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Pre-processing Algorithm for Rectification of Geometric Distortions in Satellite Images

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ABSTRACT

A number of algorithms have been reported to process and remove geometric distortions in satellite images. Ortho-correction, geometric error correction, radiometric error removal, etc are a few important examples. These algorithm require supplementary meta-information of the satellite images such as ground control points and correspondence, sensor orientation details, elevation profile of the terrain, etc to establish corresponding transformations. In this paper, a pre-processing algorithm has been proposed which removes systematic distortions of a satellite image and thereby removes the blank portion of the image. It is an input-to-output mapping of image pixels, where the transformation computes the coordinate of each output pixel corresponding to the input pixel of an image. The transformation is established by the exact amount of scaling, rotation and translation needed for each pixel in the input image so that the distortion induced during the recording stage is corrected.

Keywords: Input-to-output image transformation, polynomial affine transformation, ortho-rectification, pre-processing algorithm, image rectification, satellite images, image registration

1. INTRODUCTION

Image registration is the process of spatially aligning two or more images of the same scene obtained at different times or from different sensors[1-3]. This basic processing is important prerequisite for many image analysis applications such as change detection[4,5] object identification, image classification etc. Image registration is a critical component of remote sensing, medical image analysis and industrial imaging etc. Image registration is also known as the process of alignment of images, geometric registration, and rectification of geometric distortion or polynomial affine transformation in different literatures. The image acquired at an earlier date is known as the base image and the recently acquired image is considered as the image with error to be rectified. The process involves determining point-by-point correspondence between two images of a scene. Image registration involves following five sub-processes to achieve the end objective:

i. Pre-processing of images to remove radiometric error or error due to improper focusing of the sensor[4].
ii. Selection of features in the images, to select scale invariant features from the image which will be used to compare and establish correspondence between the base image and the recently acquired image[7].
iii. Establishing correspondence between the features of recently acquired image and the base image, Lowe[8].
iv. The correspondence is used to solve a polynomial whose coefficients are the parameters of the transformation known as affine transformation[8].
v. Apply the affine transformation established in the previous step to resample the recently acquired image. The coordinates of the correspondence points are used to establish a polynomial affine transformation to resample the distorted image so as to align it with the base image.

The above process is slightly different in the case of satellite images, because the satellite images have large portions which have null values and are masked as blank. Hence, applying any of these steps to a satellite image will yield wrong results. Computing the scale invariant features (SIF) from the images will lead to many points which have the same optical property belonging to the dark portion of the image. Hence algorithms like Low's scale invariant feature transform (SIFT), Lowe[7], will yield many spurious results, leading to failure of the entire process. Also, the actual content of the satellite image is less than the entire content which contains the blank portion of the instantaneous field of view (IFOV) of the satellite sensor. Hence, it needs special pre-processing before one can apply the above five steps to the satellite images for registration. In this paper, a new pre-processing algorithm has been proposed which prepares the satellite images so that the above five steps of registration can be carried out smoothly.

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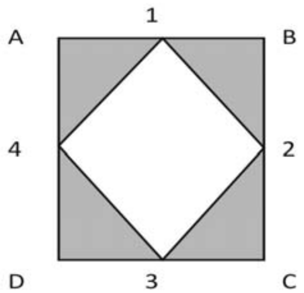
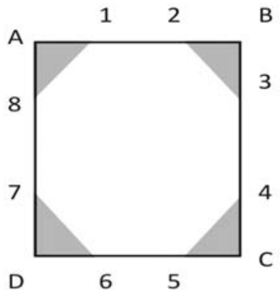
An algorithm has been discussed which computes the quantum of rotation, translation, and scaling required to rectify an input satellite image and applies the transformation back to the image to obtain the rectified image.

2. PROBLEM DEFINITION

Satellite images are 2-D arrays of digital numbers (DN), which are signatures of the earth surface corresponding to the instantaneous field of view (IFOV) of the sensor capturing the image. These are captured and stored as arrays of digital numbers in the onboard memory of the sensor and are down linked to the storage in the earth station. The 2-D image array is not a perfect rectangle because of factors such as earth rotation, path of the satellite pass, curvature of the earth, and the instability of the platform holding the sensor, etc. The IFOV of the satellite is not a square or rectangle even if the sensor grid is a square or a rectangle; it manifests itself in the form of a polygon as depicted in the Figs 1 (a) and 1(b). This is a systematic geometric distortion in the image array.



(a)



(b)

Figure 1. Distortions of satellite image of a square object in 2-D: (a) with Inclined (row, path), (b) with the IFOV making a polygonal structure with the dark portions filled with zero as entries.

Generally the satellite images are indexed in (row-number, path-number) and date and time of the IFOV. Following are some of the factors for the outline or frame geometry of the satellite image as depicted in Fig. 1:

i. The sensor grid capturing the IFOV is rectangular or square 2-D array.
ii. The IFOV is a solid angle having the cross-section with the earth surface as curved surface guided by the curvature of the earth surface.
iii. The intersection of the IFOV captured in the sensor grid is dependent on the geometry of the satellite path and the viewing angle of the sensor.
iv. Rotation of earth imparts a geometric error on the IFOV.

There is a need to remove these distortions in the satellite image to create a rectified image. This process is known as image rectification and falls under a well known technique known as image registration[9]. Many algorithms have been devised to register multi-temporal images which have been surveyed by Zitova[1], Maintz[2], Brown[3]. Image registration is a part of pre-processing in almost all geographical information systems (GIS) or digital image processing systems. The distortion is generally a mix of rotation, translation, and scaling simultaneously imparted in the image. Rectification algorithms remove these affine errors by establishing a homographic transformation through polynomial affine transformation (PAT). Establishing a PAT requires manual assistance for identification of ground control points (GCPs) and establishing the correspondence between the GCPs of the base image with those of the satellite image having affine error. Otherwise if the meta-information regarding the orientation of the sensor is known *a priori* as the health data of the satellite, then the PAT can be established and the reverse transformation can be applied to the image to obtain a corrected satellite image.

3. IMAGE RECTIFICATION

3.1 What is Ortho-rectification?

An image obtained by an off-nadir angle shows the longitude-latitude lines distorted. The lines no longer intersect at 90°. As a result, an image obtained by an off-nadir angle camera will not align with a map of the area by a rigid transformation. To preserve the geometry of a captured image even when the camera is not viewing the scene at the nadir angle, the images are transformed by a process known as ortho-rectification. Ortho-rectification, converts an image obtained at an arbitrary roll-pitch-yaw of the camera to one as if obtained when roll, pitch, and yaw were all zero. Ortho-rectification stabilises the camera as if it is always looking down and heading toward the north.

Ortho-rectified images are easier to register and analyse because these are not geometrically distorted. Correction for an image geometry by ortho-rectification, however, results in some intensity distortions in the image caused by the resampling process. Typically, intensity distortions are very small compared to the geometry corrections gained; therefore, ortho-rectification is generally believed to improve overall image quality. When the scene is not flat, ortho-rectification requires a digital elevation model (DEM) of the scene. These types of image errors in satellite images are known as ortho-errors and are primarily equivalent to composite error of three fundamental transformations, i.e. scaling, shear, and translation. These errors can be expressed in the form of corresponding transformation matrices. If the quantities of shear, rotation, and translation are known, the reverse transformation can be applied to the ortho-image to correct and prepare an ortho-rectified image. Since this is manifested through the sensor and the exact information is not known, the composite transformation is obtained by establishing the correspondence of control points of the image with a key image or its output profile. This is done by computing an affine transformation.

3.2 Polynomial Affine Transformation

The equation for a general affine transformation in R^2 is defined by $M: R^2 \to R^2$ and given by the following simple equation:

$$(k, l) = M(i, j) \tag{1}$$

where, (i, j) is the coordinate of input image with error and (k, l) is the coordinate of reference image, the digital vector map in this case, M is the affine transformation, which transforms set of $(i, j) \in R^2$ to set of $(k, l) \in R^2$. In other words, for each pixel (i, j) in the output image, compute its corresponding location (k, l) in input image, obtain the pixel from input image and put it in output image. Since a reverse computation of pixel location is used, this process is also known as reverse transformation or inverse transformation or output-to-input transformation.

The above transformation can be expressed through a pair of polynomials as

$$k = Q(i, j) = q_0 + q_1 i + q_2 j + q_3 ij \tag{2}$$

$$l = R(i, j) = r_0 + r_1 i + r_2 j + r_3 ij \tag{3}$$

These polynomial equations can be represented in matrix form also. Since the affine transformation is represented through a set of polynomials, it is named as polynomial affine transformation (PAT). The unknown coefficients q_i and r_i are obtained after solving the following system matrix representing polynomial[1].

$$\begin{bmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{bmatrix} = \begin{bmatrix} 1 & i_1 & j_1 & i_1 j_1 \\ 1 & i_2 & j_2 & i_2 j_2 \\ 1 & i_3 & j_3 & i_3 j_3 \\ 1 & i_4 & j_4 & i_4 j_4 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \tag{4}$$

i.e., $K = M\,Q$, $Q = M^{-1} K$

The dimension and condition of the system matrix M depends upon the number of GCP-CP pairs selected and their distribution on the image. At least, three pairs of non-collinear GCP need to be selected to establish an affine frame in R^2. If three pairs of GCP are selected, then one gets a 3x3 square matrix representing the transformation, which can solve the translation, rotation, and scaling distortions in the input image. If the GCPs are collinear and densely populated, then the matrix is ill-conditioned and sometimes it leads to inconsistency and rank deficiency. Hence, choice of more number of GCP-CP pairs leads to removal of highly irregular geometric distortions and with greater accuracy. Sometimes least square method (LSM) is used to avoid inconsistency and solve the above matrix equation for robust result. By definition, LSM is the one that minimises

$\| K - MQ \|^2$, which when solved leads to

$$Q_{LSM} = [M^T M]^{-1} M^T K \tag{5}$$

Similarly, matrix equation for second polynomial[2] can be derived and solved for R resulting in

$$R_{LSM} = [M^T M]^{-1} M^T L \tag{6}$$

4. PROPOSED SOLUTION

All the above factors result in an image matrix which can have geometry as described in either Figs 1(a) or 1(b). The image geometry is a polygon which can be described generically by the vertex sequence 1-2-3-4 or 1-2-3-4-5-6-7-8. The 2-D image array has digital numbers corresponding to the earth surface in the polygons and the corner regions have been filled with zeros giving the effect of shadow zone pertaining to the sensor. Hence, the satellite image has meaningful information in the polygonal zones rather than in the entire matrix which is of the order (width x height) times the radiometric resolution of the pixels.

Any meaningful analysis on the image matrix is of the order of $O(w \times h)$ and the memory footprint of the image in the computer is $O(w \times h) \times$ (radiometric resolution of the image). The radiometric resolution decides the number of bytes each pixel consumes in the memory. But the actual meaningful information content in the image is in the polygonal zone. So, to reduce the size of the image to the exposed region of the IFOV, one needs to extract the image region which has meaningful elaborate digital number rather than zeros, and store in the form of a rectangular portrait. This calls for an output-to-input mapping where the input is the original satellite image and the output is a portrait form of the image containing the digital numbers. This process is depicted in the Figs 2(a) and 2(b), respectively.

The problem is essentially a transformation which maps the pixels of the polygonal zone to the rectangular portrait. Generally this is carried out through a process known as (a) input-to-output mapping or (b) output-to-input mapping, which is a polynomial affine transformation established through correlation of ground control points(GCPs) of the image to the corners of the portrait.

In output-to-input transformation for each coordinate (i, j) of the output image, its corresponding location of the pixel from the input is selected and the value is substituted in the output image. But the output-to-input transformation has following anomalies:

- Some of the pixels in the input image may not get mapped to any coordinate location of the output image, resulting in loss of information.
- Also many pixels of the input image may get mapped to a single location of the output image, resulting in overlapped values called 'holes'.
- The reverse processes happen in input-to-output transformation where an input image coordinate gets mapped to a coordinate outside of the output image, resulting in loss of information.

Establishing this transformation process requires careful identification of GCPs in the input image and making a correspondence with the output canvas of the image. This process has been automated recently through the scale invariant feature transform (SIFT) algorithm developed by Lowe[7]. Also the accuracy of the outcome depends upon the RMS error resulting due to mismatch of the CGP to output coordinate correspondence.

5. ALGORITHM FOR REMOVAL OF GEOMETRIC DISTORTION

An algorithm has been developed which automatically generates the portrait canvas of a satellite image which

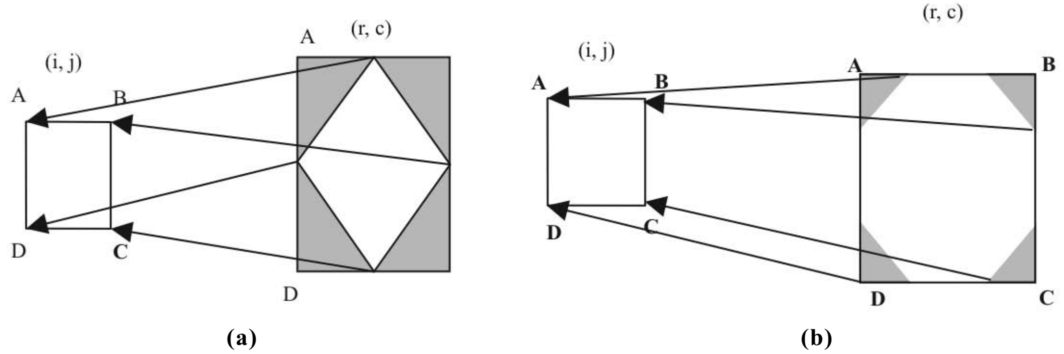


Figure 2. Mapping of the polygonal zone to image portrait (a), (b).

is in the row path form, as given in Figs 2(a) and 2(b). This algorithm does not establish the polynomial affine transformation by establishing the correspondence; rather it uses a clustering technique to identify the rotation and scaling parameters so that the row, path image can be made into a portrait form. The steps of the algorithm are supplemented with the MATLAB implementation of the algorithm.

Input: Skewed satellite image

Output: Ortho-rectified satellite image in the portrait form.

Pre-processing the image to transform from row path-based scene of the satellite to a portrait form so as to remove the shadow zone of the sensor in scene and rectify the distortion. It includes the following steps:

Step 1: Read the satellite-image to in-memory data structure 2-D array (im , image is input.jpg).
im=imread('\input.jpg');

Step 2: If image is RGB or coloured then convert to gray.
im=rgb2gray(im);
Optionally, sub-sample the image if it is very large to accommodate in the in-memory data structure of the program. (maximum image size can be 16300×16300 for MATLAB 7.1(32-bit) on Windows XP sp2 , 64-bit processor), where '*n*' is the factor by which image has to be sub-sampled.
im=imresize(im,*n*)

Step 3: Create a binary image for generating clusters using morphological operation. The binary image is clustered by morphologically removing all connected components which are fewer than '*p*' pixels from the binary image. This can be performed using the MATLAB function
bw = bwareaopen(im,*p*)
Now the image is converted into two distinct regions one having non-zero digital numbers values and the other portion which originally contained zero values.

Step 4: Now find the extreme points of the polygon described by above digital numbers in binary image. These are 4 or 8 in numbers depending upon the geometry as described by Figs 1(a) and 1(b), respectively. Extract the coordinates of extreme points of the polygon.
Find the coordinates of the left-top and left-bottom points for orientation calculation.

Step 5: Calculate the absolute orientation of the image using points left-bottom, left-top - *x* axis and *y* axis. We determine the orientation on line joining left-bottom, left-top, wrt the horizontal line of the image, through following MATLAB code.
ext=regionprop(bw,'exterm')
expts=ext.Extrema
coor=expts(8,:)-expts(1,:)
angle=atan(coor(1)/coor(2))*180/pi

Step 6: Rotate the polygonal image anti-clockwise by (angle).

Step 7: When the image is rotated, its size increases by a factor of row/cos(angle) and col/sin(angle), but the original size of the image is row and col and the part of image illuminated is even less than row and col, and thus it is required to be cropped.
For cropping. the extremes of image obtained in *Step 7* are obtained. The range of column varies from the minima of left-top, left-bottom to maxima of right-top, right-bottom. The range of row varies from the minima of top-left, bottom-left to maxima of top-right, bottom-right.
Crop-Image (x1:x2,y1:y2)

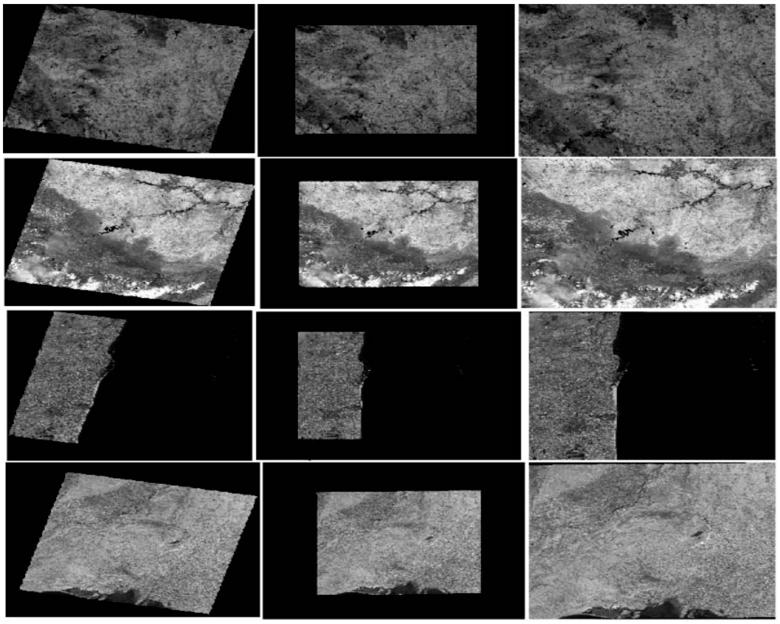
6. RESULTS AND DISCUSSION

Given in Fig. 3 are four sets of results obtained after applying the proposed rectification process to different satellite images. Each row of the result set represents: (a) input satellite image with error, (b) partially rectified image, (c) rectified and scaled image in the portrait form. The final resampled and rectified cropped images, which is rectified geometrically, are presented in the portrait form.

The results thus obtained after applying the above algorithm are rectified satellite images which can be used in many applications such as for detection of change using multi-temporal satellite images[4,9,10]. In computer vision, object recognition is carried out after detection of change using successive images obtained from surveillance cameras[11].

The proposed pre-processing algorithm has the following advantages:

- It avoids manual selection of control points in the image and establishment of correspondence between the recently acquired input image to the base frame



(a) (b) (c)

Figure 3. (a) input satellite image; (b) rotated satellite image, and (c) rectified output.

image. Hence, the algorithm is fully automatic.

- It clears the null image zone of the satellite image, i.e., image portion containing the zero digital numbers values. Hence, the rectified image only contains the information portion which is less than the size of the input image in terms of memory footprint and spatial dimension. Thus the rest of the registration steps compute on the smaller dimension image rather than the bigger input image. This saves the computation time.
- Also the feature selection algorithms such as SIFT and Harris corner detection do not have to work on the null image area leading to spurious features.

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