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A survey of pansharpening methods with a new band-decoupled variational model

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ABSTRACT

Most satellites decouple the acquisition of a panchromatic image at high spatial resolution from the acquisition of a multispectral image at lower spatial resolution. Pansharpening is a fusion technique used to increase the spatial resolution of the multispectral data while simultaneously preserving its spectral information. In this paper, we consider pansharpening as an optimization problem minimizing a cost function with a nonlocal regularization term. The energy functional which is to be minimized decouples for each band, thus permitting the application to misregistered spectral components. This requirement is achieved by dropping the, commonly used, assumption that relates the spectral and panchromatic modalities by a linear transformation. Instead, a new constraint that preserves the radiometric ratio between the panchromatic and each spectral component is introduced. An exhaustive performance comparison of the proposed fusion method with several classical and state-of-the-art pansharpening techniques illustrates its superiority in preserving spatial details, reducing color distortions, and avoiding the creation of aliasing artifacts.

1. Introduction

Many Earth observation satellites provide continuously growing quantities of remote sensing images useful for a wide range of both scientific and everyday tasks. Most of them, such as Ikonos, Landsat, Quickbird, and Pléiades, decouple the acquisition of a panchromatic image at high spatial resolution from the acquisition of a multispectral image at lower spatial resolution. The wide range of wavelengths acquired by the panchromatic represents an accurate description of the geometry of the image, while each spectral component covers a reduced bandwidth range leading to a detailed color description. Spectral sensors typically produce larger pixel sizes, thus increasing the signal noise ratio of spectral images and reducing the transmission cost. As an example, Fig. 1 displays the data captured by the Pléiades satellite and furnished to us by the *Centre National d'Études Spatiales* (CNES). In this setting, pansharpening is the fusion process by which a high-resolution multispectral image is inferred.

In remote sensing, high spatial resolution is necessary to correctly detect shapes, edges and, in general, geometric structures, but different types of land are better classified using images with multiple spectral bands. Considering this trade-off, state-of-the-art techniques (Thomas et al., 2008; Vivone et al., 2015; Ghassemian, 2016) aim at increasing the spatial resolution of the multispectral data by using the high frequencies of the companion panchromatic.

In the literature, pansharpening methods are mainly labeled into two main classes, namely component substitution (CS) and multiresolution analysis (MRA). The former relies on the use of a color decorrelation transform that converts the upsampled low-resolution channels into a new color system that separates the spatial and the spectral details. Fusion occurs by partially or totally substituting the component which is supposed to contain the spatial geometry by the panchromatic and applying the transformation back. Examples of CS methods include Intensity-Hue-Saturation transform (Carper et al., 1990; Tu et al., 2001; Zhou et al., 2014), Principal-Component-Analysis transform (Chavez and Kwarteng, 1989; Chavez et al., 1991; Shahdoosti and Ghassemian, 2016), Gram-Schmidt orthonormalization (Laben and Brower, 2000; Aiazzi et al., 2007), Brovey's (Gillespie et al., 1987), band-dependent spatial detail (Garzelli et al., 2008), and partial replacement adaptive CS (Choi et al., 2011). On the contrary,

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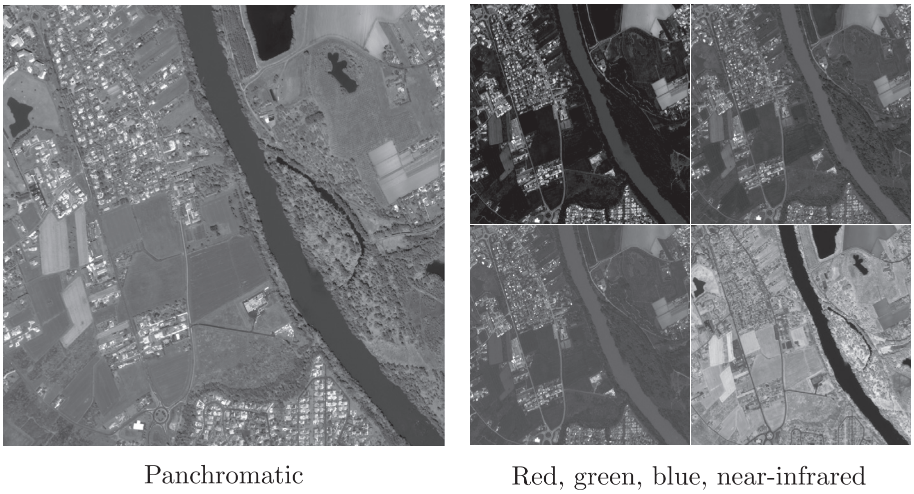

Fig. 1. Pléiades scene of Toulouse (France) provided by Centre National d'Études Spatiales (CNES). The spatial resolution is 70 cm per pixel for the panchromatic and 2.8 m per pixel for each blue, green, red, and near-infrared band.

MRA-based approaches inject the high frequencies of the panchromatic into the upsampled spectral components through a multiresolution decomposition. The fusion techniques from this family mainly differ in how the low-pass version of the panchromatic is generated at each scale. Laplacian pyramid (Aiazzi et al., 2002; Aiazzi et al., 2006; Lee and Lee, 2010), contourlet transform (Shah et al., 2008), curvelet transform (Nencini et al., 2007), ripplet transform (Ghahremani and Ghassemian, 2015), discrete wavelet transform (Yocky, 1995; Nuñez et al., 1999; Ranchin and Wald, 2000; Otazu et al., 2005; Vivone et al., 2014), high-pass filtering (Chavez et al., 1991; De Béthune et al., 1998; Schowengerdt, 2006; Khan et al., 2009), and high-pass modulation (Liu, 2000; Wald and Ranchin, 2002; Schowengerdt, 2006) are most widely used. Current MRA-based methods mainly use specified spatial filters to decrease the redundant detail injection (Kaplan and Erer, 2014; Liu and Liang, 2016). Furthermore, nonlinear MRA schemes based on morphological operators have been recently introduced by Restaino et al. (2016) as an alternative to the conventional MRA approach.

The main challenging task of pansharpening techniques is to get a good compromise between spatial and spectral quality. The two classes of methods described above exhibit complementary spectral-spatial quality trade-off. Although CS family is usually characterized by a high fidelity in rendering the spatial details in the final product (Aiazzi et al., 2007), it often suffers from significant spectral distortion. This is due to the fact that the panchromatic sensor does not cover exactly the same wavelengths as the spectral sensors (Thomas et al., 2008; Amro et al., 2011; Vivone et al., 2015). On the contrary, MRA-based fusion aims at preserving the whole content of the low-resolution data and adding further information obtained from the panchromatic through spatial filtering (Ranchin and Wald, 2000). In contrast to CS, MRA family is more successful in spectral preservation but it often experiences spatial distortions like ringing or staircasing effects (Thomas et al., 2008; Amro et al., 2011; Vivone et al., 2015). However, as pointed out by Aiazzi et al. (2006), if the frequency response of the low-pass filter used in the multiscale decompostion matches the Modulation Transfer Function (MTF) of the spectral channel into which details are injected, the spatial enhancement of MRA-based methods is comparable to that of CS.

Variational techniques have emerged as a promising direction of research since they effectively combine aspects of different methods into a single mathematical framework. Ballester et al. (2006) were the first to introduce a variational formulation for pansharpening, which they called P + XS. The authors assumed that the low-resolution channels are formed from the underlying high-resolution ones by low-pass filtering followed by subsampling. They considered a regularization term forcing the edges of each spectral band to line up with those of the panchromatic. Furthermore, P + XS functional incorporated an additional term according to which the panchromatic is a linear combination of the spectral components which are to be computed. Duran et al. (2014) proposed to keep the variational formulation introduced by Ballester et al. (2006) while incorporating nonlocal regularization that takes advantage of image self-similarities and leds to a significant reduction of color artifacts. In this setting, the panchromatic image is used to derive relationships among patches describing the geometry of the desired fused image. The general idea of diffusing a color image conditionally to the geometry of any other, in particular, to the geometry of its associated grayscale intensity image, was originally proposed by Buades et al. (2007). Several other variational models have been proposed so far (He et al., 2012; Möller et al., 2012; Palsson et al., 2012; Fang et al., 2013; Aly and Sharma, 2014; He et al., 2014; Zhang et al., 2015; Zeng et al., 2016). A detailed overview of variational techniques is given in Section 2.

Some methods cannot be easily classified in one of the above categories. There are pansharpening algorithms that combine CS and MRA approaches (Cheng et al., 2015; Song et al., 2016), while some others propose geostatistical solutions in order to preserve the spectral properties of the observed coarse images (Pardo-Igúzquiza et al., 2006; Tang et al., 2015; Wang et al., 2016).

Most of the pansharpening techniques previously mentioned make use of the linear combination assumption and need all data to be geometrically aligned. Unfortunately, both requirements are not satisfied by real satellite imagery, for which different spectral bands are not originally co-registered and their registration previously to pansharpening is not at all recommendable because of the strong aliasing. Indeed, the panchromatic and spectral bands are acquired according to the Push-Broom principle of CCD arrays placed in the focal plane of a telescope. The sensors are shifted within the focal plane in the direction of the satellite scrolling and the same point on the ground is not captured at the same time by all sensors or strictly under the same angle. Furthermore, one of the most relevant drawbacks of this acquisition system is the strong aliasing of the spectral bands, which usually produces jagged edges, color distortions, and stair-step effects. The MTF has low values near Nyquist for the panchromatic, thus almost avoiding undesirable aliasing effects. On the contrary, the MTF of the spectral bands having high values at Nyquist results in aliased spectral data as illustrated in Fig. 2. Baronti et al. (2011) studied