Detection of JL-1 Satellite's Jitter Using Multimodal Pushbroom Cameras

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***Abstract*—Pushbroom cameras are widely used for earth observation application. This sensor capture 1D image over time and sweep out a region of space and build a 2D image using the straight motion of the satellite. The attitude variation is assumed to be constant during the acquisition process. However, this assumption has been weakened due to a tendency of miniature and lightweight of satellites. In this paper, we analyze the warps of remote sensing image and introduce an improved image registration method. Then the correct images are retrieved and the satellite variation is estimated. The performances of our algorithm are shown on JL-1 satellite datasets. The results shows the possibility of the improvement in geometric processing accuracy for JL-1 imagery products and provide a good reference for satellite platform jitter source analysis.**

Keywords-multimodal image registration; satellite attitude; pushbroom cameras

I. INTRODUCTION

Pushbroom imaging spectrometers are a desirable form for Earth observations from space, since they can achieve a higher signal-to-noise ratio than their whiskbroom counterparts [1]. Comparing with conventional area array CCD camera, pushbroom camera is more effective, more flexible and more robust to the improvement of the resolution [2] [3]. Generally there are several pushbroom cameras mounted in an observation satellite to record different spectral bands, their focal planes are parallel and observe the same point on earth at different instants, The pushbroom sweeps out a region of space in one direction as the satellite move straight and orthogonally in another direction, as showed in Figure 1.

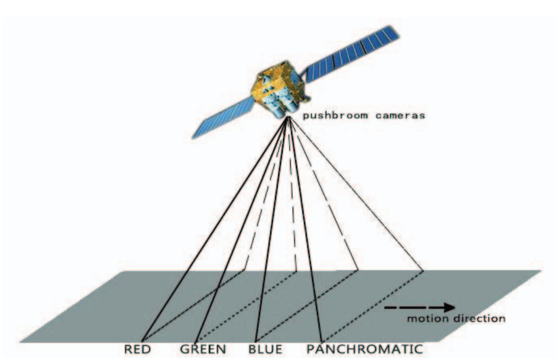

Figure 1. Model of the multi-spectral pushbroom.

It is critical for the satellite to be constant during the image acquisition of the pushbroom, which become harder to satisfy as the resolution improved. However, the mechanical jitter is common for the satellite, which originate from wheels, solar paddle, and high-gain antennas. For example, a 1 arcsec degree of jitter of a satellite with an orbit height of 800km could cause a proximately 4m drift on earth, which is unacceptable for high-resolution cameras. For the multispectral images the jitter will lead to not only the mismatch of the image color recomposing, but also the geological information inaccuracy, which will produce negative influence when used as geospatial data. The wraps of the images from remote sensor and the jitter from the spacecraft is well-known and widely-concerned [4] [5] [6].

The jitter of the satellite is tiny, inherent, sensitive and difficult to control [7]. On the one hand, it's important to take steps to isolate and suppress the jitter, on the other hand, the jitter should be detected and compensate in a direct or indirect way. Considering the existing attitude sensors in most satellites is IMU and star sensor which sample the attitude at low frequency, it's nearly impossible for them to detect what pushbroom cameras suffer from on satellite during the image acquisition. The ADS (angular displacement sensor) and ARS (angular rate sensor) have been applied successfully in measurement of the high-frequency attitude variation [8], but it's not the best choice because of its high costs especially for the small satellite. Since the deformed images contain nearly all information about the jitter, another possible solution is to estimate the attitude by the images itself based on the image processing and optimization methods without using any additional applications.

Several articles are published in this area. Article [9] proposed an original solution based on Bayesian framework. Article [10] introduces a methodology for detecting the sign of pointing jitter using the geometric consistency of line of sight (LOS) vectors. Article [11] analyze the pattern of the jitter using image correction. This article present a near real-time method to detect and compensate the attitude variation of a satellite by image registration. We first describe how deformation and mismatch occur during multispectral pushbroom image acquisition. Then, we analyze several existing algorithm and introduce a new near real-time registration method combined NCC (Zero-mean normalized cross-correlation) and Lucas Kanade technique. Finally we evaluate the performances of our solution and model and compare it over standard approaches using the data from JL-1 satellite.

II. JITTER DETECTION BASED ON IMAGE REGISTRATION

A. Design of the Multispectral Pushbroom Sensor

The pushbroom sensors mounted on the JL-1 satellite form small parallax between bands with short interval of observation time. In this parallax observation system, different sensor observe a same spot at constant intervals. Because of the Simplicity of its optical systems, which are suitable for compact optics of recent high-resolution satellite sensors [10], this kind of configuration are widely adopted in many observation satellite, such as ZY-3, Quickbird, JL-1, etc. However, the attitude fluctuation of the satellite affect the stability of the satellite and change the orientation of sensors slightly but randomly, which means, images will be warped and the matching process of images in different bands will be deteriorated due to the scanning in different time. Conversely, the warps and mismatch can be utilized by registration process to detect and estimate the jitter and obtain improved satellite-based images.

The pushbroom system of JL-1 satellite consists of four linear-array detectors working on four bands separately in red, blue, green, and panchromatic region of spectrum, as shown in Figure 3. The four linear-array detectors are arranged on the focal plane in parallel. The distance between every adjacent bands is approximately 5×10^{-3} m, and the sensor scan the same spot at a specified internal of 0.03s. From the Fig. 2, one can see that the time difference between neighboring bands is a little shorter than the gyro rate. The attitude rate is about0.25ms, which is relatively larger due to the processing of the sensor fusion and data process. The sampling internal of neighboring line of the sensor is0.4ms, which is obviously smaller than that of attitude data. So the lines are more sensitive and fragile to the high-frequency and undetectable fluctuation.

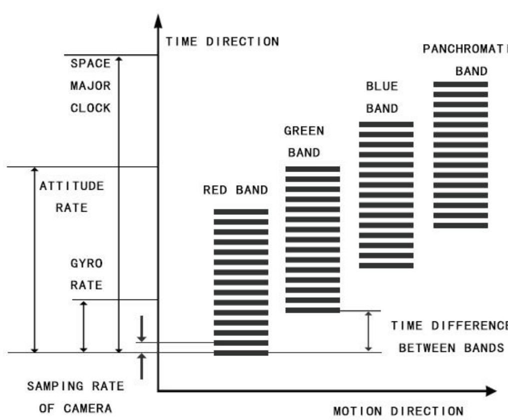

Figure 2. Sampling timetable of attitude rate and pushbroom imagery.

B. Formulation of Image Deformation

From the Fig. 1, one can see the acquisition principle of the pushbroom system with four bands. To simplify the situation, we consider the case of two adjacent pushbroom sensors set in parallel to the focal plane. Let I and J be the image functions of the two chosen adjacent camera I and J. Assume that the camera J observe the same scene after a constant time δ while the satellite moves straight and at a constant speed.

In other words, every line of image I should be mapped to the same place as the line of image J ideally with constant shifting. The relationship between the two images with the assumption of perfect satellite stability is described as follows:

$$I(x,t-\delta)-J(x,t)\sim N(0,\sigma^2) \tag{1}$$

where x is the coordinate in pixel along the scanning direction, and t is the discrete time index. $N(0,\sigma^2)$ means Gaussian distribution with standard deviation σ and zero mean, due to the sensor noise and radiometric sensitivity different. The relative pixel-based wrap error occurs when we take the jitter into account. We assume that the sampling interval between scanning lines is short enough that the attitude fluctuation is considered to be constant during scanning a line. The relationship is expressed as follows:

$$J(w(x,t)) = J(x',t') \tag{2}$$

$$I(w(x,t-\delta)) = I(x',t')) \tag{3}$$

where w is the wrap function which make the input pixel change its location. Considering the same jitter effect at the same interval, which means w only change with the variation of time factor t. For the two wrap function $w(t-\delta)$ and $w(t)$, the relation are described as below.

$$w(t-\delta)) - w(t) = w_r(\delta) \tag{4}$$

where $w_r(\delta)$ represent the relative wrap from $t-\delta$ to t. The relative wrap are caused by the rotation of the optical axis of the camera in the interval of δ, which can be decomposed into a serial of motion in three axes respectively. And the pitch, roll and yaw make different effect on the image. For convenience, we assume the rotation order is $pitch \rightarrow roll \rightarrow yaw$.The deformation on the 1-D image and the axes definition are shown in Fig. 3(a) and Fig. 3(b) respectively.

From Fig. 3(a), one can see that the roll and pitch of the optical axis make the 1-D image translate, while the yaw make it rotate in focal plane. According to present literature, the deformation caused by yaw is lower than approximately 0.02 pixel. So it's a reasonable hypothesis to neglect the effect of rotation in a relative small part of the line. The 1-D image can be divided into several parts with only translation to be considered. The translation of the image parts is different and regular due to the effect of the rotation in a large range. Method of linear fitting can be utilized to estimate the value of yaw in pixels. To estimate the displacement of the translation, several image registration algorithms are presented to solve the pitch and roll in pixels.

C. Pushbroom Motion Model

Since the jitter can be described as the displacement, then the attitude variation of the satellite can be deduced using the intrinsic parameters of the cameras. Assume dx is the pixel size in x direction, and f_x is the focal length in the same direction. The attitude variation is presented as below

$$\theta_x(t) = \arctan \frac{dx_x w_x(t)}{f_x} \tag{5}$$

where $w(x)$ is the pixel displacement due to jitter in time t and in direction x . $\theta_x(t)$ is the pitch around the x-axis, as shown in Fig. 3. The analysis above is similar for the roll. And as for the yaw, we can easily prove that the yaw almost stay constant from image coordinate system to camera coordinate system according to the geometric relationship.

Once we get the attitude variation of the satellite, it will be helpful for the establishment and analysis of the mathematic model of the jitter. What's more, the attitude can be used in ACS to suppress and eliminate the jitter by data fusion.

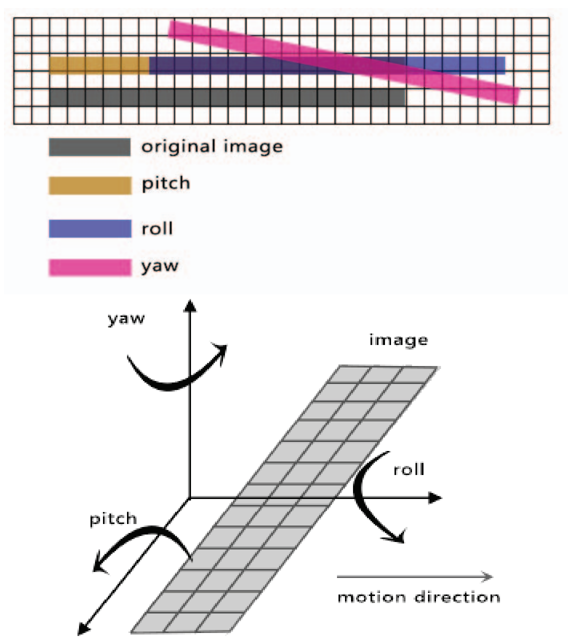

Figure 3. (a) image variation caused by axes rotation. (b) definition of axes rotation.

III. METHODS OF IMAGE REGISTRATION

A. PC and NCC Methods

There are several existing measures apply in the blocking matching of the two images. Phase correlation (PC) is widely used as the criterion of the registration error between images [12] [13] [14].

Consider two $N \times M$ images $f_1(x,y)$ and $f_2(x,y) = f_1(x+x_0, y+y_0)$, which differ by the displacement x_0 and y_0 . The cross-phase spectrum is given by using Fourier transform:

$$R(\omega_1,\omega_2) = \frac{F_1(\omega_1,\omega_2)F_{2'}(\omega_1,\omega_2)}{|F_1(\omega_1,\omega_2)F_{2'}(\omega_1,\omega_2)|} = e^{j2\pi(\omega_1 x_0 + \omega_2 y_0)} \tag{6}$$

where $F_1(\omega_1,\omega_2) = f_1(x,y)$ and $F_{2'}$ is the complex conjugate of F_2 .After applying Fourier inverse transform in the function R ,one can get the Phase-Only Correlation (POC) function $r(x,y)$ with the peak located in the point of (x,y) . To get the displacement more accurately, one can utilize low-pass filter in the frequency domain to eliminate high-frequency from the algorithm. Studies have shown that the sinc function can fit to the neighboring correction values to get the subpixel displacement. The formula is as following.

$$r(\delta_1,\delta_2) = \frac{sin\pi(x_0+\delta_1)}{\pi(x_0+\delta_1)} \frac{sin\pi(y_0+\delta_2)}{\pi(y_0+\delta_2)} \tag{7}$$

The accuracy of PC is high due to the steep peak and the processing speed is great applying the FFT. However, this algorithm estimate the displacement of correction based on gray distribution in frequency domain. The distribution will become unreliable when the pixel become rare in one dimension. So it's not suitable for the 1-D images.

Another simple but popular criterion is Zero mean normalized cross-correlation(NCC).Since the deformation caused by jitter are of a few pixels, Searching in a small neighborhood for a best matching according to NCC criterion is a direct and effective solution. The criterion is shown as the following.

$$C(m,n) = \frac{\sum_j^{L_y}\sum_i^{L_x}\left[I(i,j)-\bar{I}\right]\left[J(i-m,j-n)-\bar{S}\right]}{\sqrt{\sum_j^{L_y}\sum_i^{L_x}\left[I(i,j)-\bar{J}\right]^2 \sum_j^{L_y}\sum_i^{L_x}\left[J(i-m,j-n)-\bar{J}\right]^2}} \tag{8}$$

where the $I(i,j)$ and $J(i,j)$ are the registration images, and $\bar{I}$, $\bar{J}$ denote the average pixel values within the correlation window in I and J respectively. The integer are estimated to get the maximum of $C(m,n)$, which means the highest correlation of the two images. Next, a parabola fitting method can be utilized in the neighborhood of the peak to enhance the accuracy of displacement. However, the parabola fitting method need enough pixels to achieve high stability and accuracy, which means it's not a good choice for the 1-D image. So PC criterion only perform well at pixel level.

B. Lucas Kanade Method

To improve the accuracy of the correction, especially in sub-pixels level, another direct registration method, also known as pixel-based, or Lucas Kanade method, is considered. However, the L-K algorithm has several insufficiencies, such as: time-consuming, sensitivity to outliers, so it's necessary to raise some improving methods for standard L-K algorithm.

Considering a wrap u and a warp variation δu between the input image I and template image I_t , the sum of squared difference function (SSD) is

$$f_{SSD}(u+\Delta u) = \sum_x \left[I(w(x,u+\Delta u)) - I_t(x)\right] \tag{9}$$

Then we apply a first order Taylor expansion to the formula above:

$$f_{SSD}(u+\Delta u)=\sum_x\left[I(w(x,u)+\nabla I\frac{\partial w}{\partial v}\Delta v-I_t(x)\right]^2 \tag{10}$$

where ∇I is the gradient of the image with respect to its coordinates. A partial derivative with respect to Δv is then obtained and set the gradient to zero, the formula becomes

$$2\sum_x[\nabla I\frac{\partial w}{\partial v}]^T[I(w(x))+\nabla I\frac{\partial w}{\partial v}\Delta v-I_t(x)=0 \tag{11}$$

Then we can get the Δu

$$\Delta u=H^{-1}\sum_x\left[\nabla\frac{\partial w}{\partial v}][I_t-I(w(x,u))\right] \tag{12}$$

where the Hessian H is

$$H=\sum_x(\nabla I\frac{\partial w}{\partial v})^T(\nabla I\frac{\partial w}{\partial v}) \tag{13}$$

Considering that the wrap of the two images is almost translation, the Hessian can be rewritten as

$$H=\begin{bmatrix}\sum I_x^TI_x & \sum I_x^TI_y\\ \sum I_y^TI_x & \sum I_y^TI_y\end{bmatrix} \tag{14}$$

The computational cost of each update becomes $O(4N_x)$ for H, where N_x is the number of pixels. So making a precomputation of the Hessian may decrease the overall complexity of each iterative update to the base wrap from $O(4N_x)$ to $O(2N_x)$. This idea, which is called the inverse compositional method, are first presented by Baker and Matthews [15]. They use the gradient of the template image I_t to approximate the Hessian.

$$H=\begin{bmatrix}\sum I_{rx}^TI_{rx} & \sum I_{rx}^TI_{ry}\\ \sum I_{ry}^TI_{rx} & \sum I_{ry}^TI_{ry}\end{bmatrix} \tag{15}$$

However, this improvement cannot fit situations in this article due to the 1D dimension of the I_r, in other words, the gradient of I_r is unreliable and unstable. Since we already know the integer-pixel positions of the registration, which is near enough to the accurate position, the gradient of the position can be used to approximate the Hessian, which is expressed as follows.

$$H=\begin{bmatrix}\sum I_{x_0}^TI_{x_0} & \sum I_{x_0}^TI_{y_0}\\ \sum I_{y_0}^TI_{x_0} & \sum I_{y_0}^TI_{y_0}\end{bmatrix} \tag{16}$$

where x_0 and y_0 is the inter-pixel position data from the NCC criterion which make the Hessian constant during the iteration.

Due to the missing gradient of the template, the accuracy of another gradient image becomes critical in the direction of rare pixels. Because of the noise and outliers of the gradient image, iteration direction is much more likely to deviate and make the result inexact. So we introduce the Sobel Operator into the gradient computation to improve its accuracy and reliability [16]. The expression of vertical convolution kernel of Sobel is

$$H=\begin{bmatrix}-1 & 0 & 1\\ -2 & 0 & 2\\ -1 & 0 & 1\end{bmatrix} \tag{17}$$

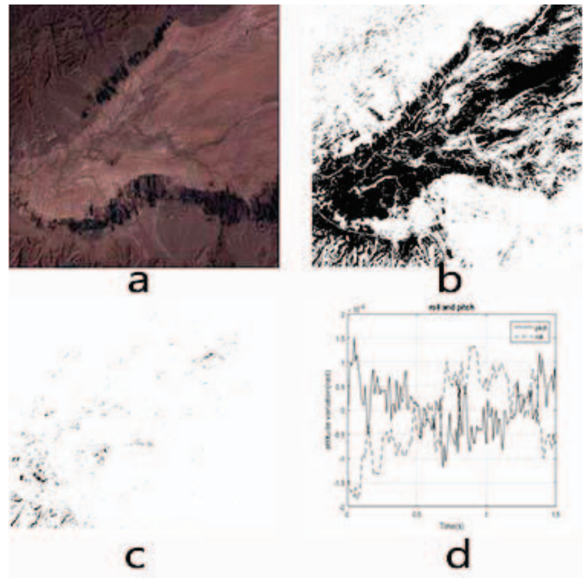

Figure 4. (a) original composite image.(b) error before processing (c) error after processing (d) estimated roll and pitch.

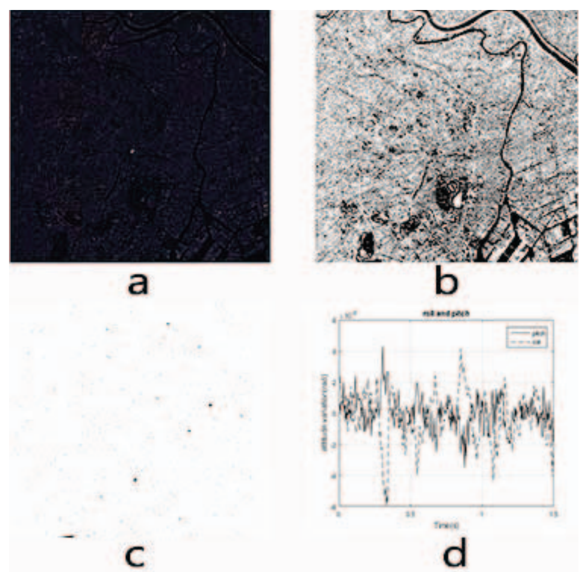

Figure 5. (a) original composite image.(b) error before processing (c) error after processing (d) estimated roll and pitch.

The key point of the Sobel Operator is finding the gradient in one direction of the image while applying

filtering in another direction. It can effectively smooth noise and make the processing more robust.

IV. EXPERIMENT RESULTS

We present experimental results on two Level-1 satellite datasets form JL-1 satellite.

Since the Level-1 datasets are not orthorectified, the line of Level-1 data products in the horizontal direction is almost equal to the scan line, so the displacement from the alignment can be a description of the attitude variation. We use MATLAB implement on a Core7 at 2GHz with 3.7GiB to process the data. All images are of size 3964×4073 and the images from different bands are aligned in pixel level.

We first use NCC algorithm and the polynomial fitting method to make sure the precision of registration can reach 0.1 pixel level. Then the L-K method in section III are applied to make the errors between images below 0.02 pixels.

The images are composed of multispectral data with blue, green and red images. We pick the blue and green images as samples for registration. Considering the stability of the polynomial fitting method, we use sub-images with size of 10×100 to get the results. We assume the jitter in 10 lines is constant in 0.1 pixel level, which is based on the fact that sampling time for every line is as fast as 0.4 ms. The time cost for this method is 3ms in average. Then we use the registration result as the initial value of the L-K method, which need 2.3 second in average to converge in approximately 20 iterations. The performance of the registration methods are shown in Fig. 4 and Fig. 5. From the image one can see that the registration process we proposed here is able to rectify images with accuracy much below than pixel unit.

After the registration, the motion model in section II is used to get the relative attitude variation, which is shown in Fig. 4(c) and Fig. 5(c). The jitter is lower than the results from other papers due to the suppression measure of the JL-1 and image pretreatment. One can see only roll and pitch are presented because the jitter in yaw direction is so small that is almost submerged in noise. Apply FFT to the jitter data, we can find out the low frequency component is mainly around 1.5Hz, and the high frequency component is not very apparent.

For comparison, we use the standard L-K method to reach the result in same result. The standard L-K method need 15s in average to converge in more than 60 iterations, and it may diverge occasionally due to the sensitivity of gradient information. However, the speed of our algorithm cannot meet the ultimate requirement of real-time by now, which should be less than 0.4ms for one line processing. An improved algorithm based on FPGA and DSP, as well as onboard processing system, are current investigating.

V. CONCLUSION

The originality of our work is to present an improved and real-time registration algorithm for multispectral pushbroom images. This method can detect and rectify the attitude variation during the image acquisition. The performance of the method is presented by the images from JL-1 satellite. The relative attitude variation is shown and analyzed. What's more, the result can be used for further estimation of the jitter from satellite platform, which is critical for the improvement of the resolution of remote sensing satellites.

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