Image Fusion Based on PCA and Undecimated Discrete Wavelet Transform

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Abstract. On the basis of analyzing the performances of popular image fusion methods, a new remote sensing image fusion method based on principal component analysis (PCA), high pass filter (HPF) and undecimated discrete wavelet transform (UDWT) is proposed. Some measure parameters are suggested to evaluate the fusion method. Experiments have been performed with the SPOT panchromatic image and the TM multi-spectral image. Both subjectively qualitative analysis and objectively quantitative evaluation verify the performance of the new method. With the same wavelet transform level, the fusion image using the proposed method preserves more sophisticated spatial details and distorts less spectral information in comparison with the fusion image using the traditional discrete wavelet transform (DWT) method.

1 Introduction

By the organic integration of various and complementary information, multi-sensor data fusion can furthest utilize multi-resource information and reduce the uncertainty or error of interpretation with the single resource, thereby greatly enhance the effectiveness of features extraction, classification, target detection, identification, etc.

Multi-spectral and panchromatic images are two kinds of data commonly used. Multi-spectral images contain abundant spectral information, but have poorly performance of the spatial details because of lower resolution. Panchromatic images have rich spatial details. The purpose of fusion is to maintain spectral information of multi-spectral images and improve the spatial details at the same time.

The classical multi-spectral and panchromatic imagery fusion methods include the High Pass Filter (HPF) method [1], the Hue-Intensity-Saturation (HIS) transform method [2], the Principal Component Analysis (PCA) method [3] and the wavelet transform (WT) method [4-5]. The HPF method improves the spatial details, but produces serious noise. The HIS transform method directly replaces the component *I* of the multi-spectral image with the high-resolution panchromatic image, and it improves the spatial details of the multi-spectral image, but produces serious spectral information distortion because the component *I* contains spectral information. The PCA method replaces the first principle component of the multi-spectral image with the panchromatic image, and it improves the spatial details, but also seriously distorts spectral information. The WT method is to replace high frequency coefficients of the multi-spectral image with corresponding components of the panchromatic image in the

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transform domain. If the decomposition level is too small, the fusion image preserves spectral characteristics of the multi-spectral image, but fails to improve the spatial details well because the discarded low frequency coefficient of the panchromatic image still contains many spatial details. When the level is increased, the performance capacity of the spatial details gradually increased in the fusion image, but the spectral information is not preserved well because the low frequency coefficient is decomposed time after time, and the mosaic phenomenon may be produced. To resolve the conflict, the usual method is to find the balance between performance capabilities of the spectral information and the spatial details with the adjustment of the wavelet decomposition level.

The fusion method based on PCA, HPF and UDWT (undecimated discrete wavelet transform) is proposed through the performance analysis of the classical image fusion methods. The performances of the new method are tested by merging the SPOT panchromatic image and the TM multi-spectral image, and experimental results verify the validity of the method. With the same wavelet decomposition level, the new method has the advantage of preserving more spatial details and distorting less spectral information in comparison with the traditional wavelet transform method.

2 Principal Component Analysis

Principal Component Analysis (PCA) is one of the linear mapping techniques. To fix notations, consider n wave bands multi-spectral images as the vector X

$$X = [x_1, x_2, x_3, \cdots, x_n]^T \ . \tag{1}$$

The variance between different wave bands is denoted as

$$\delta_{ij}^2 = E[(x_i - m_i)(x_j - m_j)],\ i, j = 1,2,3,\cdots n \ . \tag{2}$$

where x_i and x_j are the means of the wave band i and j images. The symmetric covariance matrix is Σ

$$\Sigma = \begin{bmatrix} \delta_{1,1} & \delta_{1,2} & \cdots & \delta_{1,n} \\ \delta_{2,1} & \delta_{2,2} & \cdots & \delta_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ \delta_{n,1} & \delta_{n,2} & \cdots & \delta_{n,n} \end{bmatrix} . \tag{3}$$

The covariance matrix Σ is then diagonalized, and the eigenvectors φ_r $(r = 1,2,\cdots,n)$ are calculated according to the corresponding eigenvalues from high to low. The eigenvectors vector is given by

$$\phi_n = [\varphi_1, \varphi_2, \varphi_3, \cdots, \varphi_n]^T \ . \tag{4}$$

The n wave bands multi-spectral images are mapped onto the eigenvector

$$Y = \phi_n \cdot X \ . \tag{5}$$

In the PCA method, the multi-spectral images are transformed with PCA, and the principle components $y_i\,(i=1,2,\cdots,n)$ are obtained. The panchromatic image is matched by the first principle component with the histogram matched method, and the first principle component y_1 is replaced with the matched panchromatic image. The fusion image is obtained when the new first principle component and the other principle components are transformed with the inverse PCA transform. The PCA method improves the spatial details of the multi-spectral images, but it produces serious spectral information distortion because the first component of the multi-spectral images contains much spectral information.

3 Undecimated Discrete Wavelet Transform

With the ability of multi-solution analysis and multi-resolution image decomposition, the wavelet transform has been employed for remote sensing image fusion. According to the discrete wavelet transform (DWT) method [4-5], the high frequency coefficients of the multi-spectral image are replaced with those of the panchromatic image in the wavelet transform domain. The fused image is synthesized by the inverse discrete wavelet transform (IDWT). The multi-resolution analysis of the DWT does not preserve the translation invariance because of subsampling following each filtering stage. The wavelet coefficient of an image discontinuity could disappear arbitrarily. To preserve the translation invariance, the undecimated discrete wavelet transform (UDWT) method has been introduced [6]. The downsampling operation is suppressed, and the filters of the level j are acquired by 2^j upsampling the DWT filters

$$h_k^{[j]} = h_k \uparrow 2^j = \begin{cases} h_{k/2^j}, & k = 2^j m,\ \ if \quad m \in Z \\ 0, & else \end{cases}$$
$$g_k^{[j]} = g_k \uparrow 2^j = \begin{cases} g_{k/2^j}, & k = 2^j m,\ \ if \quad m \in Z \\ 0, & else \end{cases} \quad . \tag{6}$$

The frequency response of Eq.(6) will be $H(2^j w)$ and $G(2^j w)$ respectively. The coefficients of the level j+1 obtained from the level j are the following

$$\begin{aligned} A_{j+1}(m,n) &= \sum_k \sum_l h_k^{[j]} h_l^{[j]} A_j(m+k,n+l) \\ W_{j+1}^{LH}(m,n) &= \sum_k \sum_l g_k^{[j]} h_l^{[j]} A_j(m+k,n+l) \\ W_{j+1}^{HL}(m,n) &= \sum_k \sum_l h_k^{[j]} g_l^{[j]} A_j(m+k,n+l) \\ W_{j+1}^{HH}(m,n) &= \sum_k \sum_l g_k^{[j]} g_l^{[j]} A_j(m+k,n+l) \end{aligned} \quad , \tag{7}$$

where (m,n) stands for the pixel position, A_j is the approximation of the original image at the scale 2^j, and three high frequency components W_j^{LH}, W_j^{HL} and W_j^{HH} corresponding to horizontal, vertical and diagonal spatial details. The scheme of the decimated discrete wavelet coefficient decomposition and reconstruction is depicted in Fig. 1(a), and the scheme of the undecimated discrete wavelet transform is shown in Fig. 1(b).

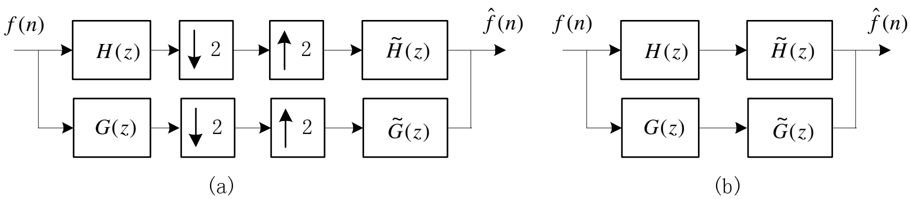

Fig. 1. Discrete wavelet decomposition and reconstruction. (a) Decimated, (b) Undecimated

4 The Fusion Method Based on PCA and UDWT

To improve the performance of the spatial details when preserving the spectral information, the new fusion method makes use of PCA, HPF and UDWT. The panchromatic image is first processed by HPF, and the fused image preserves spectral information and spatial details well when the wavelet decomposition level is small.

The whole processing program of the realization is as follows:

Step1. The multi-spectral images are transformed with PCA, and the panchromatic image is processed with HPF.

Step2. The low frequency part of the panchromatic image is matched by the first principle component of the multi-spectral image with the histogram matched method.

Step3. The matched low frequency part of the panchromatic image and the first principle component are both transformed with the undecimated discrete wavelet transform. Two sets of undecimated wavelet coefficients are obtained, including approximation (*LL*) and detail (*HL*, *LH* and *HH*) components of the original data. The first principle component of the multi-spectral image is reconstructed through the fusion process of the wavelet domain and inverse UDWT. The fusion rule in the transform domain is introduced as follow:

(1) At the level 2^j, the low frequency approximate coefficient used in the fusion process is the *LL* coefficient of the multi-spectral image.

(2) At each level, the high frequency coefficient with the higher gradient value between two sets of detail components is adopted in each direction.

Step4. The high frequency part of the panchromatic image is added to the reconstructed first principle component, a new first principle component of the multi-spectral image is acquired.

Step5. Finally, the new first principle component and the other principle components are transformed with the inverse PCA to obtain the fusion image.

5 Experimental Results and Performance Evaluation

The registration TM multi-spectral image and SPOT panchromatic image are used to verify the validity of the new method. The TM image is shown in Fig. 2(a), and the SPOT panchromatic image is illustrated as Fig. 2(b). The fusion image with the 2-level DWT method is illustrated as Fig. 2(c), and the fusion image with the 3-lelve DWT method is shown in Fig. 2(d). The fusion image using the new method with 2-level UDWT is illustrated as Fig. 2(e), and Fig. 2(f) is the fused image using the new method with 3-level UDWT.

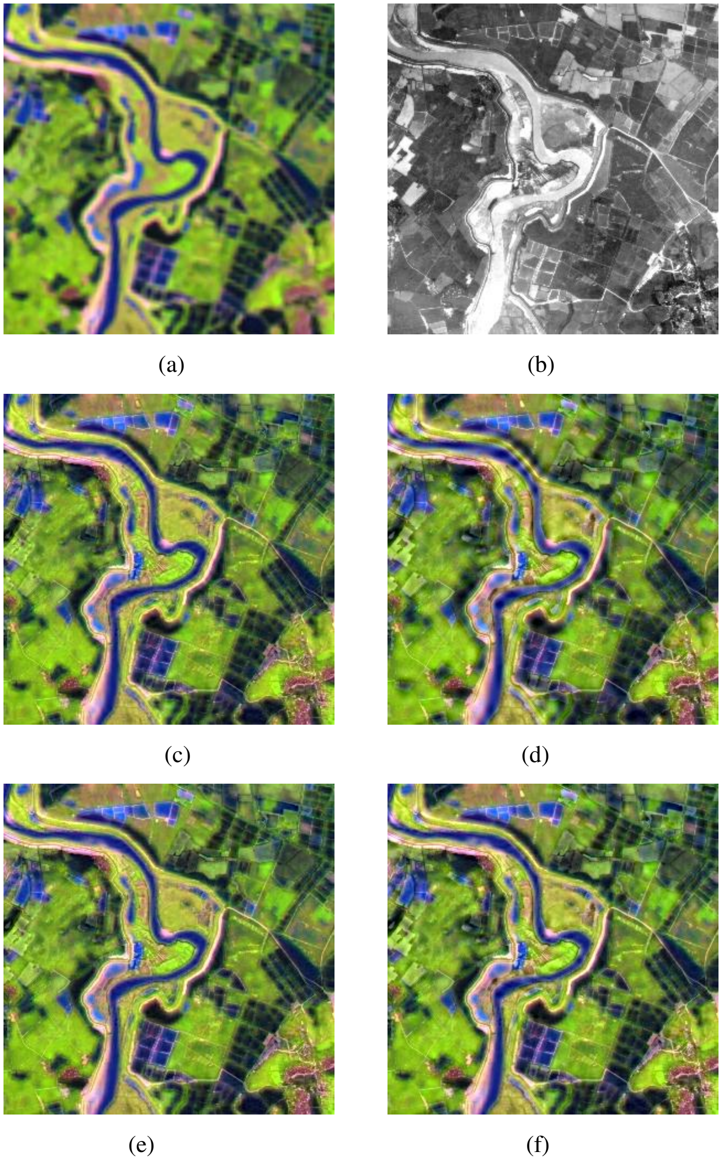

Fig. 2. The original images and fusion images. (a) The TM multi-spectral image. (b) The SPOT panchromatic image. (c) The fusion image with the 2-level DWT method. (d) The fusion image with the 3-level DWT method. (e) The fusion image using the new method with 2-level UDWT. (f) The fused image using the new method with 3-level UDWT.

Generally, the performance evaluation of the image fusion method can be divided into two ways, namely, subjectively qualitative analysis and objectively quantitative evaluation.

5.1 Subjectively Qualitative Analysis

Subjectively qualitative analysis mainly includes two areas:

(1) The visual quality of the fused image, such as spatial resolution, clarity, contrast, sophisticated details, etc.

(2) The spectral fidelity, it indicates the extent of preserving original spectral signal or spectrum characteristics.

Fig. 2(c) is the fusion image with the traditional 2-level DWT method. When the number of decomposition level is increased to 3, the fusion image Fig. 2(d) preserves more spatial details, especially in the left part of the image, but has increased spectral distortion, such as the river region of the image.

Fig. 2(e) is the fusion image using the new method with 2-level UDWT, the spatial details is more sophisticated than those of Fig. 2(c), and their spectral information are similar. Fig. 2(f) is the fused image using the new method with 3-level UDWT, its spatial details is more sophisticated than those of Fig. 2(e), but spectral information distortion begins. Compared Fig. 2(f) with Fig. 2(d), the new method preserves spectral information and spatial details well, i.e. the new method provides the better fusion solution than the DWT method with the same decomposition level.

5.2 Objectively Quantitative Evaluation

In the way of subjectively qualitative judgment, different results could be acquired by reason of differences between individual visual and psychological factors, and professional experience of observers will also affect the final conclusion. Therefore, it is necessary to define a series of quantitative evaluation parameters of the visual quality and spectral fidelity. The current quantitative parameters mainly include mean, standard deviation, average error, entropy, entropy difference, average gradient value, deviation index, correlation coefficient, etc. The information entropy, average gradient and deviation index are used to measure fusion results of different methods.

5.2.1 Entropy

Entropy is an important index to measure the information deposited in images. According to the principle of Shannon information theory, the entropy of the 8-bit image can be defined as

$$H(x) = -\sum_{i=0}^{255} P_i \log_2 P_i \ , \tag{8}$$

where p_i is the probability of the gray i in the image.

5.2.2 Average Gradient

Average gradient is sensitive to minor details of the image. It can be used to assess the ambiguous extent of the image, and is calculated as

$$\Delta\overline{g} = \frac{1}{M \cdot N}\sum_{x=1}^{M}\sum_{y=1}^{N}\sqrt{\left(\frac{\partial f(x,y)}{\partial x}\right)^2 + \left(\frac{\partial f(x,y)}{\partial y}\right)^2} \ . \tag{9}$$

Generally, the greater the average gradient, the clearer the image.

5.2.3 Deviation Index

Deviation index is introduced to measure the deviation extent between the fused image and the original multi-spectral image. It is defined as follows:

$$DI = \frac{1}{M \cdot N}\sum_{i=1}^{M}\sum_{j=1}^{N}\frac{|FUS(i,j) - MUL(i,j)|}{MUL(i,j)} \ , \tag{10}$$

where *FUS* is the fused image, *MUL* is the original multi-spectral image. Generally, the greater the deviation index, the more serious the spectral distortion.

Table 1 shows the quantitative evaluation of the fused images with three parameters. The Deviation index is acquired by calculating the deviation between the intensity component *I* of the original multi-spectral image and the intensity component *I* of the fused image.

Table 1. The statistical comparison of the fusion results

Image	Entropy	Average gradient	Deviation index
The Panchromatic image	7.6764	22.2506	
The Multi-spectral image	5.9120	9.4943	
The fusion image with the DWT method(2 level)	7.5342	19.8748	0.1104
The fusion image with the DWT method(3 level)	7.5826	20.3007	0.1717
The fusion image with the new method(2 level)	7.4077	20.2581	0.1087
The fusion image with the new method(3 level)	7.5314	20.8206	0.1376

The entropies of four fusion images are all increased as compared with the original multi-spectral image. Compared with the fusion image using 2-level DWT method, the average gradient of the fusion image using 3-level DWT method becomes greater, and the same is the deviation index. It indicates that spatial details are enhanced, but the distortion of spectral information is exacerbated. The new method with 2-level UDWT is superior to the 2-level DWT method in the average gradient, and is similar in the deviation index. Compared with the fusion image using the new method with 2-level UDWT, the average gradient of the fusion image using the new method with 3-level UDWT is greater, and the distortion of spectral information is increased. But the new method with 3-level UDWT is superior to the 3-level DWT method in the average gradient and the deviation index of the fused image. It is obvious that the conclusion of quantitative data evaluation consists with the above conclusion of subjectively qualitative analysis.

Synthesized the conclusions of subjectively qualitative analysis and objectively quantitative evaluation, it is concluded that the new method not only distinctly improves the spatial details but also preserves more spectral information of the multi-spectral image. With the same wavelet transform level, the fusion image using the proposed method has more sophisticated spatial details, and distorts less spectral information compared with the fusion image using the DWT method.

6 Conclusion

A remote sensing image fusion method based on PCA, HPF and undecimated discrete wavelet transform is presented. The performances of the proposed method are tested by merging the SPOT panchromatic image and the TM multi-spectral image. Both subjectively qualitative analysis and objectively quantitative evaluation verify the validity of the new method. The multi-spectral image contains abundant spectral information, but lacks in spatial details owing to the lower resolution. The panchromatic image is rich in details. The new method can improve the spatial details while preserving the spectral information of the multi-spectral image. Compared with the traditional discrete wavelet transform method of the same wavelet transform level, the new method has the advantage of preserving more spatial details and spectral information.

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