A CRITICAL REVIEW OF FUSION METHODS FOR TRUE COLOUR DISPLAY OF VERY HIGH RESOLUTION IMAGES OF URBAN AREAS

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ABSTRACT

This paper critically reviews state-of-the-art and advanced methods for multi-spectral (MS) and panchromatic (Pan) image fusion based on either intensity-hue-saturation (IHS) transformation, or redundant multi-resolution analysis (MRA). In either cases, lower-resolution MS bands are sharpened by injecting details taken from the higher-resolution Pan image. Crucial point is modelling the relationships between detail coefficients of a generic MS band and the Pan image at the same resolution. Once calculated at the coarser resolution, where both types of data are available, such a model shall be extended to the finer resolution to weight the Pan details to be injected. Two injection models embedded in a generalised Laplacian pyramid (GLP) decomposition will be compared on a test set of very high resolution QuickBird MS+Pan data.

INTRODUCTION

Remote-sensing image fusion techniques aim at integrating the information conveyed by data acquired with different spatial and spectral resolution from satellite and aerial platforms. The most straightforward goal is photo-analysis, but also automated tasks such as features extraction and segmentation/classification have been found to benefit from fusion. A variety of image fusion techniques is devoted to merge multi-spectral (MS) and panchromatic (Pan) images, which exhibit complementary characteristics of spatial and spectral resolutions. Pan-sharpened MS is a fusion product in which the MS bands are *sharpened* by the higher-resolution Pan image.

When exactly three MS bands are concerned, the most straightforward fusion method is to resort to an Intensity-Hue-Saturation (IHS) transformation. This procedure is equivalent to *inject*, i.e., add, the difference between the sharp Pan and the smooth intensity into the re-sampled MS bands (i). Since the histogram-matched Pan and the intensity component I do not generally have the same radiometry, i.e. local mean, when the fusion product is displayed in colour composition, large spectral distortion, i.e. colour changes, may be noticed. This occurs because the spectral response of I, as synthesised by means of the MS bands, may be far different from that of Pan. Thus, also radiance offsets, slowly space-varying, and not only spatial details, are locally injected. When more than three spectral bands are available, IHS fusion may be applied to three consecutive spectral components at a time, or better the IHS transformation may be replaced with principal component analysis (PCA). The latter does not avoid spectral distortion, even if it may be less noticeable. Generally speaking, if the spectral responses are not perfectly overlapped with the Pan bandwidth, as it happens with Ikonos and QuickBird, IHS- and PCA-based methods yield poor results in terms of spectral fidelity.

To definitely overcome this inconvenience, methods based on injecting spatial details only, taken from the Pan image without resorting to IHS transformation, have been introduced and have demonstrated superior performances. Multi-resolution analysis (MRA) provides effective tools, like wavelets and Laplacian pyramids, to help carry out data fusion tasks (ii). However, in the case of high-pass detail injection, *spatial* distortions, typically, ringing or aliasing effects, originating shifts or blur of contours and textures, may occur in fusion products. These drawbacks, which may be as much annoying as spectral distortions, are emphasised by mis-registration between MS and Pan data, especially if the MRA underlying detail injection is not shift-invariant (iii,iv).

If the goal of band-sharpening were simply to exactly transplant the spectral information content of the MS data into an image having spatial details same as Pan, satisfactory solutions would be found in the literature. However, the goal of an advanced fusion method is to increase spectral information, by unmixing the coarse MS data through the sharp Pan image. This further task requires the definition of a model establishing how the missing high-pass information to be injected is extracted from the Pan image. It may be accomplished either in the domain of approximations between each of the resampled MS bands and a low-pass version of the Pan image having the same spatial frequency content as the MS bands, or in that of medium frequency details, in both cases by measuring local matching. High frequency details are not available for MS bands, and must be inferred through the model, starting from those of Pan.

Quantitative results of data fusion are provided thanks to the availability of reference originals obtained either by simulating the target sensor by means of high resolution data from an airborne platform, or by degrading all the available data to a coarser resolution and carrying out fusion from such data. In practical cases this strategy is no longer feasible. The idea behind, however, is that algorithm parameters adjusted to yield best results at coarser scales, i.e. on spatially degraded data, should be unchanged when all the data are considered at a finer scale, which happens in practice. This assumption may be reasonable in general, but unfortunately does not hold for very high resolution data, especially when a highly detailed urban environment is concerned. The reason of this behaviour lies in the characteristics of the modulation transfer function (MTF) of the imaging system. Any inter-scale injection model should take into account that the MTF of real systems is generally bell-shaped. In particular, the MTFs of the MS sensors may be significantly different from one another in terms of decay rate, and especially are different from that of the Pan sensor. Thus, models optimised at a coarser scale may yield little enhancement when reported at the finer scale.

Experimental results carried out on QuickBird data of an urban area will be reported and discussed. Comparisons with the state-of-the art, demonstrate that a superior spatial enhancement, besides the outstanding spectral quality typical of injection methods, is achieved by means of multi-resolution fusion methods employing proper injection models (v).

METHODS

Figure 1 shows the flowchart of sharpening of low-resolution MS bands via a high-resolution P image. The multi-resolution analysis underlying the fusion procedure is furnished by the GLP and is outlined for the general case of *p/q* scale ratio between the data set to be fused. Fractional scale ratios are feasible thanks to cascaded expansions and reductions by integer factors. Notice that for a *p/q* scale ratio*,* only *one* filter with *1/p* cut-off is required. In fact, when reduction is cascaded to expansion, the low-pass filtering step can be omitted after up sampling by *q*, as well as before down sampling by *q* in the expansion, by assuming that filters exhibit frequency cut-offs that are almost ideal. The injection model is always calculated between MS bands resampled to the final scale and the low-pass approximation of the Pan image. These data sets should have the same extent of spatial frequency content to expedite model calculation. This issue may be crucial in practical case, due to the presence of a non-ideal *modulation transfer function* (MTF) generally different from one band to another. In that case, the reduction filter only may be replaced with a kernel approximating the average MTF of the MS bands. The expansion filter, which is responsible for resampling of the data sets, is left unchanged and equals one of the prototypes described in (iii).

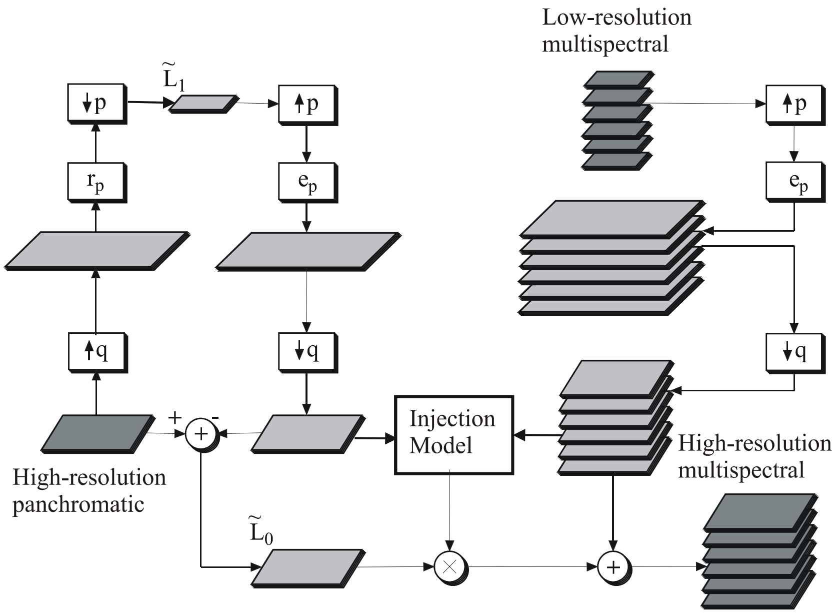

Figure 1: flowchart of GLP-based Pan-sharpening of spectral bands for the general case of scale ratio equal to p/q (p>q). The up-samplers ↑ and down-samplers ↓, together with the reduction and expansion filters (r_p and e_p, respectively) define the zero level of GLP. The injection model is calculated at the fine scale between low-pass approximation of P and expanded MS band.

RESULTS

A very high resolution image, collected by the QuickBird satellite MS scanner on the urban and suburban areas of Pavia, in Italy, was used. The four MS bands embrace the visible and NIR wavelengths; the Pan image the whole interval 450-900 nm. The data have been resampled to ground resolution of 2.8 m and 0.7 m GSD for MS and Pan. Fusion experiments have been firstly carried out on spatially degraded MS and Pan data to allow quantitative scores to be measured between fused products and true 2.8 m MS data. The methods compared are AWL (vi), HPF (vii), GLP-SDM with spectral distortion minimising injection model (v), and GLP-CBD, in which a context based decision is performed on GLP fusion (iii). Also the case in which the MS data are resampled, without injection of details, will be presented.

Table 1 reports a comparison among methods in terms of Q4 quality index (viii), spectral angle (SAM) and ERGAS (ii). CBD attains global scores better than those of the other methods. Not surprisingly the SAM attained by CBD is lower than that of SDM (identical to that of resampled MS data), thanks to the unmixing capabilities of the former compared to the latter. Both the simple SDM and the more sophisticated CBD models, when coupled with a redundant MRA, yield the best results, according to spectral and radiometric fidelity.

Table 1: Average cumulative quality indexes between 2.8 m MS spectral vectors and those obtained from fusion of 11.2 m MS with 2.8 m Pan. EXP indicates plain resampling of MS bands without enhancement from Pan. Q4 is a quality score and ranges between 0 (worst) and 1 (best). The angle SAM is the average absolute spectral error. ERGAS is a normalised average error and should be as low as possible.

	EXP	AWL	SDM	CBD	HPF
Q4	0.756	0.848	0.862	0.878	0.827
SAM (deg.)	2.14°	2.51°	2.14°	1.90°	2.59°
ERGAS	1.760	1.695	1.611	1.470	2.012

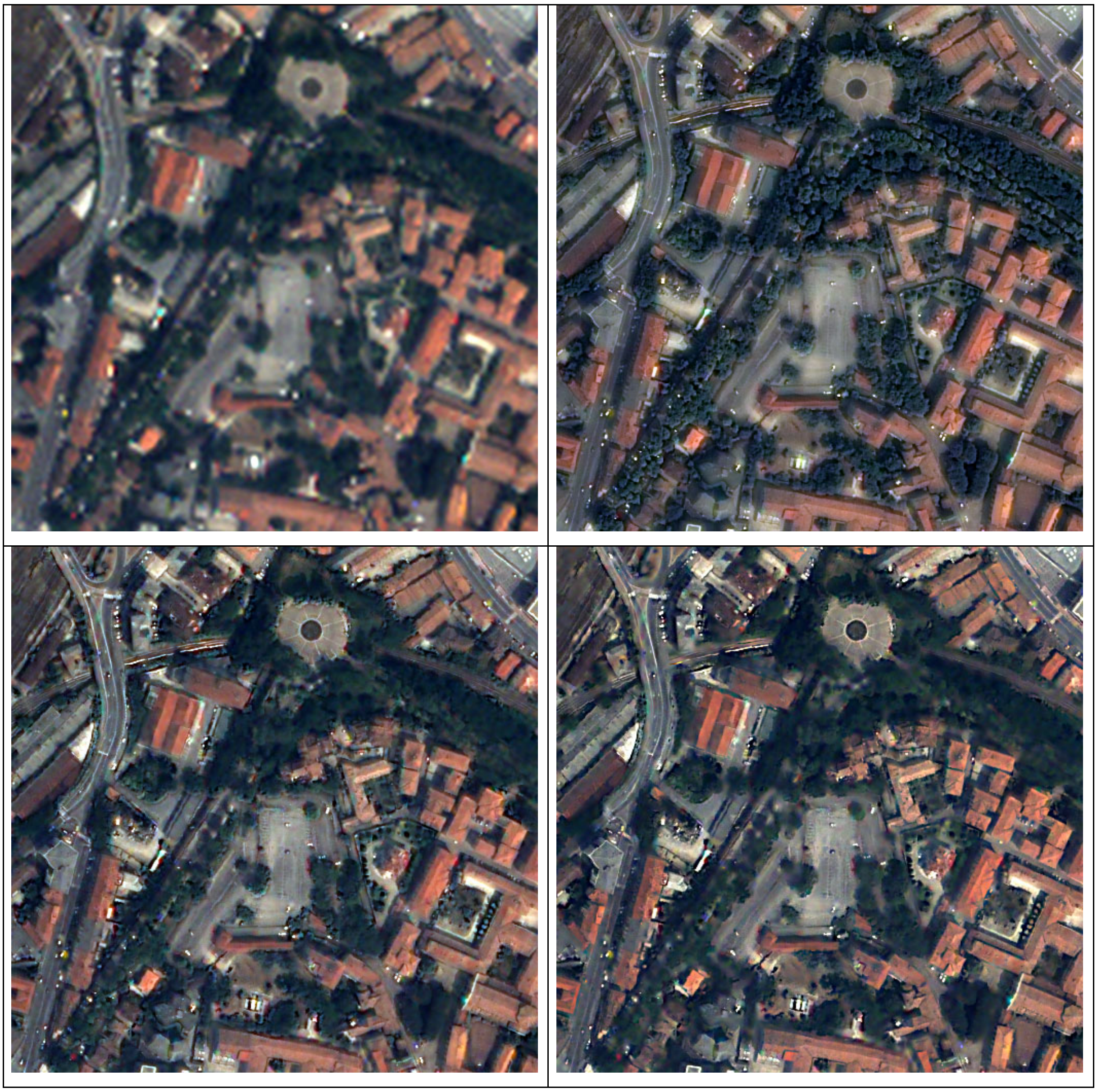

Figure 2: True-colour compositions of original and fused MS bands. Clock-wise from top-left: re-sampled 2.8 m MS, AWL fusion, CBD fusion and SDM fusion.

Figure 2 displays true-colour compositions of the resampled 2.8 m MS bands and of the spatially enhanced bands, all at 0.7 m. True-colour visualisation has been deliberately chosen, because Pan-sharpening of MS bands falling partly outside the bandwidth of Pan, as in the case of the blue band B1, is particularly critical ix. HPF yields a fused image very similar to that of AWL, even though slightly less accurate; therefore its result is not shown. The SDM and CBD models are applied to GLP, achieved through MTF-matched analysis filters (x). A visual inspection highlights that all the spectral signatures of the original MS data are carefully incorporated in the sharpened bands. Thanks to the two injection models, the texture of the canopies, which is highlighted by the Pan image, but mostly derives from the NIR band, which is outside the visible wavelengths, appears to be damped in the SDM and CBD fusion products. AWL, which implicitly accounts for the MTF in the MRA, is geometrically rich and detailed, but over-enhanced, especially on vegetated areas.

CONCLUSIONS

This paper has pointed out that Pan-sharpening of MS images for true-colour display is crucial when the spectral response of the panchromatic imager comprises the NIR wavelengths rather than the blue ones. In this cases fusion methods based on redundant MRA and exploiting an adaptive detail-injection model are preferable to conventional HPF and especially IHS methods.

The open problem of image fusion is that of quality assessment. Therefore, the efforts of the authors are devoted to the study and development of fusion assessment methods, that do not require reference originals and thus can be utilised at the full scale of Pan, without the need of carrying out simulations on spatially degraded data.

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