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A fine image motion compensation method for the panoramic TDI CCD camera in remote sensing applications

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ABSTRACT

The image motion caused by camera housing rotation is the natural component in panoramic TDI CCD camera, and it cannot be eliminated thoroughly by traditional motion compensation schemes. After researching on the operation of a typical panoramic TDI CCD imaging system, we present a fine rolling rate independent motion compensation method. Employing the correction factor *k*, a TDI CCD line transfer synchronization signal is generated by the high resolution optical encoder as long as the ground scene moves one pixel with respect to the detector. Then, the effect of the motion compensation method is evaluated using the Monte Carlo method. The simulation results indicate that the magnitude of the modulation transfer function at the Nyquist frequency increases more than three times by increasing the subdivision steps from 100 to 500, and also of the imaging experimental results show that the image quality improvement can be achieved.

1. Introduction

Time delay and integration mode of CCD provides increased sensitivity without the sacrifice of spatial resolution, and the effective integration time is increased by a factor of *N*, which is equal to the number of TDI stage, so TDI CCD is widely used in remote sensing systems for improving the low light level capability. For example, the most important payload of Chinese lunar spacecraft Chang'e II is just a push broom TDI CCD stereo camera with 96 stages. As reported, its ground resolution can approach to 1 m in the 100 km × 15 km elliptical orbit [1]. But, along with the desire for wide ground area coverage increases, the panoramic TDI CCD camera, which enlarges the field of view by rolling the camera housing across the flight direction, is drawing extensive attentions [2]. However, the wide area search mode leads to relative motion between the ground scene and the sensor along the camera rolling direction inevitably [3]. The widely used motion compensation method is to move the sensor at a rate substantially equal to the image motion rate. As for the TDI CCD camera, it can be achieved by deriving the rate of the gyroscope mounted to the plane, which is perpendicular to the primary optical axis, to generate the TDI CCD line transfer synchronization signal [4]. In a well motion compensated TDI CCD imaging system, the rate at which the sensor scans the ground (rolling rate) should perfectly synchronize with the rate at which the charge is clocked out of each TDI stage [5]. Nevertheless, due to the limitation of the gyroscope's bandwidth and linearity, their matching degree is rotation rate dependent. For low resolution remote sensing systems, the magnitude of the pixel smear presented in the systems is not serious enough to pose noticeable degradations of image quality. For high resolution imaging systems, the residual pixel smear can be a significant source of image quality degradation [6–7]. Therefore, there is an urgent requirement on the fine rolling motion compensation technique, which allows for a large range of roll motion without image quality losses.

2. Methods

As Fig. 1 illustrates, the panoramic TDI CCD camera rotates about the longitudinal axis of the aircraft in a continuous mode during exposure time, then the scene images are translating across each of the detector stages in the cross-track direction at a velocity

$$v = \omega f \tag{1}$$

where ω represents the camera rolling rate sensed by the gyroscope, f represents the lens focal length. To compensate for this image motion, and thereby preserve resolution, it is required that the charges should be transferred in the direction of the image motion from row to adjacent row at a rate that substantially

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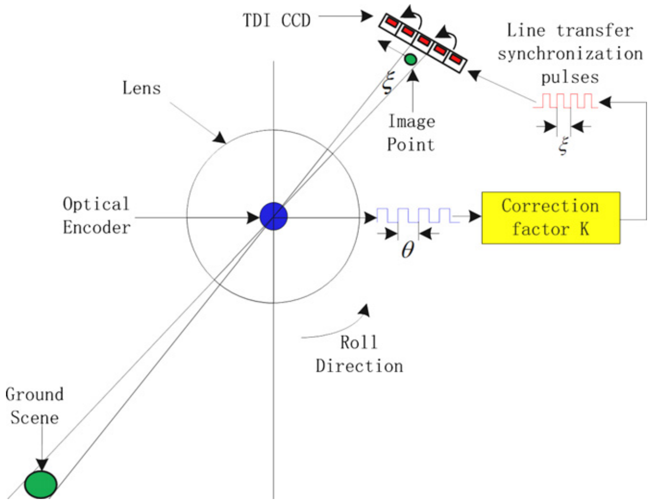

Fig. 1. Diagram of the proposed roll motion compensation method for the panoramic TDI CCD camera.

matches the image velocity

$$bf_c = \omega f \tag{2}$$

where b represents the detector pitch, and f_c represents the TDI CCD line transfer frequency. Since f and b are fixed, f_c has a linear relationship with ω, which indicates that the velocity of the image due to roll can be determined by the outputs of the fiber optic gyroscope. However, it should be emphasized that the gyroscope is an inertial measurement unit, and the amount of drift will increase as growth of running time. Therefore, f_c will have a nonlinear relationship with ω, and the caused residual pixel smear will degrade the imaging quality, especially for the high resolution aerial camera.

In this paper, a high resolution optical encoder mounted along the roll axis is used to synchronize the TDI CCD line transfer rate with the image motion. According to Eq. (2), the optimum compensation objective can be summarized as that no matter whichever pixel the ground scene moves with respect to the detector, a TDI CCD line transfer synchronization signal should be generated simultaneously by the optical encoder. In this way, the relative motion between the photon sensitive pixels and the ground scene will be eliminated completely.

The angle resolution corresponding to each pixel of the TDI CCD camera is given by

$$\xi = \frac{b}{f} \tag{3}$$

In the real imaging system, the native resolution of the optical encoder is seldom equal to the pixel angle resolution of the designed camera, which indicates that there exists no one to one relationship between each pulse signal generated from the encoder and the TDI CCD pixel pitch. Thus, a parameter k, which is independent of the rolling rate, is introduced to correct the frequency of optical encoder's original synchronization pulses

$$k = \frac{\theta}{\xi} \tag{4}$$

Generally, k is a floating point number, the higher the reconstruction precision is, the more rolling motion compensation accuracy can be achieved. Fig. 2 depicts the block diagram for the factor correction procedure.

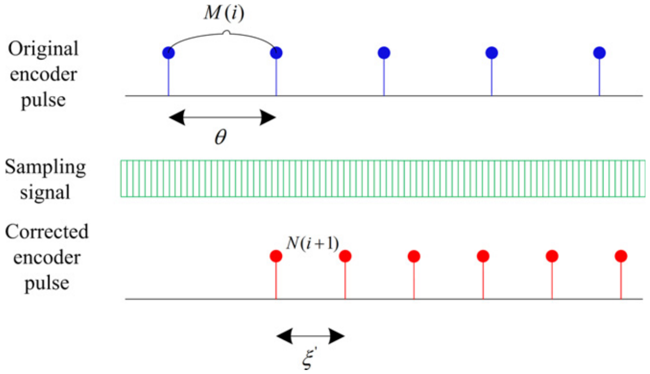

Fig. 2. TDI CCD line synchronization signal generation method.

In the ith pulse interval, the optical encoder native resolution angle θ is finely subdivided by a given sampling signal with counting number of $M(i)$. Since the camera rolling rate for a particular flight mission is a constant value, and the resolution of the optical encoder is generally higher enough. Therefore, the scene motion between two adjacent pulse intervals can be modeled as a linear uniform movement. Then the recorded number during each primary interval can be used as the unbiased estimator to generate the new synchronization pulses when the following formulas is satisfied:

$$kM(i) - 0.5 < N(i+1) \le kM(i) + 0.5 \tag{5}$$

where $N(i+1)$ is the integer number, and it will be updated only when a new encoder pulse arrives. The motion compensation is a multistep, tightly integrated process, and its accuracy depends on many aspects, such as opto-mechanical mounting error, native resolution of the measurement elements as well as servo control system precision. Herein, we only focus on the effect of the proposed pulse synchronization method on the imaging quality. Assuming that the angle resolution determined by the encoder's two adjacent pulses is completely accurate, then the angle subdivided by the sampling signal can be expressed as

$$Q = \frac{\theta}{M(i)}\left(1 + \frac{m_i}{M(i)}\right) \tag{6}$$

where m_i represents a zero mean random variable with a uniform probability distribution over the range of $[-1,1]$. Then the reconstructed optical encoder resolution, which corresponds to a TDI CCD line transfer synchronization signal, can be written as

$$\begin{aligned} \xi' &= (kM(i) + n_i)\frac{\theta}{M(i)}\left(1 + \frac{m_i}{M(i)}\right) \\ &= \xi + \frac{\xi m_i + n_i\theta + n_i m_i \theta / M(i)}{M(i)} \end{aligned} \tag{7}$$

where n_i denotes the zero mean uniform distribution within the scope of $[-0.5,0.5]$.

It can be seen that ξ' is the unbiased estimator of the genuine TDI CCD pixel angel resolution with a variance of $(12M(i)\xi + (3M(i)+1)\theta)/(36M^2(i))$. From Eq. (7) we know that the representation of the random variables is just the causes of the imaging smear, and the amount of the pixel smear for each individual TDI stage is given by

$$S_a(i) = \frac{\xi m_i + n_i\theta + n_i m_i \theta / M(i)}{M(i)} f \tag{8}$$

The blurred image can be modeled by convolving a rect function with width $S_a(i)$

$$I'(x,y) = I(x,y) \times rect\left(\frac{x}{S_a}\right) \tag{9}$$

where $I(x,y)$ is the original image, $I'(x,y)$ is the blurred image [8]. Then taking the Fourier transform of Eq. (9), the motion related MTF for each TDI stage is

$$I'(f_x,f_y) = I(f_x,f_y)\mathrm{sinc}(\pi S_a f_x) \tag{10}$$

where f_x is the spatial frequency along the rolling direction. For the TDI CCD camera, the final image is the sum of the individual images collected at all stages. Thus, the amount of the MTF associated with a detector having N TDI stage can be written as

$$MTF_{smear}(f_x)=\sum_{n=0}^{N-1}\sin c(\pi S_a(i)f_x)\exp\,(i2\pi nS_a(i)f_x) \tag{11}$$

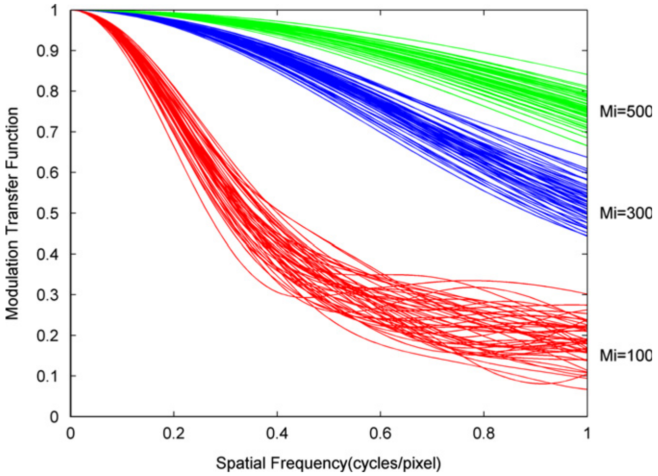

Fig. 3. The calculated MTF corresponding to 100 random vector pairs (n_i,m_i) by substituting Eq. (7) into Eq. (10) employing the Monte Carlo method. The modeled imaging system is summarized as $b=10$ μm, $f=1000$ mm, $N=96$, and $\xi=6.48''$.

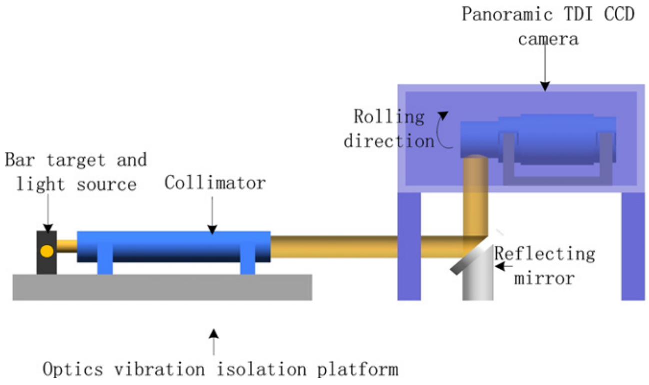

Fig. 4. The block diagram of the imaging experiment in the laboratory. The focal lens of the collimator is 4000 mm, and the parameters of the tested camera are the same as the parameters outlined in Fig. 3.

From Eq. (11), we find that there exist $N\times 2$ independent random variables, so the smear related MTF for the proposed technique is not a fixed value. Nevertheless, it does not mean that the image quality evaluation metrics fails. By performing statistical sampling experiments, the Monte Carlo method can provide approximate solutions to a variety of mathematical problems [9–10]. Thus, 100 random vector pairs (n_i,m_i) are generated to evaluate the performance of the proposed rolling motion compensation method, where n_i follows zero mean uniform distribution within the scope of [−0.5,0.5], and m_i follows zero mean uniform distribution within the scope of [−1,1]. Fig. 3 illustrates the experimental results with subdivision steps of 100, 300 and 500. We find that the amount of the MTF losses at the Nyquist frequency can approach to an accepted value by increasing the subdivision steps, and it indicates that the image quality improvement can be achieved with various rolling rates.

3. Experimental results

First, the performance of the proposed rolling motion compensation method is assessed in the laboratory. As Fig. 4 illustrates, employing the bar target, the collimator as well as the optics vibration isolation platform, the drone beam is generated which

Table 1
Optics and environmental conditions of the flight imaging test.

Parameter	Value
Optics aperture diameter (mm)	180
Focal length (mm)	1000
Spectral band pass (μm)	0.4–0.9
Optics transmission	0.7
TDI stage	96
Detector pitch (μm)	10
Imaging distance (km)	9
Look angle (deg)	−10 to 10
Flight speed (km/h)	890
Sun angle (deg)	40
Atmosphere	Middle latitude, winter, 20 km visibility

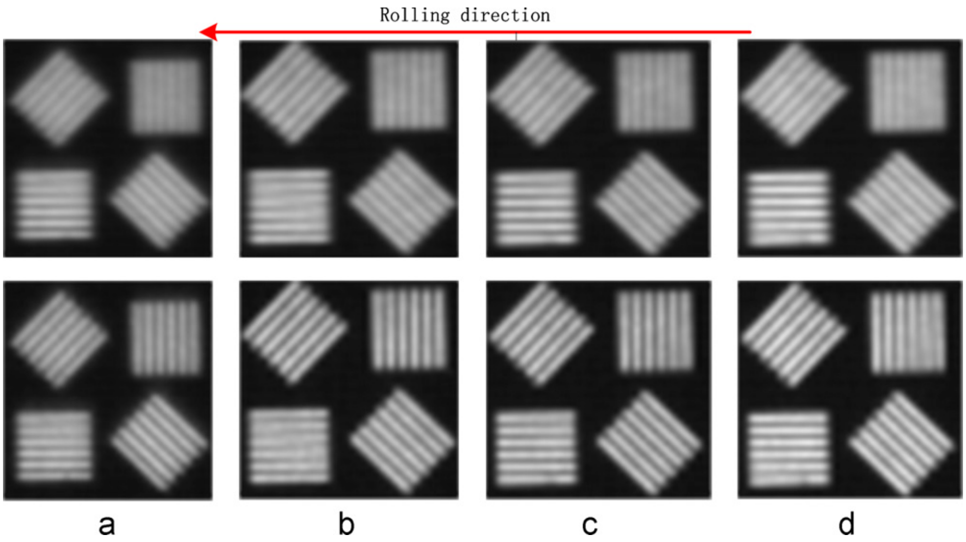

Fig. 5. The captured drones at the Nyquist frequency at rolling rate of (a) 1deg/s, (b) 5 deg/s, (c) 20 deg/s, and (d) 50 deg/s. The upper four patterns are obtained by the method used in reference [4], and the lower four patterns are obtained by the proposed method.

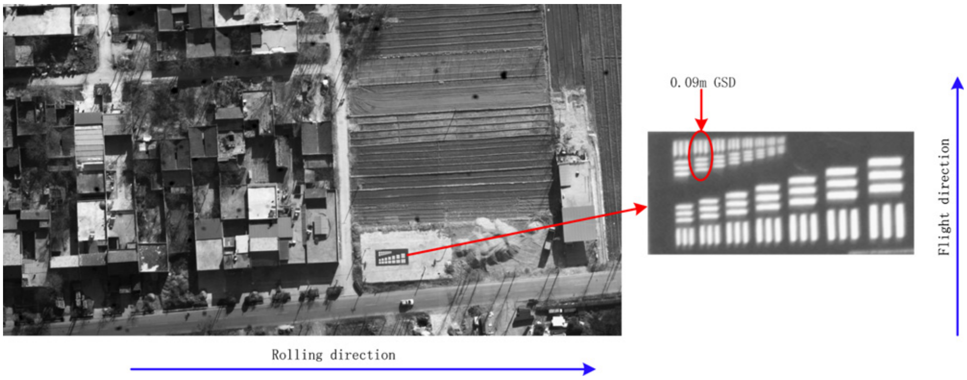

Fig. 6. The captured drones in the real flight imaging test.

seems that the object is emitting at infinity. After reflecting, the beam will go through the panoramic TDI CCD camera's entrance pupil. During operation, the camera housing rotates about its main optical axis, and the drone beam will move with the charges on the focal plane driven by the corrected synchronization pulses, after *N* stage integration, the final images are generated.

Fig. 5 shows the captured drones by our method and traditional method [4]. It can be seen that the bar targets obtained by our method perform sharper edge and exhibit higher contrast both in horizontal and vertical directions (rolling direction), which indicates the pixel smear along the rolling direction is compensated well. Furthermore, the proposed technique is also evaluated by a real flight imaging test. The optics parameters as well as the imaging conditions are outlined in Table 1.

Fig. 6 shows the captured panoramic images of the ground scene with various sizes of the drones. Five expert observers rate the experimental results, and they reach a consensus that the imaging resolution determined by the imaging system's ground sample distance (GSD), which is equal to 0.09 m, has been achieved. It confirms that the proposed technique works well in real imaging environment.

4. Conclusions

In order to improve the performance of the panoramic TDI CCD imaging system, researchers pay great attention on reducing relative motion between photosensitive pixel and image point caused by camera housing rotation. However, the motion is seldom eliminated thoroughly. In this paper, we have shown a simple, robust and precise way to compensate the pixel smear caused by the panoramic TDI CCD camera rotation motion. The presented method works well for a wide range of rolling rate. Moreover, we have provided a series of detailed mathematical formulas describing the performance of the method, and both theoretical analysis and experimental results indicate that image quality along the rolling direction improves a lot when our method is used.

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