TOOLS AND METHODS FOR FUSION OF IMAGES OF DIFFERENT SPATIAL RESOLUTION

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ABSTRACT

The usefulness of remote sensing data, in particular of images from Earth observation satellites, largely depends on their spectral, spatial and temporal resolution. Each system has its specific characteristics providing different types of parameters on the observed objects. Focusing on operational and most commonly used commercial remote sensing satellite sensors, this paper describes how image fusion techniques can help increase the usefulness of the data acquired. There are plenty of possibilities of combining images from different satellite sensors. This paper concentrates on the existing techniques that preserve spectral characteristics, while increasing the spatial resolution. A very common example is the fusion of SPOT XS with PAN data to produce multispectral (3-band) imagery with 10 m ground resolution. These techniques are also referred to as image sharpening techniques. A distinction has to be made between the pure visual enhancement (superimposition) and real interpolation of data to achieve higher resolution (e.g. wavelets). In total, the paper describes a number of fusion techniques, such as RGB colour composites, Intensity Hue Saturation (IHS) transformation, arithmetic combinations (e.g. Brovey transform), Principal Component Analysis, wavelets (e.g. ARSIS method) and Regression Variable Substitution (RVS), in terms of concepts, algorithms, processing, achievements and applications. It is mentioned in which way the results of various techniques are influenced by using different pre-processing steps as well as modifications of the involved parameters. All techniques are discussed and illustrated using examples of applications in the various fields that are part of ITC's educational programme and consulting projects.

1. INTRODUCTION

According to the EARSeL1 Special Interest Group on Data Fusion (Data Fusion SIG) data fusion is defined as "... a formal framework in which means and tools are expressed for the alliance of data originating from different sources. It aims at obtaining information of greater quality; the exact definition of greater quality will depend upon the application" (Wald, 1998). Image fusion forms a subgroup within this definition and aims at the generation of a single image from multiple image data for the extraction of information of higher quality. Having that in mind, the achievement of high spatial resolution while maintaining the provided spectral resolution falls exactly into this framework.

The concept of combining images with complementary information opens a broad field of applications. There is a vast variety of techniques to combine images from different sensors. However, this paper focuses on image fusion techniques that preserve spectral characteristics whilst increasing spatial resolution to provide images of greater quality. A very common example is the fusion of SPOT XS with PAN data to produce multispectral (3-band) imagery with 10 m ground resolution. These techniques are also referred to as image sharpening techniques and often called resolution merge. A distinction has to be made between the pure visual enhancement (superimposition) and real interpolation of data to achieve higher resolution (e.g. wavelets); the latter being proposed amongst others by Mangolini (1994) and Ranchin et al. (1996).

2. RESOLUTION MERGE

Using appropriate fusion techniques high spatial resolution panchromatic imagery can be combined with multispectral imagery of lower resolution. In this way, the spectral resolution may be preserved, while a higher spatial resolution is incorporated, which represents the information content of the images in much more detail (Franklin and Blodgett, 1993; Pellemans et al., 1993). A special case is the fusion of channels from a single sensor for resolution enhancement, e.g. TM data. The lower resolution thermal channel can be enhanced using the higher resolution spectral channels (Moran, 1990). Other approaches increase the spatial resolution of the output channel using a windowing technique on the six multispectral bands of TM (Sharpe and Kerr, 1991). The fusion of SAR/VIR does not only result in the combination of disparate data but may also be used to spatially enhance the imagery involved (Welch, 1984). Geometric accuracy and increase of scales using fusion techniques is of concern to mapping and updating (Jutz, 1988; Chiesa and Tyler, 1990; Pohl, 1996).

3. IMAGE FUSION TECHNIQUES

Image fusion for spatial resolution enhancement is performed at pixel level as one of the three fusion levels defined by Pohl and van Genderen (1998). It requires the accurate co-registration of

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1 European Association of Remote Sensing Laboratories.
the input images to link related parameters of the observed Earth surface.

After having corrected system-induced and geometric errors in the dataset as indicated in Fig. 1, the images are fused to produce the higher spatial resolution using one of the following techniques:

- RGB colour composites;
- Intensity Hue Saturation (IHS) transformation;
- Arithmetic combinations (e.g. Brovey transform);
- Principal Component Analysis;
- Wavelets (e.g. ARSIS method);
- Regression Variable Substitution;
- Combinations of techniques.

The following sections describe the context and process of various techniques in more detail.

3.1. Red-Green-Blue Colour Composites

The so-called additive primary colours allow the assignment of three different types of information (e.g. image channels) to the three primary RGB colours. Together they form a colour composite that can be displayed on conventional media, e.g. cathode ray tube (CRT), with the parallel use of a LookUp-Table (LUT). The colour composite facilitates the interpretation of multi-channel image data due to the variations in colours based on the values in the single channels. Operations on the LUT and the histogram of the image data can enhance the colour composite for visual interpretation.

The possibilities of varying the composite are manifold. Depending on the selection of the input image channels, the fused data will show different features. Very important for the colour composite is the distribution of the available 0-255 grey values to the range of the data. It might be of advantage to invert input channels before combining them in the RGB display with other data depending on the objects of interest to be highlighted (Wang et al., 1995).

3.2. Intensity-Hue-Saturation Colour Transform

The IHS transformation (Eq. 1a-c) separates spatial (I) and spectral (H, S) information from a standard RGB image. It relates to the human colour perception parameters. It separates the colour aspects in its average brightness representing the surface intensity, its dominant wavelength (hue) and its purity (saturation) (Gillespie et al., 1986; Carper et al., 1990). The IHS values, commonly expressed in cylindrical or spherical coordinates, can be mapped to Cartesian coordinates through values \( v_1, v_2 \) using a linear transformation (Harrison and Jupp, 1990):

\[
\begin{pmatrix}
I \\
v_1 \\
v_2 \\
\end{pmatrix} = 
\begin{pmatrix}
\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\
\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\
\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\
\end{pmatrix}
\begin{pmatrix}
R \\
G \\
B \\
\end{pmatrix}
\tag{1}
\]

\[
H = \tan^{-1}\left(\frac{v_2}{v_1}\right) \quad S = \sqrt{v_1^2 + v_2^2} \quad \tag{2}
\]

In order to apply this technique for the enhancement of spatial resolution, a panchromatic higher resolution channel replaces the intensity component of a lower resolution multispectral dataset.

There are two ways of applying the IHS technique in image fusion: direct and substitutional. The first refers to the transformation of three image channels assigned to I, H and S. The second transforms three channels of the dataset representing RGB into the IHS colour space which separates the colour aspects from its average brightness (intensity). Then, one of the components (usually intensity) is replaced by a fourth higher spatial resolution image channel, which is to be integrated. In many published studies the channel that replaces one of the IHS components is contrast stretched to match the latter. A reverse transformation from IHS to RGB as presented in Eq. 2 (Harrison and Jupp, 1990) converts the data into its original image space to obtain the fused image.

3.3. Arithmetic Combinations

The possibilities of combining the data using multiplication, ratios, summation or subtraction are manifold. The choice of weighing and scaling factors may improve the resulting images. Eq. 3 gives an example of a summation, and Eq. 4 of a multiplication technique used to combine Landsat TM with SPOT PAN as resolution merge (Yèsou et al., 1993).

\[
DN_f = A(w_1 * DN_a + w_2 * DN_b) + B \quad \tag{3}
\]
\[
DN_f = A*DN_a * DN_b + B \quad \tag{4}
\]

A and B are scaling and additive factors respectively and \( w_1 \) and \( w_2 \) weighting parameters. \( DN_a, DN_b \) and \( DN_f \) refer to digital numbers of the final fused image and the input images a and b, respectively.
The Brovey Transform (Hallada and Cox, 1983), a special combination of arithmetic combinations including ratio, is a formula that normalises multispectral bands used for a RGB display, and multiplies the result by any other desired higher resolution image to add the intensity or brightness component to the image. The algorithm is shown in Eq. 5 where DNfused means the DN of the resulting fused image produced from the input data in ‘n’ multispectral bands b1, b2, … bn multiplied by the high resolution image DNhighres.

\[ \text{DN}_{\text{fused}} = \frac{\text{DN}_{b1}}{\text{DN}_{b1} + \text{DN}_{b2} + \ldots + \text{DN}_{bn}} \cdot \text{DN}_{\text{highres}} \] (5)

3.4. Principal Component Analysis

PCA is a statistical technique that transforms a multivariate dataset of correlated variables into a dataset of new uncorrelated linear combinations of the original variables. The approach for the computation of the principal components (PCs) comprises the calculation of:

1. covariance (unstandardised PCA) or correlation (standardised PCA) matrix
2. eigenvalues, eigenvectors
3. PCs

An inverse PCA transforms the combined data back to the original image space. Replacing the first principal component with a higher resolution intensity image, a multi-channel dataset can be transformed into a spatial resolution image of higher ground resolution. This is called Principal Component Substitution - PCS (Shettigara, 1992). The idea of increasing the spatial resolution of a multi-channel image by introducing an image with a higher resolution. The channel, which will replace PC1, is stretched to the variance and average of PC1. The higher resolution image replaces PC1, since it contains the information which is common to all bands while the spectral information is unique for each band (Chavez et al., 1991). PC1 accounts for maximum variance, which can maximise the effect of the high resolution data in the fused image (Shettigara, 1992).

3.5. Wavelets

Wavelets, a mathematical tool developed originally in the field of signal processing, can also be applied to fuse image data, following the concept of the multi-resolution analysis (MRA). The wavelet transform creates a summation of elementary functions (= wavelets) from arbitrary functions of finite energy. The weights assigned to the wavelets are the wavelet coefficients, which play an important role in the determination of structure characteristics at a certain scale in a certain location. The interpretation of structures or image details depends on the image scale, which is hierarchically compiled in a pyramid produced during the MRA (Ranchin and Wald, 1993). Once the wavelet coefficients are determined for the two images of different spatial resolution, a transformation model can be derived to determine the missing wavelet coefficients of the lower resolution image. Using these, it is possible to create a synthetic image from the lower resolution image at the higher spatial resolution. This image contains the preserved spectral information with the higher resolution, hence showing more spatial detail. This method is called ARSIS, an abbreviation of the French definition “amélioration de la résolution spatial par injection de structures” (Ranchin et al., 1996).

3.6. Regression Variable Substitution

Multiple regression derives a variable, as a linear function of multi-variable data that will have maximum correlation with univariate data. In image fusion the regression procedure is used to determine a linear combination (replacement vector) of image channels that can replace an existing image channel. If the channel to be replaced is one of the lower resolution input bands, this procedure leads to an increase of spatial resolution. To achieve the effect of fusion, the replacement vector should account for a significant amount of variance or information in the original multivariate dataset. The method can be applied to spatially enhance data. In case of fusion of SPOT XS and PAN channels, for each pixel location three new values are computed to produce the 10 m multispectral pixels based on the known relationship between PAN and XS. The linear regression is then calculated for each channel combination, i.e. XS green band - PAN, XS red band - PAN and IR band - PAN.

4. RESOLUTION MERGE CHALLENGES

The resolution merge is relatively straightforward, when using data from the same satellite, e.g. SPOT PAN & XS, IRS-1C PAN & LISS, etc. But it is also applicable to imagery originating from different satellites carrying similar sensors, e.g. SPOT XS & IRS-1C PAN.

Some of the approaches are already implemented in commercial-off-the-shelf (COTS) software packages, e.g. PCI Geomatics and ERDAS IMAGINE. These include amongst others multiplication techniques, PCA and Brovey transform. Image providers already integrated resolution merged products into their catalogue of standard products. Examples are SPOT IMAGE (1999) and SSC Satellitbild (1999). However, very often the user has to fine-tune individual parameters of the fusion process. A good example is the use of arithmetic combinations, which allow the user to put different weights on the input images in order to enhance application relevant features in the fused product.

The major difficulty is the co-registration of images with large differences in spatial resolution. The identification of tie points can cause problems in both datasets:

- Multispectral data - difficulty of identifying corresponding points due to the lower resolution;
- Panchromatic data - shadow effect caused by buildings or similar objects due to high level of detail.

Especially in the case of spatial resolution ratios of up to 1:10, i.e. SPOT XS and Russian imagery, points or features have to be selected with care, due to the additional large difference in viewing geometry of the sensors involved. An integrated approach is the use of sensor models, which provide a re-
construction of the viewing geometry during image acquisition. It allows the correction of terrain induced distortions in case of availability of a digital elevation model (DEM) (Cheng et al., 1995).

Nevertheless, the combination of data with different spatial resolution is of benefit for visual interpretation. In the case of large spatial or spectral differences in images to be co-registered the identification of features (lines or areas) leads to more accurate results than the measurement of points only. The information contributed by the two images facilitates the extraction and identification of features. The human interpreter is able to cope with slight misregistration.

In spectral terms, the fusion of panchromatic and multispectral imagery does not invoke particular problems due to the similar nature (visible and infrared spectrum) of the images involved. This matter becomes more critical when fusing VIR and SAR. The two image types are influenced by different effects both in radiometry and geometry. The fusion of SAR/VIR does not only result in the combination of disparate data but is also used to spatially enhance the imagery involved (Welch, 1984). In particular, the effect of speckle in SAR data has a strong impact on the interpretability of the fused result. The application of speckle filters is a trade-off between speckle reduction and loss of detail.

5. RESOLUTION MERGE EXAMPLES AND CONCLUSIONS

Image fusion is used in a broad variety of applications: geology, land use / agriculture / forestry, change detection, map updating, hazard monitoring, just to name a few. The possibility to increase spatial resolution, whilst maintaining the important information source of different spectral bands is of benefit for most of these applications.

There are many publications containing suggestions on how to fuse high resolution panchromatic images with lower resolution multispectral data to obtain high resolution multispectral imagery. Details can be found in Simard2 (1982), Cliche et al. (1985), Pradines (1986), Price (1987), Welch and Ehlers (1987), Carper et al. (1990), Ehlers (1991), Mangolini et al. (1993), Munechika et al. (1993) and Pellelmeans et al. (1993).

It has been shown that even the fusion of spatially very different datasets can result in increased interpretability; an operational example is the use of space photography and pushbroom scanners, e.g. Russian imagery & SPOT XS (Pohl and Touron, 1999).

The resolution merge is one of the few generally accepted and operational fusion techniques at pixel level. That becomes very obvious from the availability of fused products from image providers, as well as COTS package processing modules. The fused products are suitable for visual interpretation and further computer aided processing. The latter is reasonable only for those techniques that result in radiometric values that are close to the original input data (e.g. ARSIS).

New and planned satellite systems have already taken into account the benefit of resolution merged products by launching integrated sensor systems with different spatial resolution sensors. Operational satellites are LANDSAT-7, SPOT-4, and IRS-1C. ESA is also planning a multisensor, multiresolution satellite called ENVISAT.

REFERENCES


2 Simulated data.


