Region Weighted Satellite Super-resolution Technology

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***Abstract* — Super-resolution techniques that process multiple images to achieve resolution enhancement for satellite images are very important. This work utilizes Vandewalle method to realize super-resolution for satellite images. Assuming the motions between images are all on the same plane, we estimate and stick images into the high resolution grid. Because of the huge size of satellite images, only partial regions are used to estimate the rotation and shift parameters in the registration phase. Bicubic interpolation is then applied to reconstruct high resolution images. The results show that the proposed method only needs 31.25% computations for image registration while keeping the same reconstruction quality.**

I. Introduction

Resource satellites can obtain and provide rich information from the earth observation. Modern technologies of remote sensing influences civil and military applications deeply, including civil engineering, mining engineering, petroleum exploring, environmental monitoring, environmental protection, and military information searching.

The most expensive part of a satellite image quality is the spatial resolution. Unfortunately, it is also the most difficult part to improve. There exist too many factors, such as sensor noise, atmosphere interference, optical imaging, and minor illuminant, that cause degradation of image quality and the deterioration of algorithm performance. Under such various constraints, modifications of optical or sensor arrays are not always feasible and probably very costly. Therefore, more solutions focus on the image post-processing methods.

Super-resolution is integrating multiple images with small differences in the same observation scene. It contains important significances that solve high-cost resolution problem of satellite images. Single image super-resolution can be performed by upsampling or pixel interpolation, but the real resolution is not actually enhanced even though the image size is increased. A typical resolution enhancement method is adding high frequency information of a particular image model. After removing aliasing of images, high resolution image can be obtained. Aliasing of images can be removed from the information in other images of the same scene.

Tsai and Huang [1] were the first who proposed high resolution image reconstruction from a series of low resolution images. Simple motion is assumed that solves registration and restoration. Registration is estimating relative motion between observed images. Restoration is estimating samples in uniform high sampling rate grid. They did not consider deformation and noise. Therefore, image interpolation is indeed needed to deal with non-uniform samples. This frequency domain method uses relation of continuous and discrete Fourier transform of low resolution frames. Kim [2] extended this method to deal with noise and blurring image, and developed weighted recursion method based on the minimum square theorem. Keren [3] realized recursive iteration super-resolution method to minimize errors between low resolution images. Wirawan [4] brought up a blind multichannel high resolution reconstruction algorithm with multiple FIR filters. It includes blind MIMO deconvolution and mixed polyphase components blind separation. Stark [5] brought up Projection Onto Convex Sets (POCS) formulizing high resolution image estimation, and proved solutions of linear equation sets could solve high resolution reconstruction and restoration spatial variations. Macel [6] used the phase correlation method to emphasize high frequency parts in estimation. Lucchese [7] developed a rotation estimation method by Fourier transform magnitude and one pair orthogonal zero-crossing lines rotation angle. Vandewalle [8] realized a registration method of using phase correlation in a purely planar motion model to increase estimation accuracy.

Super-resolution includes three main processing steps: registration, reconstruction, and filtering. Three steps can be studied separately. Registration is the first step and its accuracy usually influences super-resolution performance and image quality seriously.

This paper will discuss a highly accurate registration algorithm that based on Vandewalle super-resolution method. In addition, we utilize particular satellite information that come with the images to accelerate the super-resolution process on the promise while the registration is kept accurate. Section II gives a review on the Vandewalle method and the description on the proposed method. Section III shows the simulation results based on different satellite images. Section IV concludes this paper.

II. Method

The Vandewalle method is utilized to perform low resolution images registration in a planar motion model. This model is suitable for images with slight camera motion condition or satellite images. Generally speaking, the planar model is simpler and contains less parameter. The performance of this method surpasses many other frequency algorithms and directive spatial algorithms in terms of SNR and subjective quality

Fig. 1 shows the super-resolution development model.

High resolution source image is assumed to exist. The reconstructed high resolution image can then be compared with this reference image. Assume the high resolution image is 2N*2N, 4 low resolution images (N*N) are generated. Then, the 4 low resolution images are used as input images of the super-resolution algorithm.

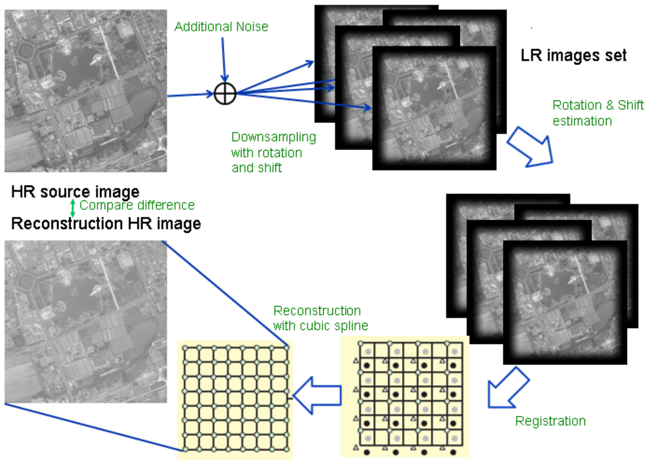

Fig. 1 Super-resolution development model

Vandewalle method

1. Multiply the images $f_{LR,m}$ by a Tukey window to make them circularly symmetric. The windowed images are called $f_{LR,w,m}$.
2. Compute the Fourier transforms $F_{LR,w,m}$ of all low-resolution images.
3. Rotation estimation: the rotation angle between every image $f_{LR,w,m}$ (m = 2, …,M) and the reference image $f_{LR,w,1}$ is estimated.
   (a) Compute the polar coordinates (r, θ) of the image samples.
   (b) For every angle α, compute the average value $h_m(\alpha)$ of the Fourier coefficients for which $\alpha-1<\theta<\alpha+1$. The angles are expressed in degrees and $h_m(\alpha)$ is evaluated every 0.1 degrees.
   (c) Find the maximum of the correlation between $h_1(\alpha)$ and $h_m(\alpha)$. This is the estimated rotation angle φ_m.
   (d) Rotate image $f_{LR,w,m}$ by $-\varphi_m$ to cancel the rotation.
4. Shift estimation: the horizontal and vertical shifts between every image $f_{LR,w,m}$ (m = 2, …,M) and the reference image $f_{LR,w,1}$ are estimated.
   (a) Compute the phase difference between image m and the reference image as $\angle(F_{LR,w,m}/F_{LR,w,1})$.
   (b) For all frequencies $-u_s + u_{\max} < u < u_s - u_{\max}$ write the linear equation describing a plane through the computed phase difference with unknown slopes Δx.
   (c) Find the shift parameters Δx_m as the least squares solution of the equations.
5. *Image reconstruction*: a high-resolution image f_{HR} is reconstructed from the registered images $f_{LR,m}$ (m = 1, ...,M).
   (a) For every image $f_{LR,m}$, compute the coordinates of its pixels in the coordinate frame of $f_{LR,1}$ using the estimated registration parameters.
   (b) From these known samples, interpolate the values on a regular high-resolution grid using for example cubic interpolation.

Proposed region weighted super-resolution method

Because of the huge size of typical satellite images, it is a computational burden to use the whole image to process in the registration phase. We propose a region-weighted super-resolution method especially for large-size satellite images. The general procedure is shown in Fig. 2. The satellite focused parameters that come with the images are utilized to reduce the input data size. For instance, only five regions in an image, shown as in Fig. 3 and Fig. 4, are used for registration. Each region is (N/4*N/4) in size, so the number of input pixels is drastically reduced as shown in Table I.

TABLE I Input data comparison

Method	Rotation	Shift x	Shift y	Total registration
Vandewalle	$4*N^2$	$4*N^2$	$4*N^2$	$12*N^2$
Proposed	$20*(N/4)^2$	$20*(N/4)^2$	$20*(N/4)^2$	$60*(N/4)^2$

A typical N of satellite image is 12000 (for SPOT5). In our simulations, a smaller image (N=512) is used because of the computation and hardware constraints.

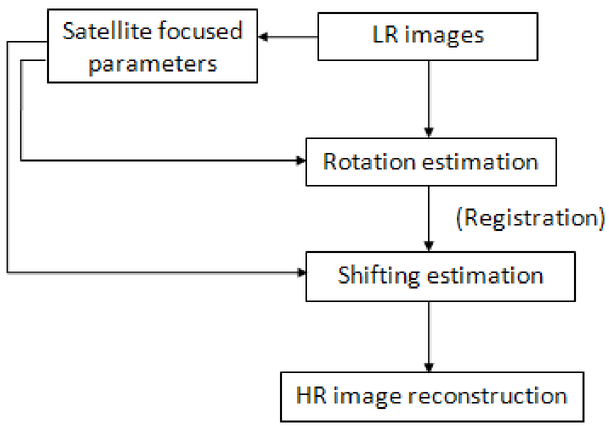

Fig. 2 Region-weighted super-resolution

Satellite focused parameter

1. Cloud cover parameter (W_c)

Because cloud covering interferes with estimation accuracy, we use cloud cover as a weighting parameter. The cloud cover values come from the satellite processing system. The weighting values are chosen as in Table II,

TABLE II Cloud cover weighting

Symbol	A	B	C	D	E
Cloud cover	0%	1~10%	11~25%	25~75%	75~100%
Weighting	4	2	0.5	0.25	0

2. Location parameter (W_L)

Satellite images are mainly used on land observation. The ocean part contains less information for this purpose. Besides, the characteristics of ocean region are often capricious. We can obtain the location from satellite images and focus the problem on land. The chosen weighting values are shown in Table III.

TABLE III Location weighting (from Fig 6)

Region	1	2	5	3	4
Location	Sea	Sea	Sea	Land	Land
Weighted	0.5	0.5	0.5	2	2

3. Spatial frequency parameter (W_F)

Regions with rich high frequency components usually contain more details. Each region is sent into high pass filters and the high frequency energy is computed. We rank all regions and give proper weighting values by experiments. An example is shown as in Table IV.

TABLE IV Spatial frequency weighting (from Fig 3)

Region	1	2	3	4	5
Weighting	0.25	0.5	4	2	1

As mentioned above, the three parameters are linearly combined to form the rotation and shift parameters in the Vandewalle method as

$$\varphi_m = \frac{\sum_{i=1}^{5} W_{ci}\varphi_{mi}}{\sum_{i=1}^{5} W_{ci}} + \frac{\sum_{i=1}^{5} W_{Li}\varphi_{mi}}{\sum_{i=1}^{5} W_{Li}} + \frac{\sum_{i=1}^{5} W_{Fi}\varphi_{mi}}{\sum_{i=1}^{5} W_{Fi}} \quad (1)$$

$$\Delta x_m = \frac{\sum_{i=1}^{5} W_{ci}\Delta x_{mi}}{\sum_{i=1}^{5} W_{ci}} + \frac{\sum_{i=1}^{5} W_{Li}\Delta x_{mi}}{\sum_{i=1}^{5} W_{Li}} + \frac{\sum_{i=1}^{5} W_{Fi}\Delta x_{mi}}{\sum_{i=1}^{5} W_{Fi}} \quad (2)$$

Then the final rotation and shifting values can be put into the reconstruction step to generate the high resolution image. Because the generated image and original high resolution image are of the same size (2N*2N), it is easy to compare the super-resolution imaging performance.

III. SIMULATION RESULTS

We use SPOT5 satellite images (1024*1024, resolution = 2.5m) to be the original high resolution image, and generate four simulated low resolution images (512*512, resolution= 5m) from it. The simulate images are used as the input the super-resolution system to reconstruct high resolution image (1024*1024, resolution = 2.5m). In the experiments, we compare the estimated motion parameters with the given motion parameters and obtain the estimation error. Besides estimation error, we also compare the super-resolution image with original image. Finally, we use two real low resolution images (512*512, resolution = 5m) to generate high resolution image, and compare its quality with the image generated from TS5 (Terminal SPOT 5).

We use two satellite images (Fig 3 and Fig 6) to evaluate the super-resolution performance. In the whole land image (Fig 3), we can learn how the spatial frequency parameters influence the super-resolution algorithm, and the key problem of this process. First, we divide the input image into five small regions of 128*128, as shown in Fig 3. Then, we only consider the five regions of each LR images in the following process. Five estimated values are obtained by estimating the mutual motion in each region. From spatial frequency parameters, we sort regions based on high frequency component in each region. Then we use the weighting values in table IV to linearly combine these values (shown in Fig 4). After weighting estimation, bicubic interpolation is applied to reconstruct HR image. PSNR between the reconstructed HR image and the original HR image shows the performance of the methods. Because only part of the input image is used for registration process, the reconstructed image quality is possibly degraded. However, from TABLE V, the result of proposed method is nearly identical to Vandewalle method and better than others. On the other hand, the total registration computation only needs 31.25% of Vandewalle method in this case. In addition, the saving in the registration computation will be even more for larger image size.

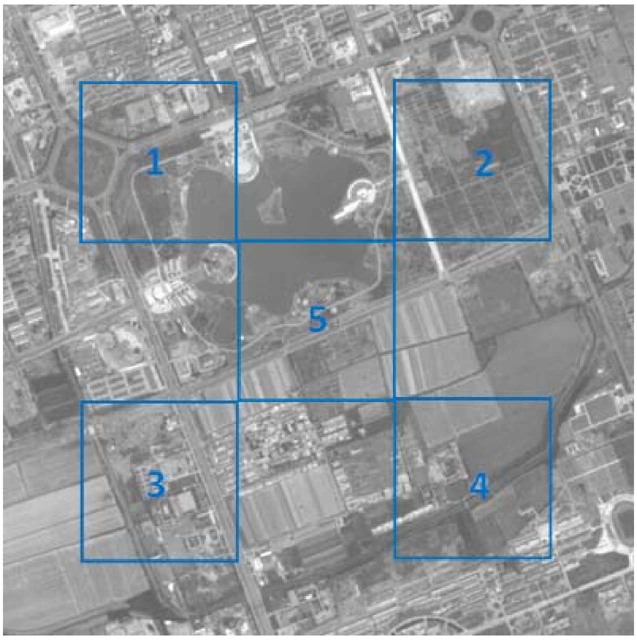

Fig. 3 Whole land image

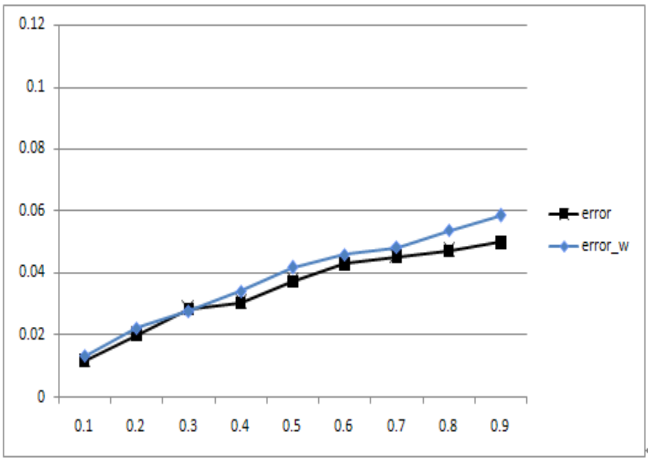

Fig 4. Weighted error comparison of Fig 3

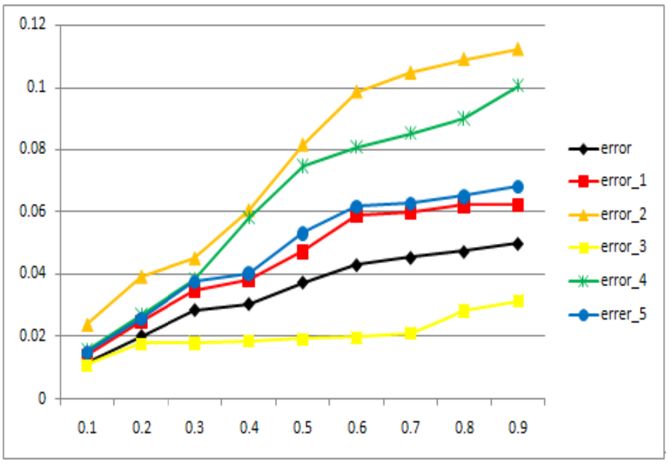

Fig 5. Region error comparison of Fig 3

TABLE V Reconstruction quality comparison of Fig 3

	Proposed	Vandewalle	Marcel	Lucchese	Keren
PSNR(db)	28.12	28.15	26.03	25.40	28.07

In the previous example, the whole land and cloud free image for proposed method only utilizes the spatial frequency weighting. Generally, satellite image is not always cloud free. Hence a more general image, shown as in Fig. 6 is used in this example. Besides the spatial frequency parameter, the image cloud values and latitude and longitude from image processing system are more useful for satellite images than nature images. From these parameters, we can focus on more meaningful regions for estimation. The estimation error can be found in Fig 7 and Fig 8. From TABLE VI, it shows that the performance of the proposed method is better than others. Because the proposed method is based on Vandewalle method, the result is very close to it. If the Vandewalle method encounters cloud or ocean interference, the reconstruction quality will be reduced. However, the proposed method may outperform the Vandewalle method because the proposed method can ignore the interference regions and maintain the reconstruction quality. Furthermore, satellite images usually are used on land observation and analysis, the location weighting makes the estimation more accurate and meaningful.

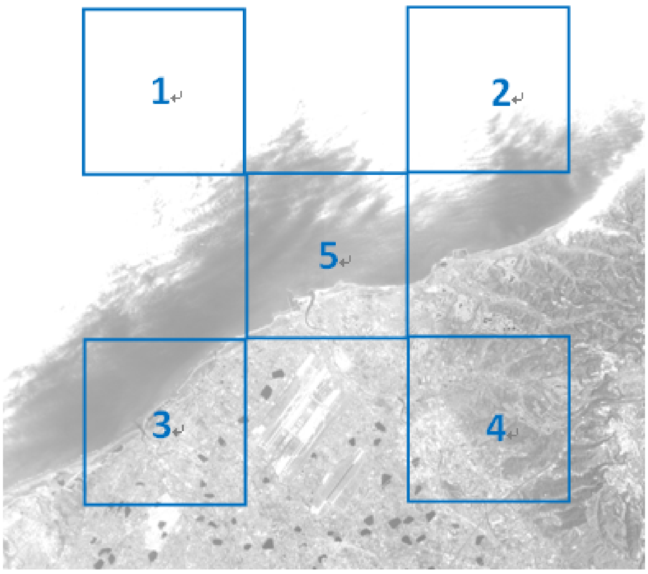

Fig 6. Cloud and ocean image

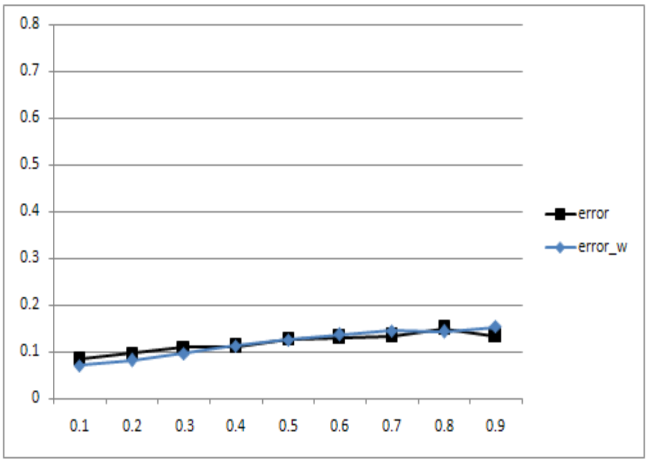

Fig 7. Weighted error comparison of Fig 6

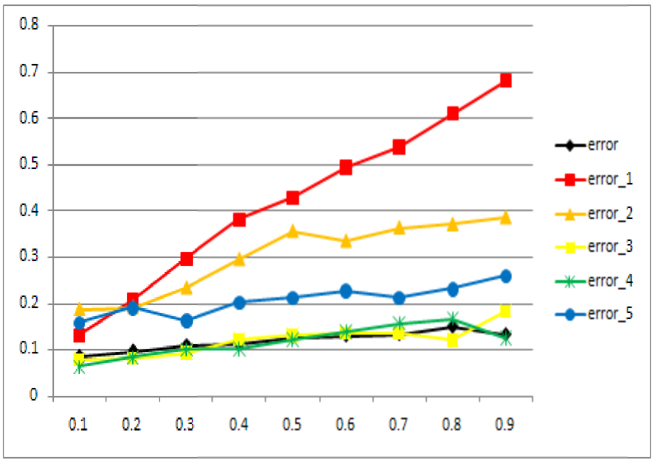

Fig 8. Region error comparison of Fig 6

TABLE VI Reconstruction quality comparison of Fig 6

	Proposed	Vandewalle	Marcel	Lucchese	Keren
PSNR(db)	27.33	27.29	25.15	24.06	26.87

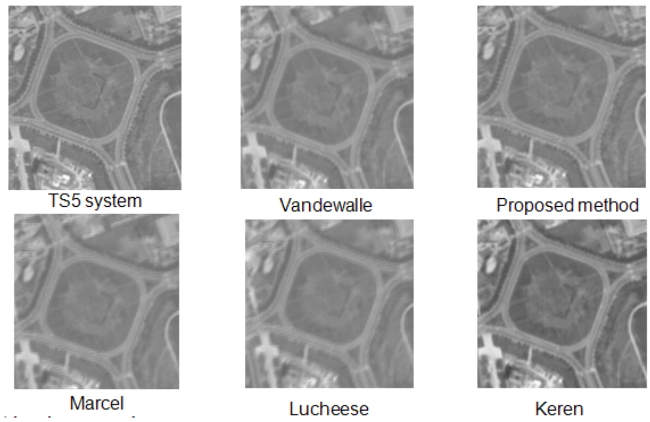

Fig 9. Visual Comparison

The visual results of these methods are shown in Fig 9. TS5 system is an actual satellite super-resolution processing system that includes extra adjusting. Its performance is the best. Compared with other methods, the proposed method can obtain better visual quality.

IV. CONCLUSION

This paper has proposed accurate registration of super-resolution for satellite images based on Vandwalle's frequency domain super-resolution method. We utilize prior information of satellite images for registration. First, assumed the motions of images are all on the same plane, we transform all low resolution images to frequency domain and estimate shifts and rotations. Then, matching the low resolution images to high resolution grids, we interpolate high resolution pixels by bicubic interpolation. Because the satellite images size are big, we only use part of images and satellite parameters to filter motion estimation and interpolation. The results show that it can reduce the computation costs and keep the reconstruction quality.

In future, proper filters and image enhancement can be added to strengthen image quality. This region-based method can also be applied to the reconstruction step to emphasize the region of interest.

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