify the most discriminative Gabor features after 3D Gabor wavelet transform. In [46], a filter-ranking feature selection method was imposed to rank the Gabor features based on their symmetrical uncertainty to the class labels and then the redundant ones were eliminated based on approximate Markov blanket. It is easy to implement the two-phrase feature extraction applied in [4,37,45,46], but it could introduce bias and retain a large number of irrelevant and redundant features in the first phase where wavelet transform is empirically configured. The greedy or filter-ranking feature selection used in the second phase could also get trapped in locally optimal feature sets. Moreover, most of the existing 3D feature extraction methods [4,37,38,45,46] are targeted at pixel-level classification, but very few are applicable to image-level classification (the differences between pixel-level and image-level classification are described in Section 2.2).

In this study, a novel memetic 3D Gabor wavelet feature extraction namely M3DGFE is proposed for both pixel-level and image-level hyperspectral imagery classification. Particularly, M3DGFE conducts 3D Gabor feature generation and selection simultaneously in a memetic algorithm (MA) framework [32]. The evolutionary search mechanism of MA optimizes both the parameter configurations of 3D Gabor wavelet transform and the selection of feature subset. In this way, Gabor wavelets transform no longer relies on empirical parameter setting and discriminative features can be picked out as desirable signatures for final classification. The performance of M3DGFE is evaluated on both pixel-level and image-level classification using two real-world hyperspectral remote sensing data and one hyperspectral face data, respectively. Comparison studies between M3DGFE and other state-of-the-art feature selection/extraction methods show that M3DGFE obtains superior classification accuracy with compact feature sets.

This work is an extension of our conference paper [54], where the prototype of the framework merely targeted at pixel-level classification was first proposed. Significant improvements have been made in both theory and experiments in this work. Particularly, the memetic framework is extended to handle both pixel-level and image-level classification problems, and a novel fitness function evaluating feature relevance is introduced. Much more extensive experimental results are also provided to demonstrate the efficiency of the proposed method. The main contributions of this study are threefold:

(1) a general memetic framework is proposed for 3D Gabor feature extraction of hyperspectral imagery classification;
(2) a novel redundancy-free relevance (RFR) measure is put forward to efficiently evaluate the fitness of candidate feature subsets. RFR enables feature selection methods to identify relevant features and at the same time eliminate irrelevant and redundant features;
(3) both pixel-level and image-level classification problems especially with small sample size are studied using various state-of-the-art feature selection/extraction methods, which could provide insights for other researchers facing similar issues.