AN EFFICIENT ALGORITHM FOR SATELLITE IMAGES FUSION BASED ON CONTOURLET TRANSFORM

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ABSTRACT:

This paper proposes a new fusion method for multiespectral (MULTI) and panchromatic (PAN) images that uses a highly anisotropic and redundant representation of images. This methodology join the simplicity of the Wavelet transform, calculated using the *à trous* algorithm, with the benefits of multidirectional transforms like Contourlet Transform. That has permitted an adequate extraction of information from the source images, in order to obtain fused images with high spatial and spectral quality simultaneously. The new method has been implemented through a directional low pass filter bank with low computational complexity. The source images correspond to those captured by the IKONOS satellite (panchromatic and multispectral). The influence of the filter bank parameters in the global quality of the fused images has been investigated. The results obtained indicate that the proposed methodology provides an objective control of the spatial and spectral quality trade-off of the fused images by the determination of an appropriate set of filter bank parameters.

1. INTRODUCTION

During the two last decades, remote sensed data integration with complementary spectral-spatial characteristics have experimented an important development. As a consequence, a large number of remote sensed images fusion methodologies have risen. All these methodologies are different as much from a conceptual point of view, like of the fused images quality (spectral/spatial) that they provide.

The most used image fusion strategies were based in multiresolution analysis techniques. From this point of view, the Discrete Wavelet Transform (DWT) can be considered as the most popular approximation, due to their good capability to multiresolution images analysis, through a joint information representation at the spatial-spectral domain, inspired in human visual system. There are different ways of calculating the Wavelet transform, among the most important are: the pyramidal algorithm of Mallat (Mallat 1999, Ranchin and Wald 2000, Pohl and van Garderen 1998, Zhou *et al.* 1998); and the redundant algorithm *à trous* ("with holes") (Dutilleux 1987).

Despite the good results provided by the DWT in the image fusion field, there are several aspects that have yet to be resolved. One aspect is the precise selection of the details, extracted from the PAN image, preserving the spectral quality of the MULTI image. And other aspect is the control of the inherent trade-off between the spatial and spectral quality of the fused image. Indeed, it has been observed that the multiresolution transforms with low anisotropy are not capable of intrinsically controlling this trade-off (Gonzalo & Lillo, 2004).

The recent appearance of new transforms, such as Curvelets (Candes and Dohono 1999 a), Ridgelets (Candes and Dohono 1999 b) and Contourlets (Do and Vetterli 2005), which are more efficient from the information representation perspective than the DWT, opens a new field of research in the image fusion algorithm area. These new transforms are highly anisotropic and produce a much more efficient extraction of spatial details in different directions. Particularly, the characteristics of the Contourlet Transform (CT) provide the bases of the fusion methodology proposed in this paper.

The Contourlet Transform (CT) improved noteworthy the TDW directional selectivity, by using two filters bank. The first is used for edge-points detection, and the second one links them for directional contour segments detection. Cunha *et al.* (2005) have proposed a non dyadic CT, jointing a nonsubsampled pyramid filters bank and a multirate directional filters bank.

Inspired in Cunha *et al.* (2005), a new highly anisotropic and redundant fusion method for multiespectral (MULTI) and panchromatic (PAN) images is proposed in this work. This new method join the simplicity of the Wavelet transform, calculated using the *à trous* algorithm (TWA), with the benefits of transforms like CT. For that a directional filters bank (Lakshmanan 2004) with low computational cost have been used. Thus, the resulting fusion method is characterized for a simple definition and implementation, as well as, a low computational cost.

2. METHODOLOGY

As it has been mentioned above, the methodology proposed in this paper, merges some ideas from the *à trous* algorithm and transform like CT to coherently integrate the low frequency information from the MULTI image and the high frequency information from the PAN image and to provide a fused image with high and balanced spatial and spectral quality.

According to the *à trous* algorithm philosophy, the source image at each level is degraded by a low pass filter. The main difference is that here this filter is directional. The filtering process is defined in the Fourier domain, as it is showed in equation (1).

$$\mathrm{Image}_{\theta_n}(x,y) = \mathrm{FFT}^{-1}\left\{\mathrm{FFT}\left\{\mathrm{Image}_{\theta_{n-1}}(x,y)\right\}\cdot H_{\theta_n}(u,v)\right\} \quad (1)$$

Where θ_{n-1} represents the degradation level prior to application of the directional low pass filter transfer function $(H_{\theta_n}(u,v))$ corresponding to θ_n level and defined as:

$$H_{\theta_n}(u,v) = \begin{cases} 1 & \text{if } \frac{(u\cos\theta_n - v\sin\theta_n)^2}{a^2} + \frac{(u\sin\theta_n - v\cos\theta_n)^2}{b^2} \le 1 \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

The parameters a and b define the filter scale and its elongation. In order to decrease the computational complexity, this filter has been implemented as the sum of two separable filters (Lakshmanan 2004):

$$H_{\theta_n}(u,v) = H^1_{\theta_n}(u) \times H^2_{\theta_n}(v) - \alpha u H^1_{\theta_n}(u) \times v H^2_{\theta_n}(v) \quad (3)$$

Where α is given by the relation $(a^2 - b^2)\sin(2\theta)/(a^2b^2)$, with:

$$H^1_{\theta_n}(u) = \exp(-u^2(\frac{\cos^2\theta_n}{a^2} + \frac{\sin^2\theta_n}{b^2})) \quad (4)$$

$$H^2_{\theta_n}(u) = \exp(-v^2(\frac{\cos^2\theta_n}{b^2} + \frac{\sin^2\theta_n}{a^2})) \quad (5)$$

It should be noted that in spite of its implementation, this filter conserves its non separable original characteristic. The most interesting property of this filter is not its elliptic form, but rather its directional character by which it assigns high weights to the corresponding values in a determined direction and low weights to their orthogonal direction.

The directional details are extracted by the differences of the directionally degraded images in two consecutive levels, defining the transform's coefficients associated at each level, as:

$$\mathrm{Coef}_{\theta_n}(x,y) = \mathrm{Image}_{\theta_n}(x,y) - \mathrm{Image}_{\theta_{n-1}}(x,y) \quad (6)$$

Since these coefficients contain the directional spatial details of the analysed image, this process corresponds to a high pass filtering.

Under the previous considerations, this paper proposes a new image fusion methodology that is formally expressed in equation (7):

$$\mathrm{FUS}^i(x,y) = \mathrm{MULTI}^i_{\theta_k}(x,y) + \sum_{n=1}^{k} \mathrm{Coef}^{PAN}_{\theta_n}(x,y) \quad (7)$$

Where $\mathrm{FUS}^i(x,y)$ represents the i^{th} band of the fused image, $\mathrm{MULTI}^i_{\theta_k}(x,y)$ represents the i^{th} band of the MULTI imaged degraded in k directions, obtained through the equation (1) and $\mathrm{Coef}^{PAN}_{\theta_n}(x,y)$ represents the PAN image coefficients (equation 6).

The two most relevant characteristics of this methodology are its high anisotropy, and the possibility of establishing an objective criterion to control the inherent trade-off, between spatial and spectral quality of the fused image. As it has been mentioned, the values of a and b determine the geometry of the low pass filter to be used. A relation between a and b close to 1 generates circular filters, while values far from 1 generate elliptical filters.

In order to evaluate the spatial and spectral goodness of the fused images, two quality indices have been used: the spectral ERGAS proposed by (Wald 2002) and the spatial ERGAS proposed by (Lillo-Saavedra *et al*. 2005). Both, indexes have a common domain of variation, facilitating their comparation and therefore, allowing to establish a trade-off criterion between the qualities measured by them.

With the aim to demonstrate the intrinsic capacity that the proposed methodology has to control both spatial and spectral quality of the fused image, a sensitivity analysis was performed, evaluating the spatial and spectral ERGAS quality indexes, as well as their average and standard deviation values, for images fused with different frequency partitioning ($k=2^1$, 2^2, 2^3, 2^4, 2^5, 2^6 and 2^7) and different combinations of a and b. It will be considered that the best trade-off will be given by a low average ERGAS and a low standard deviation simultaneously.

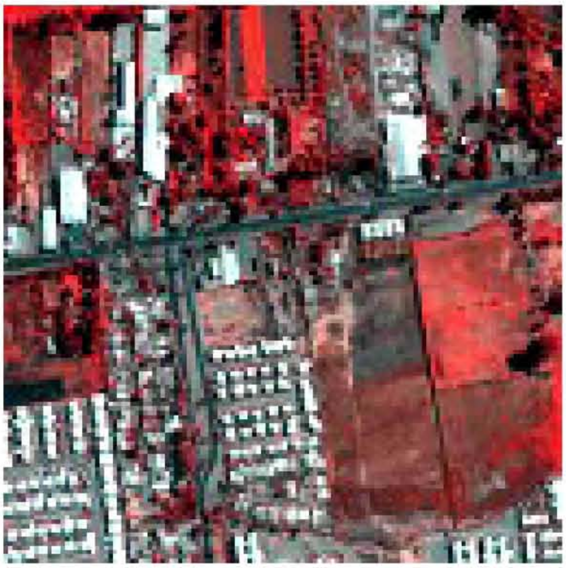
In a first analysis, the variation ranges for parameters a and b are segmented in two intervals. The first is defined between 0.1 and 0.5 with steps of 0.1, while the second one is defined between 1 and 5 with steps of 1. In this way, the combinations are considered to be 100 for each set of frequency partitioning (k). The results obtained from this study will be presented and discussed in the next section.

3. RESULTS

The data used to evaluate this methodology correspond to a 1600 m^2 scene of images recorded on March 10, 2000 by panchromatic (PAN) and multispectral (MULTI) sensors of the IKONOS satellite. Geographically, the scene is located in the Maipo Valley, near the city of Santiago, Chile. The relation between spatial resolution of the PAN image (1m) and the MULTI (4m) image is 1:4 times. To achieve a correct integration of the data coming from both source images, it was first necessary to georeference the MULTI and PAN images, and then resampled the MULTI image to the size of the PAN image.

For this study, a scene was selected where the predominant coverage were either vegetable and urban, with a large quantity of lines that defined the different estates, as well as streets and roads, which allows evaluation of the highly directional (anisotropic) characteristic of the proposed fusion algorithm. Figure 1 (a) shows a color composition of the near infrared (N), green (G), and blue (B) bands of the original MULTI image and the corresponding PAN image is showed in figure 1 (b).

The results obtained from the sensitivity analysis described in previous section, indicated that for the particular cases of k equal to 2^1 and 2^7, the fused images with better global quality are obtained when the relation between a and b is close to 1, which implies circular filters with a low or null directionality, providing images of very low spatial quality in the first case ($k=2^1$), since the number of directions in which the frequency space has been divided is very low. The second case ($k=2^7$) yields low spectral quality due to an excessive number of degradations of the original MULTI image.



a)

b)

c)

Figure 1: (a) NGB composition of the MULTI image; (b) panchromatic image; c) NGB Composition of the fused image for $k=2^3$, a=5 and b=0.6.

For the remaining space partitions, quite regular performance was observed. Sustained growth in both parameters (a and b) worsens spatial quality and an increase in spectral quality of the fused image, obtaining minimum average ERGAS values for certain combination of a and b, which at the same time depended on the number of directions considered. This result confirms the inverse compromise that exists between both qualities of the fused image, mentioned by Lillo-Saavedra *et al.* (2005).

From all experiments carried out, there are several set of fusion parameters that provide image fused with a high visual quality, which correspond to spectral and spatial ERGAS values under 2 o very close to it, simultaneously. Table 1 summarizes the values corresponding to spatial and spectral ERGAS, their average, and standard deviation (σ) for a=5, b varying from 0.5 to 1 and k= 2^2, 2^3, 2^4, 2^5. It can be observed that the ERGAS values, both spatial and spectral, were less than or very close to 2 in all considered cases.

Filter parameters		ERGAS			
k	b	Spatial	Spectral	Average	Std. Dev.(σ)
2^2	0.5	2.0326	1.7975	1.9151	0.1662
2^3	0.6	1.9738	1.8966	1.9352	0.0546
2^4	0.8	1.9575	1.9240	1.9408	0.0237
2^5	1	1.9001	2.0257	1.9629	0.0888

Table 1. ERGAS spatial and spectral values, their average and standard deviation for the images fused with a=5.

As can be appreciated in table 1, better ERGAS spatial values are obtained when a larger number of orientations in the frequency spaces are considered; however, this results in a deterioration of spectral quality, since it assumes a larger number of degradations of the MULTI image. Analyzing the average values, it can be observed that the lowest corresponds to 2^2, while the best compromise ($\sigma \approx 0$) is for $k=2^4$. In this sense, it can be considered that the best equilibrium for the average and standard ERGAS values is obtained for $k=2^3$. And then, the best set of values to fuse the image considered in this study is: $k=2^3$, a=5 and b=0.6.

Figure 1 (c) shows the image fused with $k=2^3$, a=5 and b=0.6. A visual analysis indicates an increase in spatial quality with respect to the original image (figure 1(a)) while maintaining the spectral quality, which can be appreciated in the colors conservation of the NGB composition of the MULTI. Additionally, in contrast with methodologies based in transforms with lower anisotropy, such as the Wavelet using the Mallat algorithm, the present transform does not produce the saw-tooth phenomenon in the lines with orientation distinct from the horizontal, vertical and diagonal (González-Audicana *et al.* 2005), which ratifies the highly anisotropic character of the transform using in this fusion methodology.

4. CONCLUSIONS

In this paper, it has been proposed a new highly anisotropic and redundant fusion method for multiespectral (MULTI) and panchromatic (PAN) images.

This fusion method has been implemented through a single directional low pass filter bank with low computational cost, which allows a multidirectional decomposition of the images to be fused, providing the anisotropic characteristic. Consequently this method has the capacity to extract image spatial characteristics in every orientation. This aspect is especially relevant, considering that it is one of the disadvantages of several widely used fusion methodologies, such as the DWT (Mallat).

To research the influence of the directional filter characteristics on the quality of the fused images, a study was performed for a representative range of filter parameters for different frequency partitioning. The results suggest as a general conclusion, that this methodology has the intrinsic capacity to control the global quality (spatial-spectral) of the fused images. This control is based in an adequate frequency partitioning, as well as in the selection of the filter parameters. Thus, it has been observed that when the frequency partitioning varies between 2^2 and 2^6, fused images with better global quality are obtained. Additionally, for each frequency partitioning, there is a set of filter parameters for which fused images with high spatial and spectral quality are obtained, being the average ERGAS values lesser than 2, in the majority of the cases. Concretely, for the scene considered in this study, the fused image with the most equilibrated spatial and spectral characteristics ($ERGAS_{average}$= 1.9352 and σ=0.0546) has been obtained for $k=2^3$, a=5 and b=0.6.

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