SPATIAL QUALITY EVALUATION OF FUSION OF DIFFERENT RESOLUTION IMAGES

Jun Li
Laval University, Canada
COPL, Physics department
Jli@phy.ulaval.ca

KEY WORDS: Image Fusion, Evaluation, Spatial Quality, Blur Parameter, Multi-sensor

ABSTRACT

Spatial quality and spectral quality are the two important indexes that are used to evaluate the quality of any fused image. Most of the existing methods for this purpose, however, considered only the spectral quality except for that proposed by Zhou et al., while the latter cannot be used to compare directly the spatial resolution between the fused image and original high-resolution. A new spatial quality assessment approach was presented in the paper based on the blur parameter estimation. It is based fact that the blur parameter, which is a measure of the spread of the sensor's point spread function (PSF), characterizes the spatial resolution of the sensor image. The merged images derived from IHS, PCA, HPF, and AWL methods are compared in order to evaluate the performance of the proposed spatial quality measure. Experimental results demonstrate that the spatial quality measure based on the blur parameter is more efficient in judging spatial quality of the fused image. The blur parameter is an objective quality measure based on a basic optical mechanism and thus can be used to evaluate the effectiveness of various processing or fusion schemes in terms of spatial quality of the fused image. It is also shown that the spatial resolution of the fused images can not completely match with the same spatial resolution of the high-resolution panchromatic image. The proposed approach is based upon simple concepts, easy to understand and easy to implement and use.

1 INTRODUCTION

The number of commercially available multi-sensors and the data they provide are continually increasing. Each sensor has its mission and applications. It is often desirable to simultaneously require high spatial and spectral resolution in a single image. However, in most cases instruments are not capable of providing such data either by design or by observational constraints. For example, in remote sensing SPOT PAN satellite data provides high-resolution (10-m pixels) panchromatic data while Landsat TM satellite data provides lower resolution (30-m pixels) multispectral data. The better solution to this problem could come from image fusion. The integration of spectrally and spatially complementary remote multi-sensor data can facilitate visual and automatic image interpretation.

Many fusion methods have been proposed for fusing high spectral and spatial resolution data in order to produce multispectral images having the highest spatial resolution available within the data set. However, a few quantitative methods have been proposed in current literature to evaluate the quality of the fused image (Munechika et al., 1993; Blanc et al., 1996; Ranchin et al., 1996; Wald et al., 1997; Zhou et al., 1998; Zhang, 1999). Most of the evaluations have been proposed only focus on the spectral quality of fused image. Some methods for evaluating the spectral quality are based on the calculation of the image difference between the merged image and standard image, which is the desired merged result (Yocky 1995, Li et al. 1995). However, such a standard remote sensing image is usually not available. For remote sensing applications, Chavez et al. (1991) considered that the methods used to merge data with high-spatial and high-spectral resolution properties should not distort the spectral characteristics of the original high-spectral resolution data. Not distorting the spectral characteristics is very important for ensuring that targets that are spectrally separable in the original data are still separable in the fused data set (Chavez et al. 1991). Wald et al. (1997) proposed both a formal approach and some criteria to provide a quantitative assessment of the spectral quality of the fused image. Five sets of criteria are defined. The above methods only concentrated on the evaluation of the spectral quality of a merged without the consideration of spatial quality.

However, no quantitative methods have been found in current literature to evaluate the spatial quality of the fused images except for Zhou et al. (1998). Zhou used the correlation coefficients between the high-pass filtered SPOT PAN image as index of the spatial quality. It is based on the fact that the spatial information unique in SPOT PAN is mostly concentrated in high frequency domain. But this method can not directly compare the spatial quality of the merged image with that of the high-resolution panchromatic image.

In this paper, a new approach was presented to assess the spatial quality of a fused image based on blur parameter estimation. This measurement is based on the fact the blur parameter, which is a measure of the spread of the sensor's point spread function (PSF), characterizes the spatial resolution of the sensor image.

The paper is organized as follows. A brief review of quality evaluation of the fused images is given in section 2. Section 3 presents a new scheme for spatial quality evaluation of the fused images. Experimental results for the spatial quality of the fused images based on Intensity-Hue-Saturation (IHS) (Carper et al., 1990), High-Pass Filter (HPF) (Chavez and Bowell, 1988), Principal Component Analysis (PCA) (Fung and LeDrew, 1987) and Intensity Additive Wavelet (AWL) (Nunez et al. 1999; Li et al., 1999) methods are presented in section 4.

2 QUALITY EVALUATION OF THE FUSED IMAGES

Fused images provide increased interpretation capabilities and more reliable results since data from different characteristics are combined. The fused images must have the following properties: (a). If the fused image is degraded again to the original low resolution, it should coincide with the original low-resolution image ; (b). The spatial resolution of the fused image should be as identical as possible to that of the original high-resolution image; (c). The multi-spectral set of the fused images should coincide with the multi-spectral set of the images that the corresponding sensor would observe with the original high-resolution. Therefore, the fused images should be evaluated both spectrally and spatially.

2.1 Spectral quality

The mathematical approach along with a set of criteria described by Wald et al. is used to evaluate the spectral quality of the fused images. The set of criteria is capable of quantitatively summarizing the performance of the fused image. It provides a global view of the discrepancies between the fused image and the original one. In the spectral quality assessment method, the bias is used to express the difference between the means of the original and the merged images. The difference in variances represents the quantity of information added or lost during the enhancement of the spatial resolution. The correlation coefficient shows the similarity in tiny detail between the original and the merged images. The standard deviation globally represents the level of error in any pixel.

2.2 Spatial quality

The spatial quality of the fused image is usually judged by visual inspection. However, In remote sensing applications the objective comparison of the visual quality of the fused images is a difficult and lengthy task to handle. The human visual system is not equally sensitive to various types of distortion in an image. The perceived image spatial quality strongly depends on the observed scene, the viewing conditions and observer. Thus, judgment should be determined by subjective tests on the scene being viewed, and an exact decision can be rarely given.

Recently, Zhou et al. (1998) applied the correlation coefficients between the high-pass filtered fused images and the high-pass filtered panchromatic image as an index of the spatial quality. It is based on the fact that the spatial information unique in SPOT PAN is mostly concentrated in high frequency domain. The fused images and SPOT PAN image are filtered with a Laplacaian high-pass filter resulting in the high frequency parts of the data. Then the correlation coefficients between the high frequency components of fused images and the high frequency components of SPOT PAN were calculated and used to compare the similarity. However, this method can not directly compare the spatial quality of the merged image with that of the high-resolution panchromatic image.

3 A NEW SCHEME FOR SPATIAL QUALITY EVALUATION OF THE FUSED IMAGES

Actually, the spatial quality of an image coincides with the image resolution. In other words, the higher the image resolution, the richer the detail information and the better the spatial quality of the image. The image resolution is an essential characteristic of an imaging sensor instrument. It generally depends on the physical characteristics of the sensor: the optics and the density and spatial response of the detector elements. The ultimate resolution of an instrument with a very narrow point spread function may be limited by the pixel size of the detector instead of by the performance of the optical elements. The line spread function (LSF) provides a natural procedure for establishing resolution criteria for the image, and the LSF can be derived from the point spread function (PSF). Thus, the spatial quality of the fused image can be characterized by point spread function the PSF. Here we used blur parameter as an index of the spatial quality of the fused image.

Theoretically, the sensor PSF can be obtained from the image of a point light source. However, in practice, it is difficult to create an ideal point light source that is incoherent and polychromatic (Surya, 1994). Therefore, the sensor PSF is usually estimated from the observed image. Here we assume that the PSF is a two-dimensional Gaussian function. Gaussian functions have the following properties: (1). The Gaussian function is symmetric about the mean, and the weights assigned to signal values decrease gradually with distance from the mean; (2). The width of the Gaussian function is determined by its spread parameter, i.e., the standard deviation. As the spread parameter decreases, Gaussian convolution does less smoothing. Conversely as the spread parameter increase, the amount of smoothing is increased.

The spread parameter of the Gaussian function is taken to be equal to the blur parameter σ , and therefore the PSF is:

$$PSF(x, y) = \frac{1}{2\pi\sigma^2} \exp(-\frac{x^2 + y^2}{2\sigma^2}) \tag{1}$$

To obtain the measured PSF in above equation (1), a fundamental problem is how to determine the blur parameter for a given image.

The blur parameter σ is a measure of the spread of the sensor PSF. For a circularly symmetric PSF denoted by $h(x, y)$, it is defined as

$$\sigma^2 = \int (x^2 + y^2) h(x, y) dxdy \tag{2}$$

For a PSF model based on paraxial geometric optics, it can be shown that the blur parameter σ is proportional to the blur circle radius. If R is the blur radius, then $\sigma = R/\sqrt{2}$. For a PSF model based on a 2-D Guassian function, σ is the standard deviation of the distribution of 2-D Guassian function.

Assume that there exist N step edges $EDG_i(x, y)\,(i = 1,2,\cdots, N)$ along the y-axis on the fused image $f(x, y)$. Each edge is composed of Np pixels. Let a_i be the image densities of $EDG_i(x, y)$ to the left of the y-axis and b_i be the height of the corresponding steps. Each edge-intensity can be expressed as

$$EDG_i(x, y) = a_i + b_i \cdot u(x) \tag{3}$$

where $u(x)$ is the standard unit step function. If $G_i(x, y)$ is the observed image of each edge and $h(x, y)$ is the sensor's PSF, then we have

$$G_i(x, y) = h(x, y) * EDG_i(x, y) \tag{4}$$

where $*$ denotes the convolution operation.

Now consider the derivative of G_i along the gradient direction. Since differentiation and convolution commute, we have

$$\begin{aligned} \frac{\partial G_i}{\partial x} &= h(x, y) * \frac{\partial EDG_i}{\partial x} \\ &= h(x, y) * b_i \cdot \delta(x) \end{aligned} \tag{5}$$

where $\delta(x)$ is the dirac delta function along the x axis. The above expression can be simplified to obtain

$$\frac{\partial G_i}{\partial x} = b_i \cdot \theta(x) \tag{6}$$

where $\theta(x)$ is the line spread function of the sensor defined by

$$\mathrm{q}(x) = \int_{-\infty}^{+\infty} h(x, y)dy \tag{7}$$

For any PSF $h(x, y)$ of a lossless sensor, by definition, we have

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} h(x, y)dxdy = 1 \tag{8}$$

Therefore, we obtain

$$\int_{-\infty}^{+\infty} \frac{\partial G_i(x, y)}{\partial x} dx = b_i \ , \quad (i = 1,2,\cdots,N) \tag{9}$$

Therefore, given the observed image $G_i(x, y)$ of each edge, we can obtain the line spread function $\mathrm{q}_i(x)$ of each edge image from the expression

$$\mathrm{q}_i(x) = \frac{\partial G_i}{\partial x} \bigg/ \int_{-\infty}^{+\infty} \frac{\partial G_i}{\partial x} dx \tag{10}$$

The line spread function of the sensor $\mathrm{q}(x)$ can be taken to be the average of $\mathrm{q}_i(x)$ of N edge images. Then

$$\mathrm{q}(x) = \frac{1}{N}\sum_{i=1}^{N} \mathrm{q}_i(x) \tag{11}$$

After obtaining the line spread function $\mathrm{q}(x)$, the next step is to determine the blur parameter.

The second central moment s_l of the LSF can be computed as follows:

$$\mathrm{s}_l^2 = \int_{-\infty}^{+\infty} (x - \bar{x})^2 \mathrm{q}(x)dx \tag{12}$$

Where $\bar{x}$ is the first moment of the LSF.

Therefore, we can get the blur parameter by $\mathrm{s} = \sqrt{2}\mathrm{s}_l$.

The detailed procedure of the proposed algorithm for the blur estimation is as follows:

Step 1: Calculate the difference of gray values of adjacent pixels in each row and search pixel set of each edge in $G_i(x_j)$ ($G_i(x_j)$ is the image derivative at column x_j, $x_j \in x$; $j = 1,2,\cdots Np$), whose sign changes from plus to minus.

Step 2: Compute the first moment of each edge by

$$\overline{M}_i = \frac{\sum_{j=1}^{Np} x_j \cdot G_i(x_j)}{\sum_{j=1}^{Np} G_i(x_j)}, \qquad i = 1,2,\cdots,N \tag{13}$$

where $\overline{M}_i$ is the column number where the each edge is located, and Np is total numbers of pixels for each edge.

Step 3: Determine the line spread function of each edge:

$$\theta_i(x) = \frac{G_i(x)}{\sum_{x=x_1}^{x_{Np}} G_i(x)} \tag{14}$$

Step 4: Take the average of $\theta_i(x)$ of N edges as the line spread function of the sensor $\theta(x)$ according to Equation (11).

Step 5: Calculate the second central moment σ_l of the line spread function using following equation:

$$\sigma_l = \sum_{i=1}^{N}\sum_{j=1}^{Np}(x_j - \overline{M}_i)\cdot\theta(x) \tag{15}$$

Then take the average of σ_l over all the rows in the image.

Step 6: Compute the blur parameter by $\sigma = \sqrt{2}\sigma_l$.

4 EXPERIMENTAL RESULTS

The above assessment technique is tested on fusion of SPOT panchromatic image of Ningxia area, the western of China, acquired on 17 February 1993 and the Landsat TM5,4,3 image, acquired over the same area on 28 May 1995. The Landsat-TM multi-spectral image is geometrically registered to the SPOT panchromatic image according to a moment-based approach proposed by Flusser and Suk (1994). The TM images were also up-sampled to the same pixel size as SPOT PAN image. The IHS, HPF, PCA, and the additive wavelet (AWL) methods are employed to fuse SPOT PAN and TM multi-spectral images. The color composite image of Landsat TM5,4,3 is shown in Figure 1a and figure 1b for the SPOT panchromatic image. Figure 1c, 1d, 1e and 1f show the merged results of the Landsat and the panchromatic images by the IHS, HPF, PCA, and the intensity additive wavelet (AWL) methods, respectively. It can clearly be seen that the above four fusion methods are capable of improving the spatial resolution with respect to the original Landsat TM image.

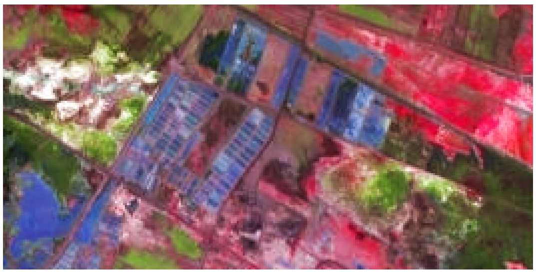
To quantify the behavior of the IHS, HPF, PCA, and AWL methods we compute the blur parameters among the different solutions and original SPOT-PAN image as well as TM images. Table 1 presents the blur parameters of original TM, SPOT images, the fused images by the IHS, HPF, PCA and AWL approaches. The first and second line of table 1 show the blur parameters of TM5,4,3 and SPOT PAN image. The blur parameter of SPOT PAN image is less than those of TM5,4,3 images. This means that SPOT PAN image has higher spatial resolution than TM images, which is in accordance with the reality.

It is shown from Table 1 that all above four fusion methods have larger the blur parameters of in band5 ,4,3 than SPOT PAN image. This means that the spatial resolution of the fused images based on the above four fusing methods can not completely reach the spatial resolution of the SPOT PAN image. On the other hands, the results derived from the above four fusion methods all have less blur parameters than TM image do. It is obvious that the four fusion methods are capable of improving the spatial resolution of the TM multi-spectral images. Therefore, multi-sensor image fusion is usually a trade-off between the spectral information from high spectral resolution sensor and the spatial structure from high spatial resolution sensor.

The last line of table 1 shows that the blur parameters of 1.076024 and 1.070834 in band 4 and band 3 are less than other blur parameters in the same columns. This means that band 4 and band 3 derived from the AWL have the best spatial quality compared with those from other schemes. The reason is that the resolution of the SPOT panchromatic image is added to the solution with discarding the resolution of TM multi-spectral images. Thus the detail information from both images is used. With the AWL method, the blur parameter in band 5 does not match with the ones in band 4 and band3. The reason is that the IHS is nonlinear transformation.

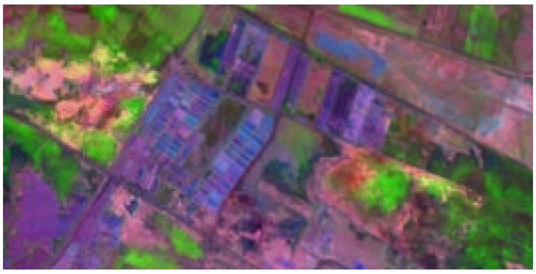
(a). Original Landsat TM5,4,3 images

(b). SPOT panchromatic image



(c). The merged result by the IHS method

(d). The merged result by the HPF method



(e). The merged result by the PCA method

(f). The merged result by the AWL method

Figure 1. The merged results of SPOT PAN and TM images by the IHS, HPF, PCA, and AWL methods

	Band 5	***Band 4***	***Band 3***
TM	**1.504875**	**1.448657**	**1.471967**
SPOT	**1.040812**		
IHS	**1.139180**	**1.135046**	**1.091190**
HPF	**1.227684**	**1.080236**	**1.086686**
PCA	**1.046694**	**1.192750**	**1.154468**
AWL	**1.128362**	**1.076024**	**1.070834**

Table 1. The blur parameters of the registered original TM, SPOT images, the fused images by the IHS, HPF, PCA and AWL approaches (unit: pixel)

For comparison with the proposed scheme, Zhou's (1998) approach in terms of the spatial quality was also used in the experiment to test different fusing technique. In the Zhou's approach, the correlation coefficients between the high-pass filtered fused SPOT PAN and TM images and the high-pass filtered SPOT PAN image are taken as an index of the spatial quality. The high-pass filter is known as a Laplacian filter as illustrated in equation (16):

$$(mask) = \begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix} \qquad (16)$$

Table 2 shows the ranks of different fusing algorithms in terms of spatial quality by the proposed and Zhou's approached. The quality measures with both the proposed and Zhou's methods are almost consistent. Only it exists slightly difference in band 5 in terms of spatial quality between the proposed and Zhou's methods. The blur parameter of the PCA method in band 5 is less than that of the AWL method in terms of the proposed quality measure while the evaluated result based on Zhou's quality measure is opposite. But the proposed method coincides with real results. The reason is that the first principal component image is replaced by SPOT PAN image so that the fused image in band 5 is closer to SPOT PAN image than other two bands.

Rank	Band 5		Band 4		Band 3	
	The proposed approach	Zhou's approach	The proposed approach	Zhou's approach	The proposed approach	Zhou's Approach
1	PCA	AWL	AWL	AWL	AWL	AWL
2	AWL	PCA	HPF	HPF	HPF	HPF
3	IHS	IHS	IHS	IHS	IHS	IHS
4	HPF	HPF	PCA	PCA	PCA	PCA

Table 2. Ranks of different fusing algorithms in terms of spatial quality using the proposed and Zhou's approaches

Among the above four fusion methods, the HPF method is the most similar to the AWL method. Both the proposed and Zhou's measures show that the HPF method is inferior to the AWL method. The reason is that the filter of the HPF has a fixed kernel size and resolution. It is difficult to find one optimal filter for various ground cover types of different sizes.

5 CONCLUSIONS

In this paper, we proposed a new assessment approach of the spatial quality of a fused image based on blur parameter estimation. This measurement is based on the fact that the blur parameter, which is a measure of the spread of the sensor's point spread function (PSF), characterizes the spatial resolution of the sensor image.

The assessment results using Zhou's evaluation method may depend on the specific high-pass filter. This is because the spatial quality measure proposed by Zhou is based on the correlation coefficients between the high-pass filtered merged images and the high-pass filtered panchromatic image. Compared with Zhou's spatial quality measure, the blur parameter is an objective quality measure based on a basic optical mechanism and thus can be used to evaluate the effectiveness of various processing or fusion schemes in terms of spatial quality of the fused image. It is also shown that the original multi-spectral (e.g. TM multi-spectral) and high-resolution panchromatic (e.g. SPOT PAN) images can be also included for a comparison. The proposed approach is based upon simple concepts, easy to understand and easy to implement and use.

ACKNOWLEDGMENTS

This work was supported by the research grant NNSFC — 49701011/49631050 from the National Nature Science Foundation of China. The author would like to thanks Prof. Yunlong Sheng, Physics Department, Laval University, Canada, for valuable comments and suggestions.

REFERENCES

Blanc, P., Blu, T., Ranchin, T., Wald, L., and Aloisi, R., 1998. Using iterated filter banks with the ARSIS concept for producing 10m Landsat multispectral images, International journal of Remote Sensing, Vol. 19, No. 12, pp. 2331-2343.

Carper, W.J., Lillesand, T.M., and Kiefer, R.W., 1990. The use of Intensity-Hue-Saturation transformation for merging SPOT panchromatic and multi-spectral images data, Photogrammetric Engineering and Remote Sensing, Vol.56, No. 4, pp.459-467.

Chavez P. S., Sides S. C. and Anderson J. A., 1991. Comparison of three different methods to merge multi-resolution and multi-spectral data: TM & SPOT Panchromatic, Photogrammetric Engineering and Remote Sensing, Vol. 57, No. 3, pp.295-303.

Chavez, P.S., and Bowell, J., 1988. Comparison of the spectral information content of Landsat Mapper and SPOT for three different sites in the Phoenix, Arizona region, Photogrammetric Engineering and Remote Sensing, Vol.54, No.12, pp.1699-1708.

Flusser, J., and Suk, T., 1994. A Moment-based approach to registration of images with affine geometric distortion, IEEE Transactions on Geoscience and Remote Sensing, Vol. 32, No.2, pp.382-387.

Fung T. And LeDrew E., 1987. Application of principal component analysis to change detection, Photogrammetric Engineering and Remote Sensing, Vol.53, No.12, pp.1649-1658.

Yocky, D. A., 1995. Image merging and data fusion using the discrete two-dimensional wavelet transform, Journal of the Optical Society of America, Part A., Vol.12, No. 9, pp. 1834-1841.

Li, J., Zhou Y.Q., and Li, D. R., 1999. PCA and wavelet transform for fusing panchromatic and multi-spectral images, SPIE's International Symposium on AeroSense: Image Exploitation and Target Recognition; Orlando, Florida, U.S.A, Vol.3719, pp.369-377, 5-9 April 1999.

Li, H., B.S. Manjunath, and S.K. Mitra, 1995. Multi-sensor image fusion using the wavelet transform, Graphical Models and Image Processing, Vol.57, No.3, pp.235-245.

Munechika, C.K., Warnick, J.S., Salvaggio, C., and Schott, J.R., 1993. Resolution enhancement of multispectral image data to improve classification accuracy, Photogrammetric Engineering and Remote Sensing, Vol. 59, No.1, pp.67-72.

Nunez, J., Otazu, X., and Fors, O., Prades A., Pala, V., and Arbiol, R., 1999. Multiresolution-based Image fusion with additive wavelet decomposition, IEEE transactions on Geoscience and Remote Sensing, Vol. 37, No. 3, pp. 1204-1211.

Ranchin, T., Wald, L., Mangolini, M., 1996. The ARSIS method: a general solution for improving spatial resolution of images by means o sensor fusion, in Proceedings of the international Conference on Fusion of Earth Data, Ranchin, T. and Wald, L. eds., pp. 53-58, Cannes, France, France, 1996.

Surya, G., 1994. Three dimensional scene recovery from image defocus, Ph.D thesis, Department of Electrical Engineering, State University of New York, Stony Brook, NY, Dec. 1994.

Wald, L., Ranchin, T. and Mangolini, M., 1997. Fusion of satellite images of different spatial and spectral resolutions: assessing the quality of resulting images. Photogrammetric Engineering & Remote Sensing, Vol.63, No.6, pp.691-699.

Zhou, J., Civco, D.L. and Silander, J.A., 1998. A wavelet transform method to merge Landsat TM and SPOT panchromatic data, Vol.19, No.4, pp.743-757.

Zhang, Y., 1999. A new merging method and its spectral and spatial effects, International Journal of Remote Sensing, Vol. 20, No. 10, pp.2003-2014.