Multi-resolution, multi-sensor image fusion: general fusion framework

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Abstract—**Multi-resolution image fusion also known as pan-sharpening aims to include spatial information from a high resolution image, e.g. panchromatic or Synthetic Aperture Radar (SAR) image, into a low resolution image, e.g. multi-spectral or hyper-spectral image, while preserving spectral properties of a low resolution image. A signal processing view at this problem allowed us to perform a systematic classification of most known multi-resolution image fusion approaches and resulted in a General Framework for image Fusion (GFF) which is very well suitable for a fusion of multi-sensor data such as optical-optical and optical-radar imagery. Examples are presented for WorldView-1/2 and TerraSAR-X data.**

I. Introduction

Multi-resolution image fusion also known as pan-sharpening aims to include spatial information from a high resolution image, e.g. panchromatic or Synthetic Aperture Radar (SAR) image, into a low resolution image, e.g. multi-spectral or hyper-spectral image, while preserving spectral properties of a low resolution image. A large number of algorithms and methods to solve this problem were introduced during the last two decades. Sometimes it is quite difficult to orient between all these methods though some classification attempts were already performed [1-4]. We propose to look at these methods from a signal processing view. This type of analysis allowed us to recognize quite easily similarities and differences of various methods and thus perform a systematic classification of most known multi-resolution image fusion approaches and methods. Additionally, it allowed us to identify methods most suitable for a fusion of multi-sensor data such as optical-optical and optical-radar imagery. Moreover, a General Framework for image Fusion - GFF - is introduced. It consists of three main steps: low image interpolation, fusion itself performed in a spectral/Fourier domain and finally histogram matching. Experiments with very high resolution multi-sensor remote sensing data such as WorldView-1/2 and TerraSAR-X were performed. Qualitative and quantitative image fusion quality assessment results confirm our ideas and show a great potential for the future.

II. General Fusion Framework

Let's denote by ms_k a low resolution image, which can be e.g. multispectral/hyperspectral or any other image, with $k = 1,..,n$ and $n \in \{1,2,...\}$ - number of bands, and pan a high resolution image, e.g. panchromatic band, intensity image of synthetic aperture radar (SAR). A lot of existing multi-resolution methods or algorithms can be seen as an implementation of a General Fusion Framework (GFF):

- Low resolution image interpolation $msi = \mathrm{I}(ms)$
- Fusion $msf = \mathrm{F}(msi, pan)$
- Histogram matching $msf = \mathrm{M}(msf, ms)$

Indices are omitted intentionally for the sake of clarity. First and third step can be included in the fusion step depending on the method. Usually, I - a bilinear or cubic convolution interpolation and F - a linear function of images. In the next section we formulate a spectral fusion method including interpolation and fusion in one step.

III. Spectral Fusion

In order to preserve spectral properties of a low resolution image ms one should add only high frequency information from high resolution image pan. The natural way to do it is in a spectral or Fourier domain (signal processing view).

A. *Spectral domain*

First, both images are transformed into spectral/Fourier space $MS = \mathrm{FFT}(ms)$ and $PAN = \mathrm{FFT}(pan)$.

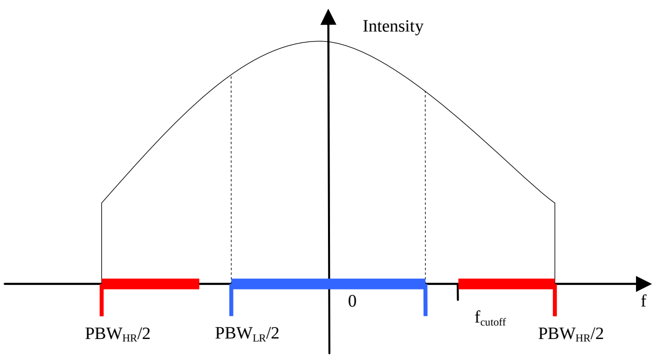

Figure 1. Addition of spectra of high resolution (HR) and low resolution (LR) images. PBW stands for processing bandwith, f – frequency and f_{cutoff} – cutoff frequency of high pass filter.

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Then, high frequencies are extracted from PAN (red color) and added to zero padded spectrum of MS (blue color, Fig. 1). The formulae is written as

$$MSF = \mathrm{ZP}(W \cdot MS) + PAN \cdot HPF\ , \tag{1}$$

where ZP stands for zero padding, W - Hamming window (aliasing and ringing avoidance) and HPF – high pass filter. Cutoff frequency allows us to control amount of details added to a low resolution image. Equivalently we can rewrite (1) for a low pass filter (LPF), which is easier to implement practically

$$MSF = \mathrm{ZP}(W \cdot MS) + PAN \cdot (1 - LPF)\ . \tag{2}$$

Finally, the inverse Fourier transform delivers a fused image with an enhanced spatial resolution $msf = FFT^{-1}(MSF)$.

B. Signal domain

We can rewrite formulae (1) in signal domain

$$msf = msi + pan * hpf\ , \tag{3}$$

where * stands for convolution and $hpf = FFT^{-1}(HPF)$. Similarly from (2) follows

$$msf = msi + pan - pan * lpf\ . \tag{4}$$

Formula (3-4) define fusion function F introduced in Sect. 2.

IV. ANALYSIS

In this section several known fusion methods (e.g. [1-7]) are presented and its relation to introduced spectral fusion (GFF) is analyzed theoretically.

A. Blending

A simple fusion is a weighted sum of *msi* and *pan* (also known as blending)

$$msf = w_{msi} \cdot msi + w_{pan} \cdot pan\ , \tag{5}$$

where $w_{msi} + w_{pan} = 1$. Of course, it has little to do with spectral fusion because low frequencies of *msi* and *pan* are mixed.

B. High frequency addition method

High frequency addition or high pass filtering method (e.g. [5, 6]) is described by same equations (3) or (4) as GFF. Still, three important differences are mainly due to the implementation in different domains. First, usually bilinear or cubic convolution interpolation for *msi* is used, whereas for GFF zero padding is proposed. Secondly, usually box filters in signal domain are used for low pass filtering making it difficult to precisely design a filter with required characteristics. Finally, a linear regression is used instead of histogram matching. One can find another so called high frequency modulation method

$$msf = msi \cdot pan / (pan * lpf)\ , \tag{6}$$

which appears to be equivalent to (4) after logarithmic transformation of data.

C. Component substitution (CS) based method

Under assumption that *msi* and *pan* are highly correlated one can calculate

$$I = \sum_{i=1}^{n} msi_i\ , \tag{7}$$

where n is a number of multispectral bands. Then, the component substitution method can be written as

$$msf = msi - I + pan\ . \tag{8}$$

Due to the above mentioned correlation one can write

$$I \approx pan * lpf\ . \tag{9}$$

By inserting (9) into (8) we end by exactly (4), what means the CS method is equivalent to spectral fusion under the correlation assumption. We have to note that in the case of $n = 1$ the method cannot be used, thus it is not applicable e.g. for radar-sharpening or multi-sensor data fusion.

D. Ehlers fusion

Ehlers fusion [7] under assumption of correlation (see previous subsection C) can be written as

$$\begin{aligned} msf &= msi - I + I * lpf1 + pan - pan * lpf2 \\ &= msi + pan - pan * lpf2 - E \end{aligned}\ , \tag{10}$$

where $E = I - I * lpf1 = I * hpf1$.

If the term E is omitted, then (10) reduces to (4). Introduction of this term seems to be redundant, even if by *msi* interpolation (e.g. cubic convolution) high frequencies are injected, then with an application of (7) these are smoothed. The main advantage of Ehlers method with respect to CS method is that it can be applied in the case of $n = 1$. From (7) we have $I = msi$ and rewrite (10) with $E = msi * hpf1$. It is again equivalent to (4) in the case $E = 0$. The term E can be good to remove high frequencies introduced by *msi* interpolation (e.g. cubic convolution).

E. Multiresolution analysis (MRA) based method

Spectral fusion applied locally (short time Fourier transform) seems to be equivalent to wavelet-based fusion methods. Detailed analysis is quite complicated and thus omitted and will be handled experimentally in the future.

V. FUSION EXAMPLES

GFF spectral fusion is applied to multi-resolution fusion of all 8 spectral bands of WorldView-2 (pan-sharpening, see Figs. 2-3) and multi-sensor fusion of WorldView-1 panchromatic band and TerraSAR-X high-resolution Spotlight intensity (radar-sharpening, see Figs. 4-7).

A. WorldView-2 pan-sharpening

For this experiment data of WorldView-2 (time: 12-July-2010 10:30:17, mode: ms+pan, look angle: 5.2° left) were collected over Munich city. Resized multispectral WorldView-2 image (bands: 5, 3, 2) to 0.5 m using cubic convolution interpolation are presented in Fig. 2. Pan-sharpening results using GFF spectral fusion method are shown in Fig. 3.

Figure 2. Resized multispectral WorldView-2 image (bands:5, 3, 2) to 0.5 m resolution using cubic convolution interpolation (Munich center).

Figure 3. Pan-sharpened multispectral WorldView-2 image (bands:5, 3, 2) using GFF spectral fusion method.

B. WorldView-1 radar-sharpening

For this experiment data of WorldView-1 (time: 18-Aug-2009 10:50:42, mode: pan, look angle: 38.3° left) and TerraSAR-X (time: 7-Jun-2008 05:17:48, mode: Spotlight HS, look angle: 49.45° right) were collected over Munich city in a special orthogonal (90°) acquisition geometry [8]. This geometry allows us to minimize displacement effects due 3D objects. Original images of WorldView-1 panchromatic sensor and TerraSAR-X intensity are presented in Fig. 4 and 5 respectively. Ground objects like streets and plazas (e.g. plaza with a monument in the middle) can be easily detected and found at the same geographical position in both images. Other structures: buildings (e.g. building block in the upper left corner of the image, church with two towers in the bottom left corner of the image) and trees can be easily indentified in both images. Only the feet of the buildings, which are differently projected in the radar image due to foreshortening in radar are found at slightly different positions. So the roofs and tree crowns are well in place and can be overlaid correctly for any further processing.

Figure 4. Original WorldView-1 panchromatic image of Munich center.

Figure 5. Original TerraSAR-X intensity image of Munich center.

Results of two fusion methods: simple blending and GFF spectral fusion are presented in Figs. 6, 7 respectively. Radar-sharpening (GFF spectral fusion) preserves spectral properties of optical image thus allowing further physical interpretation of a fusion product. Moreover, this example shows how a cloud recovery in an optical image is possible by using radar image.

Figure 6. Fusion of WorldView-1 and TerraSAR-X images by blending.

Figure 7. Radar-sharpening of WorldView-1 image with TerraSAR-X image by GFF spectral fusion.

VI. CONCLUSION

We have proposed a general fusion framework (GFF) consisting of main three steps: interpolation, fusion and histogram matching. Signal processing view allowed us to join first two steps into one by spectral fusion implemented in Fourier domain. This approach allowed us to systematically analyze most of known multi-resolution fusion methods and understand better their similarities and differences. We have demonstrated the potential of the proposed GFF fusion method for multi-resolution and multi-sensor data fusion for WorldView1/2 and TerraSAR-X imagery. Further work will be directed towards quantitative fusion quality assessment of different methods [9, 10] and new metrics analysis as e.g. in [11].

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