Multisensor Data Fusion with Singular Value Decomposition

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***Abstract* — The present study aims at multi-sensor data fusion with Singular Value Decomposition (SVD). Earth observations imaging systems collect data at different spatial and radiometric resolutions due to transmission bandwidth and other technical constraints. Fusion of multi-sensor images enables a synergy of complementary information obtained by sensors of different spectral ranges. The study illustrates the excellent potential of Singular Value Decomposition for image fusion with Quickbird panchromatic and multispectral data. The study brings out that this fusion process outscores conventional techniques used in operational environments and is illustrated with a second example by merging IRS1C panchromatic data with IRSP6 multispectral data.**

Keywords- remote sensing; earth observation satellites; data fusion; singular value decomposition;

I. INTRODUCTION

According to the EARSel Special Interest Group on Data Fusion, data fusion is defined as "…. formal framework in which means and tools are expressed for alliance of data originating from different sources". Image fusion forms a subgroup within this definition [9] and aims at the generation of a single image from multiple image data for the extraction of information of higher quality.

Earth observations imaging systems are designed to collect data at different spatial and radiometric resolutions due to transmission bandwidth and other constraints such as an economy of space, weight on board, availability of on board power etc. For instance, the now de-orbited Spot 2 has collected multispectral (MS) data with 20 meters spatial resolution, while panchromatic (Pan) data is collected with 10 meters spatial resolution. Fusion of multi-sensor images enables a synergy of complementary information obtained by sensors of different spectral ranges. Many multi-sensor fusion studies have demonstrated that it is feasible to simulate multispectral images offering the highest spatial and radiometric resolution available for a better modeling of the environment. In other words, fusion process results in generating a multispectral image with 10 meters spatial resolution from Pan and MS data.

An interesting factor in favor of image fusion is that this is a ground segment activity where in computer intensive resources are deployed for this purpose. Multi-sensor image fusion is a very economical option compared to the cost of launching a satellite equipped with multispectral sensors with highest spatial, spectral and radiometric resolutions.

II. LITERATURE SURVEY ON IMAGE FUSION

C Phol [9] and Yuhendra et al [19] give details of very frequently used image fusion techniques integrated into COTS image processing software such as PCI Geomatics, Erdas, Envi and are as under:

- RGB color composites.
- Intensity-hue-saturation (HIS) transformation [2] substituting image intensity.
- Arithmetic combinations (Brovey transformation etc).
- Principal component analysis was first proposed by Chavez[4], [[12] substituting the first principal component. This PCA approach [9] is as follows:
    - Compute the covariance/correlation matrix of MS data.
    - Subject covariance matrix for un-standardized PCA
    - Subject correlation matrix for standardized PCA.
    - Replace the first principal component with higher resolution image ie., Pan data.
    - Invert the modified data to realize pan sharpened image.
- Grahm-Smidth orthogonal approach.
- Multi-scale transformation based on wavelets [8],[9] and [10].
- Regression variable substitution (RVS) technique substituting the regression variable obtained by statistical fitting of the high- and low-resolution image.
- Radiometric method [16] substituting the component obtained by spectral fitting of high- and low resolution bands (if such fitting is possible).

A common disadvantage of spectral component substitution techniques is that all other spectral components except for the substituted one are left at their original low resolution (mere resampling cannot be considered as an actual resolution enhancement). Some authors [2] note that RVS [2] and radiometric [16] methods provide best radiometric adjustment of substituted component.

III. PROPOSED METHODOLOGY

In this section, we define an SVD and state its relationship with principal component analysis.

978-0-7695-4682-7/12 $26.00 © 2012 IEEE
DOI 10.1109/UKSim.2012.65

Subsequently, image fusion with SVD is illustrated with an example.

A. Definition of Singular Value Decomposition of a Matrix

Given $A \in C^{m \times n}$, SVD of A is a factorization of form

$A = U \Sigma V^T$ where,

- $U \in R^{m \times m}$ is an orthogonal matrix of order "m". The "m"columns of U are known as left singular vectors of matrix A.
- Σ is $\in R^{m \times n}$ diagonal matrix of order 'i' = min (m, n) with singular values σ_i ranked in ascending order.
- $V \in R^{n \times n}$ is an orthogonal matrix of order "n". The "n"columns of V are known as right singular vectors of matrix A.
- $U U^T = I_{(m \times m)}$ (definition of orthogonal matrix).
- $V^T V = I_{(n \times n)}$ (definition of orthogonal matrix).
- The singular values σ_i are also known as mode of matrix A.
- The rank of matrix A is the number of its non-zero singular values.
- Distance to singularity: Often, one needs to quantify how far the system (under consideration) from being singular. It turns out that the smallest singular value i.e. min (σ_i) is equal to that distance.
- An SVD always returns positive eigen values unlike a PCA. The sign difference is absorbed by the eigenvectors.

B. Relationship of Singular Values with Eigenvalues

As is well known, singular values of a matrix A are the square roots of its principal components, while the left and right eigenvectors are the eigenvectors of the AA^H and A^HA respectively, where A^H is the Hermitian of A. Therefore, by definition, for any rectangular matrix defined in complex domain, its singular values as well as its left and right eigenvectors are always real (as AA^H and A^HA are real), while its eigen values and eigenvectors may be imaginary. The left and right eigen vectors like eigenvectors of a matrix, can be thought of as approximating the directions of the rows/columns of a matrix.

C. Proposed SVD Image Fusion Algorithm.

SVD like principal components analysis is a statistical technique that transforms a multivariate dataset of correlated variables into a new dataset of uncorrelated variables that are a linear combination of the original data. The proposed SVD approach to image fusion is similar to Shettigara's [12] approach with PCA and is as follows:

- Resample low resolution MS data to the same resolution of Pan data which is of higher order resolution. It is noted that MS and Pan data register well on a pixel by pixel basis.
- Read MS image data of order (m, n, 3) into a matrix M of dimension (m*n, 3) where elements of each row correspond to pixel values of the three bands.
- Read Pan image data of order (m, n) into a vector P of dimension (m*n, 1).
- Compute the covariance/correlation matrix of M.
- Subject covariance matrix to singular value decomposition for un-standardized SVD.
- Subject correlation matrix to singular value decomposition for standardized SVD.
- The SVD decomposition generates three matrices uM, ΣM and vM that are left eigenvectors, singular values and right eigenvectors of order (3 * 3).
- Rotate matrix M about the eigen axis as follows:
  $yM_{(m*n,\ 3)} = M_{(m*n,\ 3)} * uM_{(3,\ 3)}$.
- Replace first column of every row in matrix yM with corresponding element from vector P i.e. pixel value of higher resolution Pan data.
- Invert modified data to realize pan sharpened multispectral image that is at Pan resolution i.e.
  $reconMS = yM_{(m*n,\ 3)} * uM^T_{(3,\ 3)}$

Figure 1. Panchromatic image of Quickbird

Figures 1, 2 and 3 are respectively the Quickbird Pan, MS and P+X images obtained with standardized SVD without any radiometric enhancements. It is noted that Pan as well as MS images are well registered on a pixel by pixel basis.

Figure 2. Multispectral image of Quickbird

Figure 3. SVD fused image of Quickbird

IV. EVALUATION METHODOLOGY

The working group "data fusion" of the European Association of Remote Sensing Laboratories (EARSeL) defined a protocol to fuse data based on the works of [7] [18]. This protocol comprises of checking with respect to two properties: the consistency property and the synthesis property. In the current scenario, the emphasis has shifted from a mere reproduction of RGB values to rendering with natural colors and rendering with colors that are more appropriate for each theme. Quality assessment of data fusion is going through many more changes as multi-sensor fusion is attempted with many other objectives; for instance radiometric fusion [16] has been attempted on sensors of IRS P6 and IRS RS2, natural color composites in preference to Pan sharpened MS images that are false color composites etc. Interactive improvements on theme based "natural color" aesthetics of a DTM for a variety of applications in geology, land use, forestry, agriculture, hazard monitoring, change detection, map updating etc are at this point of time a subject matters of research.

For the present study, we focus on radiometric fidelity and geometric registration aspects of image fusion. An analysis from a radiometric perspective has been restricted in the present study by comparing the results with PCA approach which is one of the most frequently used techniques. From a geometric perspective, registration analysis after a fusion process is a subject matter of concern and research. Most of the studies pursue them from a band to band image registration perspective as multi-sensor data, quite often, is drawn from sensors of different missions. For instance Spot or IRS pan sensors are fused in an operational environment with Landsat data to realize natural colors as has been shown in Figure 4.

V. CONCLUSION

It has been shown that even fusion with spatially very different data sets can result in increased interpretability. Over the years there has been considerable increase in user demand for these "value added" products wherein inference is made by domain experts visually. There have been some studies to adopt digital classification and clustering techniques with fused data, However, many domain experts and application scientists still prefer to use "radiometrically corrected raw" sensor data for their studies demanding digital classification.

Yuhendra et al [19] made a comparative analysis of various color fusion techniques and conclude that the Gram Smidth method and PCA preserve spectral and spatial information of objects better than other methods in their study. They also note that color recovery of PCA is much better when compared with other methods.

It is noted that proper care must be taken to select the eigen vector corresponding to the largest eigen value and otherwise there will be a disparity in colour rendering as is illustrated with Figure 4 and 5. It is noted that with a well implemented PCA fusion process, the output will correspond with Figure 5.

As already noted in section II, like all other substitution methods, we have replaced the pixel value of only one band i.e., the largest Eigen value with panchromatic image value while the other two bands retain their resampled values. This can, like with all substitution methods, sometimes result in unacceptable color combinations that are visible in patches. At the same time, it is worth noting that color rendering improvements with SVD hold a lot of promise to overcome such limitations and will be a hot topic of interest to render thematic images with "natural color".

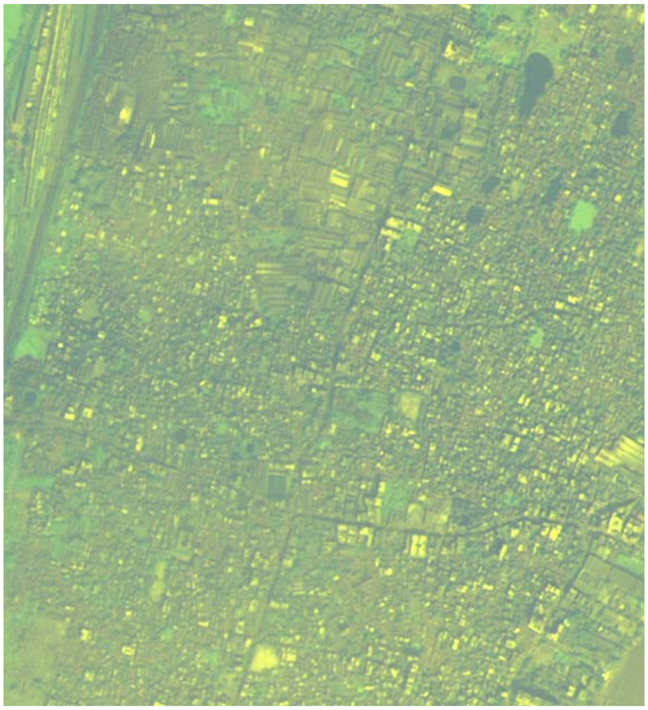

Figure 4. PCA fusion of IRS 1C (pan) and IRS P6 Mx

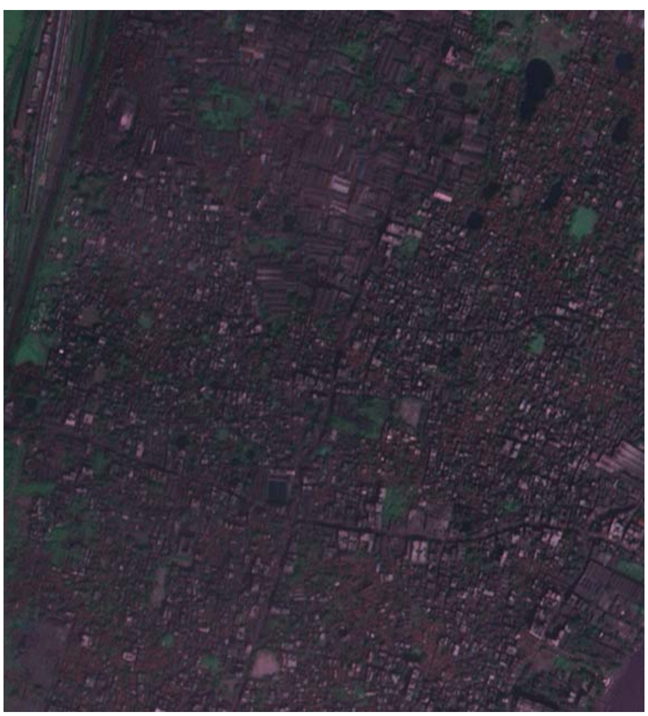

Figure.5. SVD fusion of IRS 1C (pan) and IRS P6 Mx

The inference from geometric registration is self explanatory as one can very clearly note that the MS image with a lot of anti-aliasing artifacts generates an excellent color image. The fusion of MS with PAN with SVD registers very well on a pixel by pixel basis and outscores all other methods of fusion. It is also worth noting that fusion with an SVD results in an excellent geometric registration and highlights the power of a rotation with an eigenvector. This can be clearly inferred from the illustrations of Panchromatic, Mulitspectral and fused images depicted as Fig 1, 2 and 3 respectively.

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