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Effect of image motion and vibration on image quality of TDICCD camera

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Abstract: Image motion and vibration are significant factors influencing image quality of satellite-based TDI camera. In order to learn their effect on TDICCD, motion degradation models at two directions were established. Based on the models, Line spread functions (LSF) for image motion of different types and strict expressions of MTF for abnormal linear image motion were deduced. Modulation transfer function (MTF) for sinusoidal image vibration was calculated through numerical integration. Geometric distortion was evaluated by linear part of phase transfer function (PTF). The results indicate that abnormal linear motion and high frequency vibration cause space-invariant image blur while low frequency vibration brings space-variant image blur and geometric distortion.

Introduction

Time delay and integration (TDI) CCD is a well-known optical sensor array which is used in various applications. TDICCD has many advantages compared to the conventional CCD, such as enhanced photosensitivity, increased signal-to-noise ratio, improved sensitivity uniformity of the pixels and so on [1]. Since it has high resolution without sacrificing SNR, it is widely used in high-resolution remote sensing camera. TDICCD is very sensitive to abnormal image motion and vibration, which cause not only image blur but also geometric deformation.

A lot of researches have been done about influence of image motion or vibration on image quality, but most of them are aimed to degradation of image captured by an area-array camera, whose motion degradation is space-invariant [2,3]. As to TDI camera, different rows of the image are formed at different time, so the degradation model is different from that of the area-array camera. The literatures [4,5] point out the characteristic that motion degradation of TDI camera is space-variant, and propose means of simulation for the motion blurred image and restoration methods. S. L. Smith builds the dynamic MTF model of TDI direction based on the assumption that the smear is formed by a linear motion within the integration time of the detector [6]. This paper is aiming to develop motion degradation models at two directions of TDICCD camera for any kinds of image motion and analyze image blur and geometric deformation caused by image motion.

1 Motion degradation model of TDICCD camera

If image motion is the only factor that influences image quality, and the motion function is $\varepsilon(t)$, since the overall intensity of any image point is equal to the integral of the light intensity received within the exposure time and LSF is the normalized intensity, the LSF at the moment t is $\delta(x-\varepsilon(t))$. With regard to TDICCD, the image intensity is sum of N integration stages. Suppose the line period is T, and motion function during integration time of the nth stage is $\varepsilon_n(t)$, so LSF is deduced as follows,

$$LSF_{vib}(x)=\frac{1}{NT}\sum_{n=1}^{N}\int_{t_0+(n-1)T}^{t_0+nT}\delta(x-\varepsilon_n(t))\mathrm{d}t \tag{1}$$

Since the width of LSF of image motion is not zero, motion blur is introduced. What's more, the center of gravity position may shift from its nominal position because of motion which causes geometrical deformations.

In this paper, the ideal image motion caused by normal scanning is called normal image motion, and that caused by other factors is named abnormal image motion. For a TDICCD camera, the degradations in resolution are different when the vibration occurs in different directions (TDI direction and perpendicular to TDI direction). So we build motion degradation models of two directions.

1.1 Degradation model of TDI direction

Consider the case when only abnormal image motion along TDI direction is present. Assume that for notation, the TDI direction is in the x direction, and the perpendicular direction is in the y direction, and the abnormal image motion along TDI direction is $X(t)$, the ideal image motion velocity is v, and central distance of neighbor pixels is $p=vT$. According to TDICCD's imaging principle, as to the Lth row and the nth stage, the beginning integration location is $X[(L+n-2)T]$, the instant when integration begins is $(L+n-2)T$, and image motion during the nth stage time is $v[t-(L+n-2)T]+X(t)$, so LSF under the situation that abnormal image motion exists is yielded through Eq. (1),

$$LSF_x = \frac{1}{NT}\sum_{n=1}^{N}\int_{(L+n-2)T}^{(L+n-1)T}\delta\big(x - v\big(t-(L+n-2)T\big) - X(t)\big)\mathrm{d}t = \frac{1}{NT}\sum_{k=L\text{-}1}^{N+L\text{-}2}\int_{kT}^{(k+1)T}\delta\big(x - v(t-kT) - X(t)\big)\mathrm{d}t \tag{2}$$

When there is no abnormal motion, LSF is calculated by substituting $X(t)=0$ in Eq. (2) as follows,

$$LSF_x = \frac{1}{NT}\sum_{k=L\text{-}1}^{N+L\text{-}2}\int_{kT}^{(k+1)T}\delta\big(x - v(t-kT)\big)\mathrm{d}t = \frac{1}{NT}\sum_{k=L\text{-}1}^{N+L\text{-}2}\int_{x-p}^{x}\frac{\delta(\xi)}{v}\mathrm{d}\xi = \frac{1}{p}\mathrm{rect}\left(\frac{x-p/2}{p}\right) \tag{3}$$

Where rect(•) is a rectangle function. So width of each row is p that is equal to the central distance of neighbor rows, and the mean image position shifts $p/2$ along x direction due to linear motion. Taking Fourier transform of Eq. (3), we get MTF as a sinc function.

1.2 Degradation model perpendicular to TDI direction

Suppose that the abnormal image motion perpendicular to TDI direction is $Y(t)$, according to Eq. (1), LSF of the Lth row can be written as,

$$LSF_y = \frac{1}{NT}\sum_{n=1}^{N}\int_{(L-2+n)T}^{(L-1+n)T}\delta\big(y - Y(t)\big)\mathrm{d}t = \frac{1}{NT}\int_{(L-1)T}^{(L+N-1)T}\delta\big(y - Y(t)\big)\,\mathrm{d}t \tag{4}$$

2 Analysis of influences on TDI camera of abnormal image motion

The following will discuss influences on image quality of different kinds of abnormal image motion based on the motion degradation models.

2.1 Linear motion

As to abnormal linear motion along TDI direction, assume that the abnormal velocity is $v_x>0$, and then the width scanned during the line period is larger than p, what's more, there will be a displacement between the actual beginning integration location and the ideal one. We define $\sigma_x=v_xT$ and $p'=p+\sigma_x$, and substitute $X(t)=v_xt$ in Eq.(2), and LSF of the Lth row is deduced,

$$LSF_x = \frac{1}{N(p+\sigma_\mathrm{x})}\sum_{m=L-1/2}^{N+L-3/2}\mathrm{rect}\left(\frac{x-m\sigma_\mathrm{x}-p/2}{p+\sigma_\mathrm{x}}\right) \tag{5}$$

Taking the Fourier transform yields MTF and PTF as follows,

$$MTF_x = \left| \operatorname{sinc}\left[\left(1+\frac{v_x}{v}\right)f\right] \frac{\sin(\pi Nf\, v_x/v)}{N\sin \pi f\, v_x/v} \right| \tag{6}$$

$$PTF_x = 2\pi f\left[p/2 + N\sigma_x/2 + (L-1)\sigma_x\right] \tag{7}$$

where f denotes the normalized spatial frequency.

From Eq. (6), we can see that MTFs of different rows are same and so image blur is space-invariant. What's more, with increase of N and v_x/v, degradation of MTF becomes more serious.

The linear part of PTF merely produces a bodily shift of the image. If LSF of an optical system is symmetric with its peak at the origin, if the peak shifts to the location x_0, then phase changes linearly with frequency at a rate $2\pi x_0$ [7]. So the center of LSF is displacement from the ideal location. If LSF is not symmetric, the linear part of PTF can be deduced as $PTF \approx -2\pi m_1 f$ and m_1 is the first moment of image motion function. So the shifted distance from the ideal location is,

$$S = -m_1 = -\frac{1}{t_e}\int_{t_0}^{t_0+t_e} \varepsilon(t)\mathrm{d}t \tag{8}$$

PTF shown as Eq. (7) is linear, so LSF is symmetric and the center of the Lth row is $p/2+N\sigma_x/2+(L-1)\sigma_x$. So we can get the shift of actual location from ideal one of the Lth row is $N\sigma_x/2+(L-1)\sigma_x$, and the distance between neighbor rows which is $p+\sigma_x$. Since the distance between neighbor rows changes, the ground sample distance (GSD) and swath of the x direction change. When $v_x>0$, they become larger and when $v_x<0$, they become smaller.

If there is a linear motion along y direction, assuming that the velocity is v_y and $\sigma_y=v_yT$, and referring to Eq. (4), we can get LSF of the Lth row as follows,

$$LSF_y = \frac{1}{NT}\int_{(L-1)T}^{(L-1+N)T} \delta(y - v_y t)\, \mathrm{d}t = \frac{1}{N\sigma_y}\operatorname{rect}\left(\frac{y-(L-1)\sigma_y - N\sigma_y/2}{N\sigma_y}\right) \tag{9}$$

Take the Fourier transform of LSF, MTF and PTF are deduced as follows,

$$MTF_y = \left|\operatorname{sinc}(Nfv_y/v)\right| \tag{10}$$

$$PTF_y = 2\pi f\left[(L-1)\sigma_y + N\sigma_y/2\right] \tag{11}$$

So MTF of this direction depends on N and v_y/v, and with increase of them, image blur becomes more serious. From Eq. (11), we can see that the distance of neighbor columns is still equal to p without changing in spite of image motion. But image motion at this direction causes displacement between neighbor rows along y direction, and the displacement equals to v_yT. So, the actual scanning direction deviates from the ideal one at the angle of $\alpha=\arctan(v_y/v)$.

From the above analysis, we can conclude as follows: degradation of MTF caused by abnormal linear image motion is space-invariant, and the blur extent depends on number of stages N and abnormal image motion velocity, while geometric deformation has nothing to do with N.

2.2 Sinusoidal vibration

Based on the ratio of integration time t_e to the period of vibration T_0, sinusoidal vibration are then categorized into high frequency ($t_e \geq T_0$) vibration and low frequency ($t_e < T_0$) vibration [2]. For TDI camera, the exposure time is the product of the line period (T) and number of stages (N), that is $t_e=NT$.

For high frequency sinusoidal vibration perpendicular to TDI direction, assuming that $Y(t)=A\sin\omega t$, $\omega T_0=2\pi$, $NT \geq T_0$, $V(y)=\delta(y-A\sin\omega t)$, according to Eq. (5), LSF of the 1th row is,

$$LSF_y = \int_0^{T_0/4} V(y)\mathrm{d}t + \int_{T_0/4}^{3T_0/4} V(y)\mathrm{d}t + \int_{3T_0/4}^{T_0} V(y)\mathrm{d}t = \frac{1}{\pi\sqrt{A^2-y^2}}\mathrm{rect}\left(\frac{y}{2A}\right) \tag{12}$$

From Eq. (12), the LSF is symmetric and the center is not shifted from the ideal location. When the integration time is other integer times of vibration period, LSF is still as same as the above form. In this situation, there is some blur but no geometrical deformation. The OTF for this case is given by the Fourier transform of LSF and it is a zero order Bessel function. So, the extent of blur is only affected by the vibration amplitude A and image blur is space-invariant.

As to low frequency vibration, $NT<T_0$, the initial integration time of the Lth row is $(L-1)T$, and suppose that $a=A\sin[\omega(L-1)T]$ and $b=A\sin[\omega(L+N-1)T]$. According to the relationship between the instant when integration begins and integration time, $Y(t)=A\sin\omega t$ has 5 trends during the interval between $(L-1)T$ and $(L+N-1)T$: increasing monotonously; first increasing and then decreasing; first increasing then decreasing and then increasing; monotonously decreasing; first decreasing then increasing. Limited by the length of the article, only LSFs of the first and second situations are given.

For the first situation, LSF is written as follows,

$$LSF_y = \frac{1}{NT\omega\sqrt{A^2-y^2}}\mathrm{rect}\left(\frac{y-(a+b)/2}{b-a}\right) \tag{13}$$

For the second situation, LSF is given,

$$LSF_y = \frac{1}{NT\omega\sqrt{A^2-y^2}}\mathrm{rect}\left(\frac{y-(A+a)/2}{A-a}\right) + \frac{1}{NT\omega\sqrt{A^2-y^2}}\mathrm{rect}\left(\frac{y-(A+b)/2}{A-b}\right) \tag{14}$$

From the above expressions, we can find LSF of low frequency vibration is a normalized result of a part or several parts of LSF for high frequency vibration whose NT/T_0 is an integer number.

It is difficult to calculate MTF through Fourier transform of LSF for low frequency vibration analytically. In this situation, we adopt numerical integration. Substitute $Y(t)=A\sin\omega t$, take Fourier transform of Eq. (4) and adopt numerical integration, we deduce the numerical MTF formula,

$$MTF_y = \frac{1}{NT}\left|\int_{(L-1)T}^{(L+N-1)T} \exp(-j2\pi fA\sin\omega t)\mathrm{d}t\right| \approx \frac{1}{M}\left|\sum_{i=1}^{M}\exp(-j2\pi fA\sin\omega((L-1)T+NTi/M))\right| \tag{15}$$

where M is the number of samples during integration time.

From Eq. (13) ~ Eq (15), MTFs and LSFs for different rows are different which cause space-variant image blur and geometrical deformation which are relative to the vibration amplitude, vibration frequency and the beginning integration moment.

Assuming $NT<T_0/4$ and $Y(t)$ changes monotonously during integration time, according to Eq.(8), displacement along the y direction of the Lth row is,

$$S_L = -m_1 = 2\pi A\sin[2\pi(L-1)T/T_0 + \pi NT/T_0]\sin\mathrm{c}(NT/T_0)/T_0 \tag{16}$$

From Eq.(16), it is found the displacement changes with the number of rows periodically. So low frequency vibration at the y direction causes displacements of pixels from their original positions and leads transverse wraps. The distortion is of periodicity and the spatial period is approximately T_0/T (unit: row), and the amplitude of distortion is $2\pi A\mathrm{sinc}(NT/T_0)/T_0$. It is thus clear that as A increases and N decreases, the amplitude of distortion grows bigger but the spatial period has nothing to do with N. Suppose time taken to sweep a whole image is T_z, the imaging time contains T_z/T_0 periods of image vibration and during that time, number of rows scanned is T_z/T, so the number of spatial periods is T_z/T_0 which is similar to number of periods of image vibration.

If there is a sinusoidal vibration along TDI direction, then it will be difficult to calculate MTF through LSF. So we employ numerical integration to calculate MTF and the formula is obtained by substituting $X(t)=A\sin\omega t$ in Eq. (2) and taking Fourier transform of it. The expression is as follows,

$$MTF_x \approx \frac{1}{MN}\left|\sum_{k=L-1}^{N+L-2}\sum_{i=1}^{M}\exp\left(-2\pi jf\left(ivT/M - A\sin\omega\left(iT/M + kT\right)\right)\right)\right| \tag{17}$$

We can use the above expression to calculate MTF in order to evaluate the extent of image blur. If there is a low frequency vibration along TDI direction, velocity of abnormal image motion changes with time periodically. According to the analysis result about geometric distortion caused by abnormal linear image motion along TDI direction, the sampling distance along TDI direction is non-uniform and GSD along TDI direction changes with number of rows periodically.

As seen from the above analysis, high frequency vibration of which NT/T_0 is an integer number will cause space-invariant image blur but not cause geometric distortion while low frequency vibration causes space-variant image blur and geometric distortion.

3 Conclusions

This paper studied on the image degradation of TDICCD camera caused by image motion and vibration. MTF and linear part of PTF were used to evaluate image blur and geometric distortion respectively. The meaning of our work is to establish the relationship between image motion and system's LSF and MTF, which can be used to predict and evaluate dynamic imaging quality of TDI camera, and also provide a theoretical base for simulation and restoration of motion degraded images of TDI camera.

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