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Wavelet-based image fusion and quality assessment

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Abstract

Recent developments in satellite and sensor technologies have provided high-resolution satellite images. Image fusion techniques can improve the quality, and increase the application of these data. This paper addresses two issues in image fusion (a) the image fusion method and (b) corresponding quality assessment.

Firstly, a multi-band wavelet-based image fusion method is presented, which is a further development of the two-band wavelet transformation. This fusion method is then applied to a case study to demonstrate its performance in image fusion.

Secondly, quality assessment for fused images is discussed. The objectives of image fusion include enhancing the visibility of the image and improving the spatial resolution and the spectral information of the original images. For assessing quality of an image after fusion, we define the aspects to be assessed initially. These include, for instance, spatial and spectral resolution, quantity of information, visibility, contrast, or details of features of interest. Quality assessment is application dependant; different applications may require different aspects of image quality. Based on this analysis, a set of qualities is classified and analyzed. These sets of qualities include (a) average grey value, for representing intensity of an image, (b) standard deviation, information entropy, profile intensity curve for assessing details of fused images, and (c) bias and correlation coefficient for measuring distortion between the original image and fused image in terms of spectral information.

Keywords: Quality assessment; Wavelet method; Image fusions

1. Introduction

In recent years, the launch of high-resolution satellites such as IRS-1C/1D, IKONOS, QuickBird, SPOT 5 has opened a new era for remote sensing and photogrammetry. A recent research focus for remote sensing is the development of methods for applying these high-resolution satellite imageries in different fields.

With these remote sensors, images of various spatial and spectral characteristic can be obtained. For example, from the IKONOS sensor, both 1 m resolution panchromatic and 4 m resolution multi-spectral images are available. With the high spatial resolution panchromatic image, detailed geometric features can easily be recognized, while the multi-spectral images contain rich spectral information. The

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capabilities of the images can be enhanced if the advantages of both high spatial and spectral resolution can be integrated into one single image. The detailed features of such an integrated image can thus be easily recognized and will benefit many applications, such as urban and environmental studies. Image fusion is one of the techniques, which can be used to generate this type of images.

Many methods have been developed for fusing images. These include for example, the IHS, HLS, COS and HSV fusion method (Zhang, 1999; Li and Liu, 1998; Ehlers, 1991). The wavelet analysis method provides an alternative method for remotely sensed image fusion. It has been a recent research focus among several proposed solutions. Bruno et al. employed two different tools originally used in signal processing: multi-resolution analysis and two-band wavelet transformation (Bruno et al., 1996). Nunez et al. developed an approach to fuse a high-resolution panchromatic image with a low-resolution multi-spectral image by wavelet method (Nunez et al., 1999). Sun et al. studied the fusion of remotely sensed imageries based on characteristics of wavelet transformation (Sun et al., 1998). Ranchin and Wald developed the ARSIS concept for fusing high spatial and spectral resolution imagery based on wavelet analysis (Ranchin and Wald, 2000). Similar researches have also been conducted by others (Chibani and Houacine, 2003; Simone et al., 2002). Further contribution to the two-band wavelet transformation for image fusion has been to extend it to multi-band wavelet-based image fusion. Addressing the problem of the ratio of the spatial resolutions of the images to be fused, Shi et al. initiate a method to fuse panchromatic SPOT and multi-spectral TM images by three-band wavelet transformation (Shi et al., 2003). Furthermore, Shi et al. proposed a method for fusing one meter resolution panchromatic and four meter resolution multi-spectral IKONOS imageries based on four-band wavelet transformation (Shi et al., 2005). Concerning the various methods developed for fusing various satellite images, it is necessary to give a general assessment and analysis of the fusion methods, and furthermore to assess the quality of the fused images. The result of such an analysis is then normally used as a reference for selecting the fusion method for image fusion. This paper focuses on two issues: (a) a review and analysis of various fusion methods, especially multi-band wavelet-based method and (b) quality assessment of fused images.

The remainder of this paper is organized as follows. Section 2 introduces the characteristics of wavelet, especially multi-band wavelet transformation. Section 3 reviews and analyzes the methods for image fusion, such as IHS and wavelet methods, particularly the multi-band wavelet-based image fusion methods. Section 4 describes quality assessment methods for image fusion. Furthermore, the indicators are applied to assess the fusion methods in Section 5. Finally, conclusions and recommendations are given.

2. Characteristics of wavelet transformation

Wavelet analysis was invented in 1980, and since then many studies of both theoretical and application aspects of wavelet analysis have been conducted. Applications of wavelet analysis are potentially extensive and the technique has been used in many different scientific and application fields with great success. Wavelet analysis has been greatly successful in the area of geo-spatial information, such as texture analysis of satellite images, generalization (reduction) of DEMs, image fusion, data compression, and feature detection. Applications of wavelet transformation actually further contribute to the improvement of wavelet theory itself. As a result, many new branches such as multi-band wavelet transformation, have appeared.

The multi-band wavelet can be considered as a more generic case of the two-band wavelet transformation, and can also be considered as a branch of wavelet analysis. The multi-band wavelet has been a topic of interest in wavelet research fields in recent years. Both theoretical research (Chui and Lian, 1995; Han, 1998; Bi et al., 1999; Wisutmethangoon and Nguyen, 1999; Zhu, 1998) and application studies of multi-band wavelet (Zhu et al., 2002; Shi et al., 2003, 2005) have been carried out. However, the application of this technology to remotely sensed image fusion is still limited. This section will give a brief introduction to two-band and multi-band wavelet theory.

2.1. Multi-scale analysis of multi-band wavelet

Wavelets are functions in a space $L^2(R)$ of a basic wavelet function using dilations and translations.

They are used to represent the local frequency content of the functions. The basic wavelet should be well localized, and a wavelet should have a mean equal to zero. By multi-scale analysis, a basic method to construct a wavelet can be obtained. A multi-scale analysis is an increasing sequence $\{V_j\}_{j\in z}$ that satisfies

$$\{0\} \to \cdots \subset V_{-1} \subset V_0 \subset V_1 \subset \cdots \to L^2(R),$$

and it also satisfies the following property:

$$f(x) \in V_j \Leftrightarrow f(Mx) \in V_{j+1}.$$

In a multi-band wavelet, taking a specific M-band wavelet where M is a positive integer, as an example, there are $M-1$ wavelet functions $\{\Psi_s(x) | 1 \le s \le M-1\}$ for a scaling function $\varphi(x)$ (Shi et al., 2005; Chui and Lian, 1995; Han, 1998; Bi et al., 1999; Wisutmethangoon and Nguyen, 1999; Zhu, 1998). The functions $\varphi(x)$ and $\{\Psi_s(x) | 1 \le s \le M-1\}$ satisfy the following scaling equations:

$$\varphi(x) = \sum_{k\in Z} c_k \varphi(Mx-k),$$

$$\psi_s(x) = \sum_{k\in Z} d_k^s \varphi(Mx-k)$$

where $\{d_k^s\}$ is a set of wavelet coefficients and $\{c_k\}$ a set of scaling function coefficients which satisfy the following filter equation:

$$H(z) = \frac{1}{M}\sum_{k\in Z} c_k z^k$$

$H(z)$, $\varphi(x)$ and $\Psi_s(x)$ can be found in (Shi et al., 2005; Chui and Lian, 1995; Han, 1998; Bi et al., 1999; Wisutmethangoon and Nguyen, 1999; Zhu, 1998).

A multi-band wavelet ($M > 2$) is superior to two-band wavelet in many aspects, including compact support, orthogonal aspects, and especially in its decomposition characteristics.

2.2. Decomposition and reconstruction of multi-band wavelet

By using the tensor product, two-dimensional orthogonal wavelet bases can be obtained from one-dimensional wavelet bases. Thus, the multi-band wavelet decomposition and reconstruction of an image $\{a_{0,k,l}\}$ ($k,l \in Z$) can be obtained. The decomposition formula of M-band wavelet is 2^n

$$a_{j+1,k,l} = \sum_m \sum_n c_{m-Mk} C_{n-Ml} a_{j,m,n},$$

$$b_{j+1,k,l}^{t,s} = \begin{cases} \sum_m \sum_n c_{m-Mk} d_{n-Ml}^s a_{j,m,n} \\ t=0, 1 \le s \le M-1 \\ \sum_m \sum_n d_{m-Mk}^t c_{n-ml} a_{j,m,n} \\ 1 \le t \le M-1 \\ \sum_m \sum_n d_{m-Mk}^t d_{n-Ml}^s a_{j,m,n} \\ 1 \le t, s \le M-1 \end{cases}$$

where j = 0, 1, 2,.... The reconstruction formula is

$$a_{j,k,l} = \sum_m \sum_n c_{k-Mm} c_{l-Mn} a_{j+1,m,n} + \sum_{t,s=0,s+t\neq 0}^{M-1} \sum_m \sum_n d_{k-Mm}^t d_{l-Mn}^s b_{j+1m,n}^{t,s}.$$

where j = 0, 1, 2,... $\{a_{j+1,k,l}\}$ is the low-frequency portion of the $(j+1)$th level M-band wavelet decomposition of the image $\{a_{j,k,l}\}$ and $\{b_{j+1,k,l}^{t,s}\}$ the high-frequency portion of the $(j+1)$th level. Hence, by applying the M-band wavelet transformation, the imagery is decomposed into one low-frequency portion and (M^2-1) high-frequency portions. By an inverse wavelet transformation, the original imagery can be reconstructed.

In the multi-band wavelet transformation, when $M = 2$, we have the two-band wavelet transformation. In fact, most applications of wavelets in past studies were based on the two-band wavelet transformation, unless it was specifically mentioned otherwise. Wavelet transformation can be applied to any number of bands, i.e. for different values of M.

Different transformation characteristics exist for different band wavelet transformations. To obtain a low frequency image with of a size equal to 1/4 of the size of the original image, we only need one time four-band wavelet transformation. However, it needs two times as many transformations if we choose to use two-band wavelet transformations, in order to obtain the same size of low frequency image. In terms of the number of the standard orthogonal wavelet, for example, Haar wavelet, there exists only one for a two-band wavelet. On the other hand, many standard orthogonal wavelets exist for multi-band wavelets. These basic characteristics of wavelet transformations, especially those of multi-band wavelet transformations, explain the reason why multi-band wavelet-based image fusion is not identical to other image fusion solutions.

3. Image fusion methods

In this section, we review and analyze image fusion methods that can be used for high-resolution satellite image fusion, such as those for fusion of panchromatic and multi-spectral images. Three categories of image fusion methods are addressed: (a) HIS—a commonly utilized approach for image fusion, (b) two-band wavelet method, and (c) multi-band wavelet method. Assessment of the fused images based on these methods is given in the next section.

3.1. IHS method

The IHS method is commonly used to fuse a 24-bit color image and an 8-bit black and white image, which applies the color space mapping (CSM) technique. Here, the IHS method is adopted to fuse low-resolution composite image of near infrared, red and green bands and high-resolution panchromatic imagery. In applying the IHS method, low resolution composite imagery is firstly re-sampled so as to have the same geometric size with the high-resolution panchromatic image, and each of the three bands is labeled blue, green and red, respectively. These color components are then converted into intensity (I), hue (H) and saturation (S) components using the color space mapping model. The next step is substitution of the intensity component by the panchromatic image. Finally, an inverse transformation from IHS to RGB is conducted to obtain the composite image, which has both rich spectral information and high spatial resolution.

Although the IHS method has been widely used, the method cannot decompose an image into different frequencies in frequency space such as higher or lower frequency. Hence the IHS method cannot be used to enhance certain image characteristics. However, wavelet-based fusion methods can provide a solution to overcome these problems.

3.2. Two-band wavelet method

The basic idea of image fusion, based on two-band wavelet transformation, is that a low-resolution image is replaced by the low frequency portion of the image in a two-band wavelet transformation. Studies of two-band wavelet-based satellite image fusion can be found, for example, in Ranchin and Wald (2000), where images with resolution 10, 20, and 40 m, respectively were fused. Essentially, these applications use the transformation characteristic of two-band wavelet. The main procedure for the two-band wavelet-based method is described below and in order to explain the fusion method more clearly, we use an example of the fusion of high-resolution panchromatic images and three multi-spectral images.

- Step 1: three new panchromatic images are generated, and their histograms are also specified according to the histograms of multi-spectral images respectively.
- Step 2: these new panchromatic images are decomposed into wavelet transformed images, based on the two-band wavelet transformation. The transformed images include one low frequency portion and three high frequency portions. The image size of the low frequency portion is half that of the original panchromatic images.
- Step 3: the multi-spectral images are re-sampled, so as to have the same geometric size as the low frequency portion of the high-resolution panchromatic image.
- Step 4: the low frequency portions of the wavelet transformed images are replaced by the re-sampled multi-spectral images respectively.
- Step 5: inverse wavelet transformations are carried out for the three newly replaced images respectively.
- Step 6: the three images by inverse two-band wavelet transformation are compounded into one fused image. The fused image retains the spectral information of the original multi-spectral images and also the high spatial resolution.

Fig. 1 illustrates the operation flow for fusing the panchromatic and multi-spectral composite images by using two-band wavelet. In steps 2 and 5 the two-band wavelet transformation and inverse wavelet transfor-

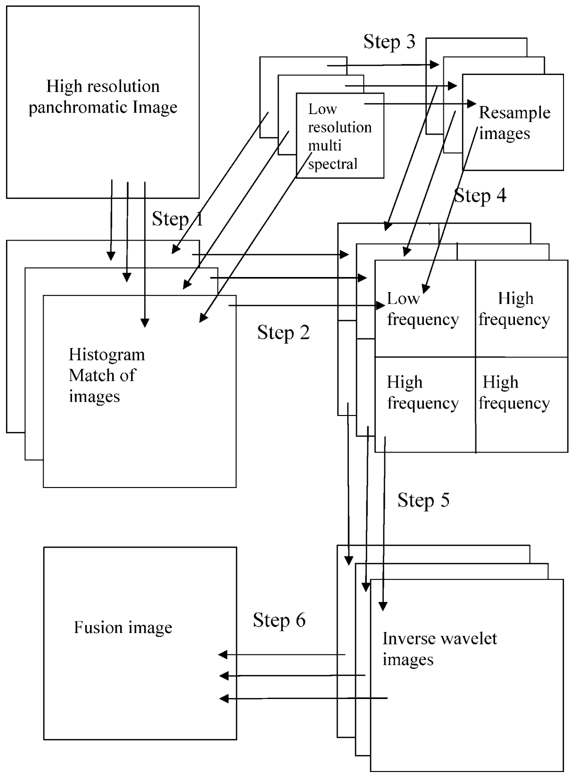

Fig. 1. The flowchart of image fusion by using two-band wavelet transformation.

mation are carried out. In the above method, the two-band wavelet transformation can be further decomposed, as a result to fulfill the ratio requirement in spatial resolution. Of course, there are also other fusion methods, which have been developed based on two-band wavelet, where the core is the two-band wavelet transformation, as illustrated in Fig. 1.

By using the above method as illustrated in Fig. 1, we can fuse images with 10 m resolution SPOT_P and 20 m resolution SPOT_XS by a two-band wavelet transformation. Thus, the resampling in step 3 can be omitted, because the size of the low frequency for the high-resolution image is equal to the size of low-resolution image, or the ratio of two images to be fused is 2. The ratio of the spatial resolutions between two images to be fused can be divided into the following two groups: (I) 2^n ($n = 1, 2, 3, \ldots$), such as 2, 4, 8 . . ., and (II) non of such relationships, such as 3, 5, 6, etc.

The two-band wavelet transformation, due to its decomposition characteristics, can be directly applied for fusing the images with the spatial resolution relationships of the type (I).

For fusing images of the type (II), the two-band wavelet cannot be directly applied. The images need to be pre-processed first before the two-band wavelet transformation can be applied. In such a case, a low-resolution image is firstly scaled to have the same image size or half the size of the high-resolution image, by a re-sampling technique. However, the spectral information may be partially lost during such a re-sampling process. Thus, two-band wavelet transformation may not be applied to fuse the images with a type (II) relationship efficiently, e.g., images with resolutions of 10 and 30 m. An alternative solution for images with a type (II) relationship is based on multi-band wavelet transformation.

3.3. Multi-band wavelet method

The multi-band wavelet method is very appropriate for fusing images if the type (II) relationships. Unlike the two-band wavelet transformation-based method, the ratio of the spatial resolution between two images is not 2^n ($n = 1, 2, 3, \ldots$). For example, the fusion of a 10 m resolution SPOT panchromatic image and three 30 m resolution multi-spectral TM images. Step 3 in Fig. 1 is needed if we use two-band wavelet transformation. This step re-samples a low-resolution image to have the same geometric size as the low frequency portion of the high-resolution panchromatic image. However, if we use a three-band wavelet transformation, step 3 can be omitted because the size of multi-spectral image is the same as the low frequency part of the high-resolution panchromatic image transformed by three-band wavelet. Thus, a fused image can contain more information using the three-band wavelet than using the two-band wavelet. A detailed description of three-band wavelet fusion method for fusing this kind of image can be found in Simone et al. (2002). Similarly, if we fuse a 1 m resolution panchromatic IKONOS image with a 4 m resolution multi-spectral IKONOS image, it is better to use four-band wavelet transformation because the size of the multi-spectral image is the same as the low frequency portion of the high-resolution panchromatic transformed image (Shi et al., 2005).

Generally, if we fuse images with the ratio between the two images to be fused as the other integer number

(M), we simply apply the corresponding band (M-band) wavelet transformation. For example, if the ratio of the spatial resolution of the images is six, we apply a six-band wavelet transformation-based image fusion method.

Based on the above analysis, the multi-band wavelet fusion method can generate a better image fusion result (containing more information) than the two-band method. From a theoretical point of view, if the ratio of the spatial resolution of the images to be fused is M, we only need to apply the M-band wavelet transformation once. However, we need to resample original images or apply the two-band wavelet more times (e.g., the ratio is 4, 8, etc.) if a two-band wavelet-based method is applied. If the two-band wavelet is used twice, the two-band wavelet transformation is first applied to the original image, and one image with lower frequency and three images with higher frequency are then generated. The two-band wavelet transformation is then applied again. This time, instead of being applied to the original image, the two-band wavelet transformation is applied to the image with lower frequency information. This means that the second time, the two-band transformation is applied to an image with less information, instead of the original image. On the other hand, resampling entails loss of information of the original image. Therefore, a fused image generated by applying two-band transformation more times, or re-sampling the original image contains less information than a fused image generated by applying the multi-band transformation once. The following experimental results support this conclusions of the theoretical analysis above.

3.4. Fusion experiments

We now present an experimental study of applying the image fusion methods. The experimental images are a 10 m panchromatic SPOT image, a 30 m multi-spectral TM image, a 1 m resolution IKONOS panchromatic image, a 4 m resolution multi-spectral image based on the multi-band wavelet fusion methods and IHS fusion method.

Fig. 2(a) is the image fused by three-band wavelet transformation using a 10 m resolution panchromatic image and three 30 m resolution multi-spectral TM images. Fig. 2(b) is the image fused by two-band wavelet transformation and the IHS method Fig. 2(c) is the image fused using the same 10 m resolution panchromatic image and three 30 m resolution multi-spectral TM images. The images indicates less improvement in the three-band wavelet method than in the two-band wavelet and IHS methods.

For the second experiment, we fuse a 1 m resolution IKONOS panchromatic image and a 4 m resolution multi-spectral image based on the wavelet and IHS fusion methods.

Careful inspection of Fig. 3 shows that the four-band wavelet method is the best method for visual effects, while the IHS method shows the worst performance in this case.

4. Quality indicators for assessing image fusion

The purpose of image fusion is to enhance the spatial and spectral resolution from several low-resolution images. It is thus necessary to propose

Fig. 2. Fused images by (a) three-band wavelet method, (b) two-band wavelet method, and (c) IHS method.

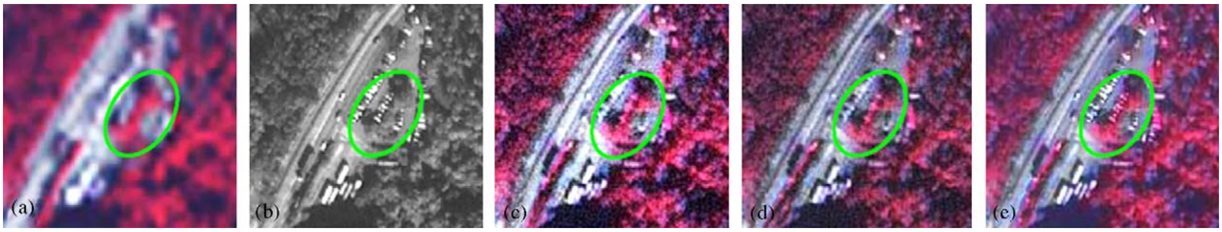

Fig. 3. (a) The original composite IKONOS image with the marked car parking area indicated by an ellipse, (b) the original panchromatic IKONOS image, (c) the fused image based on IHS method, (d) the fused image based on two-band wavelet method, (e) the fused image based on four-band wavelet method.

quality indicators to measure the quality of the images generated by different image fusion methods. Up to now, several indices have been proposed for assessing image quality, which can also be applied to assessing the quality of a fused image. Generally, image assessment methods can be divided into two classes: firstly qualitative (or subjective) methods and secondly quantitative (or objective) methods.

4.1. *Qualitative analysis*

According to prior assessment criteria or individual experiences, personal judgment or even grades can be given to the quality of an image. A final overall quality judgment can be obtained by, for example, a weighted mean, based on the individual grades. This is the so-called qualitative method. It is also called the mean opinion score (MOS) method (Wei et al., 1999). The qualitative method mainly includes absolute and the relative measures (Table 1).

This method depends on the observer's experiences or bias and some uncertainty is involved. Qualitative measures cannot be represented by rigorous mathematical models, and their technique is mainly visual.

4.2. *Quantitative analysis*

Considering the drawbacks of the subjective quality assessment method, much effort has been devoted to develop objective image quality assessment methods. Three kinds of methods exist for evaluating image quality (Table 2).

Basically, we can group the measures for an image into three groups: (a) mean value, (b) details of spatial information, and (c) spectral information.

4.2.1. *Mean value*

The mean value of an image with the size of $m \times n$ is defined as

$$\hat{\mu} = \frac{1}{n \times n}\sum_{j=1}^{n}\sum_{i=1}^{m} x_{i,j},$$

where $x_{i,j}$ denotes the gray level of a pixel with coordinate (i,j). The mean value represents the average intensity of an image.

4.2.2. *Details of spatial information*

Four indicators, including variation, information entropy, directional entropy and profile intensity curve, describe the *details* of an image.

Table 1
Objective method for image quality assessment

Grade	Absolute measure	Relative measure
1	Excellent	The best in a group
2	Good	Better than the average level in a group
3	Fair	Average level in a group
4	Poor	Lower than the average level
5	Very poor	The lowest in a group

Table 2
Methods for assessing image quality

Intensity	Mean value
Details	Variation
	Information entropy
	Profile intensity curve
Spectrum information	Bias index
	Correlation
	Warping degree

4.2.2.1. Standard variation. The standard variation of an image is given by

$$\hat{\sigma}^2 = \frac{1}{n \times n} \sum_{j=1}^{n} \sum_{i=1}^{m} (x_{i,j} - \hat{\mu})^2,$$

which corresponds to the degree of deviation between the gray levels and its mean value, for the overall image.

4.2.2.2. Information entropy. The expression of the classical information entropy of an image is

$$H = -\sum_{i=0}^{L-1} p_i \ln p_i,$$

where L denotes the number of gray level, p_i equals the ratio between the number of pixels whose gray value equals $i (0 \leq i \leq L-1)$ and the total pixel number contained in an image. The information entropy measures the richness of information in an image. If p_i is the const for an arbitrary gray level, it can be proved that the entropy will reach its maximum.

4.2.2.3. Profile intensity curve. The profile intensity curve distinguishes noise from information of geometrical features (Shi et al., 2005). The curve represents the gray (or intensity) value of a grey (or color) image along a straight line. For a color image, the profile intensity curve is given to calculate the intensity of the image along the straight line. In general, the direction of the profile is normally perpendicular to the feature line to be measured. The profile intensity curve compares the sharpness of a linear feature, before and after an image fusion process, and by different image fusion methods.

4.2.3. Spectral information

Three indicators describe spectral information of an image: bias index, correlation coefficient and warping degree.

4.2.3.1. Bias index. The bias index is defined as

$$B_{\text{index}} = \frac{1}{m \times n} \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{|x_{i,j} - x'_{i,j}|}{x_{i,j}},$$

where $x_{i,j}$ and $x'_{i,j}$represent the pixels of the original image and the fused image, respectively. The index checks the degree of the biased intensity between the low-resolution image and the fused image. The greater the value, larger the deviation.

4.2.3.2. Correlation coefficient. The correlation coefficient of two images is often used to indicate their degree of correlation. Comparing the original image with the fused image, one can find the degree of differences. If the correlation coefficient of two images approaches one, their correlation is very strong. The correlation coefficient is given by

$$\mathrm{corr}\left(\frac{A}{B}\right) = \frac{\sum_{j=1}^{n} \sum_{i=1}^{m} (x_{i,j} - \mu(A))(x'_{i,j} - \mu(B))}{\sqrt{\sum_{j=1}^{n} \sum_{i=1}^{m} (x_{i,j} - \mu(A))^2 \sum_{j=1}^{n} \sum_{i=1}^{m} (x'_{i,j} - \mu(B))^2}},$$

where A and B are two images, $x_{i,j}$ and $x'_{i,j}$ the elements of the image A and the image B, respectively. $\mu(A)$ and $\mu(B)$ stand for their mean values.

4.2.3.3. Warping degree. Warping degree represents the level of optical spectral distortion of a multi-spectral image. Its formula is

$$W = \frac{1}{m \times n} \sum_{j=1}^{n} \sum_{i=1}^{m} |x_{i,j} - x'_{i,j}|,$$

where $x_{i,j}$ and $x'_{i,j}$ denote the element of the original image and the fused image. The degree of distortion increases, when W increases.

5. Assessing image fusion methods based on quality indicators

5.1. A comparison between three-band wavelet based fusion with two-band wavelet and IHS method

In Section 3, we introduced fusion methods based on the two-band wavelet transformation, three-band wavelet transformation and the four-band wavelet transformation. This section assesses fusion results obtained by these methods and IHS. Here, we use the

Table 3
Assessment results of two-band wavelet transformation, three-band wavelet transformation and IHS methods

Index	Method		
	Two-band wavelet method	Three-band wavelet method	IHS
Information entropy	11.2665	11.7735	11.4623
Correlation coefficient	0.8798	0.9624	0.8241
Warping degree	18.324	20.158	17.915

images in Section 3 (Figs. 2 and 3) as examples. Results are shown in Tables 3 and 4, respectively.

From Table 3, we observe that the values of several quality indices obtained by three-band wavelet transformation fusion method are all much larger than those generated by the two-band wavelet transformation and IHS method. For instance, the information entropy of the fused image based on three-band wavelet transformation is 5.430, while the other two values are 5.389 and 5.213 for two-band wavelet transformation and IHS methods, respectively. As for a comparison between results from the two-band wavelet transformation and IHS methods, no consistent trend exists to indicate which is better. Therefore, based on the experimental results, we conclude that fusion methods based on three-band wavelet transformation perform better than the other two methods, in fusing the 10 m panchromatic SPOT and the 30 m multi-spectral TM image.

5.2. A comparison between four-band wavelet based fusion with two-band wavelet and IHS method

In an urban area, it is common to have several categories of objects within a small area. This is especially true for large cities such as Hong Kong where land prices are high and density of buildings is also very high. For example, in a small garden there may be grass, small ponds, paths, trees and other land cover types. These are represented as mixed patterns or mixed pixels on a satellite image, which are very difficult to interpret. With a fused image, it is possible to improve the image quality by reducing the mixed patterns. This can be demonstrated in the following examples.

Table 4
Assessment results of two-band wavelet transformation, four-band wavelet transformation and IHS method

Index	Method		
	Two-band wavelet method	Four-band wavelet method	IHS
Information entropy	5.389	5.430	5.213
Correlation coefficient	0.918	0.932	0.913
Warping degree	24.885	25.760	24.426

A multi-spectral IKONOS image has rich spectral information, from which land cover types such as vegetation can be easily recognized. However, due to its lower spatial resolution, many detailed ground objects become ambiguous, uncertain and difficult to recognize. For example, from the original composite IKONOS image, we can find there might be a car parking area (indicated by the ellipse in Fig. 3(a)) on the right side of the main road. Furthermore we can also see there is some vegetated land within the area according to the area in red on the image. However, we cannot find any cars within the area based on the original image only. On the other hand, since the IKONOS panchromatic image has higher spatial resolution, many ground objects become clearer and more easily recognized. However, due to its lack of spectral information, some other land cover types, such as vegetation, cannot be easily interpreted. For example, from the marked ellipse area on the IKONOS panchromatic image in Fig. 3(b), we can find many cars within the car parking area, but we cannot interpret any vegetation within the area using the panchromatic image alone.

We now combine the rich spectral information from the original composite IKONOS image with the original panchromatic IKONOS image using image fusion techniques, including four-band wavelet method (Fig. 3(c)), two-band wavelet transformation (Fig. 3(d)) and IHS method (Fig. 3(e)). On the fused image, we can recognize not only the cars clearly—according to the details of the spatial patterns, but also the vegetation (by its color (red) within the car parking area). The reason that we can find more spatial detail from the fused composite images is that many mixed pixels in the original composite image are decomposed into many different categories in a fused image with the improvement of the spatial resolution. The details in the car parking area, including cars and vegetation, etc., can be recognized using IHS, two-band wavelet and four-band wavelet, respectively. However, if we take a further look, the images of

Fig. 3(c)–(e), and details in the Fig. 3(e), which is generated from the four-band wavelet, is even more clear and distinguishable. This confirms the findings from the previous section; the four-band wavelet image fusion provides more detailed information, compared with IHS and two-band wavelet based methods.

We now compare the three fusion methods based on quantitative indicators. By analyzing the fusion results listed in Table 4, a consistent trend indicates that fusion based on the four-band wavelet transformation is superior to the two-band wavelet transformation method and IHS method. For example, the correlation coefficient of four-band wavelet transformation (0.932) is larger than those generated by IHS and two-band wavelet transformation methods (0.913 and 0.918, respectively). From these quantitative results, we can also conclude that the fusion result which is obtained by two-band wavelet transformation is better than the result generated by HIS.

6. Conclusions

This paper addressed two issues: (a) an analysis of image fusion methods and (b) quality assessment for images fused using different methods.

According to the transformation characteristics of wavelet and ratio of the resolutions of the images to be fused, we conclude that the multi-band wavelet fusion method can be more widely used than the two-band wavelet image fusion method. For example, we can fuse a 1 m resolution IKONOS panchromatic image and 4 m multi-spectral images by four-band wavelet transformation. In general, the *M*-band wavelet image fusion method is to be used if the ratio of the spatial resolution of the two images to be fused is *M*. The *M*-band wavelet transformation method gives a more direct solution for fusing two images of which the spatial resolution ratio is *M*. Multi-band wavelet transformation is a more precise solution, in terms of computation, than a two-band wavelet. The reason is that only a one-step computation is needed by a *M*-band wavelet transformation, while more step computations are needed for the two-band wavelet transformation. In addition, it is based on a processed image rather than the original image, which is considered to contain more detailed information.

For assessing the quality of a fused image, we classified the indicators into three groups. These indicators are applied to measure and compare the performance of the images fused by wavelet transformation-based methods and the IHS method.

Further development of image quality assessment indicators is required to distinguish between information and noise on an image. Furthermore, since a fused image is "read" by a human being, it is essential to incorporate the characteristics of human visual sensitivity (HVS) into the indicators.

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