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Novel multivariate vector quantization for effective compression of hyperspectral imagery ☆

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ABSTRACT

Although hyperspectral imagery (HSI) has been successfully deployed in a wide range of applications, it suffers from extremely large data volumes for storage and transmission. Consequently, coding and compression is needed for effective data reduction whilst maintaining the image integrity. In this paper, a multivariate vector quantization (MVQ) approach is proposed for the compression of HSI, where the pixel spectra is considered as a linear combination of two codewords from the codebook, and the indexed maps and their corresponding coefficients are separately coded and compressed. A strategy is proposed for effective codebook design, using the fuzzy C-mean (FCM) to determine the optimal number of clusters of data and selected codewords for the codebook. Comprehensive experiments on several real datasets are used for performance assessment, including quantitative evaluations to measure the degree of data reduction and the distortion of reconstructed images. Our results have indicated that the proposed MVQ approach outperforms conventional VQ and several typical algorithms for effective compression of HSI, where the image quality measured using mean squared error (MSE) has been significantly improved even under the same level of compressed bitrate.

1. Introduction

Hyperspectral imagery (HSI), through capturing hundreds of narrow and contiguous spectral bands from a wide range of the electromagnetic spectrum, has great capability in deriving comprehensive details about the spectral and spatial information of the ground material. As a result, it has been widely used in many remote sensing applications such as agriculture [1], mineralogy [2] and military surveillance [3].

In HSI, improved image quality is always desirable for better processing, which in turn results in a trend for an increase in spatial/spectral resolution, radiometric precision and a wider spectral range. Consequently, the data volume in the 3-D hypercube increases dramatically, resulting in challenges for data transmission, storage, and processing. To reduce the volume of data, effective coding and compression become a natural choice in this context.

Existing approaches for HSI compression can be divided into two main categories, i.e. lossless and lossy compression [4]. Lossless compression has been traditionally desired to preserve all the information contained in the image. However, the compression ratios which can be achieved with lossless techniques are limited. Lossless coding techniques include entropy coding and predictive modelling [5,6], where typical lossy compression approaches are transform based techniques [7,8] and vector quantization (VQ) [9,10]. In lossless compression such as predictive modelling, both intra-band spatial correlation and inter-band spectral correlation are used to determine a statistical model to estimate image values using partially observed data. The model and the estimation error are then encoded to represent the hypercube, where the performance relies on the correlation and statistical modelling [11,12].

Lossy compression yields higher compression ratio at the cost of introduced information loss. Despite the quality in the reconstructed image, these techniques are very popular, especially when the required compression could be achieved by lossy techniques. Moreover, the effect of the losses on specific applications in HSI have been assessed, such as target detection and data classification, showing that high compression ratio can be achieved with little impact in performance [7]. Several methods have been proposed for lossy compression of HSI, some of which are generalizations of existing 2D image or video algorithms, such as JPEG 2000 [13]. In [14], a Karhunen–Loeve transform was used to

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compress hyperspectral cubes. Discrete wavelet transform and Tucker decomposition were applied in [8], while a pairwise orthogonal spectral transform was developed in [15]. Also, the H.264/AVC standard for video compression was applied to hyperspectral cubes [16]. Low-complexity paradigm which is based on a prediction stage, followed by quantization, rate-distortion optimization and entropy coding was proposed [17]. It leverages the simplicity and high-performance of prediction-based compression, requiring very few operations and memory, while advanced quantization and rate-distortion optimization ensure state-of-the-art compression performance.

In VQ-based lossy compression, the spectral signature of each pixel is used to determine an optimal codebook, which is then coded along with the indexed map of each spectral vector and transmitted for decoding. Although VQ-based approaches benefit from very high compression ratios for effective data reduction, they may suffer from significant distortion of image quality in coding and compression of HSI [9,18]. Since such degradation of image quality may lead to unrecoverable information loss in follow-on data analysis, the compression should be avoided as suggested in Ref. [19]. As a result, an ideal solution is to keep the quality and preserve essential information whilst the image is compressed.

To achieve this, a novel multivariate vector quantization (MVQ) approach is proposed. For the effective compression of HSI, the pixel spectra is considered as a linear combination of two codewords from the codebook rather than only one codeword as in the conventional VQ approach. To this end, for each spectral vector, two indexed maps and one or two coefficients are determined for coding. As a result, the information contained in the reconstructed imagery is better maintained than conventional VQ based approaches.

The remaining part of this paper is organised as follows. In Section 2, a strategy for codebook design based on FCM is presented. In Section 3, the proposed MVQ approach is presented, along with discussions of conventional VQ approach and techniques used in the MVQ approach. Experimental results and evaluations are presented in Section 4. Finally, some concluding remarks are drawn in Section 5.

2. The strategy for codebook design

In this section, a strategy of codebook design for coding and compression of HSI is presented, followed by the evaluation. Details regarding the associated technique, FCM, to be embedded in codebook design are also discussed.

2.1. Fuzzy C-mean algorithm

Developed by Dunn [34] and improved by Bezdek [20], fuzzy C-means (FCM) is a method of clustering which allows a data sample to belong to more than one cluster, yet with different degrees of membership. In general, FCM is based on minimization of the following objective function:

$$J_N = \sum_{i=1}^{N} \sum_{j=1}^{C} u_{ij}^{m} \boldsymbol{x_i} - \boldsymbol{c_j}^2 \tag{1}$$

where m is any real number greater than 1, u_{ij}^m is the degree of membership of pixel spectrum x_i in the cluster j, x_i is the ith of d-dimensional measured data, c_j is the d-dimension center of the cluster, and $\|\quad\|$ is any norm expressing the similarity between any measured data and the centre.

For fuzzy partitioning, an iterative optimization of the objective function is employed, where the degree of membership u_{ij} and the cluster centres c_j are updated by

$$u_{ij} = \left\{ \sum_{k=1}^{C} \left(\frac{\boldsymbol{x_i} - \boldsymbol{c_j}}{\boldsymbol{x_i} - \boldsymbol{c_k}} \right)^{2/m-1} \right\}^{-1} \tag{2}$$

$$\boldsymbol{c_j} = \frac{\sum_{i=1}^{N} u_{ij}^{m} \times \boldsymbol{x_i}}{\sum_{i=1}^{N} u_{ij}^{m}} \tag{3}$$

This iteration stops when

$$max_{ij}\left\{ |u_{ij}^{(k+1)} - u_{ij}^{(k)}| \right\} < \delta \tag{4}$$

where δ is a pre-set termination criterion between 0 and 1; k is the iteration steps. This procedure converges to a local minimum or a saddle point of J_N.

2.2. Codebook design via blind clustering (CBC)

The best method of codebook design is to carry out an exhaustive search, which helps to determine an unstructured collection of codewords. As the full search is very time- consuming, a constrained search is usually employed to speed up this process to obtain a structured codebook. The approaches most commonly used for codebook design include the Linde, Buzo, Gray (LBG) algorithm [21], fuzzy vector quantization (FVQ) [22], Kekre's Fast Codebook Generation (KFCG) [23], and discrete cosine transform (DCT) based method.

In this paper, we present a codebook design strategy using a fuzzy C-mean (FCM) based blind clustering algorithm. According to the cost of FCM at different cluster numbers, the one with the minimum cost is chosen as the optimized cluster number. The cost in CBC is defined as follows:

$$C = N^{\theta} \times J_N \tag{5}$$

where N is the number of clusters, corresponding to N possible codewords; $\theta > 0$ is a constant, and J_N is an objective function of FCM when the data is clustered into N classes.

For a dataset, usually the sum of distortion J_N decreases with the rise of cluster numbers. If the codebook contains sufficient codewords, the distortion would approach zero. By combining the codebook size N into the defined cost function in (5), an adaptive solution for codebook design is achieved, where the codebook size and the final distortion is compromised.

2.3. Evaluation for codebook design strategy

To validate the efficacy of our proposed codebook design strategy, one simulated HSI dataset is used as an example and presented below. The simulated dataset has 30×30 pixel, including 6 classes represented in 6 vertical bars of a size 30×5 pixel, i.e. each class contains 150 pixel. Actually, the spectral data are extracted from the first HSI dataset, Salinas, as further described in Section 4, where in each class the 150 pixel are randomly selected within the corresponding class. The false colour images of the simulated hypercube are shown in Fig. 1 (left).

When CBC is applied for codebook design, 12 codewords are selected. Due to the spectral similarity of pixels from the same class, most codewords are actually selected from the corresponding class. This is illustrated in Fig. 1 (right), where pixels presented by the same colour belong to the same class.

3. Multivariate vector quantization approach

In this section, MVQ, the proposed approach for HSI compression, is presented. Relevant techniques along with descriptions of conventional VQ are introduced in detail below.