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Ant colony optimization for wavelet-based image interpolation using a three-component exponential mixture model

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ABSTRACT

Wavelet-based image interpolation typically treats the input image as the low frequency subbands of an unknown wavelet-transformed high-resolution image, and then produces the unknown high-resolution image by estimating the wavelet coefficients of the high frequency subbands. For that, a new approach is proposed in this paper, the contribution of which are twofold. First, unlike that the conventional *Gaussian mixture* (GM) model only exploits the magnitude information of the wavelet coefficients, a *three-component exponential mixture* (TCEM) model is proposed in this paper to investigate both the magnitude information and the sign information of the wavelet coefficients. The proposed TCEM model consists of a Gaussian component, a positive exponential component and a negative exponential component. Second, to address the parameter estimation challenge of the proposed TCEM model, the *ant colony optimization* (ACO) technique is exploited in this paper to classify the wavelet coefficients into one of three components of the proposed TCEM model for estimating their parameters. Experiments are conducted to demonstrate that the proposed approach outperform a number of approaches developed in the literature.

1. Introduction

Wavelet-based techniques have been widely used for performing image interpolation. A common assumption of the wavelet-based image interpolation approaches is that the input image is treated as the low frequency subbands of an unknown wavelet-transformed high-resolution image. Then the unknown high-resolution image can be reconstructed by estimating the wavelet coefficients of the high frequency subbands, followed by applying the inverse wavelet transform (Chang, Cvetkovic, & Vetterli, 1995; Temizel & Vlachos, 2006).

The challenge of conducting wavelet-based interpolation is to estimate the unknown wavelet coefficients of the high frequency subbands. The major widely-used approach is to exploit the inter-scale correlations between the high frequency wavelet coefficients and the low frequency subbsands using statistical models, particularly the *Gaussian mixture* (GM) model (Crouse, Nowak, & Baraniuk, 1998; Kim, Lee, & Cho, 2006; Kinebuchi, Muresan, & Parks, 2001; Woo, Eom, & Kim, 2004; Zhao, Han, & Peng, 2003). However, this GM model neglects the correlations among the sign information of the wavelet coefficients, since the Gaussian distribution is *symmetrical* around the zero (Temizel, 2007). Inaccurate estimation of the sign of wavelet coefficients could result in implausible artifacts in the reconstructed image. To justify this, a simulation is conducted using the *Lena* image. A one-level wavelet decomposition (using the well-known *Daubechies*-97 wavelets) is applied on the test image (shown in Fig. 1(a)), then the signs of all high frequency wavelet coefficients are changed, finally an inverse wavelet transform is applied to produce an image (shown in Fig. 1(b)). Comparing Fig. 1(a) and Fig. 1(b), one can see that the sign information of the wavelet coefficients has a critical role to control the quality of the reconstructed image.

To tackle the above challenge, a *three-component exponential mixture* (TCEM) model is proposed in this paper by formulating the probability distribution of individual wavelet coefficient using three components: (i) a Gaussian component, (ii) a positive exponential component, and (iii) a negative exponential component. Due to the fact that the exponential distribution is *not* symmetrical around the zero, the proposed model is able to exploit both the magnitude information and the sign information of the wavelet coefficients. Then, the proposed TCEM model is exploited to develop an image interpolation algorithm, by exploiting the inter-scale correlation between the low frequency wavelet coefficients and the high frequency wavelet coefficients.

There is a key fundamental issue that needs to be addressed for the proposed TCEM model; that is how to estimate the parameters of the proposed TCEM model. To tackle this issue, the *ant colony optimization* technique is used in this paper. The ACO technique is exploited to classify the wavelet coefficients into one of three

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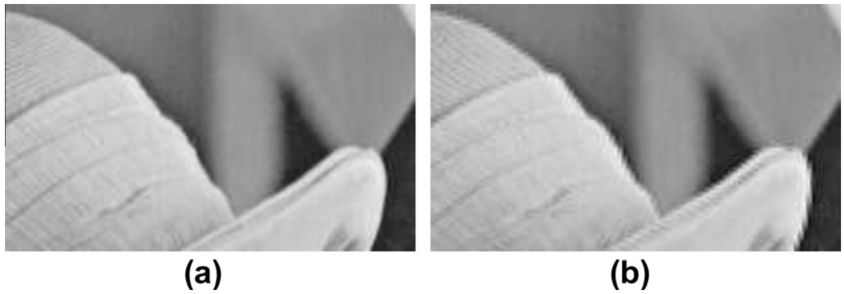

Fig. 1. (a) Original *Lena* image; (b) the reconstructed image, by applying one-level wavelet decomposition transform on the image (a) and changing the signs of high frequency wavelet coefficients, followed by applying the inverse wavelet transform.

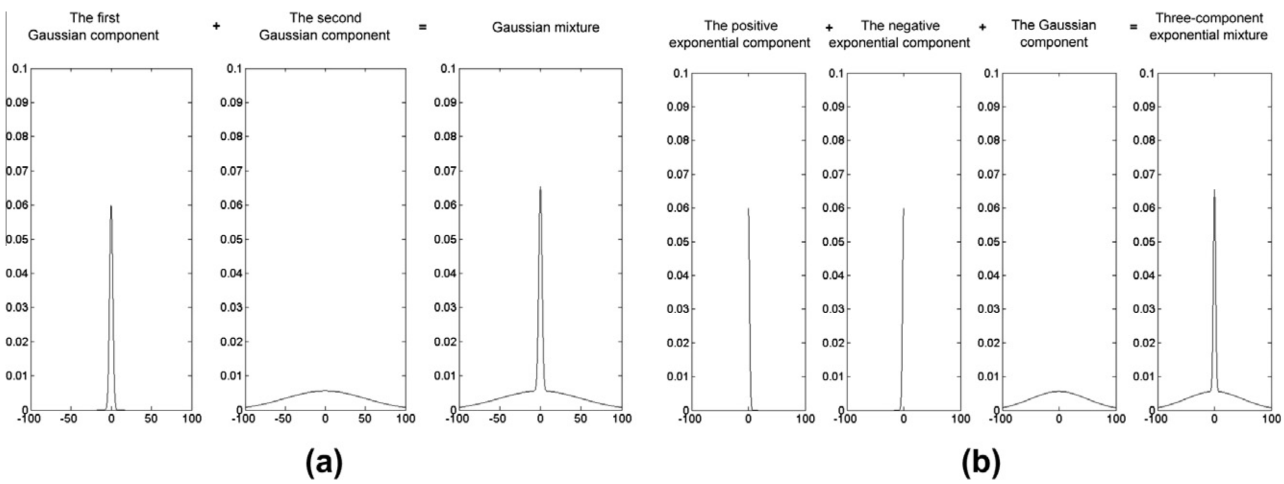

Fig. 2. A comparison between the two-component Gaussian mixture model (Crouse et al., 1998) and the proposed three-component exponential mixture model: (a) a two-component Gaussian mixture model consisting of two Gaussian components; and (b) the proposed three-component exponential mixture model consisting of three exponential components: a Gaussian component, a positive exponential component, plus a negative exponential component.

components of the proposed TCEM model, then estimate the parameters of each component. ACO is a nature-inspired optimization algorithm (Dorigo & Thomas, 2004) motivated by the natural collective foraging behavior of real-world ant colonies. Despite the fact that ACO has been widely applied to tackle numerous optimization problems (Dorigo, Gambardella, Middendorf, & Stutzle, 2002), its applications in image processing are quite a few (Hegarat-Mascle, Kallel, & Descombes, 2007; Malisia & Tizhoosh, 2006; Ouadfel & Batouche, 2003; Tian, Yu, & Xie, 2008b).

The rest of this paper is organized as follows. The proposed image interpolation approach is presented in Section 2 where a brief introduction to the conventional GM model and the proposed TCEM model is first provided, followed by estimating the parameters of the proposed TCEM model using the ACO technique. Extensive experimental results are presented in Section 3. Finally, Section 4 concludes this paper.

2. Proposed image interpolation approach

Basically, the idea of the proposed image interpolation approach is to treat the input image as the low frequency subbands of an unknown wavelet-transformed high-resolution image, and then produces the unknown high-resolution image by estimating the wavelet coefficients of the high frequency subbands. The proposed approach exploits the proposed TCEM model to formulate the statistical models of the low frequency subbands (i.e., the *known* low-resolution image), the parameters of which are estimated using the ACO technique. Then, the inter-scale correlation between the low frequency subbands and the high frequency subbands is exploited to estimate the statistical model of the coefficients of the *unknown* high frequency subbands. Finally, the coefficients of the high frequency subbands are synthesized via sampling from the above estimated model.

The key issues of the proposed approach boil down to the following three aspects: (i) build up the statistical model of the *known* wavelet coefficients, (ii) estimate the parameters of the above known statistical model, and (iii) estimate the model of the *unknown* wavelet coefficients using the inter-scale correlations among the wavelet coefficients. These three key issues are discussed in detail in the following subsections, respectively.

2.1. Statistical model of wavelet coefficients

2.1.1. Conventional Gaussian mixture model

A two-component *Gaussian mixture* (GM) model is developed in Crouse et al. (1998) for modeling the distribution of individual wavelet coefficients, as illustrated in Fig. 2(a). This is motivated by the fact that most wavelet coefficients of a natural image have small values and contain very little signal information; on the other hand, a few wavelet coefficients have large values that represent significant signal information. The above-mentioned characteristics can be mathematically formulated as follow. Denote the ith wavelet coefficient at the subband with the jth scale and kth direction as $S_i^{j,k}$. It has a distribution as

$$p\left(S_i^{j,k}\right) = q_i^{j,k} N\left(0, \sigma^2_{h_i^{j,k}}\right) + \left(1 - q_i^{j,k}\right) N\left(0, \sigma^2_{l_i^{j,k}}\right), \tag{1}$$