An improved partial SPIHT with classified weighted rate-distortion optimization for interferential multispectral image compression

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Based on the property analysis of interferential multispectral images, a novel compression algorithm of partial set partitioning in hierarchical trees (SPIHT) with classified weighted rate-distortion optimization is presented. After wavelet decomposition, partial SPIHT is applied to each zero tree independently by adaptively selecting one of three coding modes according to the probability of the significant coefficients in each bitplane. Meanwhile the interferential multispectral image is partitioned into two kinds of regions in terms of luminous intensity, and the rate-distortion slopes of zero trees are then lifted with classified weights according to their distortion contribution to the constructed spectrum. Finally a global rate-distortion optimization truncation is performed. Compared with the conventional methods, the proposed algorithm not only improves the performance in spatial domain but also reduces the distortion in spectral domain.

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The interferential spectrometer is considered as the newest development of imaging spectrometers in remote sensing. Nowadays it is widely used in many scientific and military fields such as substance classification and recognition[1,2]. The customary multispectral images compression methods[3−6] only consider the quality of reconstructed images in spatial domain without concerning the spectrum loss in Fourier domain. In this paper, we propose a new compression approach of partial set partitioning in hierarchical trees (SPIHT) with classified weighted rate-distortion optimization based on the relationship between the spectral distortion in Fourier domain and the reconstructed quality in spatial domain.

Based on the principle of the Michelson interferometer, an interferential spectrometer forms interferential multispectral images in charge-coupled device (CCD) detectors rather than the spectrum directly. Each line of an interferential multispectral image is called as an interferogram, which is a curve of the variation of interferential luminous intensity with optical path difference (OPD) of an observed point on the ground. By means of Fourier transform (FT), the interferogram can be turned to a spectrum. An example of an interferential multispectral image and an interferogram curve with its corresponding spectrum is given in Fig. 1. The distinctive characteristic of the interferential multispectral image is that the interferential luminous intensity reaches maximum where the OPD equals zero, but declines rapidly and dramatically with the increase of OPD.

We divide the interferential multispectral image into two kinds of regions, as shown in Fig. 1(a), according to the amplitude of the interferential luminous intensity: one is the major interference region, i.e. G_a, which represents the region near zero OPD, i.e. δ_0, and the other is the minor interference region, i.e. G_i, which is the rest region in the interferential multispectral image.

The contour and absorption peaks of spectrum play an important role in spectrum analysis, by which we can determine the existence and content of some substance[7]. It has been proved in Ref. [8] that the relationship between mean square error (MSE) of first diversity of spectrum in Fourier domain and distortion of reconstructed images in spatial domain is

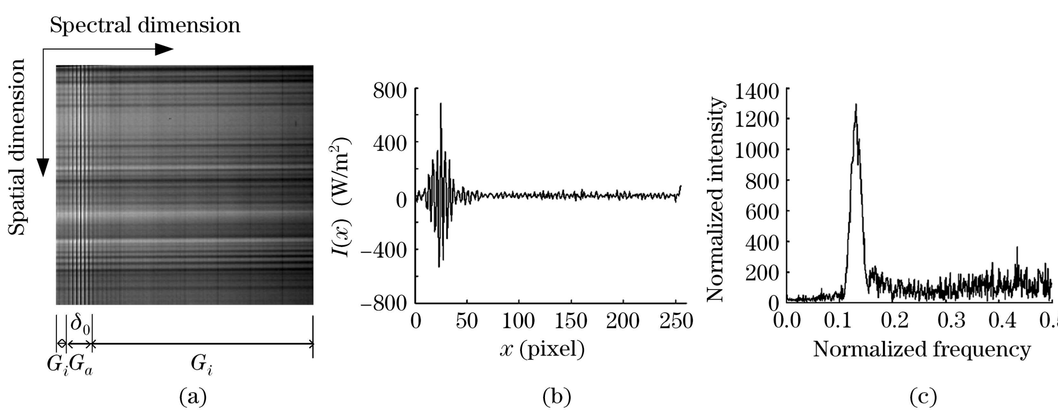

Fig. 1. (a) A sample of interferential multispectral images (256(pixel) × 256(pixel) × 12(bit)); (b) curve of the interferogram at the line 200 of (a); (c) spectrum curve of (b) by FT.

$$\underbrace{\int_{-\infty}^{\infty}\left|\frac{\mathrm{d}S(f)}{\mathrm{d}f}-\frac{\mathrm{d}S^*(f)}{\mathrm{d}f}\right|^2\mathrm{d}f}_{\text{Fourier domain}}$$

$$=\underbrace{2\pi\int_{-\infty}^{\infty}x^2\left[I(x)-I^*(x)\right]^2\mathrm{d}x}_{\text{spatial domain}}, \quad (1)$$

where x is OPD, $I(x)$ and $S(f)$ denote original interferogram and FT of $I(x)$ respectively, $I^*(x)$ is the reconstruction of $I(x)$ and $S^*(f)$ is FT of $I^*(x)$.

Considering Eq. (1), the pixels with larger OPD in the interferogram are more important for spectrum reconstruction, thus an efficient protection method should be taken during compression to the pixels far away from zero OPD more than those in the region near zero OPD. The region of interest (ROI)[9,10] coding approach is usually used, in which the background is degraded. However, it is not suitable for compression of interferential multispectral images due to the different importance of pixels in the same region. Therefore, a new compression algorithm of partial SPIHT with classified weighted rate-distortion optimization is presented, as illustrated in Fig. 2.

The problem with SPIHT is that the coding efficiency degrades as the probability of the significant coefficients (P_1) increases, especially at lower bitplanes[11,12]. To solve this problem, partial SPIHT (PSPIHT) is adopted to code each zero tree independently, by adaptively selecting one of three coding modes at each bitplane according to the relationship between P_1 and two thresholds, i.e. T_1 and T_2, at the current bitplane.

$$\begin{cases} P_1 < T_1 & \text{Mode\_A : SPIHT code} \\ T_1 \le P_1 < T_2 & \text{Mode\_B : entropy code} \\ T_2 \le P_1 & \text{Mode\_C : without code} \end{cases}. \quad (2)$$

Mode_A is the standard SPIHT algorithm. In Mode_B, the bitplane is partitioned into 2×2 sets. If all of the pixels within the 2×2 sets are insignificant, "0" is transmitted; otherwise "1" is transmitted followed by the four bits of the set. Mode_C transmits the sets without any compression. The threshold $T_2 = 1 - P_0 = 0.29$, in which P_0 is calculated by

$$P_0^4 + 5\left(1 - P_0^4\right) < 4, \quad (3)$$

which means the average number of bits transmitted per set in Mode_B is less than that in Mode_C. Similarly we can get $T_1 = 0.15$.

In order to minimize the distortion in Fourier domain and spatial domain, the classified weighted rate-distortion optimization is proposed, which truncates the bit streams of zero trees by lifting the rate-distortion slopes with different weights according to the distortion contribution of each zero tree in Fourier domain. In this way, the significant coefficients can be coded first.

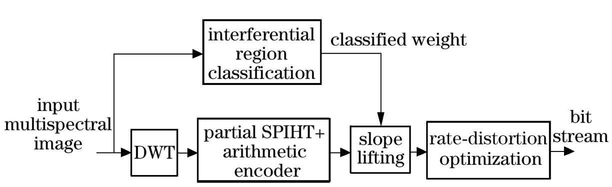

Fig. 2. Block diagram of compression system.

Given the rate $R_{\max}$, suppose that the rate of the truncated bit stream and the distortion of the reconstructed coefficients in the ith zero tree T_i are $R_i^{n_i}$ and $D_i^{n_i}$ respectively. Here n_i denotes the truncated point. Let the distortion be additive.

According to the rate-distortion optimization theory, the optimization problem with the constraint $R \le R_{\max}$ is equivalent to minimizing

$$\sum_i \left(R_i^{n_i} + \lambda D_i^{n_i}\right). \quad (4)$$

This problem is a separate optimization for each individual zero tree T_i, in which the rate-distortion slopes of candidate truncated points are

$$S_i^n = \Delta D_i^n / \Delta R_i^n. \quad (5)$$

As G_a is much smaller in size than G_i, and the distortion contribution of G_a is less than that of G_i, we choose the slope lifting function $\gamma(x)$ as follows by ignoring the difference of importance in G_a:

$$\gamma(x) = \begin{cases} 0, & x \in G_a \\ p\left|x - x_0\right|, & x \in G_i \end{cases}, \quad p > 0, \quad (6)$$

where x_0 is the location with zero OPD, and x denotes the corresponding OPD in spatial domain of any zero tree in wavelet domain.

All the slopes of candidate truncated points in each zero tree are then weighted by $\gamma(x)$, according to the category of the interference region it belongs to. The lifted slopes are

$$S_i^n(\gamma(x)) = \gamma(x) \cdot S_i^n = \gamma(x) \cdot \Delta D_i^n / \Delta R_i^n. \quad (7)$$

As the distortion contribution of any zero trees belonging to various interference regions is related to OPD, the distortion function can be weighted by $w(x)$, which is the function of OPD:

$$w(x) = \frac{N_G(x)}{\sum\limits_{x \in G}\left|I(x)\right|}, \ G = G_a, G_i. \quad (8)$$

where $N_G(x)$ denotes the total number of pixels belonging to G.

A simulation of the efficiency of the proposed method is carried out on 128 frames of interferential multispectral images ($256 \times 256 \times 12$), acquired by an interferential spectrometer in some satellite. In Table 1, we give the compression results in spatial domain by SPIHT, PSPIHT, rate-distortion SPIHT (RDSPIHT), and the proposed method. It is clear that PSPIHT provides a remarkable gain over SPIHT at high bit rates, but this gain

Table 1. Comparison of Different Compression Methods

Bit per	Average PSNR (dB)			
Pixel	SPIHT	PSPIHT	RDSPIHT	Proposed
1.0	51.86	52.20	52.24	52.26
1.5	54.18	55.10	54.73	55.28
2.0	56.30	57.25	56.84	57.40
3.0	61.90	64.37	62.41	64.08

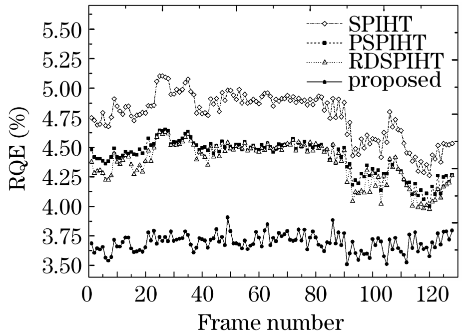

Fig. 3. RQE comparison between four different algorithms at the bit rate of 1.0 bit/pixel. The average RQEs of SPIHT, PSPIHT, RDSPIHT, and our method are 4.77%, 4.42%, 4.37%, and 3.69% respectively.

turns to decrease at lower bit rates. The rate-distortion optimization in RDSPIHT greatly improves the performance at low bit rates, but at high bit rates, the improvement over SPIHT declines obviously compared with PSPIHT. As combined with the advantages of PSPIHT and rate-distortion optimization with classified weight, our method can provide a higher peak signal-to-noise ratio (PSNR) in spatial domain over other algorithms at any bit rate.

In order to evaluate the spectral distortion in Fourier domain after compression, the relative spectral quadratic error (RQE)[13] of four coding methods above are compared in Fig. 3. The RQE is calculated by

$$\mathrm{RQE} = \frac{\sqrt{\int_0^{0.5} \left| S^*(\tilde{f}) - S(\tilde{f}) \right|^2 \mathrm{d}\tilde{f}}}{\int_0^{0.5} S(\tilde{f}) \mathrm{d}\tilde{f}}, \tag{9}$$

where $S(\tilde{f})$ and $S^*(\tilde{f})$ are respectively the original spectrum and the reconstructed one after compression, $\tilde{f}$ is the normalized frequency $(0 < \tilde{f} < 0.5)$.

From the RQE comparison, it is obvious that our method greatly reduces the spectral distortion in Fourier domain, thus protecting efficiently the contour and absorption peaks of spectrum, so that applications like substance classification and recognition can be done exactly.

In conclusion, we propose an improved partial SPIHT with classified weighted rate-distortion optimization algorithm for interferential multispectral image compression. It can not only improve the performance in spatial domain but also reduce the distortion in spectral domain.

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