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Introduction of a Fast Substitute Wavelet Intensity Method to Pan-sharpening Technique

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Abstract : Recently, González-Audícana et al. proposed the substitute wavelet intensity (SWI) method which provided a solution based on the intensity-hue-saturation (IHS) method for the fusing of panchromatic (PAN) and multispectral (MS) images. Although the spectral quality of the fused MS images is enhanced, this method is not efficient enough to quickly merge massive volumes of data from satellite. To overcome this problem, we introduce a new SWI method based on a fast IHS transform to implement efficiently as an alternative procedure. In addition, we show that the method is well applicable for fusing IKONOS PAN with MS images.

Key Words : Pan-sharpening, intensity-hue-saturation transform, wavelets, IKONOS imagery.

1. Introduction

The pan-sharpening technique, which is the fusion of a panchromatic (PAN) image with a high spatial and low spectral resolution and multispectral (MS) images with a low spatial and high spectral resolution, can provide a useful tool for remote sensing applications that require both high-spatial and high-spectral resolution (Zhang, 2004).

Among a lot of fusion techniques, the intensity-hue-saturation (IHS) method has been used as a standard procedure in many commercial softwares. Although this method provides fused MS images with enhanced spatial quality, its images have distorted spectral information when compared to the original MS images (Tu *et al.* 2001; Choi, 2007).

To solve the spectral distortion problem, multiresolution analysis (MRA)-based fusion techniques have been widely introduced in the literature (Núñes *et al.*, 1999; Ranchin and Wald, 2000). The basic concept of MRA-based fusion techniques is that the detail information extracted from a PAN image, which is not presented in MS images, is merged with the MS images in a multiresolution framework. The MRA-based approach preserves the spectral characteristics of the MS images better than the IHS method. In general, however, the fused MS images have much less spatial information than those fused by the IHS method (Choi *et al.*, 2005; Choi, 2006).

Recently, the substitute wavelet intensity (SWI) method is introduced based on the IHS and the

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MRA-based fusion technique (González-Audícana *et al.*, 2004). The SWI method eliminated drawbacks of the IHS and MRA-based methods, while keeping the advantages. However, the SWI method has high computational complexity, which makes it difficult to quickly merge massive volumes of satellite images.

To overcome this problem, we introduce an efficient implementation of the SWI method. The key idea of the proposed method is to use a fast IHS (FIHS) transform introduced by Tu *et al.* (2004), instead of the classical IHS transform. Additionally, using the linearity of convolution, we can efficiently implement the SWI method.

2. The Fast Substitute Wavelet Intensity Method

1) The FIHS Fusion Technique

The IHS fusion technique converts the RGB space of a color image into IHS color space. The intensity component in the IHS space is replaced by a high-resolution PAN image and then transformed back into the original RGB space together with the previous hue band and saturation band, resulting in IHS fused MS images. The IHS fusion for each pixel can be formulated by the following procedure:

Step 1:

$$\begin{bmatrix} I \\ v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 1/3 & 1/3 & 1/3 \\ -\sqrt{2}/6 & -\sqrt{2}/6 & 2\sqrt{2}/6 \\ 1/\sqrt{2} & -1/\sqrt{2} & 0 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} . \qquad (1)$$

Step 2: The intensity image, I, is replaced by the PAN image.

Step 3:

$$\begin{bmatrix} F(R) \\ F(G) \\ F(B) \end{bmatrix} = \begin{bmatrix} 1 & -1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/\sqrt{2} & -1/\sqrt{2} \\ 1 & \sqrt{2} & 0 \end{bmatrix} \begin{bmatrix} PAN \\ v_1 \\ v_2 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & -1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/\sqrt{2} & -1/\sqrt{2} \\ 1 & \sqrt{2} & 0 \end{bmatrix} \begin{bmatrix} I + (PAN - I) \\ v_1 \\ v_2 \end{bmatrix} \qquad (2)$$

$$= \begin{bmatrix} R + (PAN - I) \\ G + (PAN - I) \\ B + (PAN - I) \end{bmatrix},$$

where F(X) is the fused image of the X band, for X = R, G, and B, respectively.

Equation (2) states that the fused MS image $[F(R), F(G), F(B)]^T$ can be easily obtained from the original image $[R, G, B]^T$ simply by using addition operations. This method is called the FIHS fusion method. Aside from its fast computing capability for fusing images, this method can extend traditional three-order transformations to an arbitrary order (Tu *et al.* 2004).

2) The SWI method

The SWI method provides a solution based on the IHS method. They use a multiresolution wavelet decomposition to execute the detailed extraction phase, and they follow the IHS procedure to inject the spatial detail of the PAN image into the MS image (González-Audícana *et al.*, 2004). In other words, instead of using the PAN image in Eq. (2), they use the results of the PAN image and the intensity image fused by the substitutive wavelet (SW) method (Núñes *et al.* 1999). The fusion result of the PAN image and the intensity image is expressed as follows:

$$I_{SWI} = I_r + \sum_{k=1}^{n} W_{PAN_k}, \qquad (3)$$

where I_r is the low-frequency version of the wavelet-transformed intensity image and $\sum_{k=1}^{n} W_{PAN_k}$ is the sum of the high-frequency versions of the wavelet-transformed PAN image. Thus, I_{SWI} contains the structural details of the PAN image's higher spatial resolution along with the rich spectral information of the MS images.

To apply any of the methods of image fusion described in this paper, the MS image and the PAN image must be accurately superimposed. Thus, both images must be co-registered, and the MS image resampled to make its pixel size the same as the PAN image.

The steps for the fusing of PAN and MS images with the SWI method are as follows:

1) Apply the IHS transform to the RGB composition of the MS image. This transformation separates the spatial information of the MS image into the intensity component.
2) Generate a new PAN image, the histogram of which matches the histogram of the intensity image.
3) Apply the wavelet transform to the intensity image and to the 'histogram-matched' PAN image, separately. Because the spatial resolution ratio between the PAN image and the MS image is 2^n: 1, an n-level wavelet decomposition must be performed.
4) Apply the inverse wavelet transform to the set composed of the low-frequency version of the wavelet-transformed intensity image and the sum of the high-frequency versions of the wavelet-transformed PAN image. This step adds the spatial details of the PAN image to the intensity image.
5) Apply the inverse IHS transform.

3) The fast SWI method

Assume that, without the loss of generality, the SWI method is based on the FIHS fusion method instead of the traditional IHS method. This is because Eq. (2) holds.

The SWI method can be simplified with the following procedure:

$$\begin{bmatrix} F(R) \\ F(G) \\ F(B) \end{bmatrix} = \begin{bmatrix} R + (I_{SWI} - I) \\ G + (I_{SWI} - I) \\ B + (I_{SWI} - I) \end{bmatrix}$$

$$= \begin{bmatrix} R + (I_r + \sum_{k=1}^{n} W_{PAN_k} - I) \\ G + (I_r + \sum_{k=1}^{n} W_{PAN_k} - I) \\ B + (I_r + \sum_{k=1}^{n} W_{PAN_k} - I) \end{bmatrix} = \begin{bmatrix} R + (\sum_{k=1}^{n} W_{PAN_k} - \sum_{k=1}^{n} W_{I_k}) \\ G + (\sum_{k=1}^{n} W_{PAN_k} - \sum_{k=1}^{n} W_{I_k}) \\ B + (\sum_{k=1}^{n} W_{PAN_k} - \sum_{k=1}^{n} W_{I_k}) \end{bmatrix}$$

$$= \begin{bmatrix} R + \sum_{k=1}^{n} (W_{PAN_k} - W_{I_k}) \\ G + \sum_{k=1}^{n} (W_{PAN_k} - W_{I_k}) \\ B + \sum_{k=1}^{n} (W_{PAN_k} - W_{I_k}) \end{bmatrix} = \begin{bmatrix} R + \sum_{k=1}^{n} W_{(PAN - I)_k} \\ G + \sum_{k=1}^{n} W_{(PAN - I)_k} \\ B + \sum_{k=1}^{n} W_{(PAN - I)_k} \end{bmatrix}, \quad (4)$$

where $\sum_{k=1}^{n} W_{I_k}$ is the sum of the high-frequency versions of the wavelet-transformed intensity image and $\sum_{k=1}^{n} W_{(PAN - I)_k}$ is the sum of the high-frequency versions of the wavelet-transformed difference image of the PAN image and the intensity image. We call this method the FSWI method.

The steps for the fusing of PAN and MS images with the FSWI method are as follows:

(1) Obtain an intensity image, $I = (R + G + B) / 3$.
(2) Generate a new PAN image, the histogram of which matches the histogram of the intensity image.
(3) Apply the wavelet transform to the difference image of the PAN image and the intensity image, that is, PAN - I.
(4) Fill the zeros in the low-frequency version of the wavelet-transformed difference image, and then perform the inverse wavelet transform.
(5) Add to each color MS image the image obtained from steps 3) and 4).

As a result, we easily obtained fused MS images with the FSWI method: We simply added to each MS image the detailed information extracted from the difference image of the PAN image and the intensity image. Therefore, the FSWI method is much simpler and faster than the SWI method.

4) The fast SW method

In addition, the main idea of the FSWI method can be directly applied to the SW method. The SW method can be simplified with the following procedure:

$$\begin{bmatrix} F(R) \\ F(G) \\ F(B) \end{bmatrix} = \begin{bmatrix} \sum_{k=1}^{n} W_{PAN_k} + R_r \\ \sum_{k=1}^{n} W_{PAN_k} + G_r \\ \sum_{k=1}^{n} W_{PAN_k} + B_r \end{bmatrix} = \begin{bmatrix} \sum_{k=1}^{n} W_{PAN_k} + (R - \sum_{k=1}^{n} W_{R_k}) \\ \sum_{k=1}^{n} W_{PAN_k} + (G - \sum_{k=1}^{n} W_{R_k}) \\ \sum_{k=1}^{n} W_{PAN_k} + (B - \sum_{k=1}^{n} W_{R_k}) \end{bmatrix} \quad (5)$$

$$= \begin{bmatrix} R + \sum_{k=1}^{n} (W_{PAN_k} - W_{R_k}) \\ G + \sum_{k=1}^{n} (W_{PAN_k} - W_{G_k}) \\ B + \sum_{k=1}^{n} (W_{PAN_k} - W_{B_k}) \end{bmatrix} = \begin{bmatrix} R + \sum_{k=1}^{n} W_{(PAN-R)_k} \\ G + \sum_{k=1}^{n} W_{(PAN-G)_k} \\ B + \sum_{k=1}^{n} W_{(PAN-B)_k} \end{bmatrix},$$

where $\sum_{k=1}^{n} W_{R_k}$, $\sum_{k=1}^{n} W_{G_k}$, and $\sum_{k=1}^{n} W_{B_k}$ are the sum of the high-frequency versions of the wavelet-transformed MS image, respectively, and $\sum_{k=1}^{n} W_{(PAN-R)_k}$, $\sum_{k=1}^{n} W_{(PAN-G)_k}$, and $\sum_{k=1}^{n} W_{(PAN-B)_k}$ are the sum of the high-frequency versions of the wavelet-transformed difference image of the PAN and the MS images, respectively. We call this method the FSW method.

3. IKONOS Image Fusion

When IHS-like fusion methods are used with IKONOS imagery, there is a significant color distortion, due primarily to the extensive range of wavelengths in an IKONOS PAN image (see Fig. 1). This difference obviously induces the color distortion problem in IHS fusion as a result of the mismatches; that is, the PAN image and the intensity image are spectrally dissimilar. To minimize the radiance differences between the intensity image and the PAN image, Tu *et al.* (2004) included the near-infrared (NIR) band in the definition of the intensity component.

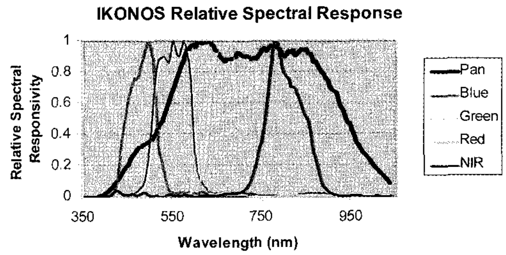

Fig. 1. Relative spectral responses of IKONOS image.

1) The extended FIHS method

The FIHS transform can be extended from three to four bands by

$$\begin{bmatrix} F(R) \\ F(G) \\ F(B) \\ F(NIR) \end{bmatrix} = \begin{bmatrix} R + (PAN - L) \\ G + (PAN - L) \\ B + (PAN - L) \\ NIR + (PAN - L) \end{bmatrix}, \quad (6)$$

where $L = (R + G + B + NIR)/4$. We call this method the eFIHS method. Indeed, compared with the IHS method, the eFIHS method provides much less color distortions in fused MS images.

2) The extended FSWI method

Similarly, the FSWI method for IKONOS image fusion can be extended from three to four bands by

$$\begin{bmatrix} F(R) \\ F(G) \\ F(B) \\ F(NIR) \end{bmatrix} = \begin{bmatrix} R + \delta \\ G + \delta \\ B + \delta \\ NIR + \delta \end{bmatrix}, \quad (7)$$

where $\delta = \sum_{k=1}^{n} W_{(PAN-L)_k}$. We call this method the eFSWI method.

4. Visual Analysis

In general, quantitative analysis is used in order to compare the performance of fusion methods. However, since the purpose of this paper is to

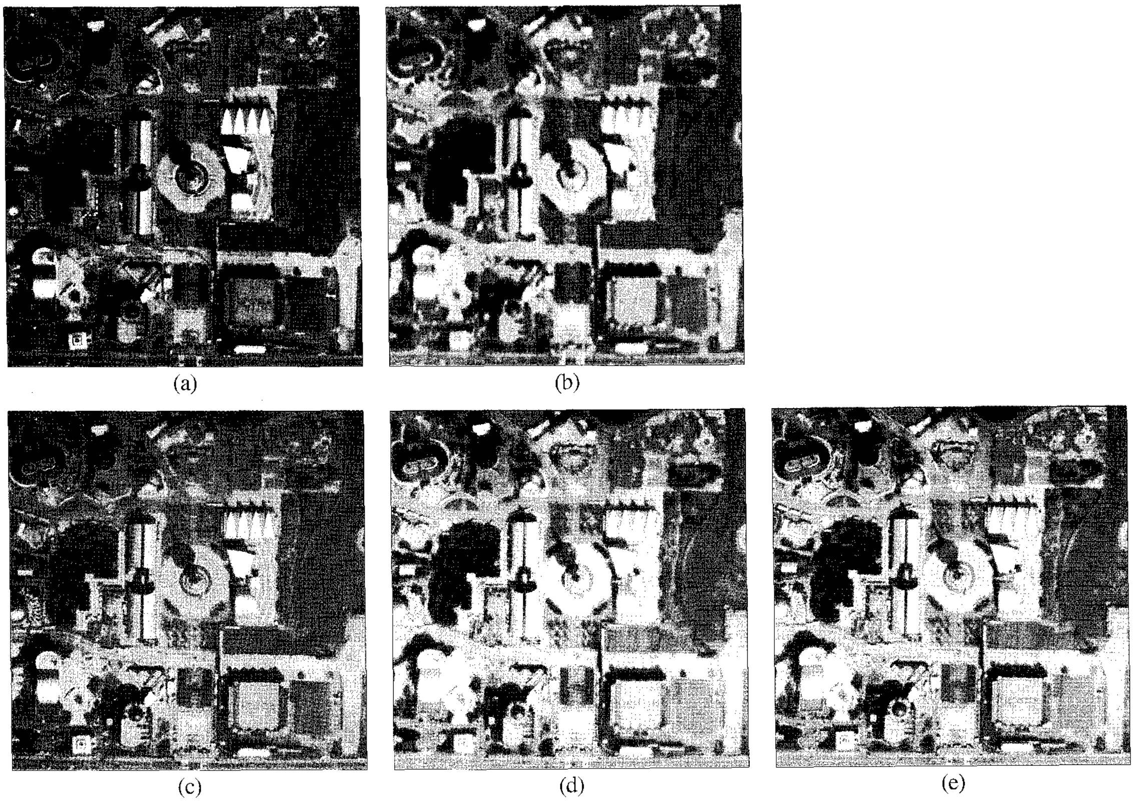

Fig. 2. The fusion results (a) the PAN image; (b) the resampled original color MS image; (c) fused by the eFIHS; (d) fused by the FSW; (e) fused by the eFSWI.

introduce the fast implementation of the SWI method, we omitted the results of quantitative analysis. Instead, we performed visual analysis with eFIHS, FSW, and eFSWI methods.

Figure 2 shows the results of an IKONOS image fusion. In the color MS image fused by the eFIHS method, all objects are sharp but the image suffers from global color distortion when compared to the original color MS image. In the FSW method, the fused color MS image is usually blurred and the contours are not sharp enough. However, in the eFSWI method, the image is enhanced as a whole; furthermore, all objects and contours are sharp and the colors are well synthesized. Consequently, the eFSWI method is acceptable for visual analysis as we expected.

5. Conclusion

We presented the new approach of the SWI method based on the FIHS method. By using just the linearity of convolution, we efficiently reduced the high computational complexity of the SWI method. Therefore, the FSWI method is much simpler and faster than the SWI method. In addition, we applied the FSWI method for the fusion of an IKONOS PAN image with MS images. Based on the visual analysis, we say that the eFSWI method is well applicable for fusing IKONOS PAN with MS images.

Appendix

In Eq. (4), we must show that

$$\sum_{k=1}^{n} W_{PAN_k} - \sum_{k=1}^{n} W_{I_k} = \sum_{k=1}^{n} W_{(PAN-I)_k}.$$

We assume that, without the loss of generality, the *à trous* algorithm can be used as a discrete wavelet transform (DWT). Other DWTs can also be used for proof.

Given image P, we construct the sequence of approximations as follows:

$$C(P) = P_1,$$
$$C(P_1) = C(C(P)) = C^2(P) = P_2,$$
$$C(P_2) = C^3(P) = P_3,$$
$$\cdots.$$

To construct the sequence of approximations, the *à trous* algorithm performs successive convolutions with a filter obtained from an auxiliary function, named a scaling function. A B_3 cubic spline, which is generally used as the scaling function, leads to a convolution with a mask of 5×5.

$$\frac{1}{256}\begin{bmatrix} 1 & 4 & 6 & 4 & 1 \\ 4 & 16 & 24 & 16 & 4 \\ 6 & 24 & 36 & 24 & 6 \\ 4 & 16 & 24 & 16 & 4 \\ 1 & 4 & 6 & 4 & 1 \end{bmatrix}.$$

That is,

$$C^k(P) = P * \underbrace{B_3 * \cdots * B_3}_{k} := P * B_3^k = P_k.$$

The wavelet planes are computed as the differences between two consecutive approximations: P_{k-1} and P_k. By letting $W_{P_k} = P_{k-1} - P_k$, $k = 1, \cdots, n$, where $P_0 = P$, we can write the reconstruction formula as

$$P = P_r + \sum_{k=1}^{n} W_{P_k},$$

where P_r is a low-frequency version of P. We then have

$$\sum_{k=1}^{n} W_{PAN_k} - \sum_{k=1}^{n} W_{I_k}$$
$$= \sum_{k=1}^{n} (W_{PAN_k} - W_{I_k})$$
$$= \sum_{k=1}^{n} ((PAN_{k-1} - PAN_k) - (I_{k-1} - I_k))$$
$$= \sum_{k=1}^{n} ((PAN_{k-1} - I_{k-1}) - (PAN_k - I_k))$$
$$= \sum_{k=1}^{n} ((PAN * B_3^{k-1} - I * B_3^{k-1}) - (PAN * B_3^k - I * B_3^k))$$
$$= \sum_{k=1}^{n} ((PAN - I) * B_3^{k-1} - (PAN - I) * B_3^k)$$
$$= \sum_{k=1}^{n} ((PAN - I)_{k-1} - (PAN - I)_k)$$
$$= \sum_{k=1}^{n} W_{(PAN-I)_k}.$$

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