Image enhancement for space object based on information between adjacent spatial-temporal frames

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Abstract: Usually the ability of the space optical camera is degraded by many factors during operation on orbit for the space object observation. The result is induced by variation of some prior parameters such as platform motion, attitude variation, jitter and drift angle during operation on orbit. So it is not satisfying to improve the image quality, only by using the parameters measured on the ground test such as the point response function of the infrared CCD camera. The simulation for the space object observation of the on-board imaging system and the enhancement is proposed here, combining with the information between adjacent spatial and temporal frames. The dynamic model is formulated, representing the characteristic of point response function during multiple exposure times. Furthermore, the enhancement algorithm is proposed based on the correlated information between two adjacent spatial and temporal frames. The norm optimization method is used in the frequency domain. The dynamic point response function of the space object observation system is simulated in the experiment. And the detecting spectrum range is mid-Infrared. The processed result is clear and sharp by the proposed method. The experimental result shows that the proposed method is better than the conventional methods.

Key words: image enhancement; space objects; adjacent spatial-temporal frames; point response function

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基于临近时空帧间信息的空间目标图像增强方法

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摘 要: 在轨空间目标观测阶段,空间光学相机的成像性能通常都会受到很多因素的影响。一般包括平台运动、姿态变化、颤振、偏流角等方面。仅依赖地面测试得到的参数,如采用地面测到的红外 CCD

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相机的点响应函数进行图像增强,已经不能有效改善图像质量了。因此,提出了一种结合相邻时空帧信息的用于空间目标观测的仿真和图像增强方法。对多次曝光时间内的系统动态点响应函数进行建模、仿真。同时,提出一种基于相邻时空帧间相关信息频域范数优化的图像增强方法。实验中对空间运动目标红外观测系统的动态点响应函数进行仿真。通过实验结果表明:与传统方法相比,所提方法处理后结果的各项质量评价指标更高,处理后的图像更清晰。
关键词: 图像增强; 空间目标; 相邻时空帧; 点响应函数

0 Introduction

The advantages of space-born surveillance system are the ability to abtain reliable and timely information. However, radiation energy from the space moving objects is too weak to be detected by space optical remote sensor. It is important to enhance awareness capabilities of detecting system. Therefore, the main principle of designing space-born surveillance system is (1) Half the columns in each array are offset from the other half by sub-pixel, providing Over-sampling in the cross scan direction. (2) Multiple snap shots on the other direction[1-4]. Hereby, more energy is achieved by over-sampling on two directions. However the space surveillance optical remote sensor is susceptible to be affected by satellite platform motion, attitude variation, jitter and drift angle during operation on orbit. This results in degradation performance of the optical imaging system. There are many factors affect precision of LOS such as momentum wheel, CMG (Control Moment Gyros), reaction jets, antenna, thermal gradient variation, pump, motors and so on[5-6]. And the vibration is inevitable outcome. In this case, over-sampling not only increase the sampling effective information but also cause more noise and blur. In this case, it is not good to use the static point response function (PRF)[7-8] to reconstruct image.

1 Proposed method

The defect of single exposure image is that the radiation of the space object is too weak to be detected easily by space remote sensor. Therefore, we formulate the model of imaging system with random vibration. And the enhancement method is proposed, combining with the adjacent exposure time information.

1.1 Mathematical model of the system

The space optical remote sensor is taken as linear system, the model can be expressed as

$$L_i=prf_{D,i}\otimes I_{\mathrm{perf}}+n \tag{1}$$

Here, L_i denotes acquisition image at the ith time exposure, $prf_{D,i}$ denotes dynamic PRF of imaging system at the ith time exposure, I_{perf} denotes the scene image, n denotes zero mean additive Gaussian and Poisson noise, $\otimes$ denotes the 2D convolution operation, h denotes static PRF of system, R_i denotes dynamic PRF of system which is different exposure time of integration function.

1.2 Model of point response function

The idea point response function is formulated as followed, which represents the characteristic of the optical imaging system

$$h=h_1\otimes h_2\otimes h_3=\frac{1}{2\pi\sigma^2}\int_0^T \delta_{k(t)}\mathrm{d}t\cdot \int_{x-\frac{1}{2}}^{x+\frac{1}{2}}\int_{y-\frac{1}{2}}^{y+\frac{1}{2}}\exp\left(\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}\right)\cdot \mathrm{sinc}(x)\mathrm{sinc}(y)\mathrm{sinc}(xvT)\exp(-\mathrm{i}\pi xvT_i)\mathrm{d}x\mathrm{d}y \tag{2}$$

Here, the term $\exp\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}$ is expression for the optical system function, $\mathrm{sinc}(x\Delta x)\mathrm{sinc}(y\Delta y)$ is expression for the detector sampling function, and $\mathrm{sinc}(xvT)\exp(-\mathrm{i}\pi xvT)$ is expression of temporal function. Thus, PRF of imaging system is written as

$$\mathrm{prf}(x,y,T)=R_{\lambda,\sigma}(\phi_1(T),\phi_2(T),\cdots,\phi_n(T),T)\otimes h=$$

$$\frac{1}{2\pi\sigma^2}\int_0^T\delta_{k(t)}\mathrm{d}t\int_{x-\frac{1}{2}}^{x+\frac{1}{2}}\int_{y-\frac{1}{2}}^{y+\frac{1}{2}}\exp\left(-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}\right)$$

$$\mathrm{sinc}(kx)\mathrm{sinc}(ky)\mathrm{sinc}(kxvT)\exp(-\mathrm{i}\pi kxvT_i)\mathrm{d}x\mathrm{d}y \quad (3)$$

Where, (x_0,y_0) denotes response function of central position, (x,y) denotes projection region of detector on the focal plane, the wavelength λ ranging into Mid-infrared. And C denotes support region of energy, σ denotes Gaussian shape function of standard variance. In addition, σ could denote diffusion radius of system PRF. It should note that $\mathrm{sinc}(x)=\frac{\mathrm{sinc}(\pi x)}{\pi x}$, T denote integration time at ith exposure time, v denote scan velocity, and $\delta_{k(t)}$ denote Delta function. Here, T is derived from $T=\frac{t}{i}$. And t is total imaging time. The Fourier transform of point response function is

$$\mathrm{PRF}_i=\mathrm{FFT}(\mathrm{prf}_i) \quad (4)$$

The formulation of adjacent exposure time information Fourier transform could be expressed as

$$F_{i-1}(\mu,v)=\frac{1}{MN}\sum_{x=1}^{M}\sum_{y=1}^{N}L_{i-1}(x,y)\exp[-j2\pi(\mu x/M+vy/N)]$$

$$\mu=1,\cdots,M \quad v=1,\cdots,N$$

$$F_i(\mu,v)=\frac{1}{MN}\sum_{x=1}^{M}\sum_{y=1}^{N}L_i(x,y)\exp[-j2\pi(\mu x/M+vy/N)]$$

$$\mu=1,\cdots,M \quad v=1,\cdots,N \quad (5)$$

Where, (M, N) is size of image, (μ,v) is size of frequency spectrum on the Sobolev space, and (x,y) is coordinate position on the Hilbert space.

2 Deconvolution method based on frequency total variation

The total variation optimization[9-13] on frequency domain is used in the proposed method. The principle is energy minimization based on bounded variation equation[14-15]. The formula is written as

$$\mathrm{argmin}\sum\|\mathrm{PRF}_i(\mu,v)F_{\mathrm{final},k}(\mu,v)-F_{i,k}(\mu,v)\|_2^2+\tau_i TV_{i,\Omega}+$$

$$\sum\beta_i\cdot\|F_{i,k}(\mu,v)-F_{i-1,k}(\mu,v)\|_1 \quad (6)$$

Where, $\sum_{m=1}^{n}\|\cdot\|_2^2$ denotes l_2 norm constraint, $\|\cdot\|_1$ denotes l_1 norm constraint, Ω denotes spectrum support region, τ_i denotes constrained parameter of bounded variation term, β_i is called correlated parameter of images during adjacent times exposure, $F_{i,k}(\mu,v)$ denotes kth iteration frequency information, $TV_{i,\Omega}$ denotes total bounded variation on the frequency space, which could be expressed as

$$TV_{i,\Omega}=\sqrt{(F_{i,k}(\mu+1,v)-F_{i,k}(\mu,v))^2+(F_{i,k}(\mu,v+1)-F_{i,k}(\mu,v))^2} \quad (7)$$

Finally, we reconstructed the image using inverse Fourier transform. It could be expressed as

$$\frac{1}{MN}\sum_{x=1}^{M}\sum_{y=1}^{N}F_{\mathrm{final}}(\mu,v)\exp[-j2\pi(\mu x/M+vy/N)]$$

$$\mu=1,\cdots,M \quad v=1,\cdots,N \quad (8)$$

3 Experimental results and analysis

In this section, the space object observation of the optical imaging system is simulated. The detecting spectrum range is Mid-Infrared, which is particularly well suited for the space object. The trajectory of the system PRF is simulated in Fig.1. And random noise is simulated as part of the factors. Then, enhancement method is used to reconstruct image, which is combined with the information between the adjacent exposure images and based on norm constraint method on frequency domain. Figure 2 is shown as the comparison of the result for various filtering method. As the result, clearer image is got by the proposed method.

Figure 1 is shown as the result of LR filtering method at single exposure time, but the effect is actually modest, at least on the visual effect of the image. The boundary between the target and the background is contaminative, and there are some "pseudo ringing" in the target edge. It shows that LR filtering method does not maintain the continuity of target edge.The restored image is shown on Fig.3 as restoration by our proposed algorithm. The effect of image enhancement is evident from both sharp edges and bright target, listed as Tab.1. We note that the proposed algorithm allows a significant improvement

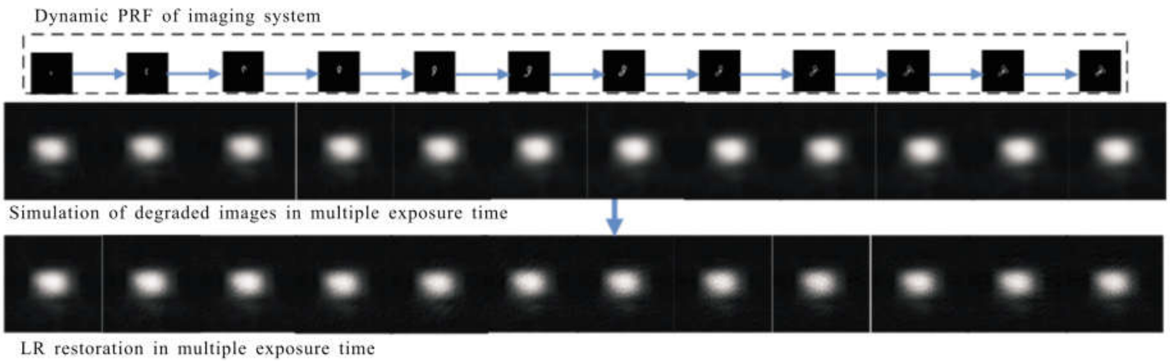

Fig.1 Trajectory of the system point response function and simulation of the degraded images on multiple exposures

of the image quality indexes such as entropy, stand derivation, Edge Preserve Index (EPI) and PSNR. And the sensitivity of high is improved for detecting space surveillance.

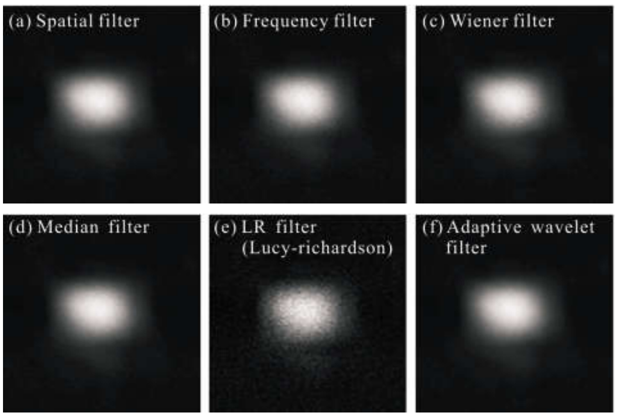

Fig.2 Comparison of the result for various filtering method

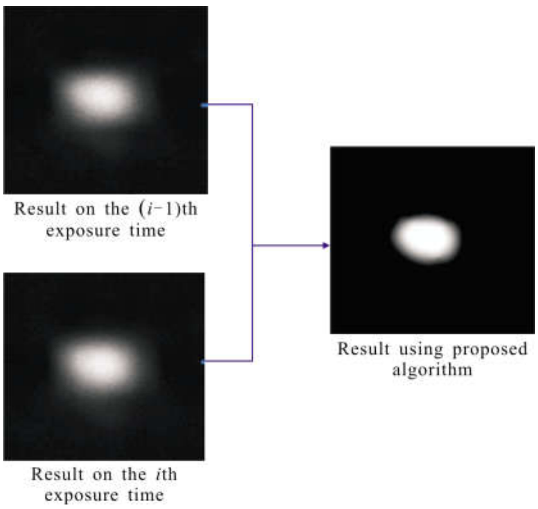

Fig.3 Restored image using information between adjacent spatial-temporal frames

Tab.1 Evaluation index of image quality

Algorithm	Index			
	Entropy	Stand derivation	EPI	PSNR
Spatial filter	4.79	37.91	0.32	33.65
Frequency filter	4.74	37.86	0.41	34.12
Weiner filter	4.31	37.62	0.39	33.76
Median filter	4.65	38.12	0.42	33.68
LR filter	4.72	37.74	0.47	34.68
Adaptive wavelet filter	4.78	38.08	0.56	34.76
Proposed algorithm	5.93	49.03	0.64	36.08

4 Conclusions

In this paper, we formulate the model of imaging system. The dynamic PRF of the optical imaging system is simulated during multiple exposure times. And we propose the enhancement algorithm based on information of the adjacent exposure time images. The norm optimization method is used on the frequency domain. As a result, the corrupted image can be better restored and enhanced. The proposed algorithm is better than conventional algorithm by being measured of evaluation index. For future work, the proposed model is extended to blind restoration. And the real-time retrieval of space object is also an interesting future research direction.

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