Survey on Gap Filling in Satellite Images and Inpainting Algorithm

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Abstract—**Gap filling in satellite images aims at filling gaps occur due to instrumentation error, losses of image data during transmission; such area involve reconstruction in satellite image referred as gapped area in satellite images. Gap filling in satellite images can be classified as single source, multi-source and hybrid methods. Multi-source methods involve more than one image for reconstruction. Single source methods use same image information to fill gaps. Hybrid method combines both of the above approach. There is ongoing research in the field of inpainting also aimed at reconstruction of images in plausible way. Inpainting methods can be classified as based on PDE, based on exampler based inpainting and based on classification of blocks. Here survey and comparative study of gap filling methods and image inpainting methods are done.**

Index Terms—**Inpainting, reconstruction, satellite image.**

I. INTRODUCTION

Imagery gaps can have several reasons, e.g., instrumentation errors, gap occurred while transferring data. The need of Gap filling occurs when there is requirement to remove some objects from images. The Landsat7 scan-line corrector (SLC), a mechanism designed to correct the under sampling of the primary scan mirror, failed on May 31, 2003. With the SLC now permanently turned off, the ETM+ is losing approximately 22% of the data due to increased scan gap. Many algorithms have been proposed for gap filling in Landsat7 SLC-off images. Proposed algorithm for Landsat7 SLC-off image gap filling can be characterized as multi source, single source and hybrid. In the first category gap areas are constructed using other useful sources. The second category mostly is based on within image pixel similarities/dissimilarity rules where gapped areas are constructed using non-gapped areas in the image itself. Hybrid techniques make use of both single source and multisource gap filling technique.

Many algorithms have been proposed for image reconstruction known as inpainting algorithms in the field of digital image processing, e.g. Bertalmio's inpainting algorithm, Oliveira's inpainting algorithm, Criminisi's algorithm etc. Here idea is to apply inpainting algorithm for gap filling in satellite images. After examining various image inpainting algorithms we have categorized it into three categories; based upon PDE, based upon exampler based inpainting algorithm, based on classification of image block.

II. GAP FILLING IN SATELLITE IMAGES

A. Multi Source

In Multi-Source Gap Filling methods gap areas are filled with other image of the same scene. In Multi-Source Image gap filling gapped image can be filled with other image of same satellite or in literature some methods have been proposed for filling gapped image using other image of other satellite [1],[2],[3]. Many multi-source algorithms are proposed for reconstruction in landsat7 images. Images of Landsat7 after failure of SLC taken are known as SLC-off images which contain gapped areas.

In **LLHM Method**, first gaps are located. Then linear transformation between one image and another image is found. The pixel values of the SLC-Off image to be filled (the 'primary scene') can be generated by applying a corrective gain and bias to the pixel values of an SLC-On image (the 'fill scene'). Rather than performing a computationally expensive linear fit, the corrective gain and bias can be found using the mean and standard deviation of the data. This transformation can be applied to the entire fill scene, giving a global linear histogram match. For greater precision and a product which is visibly better looking, the corrective gains and biases can be calculated in a moving window around each pixel in the scene. This is the basis of the localized linear histogram match (LLHM) known as phase 1 method for gap filling in SLC off scene in Landsat 7 images [4].

In **AWLHM:** Phase 2 is an enhancement of the Phase 1 algorithm for gap filling in Landsat-7 SLC off images that allows users to choose multiple scenes and to combine SLC-off scenes. [2]

Other satellite images can be used to reconstruct image which was proposed in [3]. In this paper author uses CBERS-02B data for gap filling in Landsat7 SLC-off images. They have used same algorithms proposed in phase 1, phase 2 gap filling algorithm by USGS, but variation is instead of using same satellite data as reference image they have used another satellite image as reference scene and one additional method known as replacement method is also suggested. In replacement method gap value in SLC-off images of Lansat7 is replaced by corresponding value of CBERS-02B values. Reference [3] shows that AWLHM give more accurate result if computational speed is ignored. If computational speed is more important than statistical error LLHM should be used. Simple replacement method can't give good results.

Reference [5] shows various methods such as Global histogram matching based on mean and based on mean and variance for gap filling in Landsat7 SLC-off images are

compared. Local histogram matching algorithm takes into account the brightness of different problems in different locations. The image is divided into several sub-windows, child window in each histogram matching repair. The local histogram matching algorithm based on improved adaptive sub-window size set rules in this sub-window histogram matching, set the child current designations.
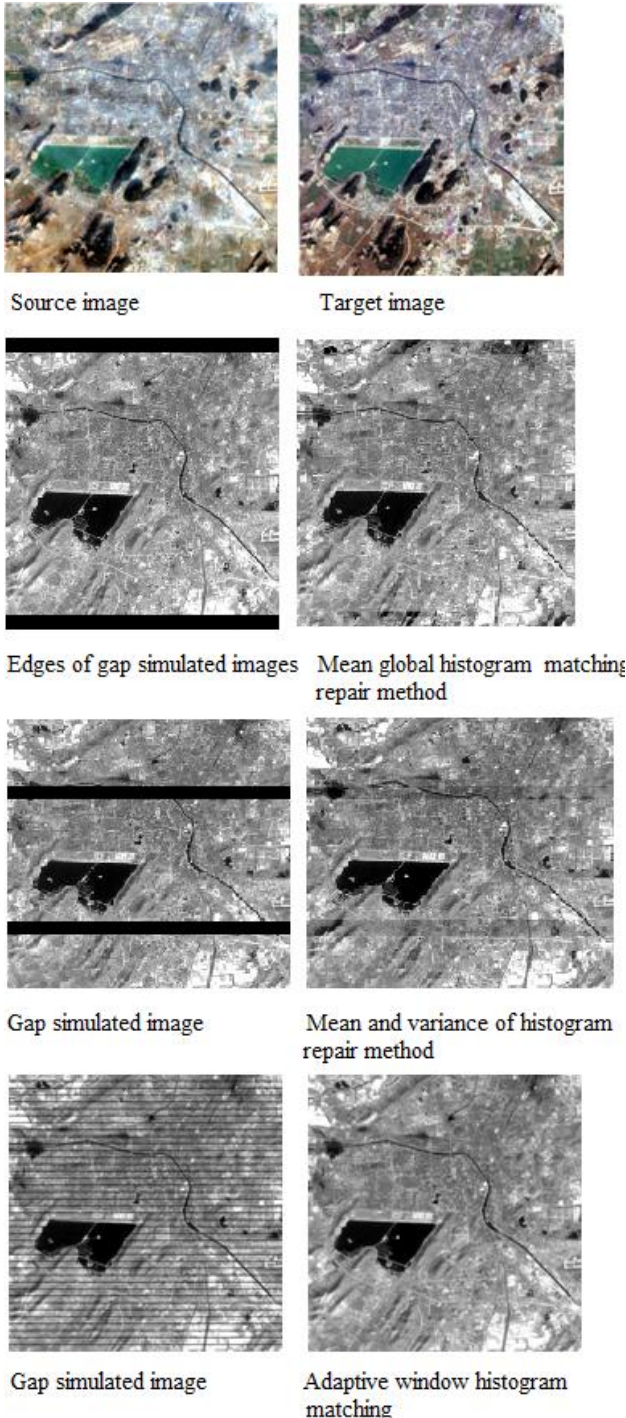

Fig. 1. Result of various multi-source gap filling in [5].

In **PCT-gap fill** methodology the basic idea is to fill gap areas in multispectral images by the help of valuable pixels from the fill images. For the purpose of illustration let FI and VA be the Fill Image and the valuable Area for fill gaps; GA and NGA be the Gapped Area and Non-Gapped Area from the Gap Image GI. The procedure of which will follow the following steps

1) Pixels in VA numerically adaptation to pixels in NGA.
2) Using NGAs for calculation the needed statistics for Inverted PCT (IPCT), i.e. the empirical mean, correlation matrix and Eigen values.
3) VAs conversion to Transformed VAs (TVAs) using the principal component transformation.
4) Inversely transformation of the TVAs using the obtained statistics from step (2) to make the New VAs (NVAs).
5) Replacing the NVAs to the GA to form a Reconstructed Image (RI). [1]

B. Single Source

Single source category mostly is based on within image pixel similarities/dissimilarity rules where gapped areas are constructed using non-gapped areas in the image itself.

In **averaging** method line drop is overcome by replacing zero value by means of all the pixels in previous and following lines. For modern detector stripping is along with column instead of row. E.g. If line 1 is to be corrected can be corrected by averaging of line 0 and line 2nd value. [6]

Various known interpolation methods such as nearest neighbor, bilinear etc are used for gap filling in satellite images. In bilinear interpolation output pixel value is weighted average of 2 by 2 neighborhoods. In cubic interpolation output pixel value is weighted average of 4 by 4 neighborhoods.

C. Hybrid

Hybrid method is combination of single source and multi-source method for filling gaps in satellite images.

III. INPAINTING ALGORITHM

Inpainting is the process of filling missing data in image in plausible way such that it cannot be detectable. Bertalmio et al is the pioneered of digital image inpainting algorithm. Various other inpainting algorithms have also been proposed. Inpainting algorithm are classified into three category. Inpainting algorithm based on PDE, based on exampler based inpainting, based on classification of image block.

A. Based on PDE or Convolution

Bertalmio's inpainting algorithm is based on PDE. In this algorithm Ω stand for the region to be inpainted, and $\partial\Omega$ for its boundary. Intuitively, the technique will prolong the isophote lines arriving at $\partial\Omega$, while maintaining the angle of "arrival." Drawing from $\partial\Omega$ is proceeding inward in this way, while curving the prolongation lines progressively to prevent them from crossing each other. Conservators at the Minneapolis Institute of Arts were consulted for this work and made it clear that inpainting is a very subjective procedure, different for each work of art and for each professional. There is no such thing as "the" way to solve the problem, but the underlying methodology is as follows: (1.) The global picture determines how to fill in the gap, the purpose of inpainting being to restore the unity of the work; (2.) The structure of the area surrounding is continued into the gap, contour lines are drawn via the prolongation of those arriving at $\partial\Omega$ (3.) The different regions inside, as defined by the contour lines, are filled with color, matching those of $\partial\Omega$

and (4.) The small details are painted (e.g. little white spots on an otherwise uniformly blue sky): in other words, "texture" is added. A number of lessons can immediately be learned from these basic inpainting rules used by professionals. Bertalmio's algorithm simultaneously and iteratively, performs the steps (2.) and (3.) above. They progressively "shrink" the gap by prolonging inward, in a smooth way, the lines arriving at the gap boundary $\partial\Omega$ [7].

Fig. 2. Results of Inpainting. Top left is original image. Top right is inpaintied Oliveria's method. Bottom left is inpainted using Bertalmio's method [8].

Oliveria's algorithm gives improvement in result in terms of computational time over Bertalmio's inpainting algorithm. The simplest version of the algorithm consists of initializing Ω by clearing its color information and repeatedly convolving the region to be inpainted with diffusion kernel. $\partial\Omega$ is a one-pixel thick boundary and the number of iterations is independently controlled for each inpainting domain by checking if none of the pixels belonging to the domain had their values changed by more than a certain threshold during the previous iteration. Alternatively, the user can specify the number of iterations. As the diffusion process is iterated, the inpainting progresses from $\partial\Omega$ into Ω. Convolving an image with a Gaussian kernel (*i.e.*, computing weighted averages of pixels' neighborhoods) is equivalent to isotropic diffusion (linear heat equation). Algorithm uses a weighted average kernel that only considers contributions from the neighbor pixels (*i.e.*, it has a zero weight at the center of the kernel) .It takes 1.29 seconds to inpaint image of Fig 2(Three girls) on PIII, 450 MHz. This method fails to inpaint large area [8].

B. Based on Exampler Based Search

Some inpainting algorithms are based on exampler based inpainting. Criminisi's algorithm is exampler based inpainting algorithm. Previous algorithms were either based on Texture synthesis or based on inpainting which can be used to fill in small area of structure. This algorithm combines advantages to both the algorithms. Algorithm iterates the following three steps until all pixels have been filled

1) Computing patch priorities
2) Propagating texture and structure information
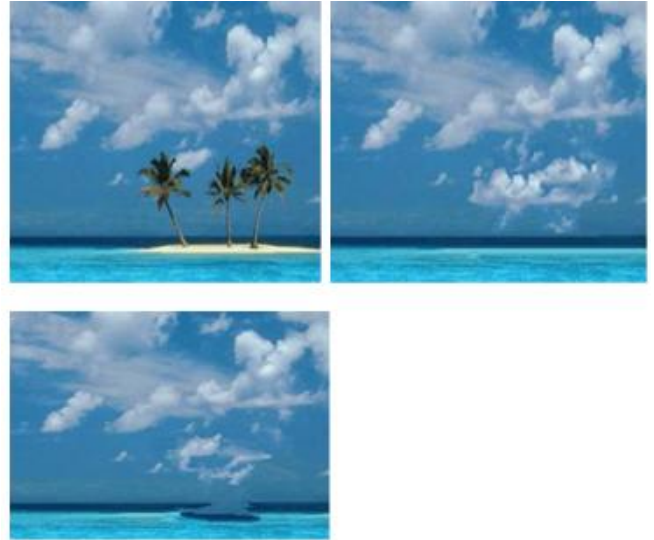3) Updating confidence values [9].

Fig. 3. Results of Inpainting. Top left is original image. Top right is inpaintied using fast and enhanced exampler based method. Bottom left is method. [10].

Another algorithm based on Exampler based inpainting is Fast and enhanced exampler based inpainting algorithm by Pulkit Goyal. [10] The basic idea behind this approach is to find examples (i.e. patches) from the image and replace the lost data with it. They modified existing Exampler based inpainting by Criminisi. Cheng et al. discovered that the confidence term that was defined in Criminisi's algorithm decreases exponentially and thus the multiplicative definition of the priority term needs to be replaced. They also proposed that the confidence term in the additive form of priority did not match the order of the data term. Thus they modified the confidence term with the regularized confidence term. This algorithm provides better results than Criminisi for their shown example in their research paper. [10]

C. Based on Classification of Blocks

Third category of inpainting algorithm is based on classification of image blocks as described in research paper "Structure and Texture Filling–In of Missing Image Blocks in Wireless Transmission and Compression Applications". The reconstruction of lost blocks follows three computationally efficient steps

1) Classify lost blocks into texture and structure;
2) Synthesize blocks which were classified as texture (use texture synthesis);
3) Fill in blocks which were classified as structure (use image inpainting).

For classification of blocks coarseness measure is used. Coarseness measure is given by the number of local extrema in the neighborhood of the lost block. The number of local extrema is simply the pixels which are local row extrema as well as local column extrema. Local extrema in s x s window

size is given by $S^2 \cdot$ (UB+LB)/2. Where UB and LB are respectively the upper and lower bounds for texture coarseness and are selected by the user. S is window size. This coarseness values vary from 0 (no extrema) to 1 (all pixels in the selected window are extrema). If UB=0.16 , LB=0.04 ,s=8 gives local extrema equals to 6.4,If a 8x 8 block has fewer than extrema, it is classified to have structure, else is considered to contain texture. The above technique is applied for each available block of 8x8 pixels in the immediate neighborhood of the lost block. Even if a single block from this neighborhood contains structure, first consider a decision in favor of structure. By considering the 8-neighborhood of 8x8 block and calculating differences between the average values of the blocks on opposite sides of the center block (considering only available blocks), If the four resulting differences are above a threshold, then block is designated as structure.[11]

Fig. 4. (a) is original image.(b) is received image(c)is reconstructed image using structure and texture filling method in[11]
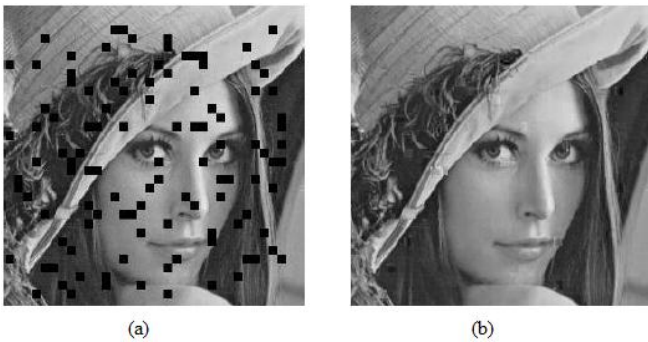

Fig. 5. (a) is image with simulated loss.(b)is reconstructed image using wavelet domain reconstruction in[12]

Another algorithm based on wavelet domain reconstruction of lost blocks. Once the missing block has been detected, the reconstruction of lost blocks includes the following steps:
1) Classify lost blocks into "edgy" and "non-edgy,"
2) Reconstruct edgy blocks from selected edgy blocks in the 8-neighborhood
3) Non-edgy blocks from selected non-edgy blocks in the 8-neighborhood.[12]

IV. COMPARATIVE STUDY

Purpose of both type of algorithms gap filling in satellite image and inpainting algorithm is same. So, here comparative study of gap filling algorithm and inpainting algorithm are done.

TABLE I: COMPARATIVE STUDY OF GAP FILLING METHODS AND INPAINTING ALGORITHM

Approach	Single or Multi-source	Limitations
Averaging of nearby pixels	Single	Cannot correct four or more simultaneous line drops
LLHM Method	Multi-source	Based on the obtained results if images have specific criteria like minimum temporal shifts, seasonal differences, and land cover changes the filled gaps are reliable and effective. But the problem will appear when there are sharp differences in target radiances due to land cover changes, atmospheric effects, or sun glint changes.
AWLHM Method	Multi-source	The adaptive local linear histogram adjustment algorithm can yield poor results if scenes being combined exhibit radical differences in target radiance due, for example, to the presence of clouds, snow, or sun glint. Although attempts were made to include cloud detection and masking capability in the Phase 2 gap-fill process, the problems associated with identifying thin clouds and cloud edges as well as cloud shadows proved to be too difficult to overcome in the available time.
Projection Transformation Gap Filling	Multi-source	Superior over LLHM (Linear Histogram Matching technique). This method cannot be used when per pixel accuracy is required.
Other Satellite Image Used for Gap Filling by using various methods such as Simple filling, LLHM,GLHM, AWLHM	Multi-source	AWLHM give more accurate result if computational speed is ignored. If computational speed is more important than statistical error LLHM should be used. Simple replacement method can't give good results. As this is multi-source method various parameter such as sun glint change, atmospheric change etc can effect.
Bertalmio's PDE based Inpainting	Single	Problem associated with reproduction of large texture region and it requires time in minutes which is unacceptable for small region.
Oliveria's Inpainting Algorithm	Single	Restoration of 1865 Photograph of Abraham Lincon takes only 0.61 second to restore, but large region to be inpainted is not supported.
Fast and Enhanced Exampler Based Inpainting Algorithm	Single	Results are more promising than Criminisi's approach. But it takes 52378 seconds to reconstruct image of 60492 pixels with 14.62 % area to be removed.

Wavelet Domain Reconstruction	Single	It works at lower computational speed, algorithm has no specific solution for perfect 45 degree diagonal edges.
Structure and texture filling	Single	Authors have tried structure and texture information to improve to enhance performance. By providing more image information performance can be improved.

V. Software Tools and Technology

ArcGIS and MATLAB provide various interpolation techniques. ExInpaint provides implementation of exampler based inpainting algorithm. Adobe photoshop-"Dust and scratches" filter works best on small area of Landsat scene. Photowipe is image processing tool for image inpainting. Java and other programming language such as c++ can be used for developing various gap filling and inpainting algorithms. However, Java provides more robustness, platform independence. Hence use of it to be more useful.

VI. Conclusion

Various gap filling method for satellite image and inpainting algorithm exists, Multi-source gap filling suffers from sharp radical changes in two images such as sun glint change, snow, cloud etc. In single-source inpainting algorithm if it can reconstruct large area it takes more computational time, if it takes less computational time it can reconstruct small area in image. There is need of powerful method which can reconstruct in large as well as small area in less computational time. Future work should be to apply inpainting algorithms for gap filling in satellite images.

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