A STATISTICAL APPROACH TO MULTIRESOLUTION IMAGE FUSION

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ABSTRACT

In remote sensing applications, lower spatial resolution multispectral images are fused with higher spatial resolution panchromatic ones. The objective of this fusion process is to enhance the spatial resolution of the multispectral images to make important features more apparent for human or machine perception. This enhancement is performed by injecting the high frequency component of the panchromatic image into the lower resolution ones without deteriorating the spectral component in the fused product. In this work, we propose a novel pixel based image fusion technique which exploits the statistical properties of the input images to compose the outcome images. Criteria for an optimal image fusion are proposed. The fused image is essentially constructed by using the statistical properties of panchromatic and multispectral images within a window to determine the weighting factors of the input images. This paper describes the principles of the proposed approach, assesses its properties and compares it with other popular fusion techniques. This study is carried out using Ikonos, QuickBird and SPOT images over areas with both urban and rural features. Analytical derivation, numerical analysis and graphic results are presented to support our discussions.

INTRODUCTION

Image fusion can be described as a process of combining the information from two or more images to produce a new image that has superior properties over the individual input images. In optical remote sensing, some satellite sensors supply the spectral bands (multispectral images) needed to distinguish features spectrally, while other satellite sensors supply the spatial resolution (panchromatic band) for distinguishing features spatially (Wang, 2005). In remote sensing, panchromatic (pan) images are fused with multispectral (XS) images to combine the advantages of these images into a new fused one. For the same satellite, pan images have a better spatial resolution than the XS images. However, pan images are black and white while XS images are in color. Some GIS applications demand high resolution XS images. Image classification applications also can give a better result if higher resolution XS images are used. Thus, low resolution XS images are fused with higher resolution pan images to get higher resolution XS images. The purpose of the fusion process is to improve the spatial resolution of the original XS image by injecting the high spatial resolution from the pan image while keeping the original color content of the original XS images.

Pohl et al (1998) categorize the image fusion into two groups: color related and statistical/numerical techniques. Statistical/numerical techniques can also be separated into individual groups as statistical and numerical techniques. Color related techniques include the methods such as IHS (Intensity-Hue-Saturation) or HSV (Hue-Saturation-Value) which include the color composition of three image channels in the RGB color space. IHS method transforms three XS images into IHS space and the intensity image is replaced with the pan image, then fused image is generated using the inverse IHS transformation (Park, 2004). Statistical methods employ statistical approaches based on channel statistics and filters. For example, PCA (Principle Component Analysis) method can be put into this group. The numerical methods, however, make use of arithmetic operations, such as image differencing, adding and ratios between the image channels. Brovey and Multiplicative fusion techniques belong to this group. Sophisticated numerical approaches use wavelet transform in multi-resolution image fusion (Gungor and Shan, 2004). Some recent approaches combine wavelet and HIS transforms (Nunez et. al, 1999; Hong and Zhang, 2003).

The existing PCA, Brovey or multiplicative fusion methods have some technical limitations such as color distortion. These methods produce good results for the fusion of Spot pan with lower resolution XS images such as Spot XS, IRS XS or TM XS images. However, these methods have significant color distortion when high resolution Ikonos or Quickbird pan images are fused with low resolution Spot, IRS or TM. The cause of the color distortion is

the difference between the wavelength extension of the Quickbird/Ikonos Pan and Spot/IRS Pan images. This makes the grey values of the Quickbird and Ikonos images different from the others (Zhang, 2002). Methods like PCA, Brovey and Multiplicative can not handle this problem properly. Thus, new approach is needed to control the color distortion when the images from different sensors are fused. In this study, a novel pixel based image fusion technique is introduced, which exploits the statistical properties of the input images to compose the outcome images.

The proposed approach expresses the fusion result as a linear combination of the input pan and XS images. A local window is used to determine this relationship to calculate the pixel value of the fused pixel. The amount of spatial gain from pan image or spectral distortion of the XS images can be controlled by changing the window size. The fusion process is conducted pixel by pixel till the entire images are covered. To evaluate its performance, the satellite images over DPAC (Davis-Purdue Agricultural Center) area and Purdue University Campus area are fused. Comparison is also made with the results from PCA, Brovey and multiplicative methods. The results are compared visually and quantitatively to study the performance of the proposed method in terms of spatial resolution improvement and spectral content conservation. Used in this study are Quickbird pan and XS, and Ikonos XS images over DPAC area, and Ikonos pan and Spot XS images over Purdue Campus. The images and their properties are given below in Figure 1, Figure 2 and Table 1.
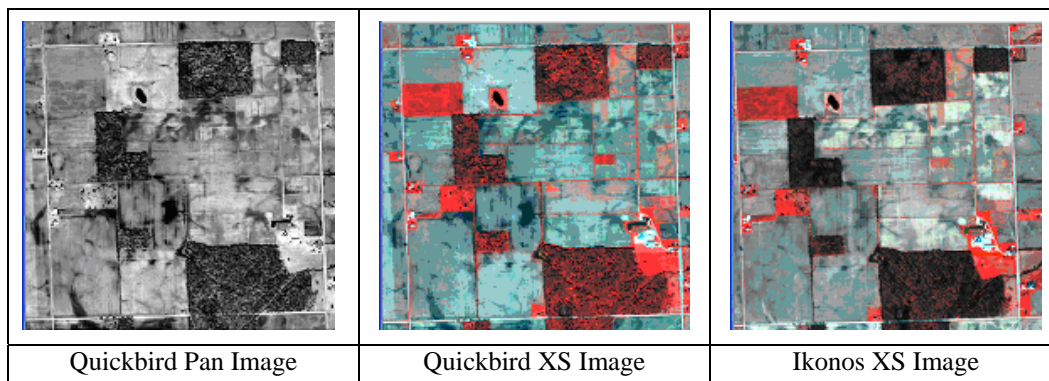

| Quickbird Pan Image | Quickbird XS Image | Ikonos XS Image |

Figure 1. Original Panchromatic and Multispectral Images (DPAC Area).

Ikonos Pan Image (Purdue Campus)

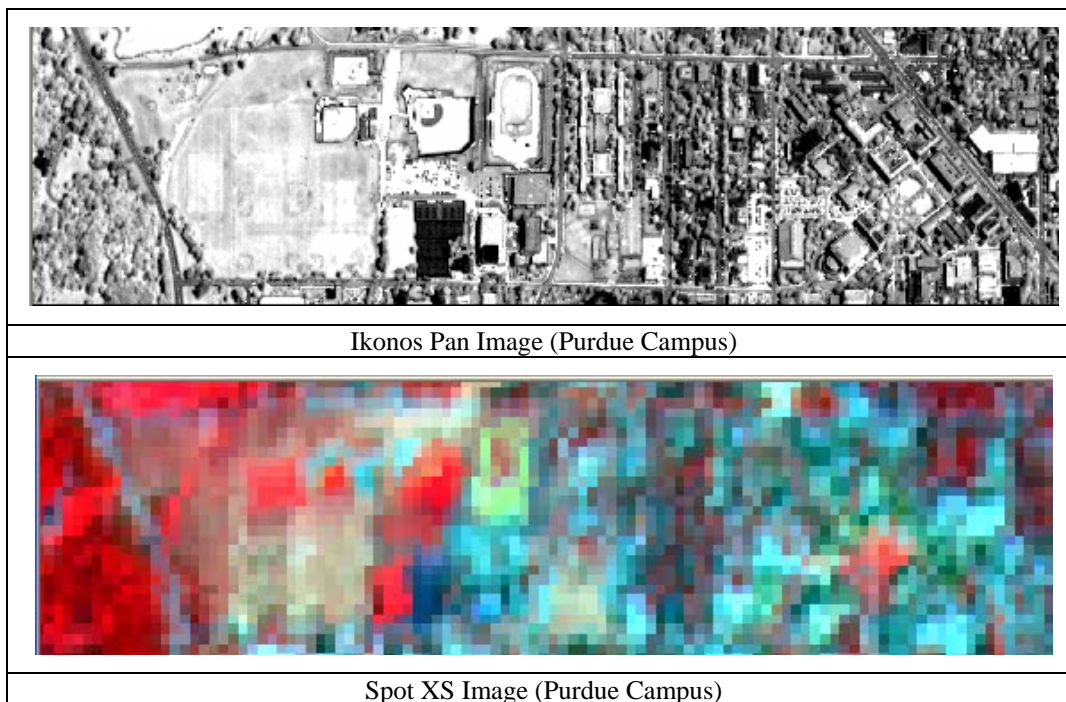Spot XS Image (Purdue Campus)

Figure 2. Original Ikonos Panchromatic and Spot Multispectral Images (Purdue Campus).

Table 1. Properties of the Input Images

Satellite	QuickBird (DPAC)		Ikonos (DPAC)		Ikonos (Purdue)	Spot (Purdue)
Image	Pan	XS	Pan	XS	Pan	XS
# Bands	1	4	1	4	1	3
XS Band #	Blue: 1; Green: 2; Red: 3; Near infrared: 4					
# bits	11	11	11	11	8	8
CE90% (m)	23	23	25.4	25.4	25.4	-
RMSE (m)	14	14	11.8	11.8	11.8	-
Collection date	May 3, 2002		April 16, 2002		July 8, 2000	Sept. 25,1997
Resolution (m)	0.7	2.8	1	4	1	20
Dimension (row x col)	2600x 2600	650x 650	Not Used	650x650	2076x551	104x27
Projection	UTM WGS 84					

FUSION PRINCIPLE

The proposed approach constructs the fused images as a linear combination of the pan and XS images. To create a new fused pixel, corresponding pixels in the pan and XS images are multiplied by the weighting factors "a" and "b" respectively. The sum of the new weighted pixels from the pan and XS images will form the new fused pixel. This can be expressed by the following expression

$$F_{k_{(m,n)}} = n_{(m,n)} \times I_{o_{(m,n)}} + b_{(m,n)} \times I_{k_{(m,n)}} \tag{1}$$

where m and n are the row and column numbers, k = 1,2, …., N (N = number of XS bands); F_k is the fused image, I_o is pan image and I_k is the XS band. The above relationship is only valid for a certain window, i.e., the a and b coefficients must be determined window by window (see below for detail discussions). For the simplicity of notations, the following derivation uses 1-D subscript i for window locations and the band number k is ignored. For window i, the variance (covariance) and mean of fused image can be written as

$$Cov(F_i, F_i) = a_i^2 \sigma_o^2 + 2a_i b_i \sigma_{oi} + b_i \sigma_i^2 \tag{2}$$

$$Mean(F_i) = a_i \mu_o + b_i \mu_i \tag{3}$$

where F_i is the fused window, a_i and b_i are the coefficients to be determined to construct the fused pixel, σ_o^2 and σ_i^2 are the variances of the pan and XS windows respectively, σ_{oi} is the covariance between pan and XS windows; Mean(F_i) is the mean of the fused window, μ_o is the mean of the window in pan image and μ_i is the mean of the window in XS band. To determine the coefficients a and b, we introduce the following two fusion criteria.

Criterion 1: the variance of the fused image should be equal to one of the pan image, i.e.

$$Cov(F_i, F_i) = a_i^2 \sigma_o^2 + 2a_i b_i \sigma_{oi} + b_i \sigma_i^2 = \sigma_o^2 \tag{4}$$

Criterion 2: the mean of the fused image should be equal to the one of the XS image, i.e.

$$Mean(F_i) = a_i \mu_o + b_i \mu_i = \mu_i \tag{5}$$

Combination of Equation (4) and (5) will yield the coefficients a and b. From Equation (5), we obtain

$$a_i = \frac{\mu_i}{\mu_o}(1 - b_i) \tag{6}$$

Substituting a_i to Equation (4) will lead to the following 2nd order polynomial equation about the coefficient b_i

$$\left(\frac{\sigma_o^2 \mu_i^2}{\mu_o^2} + \sigma_i^2 - \frac{2\sigma_{oi}\mu_i}{\mu_o}\right)b_i^2 + \left(\frac{2\sigma_{oi}\mu_i}{\mu_o} - \frac{2\sigma_o^2 \mu_i^2}{\mu_o^2}\right)b_i + \left(\frac{\sigma_o^2 \mu_i^2}{\mu_o^2} - \sigma_o^2\right) = 0 \tag{7}$$

Equation (7) has two roots for b_i and hence two corresponding a_i values will be obtained from Equation (6). Because the fusion process is expected to transfer spatial details from Pan image into the fused one, we keep the solution that has the largest "a" magnitude. The other solution would make more contribution from XS image, which would result in poor spatial detail in the fused image. In some cases, the "b" and "a" coefficients are complex numbers. Under such circumstance, the real components of the complex roots are taken as "a" and "b" coefficients, since they can make Equation (7) closest to zero in the domain of real roots.

As addressed earlier, the above formulation applies to a window of images. The larger the windows, the more spatial contribution will be gained from the pan image. This means that larger window size will produce spatially sharper fused images. However, larger window size will also result in degradation in the color. Therefore, there is a trade-off between spatial resolution gain and spectral content loss resulting from the window size. Hence, an optimal window size should be selected during the fusion process. For Quickbird pan and Quickbird XS data, a 27x27 window is used. Fusion of Quickbird pan and Ikonos XS gave the best results with a 15x15 windows. Finally, for the Ikonos pan and Spot XS, the window size is chosen as 31x31. The selected sizes gave the best results in terms of spatial detail gain and color conservation at the same time. Although the above window sizes are selected by trial-and-error, they provide a general guideline on the range of good candidate windows.

Figure 3 below illustrates the window by window implementation steps of the proposed approach. For simplicity, 3x3 and 5x5 windows are used in the figure. To calculate the $a_{(6,6)}$ and $b_{(6,6,)}$ coefficients, a 3x3 window is selected such that Pan$_{(6,6)}$ and XS$_{(6,6)}$ pixels are the center pixels of the 3x3 window. Once $a_{(6,6)}$ and $b_{(6,6,)}$ coefficients are determined using the two criteria introduced above, the fused pixel F$_{(6,6)}$ is calculated via Equation (1). If user wants the fused image with the same size of the input images, then padding process will be needed for the border regions of the input images. The blue pixels surrounding the input images represent the padding area. To calculate F$_{(12,12)}$ with a 5x5 window, pan and XS images are enlarged such that all the pixels within the window has a pixel value. There are various padding approaches in the literature (e.g., zero padding approach which extends the images with zeros). In this study no padding was used. Therefore, the fused images are smaller in size than the input images depending on the window sizes used.
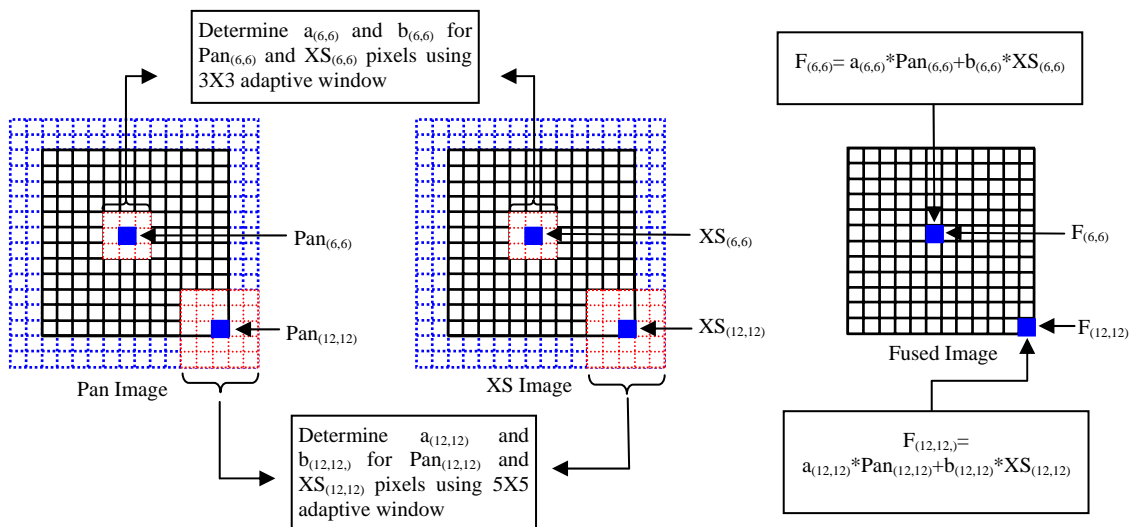

Figure 3. Construction of fused pixels using adaptive windows.

FUSION RESULTS AND EVALUATION

Preprocessing of input images

The first step in image fusion is to preprocess the input images. This includes registration, resampling and histogram matching of the input images. Registration is done by geo-referencing the images to a map projection such as UTM (Universal Transverse Mercator). If the images are from the same sensors and taken at the same time, they are usually already co-registered and can be directly used for fusion processing (Gungor and Shan, 2004). However, if the images are from different sensors, and even if they are georeferenced by the image vendors, a registration refinement is likely still needed to ensure that pixels in the input images exactly represent the same location on the ground. In this study the pan images are used as the reference images for registration.

Image fusion essentially occurs when the involved images have the same spatial resolution. Thus, XS images need to be resampled such that they have the same spatial resolution with the pan image. For resampling, nearest neighbor method was used to keep the color content of the original XS image unchanged. Nearest neighbor method is the simplest one among other resampling methods such as bilinear interpolation, cubic approximation to sinc function or 8-point or 10-point sinc function interpolation methods. In nearest neighbor method the new pixel value is assigned as the value of the nearest pixel. i.e., the original pixel values repeat. However, other methods mentioned above interpolate new pixel values using the surrounding neighbor pixels, which changes the spatial distribution and color content of the original image. In this study nearest neighbor method was used, for the other methods have a deteriorating effect on the original structure of the XS image.

Histogram matching should be applied to the input images before fusion process occurs. Histogram matching is crucial; in particular, when input images are collected from different sensors. The images from different sensors will have different brightness levels due to different angles of the sensor platforms and different illumination conditions of the scene resulting from different image acquisition times and the difference between the wavelength extensions of the different satellites. Histogram matching converts the histogram of one image to resemble the histogram of another. Thus, histogram matching has to be applied to the input images such that histogram of the XS image is matched to the histogram of the pan image. It will adjust brightness level of the XS image with respect to the pan.
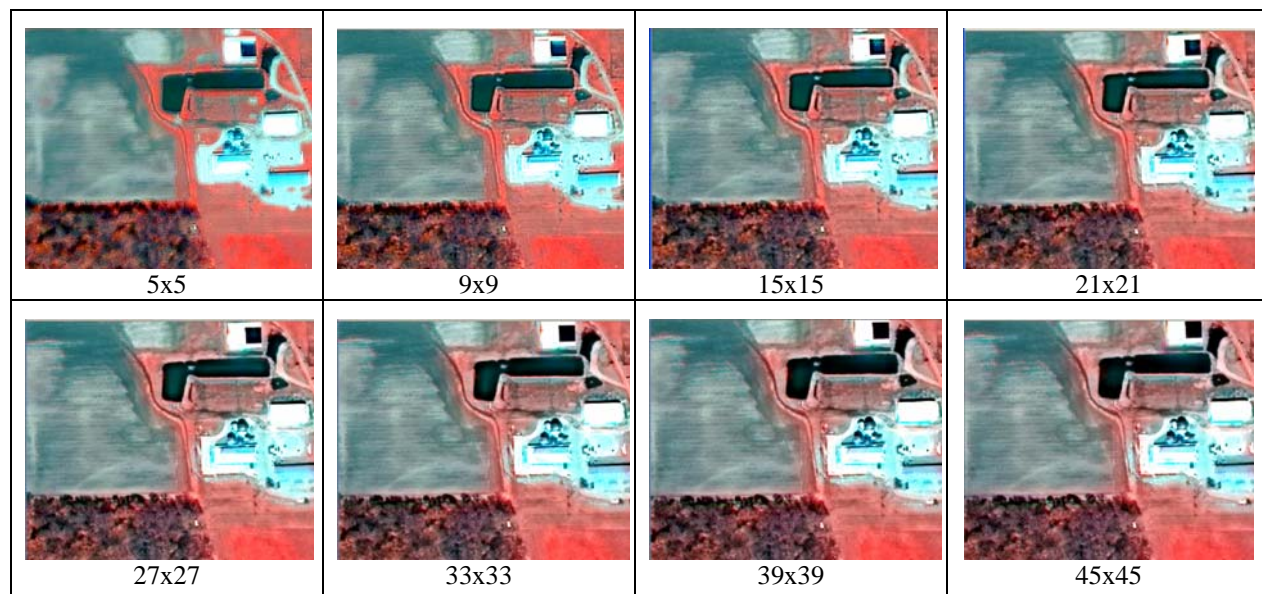

Figure 4. Fusion results of Quickbird Pan and XS with different window sizes (DPAC Area)

Window size

The proposed method has an important advantage over the other methods in that it is possible to control the amount of spatial gain or spectral content loss in the fused image simply by changing the window size used in fusion process. When the window size is enlarged, more spatial detail is transferred from pan image, whereas more color loss occurs in the fused outcome. Therefore, the window size essentially controls the trade-off between the spatial

detail gain or color loss. Fusion results from different window sizes are shown in Figure 4. To further illustrate the trade-off between spatial detail gain and color loss in the fused images, the correlation coefficients between input images and fused ones are calculated. First, correlation coefficients between original pan and fused XS bands are calculated. In this case, the higher the correlation, the more spatial details are transferred from pan image. Secondly, the correlation coefficients between original XS bands and fused XS bands are calculated. This time, the higher the correlation, the more spectral content is preserved in the fused image. Correlation coefficients obtained at different window sizes are listed in Table 2 and plotted in Figure 5.
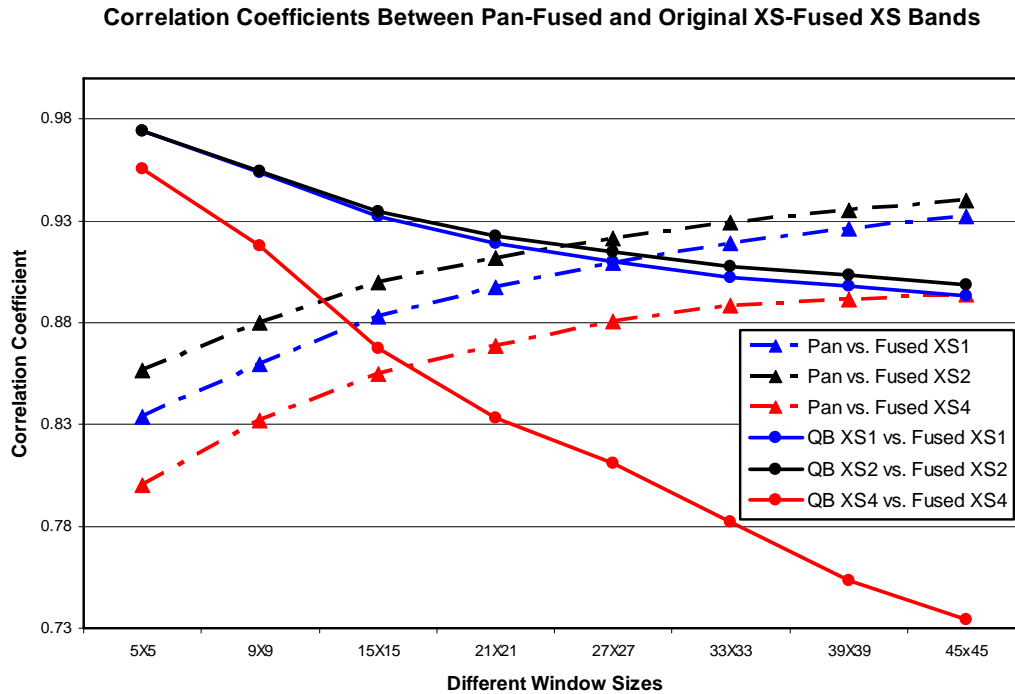
Correlation Coefficients Between Pan-Fused and Original XS-Fused XS Bands

Figure 5. Correlation coefficients as a function of window size

Table 2. Correlation coefficients for different windows sizes (DPAC QB Images)

	Window Size	Band-1	Band-2	Band-4
Correlation Between QB Pan and Fused XS Images	**5x5**	0.8340	0.8569	0.8002
	9x9	0.8599	0.8803	0.8319
	15x15	0.8828	0.8996	0.8550
	21x21	0.8974	0.9120	0.8687
	27x27	0.9094	0.9216	0.8808
	33x33	0.9191	0.9293	0.8885
	39x39	0.9265	0.9350	0.8914
	45x45	0.9324	0.9399	0.8938
Correlation Between QB XS and Fused XS Images	**5x5**	0.9742	0.9742	0.9558
	9x9	0.9537	0.9544	0.9179
	15x15	0.9324	0.9348	0.8676
	21x21	0.9191	0.9228	0.8333
	27x27	0.9099	0.9148	0.8108
	33x33	0.9024	0.9078	0.7821
	39x39	0.8981	0.9037	0.7532
	45x45	0.8935	0.8984	0.7342

Selected window sizes also affect the fusion results. The larger the window size, the more contribution is gained from the pan image to enhance the fused image spatially. On the other hand, the larger the window size, the more spectral loss occur in the fused product. This trade-off is displayed in Figure 5 using the calculated correlation coefficient between pan/fused bands and XS/fused bands. Correlation coefficients between pan and fused bands are

increasing when larger window sizes are used. Conversely, correlation coefficients between original XS bands and fused bands are decreasing when larger window sizes are used. This trade-off also can be seen from Table 2.

Evaluation and comparison

Three different fusion cases are used to evaluate the performance of the proposed method. First, Quickbird pan image of DPAC area is fused with Quickbird XS image. This test is to examine the properties and performance of the method when used for high resolution images collected by the same sensor. Fusion results are given in Figure 6. Secondly, Quickbird pan image of DPAC area is fused with Ikonos XS image. This fusion is executed to observe the behavior of the new method when the input images come from different sensors. Such fusion results are collected in Figure 7. Finally, Ikonos pan image of Purdue Campus area is fused with a Spot XS image. Ikonos image has one meter spatial resolution, whereas Spot XS image has 20 meter spatial resolution. This test is designed to evaluate the performance of the proposed method for images with large resolution difference. Figure 8 presents the fusion results of this test. In each test, the input images are also fused using the PCA, Brovey, Multiplicative fusion methods for comparison purpose.

It is clearly seen from the fusion results that the output images have a better spatial resolution after the fusion. However, there is degradation in the original color composition of the XS images in the fused products. This degradation becomes worse in different sensor case (Figure 7 and 8 vs Figure 6) and may cause loss of contrast or sharpness of the fused images. For example, the building next to the man-made circular structures (blue rectangular area in Figure 6) is not clear in the images created using PCA, Brovey or Multiplicative fusion methods. However, this building is clearly seen in the image produced using new method, though, this structure is not clearly seen in the original pan image.

The new method uses local windows. For this reason, fusion occurs only within the windows instead of the entire images. However, other methods use the entire images for their fusion rules. Using the entire images may affect the quality of the fusion results when the input images have small sizes. Using local windows also gives the proposed method an advantage over other methods. The new method creates very smooth fused images even the XS image has a very poor spatial resolution. For example, in fusing Spot XS and Ikonos Pan, results from the proposed method are satisfactory, while other methods have some blocking artifacts after fusion (Blue circular area in Figure 8), whereas new method has a very smooth transition among different geographical features.

As seen from Table 3, PCA and Brovey method are two best ones in terms of spatial detail gain for band 1 and band 2. On the other hand, PCA and Brovey have the largest spectral content loss for band 1 and band 2. This means that PCA and Brovey methods transfer more spatial detail to the fused image; however, these methods sacrifice spectral content on the XS image in the fused ones (Spectral lost is 25% for PCA and 48% for Brovey method for band 1). The new approach and multiplicative methods have better spectral content conservation (spectral lost is 9% for new approach and 13% for multiplicative method for band 1 with 27x27 window). Multiplicative method is also worst in terms of spatial resolution gain for band 1 and band 2. For band 1 and band 2, the new approach gives the best spectral content conservation (91% for band 1 and 92% for band 2). PCA and Brovey method are not successful for spatial detail gain for band 4 (64% spatial detail gain with PCA and 44% spatial detail gain with Brovey method). New approach has 88% spatial detail gain for band 4.

Table 3. Correlation coefficients of different fusion methods

|	Method	Band-1	Band-2	Band-4
Correlation Between QB Pan and Fused XS Images	**New Method w. size: (27X27)**	0.9094	0.9216	0.8808
	PCA	0.9782	0.9925	0.6355
	Brovey	0.9606	0.9876	0.4380
	Multiplicative	0.8259	0.8332	0.8927
Correlation Between QB XS and Fused XS Images	**New Method w. size: (27X27)**	0.9099	0.9148	0.8108
	PCA	0.7479	0.7484	0.9318
	Brovey	0.5182	0.6095	0.8637
	Multiplicative	0.8661	0.8694	0.8137
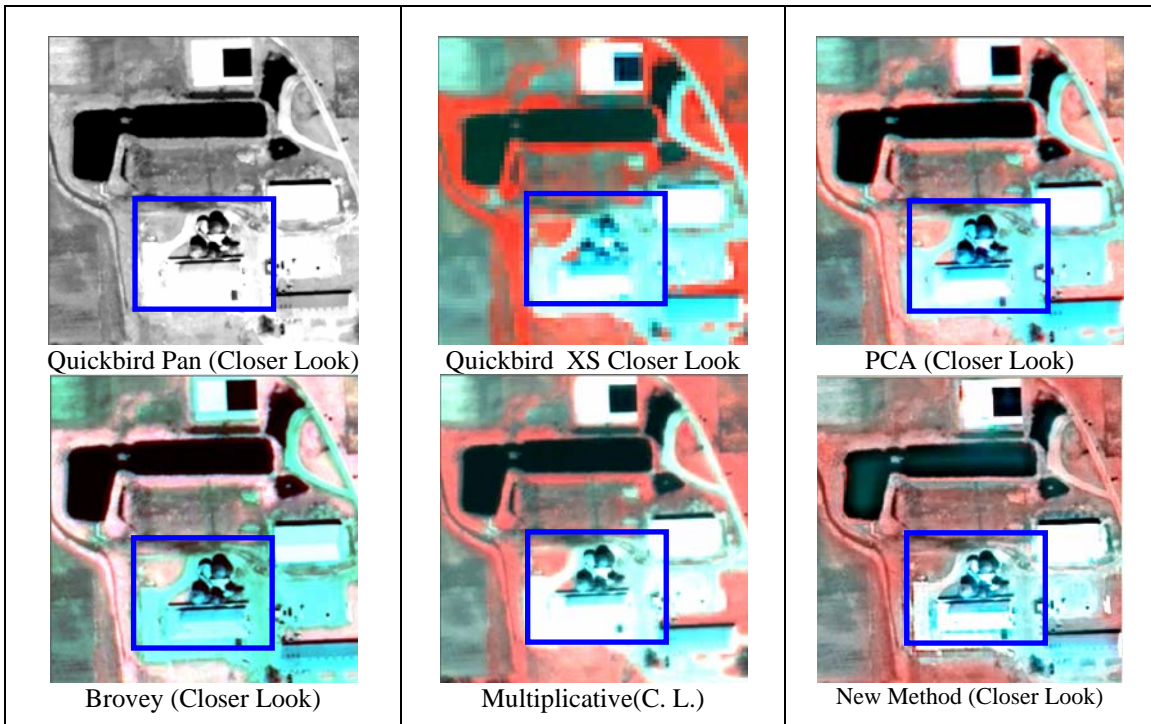
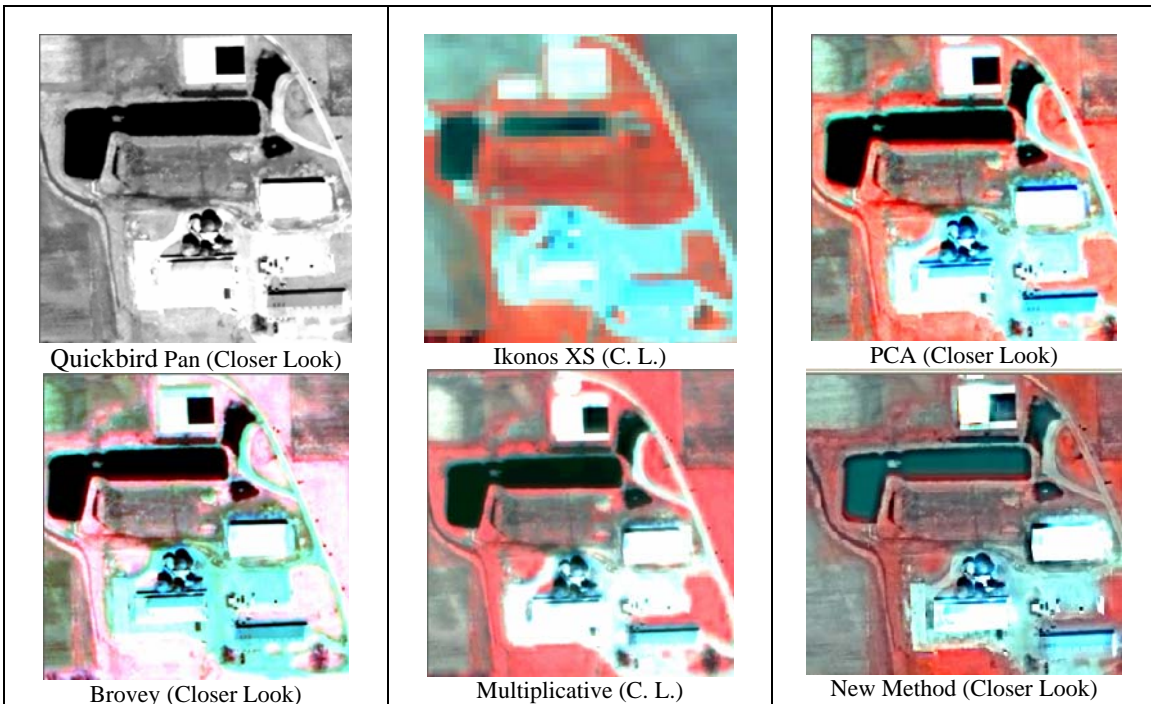Figure 6. Fusion results QB pan and QB XS over the DPAC area

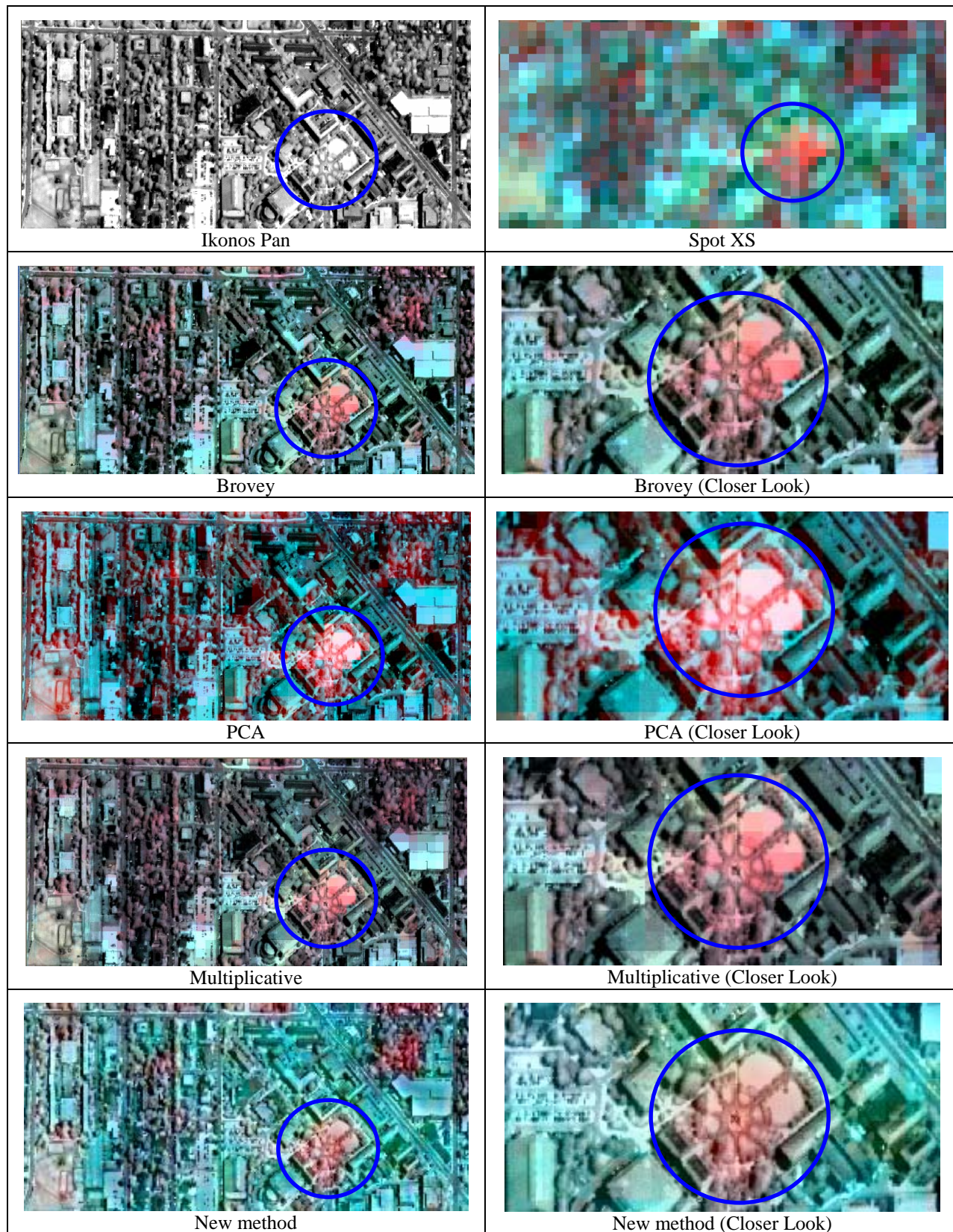Figure 7. Fusion results of QB pan and Ikonos XS over the DPAC area

Figure 8. Fusion results of Ikonos Pan and Spot XS over Purdue Campus

CONCLUSION

In this study, a novel image fusion method is introduced. The fusion outcome is regarded as a linear combination of the input panchromatic and multispectral images. This relationship is determined window by window. It is shown that the window size affects the quality of the fusion results. When the window size is increased, the spatial detail transferred from the panchromatic image is also increased, whereas color degradation occurs in the output images. For this reason a window size should be carefully chosen for the optimum solution in terms of spatial detail gain and spectral content loss. The properties of the fusion results are characterized by two fusion criteria. Statistically, the fusion image has the same variance as the input panchromatic image and the same mean as the input multispectral image. The fusion outcome is optimal under these fusion criteria.

Tests with images collected by three different sensors reveal that the proposed method is satisfactory. It successfully transfers spatial details of the panchromatic image to the XS images for both rural and urban areas. The method also is compared with the other methods using the correlation coefficients. The higher the correlation coefficients between the panchromatic and multispectral images, the more spatial detail are retained. The higher the correlation coefficients between the original XS bands and fused XS bands, the more color is conserved in the fused images. It is observed that PCA and Brovey method gave the best correlation coefficients for spatial detail transfer for band 1 and band 2 with 27x27 window size (see Table 3). On the other hand, these two methods are the worst in color conservation for band 1 and 2. Multiplicative method is also worst in terms of spatial resolution gain for band 1 and band 2. For band 1 and band 2, the new approach gives the best spectral content conservation among all methods (91% for band 1 and band 2) with 27x27 window size. PCA and Brovey method are not successful for spatial detail gain for band. New approach has 88% spatial detail gain for band 4, which is the second best one among four methods.

The proposed method is also successful for the fusion among images with large resolution difference, e.g Ikonos Pan and Spot XS. Even the XS image has a very poor spatial resolution, the proposed method still yields better results than other tested methods. The proposed method has a very smooth transition among different geographic features, however, other fusion methods produce blocking artifacts in the fused images.

Further more work is needed to improve the new approach to achieve the best performance. We will concentrate on developing an algorithm to select the optimal window size for the best fusion. Our research is also undergoing to understand the properties of the complex coefficients "a" and "b". It is also been sought the potential of combining the new method with the existing fusion methods.

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